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Energy fluxes and the Priestley–Taylor parameter over winter wheat and maize in the North China Plain

Yongqiang Zhang,[1,2]* Changming Liu,[1] Qiang Yu,[1] Yanjun Shen,[3] Eloise Kendy,[4]
Akihiko Kondoh,[5] Changyuan Tang[3] and Hongyong Sun[2]

[1] *Institute of Agricultural Modernization, Chinese Academy of Sciences, Shijiazhuang 050021, People's Republic of China*
[2] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, People's Republic of China*
[3] *Graduate School of Science and Technology, Chiba University 1-33 Yayoi, Inage, Chiba 263-8522, Japan*
[4] *Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA*
[5] *Center for Environmental Remote Sensing, Chiba University 1-33 Yayoi, Inage, Chiba 265-8522, Japan*

Abstract:

Surface energy fluxes above the canopies of well-irrigated winter wheat and maize in the North China Plain were measured by the Bowen-ratio energy balance technique in 1999–2000. Seasonal variation of the ratio of latent heat flux λE to available energy $R_n - G$ showed that the ratio of λE to $R_n - G$ exceeded 83% when leaf area index (LAI) varied from 2·0 to 6·0. The seasonal trend of evaporative fraction (EF) for winter wheat was similar to that of LAI before senescence stage, which is a critical factor controlling EF, which itself reflects the partitioning of available energy into λE. The Priestley–Taylor parameter α over the wheat and maize canopies changed greatly over the course of a growing season, and the seasonal average α of winter wheat was 1·17 and 1·26, and that of maize was 1·06 and 1·09 in the two consecutive years. α for winter wheat was exponentially correlated to 0–20 cm surface soil moisture, but not for maize and with the increase of soil depths, the correlation between α and soil moisture was weak. Under different soil moisture conditions, a linear correlation between extractable soil water and leaf water potential ψ for winter wheat was found. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS surface energy fluxes; Priestley–Taylor parameter; soil moisture; winter wheat; maize; North China Plain (NCP)

INTRODUCTION

Water shortage is a serious constraint on crop production in the North China Plain (NCP), a major wheat and maize production area in China (Wang *et al*., 2001). The situation has been aggravated since 1990s with an increase in agricultural and industrial demand for water. To manage limited water resources, it is crucial to quantify actual crop water use. Although regional studies are useful for large-scale planning, ultimately, water is managed at the field scale. Therefore, field-scale analysis of evapotranspiration (ET) is essential for on-the-ground water management.

Several approaches are available for determining field-scale evapotranspiration. These include measurement of surface energy fluxes and solution of the Priestley–Taylor equation. As a technique of energy fluxes, the Bowen-ratio energy balance (BREB) technique has been used extensively to determine ET over short time intervals owing to its portability and low cost relative to other micrometeorological techniques (Ashktorab *et al*., 1989; Cellier and Brunet, 1992; Bland *et al*., 1996; Steduto and Hsiao, 1998a,b; Shen *et al*., 2002, 2004; Zhang *et al*., 2002). However, long-term surface energy flux measurements are seldom undertaken in the NCP, especially on a seasonal basis. The Priestley–Taylor (P–T) approach to estimating ET depends on accurate

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* Correspondence to: Yongqiang Zhang, Hydrology and Water Resources Branch, Institute of Geographical Sciences and Natural Resources Research, CAS Building 917, Datun Rd, Anwai, Beijing 100101, China. E-mail: zhangyq@igsnrr.ac.cn

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determination of the P–T parameter α, which is a function of the Bowen ratio β and evaporative fraction EF. A value of α-1·26 is usually adopted for wet surfaces (Priestley and Taylor, 1972; Stannard, 1993). Flint and Childs (1991) reported α values, calculated from numerous studies over various landscapes, ranging from 0·7 to 1·6. Jury and Tanner (1975) found α values as large as 1·57 under strongly advective conditions. Pereira and Nova (1992) indicated that the original proposition of $\alpha = 1\cdot26$ is suitable for potential conditions, but not for advective conditions. Previous studies have determined α for the NCP only at the regional scale. To determine ET accurately at the field scale, seasonal variations of α must be locally determined at that scale. The relationship between α and soil moisture improves our understanding of the effects of crop water stress on ET. Variation in α has been related to sensible heat flux and canopy resistance, based on model simulations of atmospheric boundary-layer development (de Bruin, 1983; McNaughton and Spriggs, 1989; Kustas *et al.*, 1996). Flint and Childs (1991) calculated α by assuming an exponential decrease in ET as soil water content decreases. Crago and Brutsaert (1992) described other efforts to explain the relationship between α and surface soil moisture. Slabbers (1980) developed a practical approach for relating soil water stress to ET which, until now, could not be applied to the NCP.

The objectives of this study were to:

1. Investigate the processes of surface energy fluxes, i.e. soil heat flux G, sensible heat flux H and latent heat flux λE, in the NCP.
2. Study the variation of the P–T parameter α during different wheat and maize growth stages in the NCP.
3. Study the effect of soil moisture stress on α and ET.

MATERIALS AND METHODS

Site description

This study was conducted at Luancheng Agro-Ecosystem Station (37°53′N, 114°41′E, 50·1 m a.s.l.), one of 29 agricultural ecosystem stations of the Chinese Ecological Research Network. The observation was done at the experimental site of the station (Figure 1). The experimental site is located in a high-yield agricultural area of the NCP, with fertile loam soil. With the typical winter wheat–summer maize rotation, the area produces two crops annually. The rotation at the site is the same as that around the site.

