Study on energy and water balance of pepper field in arid areas

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Abstract

The middle Heihe River Basin (MHRB) in arid areas in China faces the challenge of sustainability, but frequent over-irrigation deteriorated the situation. The water balance and energy budget have not been widely used for the quantifying evaluation of over-irrigation. Although some studies have measured the energy budget and water balance in cropland, the energy and water balance in pepper fields is still unclear. An experiment was conducted using an eddy covariance system, SmartView fluke and other measurements in MHRB. The leaf area index (LAI) for pepper increased in the first two months, then decreased thereafter. After Aug. 4, the daily evapotranspiration (ET) decreased during the maturation stage. The soil moisture was higher than the field capacity frequently, indicating that over-irrigation had occurred. Soil water content was relatively high at 100 cm depth, causing high percolation. The water inputs were 1.5 times ET, and the deep percolations accounted for 74% of the total irrigation inputs. Irrigation water could be conserved 301 mm, in case that percolation was avoided. Therefore, the irrigation amount (per time and total) should be reduced to achieve high water use efficiency (WUE). The latent heat flux (LE) consumed 80% of the net radiation (Rn). In July, the LE/Rn was the highest among all months, whereas H/Rn was the lowest due to the highest value of LAI in July. The net radiation had a significant positive linear correlation with the latent heat flux because of the high water supply. Our study showed that there was considerable room for water conservation in MHRB. Keywords: Sensible heat flux; Soil water content; Evapotranspiration; Latent heat flux; Leaf area index

1. Introduction

Drought and unsustainable water use are becoming major obstacles to economic welfare and sustainable development in arid areas (Zhang et al., 2018). Water and energy balances are necessary for efficient irrigation scheduling at field scale (Roost et al., 2008; Taghvaeian and Neale, 2011; Knipper et al., 2020).

The Heihe River Basin (HRB) is the second largest inland river basin in northwestern China. Irrigation in the middle reaches of the Heihe River Basin (MHRB) represents more than 90% of water consumption, which causes desertification and lake contraction of the lower reaches (Fu et al., 2014; Tan, 2019). Water deficit and competition have increased in the last decades (Qi and Luo, 2005), which has led to a decrease in the water allocated for MHRB.

Li et al. (2018) found that the overexploitation led to a reduction in the groundwater table in MHRB. Meanwhile, irrigation water is not efficiently consumed for agriculture (Li, 2020). Most of fields in MHRB were owned by commercial companies, which aim to achieve high yields rather than saving water. Therefore quantifying the agricultural water use in MHRB is important to the efficient and fair allocation of the precious water resources for both the local economy and the natural environment protection. Moreover, the water balance and energy budget have not been widely used for the quantifying evaluation of over-irrigation (Yang et al., 2015), especially in pepper fields.

Evapotranspiration (ET) is a considerable part of the water budget as well as the energy balance, and strongly controls energy transport and water cycling (Tian et al., 2013; Haghighi and Kirchner, 2017). In

addition, ET is related to soil moisture, therefore an accurate estimation of ET for irrigated agriculture is fatal for the efficient management of water resources in arid areas (Li, 2020). In the past, ET , water and energy budgets were difficult to get due to the backward observation technique in MHRB. Fortunately, the eddy covariance (EC) technique employs micrometeorological mass transfer methods to measure the energy budget and ET (Uddin et al., 2013). During the last decade, several studies were conducted to measure sensible heat flux (H) and latent heat flux (LE) above the maize canopy in MHRB using the EC method (Ji et al., 2011; Ma et al., 2015; Xu et al., 2017).

Through ET and LE , the energy budget is closely associated with the water balance. Hence, research on the energy budget of croplands is critical for understanding the water budget for decision makers (Cheng et al., 2014). Although some studies have measured the energy budget (Gao et al., 2018) and water balance in cropland, few have studied the energy budget and water balance in pepper (one of the representative vegetables in MHRB) fields. The plant area for pepper in China represented 35% of the gross area for pepper in the world (Huo et al., 2015).

Therefore, we characterized ET , the water balance and energy budget of a pepper field in MHRB in this study. The objective of this study is to promote a better understanding of energy and hydrologic processes in vegetable fields to improve the agricultural water use efficiency and sustainable irrigation water management in arid lands.

2. Materials and methods

2.1. Study area

The experimental field (Fig. 1) was located in the arid MHRB in Gansu Province, Northwest China. Annual precipitation is low with an arid and cold climate (Jiang et al., 2015).

