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Article

Insentek Sensor: An Alternative to Estimate Daily Crop Evapotranspiration for Maize Plants

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Received: 25 November 2018; Accepted: 17 December 2018; Published: 24 December 2018

Abstract: Estimation of ground-truth daily evapotranspiration (ET_c) is very useful for developing sustainable water resource strategies, particularly in the North China Plain (NCP) with limited water supplies. Weighing lysimetry is a well-known approach for measuring actual ET_c. Here, we introduced an alternative to lysimetry for ET_c determination using Insentek sensors. A comparison experiment was conducted for maize plants at Xuchang Irrigation Experiment Station, in the NCP, in 2015 and 2016. Insentek ET_c was evaluated using data on clear days and rainy days independently. We found that daily ET_c increased gradually from VE (emergence) to VT (tasseling) stages, peaked at the R1 (silking) stage with the highest value of 7.8 mm·d^{-1}, and then declined until maturity. On average, cumulative total of lysimetric ET_c was 19% higher than that of Insentek ET_c. The major depth of soil water extraction might be 60 cm for maize plants on lysimeters according to soil water depletion depth monitored by Insentek sensors. Daily ET_c significantly related to soil water content (SWC) in topsoil (0–30 cm) in an exponential function (coefficients of determination (R^2) = 0.32–0.53), and to precipitation (Pre) in a power function (R^2 = 0.84–0.87). The combined SWC (0–30 cm)–Pre–ET_c model may offer significant potential for accurate estimation of maize ET_c in semi-humid environment of the NCP.

Keywords: water balance; automatic soil moisture record; lysimetry; North China Plain; *Zea mays* L.

1. Introduction

The North China Plain (NCP) produces 58 and 33% of the domestic wheat and maize yields in China, ensuring China's food security [1]. In 2016, maize (*Zea mays* L.), with a total yield of 220 million tons, was planted on a 36 million hectare across China, making a 49% contribution to domestic increase in grain production [2]. Maize is also known as one of the highest water-using crops in different regions [3,4]. Thanks to a continent monsoon climate, annual precipitation falls between 400 and 600 mm in the NCP, with 65% of precipitation occurring in maize seasons [5], while annual evapotranspiration ranges from 800 to 900 mm: 50–100% higher than precipitation [6]. For decades, crop water consumption has been being supplemented by extracting the declining groundwater in the NCP at a speed exceeding aquifer recharge [7]. In the future, immense volumes of groundwater will be required for the agricultural sector with an ever-growing population [8]. Nevertheless, agronomic practices, such as cultivar updating and irrigation optimizing, have been made to extend the life of the aquifer. Consequently, only a 10% increase in crop evapotranspiration (ET_c) contributed to a 50%

yield increase over the past two decades [9]. Of those practices, ET_c-based irrigation scheduling is considered a powerful tool to decrease long-term aquifer extraction [10].

In general, ET_c is the process where water is consumed through soil evaporation and plant transpiration during the water cycling [11]. It has always been considered as an equivalent to crop water use [12]. Water balance equation is the most widely used method to estimate ET_c. In the equation, ET_c stands for water loss from soil surface and plants whereas precipitation and irrigation represents water input. Water-saving strategies largely depend on the monitoring and controlling of ET_c [5,6]. There are numerous methods available for estimating ET_c [12–15], among which weighing lysimetry is normally used as a standard means [16]. However, its construction is expensive and its operation requires professional personnel [17]. This restricts the popularity of lysimetry. Alternatives should be developed to facilitate ET_c monitoring. ET_c estimation based on the oven-drying method is simple; however, it is laborious and time-consuming [4]. Another way is to adopt the neutron probe method [18]. This enables the estimation of ET_c regardless of crop types and soil properties. However, this method usually needs a span of time to measure soil water content (SWC), and is difficult to estimate daily or sub-daily ET_c [19]. Another approach for ET_c estimation is remote sensing technology. It enables us to use satellite observations to estimate ET_c at a global and regional scale [20]. However, studies have shown that different algorithms of remote sensing models for ET_c estimation have strong divergence [21]. Usually, the algorithms to estimate ET_c have been based on a surface energy budget using thermal infrared data, which required plenty of ground-based measurements and were affected by cloud contamination, providing uncertainties to the ET_c estimates [21,22]. Therefore, a real-time ground-truth monitoring of ET_c is needed.

The Insentek sensor (Beijing Oriental Ecological Technology Ltd., Co., Beijing, China) is an emerging technology that can automatically monitor soil moisture data hourly or sub-hourly (Figure 1). It is an apparatus for real-time soil moisture monitoring powered by solar energy. Insentek sensor allows the determination of daily changes in soil water storage (SWS), making the calculation of daily ET_c possible. Our previous study showed that root mean square error (RMSE) of SWC between the Insentek sensor and the oven-dry method was 0.927 $cm^3 \cdot cm^{-3}$, and relative prediction deviation (RPD) was 7.99 for silt loamy soils, indicating Insentek sensor is a reliable tool to represent real SWC values (Table 1). The latest figure have shown that there have been more than 15,000 sensors already installed across China, including remote areas such as Tibet (personal communication). An ET_c monitoring network that covers the whole country has been formed. Through checking the year-round data, Insentek sensors have showed better continuity and stability than other soil moisture techniques (e.g., time-domain reflectometry, neutron probe, and oven-drying etc.). In this study, weighing lysimeters were adopted to continuously monitor ET_c of summer maize along with Insentek sensors.

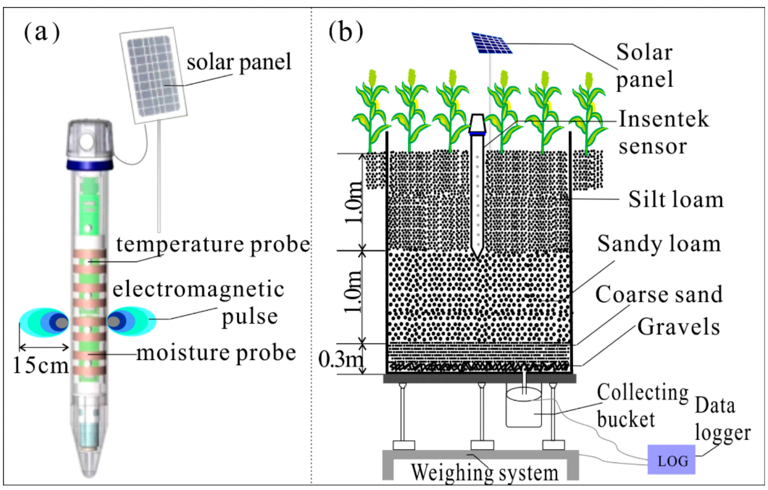

Figure 1. Insentek sensor and design of lysimeter experiment. (**a**) The structure and principle of an Insentek sensor; (**b**) lysimeter setup details and installation of an Insentek sensor.