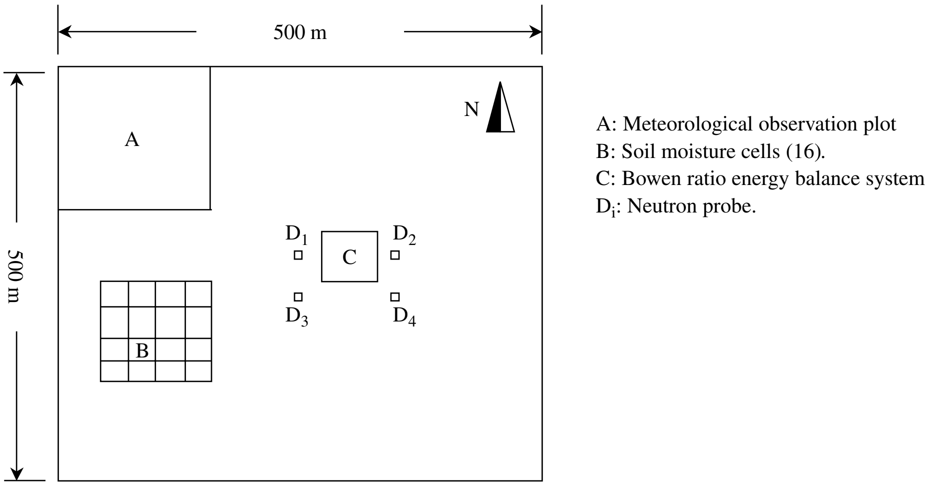

Figure 1. Layout of the experimental site at Luancheng Agro-Ecosystem Station. The conditions of the surrounding field of the site, including terrain, the method of irrigation and crop structure, are completely the same as those of the experimental site

With its semi-arid monsoon climate, precipitation in the NCP mostly occurs from July to September (Figure 2). Mean annual precipitation, temperature and global radiation at the station over past 20 years were 480·7 mm, 12·2 °C, and 524·2 kJ cm^{-2} respectively. During the summer, precipitation is usually sufficient to meet the water consumption demands of maize. However, drought often occurs during the winter wheat season (Table I), when the average ET rate of about 480 mm greatly exceeds the average precipitation rate of about 130 mm. Irrigation from groundwater is used to meet the water deficit requirement for winter wheat, resulting in chronic groundwater table declines in the NCP. At the research station, the groundwater table has declined about 0·7 m year^{-1} for at least the last 20 years.

Winter wheat is planted in early October, emerges in mid October, and is dormant from late November to late the following February (Table I). During these stages, soil moisture changes slowly because of the small leaf area index (LAI) and less soil evaporation. The crop revives in early March, it grows quickly, and the

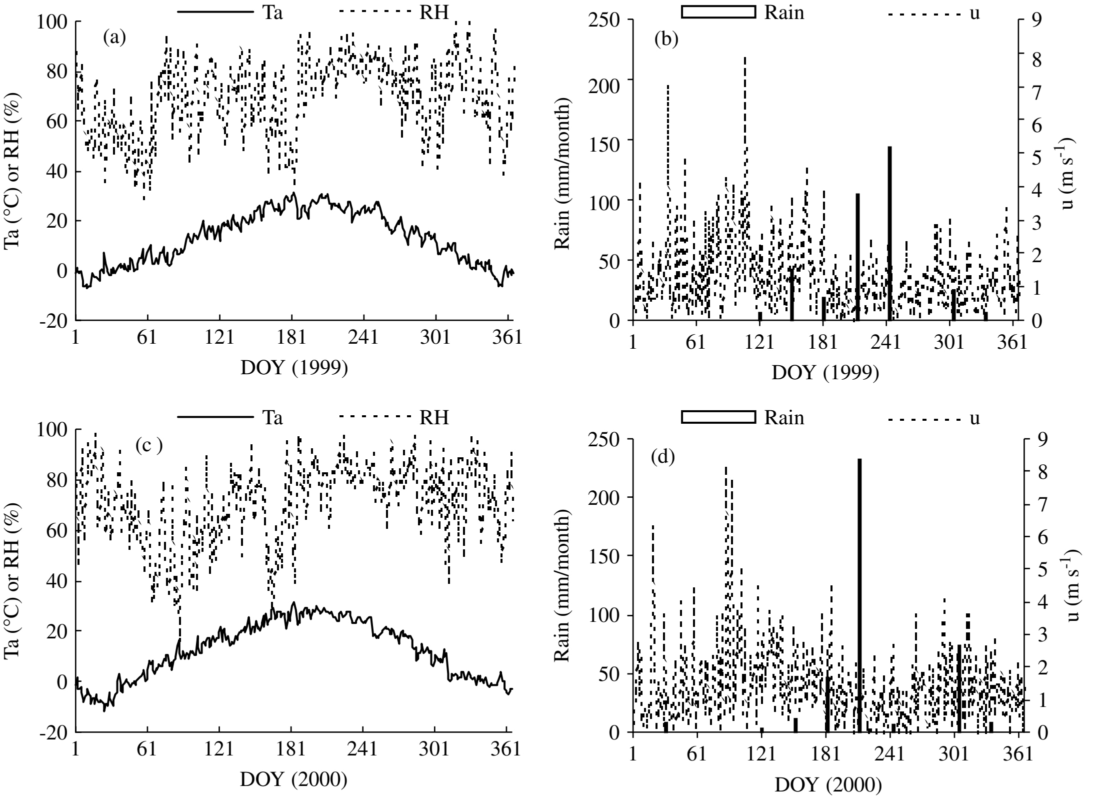

Figure 2. Seasonal trends in air temperature T_a, relative humidity (RH), wind speed u, and rainfall (mm/month) in 1999 and 2000. T_a, RH and u are daily averages of measurements taken at 8 : 00, 14 : 00 and 20 : 00

