

Evaluating Responses of Crop Water Use, Soil Water Storage and Infiltration to Precipitation Using Insentek Probes

Anzhen Qin¹, Dongfeng Ning^{1,*}, Zhandong Liu¹, Bin Sun², Ben Zhao¹, Junfu Xiao¹ and Zugui Liu¹

¹Key Laboratory of Crop Water Use and Regulation, Ministry of Agriculture, Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China

²Xuchang Irrigation Experiment Station, Xuchang Water Authority, Xuchang 461000, China

*Corresponding author

Abstract—Precipitation has been shown to increase soil water storage (SWS) and soil infiltration depth (SID) while significantly restrain crop water use (i.e., crop evapotranspiration, ET_c) during rainy days. However, the reducing effects on ET_c and increasing effects on SWS and SID has not been well quantified due to a lack of automatic soil moisture measurement. Insentek probe is a newly developed soil moisture monitoring equipment that achieves automatic measurement of soil moisture. This enables the calculation of SWS and SID related to precipitation. Four Insentek probes were installed in four corresponding lysimeters to monitor SWS, SID and ET_c for maize plants during rainy days at Xuchang Irrigation Experiment Station, in 2015 and 2016. Both lysimeter and Insentek ET_c was related to precipitation in a power function. The reducing effect of precipitation on Insentek ET_c was greater compared with lysimeter ET_c . The relationships between SWS increment and precipitation, and between SID and precipitation were fitted to a positively linear function. The linearity indicated that per 10mm precipitation averagely increased SID by 17.9 cm and SWS by 7.3 mm, respectively. We conclude that precipitation is an independent factor that determines ET_c of maize on rainy days despite of current soil moisture status in semi-humid climate in the North China Plain.

Keywords—insentek; precipitation; crop water requirement; lysimetry; zea mays L

I. INTRODUCTION

Maize is known as one of the highest evapotranspiration (ET) crops both daily and seasonally around the globe [1]. Crop evapotranspiration (ET_c) of maize ranges from 400 to 600 mm during the entire growing seasons in the North China Plain [2]. Over the past two decades in the NCP, ET_c of maize has increased by 10% along with the improvement of grain yield due to the breeding of new varieties and improving of agronomic practices [3]. Accurately estimating ET_c provides valuable information for effective irrigation water management, which is essential to mitigating the fresh water shortage problem and ensuring food security for ever-growing population [4]. There exist a variety of methods available for simulating ET_c , including lysimeter water balance method, eddy covariance method, and thermal flux method, etc. [4–6]. Among them, large-scale precision weighing lysimeters are the most precise means to estimate ET_c in a relatively high resolution through measuring weight changes of lysimeter mass.

Traditionally, ET_c in a crop growth phase can be calculated using water balance equation based on soil water storage changes [4]. Soil water balance is a water exchange between soil and atmospheric interfaces, including ET standing for water loss and precipitation representing water input. Previous studies usually chose ET_c on clear days to analysis relationships between ET_c and soil moisture [5–6]. Data during rainy days were not included because they lacked an automatic technique to monitor soil moisture on rainy days at field scales [9]. This restricts our knowledge on how ET_c responses to precipitation on rainy days. It is wrong to simply take ET_c during clear days for granted to represent a seasonal total of crop water use although ET_c during rainy days is relatively low. Insentek probe method is an innovative technique to automatically monitor soil moisture instead of conventional methods (e.g., neutron probe method and oven-drying method etc.). It is a kind of real-time soil moisture monitoring which transmits data wirelessly through GPRS network. However, merely were Insentek probes applied to monitor ET_c during rainy days. Moreover, Insentek is a powerful means to detect soil water storage increment and soil infiltration depth due to precipitation. In this study, weighing lysimeters were adopted to continuously monitor ET_c of maize along with Insentek probes. Precipitation data were recorded by a nearby weather station. We hypothesized that ET_c , SWS and SID during rainy days was a function of precipitation regardless of current soil moisture status. The objectives of this study is to quantify the responses of ET_c , SWS, SID to precipitation using Insentek probe method.