Table 1. Test for goodness of fit between soil water content (soil water content (SWC), $cm^3 \cdot cm^{-3}$) measured using an Insentek sensor and oven-dry method across different soil textures.

Soil Texture	SWC Measured by Insentek Sensor			Goodness of Fit		Correlation	Significance
	Maximum	**Minimum**	**Mean**	**RMSE**	**RPD**	R^2	p
Sand	3.46	28.64	18.09	1.044	6.78	0.997	0.0001
Silt loam	7.26	35.11	22.71	0.927	7.99	0.995	0.0001
Clay	17.74	33.71	25.35	0.897	5.61	0.997	0.0001

RMSE is root mean square error used to evaluate the differences between estimated and observed SWC; RPD is relative prediction deviation, values measured by Insentek sensor are reliable with RPD $\geq$ 2.0 [23]; R^2 is coefficient of determination; p is probability.

Until now, the degree to which ET_c from Insentek sensor method represents that of the lysimetry has not been well tested. In this study, we started the comparison work between the two. Moreover, precipitation was recorded by a nearby weather station to analyze the relationship between ET_c and precipitation. We hypothesized that ET_c from the Insentek sensor method was similar to that of lysimetry, and that ET_c was significantly related to precipitation and soil moisture. The objectives of this study were to evaluate the efficacy of Insentek sensor method using lysimetric data, and to quantify the relationships among ET_c, SWC and precipitation for maize plants in the NCP.

2. Materials and Methods

2.1. Site Description

The experiment was carried out at the Xuchang Irrigation Experiment Station, North China Plain, in 2015 and 2016 (34°08′25″ N, 113°59′04″ E, a.s.l. 71 m) (Figure 2). Four sets of large-scale weighing lysimeters (2.0 m wide × 2.4 m long × 2.3 m in depth) along with four Insentek sensors were adopted to compare daily ET_c. The place had a continent temperate monsoon climate. The soil was a fluvo-aquic soil. Soil characteristics of the lysimeters are presented in Table 2. The bottom 30 cm was filled with a very coarse sand and <3 cm gravels to permit drainage towards lysimeter outlet.

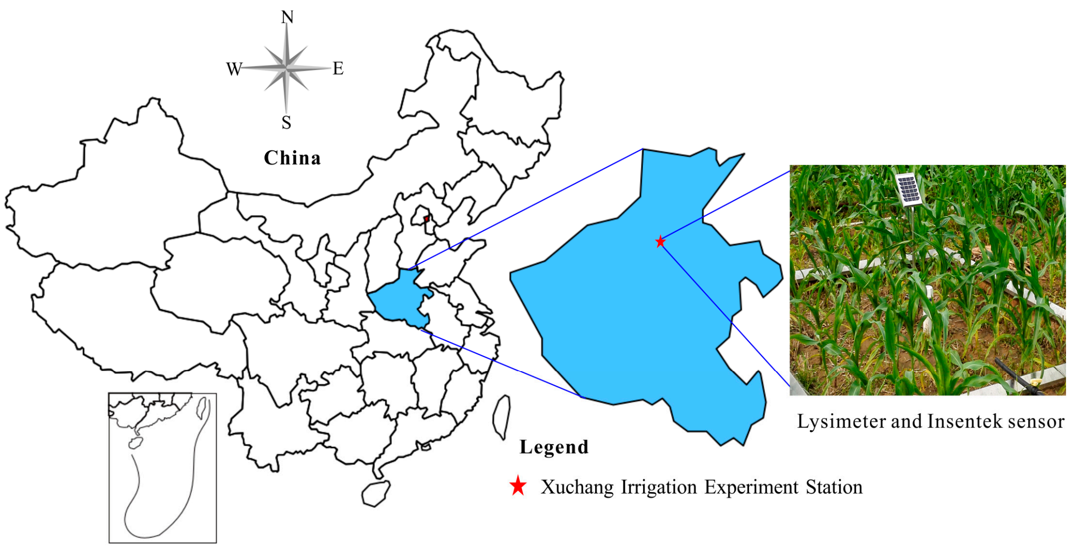

Figure 2. Schematic location of the Xuchang Irrigation Experiment Station and the lysimeter and Insentek sensor at the Station.

Table 2. Soil physical properties prior to the start of the experiment at the Xuchang experiment station, North China Plain, in 2015.

Soil Layers (cm)	Clay (<0.002 mm)	Silt (0.002–0.05 mm)	Sand (>0.05 mm)	Soil Texture [1]	Wilting Point	Field Capacity	Soil Bulk Density
0–30	22%	36%	42%	Silt loam	13.4	27.3	1.43
30–60	24%	39%	37%	Silt loam	12.5	25.8	1.46
60–100	20%	41%	39%	Silt loam	12.2	26.9	1.43
100–150	15%	32%	53%	Sandy loam	10.4	24.1	1.54
150–200	10%	22%	68%	Sandy loam	9.4	22.9	1.51

[1] Soil texture was determined according to the Chinese Soil Classification System [24].

Mean annual precipitation is 640.9 mm, of which 65% falls during the maize growing season. Mean annual temperature is 14.7 °C, and annual sunshine hours are 2280 h [4]. Soil bulk density at the 0–60 cm soil layer was 1.45 g·cm^{-3} and soil organic matter at the same layer was 16.5 g·kg^{-1}. Available N, P_2O_5, and K_2O at the same layer were 36.5, 23.4, and 219.8 mg·kg^{-1}, respectively [25]. The water table was detected more than 5 m below the soil surface.

2.2. Experimental Design

Crops were grown in a winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) relay cropping system. The lysimeters were made of steel metal sheets. Total lysimeter weight was approximately 24 t, including the container mass. The lysimeter was built in 2012, and ET_c data have been monitored since March, 2014. Insentek sensors were installed at the center of each lysimeter in October, 2014. After three years of natural packing, the lysimeter monolith was regarded to duplicate the natural soil status [26].