Table I. Growth stages of winter wheat and maize at Luancheng Agro-Ecosystem Station, 1999–2000

	Stage (day of year (DOY))						
	Emergence	Winter dormancy	Revival	Stem extension	Heading	Flowering	Grain filling
Winter wheat	285	320	61	100	121	125	131
Maize	167	—	—	200	—	223	233

soil moisture decreases drastically, requiring two or three irrigations, of about 60–80 mm per irrigation, from its revival stage to its grain filling stage. Wheat is harvested in mid June.

Maize is planted between rows of wheat in early June and grows quickly after emergence. The LAI of maize reaches its maximum during the flowering stage, and decreases thereafter. Heavy summer rains usually can meet the crop water demands from its stem extension to its flowering stage.

Data collection

The BREB instrument was at site C, where enough irrigation was applied during the winter wheat and summer maize growing seasons of 1999 and 2000. Soil water stress experiments for this study were conducted at site B from April to May 2001 (Figure 1).

Meteorological parameters. All meteorological parameters of the energy balance were measured by the BREB technique (Campbell Scientific, Logan, UT). BREB measurements include net radiation, soil heat flux, temperature, vapour pressure gradient, and wind speed. Net radiation was measured by a Q7-1 net radiometer with sensor surfaces protected by hemispherical polyethylene windshield domes. Soil heat flux was measured by two HFT3 soil heat flux plates buried inter-rows and inter-plants at 2 cm beneath the soil surface. Air temperature at two heights, used to calculate the Bowen ratio, was measured by Type E chromel–constantan thermocouples. The lower arm was positioned 50 cm above the surface of the canopy with ventilation, and the upper arm was 1·0 m higher than the lower arm. Vapour pressure at the same two heights, also used to calculate the Bowen ratio, was measured by a single dew-cell hygrometer (Dew-10, general Eastern, Water Town, MA). A three-cup anemometer measured wind speed. In the winter wheat season and the prophase of the maize season, the anemometer was installed at 2 m above the ground; when the height of maize canopy was over 2 m, it was installed at 3 m above the ground. All parameters were recorded every 0·625 s, averaged every 20 min and logged with a data logger (Model CR10X, Campbell Scientific, Logan, UT) (Zhang *et al.*, 2002). The prevailing wind is in the southeast direction, where there is a >500 m wide fetch distance.

Canopy and soil moisture parameters. Stomatal resistance was measured at site B with a porometer (Model AP4-type, Delta-T Devices Corp., UK). Stomatal resistance was measured in 16 separate 5×10 m^2 cells (site B, Figure 2). The 16 cells represent five irrigation treatments: treatment A had four replicates, and the other four treatments each hard three replicates (Table II). Each cell for a treatment was randomly selected. Ten sun-lit leaves were randomly sampled from each treatment for stomatal resistance measurement. Before each measurement, the humidity around the porometer sensor was calibrated to ambient air conditions. The water potential of leaves ψ was measured with a pressure chamber (Lanzhou University, P. R. China). On selected cloudless days, five flag leaves from each treatment were measured. On clear days, ψ was observed every 2 h from 07:00 to 19:00.

Table II. Irrigation schedules for different winter-wheat treatments

Treatment[a]	Growth stage and irrigation treatment (θ/θ_{FC})[b]				
	Winter dormancy	Revival	Stem extension	Heading	Grain filling
A	—	—	—	—	—
B	1·0	—	0·8	0·8	0·8
C	1·0	0·8	—	0·8	0·8
D	1·0	0·8	0·8	0·8	—
E	1·0	1·0	1·0	1·0	1·0

[a] A: drought stress; B: stress during revival stage; C: stress during stem extension stage; *D*: stress during grain filling stage; E: no stress.
[b] θ represents soil-water volume in the root zone after irrigation; θ_{FC} represents volumetric field capacity; the dashes show that winter wheat is water-stressed and the ratio of θ to θ_{FC} is not controlled after irrigation.

Plant height and plant density were measured every 5 days at site C throughout the growing seasons, and 10 random leaves at site C were cropped to measure leaf area and biomass at the same time. Volumetric soil moisture was measured by a neutron probe (Institute of Hydrology, UK). Four access tubes were installed around the Bowen-ratio system, and one additional tube was installed in each of the 16 cells at site B. Soil moisture was measured at 20 cm intervals from depths of 0–200 or 0–180 cm approximately every 5 days during the growing seasons; soil moisture at 0–20 cm was supplemented by gravimetric samples. The 0–200 cm neutron-probe readings were calibrated by gravimetric soil moisture when the neutron probes were installed in 1998. Before and after most irrigation and precipitation events, additional measurements were taken.