II. MATERIALS AND METHODS

A. Site Description

The experiment was carried out at the Xuchang Irrigation Experiment Station, North China Plain, in 2015 and 2016 (34°76' N, 113°24' E, a.s.l. 72.8 m). The place has a continent temperate monsoon climate. Mean annual precipitation is 640.9 mm, of which 65% falls in the maize growing season. Mean annual temperature is 14.7 °C, and annual sunshine hours are 2280 hr. Soil bulk density at 0–60 cm soil layer is 1.45 g cm⁻³ and soil organic matter at the same layer is 16.5 g kg⁻¹. The soil is a *fluvo-aquic* soil with silt loam texture. Water table at the station is detected more than 5 m below the soil surface.

B. Experimental Design

A popularly used maize seeds (*cv.* Pioneer 335) were hand-sown on June 5, 2015 and 2016 on lysimeters. Maize was planted in row spacing of 50 cm and plant-to-plant spacing 30 cm. Maize plants were thinned to 32 plants per lysimeter. Application rates of fertilizer for each lysimeter were 225 kg N ha⁻¹, 180 kg P₂O₅ ha⁻¹, and 55 kg K₂O ha⁻¹, respectively. Diammonium phosphate and potassium sulfate were broadcast as base fertilizer prior to sowing. One half amount of urea was applied as base fertilizer before sowing, whereas the rest amount of nitrogen was top-dressed at heading stage. Fertilizer was incorporated into soils to a depth of 20 cm by hoe. Except a flood irrigation (55 mm) after maize sowing to guarantee seed germination, no supplemental irrigation was added to maize plants because seasonal precipitation basically met the crop water requirement in the two consecutive years. Weeds and pests control practices were applied according to the local governmental recommendations.

C. Data Measurements and Calculations

Crop water use (ET_c) was monitored by four large precision weighing lysimeters (2.0m wide × 2.4m long × 2.3m in depth). The large-scale weighing lysimeter system contains a main body, load cell, and data logger system. Weighing precision was ±100 g, equal to ±0.1 mm of water column. The resolution enables accurate determination of daily ET_c. The masses of lysimeters were measured every 10 s, and the data were reported as 30-min means. Daily ET_c was determined as the difference between the mass losses and gains on a whole day basis divided by the lysimeter area of 6.6 m².

Insentek probes were installed at the center of each lysimeter to a depth to 1 m. In this study, soil water storage (SWS) was a product of volumetric water content by the thickness of soil layer. For Insentek probe method, ET_c was calculated based on soil water storage changes on a daily basis using soil water balance equation as follows:

$$ET_c = Pr e + I + WS_d - WS_{d+1} \quad (1)$$

Where ET_c is crop daily evapotranspiration (mm); *P* is precipitation (mm) monitored by a rain gauge of the nearby weather station; *I* is irrigation quota (mm) measured using a flow meter installed at the outlet of a pipeline; WS_{*d*} and WS_{*d*+1} is soil water storage (mm) to a depth of 1 m on the current and the next day, respectively.

Daily ET_c during rainy days was inhibited by precipitation, especially for precipitation with amount larger than 15 mm. In this study, ET_c on rainy days was related to precipitation in a negatively power function as follows:

$$ET_c = a \times Pr e^{-b} \quad (2)$$

Where ET_c is crop daily evapotranspiration (mm); *Pre* is precipitation (mm); *a* and *b* are function parameters to be fitted.

Soil water storage increment (ΔSWS) due to rain-water input on rainy days were estimated by subtracting SWS a day before a rainfall event from SWS on the rainfall day. The

relationship between ΔSWS and precipitation was quantified using a positive linear equation:

$$\Delta SWS = a \times Pre - b \quad (3)$$

Soil moisture was automatically monitored hourly by the Insentek probes, allowing for the calculation of soil infiltration depth (SID) due to precipitation. Soil water infiltration was estimated by determining the depth of soil moisture increasing one day after a rainfall event, which was easily detected by Insentek probes. The magnitudes of SID on rainy days were assumed to associate with precipitation in a positively linear manner as follows:

$$SID = a \times Pre + b \quad (4)$$

D. Statistical analysis

Data were analyzed using analysis of variance with Statistical Analysis Software (version 19.0, SPSS Inc., Chicago, IL, USA). Significance was declared at the probability level of 0.05. Relationships among ET_c, SWS, SID, and precipitation were analyzed by means of the Levenberg-Marquardt Algorithm.

