Simulating Crop Evapotranspiration Using Insentek Soil Moisture for Maize Plants on Lysimeters

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Abstract. Crop evapotranspiration (ETc) simulation is important to modeling hydrological process in agro-ecosystem. In this study, ETc was monitored using a large-scale weighing lysimeter system, along with Insentek soil moisture probes at Xuchang Irrigation Experiment Station in 2015 and 2016. Relationships among daily ETc, leaf area index (LAI) and soil water content (SWC) were determined using the Levenberg–Marquardt Algorithm. Our results showed that ETc was significantly correlated with SWC in 0-40 cm soil layers, but not correlated with SWC below 40 cm soil layer. ETc was related to SWC in an exponential function combined with a quadratic function. Effects of SWC in 0-30 cm soil layers accounted for 32-53% variations of ETc. Averaging SWC across the 0-30 cm soil depth, it contributed 46% variations of ETc. Moreover, ETc was correlated with LAI in a negative linear manner, but its correlation coefficient is not significant (P>0.05). We concluded that SWC at top soil layer can be adopted to calibrate Insentek ETc simulation for maize plants.

Introduction

Detailed knowledge of ETc simulation is useful to understand the crop response to future climatic changes [1]. One such a method to monitor ETc is to use large-scale weighing lysimeters. However, the cost of construction for weighing lysimeters is expensive [2]. In this study, Insentek soil moisture probes were installed in lysimeter soils allowing to record daily dynamics of soil moisture to a depth of 1 m. This provides an alternative to simulate daily ETc using water balance equation instead of lysimeters. Previous studies have been conducted to compare lysimeter ETc and ETc estimated using traditional profile water content storage methods. Some concluded that there was no difference between them, while others found ETc from lysimeters was greater than that from traditional methods [3, 4]. However, soil coring for soil moisture measurement was time consuming and labor intensive, so ETc calculation based on oven-drying method was limited [5]. In this study, an innovative Insentek ETc measuring method was proposed. Using this method, soil moisture can be automatically recorded without labor input, directly improving the convenience for ETc estimation. Till now, there has been no calibration work of Insentek ETc in comparison to lysimeter ETc. Therefore, we start the work to calibrate daily ETc using Insentek soil moisture data. We hypothesized that daily ETc was related to daily soil water content, and it could be well simulated using Insentek soil moisture if modification models were validated. The objective of this study was to quantify the relationships among ETc, soil water content and leaf area index in order to provide theoretical basis for Insentek ETc simulation.

Materials and Methods

Lysimeter experiments were carried out at the Xuchang Irrigation Experiment Station, North China Plain, in 2015 and 2016, on a silt loam soil (34°76’ N, 113°24’ E, a.s.l. 72.8 m). Four sets of large-scale weighing lysimeters (2.0 m wide × 2.4 m long × 2.3 m in depth) were adopted to monitor ETc. Soil water content (SWC, cm³ cm⁻³) was measured at 10-cm increments to a depth of 100 cm using Insentek soil moisture probes (Beijing Oriental Ecological Technology Ltd. Co., China). It
reports soil moisture hourly. A SIM card was installed in the Insentek data logger and was used to transmit data wirelessly throughout a GPRS communication network. The probes were powered by a rechargeable battery that can be recharged via solar panels. Users can view soil moisture data via logging into an internet platform bounding the probes through a computer or a mobile phone (Fig. 1).

Figure 1. Insentek soil moisture probe and solar panel installed at the center of a lysimeter.

Popularly used maize seeds (cv. Xianyu 335) were sown on June 5, 2015 and 2016. Maize was planted in row spacing of 50 cm and plant-to-plant spacing 30 cm, equivalent to a plant density of 66,667 plants ha\(^{-1}\). Application rates of fertilizer were 225 kg N ha\(^{-1}\), 180 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 55 kg K\(_2\)O ha\(^{-1}\), respectively. One half amount of nitrogen was applied as base fertilizer before sowing, whereas the rest was top-dressed at heading stage. Fertilizer was incorporated into soils to a depth of 20 cm using rotary tillage prior to planting. Except for a flood irrigation after maize sowing to guarantee seed emergence, no supplemental irrigation was added to maize plants during the entire growing seasons.

Leaf area index (LAI) were recorded as a product of leaf length and its maximum width with a coefficient of 0.70. Leaf area index was then calculated by the value and the plant density. Cumulative days after sowing (DAS, d) is considered as a major factor determining maize leaves growth. Our study showed that there existed a good correlation between DAS and LAI, and the regression between DAS and LAI was fitted to \(i\)-th order \((i = 0, ……, 5)\) logistic curve, where the 5th–order logistic curve gave the best goodness of fit:

\[
LAI = \frac{A}{1 + \exp\left(\sum_{i} B_i \left(\frac{DAS}{DAS_{\text{max}}}\right)^i\right)}
\]  

where \(A\) is the maximum \(LAI\) of maize; \(DAS\) is days after sowing, and \(DAS_{\text{max}}\) is the maximum value of \(DAS\) (that is, total number of days for a maize plant to complete its life cycle); \(i\) is the \(i\)-th power of the logistic curve; \(B_i (i=0, ……,5)\) is empirical coefficient to be fitted.

To determine the response of \(ET_c\) to soil water content, an exponential function combined with a quadratic function was adopted as follows:

\[
ET_c = e^{a + b \times SWC + c \times SWC^2}
\]  

where \(ET_c\) is crop evapotranspiration; \(SWC\) is soil water content; \(a\), \(b\), \(c\) are empirical parameters to be fitted.

Data were analyzed using analysis of variance with Statistical Analysis Software (version 19.0, SPSS Inc., Chicago, IL, USA). Relationships among \(ET_c\), LAI and SWC were analyzed by means of the Levenberg–Marquardt Algorithm.