Methods

The energy balance above the crop canopy can be expressed as

$$R_\mathrm{n} = \lambda E + H + G \tag{1}$$

where R_n (W m^{-2}) is net radiation flux, λE (W m^{-2}) is the flux of latent heat of evapotranspiration from the canopy and soil, H (W m^{-2}) is sensible heat flux from the canopy and soil, and G (W m^{-2}) is soil heat flux from the soil surface.

The Bowen ratio β is defined as $H/\lambda E$; knowing β allows estimation of λE using:

$$\lambda E = \frac{R_\mathrm{n} - G}{1 + \beta} \tag{2}$$

The Bowen ratio is estimated from measurements of gradients of temperature and vapour pressure above an evaporation surface, i.e:

$$\beta = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} \tag{3}$$

where γ is the psychrometric constant (0·0654 kPa °C^{-1}) and ΔT and Δe are respectively the vertical temperature (°C) and vapour pressure (kPa) differences above a crop canopy.

The latent heat flux of components of the energy balance can be gained by analysing the dimensionless evaporative fraction EF, defined as

$$EF = \frac{\lambda E}{R_\mathrm{n} - G} \tag{4}$$

Because EF is a ratio of latent heat flux to available energy ($R_\mathrm{n} - G$), it is used to characterize the energy partition over land surfaces and has potential for inferring daily energy balance information based on midday measurement (Nichols and Cuenca, 1993).

The P–T parameter α is computed thus:

$$\alpha = \frac{\lambda E(\Delta + \gamma)}{\Delta(R_\mathrm{n} - G)} = \frac{\Delta + \gamma}{\Delta(1 + \beta)} \tag{5}$$

A value of $\alpha = 1{\cdot}26$ has been adopted for most wet surfaces (Priestley and Taylor, 1972). However, α ranging from 0·7 to 1·6 over various landscapes was reported (Flint and Childs, 1991).

From Equations (4) and (5) we have

$$\mathrm{EF} = \frac{\Delta}{\Delta + \gamma}\alpha \tag{6}$$

Soil moisture has a direct impact on α (Crago and Brutsaert, 1992; Crago, 1996). The relationship can be given by an exponential relation as follows (Crago, 1996):

$$\alpha = k\left[1 - \exp\left(-c\frac{\theta - d}{\theta_\mathrm{fc}}\right)\right] \tag{7}$$

where k, c, and d are empirical parameters, θ is the volumetric soil moisture and θ_{fc} is the field capacity.

The extractable soil water (ESW) is defined as

$$\mathrm{ESW} = \frac{\theta - \theta_{\mathrm{wp}}}{\theta_{\mathrm{fc}} - \theta_{\mathrm{wp}}} \tag{8}$$

where θ_{fc} and θ_{wp} are field capacity and wilting point respectively.

A simple way to account for the effects of soil water deficit on ET is to express the ratio of actual ET to potential ET ($\mathrm{ET_p}$) as a function of volumetric soil moisture in the root zone. To indicate the effects of water deficit on ET, Slabbers (1980) suggested a practical way of estimating ESW as a function of leaf water potential ψ (bar) and $\mathrm{ET_p}$ (mm day^{-1}):

$$\mathrm{ESW} = a + b\frac{\psi}{\mathrm{ET}_p} \tag{9}$$

where a and b are empirical parameters; ESW ranges from 1·0 (indicating no water-stress), to 0·0 (indicating a most serious soil water deficit); $\mathrm{ET_p}$ is calculated according to daily accumulation of potential latent heat flux λE_{p} as follows:

$$\lambda E_{\mathrm{p}} = \frac{\Delta(R_{\mathrm{n}} - G) + \dfrac{\rho_{\mathrm{a}} C_p D}{r_{\mathrm{a}}}}{(\Delta + \gamma)} \tag{10}$$

where Δ (kP$_{\mathrm{a}}$ °C^{-1}) is the slope of the function relating saturation vapour pressure to air temperature, γ is the psychrometric constant, r_{a}(s m^{-1}) is the aerodynamic resistance of water vapour ρ_{a} (mol m^{-3}), is air density C_p (J mol^{-1} °C^{-1}) is the specific heat capacity of air at constant pressure, and D (kPa) is the vapour pressure deficit. r_{a} is calculated according to

$$r_{\mathrm{a}} = \frac{u(z)}{u_*^2(z)} \tag{11}$$

where $u(z)$ and $u^*(z)$ (m s^{-1}) are the wind speed and friction velocity at a reference height z (m) above the ground. $u^*(z)$ is calculated according to the log law of wind speed:

$$u^* = \frac{k}{\ln\left(\dfrac{z-d}{z_0}\right)} u_z \tag{12}$$

where k is the von Karman constant (0·42 used), d is the zero plane displacement, which was calculated as $d = 0{\cdot}64\ h_{\mathrm{c}}$ (crop height), and z_0 is roughness length as $z_0 = 0{\cdot}13 h_{\mathrm{c}}$.