III. RESULTS AND DISCUSSION

A. Statistics for Precipitation and Temperature

Because there existed no year × data interaction in maize growing seasons of both years, we averaged the two years' data for analysis. Precipitation grades were classified according to the recommendations of China Meteorological Administration (Table I). Most rainfall events fell in the light rainfall range with an average precipitation of 4.75 mm d⁻¹ and average numbers of 26 d. Day numbers of moderate and heavy rainfall events were 4 to 6 d with an average precipitation of 13.3 mm d⁻¹ for moderate rainfall and 33.5 mm d⁻¹ for heavy rainfall, respectively. In each year, there was one storm event with precipitation amount exceeding 50 mm d⁻¹. Precipitation intensity had no significant effect on air temperature, which might be influenced by solar radiation, relative humidity and air velocity [7].

B. Crop Evapotranspiration Response to Precipitation

Both Insentek and lysimeter ET_c was significantly inhibited by precipitation. Our result showed that precipitation explained 84% to 87% variations of daily ET_c during rainy days regardless of current soil water content (Figure I). Moreover, precipitation, as an independent factor controlling ET_c, reduced ET_c on rainy days in a negatively power manner. Compared to ET_c during rain-free days, Insentek ET_c was reduced by 30.2%, 50.8%, 66.1%, and 68.1%, respectively, during light rain days, moderate rain days, heavy rain days, and storm rain days. Similarly, lysimeter ET_c was reduced by 31.1%, 73.2%, 90.3% and 93.5%, respectively, during the corresponding rain days. Lysimeter ET_c showed a faster response to precipitation than did Insentek ET_c.

C. Crop Evapotranspiration, Soil Water Storage Increment, and Soil Infiltration Depth Related to Precipitation

Both lysimeter and Insentek ET_c was related to precipitation in a negatively power function (Figure I). The reducing effect of precipitation on Insentek ET_c was greater compared with lysimeter ET_c . We found that lysimeter had an immediate response to weight losses due to ET_c after precipitation, weakening the sensitiveness of daily ET_c total to precipitation, whereas Insentek ET_c was estimated using soil water storage increment (ΔSWS) occurring after soil infiltration, which needed time to finish the process. Moreover, lysimeter ET_c was more sensitive to canopy transpiration than did Insentek ET_c . This part of weight losses also contributed to the fast response of lysimeter to actual ET_c variations. The relationships between ΔSWS and precipitation, and between soil infiltration depth (SID) and precipitation were fitted to a positively linear function. The linearity indicated that per 10mm precipitation averagely increased SID by 17.9 cm and ΔSWS by 7.3 mm, respectively (Figure II).

TABLE I. STATISTICS OF MEAN CROP EVAPOTRANSPIRATION DETERMINED BY INSENTEK PROBE METHOD AND LYSIMETRY AT DIFFERENT PRECIPITATION GRADES IN 2015 AND 2016, AT XUCHANG IRRIGATION EXPERIMENT STATION.

Precipitation grades ^a	No rain	Light rain	Moderate rain	Heavy rain	Storm
Pre ^b intensity (mm d ⁻¹)	0	0.1–9.9	10–24.9	25–49.9	50–99.9
Mean Insen ET_c (mm)	3.01	2.1	1.48	1.02	0.96
Mean lysi ET_c (mm)	3.7	2.55	0.99	0.36	0.24
Mean T _{air} (°C)	24.7	25.1	21.5	21.4	30.5
Number of days	81	26	4	6	1
Mean Pre (mm)	0	4.75	13.3	33.5	56.2

a. Precipitation grades were classified based on the instructions of China Meteorological Administration.
b. Pre, precipitation; T_{air}, air temperature.