2.2. Observations, data collection and quality assurance

The field experiments were conducted in “Heihe Watershed Allied Telemetry Experimental Research” (HiWATER) (Li et al., 2013; Xu et al., 2013) project from June to September 2012. The pepper (*Capsicum annuum* L.) was sowed on June 8, and harvested on Sep. 19. The soil is silt loam. Fertilization and irrigation practices were set in accordance with the practices of local farmers and companies. The following measurements were conducted in the pepper field.

The sensible heat flux and latent heat flux were observed with an eddy covariance system (Fig. 1), including a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, USA) and a fast-response infrared gas analyzer (LI7500A, LI-COR Inc., Lincoln, Nebraska, USA), with a sampling frequency 10 Hz. The averages were automatically calculated and recorded every 30 min. ET was derived from the LE data. The consistency of the EC systems and data quality were guaranteed by five procedures, such as errors minimization by the consistency test, raw data procession using the EdiRe software package, empirical gap filling of missing data, and so on (Ran et al., 2016). The missing data were gap-filled using the ‘look-up’ table method (Falge et al., 2001). Meteorological data, including wind speed and direction, precipitation, air pressure, air temperature and humidity were recorded at an automatic weather station (AWS) (Campbell Co., Ltd.). A CNR-4 radiometer (Kipp & Zonen, Netherlands) was set at 2 m above the ground to observe the upward and downward components of longwave and shortwave radiations.

Soil heat flux was measured by two heat flux plates (HFP01SC, Hukseflux, Netherlands) in the row at 0.05 m below the ground. Time domain reflectometry (TDR) (TRIME-PICO IPH, Germany) system was used to measure soil moisture in seven layers to a depth of 100 cm in the pepper field. HiWATER team carried out comparative work before the experiment and found that for the saturated soil, compared with the gravimetric method, a mean underestimation of the TDR was 0.025 (Gao et al., 2014). Deep percolation was calculated using the water balance method.

The energy closure balance was shown in Fig. 2 and Table 1. The average energy closure ratio “ $(H + LE)/(R_n - G)$ ” in the pepper field exceeded 90%, which indicated that the reliability of the EC measurements

was high.

Precipitation and irrigation in the pepper field are shown in Fig. 3, which indicates that irrigation was the primary source of water.

2.3. Leaf area index (LAI) and fractional vegetation coverage (FVC) estimation based on thermal images

To measure and monitor the vegetation coverage and its variations, we applied the concept of *FVC* (Bian et al., 2017; Jiapaer et al., 2011). The definition of *FVC* is given by Zhang et al. (2001). *FVC* was retrieved from the Normalized Difference Vegetation Index (*NDVI*) (Badzmirowski et al., 2019; Ricci et al., 2019), which is the most commonly used index for measuring plant performance or stress indicator:

where *Red* is the reflectance in the red band and *NIR* is the reflectance in the near-infrared band.

The TIF files of infrared images were exported from SmartView fluke, and were opened with ENVI5.3 to obtain images of four bands. *NDVI* grayscale images were calculated using formula (1).

FVC was calculated by pixel bisection model (Li, 2003; Deng et al., 2021).

using 5% confidence interval, *NDVI*₅ is the *NDVI* value with 5% cumulative percentage, and *NDVI*₉₅ is the *NDVI* value with 95% cumulative percentage. The vegetation coverage value is the average value of statistical data for *FVC*.

LAI was calculated using *NDVI* (Yan, 2018).

We measured the thermal images of the surfaces every two hours in the daytime during the growth stage of pepper by an IR Flexcam Ti55 Thermal Imager (Fluke Corp., USA) (Fig. 1). An example of the thermal images of the pepper field was shown in Fig. 4, which indicated that the surface temperature of the pepper plant was lower than the soil.

3. Results and discussion

3.1. FVC, LAI and Evapotranspiration

The crop *FVC* for pepper was 0.25-0.54 (Fig. 5). The *FVC* increased from the beginning of the experiment to the middle of the growth stage of the pepper, and reached the highest value on July 26, thereafter decreased gradually (Fig. 5), which reflected the variation process of growth and maturation of the pepper. The *LAI* for pepper increased in the first two months, then decreased thereafter (Fig. 5), which is similar with several reports (Sezen et al., 2014; Huo et al., 2015; Cndido et al., 2017; Yue et al., 2018).

The total *ET* in the growing season in the pepper field was 368 mm (Fig. 6). The daily average *ET* was 4.23 mm. After Aug. 4, the daily *ET* decreased (Fig. 6) because leaves withered gradually during the maturation stage (Fig. 5). The peak values of *ET* on June 29 and July 31 were higher than those on Aug. 21 and Sep. 14 (Fig. 7). On July 31, *ET* at 21:00 was -0.05 mm (Fig. 7b), which indicated dew formation in the pepper field.

