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Energy Balance of Irrigated Intercropping Field in the Middle Reaches of Heihe River Basin

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Abstract: Based on the experiments conducted in an irrigated intercropping field in Zhangye Oasis in the middle reaches of Heihe River basin in 2004, the characteristics of radiation budget are analyzed. Furthermore, energy balance is calculated by using Bowen-Ratio Energy Balance (BREB) method. The results show that the ratio of the absorbed radiation to the incoming short radiation in intercropping crop canopy-soil system is increasing with growing stages, from 0.81 in the initial growing stage (IGS) to 0.86 in the late growing stage (LGS). The net radiation, which is smaller in IGS, increases rapidly in the first period of the middle growing stage (MGS) and reaches the maximum value in the second period of MGS. It then somewhat decreases in LGS. The ratio of net radiation to total radiation has a similar trend with the net radiation. In the whole growing stages, latent heat flux, which takes up 70% or so of the net radiation, is the dominant item in energy balance. Sensible heat flux shares 20% of the net radiation and soil heat flux has a percentage of 10%. The characteristics of heat balance vary distinctly in different growing stages. In IGS, the ratios of latent heat flux, sensible heat flux and soil heat flux to net radiation are 44.5%, 23.8% and 31.7% respectively. In MGS, with the increasing of latent heat flux and the decreasing of sensible heat flux and soil heat flux, the ratios turn into 84.4%, 6.3% and 9.3%. In LGS, the soil heat flux maintains 0W/m^2 or so, and latent heat flux and sensible heat flux take up 61.4% and 38.6% respectively. The energy balance also shows an obvious daily variation characteristic.

Keywords: radiation budget; energy balance; intercropping field; Heihe River basin

1 Introduction

Most of the solar radiation that ecosystem seizes is consumed on latent, sensible and soil heat flux. Among them, latent heat flux shares the biggest part (Gutierrez and Meizer, 1994; Ham et al., 1991; Rachidi et al., 1993). The radiation budget and the energy balance are crucial to water conversion and effective water utilization. Also, they are important parts of research of water-saving agriculture (Mo et al., 1997).

At present, the researches on radiation budget and energy balance in agricultural ecosystem focus on the equilibrium regulation of heat, methods to calculate radiation and its partitioning through observation and analyses. In the 1950s, Tanner (1960) began to study energy balance in farmland. In 1966, Philip put forward the concept of SPAC (Soil-Plant-Atmosphere Continuum). After that, many scholars have made a lot of researches on energy balance on different crops (Kim, 1989; Villalobos and Fereres, 1990; Ham et al., 1991; Rachidi et al., 1993; Gutierrez and Meizer, 1994; Domingo et al., 1999; Amarakoon et al., 2000; Inman-Bamber and Mcglinchey, 2003). In China, the progress of such kind of research was made mainly in North China Plain, the Huang-Hui-Hai Plain and the Loess Plateau (Xie, 1993; Kang et al., 1994; Liu and Yu, 1997.) Some researches were carried out (Li and Huang, 1996; Huang, 1996) in wheat, cotton, and rice farmland in oasis in Xinjiang.

The middle reaches of Heihe River basin is one of the most important commodity grain base of Gansu Province. The intercropping of spring wheat and maize, a traditional planting system in the middle reaches of Heihe River basin in the 1980s-1990s, has such characteristics as higher yield, better economic benefits and larger water consumption (Li and Zhao, 2004). Owing to two kinds of crops growing in the same plot in the same growing season, the radiation budget and the energy balance in the field must have special characteristics. Using the data from a set of automatic weather stations which were set up in a field in Zhangye Oasis in the middle reaches of Heihe River basin, the radiation budget and the energy

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balance in the intercropping plot were analyzed. The research is important for better understanding of the equilibrium regulation of energy in farmland and developing water-saving agriculture in arid regions.

