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Canopy water use efficiency of winter wheat in the North China Plain

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ABSTRACT

Canopy water use efficiency (*W*), the ratio of crop productivity to evapotranspiration (ET), is critical in determining the production and water use for winter wheat (*Triticum aestivum* L.) in the North China Plain, where winter wheat is a major crop and rainfall is scarce and variable. With the eddy covariance (EC) technique, we estimated canopy *W* of winter wheat at gross primary productivity (W_G) and net ecosystem productivity (W_N) levels from revival to maturing in three seasons of 2002/2003, 2003/2004 and 2004/2005 at Yucheng Agro-ecosystem Station. Meanwhile we also measured the biomass-based water use efficiency (W_B). Our results indicate that W_G, W_N and W_B showed the similar seasonal variation. Before jointing (revival-jointing), W_G, W_N and W_B were obviously lower with the values of 2.09–3.54 g C kg^{-1}, −0.71 to 0.06 g C kg^{-1} and 1.37–4.03 g kg^{-1}, respectively. After jointing (jointing-heading), the winter wheat began to grow vigorously, and W_G, W_N and W_B significantly increased to 5.26–6.78 g C kg^{-1}, 1.47–1.86 g C kg^{-1} and 6.41–7.03 g kg^{-1}, respectively. The maximums of W_G, W_N and W_B occurred around the stage of heading. Thereafter, W_G, W_N and W_B began to decrease. During the observed periods, three levels of productivity: GPP, NEP and aboveground biomass (AGB) all had fairly linear relationships with ET. The slopes of GPP–ET, NEP–ET and AGB–ET were 4.67–6.12 g C kg^{-1}, 1.50–2.08 g C kg^{-1} and 6.87–11.02 g kg^{-1}, respectively. Generally, photosynthetically active radiation (PAR) and daytime vapor pressure deficit (*D*) had negative effects on W_G, W_N and W_B except for on some cloudy days with low PAR and *D*. In many cases, W_G, W_N and W_B showed the similar patterns. While there were still some obvious differences between them besides in magnitude, such as their significantly different responses to PAR and *D* on cloudy and moist days.

1. Introduction

Winter wheat (*Triticum aestivum* L.), with an area of 14,560,000 hm^2, is a major crop in the North China Plain and accounts for 53% of wheat production in China (Liu and Chen, 2005). However, shortage of water resources has become the major limiting factor for wheat production (Liu et al., 2002; Zhang et al., 2005; Sun et al., 2006).

Investigating water use efficiency (*W*) is a valuable approach for analysis of water use by plants (Cowan, 1982; Hsiao, 1993; Shao et al., 2007). *W* has different definitions depending on the time and space scales of the processes and

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system aggregation it refers to (Steduto and Albrizio, 2005). At the leaf scale, W can be defined as the ratio of photosynthesis to transpiration. Leaf W is usually monitored by leaf cuvette method. Consequently, leaf W is difficult to monitor over long periods and usually cannot explain the differences observed at the canopy scales (Steduto et al., 1997; Asseng and Hsiao, 2000). At the canopy scale, W can be defined as the ratio of crop productivity to evapotranspiration (ET). Large gas chamber is the traditional tool used to measure the canopy W. However, the placement of the chamber changes the crop microenvironment and may produce biases and artifacts. In addition, the spatial extent of the chamber is relatively small (Baldocchi, 2003). More conveniently and for agronomic assessment, W has been expressed as the ratio of biomass produced to ET, referred to as biomass-based W (W_B). Usually W_B measurements are invasive and discontinuous. In recent years, some micrometeorological methods such as the eddy covariance (EC) method and the Bowen ratio/energy balance/CO_2 gradient method have been adopted as the direct and scale-appropriate methods to assess the canopy W. And the EC method is widely considered to be more definitive because it is based on theories of turbulence transport (Baldocchi, 2003; Yu et al., 2005).

There have been a number of studies on the yield and water use for winter wheat in the North China Plain (e.g. Zhang et al., 2005; Sun et al., 2006). And observations on leaf photosynthesis and transpiration also have been reported by many authors (e.g. Yu et al., 2002; Gao et al., 2004). However, less effort has been devoted to estimate the canopy W for the methodological difficulties in measurements. Zhu et al. (2004) firstly reported their measurements of the carbon dioxide flux (F_C) and water flux (F_W) with the EC technique over a winter wheat ecosystem in the North China Plain. F_C and F_W are also referred to as net ecosystem productivity (NEP) and ET, respectively. They assessed the diurnal variation of canopy water use efficiency (F_C/F_W) over 2 days. Wang et al. (2005) reported the seasonal courses of F_C and ET in a whole winter wheat season, but did not analyze W. Li et al. (2006a) measured the F_C of winter wheat in two seasons using the same flux tower as ours; and calculated the daily gross primary productivity (GPP), but did not estimate ET and W. In other areas, Baldocchi (1994) measured the F_C and ET over a winter wheat canopy using chamber method. Anthoni et al. (2004) reported the F_C and ET over a winter wheat canopy using EC technique and calculated GPP.

Here, we measured the canopy W of winter wheat by the EC method for the first time in the North China Plain. The objectives of this work were to: (1) assess the magnitude and pattern of the canopy W for winter wheat in the North China Plain; (2) compare the canopy W at three productivity levels: GPP (W_G), NEP (W_N) and aboveground biomass (AGB) (W_B) and (3) estimate the meteorological effects on W_G, W_N and W_B.

2. Experimental site, instrumentation and methodology

2.1. Site description

Measurements were conducted at Yucheng Agro-ecosystem Station from winter wheat revival (later February or early March) to maturing (later May or early June) in 2003, 2004 and 2005. The station is located in an irrigated agricultural field (36°57′N, 116°36′E, 28 m a.s.l.) in the North China Plain. The soil is mostly silt, light loam and medium loam. The groundwater table varies from 1.5 to 3.5 m with an average of 2.5 m. This site represents the largest agricultural area of winter wheat production in the North China Plain (Yu et al., 2006).

