Seasonal variation of energy partitioning in irrigated lands

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Abstract:
The energy balance components were measured above the surface of an irrigated wheat and maize field over three successive years using the Bowen ratio technique. The experiments were carried out at Luancheng Experimental Station of Agro-ecosystem (LESA), Heibei, China, from December 1999 through to September 2001. The seasonal course of energy balance over an irrigated field, the diurnal Bowen ratio patterns in different seasons, and the effect of leaf-area index (LAI) and soil moisture on the energy balance are discussed. Over 3 years, the net radiation $R_n$ varied from 31 to 668 W m$^{-2}$, and the soil heat flux $G$ varied from $-12$ to $170$ W m$^{-2}$. The latent heat flux $LE$ also shows apparent correspondence with the development of phenology, e.g. LAI. The diurnal course of the Bowen ratio in different seasons can be categorized into three typical patterns: (1) a ‘wheat pattern’, characterized by a steep morning peak followed by a decrease with the daytime mean value of around 0–30; (2) a ‘maize pattern’, which is a relatively flat course with a daytime mean $\beta$ of around 0–20–0–25; and (3) a ‘winter pattern’, with a near-noon high peak with a daytime mean $\beta$ of more than 10 times that those for wheat or maize. There are linear correlations between evaporative fraction (EF) and LAI for both wheat and maize before senescence seasons. The correspondence of EF appears more dependent on LAI for maize than for wheat. The EF does not appear correlated to soil water status, whereas the Bowen ratio is affected by extractable soil water content for wheat to some extent. No correlation for maize is found. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS energy partitioning; Bowen ratio; evaporative fraction; LAI; extractable soil water content; wheat; maize

INTRODUCTION

During the past decades, increasing interest has been focused on evapotranspiration (ET) from the land surface as a key component of the water cycle. ET links energy partitioning, stomatal conductance, carbon exchange, and water-use efficiency in plant communities, and it serves as a key regulator of ecosystem processes (Woodward and Smith, 1994; Sellers et al., 1996). In particular, it is also considered as the interaction of vegetation with the atmosphere from the aspect of global climate change.

In the context of the North China Plain (NCP), wheat and maize are the main crops cultivated in rotation and constitute a major part of the landscape. Their land surface radiation balance, energy partitioning and groundwater table change are therefore crucial for the regional climate and hydrology, as well as the attention focused on food problems (e.g. Brown and Halweil, 1998). Therefore, it is important to quantify the energy balance components, to understand the different factors and their influence on these terms, their rhythmic change and the monitoring of the evaporative processes over the region.

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Today, we have fairly good knowledge about the mechanisms that control transpiration, or stomatal conductance of plants, from porometer (or chamber) measurements (e.g. Shuttleworth and Wallace, 1985; Jones, 1992), and, in recent years, also from a number of studies based on micrometeorological measurements (e.g. Steduto and Hsiao, 1998a–d; Villalobos et al., 2000), or application of models (e.g. Alves and Pereira, 2000; Calvet, 2000; Mo and Liu, 2001). Many other significant results have also been reported from the international study programs such as GEWEX/GAME, IGBP/FLUXNET, etc. in the last decade. One of the major problems in using this knowledge for climate modelling, for example, is the up-scaling from leaf to plant, from plant to canopy, and from canopy to landscape. Thus, there is still a need for a better understanding of the processes controlling ET and the energy partitioning of the entire crop community (Grelle et al., 1999). There is also a need for a better understanding of the seasonal dynamics, where the phenology of vegetation and variations in soil moisture and temperature play an important role (Viterbo and Beljaars, 1995). Till now, long-term studies of ET have been based on indirect methods, e.g. water balance, with low time resolution only. However, in order to improve the understanding of ET and energy partitioning processes, high temporal resolution data are essential in many cases. In this context, the Bowen ratio technique was employed as a tool for measuring the available energy partitioning into ET and sensible heat fluxes from a wheat–maize rotation field. Most Bowen ratio experiments that have been carried out in grain fields are limited to short periods of a few days to several weeks (e.g. Baldocchi, 1994a,b). This is mainly due to difficult maintenance, in spite of the advantages of easy installation and a relatively little fetch demand of 20:1, as expounded in the recent review by Rana and Katerji (2000). There is, however, no doubt that the Bowen ratio method can be used to estimate seasonal (Shen et al., 2002; Zhang et al., 2002) or inter-annual changes (Rosset et al., 2001) in the energy balance in a long-term analysis.