The study was conducted at Zhangye Oasis (38°50′N, 100°26′E), located in the arid region of Ganzhou Prefecture, Gansu Province, Northwest China. The experimental area is 1570m above sea level. The mean annual temperature is 7.1℃, and 160 days or so are frost-free. The mean annual precipitation, about 60% of it occurring from July to September, is 127mm. The potential evaporation is over 2340mm. The prevailing wind direction in this area is NW and mean annual wind speed is 2.6m/s. Drought and windiness are main climatic characteristics in this area. The experimental area lies at the plain in front of Qilian Mountain. The soil in experimental area is light soil. The average density of soil from 0 to 200cm is 1.38×10^3kg/m^3 and pH is 8.7-8.8. The crops planted in the experimental field are spring wheat and maize for seed. In 2004, the precipitation was 93mm, lower than the mean level, and the water demanded by the crops was mainly from irrigation.

2 Data and Method

2.1 Data

An automatic weather station (AWS) was set up, with an area of 6m×7m in the center of the experimental field (near 630m^2) in August 2003. The measurements of wind speed (014A wind sensor, Met One, USA), air temperatures (HMP45D temperature probe, Vaisala, Finland), relative humidity (HMP45A relative humidity probe, Vaisala, Finland) were made in two subsequent levels. The two levels were adjusted by the height of crops. The lower level was 0.5m higher than the canopy height while the upper is 2.5m higher. Short wave and long wave radiation from the sky and the land surface, respectively, were measured with a net radiometer (CNR-1; Kipp and Zonen, the Netherlands) at 2.2m above the ground. Soil heat flux was measured at the depth of 0cm. The observation site has a fetch of 80m in all directions. Soil temperature thermometers were buried 0, 0.05, 0.10, and 0.30m, respectively. Those data were recorded with a data-logger (CR10; Campbell Scientific Inc. (CSI), USA) at 10min intervals. Leaf area index (LAI) was measured with LAI 2000 analyzer (it was destroyed on August 20, 2004) every 6–10 days. The height of crops was measured every 7 days.

The spring wheat was sown on March 8, 2004, and harvested on July 12, 2004. The maize was planted on April 16, 2004 and harvested on September 20, 2004. Considering the maize was still green when harvested, a few days were delayed. The data from March 8, 2004 to September 24, 2004 are presented in this study.

In this study, we considered the wheat and maize as a single, consecutive growing crop. According to the procedure proposed by Allen et al. (1998) and the real conditions in study area, the growing stages of intercropping crops were divided Table 1.

Table 1 Division of growing stages of intercropping crops in the middle reaches of Heihe River basin

Growing stage	Period	Days	Of total days (%)
IGS	March 8- April 21	45	22.3
MGS-1①	April 22-June 8	48	23.8
MGS-2②	June 9-August 20	73	36.1
LGS	August 1-September 25	36	17.8
Total	March 8-September 25	202	100.0

Notes: ① in this stage, the growth of wheat is dominate;
② in this stage, the growth of maize is dominate

2.2 Method

The radiation budget in an intercropping field can be expressed as follows:

$$R_n = (R_s - R_r) + (R_{ld} - R_{lu}) \tag{1}$$

where R_n is net radiation (W/m^2); R_s and R_r are solar radiation and reflecting radiation respectively (W/m^2); R_{ld} and R_{lu} are downward and upward long wave radiation respectively (W/m^2).

Based on the law of the conservation of energy and the gradient diffusion equation, surface energy balance can be expressed in the following equations:

$$R_n = LE + H + G \tag{2}$$

$$H = \rho c_p K_h \Delta t/\Delta z \tag{3}$$

$$LE = (1/\gamma)\rho c_p K_w \Delta e/\Delta z \tag{4}$$

where R_n is the net radiation (W/m^2); H and LE are the sensible and latent heat fluxes respectively (W/m^2); G is the soil heat flux (W/m^2); ρ is air density; c_p is the specific heat capacity of air; γ is the psychometric constant; K_h and K_w are the eddy diffusivities for heat and for water vapor respectively; and Δt, Δe and Δz are the gradients of temperature, vapor pressure and height respectively.