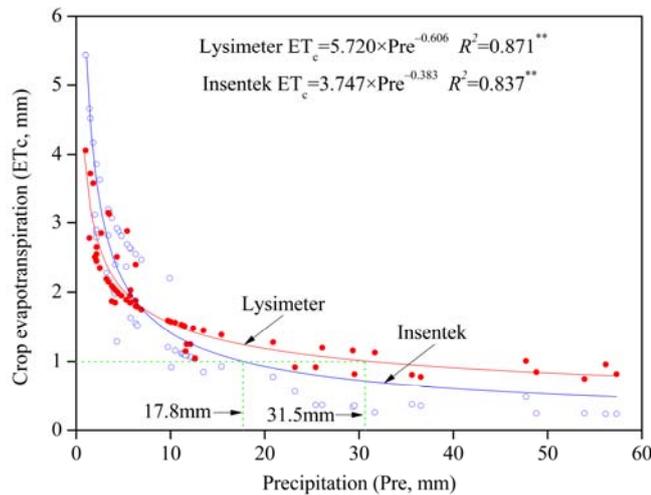


FIGURE I. RELATIONSHIP BETWEEN PRECIPITATION AND CROP EVAPOTRANSPIRATION MEASURED BY INSENTEK PROBE METHOD AND LYSIMETRY. BOTH YEARS' DATA WERE SUBJECTED FOR REGRESSION ANALYSIS

D. Mean Daily Evapotranspiration during Different Growth Phases

In this study, mean daily ET_c were calculated for different maize growth phases in 2015 and 2016 growing seasons (i.e.,

emergence (VE) to six leaves (V6) phase; V6 to silking (R1) phase; R1 to milk (R3) phase; and R3 to physical maturity (R6) phase) (Table II). Daily ET_c was generally considered as a representative of crop water use intensity [8]. Mean daily ET_c estimated by Insentek probe method and lysimetry both peaked during V6 to R1 phase in both growing seasons, achieving an mean daily ET_c of 3.56 mm d⁻¹ (Insentek) and 4.21 mm d⁻¹ (lysimeter) in both years. Mean daily ET_c during R1 to R3 was significantly lower in 2016 than in 2015 due to continuous overcast and rainy days during that period of 2016. Significantly lowered air temperature and air velocity during overcast days gave rise to lower ET_c rates [10]. Compared to lysimeter ET_c , Insentek probe method underestimated mean daily ET_c by 15.7% and 14.6% in 2015 and 2016, respectively.

TABLE II. MEAN DAILY EVAPOTRANSPIRATION SEPARATED BY CROP GROWTH PHASES IN MAIZE GROWING SEASONS OF 2015 AND 2016, AT XUCHANG IRRIGATION EXPERIMENT STATION.

Year	Method	Mean Daily Evapotranspiration (mm d ⁻¹)			
		VE to V6 ^a	V6 to R1	R1 to R3	R3 to R6
2015	Insentek	2.38 b ^b	3.57 c	3.20 b	2.18 b
	Lysimeter	2.52 b	4.05 b	4.01 a	2.86 a
2016	Insentek	2.84 a	3.55 c	2.11 c	2.26 b
	Lysimeter	2.96 a	4.41 a	2.46 c	2.77

a. VE, emergence; V6, six leaves phase; R1, silking phase; R3, milk phase; R6, physical maturity.
b. Different letters in each column indicate significant difference at P < 0.05.