RESULTS

Variation of surface energy fluxes over crop growth stages

Figure 3 shows the seasonal trends of the components of the surface energy above canopies of winter wheat and maize in 1999 and 2000. All fluxes in Figure 3 are midday averages from 10:00 to 15:00. The data show that the noon energy-balanced components are less scattered than the daytime average values. Energy fluxes for winter wheat are shown from the revival to the grain filling stage, and those of maize are shown from the stem extension to the grain filling stage (Table I correlates growth stages described in the text to DOY notation shown in the figures). Midday fluxes on rainy days are not shown. Figure 3 shows that R_{n} and λE varied drastically, but exhibited similar seasonal trends. H and G were relatively small. Average EF (same as $\lambda E/(R_{\mathrm{n}} - G)$) all exceeded 83% during the four growing stages, and $H/(R_{\mathrm{n}} - G)$ varied between 0·13 and 0·17. EF and $H/(R_{\mathrm{n}} - G)$ for winter wheat were almost the same as for maize (Table III). The

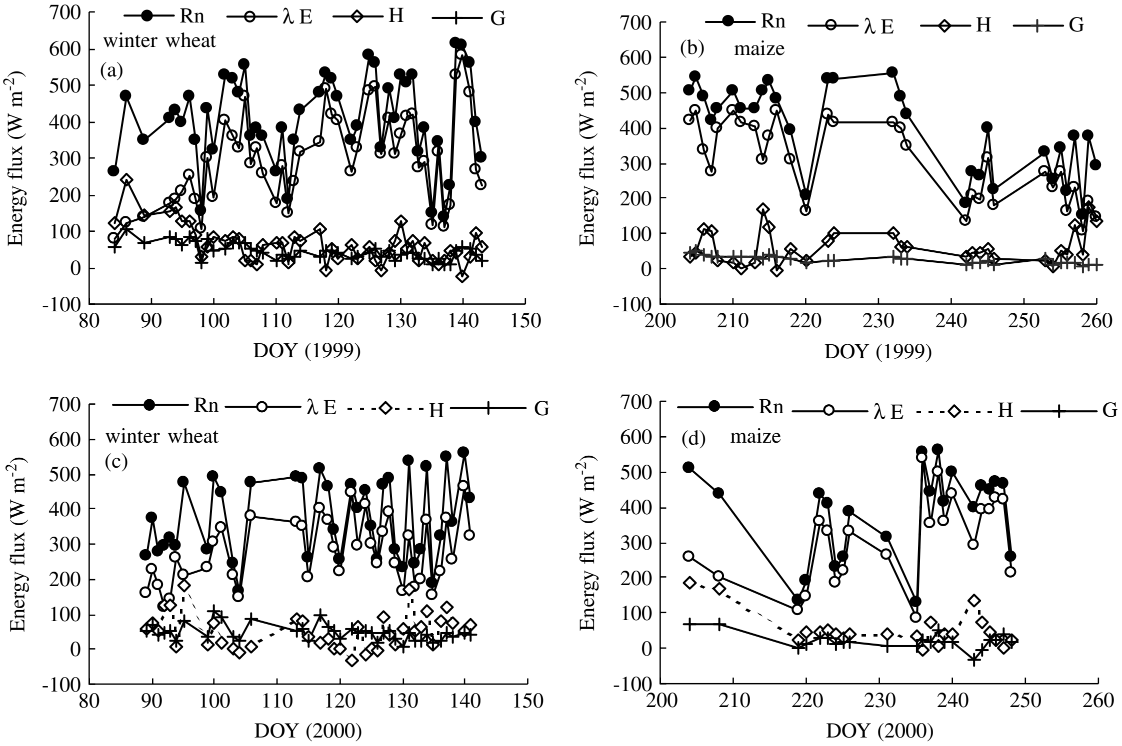

Figure 3. Seasonal variation of surface energy fluxes in 1999 and 2000. Net radiation flux R_n, latent heat flux λE, sensible heat flux H, and soil heat flux G were measured by the BREB technique, and averaged from 10:00 to 15:00

Table III. Seasonal average surface energy fluxes and ratios in 1999 and 2000

Growing season	R_n (W m^{-2})	λE (W m^{-2})	H (W m^{-2})	G (W m^{-2})	$\lambda E/(R_n - G)$ (W m^{-2})	$H/(R_n - G)$ (W m^{-2})	β
Wheat (1999)	406·45	297·99	63·82	44·63	0·83	0·17	0·31
Maize (1999)	392·83	303·78	62·51	26·53	0·83	0·17	0·25
Wheat (2000)	374·77	276·91	50·86	47·01	0·84	0·16	0·22
Maize (2000)	381·91	309·45	51·43	21·03	0·87	0·13	0·22

energy balance reveals that, following the stem extension growth stages of both winter wheat and maize, the available energy ($R_n - G$) was used mainly for crop ET.

As expected, EF and $H/(R_n - G)$ varied considerably from day to day, depending on the conditions of weather, soil moisture and crop growing stages. Average midday EF for winter wheat ranged between 0·34 and 1·08, and average midday $H/(R_n - G)$ varied from −0·08 to 0·64; average midday EF for maize ranged between 0·52 and 1·01, and average midday $H/(R_n - G)$ varied from −0·01 to 0·48 (Figure 4). Peak EF for winter wheat occurred from the stem extension stage to grain-filling stage, whereas EF for maize exhibited no evident peak values. The seasonal trend of EF for winter wheat was similar to that of LAI before senescence stage, which varied from 2·0 to 6·0 (Figure 4). Unfortunately, owing to instrument problems, no energy balance components were acquired during the senescence stage in 1999 and 2000. The seasonal variation of EF for winter wheat showed the importance of LAI in controlling energy partitioning. The LAI of maize in 1999 was not obtained because we did not hire workers. In 2000, EF for maize did not exhibit a similar trend