If we assume $K_h = K_w$, the Bowen Ratio (β) can be defined as follows:

$$\beta = \frac{H}{LE} = \gamma\frac{t_1 - t_2}{e_1 - e_2} = \gamma\frac{\Delta t}{\Delta e} \tag{5}$$

and, LE and H can be expressed as:

$$LE = \frac{R_n - G}{1+\beta} \tag{6}$$

$$H = \frac{\beta(R_n - G)}{1+\beta} \tag{7}$$

3 Results and Analyses

3.1 Radiation budget and its variation

3.1.1 Variation of radiation partition in growing stages

The solar radiation R_s varied violently and displayed a shuttle-like trend during the whole growing season (DOY68–DOY269) (Fig. 1). Meanwhile, the average results showed it inclined to an uptrend in the all stages (Table 2). The main reason for this was that some lower values in middle growing stage (MGS) made the average smaller. For instance, the minimum value of R_s was 56.0W/m^2 and it appeared also in MGS.

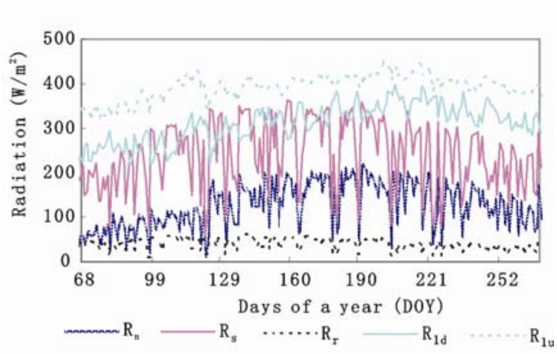

Fig. 1 Variation of radiation in the whole growing period

The reflecting radiation R_r, averaged at 38.7–44.3 W/m^2, varied weakly during the growing stages (Fig. 1). In the second stage of MGS, it decreased a little owing to the increase of leaf area index (LAI).

Two kinds of long wave radiation showed the same variety trend during the growing stages (Fig. 1). They were small in initial growing stage (IGS), increased greatly in the first stage of MGS and got to peak value in the second stage of MGS, decreased at the late growing stage (LGS).

Net radiation R_n is the balance result of the four partitions mentioned above. It was small, with a daily mean of 75.2W/m^2, in IGS. R_n increased sharply in the first stage of MGS and reached 128.3W/m^2. In the second stage of MGS, R_n got to its maximum daily mean value, 5.0W/m^2. It decreased markedly in LGS with a daily mean of 116.7W/m^2. The daily variation extent of R_n was larger and in accord with the variation of R_s.

Table 2 Characteristic values of climatic and radiation factors during different growing stages

Growing stage	Days of a year (DOY)	Air temperature (℃)	Relative humidity (%)	Wind speed (m/s)	Mean radiation (W/m^2·d)				
					R_n	R_s	R_r	R_{ld}	R_{lu}
IGS	68–112	7.3	39	1.3	75.2	215.0	40.1	257.6	357.3
MGS-1	113–160	15.2	48	1.1	128.3	259.7	44.3	303.9	391.0
MGS-2	161–233	20.2	63	0.3	155.0	261.6	38.7	346.4	414.3
LGS	234–269	15.7	62	0.2	116.7	293.0	42.6	318.4	402.0
Average		15.3	56	0.6	124.3	242.3	38.9	312.8	392.0

3.1.2 Variation of radiation budget

The ratio of net radiation to solar radiation (R_n/R_s) could be divided into 4 stages (Fig. 2). It varied with the vegetation degree. In IGS (DOY68–DOY112), bare soil or low vegetation degree led to a lower ratio of 0.35. In the first period of MGS (DOY113–DOY161), with the growing of wheat, the ratio increased to 0.49. In the second period of MGS (DOY162–DOY233), while the maize entering into its middle growth stage, R_n/R_s got to 0.59. In LGS, the ratio reduced to 0.54.