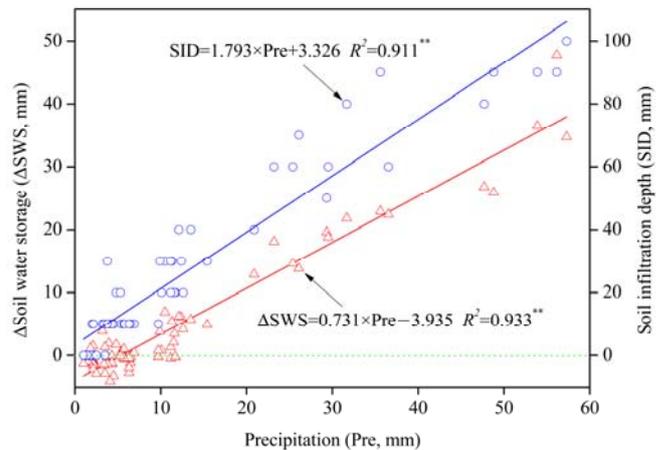


FIGURE II. RELATIONSHIP BETWEEN PRECIPITATION AND SOIL INFILTRATION DEPTH, AND BETWEEN PRECIPITATION AND SOIL WATER STORAGE INCREMENT ESTIMATED USING INSENTEK PROBE METHOD. BOTH YEARS' DATA WERE SUBJECTED FOR REGRESSION ANALYSIS.

E. General Discussion

Insentek probe method had several advantages over lysimetry, including the ease of deployment, lower initial expense, and wireless transmission of data. However, there still existed limitations for Insentek method to precisely simulate ET_c . For example, Insentek method led to a weaker ET_c response to precipitation as the probe needs time to detect rain-water infiltration and soil water storage increment in comparison to direct measurement of weight losses of lysimeter. This led to lower daily ET_c rates during rainy days using Insentek probes, as demonstrated by a 15%

underestimate of mean daily ET_c by Insentek probe method. Alternatively, one probable method to improve accuracy of Insentek ET_c data was to adopt longer Insentek probes comparable to the depth of lysimeter soil column, instead of 1 m long Insentek probes.

Previous studies usually chose ET_c rate during clear days to compare simulated ET_c rates by neutron probe method, eddy covariance method, and lysimetry etc [11–13]. They often neglected the reducing effect of precipitation on actual ET_c rates on field scale due to a lack of automatic soil moisture measurement technique [14]. Also, problems about infrequent measurements with neutron probe method can be well solved by Insentek automatic soil water probes, allowing accurate estimates of ET_c during rainy days at daily and sub-daily intervals [15–16]. In this study, we found that simulated ET_c from precipitation data during rainy days was significantly lower than expected because precipitation markedly inhibits actual ET_c . Therefore, we shifted our attention to the relationship between daily ET_c and precipitation. We found that precipitation can be an independent factor determining daily ET_c on rainy days despite of the current soil water status. Therefore, ET_c during rainy days can be derived from precipitation data only, and the simulation results are in good agreement with the ET_c data measured by lysimeters.

IV. CONCLUSIONS

In semi-humid regions of China, precipitation plays an important role in soil water balance calculation of ET_c . In this study, daily ET_c was related to precipitation in a negatively power function, whereas the relationships between ΔSWS and precipitation, and between SID and precipitation were fitted to a positively linear function. Response of Insentek probes to precipitation was slower than did the lysimeters, resulting lower ET_c rates by Insentek probe method. Since ET_c from precipitation data during rainy days was significantly lower than expected, precipitation can be an independent factor determining daily ET_c during rainy days. Till now, few studies have been conducted to quantify the responses of crop water use, soil water storage increment and soil infiltration depth to precipitation for maize plants in the North China Plain. This study starts to fill this gap.

ACKNOWLEDGMENT

This research was financially supported by the National Key Research and Development Program (2017YFD0301102), the China Agriculture Research System (CARS-02), the Agricultural Science and Technology Innovation Program (ASTIP), and the Central Public-interest Scientific Institution Basal Research Fund (Farmland Irrigation Research Institute, CAAS, FIRI2017-05).

REFERENCES

[1] T. Howell, S. R. Evett, J. A. Tolk, A. D. Schneider, and J. LSteiner, "Evapotranspiration of corn, southern high plains," In: C. R. Camp, E. J. Sadler, R. Yoder, (Eds.), "Evapotranspiration and Irrigation Scheduling," Am. Soc. Agric. Eng., St. Joseph, MI, pp. 158–166, 1996.