In the present study, the surface energy partition based on Bowen-ratio technique measurements over an irrigated wheat and maize field in the NCP has been evaluated and related to soil water availability. The evaluation period extends from December 1998 to the end of September 2001, thus covering almost three entire crop years. The objectives of the present paper are:

- To study the seasonal characteristics of the energy balance over irrigated wheat and maize fields.
- To explore the diurnal courses of energy partitioning in different seasons.
- To demonstrate the importance of leaf-area index (LAI) and soil water status upon energy partitioning.

SITE DESCRIPTION

The experiments were carried out at Luancheng Experimental Station of Agro-ecosystem (LESA), a basic station of the Chinese Ecological Research Network (CERN). LESA (37°53’N, 114°41’E, altitude 50.1 m) is located in the middle of the piedmont plain of the Taihang Mountains, China. It provides a good representation of farmland in the NCP. The station has a long history of cultivation and a high annual production of ~13,500 kg ha⁻¹. Wheat–corn rotation is a popular cultivation system in this area. Generally, the growing season of winter wheat is from early October through to the next mid-June, and the corn season is from June to late September.

The study area has a temperament semi-arid monsoon climate, with a mean annual temperature of 12 °C, mean annual global radiation of 524.2 kJ cm⁻², and mean annual precipitation of 480 mm, most of which occurs from July to September (Table I). On average, precipitation during the maize season can almost meet the crop water requirement. The average evapotranspiration for the whole wheat growing season is about 480 mm (Shen, 1998); however, the precipitation is only about 130 mm in the same period. Thus, the deficit needs to be met by irrigation supplied by extracting groundwater. Owing to the emphasis placed on high production levels, more and more groundwater is being extracted for irrigation. As a result, the groundwater table has suffered a continuous decline from ~10 m below the surface in the early 1980s to 30 m below the surface at present.
At the experimental site, there is a maximum fetch of 3 km towards the south and a minimum fetch determined by LESA’s courtyard 800 m from the mast towards the northwest. Practically, this site is ideal for meteorological measurements because of the prevailing southeast wind during summer.

EXPERIMENTS AND CALCULATIONS

Experiments and measurements

The experiments were carried out from December 1998 through to September 2001. The observations include Bowen-ratio system measurements (net radiation, soil heat flux, temperature and vapour pressure gradient, wind speed), soil moisture (using neutron probe and time-domain reflectometry (TDR) techniques), soil water potential (tensiometer), LAI and biomass. All measurements have a 20 min time resolution, except the LAI and biomass measurements, which are of a 1 week resolution. The experiments cover nearly three entire crop years: three wheat seasons and three maize seasons. The precipitation and irrigation inputs to the field during the 3 years are shown in Figure 1. The total precipitation is 1100 mm, and irrigation is about 900 mm.

ET was estimated using the Bowen-ratio energy balance method. The ambient temperature gradient was measured with a pair of E-type chromel–constantan thermocouples installed on two arms. The lower arm was positioned 50 cm above the canopy surface and the upper arm was 1.0 m higher than the lower arm. Measurements were taken every 0.625 s and samples were averaged over 20 min.

Vapour pressure measurements were made by air sampling through an inlet on each arm, at a rate of 0.4 l min\(^{-1}\) for a 2 min period. After an initial 40 s equilibrium period, a dew-point temperature monitored by a cooled-mirror hygrometer (Dew-10. General Eastern, Water Town, MA) was obtained at 1 s intervals for 80 s. Thus, the dew point was measured at each height alternatively in 2 min interval cycles. This system provided five sets of dew-point temperature readings for each height averaged over a 20 min period (Campbell Scientific Inc., 1996). The dew-point temperatures were later transformed to air vapour pressure using a polynomial expression. The cooled mirror was cleaned once a week; simultaneously, the dew point was manually adjusted to suit the new conditions.