The ratio of the absorbed radiation to the incoming short radiation ((R_s–R_r)/R_s) in intercropping canopy-soil system was increasing with the growing stage. This increasing trend was insignificant. A lager albedo of bare soil made the absorbed radiation smaller, and the ratio was 0.81 in IGS. With the growing of crops and the decrease of albedo, (R_s-R_r)/R_s finally reached 0.86 in LGS.

The ratio of energy used for turbulence to net radiation ((R_n-G)/R_n) had an increasing trend in the whole growing season (Fig. 2). In IGS, the ratio was 0.69 and was the smallest. It showed that the soil absorbed 30% of R_n to warm the soil. Owing to low vegetation and large variation of radiation, the ratio varied greatly in IGS. At the first stage of MGS, the ratio increased much and the mean value came to 0.89. In the second stage of MGS, the ratio maintained around 0.97. In LGS, (R_n-G)/R_n was averaged to 1.01. All the energy was consumed on turbulence. During the whole growing season, the ratio of (R_n-G)/R_n was 0.90. That is to say, 90% of net radiation was consumed on turbulence and only 10% for soil heat flux.

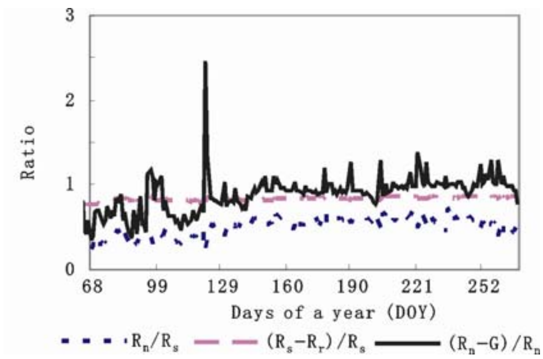

Fig. 2 Variation of radiation budget in different growing stages

3.2 Energy balance and its variation

3.2.1 Variation of energy balance during growing season

Net radiation (R_n), latent heat flux (LE), sensible heat flux (H) and soil heat flux (G) varied during the whole growing season (Fig. 3).

In IGS (DOY68–DOY112), R_n maintained a low level. In the beginning of IGS, i.e., from the sowing to sprouting of wheat, G and H were larger than LE. Since the bare soil absorbed much of solar radiation, soil temperature was higher than air temperature and led to an increase of upward sensible heat flux. At the same time, because of little rain and the frozen soil, which interrupted the vapor transportation from the lower soil layers, soil water content in upper layer was very small, and as a result, the

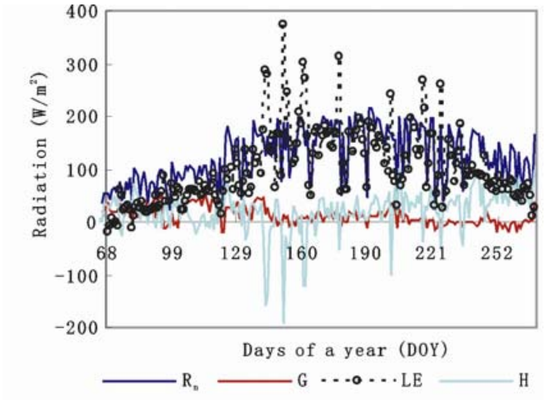

Fig. 3 Variation of R_n, G, LE and H in whole growing season

energy consumption on latent heat flux was small. In the middle and end of IGS, with the growth of wheat, the area of bare soil was smaller and smaller. More and more energy was consumed on soil evaporation and plant transpiration. LE increased and was larger than G and H at this time. During the total IGS, the mean R_n was 75.7W/m^2. LE was 33.7W/m^2 and took up 44.5% of R_n. G was 24.0W/m^2 and shared a percentage of 31.7%. H was 18.0W/m^2 and took up 23.8% of R_n.