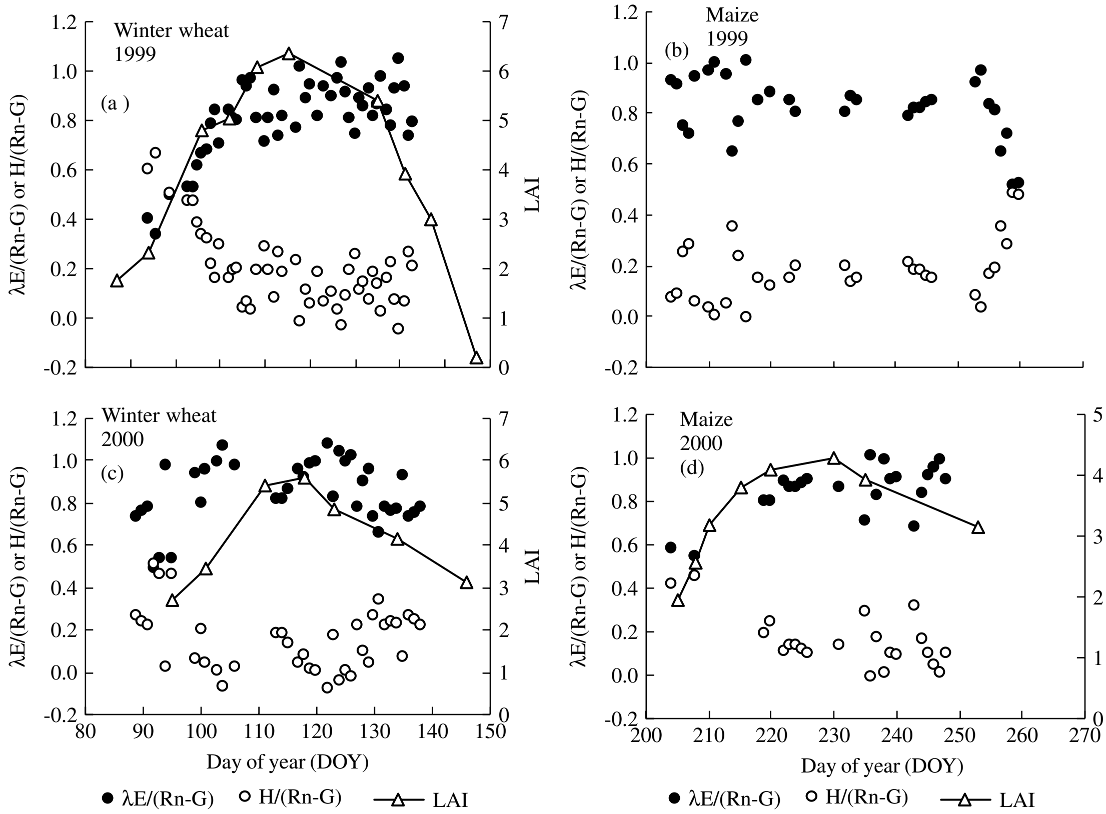

Figure 4. Seasonal variation of $\lambda E/(R_n - G)$ (defined as EF), $H/(R_n - G)$ and LAI from 1999 and 2000. Averaged from 10:00 to 15:00

to LAI. During the maize rainy season, the weather often changes dramatically over the course of a single day, so, unlike LAI, midday EF did not show an apparent seasonal pattern.

Variation of Bowen ratio and P–T parameter over crop growth stages

The Bowen ratio β reflects the partitioning of $R_n - G$ into H and λE. The P–T parameter α is a function of β and air temperature (Equation (5)). Surface energy fluxes from the land surface change seasonally at the experimental plot, where the main crops are winter wheat and maize. Figure 5 shows that β for winter wheat varied from 0 to 2·0, with the maximum value occurring during the revival stage. After revival, β decreased quickly and then stabilized near zero. Seasonal average β values were 0·31 and 0·22 in 1999 and 2000 respectively (Table III). β for maize varied more drastically than for winter wheat, showing no obvious seasonal trend before the grain filling stage in 1999, after which β increased. No data are available for the grain filling stage in 2000, when the BREB system was removed.

The seasonal trend of α is negatively correlated with β (Equation (5)). In our experiment, α generally ranged between 0·5 and 1·5 (Figure 5). For winter wheat, α was lower than 1·0 during the revival stage and higher than 1·0 thereafter in 1999. Seasonal average α values for winter wheat were 1·17 and 1·26 in 1999 and 2000 respectively. For maize, α was lower than 1·0 during grain filling. Before grain filling, α almost reached 1·0 on most days in 2000. Seasonal average α values for maize were 1·06 and 1·09 in 1999 and 2000 respectively. On the whole, α for wheat was higher than for maize under our experimental conditions.