Net radiation was determined with a Q7-1 net radiometer, with hemispherical polyethylene windshield domes protecting the sensor surfaces. Soil heat flux was determined using two HFT3 soil heat flux plates, one of which was buried inter-row and other inter-plant at 2 cm (Dong and Yu, 1994) beneath the soil surface. All measurements were averaged in a 20 min interval, and all data were logged using a Campbell’s CR10X data logger.

Soil moisture was measured by an IH-2 neutron probe and weight method (only for 30 cm of the top layer). Four access tubes were installed around the 023A Bowen-ratio system mast. Soil moisture was measured at

![Figure 1. Precipitation and irrigation from 1999 to 2001 (in total, precipitation is 1100.0 mm and irrigation is 900.0 mm)](image-url)
10, 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 cm in depth with a frequency of 5 days. Gravimetric samples were simultaneously sampled with the neutron probe observation. Before and after irrigation or precipitation events, incremental measurements were conducted. From May 2000 onwards, three TDR probes were buried at depths of 5, 15, and 30 cm near the mast to monitor the variation of soil moisture continuously. From September 2000, four more TDR probes (CS615 model, made by Campbell, USA) and seven soil tensiometers were also added. A fine soil moisture monitoring system was successfully constructed and started observation. This system is composed of seven TDR probes (CS615 model, made by Campbell, USA) and seven tensiometers (UNSUC model, Sankeirika, Japan). The TDR probes and tensiometers were buried at depths of 5, 10, 30, 60, 90, 120, and 200 cm. The observation interval was set to 20 min. All data were logged with a CR10X data logger.

Calculation of Bowen-ratio energy balance

The basic energy balance equation of the Earth’s surface is

\[ R_n = LE + H + G \]

where \( R_n \) (W m\(^{-2}\)) is net radiation flux, \( G \) (W m\(^{-2}\)) is soil heat flux, \( LE \) (W m\(^{-2}\)) is latent heat flux, and \( H \) (W m\(^{-2}\)) is sensible heat flux. \( R_n \) and \( G \) can be directly measured through instruments. The difference between \( R_n \) and \( G \) is usually called the available energy.

According to Bowen-ratio energy balance method, the components of energy partitioning, \( LE \) and \( H \), can be calculated thus:

\[ LE = \frac{R_n - G}{1 + \beta} \]

\[ H = \frac{\beta}{1 + \beta}(R_n - G) \]

where \( \beta \) is Bowen ratio.

Calculation of evaporative fraction

The partitioning of the available energy balance can be evaluated by analysing the dimensionless evaporative fraction (EF), defined as

\[ EF = \frac{LE}{R_n - G} \]

Because EF is a ratio of latent heat flux to available energy flux, it is usually used to characterize the energy partition over the land surface and has the potential for inferring daily energy balance information based on midday measurements (Nichols and Cuenca, 1993). One of the perceived advantages of using EF is its apparent stability during daytime hours (Shuttleworth et al., 1989; Gurney and Hsu, 1990).

Estimation of extractable soil water content

The extractable soil water (ESW) is an effective indicator of soil water status related to plant growth. ESW is defined as (e.g. Gollan et al., 1986; Calvet, 2000)

\[ ESW = \frac{\theta_a - \theta_w}{\theta_l - \theta_w} \]

where \( \theta_a \), \( \theta_w \), and \( \theta_l \) are the actual soil water content, the wilting point, and the field capacity of the soil layers at the root zone respectively. In the present study, the values of \( \theta_w \) and \( \theta_l \) are 0-108 and 0-355 respectively. Thus, ESW is a number between zero and one, which indicates the fraction of plant-available soil water status, or relatively efficient soil water content.