The measurement plot in this study is a field of winter wheat rotated with summer corn. The winter wheat growth stages, grain yield and nitrogen applied are showed in Table 1. In the North China Plain, sunlight and heat usually are plentiful for winter wheat production, but precipitation is scarce, especially from March to May, so irrigation is needed. The crop was well watered and fertilized. No pest and disease occurred in the whole seasons. Over 85% of carbon assimilation (Wang et al., 2005; Li et al., 2006a) and over 70% of ET (Liu et al., 2002; Wang et al., 2005) occur during the observed period. Meanwhile the EC system worked well in this period.

2.2. Measurements

Canopy CO_2 and H_2O fluxes have been continuously measured by the EC system since October 20, 2002. The system mainly composed of a 3D sonic anemometer (model CSAT3, Campbell Sci., Logan, UT) and an open path CO_2/H_2O analyzer (IRGA, Li-7500, Li-Cor Inc., Lincoln, Nebraska, USA), which could measure fluctuations and averages of wind velocity, temperature, water vapor and CO_2 concentrations. Data were sampled at 10 Hz and averaged over 30 min.

Along with the fluxes measurements, standard meteorological data were collected including vapor pressure, air temperature (T_a), relative humidity, photosynthetically active radiation (PAR), net radiation, precipitation (P), soil temperature, soil moisture, etc. Crop leaf area index (LAI) and AGB (dry weight) were measured about weekly.

2.3. Data analysis

To correct the effect of sensor tilt and sloping field on CO_2 and H_2O fluxes, the measured fluxes were corrected by rotating wind velocity axes with traditional triple rotation method to compute flux covariance that were aligned normal to the mean streamlines (Wilczak et al., 2001). Correction was made

Table 1 – The winter wheat growth stages, grain yield and nitrogen applied in three seasons of 2002/2003, 2003/2004 and 2004/2005

Wheat variety	Sowing date	Revival date	Jointing date	Heading date	Maturing date	Grain yield (kg hm^{-2})	Applied N (kg N hm^{-2})
Keyu13	15 October 2002	13 February 2003	25 March 2003	28 April 2003	4 June 2003	5260.6	182.5
Keyu13	23 October 2003	1 February 2004	9 March 2004	23 April 2004	4 June 2004	5235.3	215.3
Keyu13	14 October 2004	27 February 2005	27 March 2005	10 May 2005	8 June 2005	5169.3	195.5

on carbon dioxide and vapor flux for the density effects due to heat and water vapor transfer (Webb et al., 1980). We eliminated the data of abnormal and measured during the period of inadequate turbulence ($u^* < 0.15\ \mathrm{m\ s^{-1}}$). The flux data treatment was detailed in Yu et al. (2006). Daytime data gaps were filled using the equation of Michaelis–Menten (Michaelis and Menten, 1913). The nighttime data gaps were filled using the equation of Lloyd and Taylor (1994).

GPP was calculated as:

$$\mathrm{GPP} = \mathrm{NEP} + R_{\mathrm{ec}} \tag{1}$$

Here NEP is the net ecosystem productivity; NEP is measured directly by the EC system with the unit of $\mathrm{g\ C\ m^{-2}\ day^{-1}}$; R_{ec} ecosystem respiration calculated from the relationships between nighttime NEP and soil temperature in the upper 5 cm layer using the equation of Lloyd and Taylor (1994); R_{ec} is positive. Daily GPP was calculated as the sum of daytime NEP and R_{ec} with the unit of $\mathrm{g\ C\ m^{-2}\ day^{-1}}$. Daytime was defined as the time when PAR is more than 1 $\mu\mathrm{mol\ m^{-2}\ s^{-1}}$. Daily ET was calculated as the sum of the H_2O flux. Daytime vapor pressure deficit (D) was calculated as the average of the half-hour values during the daytime.

W_G, W_N, and W_B were calculated as:

$$W_G = \frac{\mathrm{GPP}}{\mathrm{ET}} \tag{2}$$

$$W_N = \frac{\mathrm{NEP}}{\mathrm{ET}} \tag{3}$$

$$W_B = \frac{\mathrm{AGB}}{\mathrm{ET}} \tag{4}$$

In order to analyze the effects of the meteorological factors, we only chose the data in the periods when LAI $> 4\ \mathrm{m^2\ m^{-2}}$ (DOY 101–136, 2003; DOY 94–132, 2004; DOY 101–141, 2005). And removed the data occurred on rainy and irrigation days. On these studied days, the canopy was well closed and the soil water conditions were suitable. We filled the daily values of LAI on the assumption that LAI varied with the same rate from the former measurement to the next measurement. These values of LAI showed no significant covariance with W_G, W_N, and W_B (t test), although they still had positive correlation with GPP, NEP and ET. Meanwhile, the daily average volumetric soil water content in the upper 10 cm depth (θ) showed no significant influence on W_G, W_N, and W_B (t test), either.