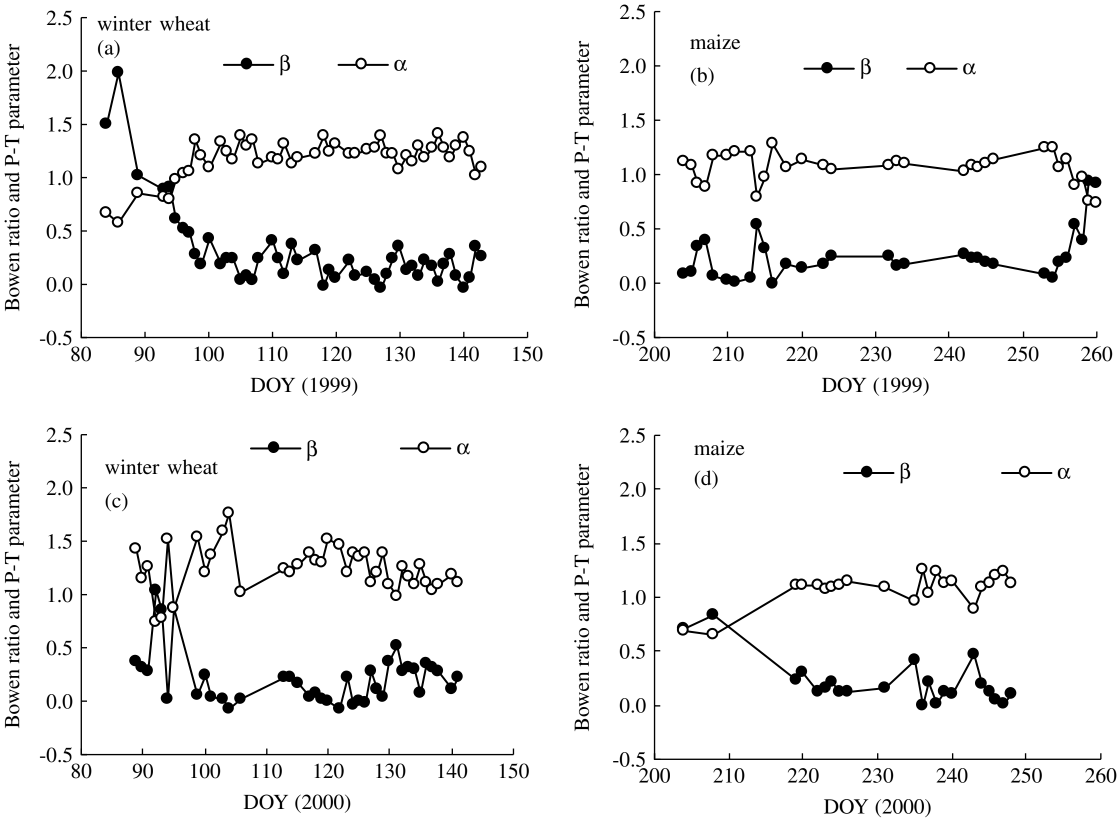

Figure 5. Seasonal variation of Bowen ratio β and P–T parameter α for winter wheat and maize in 1999 and 2000. β and α were averaged from 10:00 to 15:00

Comparison of midday EF and midday α

The temperature condition determines the correlation between EF and α (Equation (6)). Because of the different growing seasons between winter wheat and maize, the temperature environment around the winter wheat canopy is different from that around the maize canopy. EF was about $0{\cdot}686\alpha$ in the winter wheat season and was about $0{\cdot}782\alpha$ in the maize season. The correlation coefficient between the two variables was $R^2 = 0{\cdot}864$ in the wheat season, and was $R^2 = 0{\cdot}922$ in the maize season (Figure 6a and b). The correlation between EF and α indicates that midday $\Delta/(\Delta + \gamma)$ for wheat averages about 1/1·46; for maize it averages about 1/1·28.

Effects of soil water stress on ET, and α over winter wheat canopy

In our experiments, ESW usually varied between 0·22 and 0·73 under treatments B, C, D, and E (Table II), and between 0·02 and 0·05 under treatment A (drought deficit) during the heading and grain filling stages of winter wheat. Under the five soil moisture conditions we observed, ψ and ESW were linearly correlated by Equation (8). The parameter a varied between 0·34 and 0·46, and b varied between 1·06 and 1·65 from hour-to-hour during the observed days. The parameters a and b were 0·36 and 1·123 respectively from day-to-day in the winter wheat season (Figure 7).

The correlation between α and 0–20 cm soil moisture for winter wheat showed that midday α showed a certain change with the surface soil moisture (Figure 8) and midday α was expressed as the function of the surface soil moisture (Equation 7) according to Cargo (1996). The root mean square error (RMSE) between

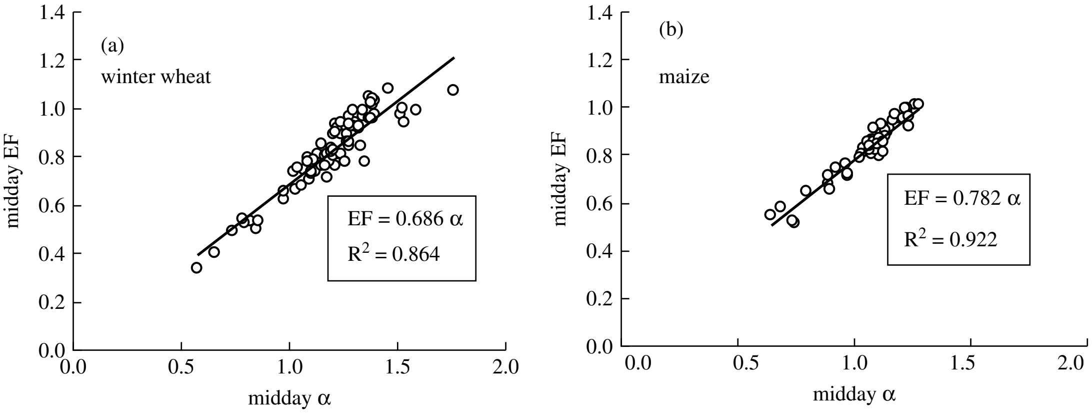

Figure 6. Comparisons of the midday EF and P–T parameter α in winter wheat season (a) and maize season (b) in 1999 and 2000