RESULTS AND DISCUSSION

Seasonal trends of energy balance

Figure 2 shows the seasonal courses of the components of the energy balance and their relation to LAI and soil water storage in an irrigated wheat and maize field during three successive years. The data in Figure 2 represent midday averaged values from 10:00 h to 15:00 h. The changes in net radiation $R_n$ show the well-known sine curve, with the peak occurring in June and the valley in December. Seasonally, the midday averaged $R_n$ varies in a huge range from 31.6 to 668.1 W m$^{-2}$. The course of soil heat flux $G$ does not change significantly through the years. Except during the senescence stages, $G$ shows evidently declining trends both during the main growing stages of maize and in wheat after its revival. It reaches a peak in mid June, when the wheat is harvested and the maize is undeveloped. Evidently, the course of $G$ is affected by the development of the crop canopy, or LAI. Midday averaged $G$ varies from $-12.7$ to $170.9$ W m$^{-2}$, with an average value of around $53.2$ W m$^{-2}$. According to Zhang et al. (2004), the ratio of $G/R_n$ for wheat during the jointing to senescence stages is around 10–13%, which is much higher than that for the maize season (5–7%).

The latent heat flux $LE$ shows two main peaks and a sub-peak during its annual course (Figure 2). The main peaks occur during each crop season, once in the wheat season and once in the maize season. But the sub-peak appears in early November, when the wheat has emerged and entered its first flourishing growing stage. Regretfully, due to instrumental errors, we could not record declining courses of $LE$ for wheat in late May 1999 and 2000, or that in 2001 during the senescence stage. However, we find that the course of $LE$ agrees with the course of LAI, which implies that $LE$ is largely dependent on LAI to a certain extent. The relation of LAI to energy partitioning will be discussed later in detail. The midday averaged latent heat flux varies in a very large range from about 0.2 to 611.9 W m$^{-2}$ during the 3 years. This is mainly determined by climate variables, such as solar radiation, temperature, air vapour pressure deficit, and so on, since no soil water stress occurred in the irrigated grain field. However, we cannot give an average daily value of latent heat flux, or in evaporative intensity, the daily ET, for the three full years, since there were no measurements during some periods.

Diurnal patterns of Bowen ratio in different seasons

To explore the diurnal patterns of energy partitioning over wheat and maize fields, the ensemble average diurnal courses of Bowen ratio are shown in Figure 3 for different months. In Figure 3, each point represents the average of all days at the corresponding time. The daytime mean values of each month are also plotted as black dots along with their values.

The diurnal curves for April 1999 and 2000 show more or less the same pattern: the Bowen ratio ($\beta$) has a steep rise in the early morning, and reaches the maximum at around 9:00 h. Then $\beta$ declines gradually until sunset. In April 2000, it decreases rapidly after the maximum, with a near linear decline, which is the same as other reports (Soegaard, 1999; Shen et al., 2002). But, in April 1999, the averaged declining trend differs slightly from that of a linear decline.

The daytime averaged $\beta$ is 0.30 and 0.28 in April 1999 and 2000 respectively. This suggests that the Bowen ratio of wheat is less than one-third of its value in its prolific growth stages. Moreover, the daytime averaged $\beta$ is nearly equal to the midday values. This means that the midday parameters for energy partitioning or evaporation, such as Bowen ratio ($\beta$) and evaporative fraction (EF), can be used to estimate evaporative flux to atmosphere during daytime hours through temporal up-scaling in this period. Crago and Brutsaert (1996) gave a detailed discussion on estimating daytime evaporation using the instantaneous midday Bowen ratio and EF. They concluded that the constant EF assumption is superior to the constant Bowen ratio assumption for estimation of daytime evaporation.