The upper 2.0 m depth of soil monolith in each lysimeter was filled with undisturbed monolith. The large-scale weighing lysimeter system contains a main body, load cell, and data logger system (Figure 1). Weighing resolution was ±100 g, equal to ±0.1 mm of water column. The masses of the lysimeters were measured every 30 s, and the data were reported as 30 min means. The depth of lysimeter (2.3 m) permits development of normal rooting and water extraction for summer maize in the NCP [27]. Collecting buckets were suspended from the bottom of lysimeters to hold gravity drainage effluent. Load cells connected to the bucks were adopted to separately measure drainage mass without varying total weight of the lysimeters. Insentek sensors were installed between maize rows at the center of lysimeters. Insentek ET_c was computed using water balance equation at daily interval. Lysimetric data are usually noisy due to wind and other external disturbance. The lysimeter noise was separated from signals using a filtering routine [28]. Additionally, biases on lysimeters were controlled by careful management of sowing, fertilization and irrigation.

A popular form of maize seeds (*cultivar* Pioneer 335) was sown on 5 June 2015 and 7 June 2016 (Figure 3). Maize was planted in a row with a spacing of 50 cm and plant–to–plant with a spacing of 30 cm. After maize plants were thinned, there were 32 plants left per lysimeter, equal to a density of 66,700 plant ha^{-1}. Application rates of fertilizer for each lysimeter were 225 kg·ha^{-1} N, 180 kg·ha^{-1} P_2O_5, and 55 kg·ha^{-1} K_2O, respectively. Diammonium phosphate and potassium sulfate were broadcast as base fertilizer prior to planting. One half amount of urea was applied as base fertilizer before sowing, whereas the rest amount of nitrogen was top-dressed at VT (tasseling) stage. Fertilizer was incorporated into soils to a depth of 20 cm using hand-cultural method. Besides a flood irrigation (55 mm) after maize sowing to guarantee seed germination, no supplemental irrigation was added as rainfall met the crop water requirement in both years. Weeds and pests control was applied according to the local governmental recommendations.

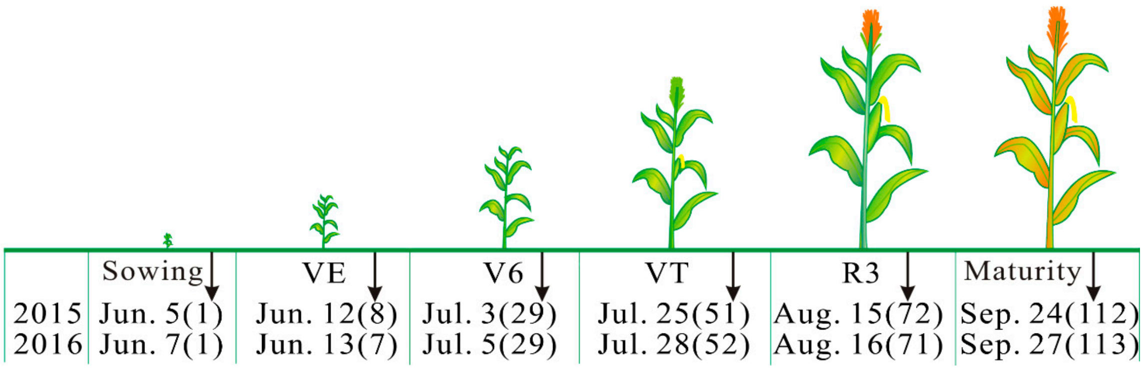

Figure 3. Seasonal schedule of crop growth stages of summer maize (VE, emergence; V(n), (n)-leaf stage; VT, tasseling stage; R3, milk stage) at the Xuchang Irrigation Experiment Station. The date in the figure was recorded when more than three quarters (>75%) of the crops developed into the particular growth stage. The number in parentheses is days after sowing.

2.3. Data Collection and Measurements

2.3.1. Soil Water Content

Insentek sensors (Beijing Oriental Ecological Technology Ltd., Co., Beijing, China) were used to monitor soil water content (SWC, $cm^3 \cdot cm^{-3}$) at 10 cm increment to a depth of 100 cm. The radius of soil volume prospected by the Insentek sensors is 15 cm (Figure 1). The sensor is a wireless soil moisture sensor powered by a rechargeable battery, which was, in turn, charged by a solar panel. In order to evaluate the performance of Insentek sensors, relevant tests were conducted. Our experimental results showed that, compared to the oven-drying method, the Insentek sensor method is a promising tool for monitoring moisture across various soil textures.

2.3.2. Daily Crop Evapotranspiration

Daily lysimetric ET_c was determined as the difference between the mass losses and gains on a whole day basis divided by the lysimeter area (4.8 m^2), and the density of water (1.0 $g \cdot cm^{-3}$), converting lysimeter mass in kg to the equivalent depth of water in mm. Daily ET_c was calculated using Equation (1):

$$ET_c = \Delta SWS + Pre + I - R - D \tag{1}$$

where ΔSWS is the daily changes in soil water storage (mm) of lysimeter; Pre is the precipitation (mm); I is the irrigation quota (mm); R is the surface runoff, assumed to be negligible due to flat surface and lysimeter freeboard; and D is the drainage flux, measured by vacuum drainage systems.

Daily ET_c estimated using Insentek sensors was calculated on a daily basis using the same water balance as in Equation (1), except the calculation of ΔSWS, which was calculated based on the soil volumetric water content in 0–100 cm depth.

2.3.3. Grain Yield and Water Use Efficiency

At physiological maturity, all maize plants from each lysimeter were sampled. To determine the grain yield, the ears of all plants of maize in each lysimeter were air dried until constant mass, and then the grain was separated, cleaned, and weighed. Grain yield was calculated on a dry-matter basis. Water use efficiency (WUE, $kg \cdot ha^{-1} \cdot mm^{-1}$) was calculated as the grain yield ($kg \cdot ha^{-1}$) produced per unit of ET_c (mm).

2.3.4. Relationship between ET_c and Soil Water Content

To determine the response of ET_c to SWC on clear days, an exponential function combined with a quadratic function was used as follows:

$$ET_c = e^{a+b\times SWC+c\times SWC^2} \quad (2)$$

where ET_c is crop evapotranspiration ($mm\cdot d^{-1}$) and SWC is soil water content ($cm^3\cdot cm^{-3}$) on clear days; *a*, *b*, and *c* are parameters to be fitted.

2.3.5. Relationship between ET_c and Precipitation

Daily ET_c on rainy days was restrained by precipitation, especially for moderate to heavy rain. In this study, ET_c on rainy days was related to precipitation in a negative power function as follows:

$$ET_c = a \times Pre^{-b} \quad (3)$$

where as ET_c is crop evapotranspiration ($mm\cdot d^{-1}$) on rainy days; Pre is precipitation (mm); *a* and *b* are function parameters to be fitted.

2.3.6. Meteorological Data

A weather station was built adjacent to the lysimeter fields. The net radiation, air temperature, relative humidity, and wind speed and direction were recorded at 2.0 m height over mowed grass on an hourly basis.

