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

Anzhen Qin 1, Dongfeng Ning 1,*, Zhandong Liu 1,*, Bin Sun 2, Ben Zhao 1, Junfu Xiao 1 and Aiwang Duan 1

1 Key Laboratory of Crop Water Use and Regulation, Ministry of Agriculture and Rural Affairs, Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China; qinzhen@126.com (A.Q.); zhaoben@caas.cn (B.Z.); xiaojunfu@caas.cn (J.X.); duanaiwang@caas.cn (A.D.)

2 Xuchang Experiment and Extension Station of Farmland Water Conservancy, Xuchang 461000, China; xcsyzsun@163.com

* Correspondence: ningdongfeng@caas.cn (D.N.); liuzhandong@caas.cn (Z.L.); Tel.: +86-373-339-3321 (Z.L.)

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Abstract: Estimation of ground-truth daily evapotranspiration (ET\textsubscript{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\textsubscript{c}. Here, we introduced an alternative to lysimetry for ET\textsubscript{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\textsubscript{c} was evaluated using data on clear days and rainy days independently. We found that daily ET\textsubscript{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\textsuperscript{−1}, and then declined until maturity. On average, cumulative total of lysimetric ET\textsubscript{c} was 19% higher than that of Insentek ET\textsubscript{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\textsubscript{c} significantly related to soil water content (SWC) in topsoil (0–30 cm) in an exponential function (coefficients of determination (R\textsuperscript{2}) = 0.32–0.53), and to precipitation (Pre) in a power function (R\textsuperscript{2} = 0.84–0.87). The combined SWC (0–30 cm)–Pre–ET\textsubscript{c} model may offer significant potential for accurate estimation of maize ET\textsubscript{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\textsubscript{c}) contributed to a 50%
yield increase over the past two decades [9]. Of those practices, ETc-based irrigation scheduling is considered a powerful tool to decrease long-term aquifer extraction [10].

In general, ETc 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 ETc. In the equation, ETc 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 ETc [5,6]. There are numerous methods available for estimating ETc [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 ETc monitoring. ETc 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 ETc 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 ETc [19]. Another approach for ETc estimation is remote sensing technology. It enables us to use satellite observations to estimate ETc at a global and regional scale [20]. However, studies have shown that different algorithms of remote sensing models for ETc estimation have strong divergence [21]. Usually, the algorithms to estimate ETc 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 ETc estimates [21,22]. Therefore, a real-time ground-truth monitoring of ETc 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 ETc 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$^3$·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 ETc 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 ETc 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$^3$·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 | 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$_2$O$_5$, and K$_2$O 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$_2$O$_5$, and 55 kg·ha$^{-1}$ K$_2$O, 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.
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$^3$·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·cm$^{-3}$), converting lysimeter mass in kg to the equivalent depth of water in mm. Daily ET$_c$ was calculated using Equation (1):

$$\text{ET}_c = \Delta \text{SWS} + \text{Pre} + \text{I} - \text{R} - \text{D}$$

where $\Delta \text{SWS}$ is the daily changes in soil water storage (mm) of lysimeter; $\text{Pre}$ is the precipitation (mm); $\text{I}$ is the irrigation quota (mm); $\text{R}$ is the surface runoff, assumed to be negligible due to flat surface and lysimeter freeboard; and $\text{D}$ 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 $\Delta \text{SWS}$, 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·ha$^{-1}$·mm$^{-1}$) was calculated as the grain yield (kg·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:
ETc = \alpha + b \times \text{SWC} + c \times \text{SWC}^2 \quad (2)

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

2.3.5. Relationship between ETc and Precipitation

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

\[ ETc = a \times \text{Pre}^{-b} \quad (3) \]

where as ETc is crop evapotranspiration (mm·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 ETc 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 ETc 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):

\[ \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (x_{\text{Insen}} - x_{\text{lysi}})^2}{n}} \quad (4) \]

where RMSE is the root mean square error; \(x_{\text{Insen}}\) and \(x_{\text{lysi}}\) are corresponding ETc 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):

\[ \text{RPD} = \frac{\text{STDEV}(x_{\text{lysi}})}{\text{RMSE}} \quad (5) \]

where RPD is the relative prediction deviation and STDEV is the standard deviation of lysimetric ETc values. RPD \(\geq 2.0\) indicates Insentek data are reliable; \(1.4 < \text{RPD} < 2.0\) 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 ETc, 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](image-url)  
*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 ETc. Lysimeter and Insentek produced similar trends in daily ETc (Figure 5). Lower ETc rates were observed when precipitation >15 mm. However, ETc increased markedly after precipitation occurrence due to an increase in soil water evaporation. On average, peak ETc 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 ETc rates were 29% higher than Insentek ETc (4.87 vs. 3.83 mm·d⁻¹) in both growing seasons. The highest ETc rates occurred on days after sowing (DAS) 53 (VT) in 2015, and on DAS 43 (V12) in 2016, respectively. Daily ETc decreased appreciably and was kept to a relatively lower level until maturity. Throughout the seasons, variations in daily lysimetric and Insentek ETc 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 ETc than was expected.

![Figure 5](image_url)

**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 ETc was 310 mm with an average of 2.63 mm·d⁻¹ in both years (Figure 6). Lysimeter produced 19% higher cumulative ETc 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 |
|----------------|----|----|----|----|----|----|----|----|----|-----|
| Lysimetric ET$_c$ |     |     |     |     |     |     |     |     |     |     |
| Insentek ET$_c$ |     |     |     |     |     |     |     |     |     |     |

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.
Table 3. Correlation coefficient (R) of evapotranspiration (ETc) 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 (ETc, mm) and soil water content (SWC, \( \text{cm}^3 \cdot \text{cm}^{-3} \)) on clear days at 10 cm interval to a depth of 30 cm. (a) ETc related to 10 cm SWC; (b) ETc related to 20 cm SWC; (c) ETc related to 30 cm SWC; (d) ETc related to 0–30 average SWC.