During August, the diurnal courses of Bowen ratio are very different from those in April, showing a nearly stable course through the daytime. The morning peak is not so apparent and high as that of wheat. After the morning peak, there are also some small oscillations in its course. The oscillation in August 1999 is greater
Figure 2. Long-term energy balance over irrigated field at LESA. The X-axis represents the days from 1 January 1999. Soil water storage represents water storage in 0–100 cm layers measured by neutron probe (circles) and TDR (line).
Figure 3. Diurnal patterns of Bowen ratio $\beta$ for three typical types: wheat type (April), maize type (August), and winter type (December). Black dots and the values beside them represent daytime averaged $\beta$ values.

than that in 2000, which is mainly caused by the weather conditions. In August 1999, there were 12 raining days and around 144 mm rainfall, whereas there were only 6 mm rainfall for 5 days during August 2000 (Figure 1). During rainy or cloudy days, the latent heat flux is sharply decreased; hence, $\beta$ will be larger than on clear days since sensible heat flux is not decreased so sharply as latent heat. The daytime averaged $\beta$ values are 0.25 and 0.20 in 1999 and 2000 respectively. These values are less than those from wheat. During clear days, e.g. August 1999, midday $\beta$ is almost equal to the daytime averaged value, whereas the daytime averaged $\beta$ is less than its midday values (e.g. in August 2000) if many cloudy or raining days are observed.

During the winter month of December, there is a completely different diurnal course of $\beta$ from those in April and August. A single peak occurs before (1999) or after (2000) noon during its diurnal course. The magnitude of the peak is also much higher than that in April and August; actually, there is about a one order difference between them. The magnitude of daytime averaged $\beta$ is around 10 times that of those from the active growing stages of wheat (April) and maize (August). Moreover, midday $\beta$ deviates markedly from its daytime mean value. So, this pattern can be termed the ‘winter type’ to distinguish it from both the ‘wheat type’ (which is characterized by a sharp morning peak and a decreasing course thereafter, with a mean $\beta$ of around one-third) and from the ‘maize type’ (characterized as a relatively flat course with a mean $\beta$ of around 0.20–0.25).
Annual courses of Bowen ratio $\beta$ and EF

In Figure 4, the annual courses of Bowen ratio (a) and EF (b) are shown for three successive years. The Bowen ratio is calculated from the midday averaged sensible and latent heat fluxes during 10:00 h to 15:00 h, as shown in Figure 2.

The annual courses of Bowen ratio for 1999, 2000, and 2001 basically display the same pattern, i.e. the course of $\beta$ follows a ‘W’-type curve. The peaks occur in February, June, and October/December, whereas the valleys with horizontal bottoms occur in April/May and August/September, which are the flourishing growing stages of wheat and maize respectively. During other months, such as March, July and October, which can be considered as transition periods, the Bowen ratio transits the line of $\beta = 1$. The reverse trend is noted in the month of October.

The EF shows the reverse trend to that of the Bowen ratio, because EF is an inversely proportional function of $1 + \beta$. Whereas, the rhythmically seasonal trend of energy partitioning into latent heat can be shown more clearly: two peaks around EF = 1 occurs in May, and August and September; and a sub-peak of around 0.6 occurs in early November.

Energy partitioning in relation to LAI

Steduto and Hsiao (1998b) have reported that LAI can be a main controlling factor of maize ET and net assimilation in senescence stages because senescence results in leaf area reduction, which is superior
to a decline in stomatal conductance on effecting canopy ET. They also indicated that the maize canopy conductance depends linearly on LAI in the case of LAI < 4.5.

Here, in order to examine the apparent importance of LAI in energy partitioning of the irrigated field shown in Figure 2 further, the midday averaged EF versus LAI is plotted for both the wheat and maize seasons (Figure 5).

Kondoh and Higuchi (2001) found that the ET from grassland responds linearly to the normalized difference vegetation index through the whole growth season. Here, it is clearly shown that EF is linearly dependent on LAI before senescence. In the senescence stage, however, the relations are not apparent. In the wheat season, the slopes of the EF–LAI lines are almost same in 1999 and 2000. But the interception in 2000 is around 0.26 more than that in 1999. This suggests that, in the irrigated wheat field, the dependence of EF on LAI is nearly the same, d(EF)/d(LAI) = 0.13, in different years; the absolute value of EF, however, is different because the energy partitioning is also affected by some other factors, such as soil water status, crop growth status, climate conditions, and so on. In the maize season, the situation is the same as in wheat season, but the dependence of EF on LAI, i.e. the slope of the fitted line (around 0.18), is higher than that in wheat season. This implies that LAI is more important in energy partitioning for maize than wheat.