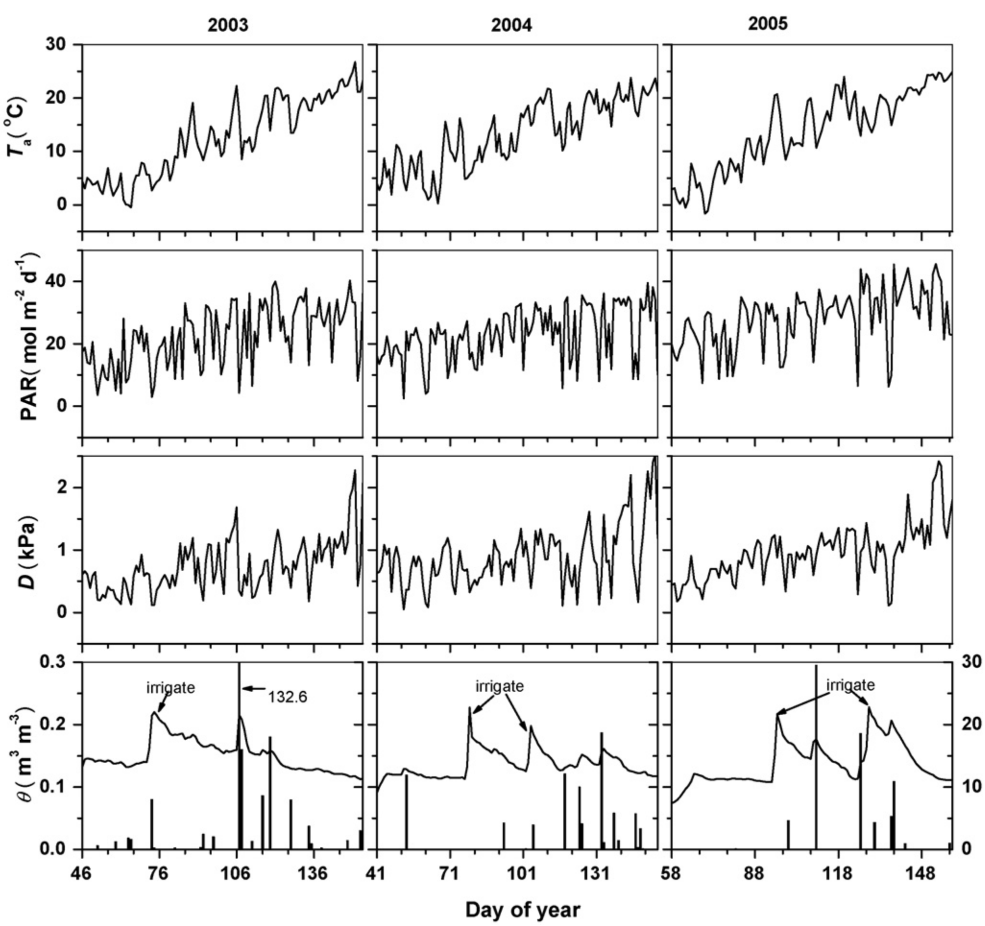

Fig. 1 – Seasonal courses of daily average air temperature (T_a), daily photosynthetically active radiation (PAR), averaged daytime vapor pressure deficit (D), daily average volumetric soil water content (θ) in the upper 10 cm layer and precipitation (P) from winter wheat revival to maturing in 2003, 2004 and 2005. A big precipitation of 132.6 mm occurred on DOY 107, 2003.

Table 2 – The averages of GPP, NEP and ET in stages of revival-jointing (R-J), jointing-heading (J-H) and heading-maturing (H-M) for seasons of 2003, 2004 and 2005

	GPP (g C m^{-2} day^{-1})			NEP (g C m^{-2} d^{1})			ET (kg m^{-2} day^{-1})		
	R-J	J-H	H-M	R-J	J-H	H-M	R-J	J-H	H-M
2003	1.42	11.23	11.39	0.14	3.54	2.49	0.68	2.13	2.78
2004	1.29	14.06	16.38	−0.26	3.82	3.07	0.57	2.06	2.97
2005	3.61	20.30	19.42	0.18	5.77	4.48	1.04	3.11	3.38

3. Results and discussion

3.1. *Cropland microenvironment, LAI and AGB*

Fig. 1 shows the seasonal courses of some key meteorological and soil variables during the three study periods from the winter wheat revival to maturing (DOY 46–155, 2003; DOY 41–156, 2004; DOY 58–159, 2005). T_a increased obviously from the winter wheat revival (later February or early March) to maturing (later May or early June). The minimum and maximum of T_a were −0.47 °C (DOY 65, 2003) and 26.74 °C (DOY 155, 2003), 0.24 °C (DOY 66, 2004) and 23.75 °C (DOY 145, 2004), −1.64 °C (DOY 70, 2005) and 24.91 °C (DOY 159, 2005), respectively.

PAR tended to increase during the observed period. In 2003, 2004 and 2005, the averages of PAR were 26.33, 24.70 and 30.60 mol m^{-2} day^{-1}, respectively. The maximums of PAR were 40.34 mol m^{-2} day^{-1} (DOY 150) for 2003, 39.55 (DOY 152) for 2004 and 45.66 (DOY 153) for 2005, respectively. On some cloudy and rainy days, the PAR could drop to very low levels (e.g. DOY 107, 2003).

Influenced by T_a, D showed some increasing tendency during the observed period. Meanwhile, D fluctuated significantly as the influence of weather conditions. On some cold or moist days, D was very low and even near to zero (e.g. DOY 53, 2003; DOY 134, 2003); on the warmer and dryer days, D was higher. The maximums of D were 2.27 kPa (DOY 152) in 2003, 2.52 kPa (DOY 155) in 2004 and 2.42 (DOY 154) in 2005, respectively.

Since the winter wheat was well watered, the volumetric soil water content in the upper 10 cm layer (θ) almost kept in the suitable arrange of 0.15–0.20 m^3 m^{-3} in the observed periods. θ was obviously influenced by P and irrigation. In 2003, 2004 and 2005, the P was 200.1, 70.8 and 75.2 mm, respectively. In 2003, there was much more P because there was a big precipitation of 132.6 mm (DOY 107, 2003). In 2003, the crop was irrigated one time (122.0 mm, DOY 60, 2003). In 2004 and 2005, the crop was irrigated two times (137.5 mm, DOY 79, 2004; 97.5 mm, DOY 104, 2004; 128.7 mm, DOY 91, 2005; 100.7 mm, DOY 121, 2005).