2.3.7. Evaluation of Insentek Data

Performance of the Insentek sensor method to estimate daily ET_c was evaluated using a combination of graphical and statistical methods. The evaluation factors include slope and intercept for linear regression between the lysimetric and Insentek data, coefficient of determination (R^2), root mean square error (RMSE), and relative prediction deviation (RPD). The R^2 describes the proportion of variance in lysimetric ET_c explained by Insentek data. The RMSE can be used to investigate the differences between lysimetric and Insentek values. The RMSE is calculated using Equation (4):

$$RMSE = \sqrt{\sum_{i=1}^{n}\left(x_{Insen} - x_{lysi}\right)^2/n} \quad (4)$$

where RMSE is the root mean square error; x_{Insen} and x_{lysi} are corresponding ET_c values estimated based on Insentek and lysimetry, respectively; and *n* is the number of values evaluated. The smaller the RMSE values are, the more accurate the Insentek data turn out to be.

The RPD is used to indicate the reliability of Insentek data. RPD is calculated using Equation (5):

$$RPD = STDEV\left(x_{lysi}\right)/RMSE \quad (5)$$

where RPD is the relative prediction deviation and STDEV is the standard deviation of lysimetric ET_c values. $RPD \geq 2.0$ indicates Insentek data are reliable; $1.4 < RPD < 2.0$ means the data are feasible but need to be improved; and $RPD \leq 1.4$ indicates the data are unreliable [23].

2.4. Statistical Analysis

Data were analyzed using an 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, unless otherwise stated. Relationships among ET_c, SWC, and precipitation were analyzed by means of the Levenberg–Marquardt Algorithm. Figures were plotted using Original Pro 9.1 (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Dynamics of Insentek Soil Moisture

Soil water content (SWC), monitored by Insentek sensors, was between 10.6 and 37.2 cm^3·cm^{-3} in 0–30 cm depth, 23.4 and 38.4 cm^3·cm^{-3} in 30–60 cm depth, and 27.3 and 38.8 cm^3·cm^{-3} in 60–100 cm depth in both seasons (Figure 4). Precipitation mainly increased SWC for 0–60 cm depth. On average, SWC increased by 33%, 11%, 10%, 8%, 5%, and 4% for 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, and 50–60 cm soil depths, respectively, by precipitation >15 mm. A limited effect on SWC was observed in 60–80 cm depth and minor effect in 80–100 cm depth. Except early vegetative phase before days after sowing (DAS) 40 (mid of July), a precipitation affect for SWC was discovered when soil depth was below 80 cm. In the rooted soil layers (0–60 cm), SWC gradually declined from DAS 40 to maturity, whereas in 60 cm below soil layers, it remained stable, indicating the major depth of soil water extraction for lysimeter maize might be 60 cm.

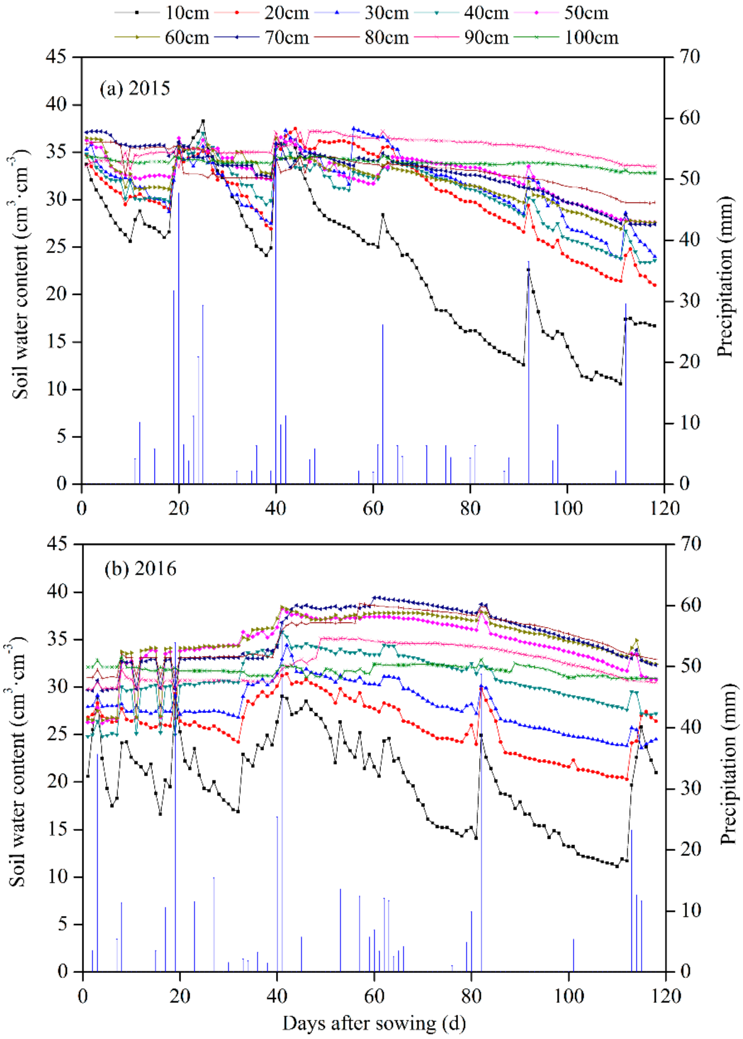

Figure 4. Seasonal variations in soil water content (cm^3·cm^{-3}) at 10 cm interval to a depth of 100 cm measured by Insentek sensors during maize growing seasons of (**a**) 2015 and (**b**) 2016. Vertical drop lines represent daily precipitation.

3.2. Daily Crop Evapotranspiration

Precipitation was 4% and 6% above normal in the maize growing seasons of 2015 and 2016. No supplemental irrigation was added after maize emergence (VE); thus, soil moisture was mainly affected by precipitation and ET_c. Lysimeter and Insentek produced similar trends in daily ET_c (Figure 5). Lower ET_c rates were observed when precipitation >15 mm. However, ET_c increased markedly after precipitation occurrence due to an increase in soil water evaporation. On average, peak ET_c rates, usually occurring in intermittent periods of precipitation, exceeded 2.5 and 4.5 mm·d^{-1} over vegetative and reproductive phases of maize. However, mean peak lysimetric ET_c rates were 29% higher than Insentek ET_c (4.87 vs. 3.83 mm·d^{-1}) in both growing seasons. The highest ET_c rates occurred on days after sowing (DAS) 53 (VT) in 2015, and on DAS 43 (V12) in 2016, respectively. Daily ET_c decreased appreciably and was kept to a relatively lower level until maturity. Throughout the seasons, variations in daily lysimetric and Insentek ET_c basically changed with dynamics of daily mean temperature, except the period from DAS 55 (VT) to DAS 85 (R4) in 2016 with ongoing overcast and rain, giving rise to lower ET_c than was expected.