Results and Discussion

Integrating the two consecutive years' data of LAI, we found that changes of LAI with DAS were best fitted to a 5-th order logistic curve (Fig. 2). Detailed study showed that \(B_1, B_2, B_3, B_4,\) and \(B_5\) equaling
to 56.6, -342.0, 700.3, -607.4, and 191.9 were parameters to be best fitted in the Eq. (1). In the near future, the model can be adopted in automatic simulation in computer software to describe maize leaf evolution.

Data of ET<sub>c</sub>, SWC, and LAI in maize growing seasons of 2015 and 2016 were subjected to SPSS for correlation analysis. Our results showed that, over the two years, ET<sub>c</sub> was significantly correlated with SWC at the 0-40 cm layers, but not correlated with the SWC below 40 cm soil layer. Furthermore, ET<sub>c</sub> was not correlated with LAI (<i>P</i> > 0.05) (Table 1). Detailed analysis showed that ET<sub>c</sub> increased with SWC in 0-30 cm soil layers in an exponential function combined with a quadratic function. However, this combined function did not fit to SWC at 40 cm layer. Effects of SWC at 10 cm interval to 30 cm depth accounted for 32-53% variations of ET<sub>c</sub>, and the contributions of SWC to ET<sub>c</sub> declined from 10 cm to 30 cm layers. Averaging SWC across the 0-30 cm soil depth, it contributed 46% variations of ET<sub>c</sub> (Table 2).

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>R</em>-lysimeter ET&lt;sub&gt;c&lt;/sub&gt;</td>
<td>0.67&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.57&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.53&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.31&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.19</td>
<td>0.17</td>
<td>0.12</td>
<td>0.09</td>
<td>-0.04</td>
<td>-0.12</td>
<td>-0.09</td>
</tr>
<tr>
<td><em>R</em>-Insentek ET&lt;sub&gt;c&lt;/sub&gt;</td>
<td>0.68&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.58&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.52&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.32&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.21</td>
<td>0.05</td>
<td>0.01</td>
<td>-0.11</td>
<td>-0.17</td>
<td>-0.05</td>
<td>-0.19</td>
</tr>
</tbody>
</table>

† Crop evapotranspiration was the ET<sub>c</sub> rates determined using lysimeters and insentek probes; ** and * refer to significant correlation at <i>P</i> < 0.01 and <i>P</i> < 0.05 levels, respectively.

Our result of LAI dynamics was in good agreement with the findings of Liu et al. (2017) [6], who conducted a similar simulation between LAI and relative growth degree day (RGDD). But we obtained a better fitness for the logistic model due to a greater order curve (i = 5). Regression between ET<sub>c</sub> and LAI demonstrated that there was no significant correlation between them. Previous studies determined the relationships between E/ET (ratio of soil evaporation to ET<sub>c</sub>) and LAI, and some of them concluded a high correlation between them [7, 8]. It is no surprising that LAI significantly influenced E/ET as E/ET was closely related to crop canopy coverage. We concluded that LAI is a good indicator to predict E/ET variations, but is not suitable for daily ET<sub>c</sub> simulation.

Previous studies found that root length density of maize plants in 0-40 cm soil layers was greater in lysimeter than that in field condition, which might increase actual ET<sub>c</sub> in lysimeter compared to field crops [9, 10]. However, some other studies considered that crop root length in lysimeters was dependent upon water stress [11]. In non-water stress environment, an increase of maximum rooting depth below 40 cm depth was not observed due to adequate water in the top layers [12]. In this study, seasonal precipitation in maize growing seasons was 433.8 mm and 441.9 mm in 2015 and 2016. Soil moisture in root zones was adequate for water uptake of maize. Also, Insentek soil moisture data...
showed that soil water content below 40 cm soil layer kept almost unchanged after DAS 40 (mid-July). This implied that water extraction depth mainly concentrated in the 0-40 cm soil layer for maize plants on lysimeters. This was probably due to favorable climate conditions, i.e., adequate rainfall, and good soil water capacity and nutrient storage of the studied soils [13]. Therefore, ETc in the present study was mainly related to SWC in soil layers of 0-40 cm. However, when we put the SWC data in Eq. (2) to quantify the relationship between ETc and SWC, only SWC at the 0-30 cm soil layers had significant correlation with ETc.

Table 2. Relationships between crop evapotranspiration (ETc, y, mm) and soil water content (SWC, x, cm⁻³ cm⁻³) at 10 cm interval to 30 cm depth fit to an exponential function combined with a quadratic function.

<table>
<thead>
<tr>
<th>SWC at 10 cm interval</th>
<th>Lysimeter ETc</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 cm</td>
<td>y = exp(0.6330+0.0123x+0.0011x²)</td>
<td>0.528**†</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>y = exp(4.5292−0.3271x+0.0077x²)</td>
<td>0.413**</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>y = exp(4.6705−0.3151x+0.0069x²)</td>
<td>0.323**</td>
</tr>
<tr>
<td>0-30 cm average</td>
<td>y = exp(1.8260−0.1147x+0.0037x²)</td>
<td>0.460**</td>
</tr>
</tbody>
</table>

†** means significant correlation between ETc and SWC at P < 0.01 level.

Summary
This study provides a robust method for ETc simulation using soil water content in 0-30 cm soil layers. We believe that this method has the potential to be extended to wider regions and cropping systems with low cost, compared with lysimeters. It is concluded that using the models based on soil water content, errors in ETc simulation using Insentek probes can be minimized. In the near future, the models can be used to develop a software system to optimize irrigation scheduling, and the software can process soil water content and estimate actual ETc to calculate the irrigation valves in real time.

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Reference