In MGS (DOY113–DOY233), net radiation R_n increased rapidly and reached 142.3W/m^2. With the growing of wheat and maize, the transpiration of crops increased sharply. Meanwhile, irrigation and precipitation made soil water content higher in upper soil layers. So, most of the energy was consumed on latent heat flux. In fact, During the total MGS, LE was 120.2W/m^2, and took up 84.4% of R_n. G was 13.3W/m^2, and shared a percentage of 9.3%. H was 8.9W/m^2, and took up 6.3% of R_n.

In LGS (DOY234–DOY269), R_n decreased gradually and came to 117.8W/m^2. The variation of G was very small and maintained about 0W/m^2. Sensible heat flux increased rapidly and reached 45.4W/m^2. It shared 38.6% of R_n during this stage. At the same time, LE reduced sharply to 72.4W/m^2, and took up 61.4% of R_n.

3.2.2 Hourly variation of energy balance

Net radiation, latent heat flux, sensible heat flux and soil heat flux show obvious hourly variety (Fig. 4). The variety differed much on intensity and time in different growing stages.

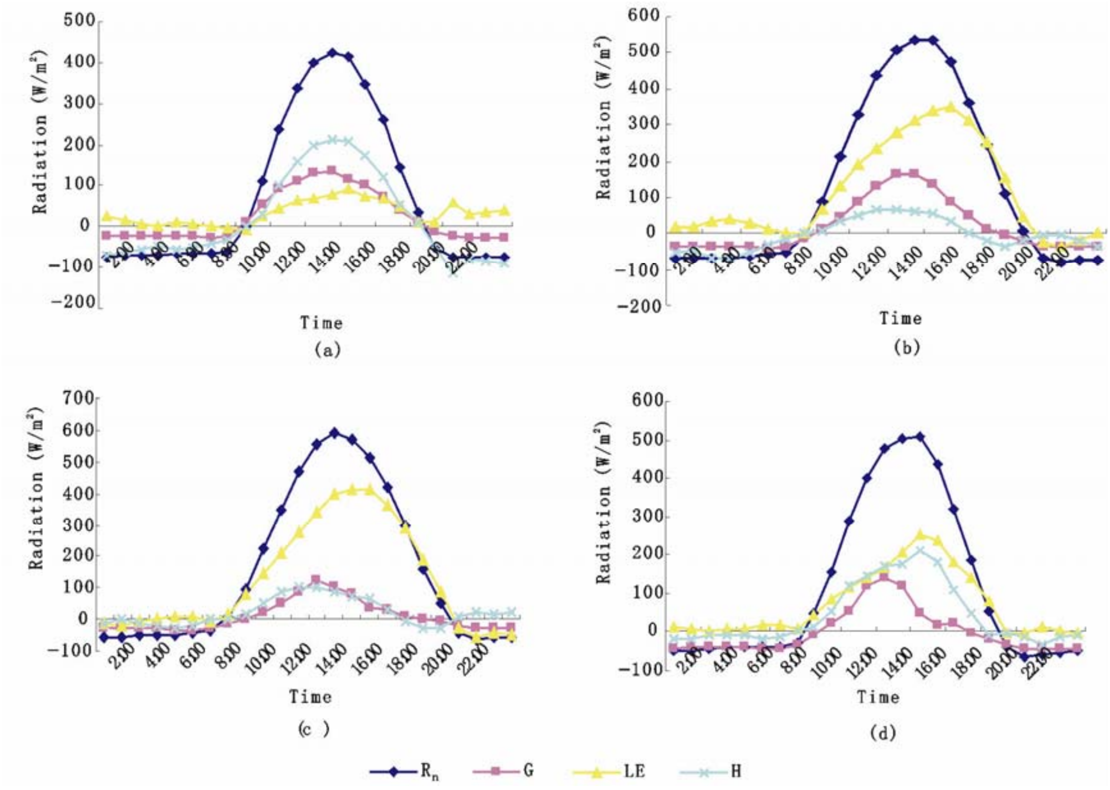

Fig. 4 Daily variation of R_n, G, LE and H in different growing stages

In IGS (Fig. 4a), R_n in nighttime (19:00-7:00) distributed between –77.7W/m^2 and –53.3 W/m^2. Its variation was very small. At 8:00, R_n turned positive. After that, it increased greatly and reached its maximum value of 425.1W/m^2 at 13:00. Later, R_n decreased greatly and changed into negative value at 18:00. The other three partitions had the same variety trend as R_n's. In daytime (8:00-18:00), the mean values of G, LE and H were 79.8W/m^2, 52.0W/m^2 and 114.9W/m^2, and occupied 32.4%, 21.1% and 46.6% of net radiation, respectively.