Fig. 2 shows the seasonal variations of LAI and AGB. Usually, winter wheat started to revive when daily average T_a exceeded 0 °C; and when daily average T_a reached 10 °C, winter wheat was re-greened and the stem began to joint. Before jointing, LAI and AGB were small and grew slowly. When the winter wheat started to joint, the crop grew vigorously and the LAI expanded rapidly. After heading, the LAI reached the peaks with the values of 5.59 (DOY 118) in 2003, 6.69 (DOY 114) in 2004 and 5.68 m^2 m^{-2} (DOY 130) in 2005, respectively. Thereafter the LAI began to decrease for the leaf senescence. At the end of the seasons, the AGB reached 1.64 for 2003, 1.79 for 2004 and 1.62 kg m^{-2} for 2005, respectively.

3.2. *Seasonal variations of GPP, NEP and ET*

GPP, NEP and ET showed the similar seasonal variations in the three observed periods (Fig. 3). Before jointing, GPP, NEP and ET were small and varied unobviously because the winter wheat was short and grew slowly at this stage. After jointing, GPP, NEP and ET increased rapidly accompanied with quick crop growing. The highest levels of GPP, NEP and ET occurred around the stage of heading. Thereafter, they decreased till the ending of the vigorous crop growth. Table 2 shows the averages of GPP, NEP and ET in the stages of revival-jointing (R-J), jointing-heading (J-H) and heading-maturing (H-M). Before jointing (R-J), the averages of GPP, NEP and ET were just 1.92–3.61 g C m^{-2} day^{-1}, 1, −0.26 to 0.18 g C m^{-2} day^{-1} and 0.57–1.04 kg m^{-2} day^{-1}, respectively. After jointing (J-H), the GPP, NEP and ET increased to 11.23–20.30 g C m^{-2} day^{-1}, 3.54–5.77 g C m^{-2} day^{-1} and 2.06–3.11 kg m^{-2} day^{-1}. At the stage of H-M, the GPP, NEP and ET were 11.93–19.42 g C m^{-2} day^{-1}, 2.49–4.48 g C m^{-2} day^{-1} and 2.78–3.38 kg m^{-2} day^{-1}. The maximums of daily GPP were 21.05 (DOY 111) in 2003, 27.02 (DOY 130) in 2004 and 31.41 g C m^{-2} day^{-1} (DOY 132) in 2005, respectively. The

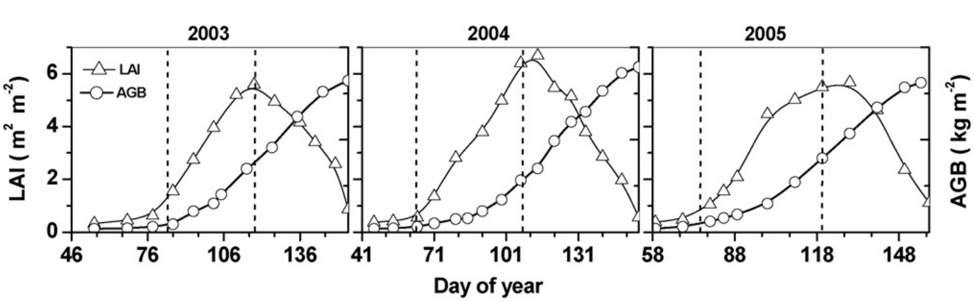

Fig. 2 – Seasonal variations of leaf area index (LAI) and above-ground biomass (AGB, dry weight) for winter wheat from revival to maturing in 2003, 2004 and 2005. The broken vertical lines indicate the dates of jointing (right) and heading (left).