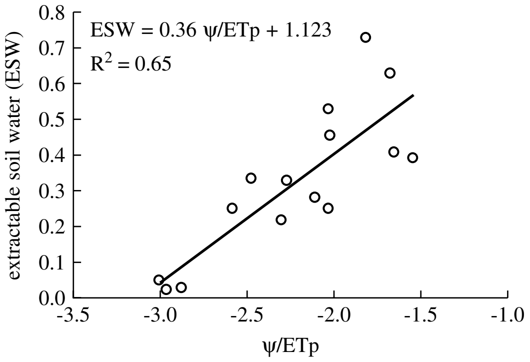

Figure 7. The correlation of $\psi/\mathrm{ET_p}$ (ψ is the leaf water potential; $\mathrm{ET_p}$ is potential ET) and ESW from heading to grain-filling stages of winter wheat in 2001

measured α and simulated α was about 0.06. By observation, it appeared that α was a stronger function of 0–20 cm soil moisture than 0–40 cm soil moisture or the soil moisture in the soil layers over 0–40 cm. The correlation between α and soil moisture for maize was weak, and no exponential correlation was found between α and 0–20 cm soil moisture. Kustas *et al.* (1996) and Crago and Brutsaert (1992) also found that near-surface soil moisture was not correlated with α. This is in contrast to Flint and Childs (1991), who believed that α was exponentially correlated with relative water saturation. The correlation between α and soil moisture for winter wheat or maize indicates that α is more easily dependent on surface soil moisture under slightly rainy weather conditions than under rainy weather conditions.

CONCLUDING DISCUSSION

Because winter wheat and maize are the two major crops produced in the NCP, it is very important for water-saving agricultural research to quantify their water consumption processes. The seasonal energy balance for wheat and maize shows that over 83% of available energy ($R_n - G$) is used for crop ET after revival growth stage. $H/(R_n - G)$ varied between 0·13 and 0·17 during the four observation seasons in 1999–2000. The seasonal trend of EF for winter wheat was similar to that of LAI before senescence stage. During these stages, LAI varies from 2·0 to 6·0, which is a critical factor controlling EF, which itself reflects the partitioning of available energy into λE.

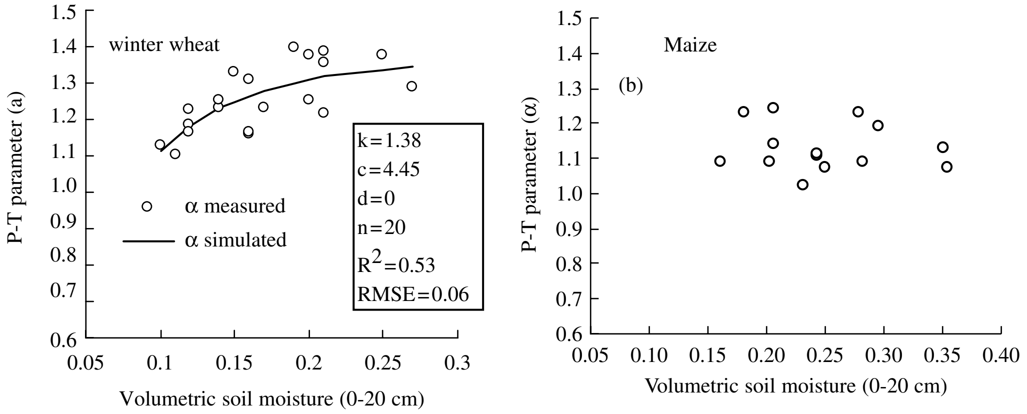

Figure 8. Midday values of the P–T parameter α for winter wheat (a) and maize (b) versus surface (0–20 cm) volumetric soil moisture

It is relatively simple to apply the P–T equation to calculate crop ET, especially over a large region. The key is to quantify α. Our experimental data show that α over wheat and maize canopies changes greatly over the course of a growing season, and the seasonal average α of winter wheat is higher than that of maize. Thus, α depends strongly on surface vegetation, microclimate conditions and surface soil moisture. We found there was an exponential correlation between 0–20 cm surface soil moisture and α for winter wheat, but not for maize, and soil moisture in deep soil layers (more than 20 cm deep) was not significantly correlated to α. In the maize season, microclimate conditions are more variable than those in the wheat season, which may reduce the effect of soil moisture on α. Translating these results from the field scale to the regional scale may require obtaining more information about scaling up of ET from the field scale to the regional scale. For instance, how can we evaluate regional evaporation in the NCP using the P–T equation under soil water deficit conditions? First, we must find the correlation between α and soil surface moisture at the field scale. Then, the regional evaporation can be determined based on a correlation of α between field and regional scales. Future research should be focused on the effect of soil moisture stress on α at the different experimental sites.

The correlation equation between ESW and ψ is a practical way to express the effect of soil water stress on ET in the NCP. The values of parameters a and b reflect the effect of ψ on ESW. Therefore, these constants may be used to diagnose the degree of crop water stress.

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