3.2. Soil water content

The soil water content was relatively high in the pepper field (Fig. 8). The field capacity of silt loam in MHRB was about 33% (Li et al., 2016). The soil water content exceeded the field capacity frequently, indicating that over-irrigation had occurred. At a depth of 60-100 cm, the soil water content throughout the growth stage in the pepper field was higher than 0.4 (Fig. 8a). In most cases the soil water content from 60-100 cm depth was higher than 0-20 cm due to *ET*. Wang et al. (2011) also showed that soil water content at 50 cm in farmland was relatively high because *ET* mainly consumes soil water above a depth of 50 cm. The daily variation amplitude of soil moisture at depth 2 cm was the highest among all depths, whereas 100 cm was the lowest (Fig. 8a). The soil water content increased with soil depth from 2 cm to 60 cm, and decreased from 60 cm to 100 cm (Fig. 8a).

The distribution of soil water content in the soil profiles (Fig. 8b) showed that the soil water content in the top soil layer (0-10 cm) was the lowest in the entire soil profile. Yang et al. (2015) reported that seed maize obtained water primarily from 0-10 cm soil layer, with a median absorption ratio of $87 \pm 15\%$ in MHRB, and a large amount of irrigation water was lost as deep leakage. In the pepper field, the soil water content was highest at a depth of 60 cm (Fig. 8b). The soil water content was also relatively high at a depth of 100 cm, which easily resulted in high percolation (Fig. 9), suggesting that the current volume of irrigation in MHRB should be reduced to save water.

The *FVC* in middle and late August was higher than that in June (Fig. 5), whereas the *ET* in middle and late August was lower than that in June (Fig. 6) because the soil water content in middle and late August was lower than that in June (Fig. 8). Markos and Radoglou (2021) reported that evapotranspiration was mostly affected by soil moisture and net radiation.

3.3. Water budget

Characterizing the water budgets during the growth stage in the pepper field (Fig. 9) showed that the amount of *ET* was lower than irrigation, indicating that over-irrigation had been applied to the fields. The water inputs (precipitation and irrigation) totaled 563 mm, or 1.5 times *ET*. These values showed that total irrigation amount was too high to be used effectively, and a large volume of excess water percolated into the deep soil layers in the field (Fig. 9). The *ET* in the pepper field was 368 mm, 196 mm lower than the water inputs (precipitation and irrigation) (Fig. 9). Irrigation water could be conserved 301 mm for the pepper field, in case that percolation was avoided. The deep percolations accounted for 74% of the total irrigation inputs (Fig. 9), which was consistent with the finding of Li (2020) who reported that deep leakage below the 1.5 m soil occupied 68% of irrigation water during the growth stage of maize in MHRB. Li et al. (2015) also indicated that deep percolation was higher than transpiration due to over-irrigation in a seed corn farmland in MHRB. High leakage was also mentioned by Tong et al. (2007), Zhao et al. (2010), Li et al. (2012) and Jiang et al. (2015) in northwestern China, and these authors also noted that this condition led to low irrigation efficiency, which indicated that appropriate irrigation measures should include adjusting irrigation schedule as well as employing upgraded irrigation methods.

Water use efficiency was low in MHRB because of the excessive use of irrigation water and inequity of water delivery. Therefore, the irrigation amount (per time and total) should be reduced to achieve high water use efficiency; the field may be irrigated more frequently with less water per time to avoid large deep percolation and maintain proper soil moisture, especially in arid regions. In fact, Jiang et al. (2015) reported that improving water transfer and irrigation management may bring about a 30% reduction of deep leakage.

The experimental field in our study in MHRB was owned by commercial companies, which aim to achieve high yields rather than saving water. Hence, an appropriate water price policy could encourage water conservation at both the farm and canal levels.

3.4. Energy budget and fluxes variations

During the entire growth season, the average energy closure ratio " $(H + LE)/(R_n - G)$ " in the pepper field exceeded 90% (Table 1). The average latent heat flux accounted for over 80% of R_n , which indicated that *ET* consumed a large amount of radiation. Tian et al. (2017) indicated that irrigation supplied enough water for *ET* and thus increased *LE*. The value of LE/R_n throughout the entire growth period in our study is similar with a cotton field (Tian et al., 2017) and even a paddy field (Liu et al., 2015), but higher than those have been indicated in several literatures. Taking an example, a figure of 59% has been showed in the North China Plain (Lei and Yang, 2010). In September, the sensible heat flux accounted for over 20% of R_n because of a decline in *LE* as leaf area decreased during the crop maturation stage in our study (Table 1); these results are accordance with report of Wu et al. (2006). In July, the LE/R_n was the highest among all months, whereas H/R_n was the lowest due to the highest values of *FVC* and *LAI* in July (Fig. 5). The *LE* is the primary turbulent flux, which is 8 times *H* in the pepper field. Our research agreed with a report on cornfields in northwestern China (Ding et al., 2010).