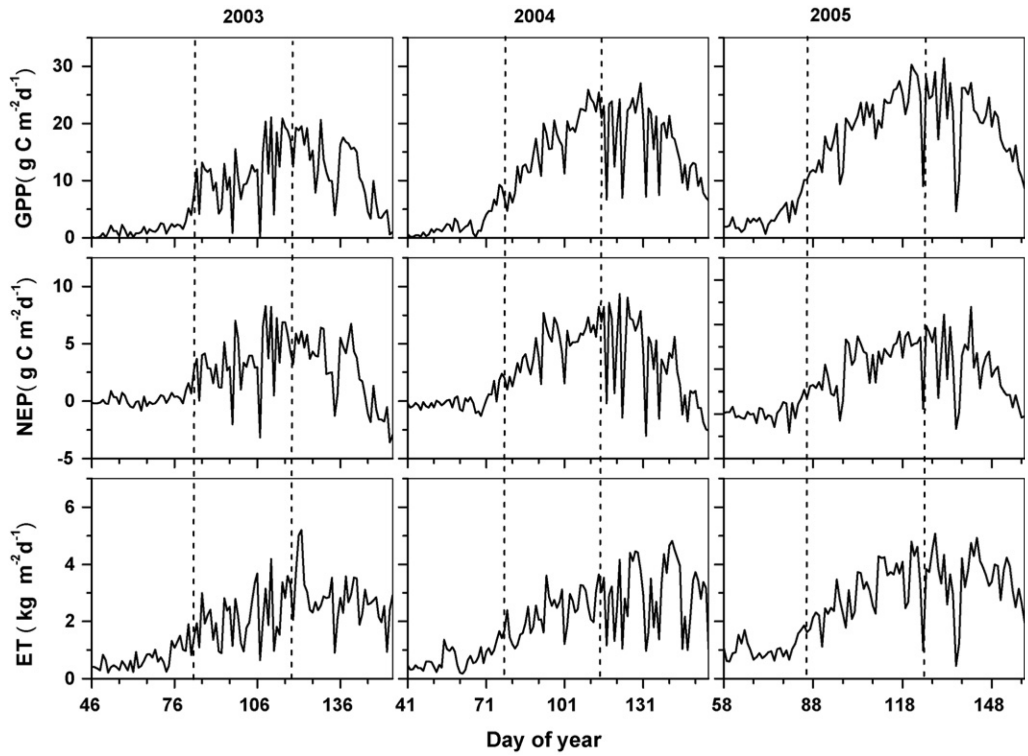

Fig. 3 – Seasonal courses of daily gross primary productivity (GPP), daily net ecosystem productivity (NEP) and daily evapotranspiration (ET) for winter wheat from revival to maturing in 2003, 2004 and 2005. The broken vertical lines indicate the dates of jointing (right) and heading (left).

maximums of daily NEP were 8.29 (DOY 109) in 2003, 9.33 (DOY 122) in 2004 and 11.99 g C m^{-2} day^{-1} (DOY 141) in 2005, respectively. The maximums of daily ET were 5.20 (DOY 122) in 2003, 4.82 (DOY 142) in 2004 and 5.07 kg m^{-2} day^{-1} (DOY 129) in 2005, respectively. On some cloudy days, GPP, NEP and ET might sharply drop down due to the limitation of low solar radiation such as on DOY 136 of 2005 (GPP = 4.61 g C m^{-2} day^{-1}, NEP = −1.64 g C m^{-2} day^{-1}, ET = 0.45 kg m^{-2} day^{-1} with PAR = 6.25 mol m^{-2} day^{-1} and D = 0.11 kPa).

The magnitude and seasonal patterns of GPP and NEP are very similar to the results obtained by Li et al. (2006a,b) at the same site. Anthoni et al. (2004) reported the similar results on winter wheat GPP and NEP in Thuringia, Germany. The values of daily ET are almost equal to Wang's et al. (2005) report in 2003 at a nearby site. And the seasonal pattern of ET is also very similar to Liu's et al. (2002) measurement using a large-scale weighing lysimeter in the North China Plain. The seasonal variations of GPP, NEP and ET showed a good accordance with the seasonal variation of LAI (Fig. 2), because GPP, NEP and ET were highly dependent on LAI (Falge et al., 2002; Law et al., 2002; Li et al., 2003, 2006a,b).

3.3. *Seasonal variations of W_G, W_N and W_B*

W_G, W_N and W_B showed a similar seasonal variation pattern (Fig. 4). Before jointing, W_G, W_N and W_B were low. At this stage, the winter wheat was still short and comparatively water lost from soil surface dominated. Thus the winter wheat could not use water with high efficiency. According to Liu's et al. (2002) empirical equation for winter wheat in the North China Plain, over 43–62% of ET was accounted for by soil surface evaporation at this stage with the LAI less than 0.92–1.66 m^2 m^{-2}. After jointing, the winter wheat started a vigorous growth and LAI expanded rapidly; meanwhile W_G, W_N and W_B increased significantly. After heading, W_G, W_N and W_B began to decrease due to leaf senescence. Table 3 shows the averages of W_G, W_N and W_B in the stages of R-J, J-H and H-M. Before jointing (R-J), W_G, W_N and W_B were obviously lower with the values of 2.09–3.54 g C kg^{-1}, −0.71–0.06 g C kg^{-1} and 1.37–4.03 g kg^{-1}, respectively. After jointing (J-H), W_G, W_N and W_B increased significantly to 5.26–6.78 g C kg^{-1}, 1.47–1.86 g C kg^{-1} and 6.41–7.03 g kg^{-1}, respectively. At the stage of H-M, W_G, W_N and W_B were 4.14–6.04 g C kg^{-1}, 0.78–1.10 g C kg^{-1} and 6.09–9.11 g kg^{-1}, respectively.

Compared with the seasonal variations of GPP, NEP and ET, the seasonal variation of W was less significant because the two components of W equation (Eqs. (2)–(4)) co-varied closely and had fairly linear relationship (Fig. 5). The slopes of GPP–ET, NEP–ET and AGB–ET were 4.67–6.12 g C kg^{-1}, 1.50–2.08 g C kg^{-1} and 6.87–11.02 g kg^{-1}, respectively. The fairly good correlations between crop productivity and ET have been widely observed in many ecosystems and at different scales (Stanhill, 1986; Hsiao, 1993; Law et al., 2002; Steduto and Albrizio, 2005).