In MGS (Fig. 4b and 4c), R_n in nighttime (20:00-6:00) distributed between –78.3W/m^2 and –39.2W/m^2. Its variation was larger than that in IGS. R_n began to be positive at 7:00 and increased greatly later on. At 13:00, it came to the maximum value of 535.0W/m^2 (the first stage of MGS) or 589.6W/m^2 (the second stage of MGS). After that, R_n decreased and came into negative value at 20:00. The variety trend of *LE* was same as that of R_n. The difference was that the peak value of *LE* appeared at 14:00. Compared with IGS, *LE* occupied the predominant position in MGS. During daytime (7:00–19:00), mean *LE* was 206.2W/m^2 (the first stage of MGS) or 247.2W/m^2 (the second stage of MGS) and took up 69.8% or 74.9% of R_n, respectively. For the sensible heat flux, it was positive during 7:00–17:00. At 11:00 or 12:00, it came to its maximum value 100W/m^{2}or so. In the first stage of MGS, the daytime mean value of *H* was 23.8W/m^2, taking up 8.1% of R_n. In the second stage, *H* rose to 43.0W/m^2 and occupied 13.0% of R_n. At 8:00–17:00, the soil heat flux kept positive and the peak value appeared at 12:00. During daytime in the first and second stages of MGS, averaged *G* was 65.3W/m^2 and 40.1W/m^2, occupying 22.1% and 12.1% of R_n, respectively.

In LGS (Fig. 4d), R_n was positive in daytime (8:00–18:00) and its mean value was 307.4W/m^2. At 14:00, it got to the maximum value of 510.3W/m^2. Because maize tended to be mature, the consumption of the latent heat lowered significantly. In daytime, its average was 149.8W/m^2 and shared 48.7% of R_n. By contrast, the sensible heat flux contained significant increment. Its daytime average was 111.1W/m^2, and took up 36.1% of R_n. Compared with the soil heat flux in MGS, it changed little. The daytime mean value was 46.6W/m^2 and shared 15.1% of R_n.

3.3 Energy balance and leaf area index (LAI)

LAI was measured on DOY115 for the first time. With the variation of *LAI*, net radiation (R_n), latent heat flux (*LE*) , sensible heat flux(*H*) and soil heat flux(*G*) also varied during the middle and late growing season (Fig. 5).