With respect to the direct effect of LAI on ET, it is also found that the evaporative ratio (E/E_o, where E_o is reference evaporation) of maize is linearly related to LAI, and leaf area remains one of the dominant factors controlling field crop water relations when water deficit develops gradually, as opposed to leaf epidermal conductance which appears to play a minor role (Steduto and Hsiao, 1998b).

Effects of soil water status on energy partitioning

There is some evidence to suggest that there is no correlation between EF and soil water content when soil water is not limiting (Nichols and Cuenca, 1993; Zhang and Lemeur, 1995). The difference in EF corresponding to available energy before and after irrigation was compared in our wheat ET experiments (Zhang et al., 2002). Figure 6 shows the relationship between extractable soil water and Bowen ratio. Except for a transition period (Figure 6a), the data for both wheat (Figure 6b) and maize (Figure 6c) are from the

![Figure 5. Dependence of evaporative fraction (EF) on LAI in different crop seasons: (a) wheat (1999); (b) wheat (2000); (c) maize (2000); (d) maize (2001); circles: before senescence stages; black dots: senescence stages](image-url)
periods with full canopy cover; once the canopy cover of the ground is complete, any further increase in LAI has little influence on ET. For wheat, it is illustrated that the Bowen ratio is determined by soil water status to some extent, even though the result of 1999 and 2000 for full cover are very scattered. With a full canopy cover, the Bowen ratio of the wheat–soil system is linearly limited by soil moisture, i.e. the Bowen ratio will increase as the soil becomes drier, and vice versa. This is because soil water status can affect leaf stomatal conductance significantly (Gollan et al., 1986; Jones, 1992; Shen et al., 2002), through which the ET of the whole canopy is influenced. Hence, the balance between latent and sensible heat will also be changed. Owing to a lack of measurements in the milkling stages (nearly the whole May) in 1999 and 2000, the results for these 2 years show little coupling of Bowen ratio to soil water (black dots in Figure 6b).

The weak correlation between Bowen ratio and ESW for maize (Figure 6c), indicates that ET was not limited by available soil water. Generally, during the maize season, the soil water status plays a minor role in controlling the energy partitioning under a relative higher water regime.

CONCLUSIONS

Land surface available energy partitioning into latent and sensible heat is a basic hydrological process connecting vegetation and atmosphere. From the energy balance components’ measurements during three successive years, we discussed the seasonal characteristics of energy partitioning processes over land surface of an irrigated wheat and maize field.
Over 3 years, the net radiation $R_n$ varied from 31.6 to 668.1 W m$^{-2}$ and soil heat flux $G$ varied from $-12.7$ to $170.9$ W m$^{-2}$. The latent heat flux $LE$ also shows an apparent correspondence with the development of phenology, e.g. consistent with the trend of LAI. On an annual basis, the Bowen ratio exhibits a ‘W’-shaped curve, with the middle peak occurring in June; on the contrary, $EF$ shows the reverse trend, with two peaks appearing in May and August–September, with a sub-peak in early November.

The Bowen ratio shows three typically different types in its diurnal pattern. The ‘wheat pattern’ is characterized by a steep morning peak followed by a decrease, with a daytime mean value of around one-third; the ‘maize pattern’ is a relatively flat course with a mean $\beta$ of around 0.20–0.25; the ‘winter pattern’ shows a near-noon high peak with a daytime mean $\beta$ of more than 10 times that for wheat and maize. In addition, the daytime mean $\beta$ values of the ‘wheat pattern’ and ‘maize pattern’ are very close to each other, whereas the daytime mean of the ‘winter pattern’ is far from its midday value.

Before senescence, there are linear correlations existing between $EF$ and LAI for both wheat and maize seasons. The correspondence of $EF$ appears to be more dependent on LAI for maize than for wheat. The $EF$ does not appear correlated to soil water status, whereas only the Bowen ratio for wheat is found to be affected by extractable soil water content to some extent. No correlation for maize is found.

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