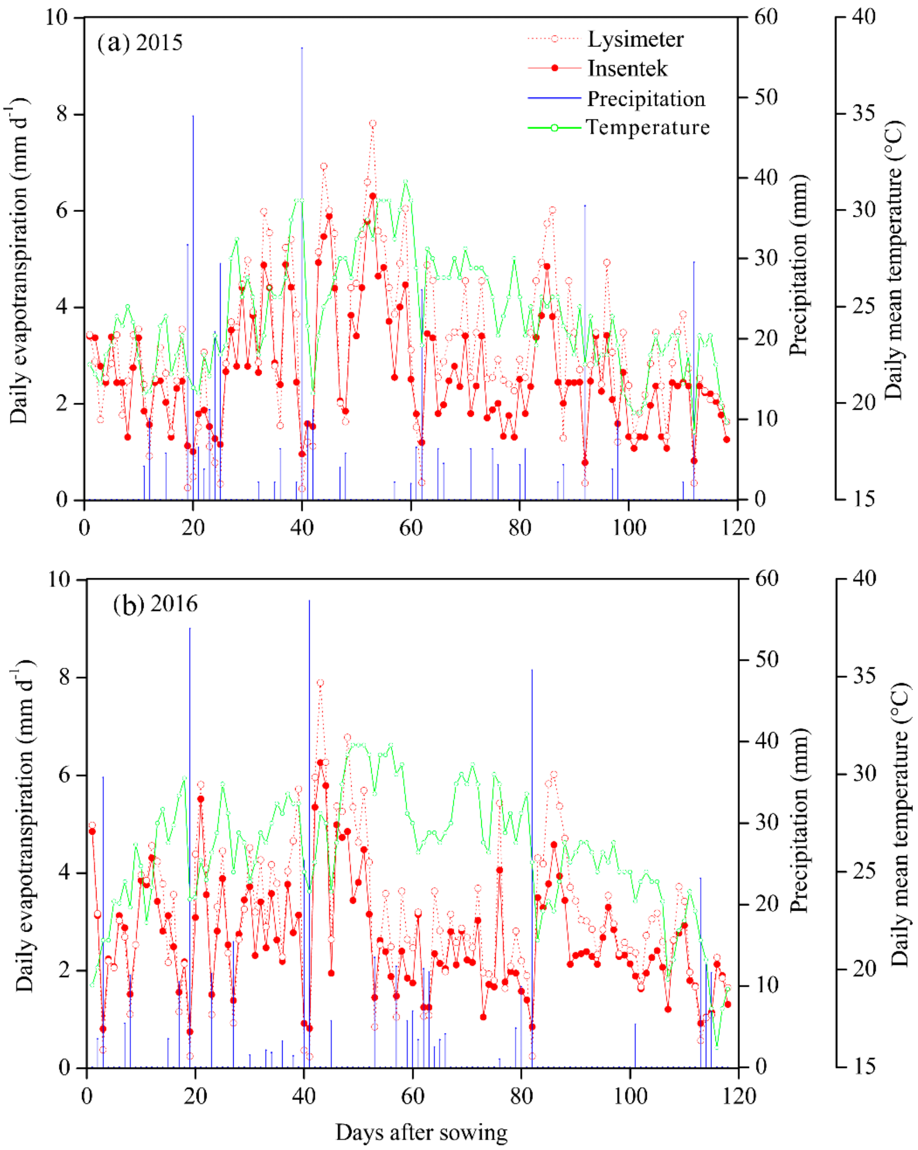

Figure 5. Daily evapotranspiration, air temperature, and precipitation during maize growing seasons of (**a**) 2015 and (**b**) 2016, at the Xuchang Irrigation Experiment Station, in the North China Plain. Vertical drop lines represent precipitation and solid green lines stand for temperature.

3.3. Cumulative Crop Evapotranspiration

On average, cumulative Insentek ET_c was 310 mm with an average of 2.63 mm·d^{-1} in both years (Figure 6). Lysimeter produced 19% higher cumulative ET_c than did Insentek. Cumulative lysimetric ET_c became constantly higher after DAS 40 (V10), and the discrepancies between them gradually grew from then on. Cumulative ET_c increased with the accumulation of air temperature in a positive linear relationship. Lysimetric ET_c showed a rapid response to precipitation with an average increase in ET_c from 0.24 to 7.42 mm·d^{-1} during the following 5 days after heavy rainfall (>50 mm), whereas the response of Insentek ET_c lagged behind lysimetric ET_c, with a smaller increase from 0.89 to 5.87 mm·d^{-1}.