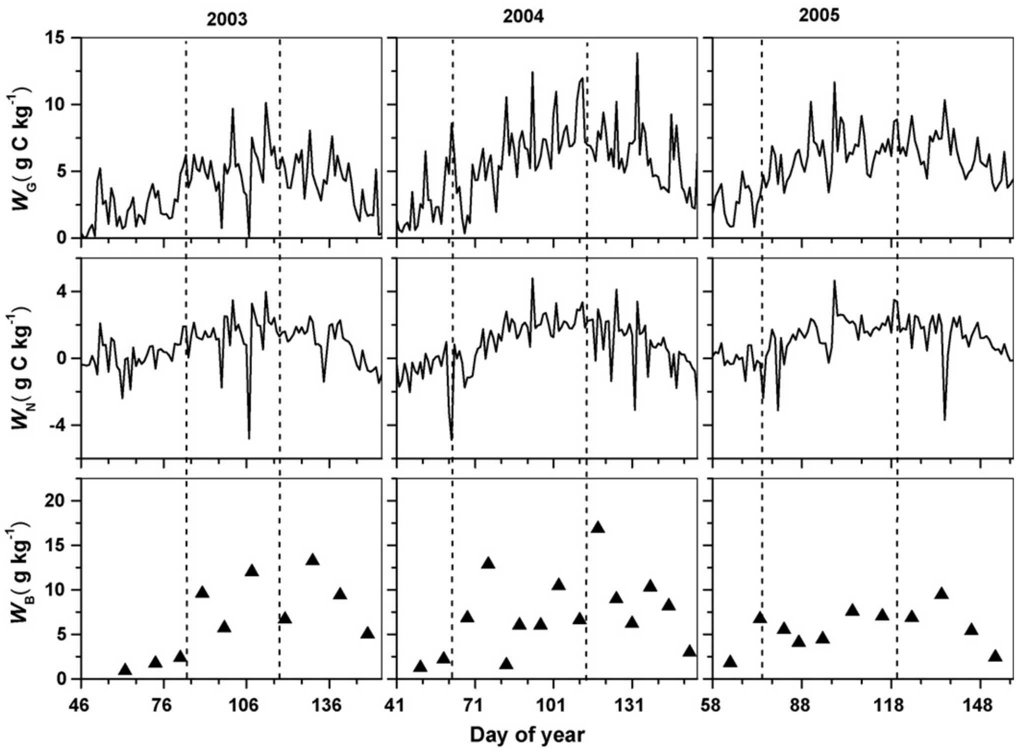

Fig. 4 – Seasonal variations of water use efficiency (*W*) on GPP (W_G), NEP (W_N) and AGB (W_B) levels for winter wheat from revival to maturing in 2003, 2004 and 2005. The broken vertical lines indicate the dates of jointing (right) and heading (left).

3.4. *The effects of PAR and D on W*

3.4.1. *The effects of PAR and D on* W_G

W_G decreased with increasing PAR (Fig. 6a). The relationship between GPP and PAR was curvilinear, with apparently less increase in GPP per unit of increase in PAR at the higher values of PAR (Fig. 7a). However, the relationship between ET and PAR was linear (Fig. 7c). This systemic difference between GPP–PAR and ET–PAR caused the negative relationship between W_G and PAR. The similar non-linear relationship of GPP–PAR was also reported by Wang et al. (2005) and Li et al. (2006a,b), and also widely observed in many other ecosystems (Law et al., 2002). Mahrt and Vickers (2002) observed that ET linearly increased with solar radiation and net radiation, for solar radiation was the principle source of energy for ET. Song et al. (2006) reported the negative response of W_G to net radiation in a subtropical plantation.

The responses of GPP and ET to *D* all could be best regressed as parabolas; while the differential coefficient of (GPP/*D*)′ (=−12.36, −21.54 and −21.28 for 2003, 2004 and 2005, respectively) (Fig. 7d) was more negative than (ET/*D*)′(=−3.12, −1.17 and −0.86 for 2003, 2004 and 2005, respectively) (Fig. 7f). Thus W_G showed significantly negative response to *D* (Fig. 6d). The similar curvilinear relationships of GPP–*D* and ET–*D* were observed in many ecosystems (e.g. McCaughey et al., 2006). And the negative response of W_G to *D* has also been reported by many authors (e.g. Law et al., 2002; Song et al., 2006).

3.4.2. *The effects of PAR and D on* W_N

Fig. 6b shows the response of W_N to PAR. At higher values of daily PAR >20 mol m^{-2} day^{-1}, W_N showed some negative response to PAR (the correlation coefficients were −0.487, −0.15 and −0.124 in 2003, 2004 and 2005, respectively). This could be explained by the systemic difference between NEP–PAR and ET–PAR. Similar to the GPP–PAR relationship, the response of NEP to PAR was curvilinear with apparently less increase in NEP per unit of increase in PAR at the higher values

Table 3 – The averages of W_G, W_N and W_B in stages of revival-jointing (R-J), jointing-heading (J-H) and heading-maturing (H-M) for seasons of 2003, 2004 and 2005

	W_G (g C kg^{-1})			W_N (g C kg^{-1})			W_B (g kg^{-1})		
	R-J	J-H	H-M	R-J	J-H	H-M	R-J	J-H	H-M
2003	2.09	5.26	4.14	0.06	1.47	0.79	1.37	7.03	9.11
2004	2.64	6.78	6.04	−0.71	1.71	0.78	1.91	6.50	8.49
2005	3.54	6.77	5.98	0.06	1.86	1.10	4.03	6.41	6.09