3.5. Responses of ETc to Precipitation

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

3.6. Goodness of Fit

There exists a significant positive linear correlation between Insentek and lysimetric ETc data, with a slope of 0.68–0.69, and an intercept of 0.48–0.51, taking Insentek ETc 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 ETc of summer maize in the NCP (Table 4). Slopes smaller than 1.0 indicated that Insentek ETc was generally smaller than lysimetric ETc, though they have similar ETc 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 | 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$^{-1}$) | $SWS_0$ (mm) | $SWS_h$ (mm) | $ET_c$ (kg·ha$^{-1}$·mm$^{-1}$) | WUE$^3$ (kg·ha$^{-1}$·mm$^{-1}$) |
|------|-----------|----------------|-------------------|--------------------------|-------------|-------------|-----------------|----------------|
| 2015 | Insentek  | 55             | 434               | 7919                     | 86 $^b$     | 264 $^b$    | 311 $^b$        | 25.4 $^a$      |
|      | Lysimeter | 55             | 434               | 7919                     | 197 $^a$    | 314 $^a$    | 372 $^a$        | 21.3 $^b$      |
| 2016 | Insentek  | 55             | 442               | 7670                     | 101 $^b$    | 289 $^b$    | 309 $^b$        | 24.8 $^a$      |
|      | Lysimeter | 55             | 442               | 7670                     | 203 $^a$    | 338 $^a$    | 362 $^a$        | 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 ETc 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 ETc on an irrigated cotton field [18,19]. In this study, maize plants were grown under a semi-humid climate with seasonal precipitation ≥450 mm. Initially, the SWC in the upper layers was extremely low at maize sowing, giving rise to discrepancy between Insentek and lysimetric ETc, 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, ETc 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, ETc estimates by a network of soil moisture sensors were considered as viable source of ground truth ETc data that were convincing both in theory and practice [34]. Previous studies have shown that ETc determined by the neutron probe method can represent lysimetric ETc, however, it wasn’t able to calculate ETc 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 ETc. For example, the Insentek method led to weaker ETc responses to precipitation compared to the lysimetry method [25]. This led to a bias in ETc simulation on rainy days. Nevertheless, Insentek method had merits to reduce potential ETc errors induced by animal invasion and other disturbance factors. Although response of Insentek ETc to precipitation lagged behind lysimetry, it increased stability of ETc estimation due to a good performance in keeping out outside disturbance factors.

4.2. Cumulative Evapotranspiration Responses to Soil Water Content

Cumulative ETc varied from 309 to 372 mm for summer maize in 2015 and 2016. The values were consistent with previous ETc 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 ETc 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 ETc 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 ETc 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 ETc 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 ETc based on a 100 cm deep access tube was sufficient to represent lysimeter ETc [40], there was still a 14% under-estimate of mean daily ETc by the Insentek
sensor method compared to the lysimetry method in the present study. One probable approach to improve the accuracy of Insentek ET<sub>c</sub> was to adopt a 200 cm long probe equivalent to lysimeter depth, which will be conducted in further study. A comparison of ET<sub>c</sub> 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<sub>c</sub> from lysimeters was greater than that of the oven-drying or neutron probe method [43,44]. Using remotely sensed ET<sub>c</sub>, it was found that the ET<sub>c</sub> 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<sub>c</sub> 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<sub>c</sub> estimation.

4.4. Simulating Crop Evapotranspiration on Rainy Days

Using a remote sensing ET<sub>c</sub> model, it was found that ET<sub>c</sub> 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<sub>c</sub> to daily precipitation as was done in this study. Through analysis, we found that precipitation with an amount ≥15 mm significantly inhibited daily ET<sub>c</sub>. Thus, ET<sub>c</sub> data on rainy days were independently used to analyze the correlation. Our results showed that simulated ET<sub>c</sub> were in good agreement with the actual ET<sub>c</sub> on rainy days. Both lysimetric and Insentek ET<sub>c</sub> was related to precipitation in a negative power function. The effect of precipitation on Insentek ET<sub>c</sub> was smaller compared to lysimetric ET<sub>c</sub>, indicating a weaker response to precipitation. A probable reason was that Insentek ET<sub>c</sub> 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<sub>c</sub> was evaluated in comparison with lysimetry in the NCP. Insentek ET<sub>c</sub> had a significant linear correlation (R<sup>2</sup> = 0.83–0.86) to lysimetric ET<sub>c</sub>, with RMSE < 0.87 mm, and RPD < 2.1, indicating that Insentek sensors are efficient tools in estimating maize ET<sub>c</sub> in the NCP with acceptable accuracy. Since precipitation and SWC play an important role in water balance calculation for ET<sub>c</sub>, responses of ET<sub>c</sub> to them were analyzed on different weather days. The results indicated that ET<sub>c</sub> significantly relates to precipitation (Pre) on rainy days in a power function (R<sup>2</sup> = 0.84–0.87). On clear days, ET<sub>c</sub> significantly relates to SWC in topsoil (0–30 cm) in an exponential function (R<sup>2</sup> = 0.32–0.53). The combined SWC (0–30 cm)–Pre–ET<sub>c</sub> model may offer significant potential for predicting ET<sub>c</sub>. Our method provides a reference for reducing lysimetric data noise and may be useful to the study on responses of ET<sub>c</sub> to climatic change in the NCP.

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