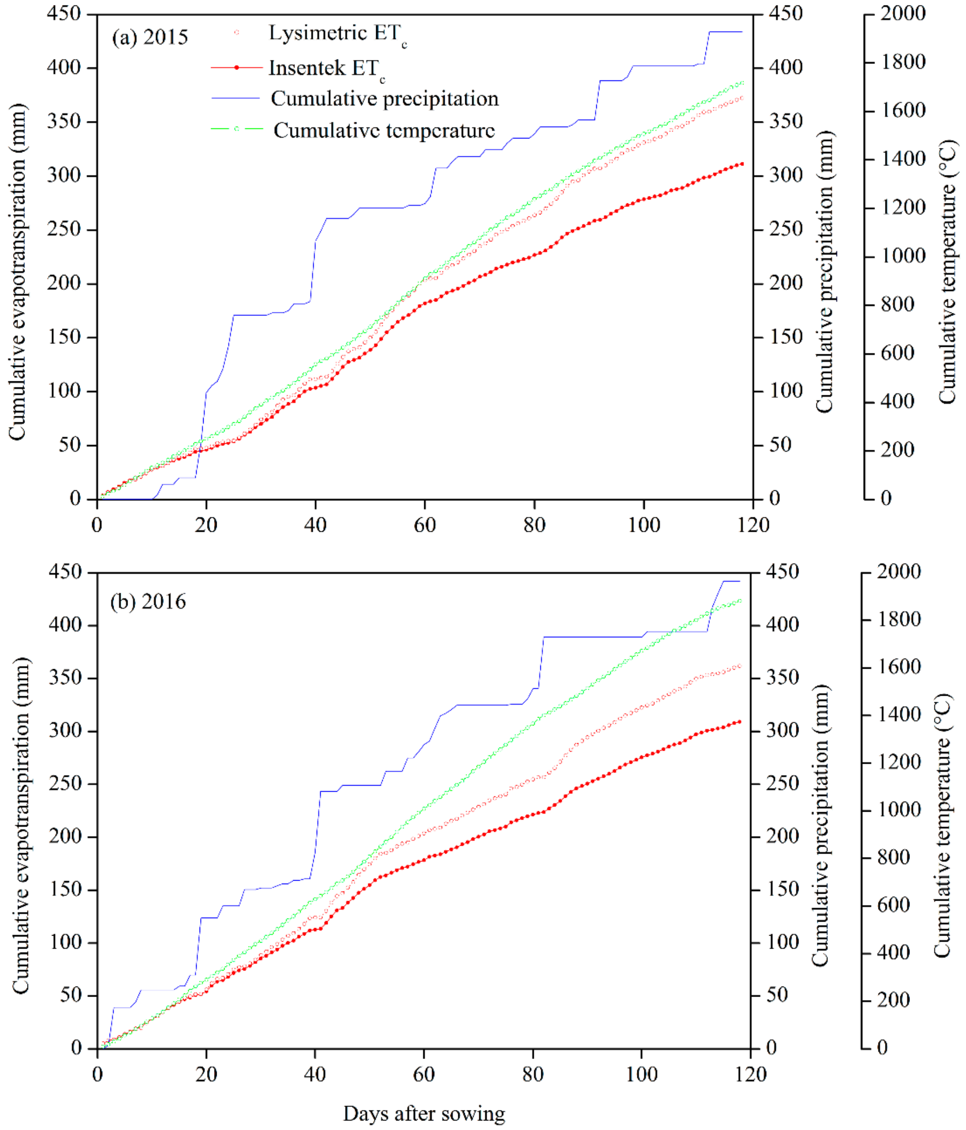

Figure 6. Cumulative evapotranspiration, cumulative air temperature, and precipitation during maize growing seasons of (**a**) 2015 and (**b**) 2016, at the Xuchang Irrigation Experiment Station, in the North China Plain.

3.4. Responses of ET_c to Soil Water Content

As precipitation >15 mm noticeably reduced ET_c, and increased SWC, only data collected on clear days were selected for correlation analysis between ET_c and SWC. Our results showed that, over the two years, ET_c was significantly correlated with SWC in 0–30 cm depth; however, it was not correlated with the SWC below 30 cm depth (Table 3). A detailed study showed that ET_c increased with SWC in 0–30 cm depth in an exponential function combined with a quadratic function (Figure 7). Effects of SWC at 10 cm interval to 30 cm depth accounted for 32–59% (R^2) of ET_c variations, and the contributions of SWC to ET_c declined from 10 to 30 cm soil layer.

Table 3. Correlation coefficient (R) of evapotranspiration (ET_c) related to soil water content at each soil depth.

Soil Depth (cm)	10	20	30	40	50	60	70	80	90	100
Lysimetry	0.67 **	0.57 **	0.53 **	0.21	0.19	0.17	0.12	0.09	−0.04	−0.12
Insentek	0.68 **	0.58 **	0.52 **	0.22	0.21	0.05	0.01	−0.11	−0.17	−0.05

** refers to significant correlation at $p < 0.01$.

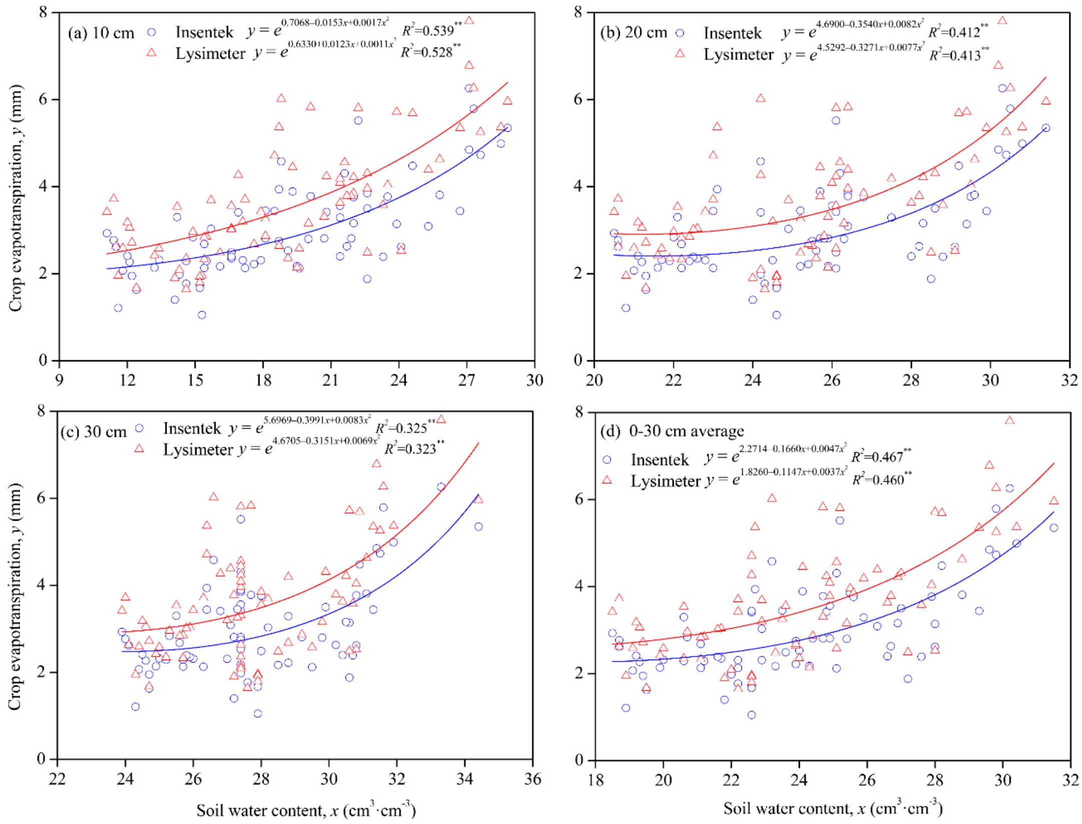

Figure 7. Relationships between crop evapotranspiration (ET_c, mm) and soil water content (SWC, $cm^3 \cdot cm^{-3}$) on clear days at 10 cm interval to a depth of 30 cm. (**a**) ET_c related to 10 cm SWC; (**b**) ET_c related to 20 cm SWC; (**c**) ET_c related to 30 cm SWC; (**d**) ET_c related to 0–30 average SWC.