[2] Y. Liu, and L. Yi, "A consolidated evaluation of the FAO-56 dual crop coefficient approach using the lysimeter data in the North China Plain," *Agric. Water Manage.*, vol. 97, pp. 31–40, 2010.

[3] X. Y. Zhang, S. Y. Chen, D. Pei, M. Y. Liu, and H. Y. Sun, "Improved water use efficiency associated with cultivars and agronomic

management in the North China Plain," *Agron. J.*, vol. 97, pp. 783–790, 2005.

[4] X. Y. Zhang, S. Y. Chen, H. Y. Sun, Y. M. Wang, and L. W. Shao, "Water use efficiency and associated traits in winter wheat cultivars in the North China Plain," *Agric. Water Manage.*, vol. 97, pp. 1117–1125, 2010.

[5] S. R. Evett, W. P. Kustas, P. H. Gowda, J. H. Prueger, and T. A. Howell, "Overview of the Bushland Evapotranspiration and Agricultural Remote sensing Experiment 2008 (BEAREX08): A field experiment evaluating methods quantifying ET at multiple scales," *Adv. Water Resour.*, vol. 50, pp. 4–19, 2012.

[6] R. Ding, S. Kang, F. Li, Y. Zhang, L. Tong, and Q. Sun, "Evaluating eddy covariance method by large-scale weighing lysimeter in a maize field of Northwest China," *Agric. Water Manage.*, vol. 98, pp. 87–95, 2010.

[7] G. Stanhill, R. Rosa, and S. Cohen, "The roles of water vapour, rainfall and solar radiation in determining air temperature change measured at Bet Dagan, Israel between 1964 and 2010," *Int. J. Climatol.*, vol. 33, pp. 1772–1780, 2013.

[8] Z. Liu, A. Qin, J. Zhang, J. Sun, D. Ning, and B. Zhao, et al., "Maize yield as a function of water availability across precipitation years in the North China Plain," *Crop Sci.*, vol. 57, pp. 2226–2237, 2017.

[9] S. R. Evett, R. C. Schwartz, J. A. Tolk, and T. A. Howell, "Soil profile water content determination: spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes," *Vadose Zone J.*, vol. 8, pp. 926–941, 2009.

[10] S. R. Evett, R. C. Schwartz, T. A. Howell, R. L. Baumhardt, and K. S. Copeland, "Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET?" *Adv. Water Resour.*, vol. 50, pp. 79–90, 2012.

[11] S. R. Evett, J. A. Tolk, and T. A. Howell, "A depth control stand for improved accuracy with the neutron probe," *Vadose Zone J.*, vol. 2, pp. 642–649, 2003.

[12] J. A. Tolk, and S. R. Evett, "Lysimetry versus neutron moisture meter for evapotranspiration determination in four soils," *Soil Sci. Soc. Am. J.*, vol. 73, pp. 1693–1698, 2009.

[13] S.R. Evett, R. C. Schwartz, R. J. Lascano, and M. G. Pelletier, "In-soil and down-hole soil water sensors: Characteristics for irrigation management," In *Proceedings of 5th Decennial National Irrigation Symposium*, pp. 5–8, Dec. 2010, Phoenix, Arizona. Paper No. IRR10–8346. ASABE, St. Joseph, Mich. 2010.

[14] T. A. Howell, S. R. Evett, J. A. Tolk, and A. D. Schneider, "Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the northern Texas High Plains," *J. Irrig. Drainage Eng.*, vol.130, pp. 277–285, 2004.

[15] S. R. Evett, "Neutron moisture meters," In: S. R. Evett, L. K Heng, and P. Moutonnet, (Eds.), "Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology," International Atomic Energy Agency, Vienna, Austria, Chapters 2–3, 2008.

[16] S. R. Evett, T. A. Howell, A. D. Schneider, D. F. Wanjura, and D. R. Upchurch, "Water use efficiency regulated by automatic drip irrigation control," In: "2001 Proceedings of International Irrigation Show," October 31–November 7, San Antonio, TX. The Irrigation Association, Falls Church, Virg., pp. 49–56, 2001.