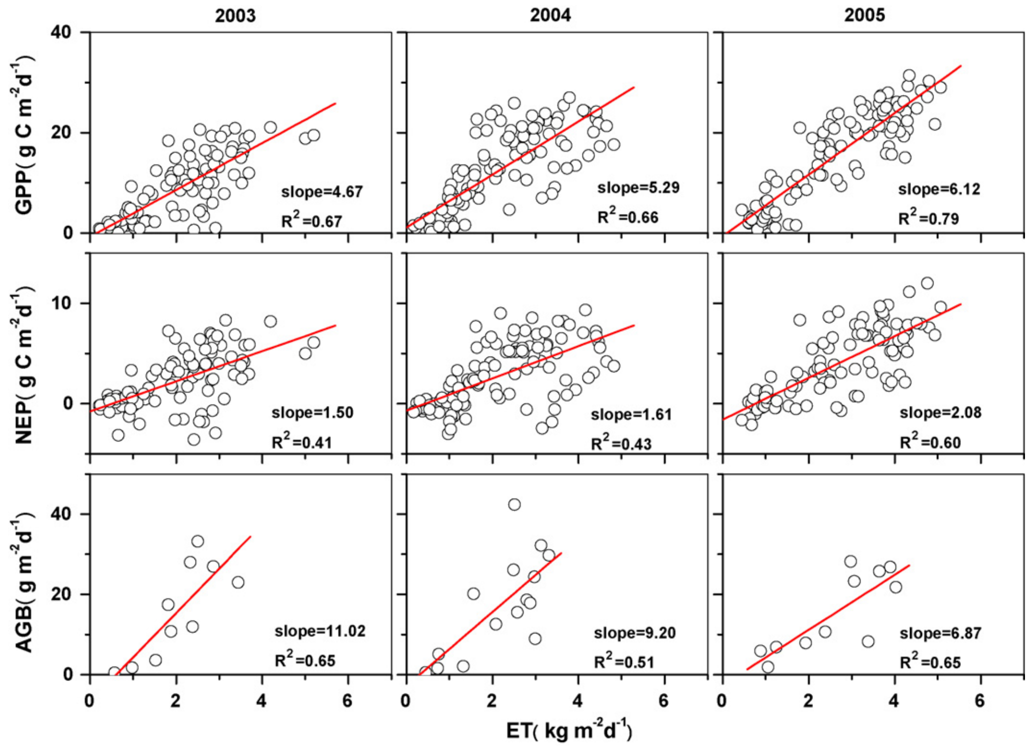

Fig. 5 – The links of GPP–ET, NEP–ET and AGB–ET.

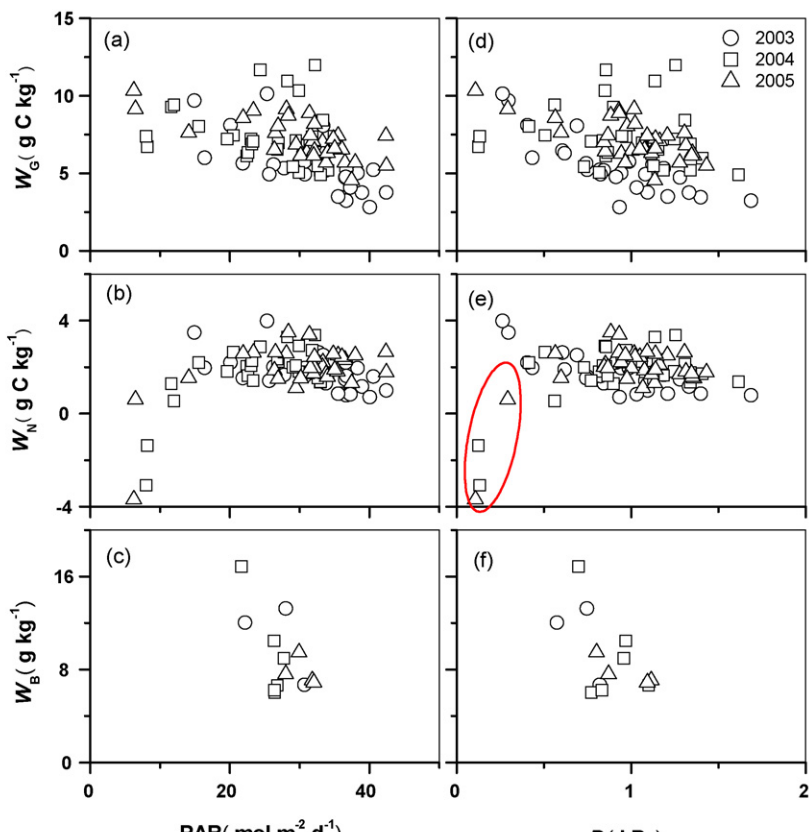

Fig. 6 – The dependences of daily W_G, daily W_N and averaged daily W_B on daily PAR and averaged daytime D. The four encircled points are described in detail in the text.

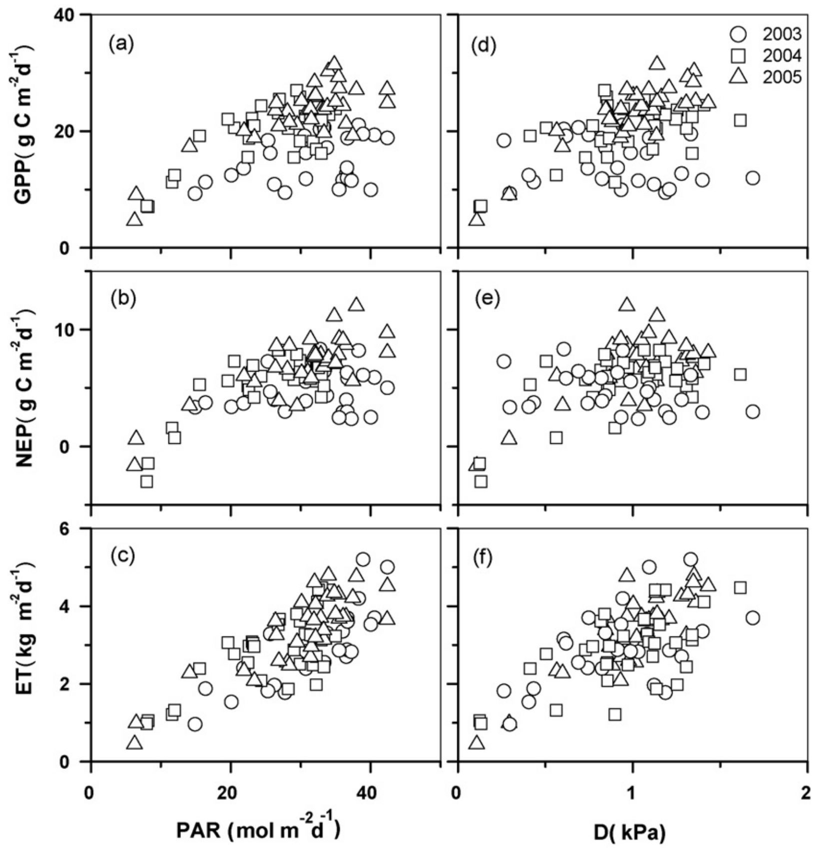

Fig. 7 – The dependences of daily GPP, daily NEP and daily ET on daily PAR and daytime *D*.