3.5. Responses of ET_c to Precipitation

Both Insentek and lysimetric ET_c was significantly reduced on rainy days. Our results showed that precipitation explained 84–87% variations of daily ET_c on rainy days (Figure 8a). Moreover, precipitation, as an independent factor controlling ET_c when it rains, reduced daily ET_c in a negative power function. Compared to ET_c on clear days, precipitation averagely reduced lysimetric ET_c by 72%, and Insentek ET_c by 54%, indicating a faster response of lysimetric ET_c to precipitation than Insentek ET_c.

3.6. Goodness of Fit

There exists a significant positive linear correlation between Insentek and lysimetric ET_c data, with a slope of 0.68–0.69, and an intercept of 0.48–0.51, taking Insentek ET_c as y values (Figure 8b). A test for goodness of fit showed that the RMSE values were less than 0.87 mm, and RPD values were around 2.0, indicating the Insentek sensors method is, to some extent, reliable for predicting real ET_c of summer maize in the NCP (Table 4). Slopes smaller than 1.0 indicated that Insentek ET_c was generally smaller than lysimetric ET_c, though they have similar ET_c trends. Thus, improvements should be considered to enhance Insentek sensors accuracy. Those measures include, but are not limited to, using longer Insentek sensors (e.g., 200 cm long) to represent SWC dynamics in deeper layers.

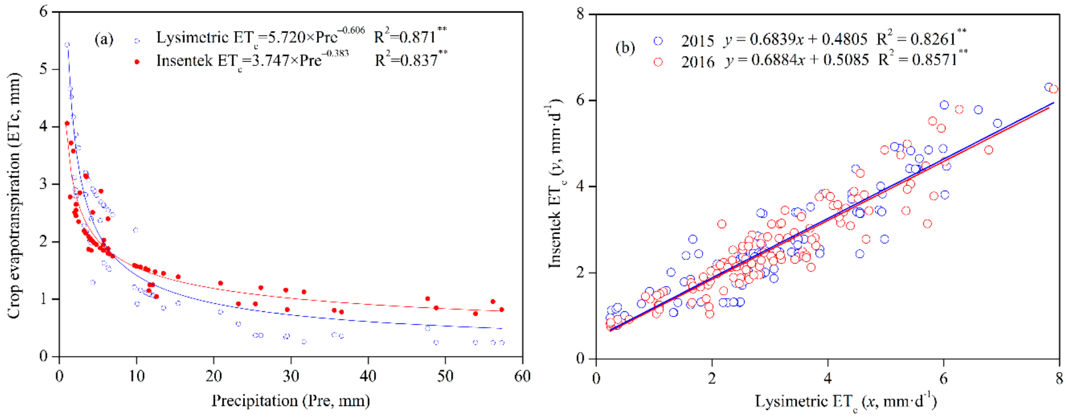

Figure 8. (**a**) Relationships between crop evapotranspiration (ET_c, mm) and precipitation (Pre, mm) on rainy days fitted to a negative power function. (**b**) Linear regression between Insentek ET_c and lysimetric ET_c.

Table 4. Test for linear regression and goodness of fit between Insentek ET_c (y) and lysimetric ET_c (x) data of summer maize in 2015 and 2016.

Year	Linear Correlation			Goodness of Fit		Significance
	Slope	Intercept	R^2	RMSE	RPD	p
2015	0.6839	0.4805	0.8261	0.872	1.921	0.001
2016	0.6884	0.5085	0.8571	0.776	2.061	0.001

R^2 is coefficient of determination; RMSE is root mean square error used to evaluate the differences between estimated and observed ET_c; RPD is relative prediction deviation, values measured by Insentek sensor are reliable with RPD $\geq$ 2.0 [23]; p is probability.

3.7. Grain Yield and Water Use Efficiency

In the NCP, maize is usually planted after the harvest of wheat in a winter wheat-summer maize double-cropping system. Due to soil water extraction by wheat and scarcity of rainfall, initial soil water storage (SWS_0) prior to maize sowing was extremely low (Table 5). This necessitated an irrigation immediately after sowing to guarantee seed germination. Grain yields were on average 15% lower than the yield (9165 kg·ha^{-1}) from surrounding field experiment, probably due to soil compaction and saline stress in a lysimetric environment. Because the Insentek sensor stood for 100 cm soil depth, whereas lysimeter for 200 cm, as well as lower SWC in upper layers, the Insentek SWS_0 was extremely lower in 2015 and 2016. At harvest, lysimetric SWS_h was 19% and 17% higher than Insentek SWS_h. Consequently, lysimetry reported a 20% and 17% higher ET_c in 2015 and 2016, resulting in a 16% and 14% lower WUE than the Insentek method.

Table 5. Grain yield and estimated soil water storage, crop evapotranspiration, and water use efficiency using the Insentek and lysimetric methods, at the Xuchang Irrigation Experiment Station in 2015 and 2016.

Year	Treatment	Irrigation (mm)	Precipitation (mm)	Grain Yield (kg·ha^{-1})	SWS_0 [1] (mm)	SWS_h [1] (mm)	ET_c (mm)	WUE [3] (kg·ha^{-1}·mm^{-1})
2015	Insentek Lysimeter	55	434	7919	86 b [2] 197 a	264 b 314 a	311 b 372 a	25.4 a 21.3 b
2016	Insentek Lysimeter	55	442	7670	101 b 203 a	289 b 338 a	309 b 362 a	24.8 a 21.2 b

[1] SWS_0 and SWS_h is soil water storage prior to sowing and after harvest of maize, respectively, as estimated by the Insentek and lysimetric method; [2] Different letters stand for significant differences at $p < 0.05$; [3] WUE is water use efficiency.