The maximum daily R_n was observed from 12:30-14:30 (Fig. 10), which is accordance with the results from a cultivated area in West Africa (Mamadou et al., 2014). With the exception of August, which had many cloudy and rainy days, the peak value of R_n was about 600 W m^{-2} in other three months (Fig. 10). The daily cycle of R_n has direct effect on turbulent fluxes, which exhibited a similar diurnal shape except that H was slightly shifted. LE generally rose in the morning along with net radiation, whereas it declined more slowly in the late afternoon (Fig. 10). Overall, a large portion of R_n was converted into latent heat flux; this value reached 400 W m^{-2} at approximately 14:00, except during September. Positive latent heat fluxes were observed from the evening to midnight (Fig. 10), which can likely be attributed to the advection of dry air (from the desert around the oasis) over a wet surface. Mauder et al. (2007) reported a similar phenomenon in Nigeria.

Except during September, G and H were similar in the pepper field (Fig. 10). The maximum values of soil heat flux were $28\text{-}60 \text{ W m}^{-2}$ (Fig. 10), which were slightly higher than that in an Inner Mongolian steppe ecosystem (Hao et al., 2007). The slightly negative value of G during night (Fig. 10) indicated that energy was transmitted from the soil to the surface, which was similar to other crop fields in northwestern China (Chen et al., 2016). The flux residual (Res) reached its peak value in the morning (Fig. 10), which is consistent with the results of Chow et al. (2014).

Net radiation has a significant linear positive correlation with latent heat flux (Fig. 11) because of the high water supply. The linear slope of the relationship between net radiation and LE in the HRB (Fig. 11) was similar to the slope in the Shiyanghe River Basin, another arid region of northwestern China (Ding et al., 2013).

3.5. Over-irrigation in MHRB and the potential strategies for water conservation

Hydrological processes in MHRB are greatly affected by human activities, exceeding climate change (Liu et al., 2008; Luo et al., 2016). Over-irrigation of arid oasis has been a challenge in China for water saving (Tan, 2019), but few measures have been effectively applied by farmers and companies because of lacking practicable water management advices. Deep percolation was commonly high in MHRB due to over-irrigation (Jiang et al., 2015; Li et al., 2015). Although irrigation is highly beneficial for agriculture, it has many negative environmental impacts, including pollution and depletion of surface and groundwater resources (Pereira et al., 2002).

Poor water management and the push for greater economic profits caused over-irrigation (Zhou et al., 2014a). In fact, except for deep percolation, yields have not been enhanced and the water use efficiency is low in conditions of over-irrigation. Irmak et al. (2016) reported that over-irrigation caused a decrease in yield. Su et al. (2014) also reported that irrigation water use efficiency decreased with increasing irrigation amount on sandy farmland in MHRB. Water demand of spring crops would be satisfied by a 40% of current irrigation quota of each irrigation event with a great decrease of deep percolation and an increase of crop water utilization in MHRB (Li, 2020).

Osroosh et al. (2015) suggested that over-irrigation could be avoided using automatic irrigation. Meng et al. (2017) reported that water diversion density was oversize and should be reduced by 34.8% in MHRB, therefore allocating limited water resources reasonably, popularizing water saving projects, strategies (Kharrazi et al., 2016) and measures industriously are the main methods to improve oasis water use efficiency. In addition, wet or dry year should be considered in irrigation schedule. Chen et al. (2015) indicated that irrigation volume usually did not change every year, although the irrigation demand of vegetation declined in wet years. There is a large room for the improvement of water use efficiency and water conservation in arid regions throughout China.

4. Conclusions

The amount of ET was lower than irrigation. After Aug. 4, the daily ET decreased during the maturation stage. The soil water content was higher than the field capacity frequently, indicating that over-irrigation had occurred. The water inputs (precipitation and irrigation) were 1.5 times ET , and the deep percolations

accounted for 74% of the total irrigation inputs. Irrigation water could be conserved 301 mm for the pepper field, in case that percolation (below the 1 m soil) was avoided. Therefore, the irrigation amount (per time and total) should be reduced to achieve high water use efficiency (WUE). The latent heat flux (LE) consumed more than 80% of the net radiation (R_n). In July, the LE/R_n was the highest among all months, whereas H/R_n was the lowest due to the highest values of FVC and LAI in July. The net radiation had a significant positive linear correlation with the latent heat flux because of the high water supply. Our study showed that there was considerable room for water conservation in MHRB.

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