of PAR (Fig. 7b). At higher levels of PAR, the data might become more scattered. The similar curvilinear pattern for NEP–PAR has been observed widely (e.g. Li et al., 2005; Fu et al., 2006). Here, at higher levels of PAR (>20 mol m^{-2} day^{-1}), NEP had no significant correlation with ET except for in 2005, while ET still increased significantly with PAR (Fig. 7c). Thus W_N, as the ratio of NEP and ET, showed negative response to PAR at the higher levels of PAR (>20 mol m^{-2} day^{-1}). This is similar as the response of W_G–PAR analyzed above. Baldocchi et al. (1981) found the negative response of W_N to net radiation in an alfalfa field. It is interesting that W_N showed significantly positive response to PAR for cloudy days when PAR <20 mol m^{-2} day^{-1}. On these days, NEP was limited by PAR and had significantly positive dependence on PAR (NEP = 0.59PAR − 5.45, R^2 = 0.82, for the three observed years; Fig. 7b); while ET showed less positive dependence on PAR (ET = 0.15PAR − 0.31, R^2 = 0.71; Fig. 7c). It is clear that there was more increase in NEP than in ET per unit of increase in PAR. Thus W_N showed positive response with PAR when PAR <20 mol m^{-2} day^{-1}.

W_N showed negative dependence on *D* (the correlation coefficients were −0.761, −0.26 and −0.294 for 2003, 2004 and 2005, respectively) except 4 days (DOY 83 and 92, 2004; DOY 68 and 79, 2005) (Fig. 6e). Since *D* was the driving force for ET, *D* usually showed more positive effect on ET (Fig. 7f) than on NEP (Fig. 7e). This was similar as the more positive response of ET to *D* than that of GPP to *D*, as discussed above (Section 3.4.1). As the result of the systemic difference between NEP–*D* and ET–*D* relationships, W_N showed negative dependence on *D*. The negative relationships between W_N and *D* have been widely observed, especially under dry weather conditions (e.g. Baldocchi, 1994; Mahrt and Vickers, 2002). However, the range of *D* was not wide at the site and the highest value of *D* was just 1.69 kPa (ranging 0.26–1.69 kPa in 2003; 0.12–1.62 kPa in 2004; 0.11–1.43 kPa in 2005), the negative correlation of W_N–*D* was still very significant in 2003. While in 2004 and 2005 (except circled 4 days in Fig. 6e), the negative correlation of W_N–*D* was not significant. When added some data with higher *D* (3 m^2 m^{-2} < LAI < 4 m^2 m^{-2}), W_N would show significant negative relationship with *D*. It was worth noting that there were 4 days when W_N obviously deviated (encircled in Fig. 6e). On these 4 days, it was cloudy and moist with *D* < 0.3 kPa and PAR <10 mol m^{-2} day^{-1}. These weather conditions might account for the deviation of W_N. There were also 2 days in 2003 *D* < 0.3 kPa (DOY 56 and 68, 2003), but their PAR were not so low (the values of PAR were 14.89 and 25.34 mol m^{-2} day^{-1}, respectively).

3.4.3. *The effects of PAR and D on W_B*

W_B showed negative correlations with both PAR and *D*, although the data points were seldom for the discontinuous measurements (Fig. 6c and f). The correlation coefficients of W_B–PAR and W_B–*D* were −0.614 and −0.599, −0.851 and −0.452, −0.431 and −0.858 in 2003, 2004 and 2005, respectively. The effects of PAR and *D* on W_B can be explained by the effects of PAR and *D* on W_G because the AGB was the main pool of the leaf assimilation (i.e. GPP at the canopy scale). The negative effect of D on W_B has been widely observed (e.g. de Wit, 1958; Abbate et al., 2004). And the negative effect of stronger radiation on W_B also has been reported (e.g. Nicolás et al., 2005).

4. Summary

In our results, W_G, W_N and W_B showed the similar seasonal variation: before jointing they were low, and then increased with plant growth; the largest values occurred around the stage of heading; and then decreased due to the leaf senescence. Three levels of productivity: GPP, NEP and AGB all had significant correlation with ET. Generally, both PAR and D had negative effects on W_G, W_N and W_B except for on some cloudy days with low PAR and D.

GPP is the total of leaf assimilation. Thus W_G may be a suitable parameter to estimate the physiological mechanism of crop productivity and water lose. In our results, GPP, compared with NEP and AGB, showed the best correlation with ET (Fig. 5). This feature of W_G might give us very useful information for understanding the relationship between crop productivity and water use. As for W_N, it fairly indicates the ratio of NEP to ET, and also can give useful information on the carbon and water fluxes. In addition, W_N can be calculated by the flux data directly. W_B can give useful information for understanding the relationship between crop growth and water use. It has been wide measured. As our results, W_G, W_N and W_B showed fairly similar patterns in many cases. This is easy understood because GPP, NEP and AGB are well linked. Nevertheless, there were still some obvious differences between W_G, W_N and W_B besides in magnitude. Firstly, W_N might be minus, for NEP might be minus; however, W_G and W_B are always positive. Secondly, on some cloudy days with low PAR and D, W_N might not show negative dependences on PAR and D, while neither W_G nor W_B showed this pattern. Thirdly, compared with W_G and W_N, W_B might be insufficient to give more deep and detailed information because the measurements were seldom and discontinuous. Lastly, since GPP showed more significant correlation with ET (Fig. 5), W_G might be more conservative than W_N and W_B.

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