4. Discussion

4.1. Advantage and Disadvantage of Lysimetry and Insentek Method

The Insentek sensor method had several advantages over the lysimetry method, including ease of deployment, lower initial expense, and wireless transmission of real-time data [4,25]. In this study, Insentek sensors were installed inside lysimeter soils, allowing to record daily dynamics of SWC to a depth of 100 cm. Previous studies indicated SWC measurement depth for ET_c estimation should extend to the major depth of soil water extraction, which was flexible with crop types and weather conditions [11,29]. In Bushland, Texas, in a semiarid climate, it was found that 100 cm long neutron probe access tubes were sufficient to represent lysimetric ET_c on an irrigated cotton field [18,19]. In this study, maize plants were grown under a semi-humid climate with seasonal precipitation $\geq$450 mm. Initially, the SWC in the upper layers was extremely low at maize sowing, giving rise to discrepancy between Insentek and lysimetric ET_c, which was calculated based on different depths. This was probably attributable to the water uptake depth for wheat exceeding 100 cm under traditional border irrigation, and low water availability at wheat harvest in the NCP [30,31]. Maize crops usually have a shallower rooting system due to the high frequency of precipitation [32,33]. Nevertheless, according to soil water depletion depth monitored by Insentek sensors, the major depth of water extraction of maize on lysimeters might be 60 cm. Therefore, ET_c rates simulated by a 100 cm long Insentek sensor can be assumed as representative of actual rates. Additionally, compared with the eddy covariance and remote sensing methods, ET_c estimates by a network of soil moisture sensors were considered as viable source of ground truth ET_c data that were convincing both in theory and practice [34]. Previous studies have shown that ET_c determined by the neutron probe method can represent lysimetric ET_c, however, it wasn't able to calculate ET_c on a daily or sub-daily scale due to a lack of automatic measurement [35,36]. This shortcoming can be overcome by Insentek sensors.

However, there still exist limitations for Insentek sensors to simulate ET_c. For example, the Insentek method led to weaker ET_c responses to precipitation compared to the lysimetry method [25]. This led to a bias in ET_c simulation on rainy days. Nevertheless, Insentek method had merits to reduce potential ET_c errors induced by animal invasion and other disturbance factors. Although response of Insentek ET_c to precipitation lagged behind lysimetry, it increased stability of ET_c estimation due to a good performance in keeping out outside disturbance factors.

4.2. Cumulative Evapotranspiration Responses to Soil Water Content

Cumulative ET_c varied from 309 to 372 mm for summer maize in 2015 and 2016. The values were consistent with previous ET_c total for summer maize in the NCP [37], but were up to 50% lower than that of irrigated spring maize in semi-arid region of northern China [38]. Additionally, the values were up to 100% lower than reported for the southern High Plains in the USA [3]. The lower ET_c rates could be attributed to short growth duration (<90 days) and the almost rain-fed condition for summer maize in the NCP. In this study, water extraction depth mainly concentrated on 0–60 cm soil layer. This was probably due to favorable climate conditions such as adequate precipitation. Our study showed that daily ET_c had a positive exponential relationship with soil moisture in topsoil (0–30 cm). One of the reasons might be that the largest variations in soil moisture occurred in topsoil because the shallow zone had the largest root density and water extraction by maize plants [19]. Some used neutron probe method to estimate ET_c variations on a weekly basis; however, the Insentek sensor method had advances in automatic records of SWC, and was safe from radiation. Significant correlation between ET_c and near surface SWC can be verified by the finding that only SWC in the upper 30 cm of soil significantly varied in irrigated cotton fields at Bushland, Texas [39].

4.3. Comparison of Insentek Method to Other Methods

Although prior studies concluded that ET_c based on a 100 cm deep access tube was sufficient to represent lysimeter ET_c [40], there was still a 14% under-estimate of mean daily ET_c by the Insentek sensor method compared to the lysimetry method in the present study. One probable approach to improve the accuracy of Insentek ET_c was to adopt a 200 cm long probe equivalent to lysimeter depth, which will be conducted in further study. A comparison of ET_c calculated using lysimetry and neutron probe method has been conducted [35]. Some concluded that there was no difference between them [18,41,42], while others found that ET_c from lysimeters was greater than that of the oven-drying or neutron probe method [43,44]. Using remotely sensed ET_c, it was found that the ET_c produced differences of around 20–45% with the ground measurements using large aperture scintillometer systems during the growing season, and the model performance deteriorated for cloudy days [20]. Larger errors of daily ET_c estimates were associated with clouds and rain events, which affected satellite normal mapping, adding additional data noise [45]. Compared with remote sensing methodology, the Insentek method produced smaller differences. Compared with soil coring and neutron probe methods, Insentek sensors recorded soil moisture hourly without labor cost, directly improving the convenience and efficiency of ET_c estimation.

4.4. Simulating Crop Evapotranspiration on Rainy Days

Using a remote sensing ET_c model, it was found that ET_c had a negative correlation with precipitation in areas where the growing-season precipitation was 250 mm [21]. However, in arid areas with precipitation less than 200 mm, the correlation becomes weaker due to insufficient precipitation and a more complex water-heat flux interaction [46]. It should be noticed that those correlations by remote sensing were calculated mostly on an annual basis [47]. It did not reflect the instantaneous response of ET_c to daily precipitation as was done in this study. Through analysis, we found that precipitation with an amount $\geq$15 mm significantly inhibited daily ET_c. Thus, ET_c data on rainy days were independently used to analyze the correlation. Our results showed that simulated ET_c were in good agreement with the actual ET_c on rainy days. Both lysimetric and Insentek ET_c was related to precipitation in a negative power function. The effect of precipitation on Insentek ET_c was smaller compared to lysimetric ET_c, indicating a weaker response to precipitation. A probable reason was that Insentek ET_c was estimated using soil water storage changes after rain-water infiltration, which needed time to finish the process [4].

5. Conclusions

The North China Plain (NCP) produces one third of China's maize production (≈220 million tons per year), and is one of the most productive granaries in China. In this work, an alternative based on Insentek soil moisture data to estimate ET_c was evaluated in comparison with lysimetry in the NCP. Insentek ET_c had a significant linear correlation (R^2 = 0.83–0.86) to lysimetric ET_c, with RMSE < 0.87 mm, and RPD < 2.1, indicating that Insentek sensors are efficient tools in estimating maize ET_c in the NCP with acceptable accuracy. Since precipitation and SWC play an important role in water balance calculation for ET_c, responses of ET_c to them were analyzed on different weather days. The results indicated that ET_c significantly relates to precipitation (Pre) on rainy days in a power function (R^2 = 0.84–0.87). On clear days, ET_c significantly relates to SWC in topsoil (0–30 cm) in an exponential function (R^2 = 0.32–0.53). The combined SWC (0–30 cm)–Pre–ET_c model may offer significant potential for predicting ET_c. Our method provides a reference for reducing lysimetric data noise and may be useful to the study on responses of ET_c to climatic change in the NCP.

Author Contributions: Conceptualization, A.Q. and J.X.; methodology, D.N.; software, Z.L.; validation, B.S., and B.Z.; formal analysis, A.Q.; investigation, D.N.; resources, A.D.; data curation, A.D.; writing—original draft preparation, A.Q.; writing—review and editing, D.N.

Funding: This research was funded 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, FIRI2017–04).

Acknowledgments: The authors sincerely thank the three anonymous reviewers who made valuable comments on this paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study, in the collection, analyses, or interpretation of data.

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