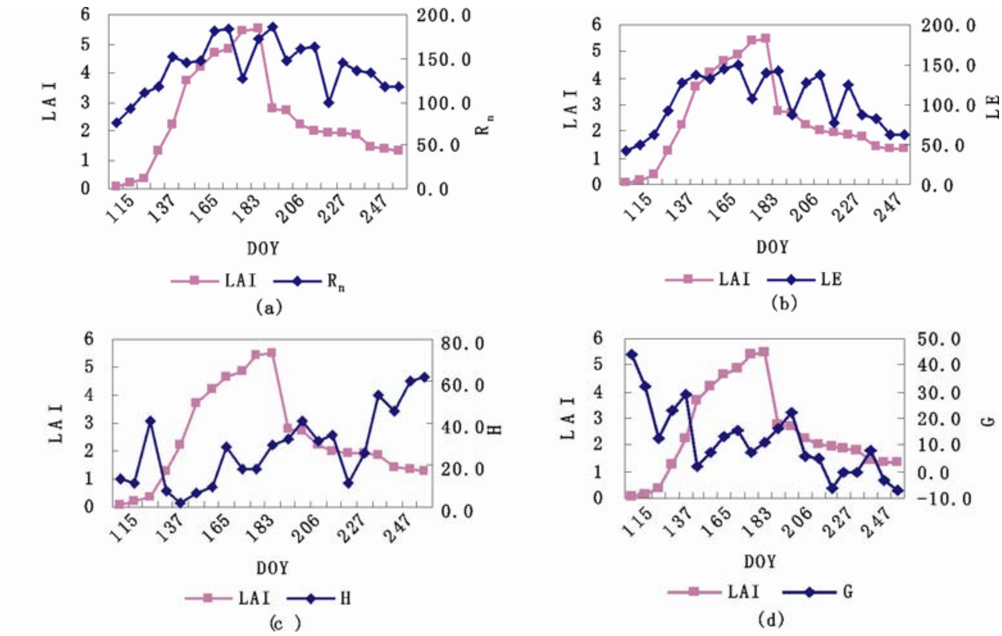

Fig. 5 Variation of R_n , *G* , *LE* and *H* with *LAI* in middle and late growing stages

The variation of R_n and *LE* with the *LAI* nearly had the same trend (Fig. 5a and 5b). In the first stage of MGS (DOY113–DOY161), the *LAI* increased slowly and also, R_n and *LE* increased gradually. The *LAI* increased rapidly in the beginning of the second stage of MGS owing to the growth of wheat and maize. On DOY195, due to the harvest of wheat, the *LAI* decreased suddenly. The variation of R_n and *LE* showed the same change. With the gradual decrease of *LAI* in LGS (DOY234–DOY269), R_n and *LE* lowered gradually.

In the first stage of MGS, the *LAI* increased slowly, but *H* and *G* showed a decreasing trend (Fig. 5c and 5d). *H* and *G* had a same variation trend with *LAI* in the second stage of MGS. At the beginning of the second stage of MGS, both *LAI* and *H* increased and at the end stage, both decreased. In LGS, with the gradual decrease of *LAI*, *H* increased sharply while *G* decreased.

4 Conclusions

(1) The radiation budget in intercropping canopy-soil system varied with the growing stages. For shortwave radiation, the ratio of the absorbed to the incoming short radiation was 0.81 in IGS. With the decrease of reflecting ratio in canopy-soil system, the ratio increased to 0.86 in LGS. For long wave radiation downward or upward, they maintained a low level in IGS, and got to their maximum values in MGS and decreased in LGS.

(2) The net radiation was small in IGS. Entering into the first stage of MGS, it increased sharply and reached

the maximum in the second stage of MGS. It dropped markedly in LGS. The ratio of net radiation to solar radiation showed the same trend as the variation of net radiation. It was 0.35, 0.49, 0.59 and 0.54 in IGS, the first stage of MGS, the second stage of MGS and LGS, respectively.

(3) During the whole growing season of intercropping crops, about 90% of net radiation was consumed on latent heat flux (*LE*) and sensible heat flux (*H*). The other 10% was used by the soil heat flux (*G*). In different growing stages, the balance of energy varied sharply. In IGS, the percentages of *LE*, *H* and *G* to net radiation were 44.5%, 23.8% and 31.7%, respectively. With the increase of latent heat flux in MGS, those percentages changed into 84.4%, 6.3% and 9.3%. In LGS, with the decrease of soil heat flux and increase of the sensible heat flux, they were 61.4%, 38.6% and 0%, respectively.

(4) Energy balance showed different daily variations in different growing stages. During nighttime, R_n, *LE*, *H* and *G* were below 0W/m^2, and varied slightly. In daytime, energy balance varied with different growing stages. In IGS, the ratios of *LE*, *H* and *G* to net radiation were 21.1%, 46.6% and 32.4%, respectively. Sensible heat flux was the main consumption item of net radiation. The latent heat flux dominated the consumption of net radiation in MGS, whose percentages changed into 72.8%, 10.1% and 17.1%. In LGS, with the decrease of latent heat flux and increase of the sensible heat flux, they were 48.7%, 36.1% and 15.1%, respectively.

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