Multi-temporal variation in water consumption of summer maize as determined by the Water Transformation Dynamical Processes Experimental Device

Yali Wu, Xianfang Song, Ying Ma, Hongmei Bu, Shengtian Yang, Dongmei Han and Yinghua Zhang

ABSTRACT

A better understanding of the multi-temporal variation in evapotranspiration (ET) at different crop growth stages is the key for determining a reasonable irrigation schedule. In this study, a new device known as ‘Water Transformation Dynamical Processes Experimental Device’ (WTDPED) was used to monitor ET for maize under controlled environmental and groundwater conditions, and the multi-temporal variations of ET considering the combined impact of environmental factors (air temperature (AT), relative humidity (RH)) and groundwater in homogeneous and layered soils were focused on. During the whole growing period, the ET peaked at 14:00–15:00 on a daily basis. The variation in daily ET followed a bell curve during the entire growing period. The 5-day ET reached its maximum during the 12th leaf and maturity stage. The correlation coefficient between ET and AT reached its maximum value of 0.70 during planting and the third leaf stage. The negative correlation coefficient between RH and ET reached its maximum during the 12th leaf and tasseling-silking stage. Groundwater recharge was positively correlated to ET and the daily contribution was up to 10.07%. The silt sandy loam–loam layered soil was favorable for water and nutrient uptake during the entire growing period of maize.

Key words | evapotranspiration, homogeneous soil, layered soil, summer maize, Water Transformation Dynamical Processes Experimental Device

INTRODUCTION

As water scarcity is one of the most urgent food security issues in China, identifying and utilizing the most effective water use management methods for improving water productivity is important. The further increase in maize production is limited by several factors, among which water management is possibly the most important, especially in North China (Liu et al. 2002; Li et al. 2005). For maximizing crop water productivity, water use efficiency needs to be increased by minimizing non-beneficial water uses (Suyker & Verma 2009; Liu et al. 2010; Pour-Ali Baba et al. 2013). Therefore, having detailed information on water consumption during crop growth periods is essential for water resource planning, irrigation control, and agricultural production (Li et al. 2013). Actual crop evapotranspiration (ET) involves soil evaporation and plant transpiration. ET is a comprehensive index that represents the overall crop water consumption and is among the main factors affecting crop productivity (Liu et al. 2002, 2016; Li et al. 2013). However, ET is significantly affected by many factors, including climatic factors (rainfall, air temperature (AT), and relative humidity (RH)) (Yang et al. 2013), crop characteristics (crop variety and development stage) (Liu et al. 2002), soil properties (soil texture, soil management, and soil water) (He et al. 2013), and groundwater conditions (water table, salinity and toxicity levels in ground water) (Soppe & Ayars 2003). In addition, these
factors have multi-scale variations from hourly, daily, and development stage to annual and perennial. Studying ET on a single time scale does not consider the comprehensive influences of these factors on different time scales, and thus overlooking various underlying factors is easy. Accurately monitoring the multi-temporal variation of ET and its influencing factors plays an increasingly important role in revealing the main driving factors affecting various others. Moreover, it may be useful in planning, designing, and operating irrigation systems and crop planning in the future.

Many studies have focused on the variation of ET on perennial (Jun et al. 2012; Yang et al. 2013), annual (López-Urrrea et al. 2006; Li et al. 2013; Ngongondo et al. 2013; Ma et al. 2015; Koedyk & Kingston 2016), seasonal (Tyagi et al. 2000; Kashyap & Panda 2001; Kang et al. 2003; Rana et al. 2005; Benli et al. 2006; Zhang et al. 2007; Suyker & Verma 2009; Liu et al. 2010, 2011, 2016; Beeson 2015; Li et al. 2017), and daily scales (Pour-Ali Baba et al. 2013). Using different methods, these studies established that the variations of climatic factors have complicated effects on ET change in different regions of the world. Nevertheless, most of these studies on the perennial or annual scale variation of ET overlooked the influence of crop characteristics and soil properties. In addition, some of these studies on the seasonal or daily scale variation of ET did not consider soil factors. Several studies that focused on the variation of ET on more than one time scale proved that considering the meteorological factors and crop characteristics in studying the multi-scale variation of ET is necessary (Liu et al. 2002; Li et al. 2003, 2008, 2013). However, previous studies paid little attention to the combined effects of climatic factors, groundwater, and soil structure on temporal variation of ET.

The multi-temporal variation of ET can be measured (directly or indirectly) or estimated. There are various methods for measuring crop ET, and they are classified into hydrological, micrometeorological, and plant physiology approaches (Rana & Katerji 2000; Wang & Dickinson 2012). Hydrological approaches are based on the principle of soil–water balance (Kashyap & Panda 2001; Li et al. 2005; Rana et al. 2005; Liu et al. 2011) and the weight of lysimeters (Tyagi et al. 2000; Liu et al. 2002; Kang et al. 2003; Benli et al. 2006; López-Urrrea et al. 2006; Beeson 2011). Most micrometeorological approaches (Zhang et al. 2007; Li et al. 2008) are determined by energy balance, the Bowen ratio, aerodynamic estimates, and the eddy-covariance method. Most plant physiology approaches use the sap-flow method and chamber systems (Rana & Katerji 2000). Most of these studies used field experiments or field lysimeter experiments to focus on the effects of different crop varieties, irrigation practices, and climatic conditions on crop-water consumption at a specific location and time. Several studies adopted laboratory soil columns to investigate crop water use (Stauffer & Dracos 1986; Krzyszowska et al. 1994; Ma et al. 2010). However, several of these studies did not consider the multi-temporal variation of ET and some of them did not factor in the combined effects of soil structure, groundwater, and climatic factors. A method that estimates ET, instead of directly measuring it, was developed, and involves an analytical approach (Penman–Monteith model) (Jun et al. 2012; Li et al. 2013, 2017; Ngongondo et al. 2013; Yang et al. 2013; Ma et al. 2015) and an empirical approach (Ngongondo et al. 2013; Hao et al. 2015; Ma et al. 2015; Koedyk & Kingston 2016; Liu et al. 2016). The method regulates the environmental variables and boundary conditions of models by estimating ET. However, selecting reasonable parameters was difficult because of their complexity.

Soil texture is one of the most important soil factors affecting the multi-temporal variation of ET. The texture, thickness, and sequence arrangement of soil layers have significant effects on water movement in the vadose zone (Stauffer & Dracos 1986; Ma et al. 2010; He et al. 2013). He et al. (2013) concluded that water movement and crop growth varied among soil profiles because of the differences in the thickness and position of soil layers. The ET during the growing period of wheat–maize accounted for 72% of the total water input in silt loam–clay layered soil, thus causing relatively low water losses. Stauffer & Dracos (1986) also showed that water transport was strongly affected by the layers of packed sand. Therefore, comparing water transport in layered and homogeneous soils is necessary.

The Water Transformation Dynamical Processes Experimental Device (WTDPED) was developed by the Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research (IGSNRR), University of Chinese Academy of Sciences (UCAS), Beijing, China. WTDPED can be
used to monitor the variation of ET and other water balance components on different temporal scales simultaneously and precisely under controlled climatic factors and groundwater conditions. Therefore, it is useful for studying the relationship of ET and its main influencing factors at different temporal scales under controlled climatic factors and groundwater level conditions with high precision. This study aimed to investigate the multi-temporal variation in ET throughout the growing season of summer maize in homogeneous and layered soils under combined climatic factors and groundwater conditions. It also explained the combined effects of the main environmental factors, groundwater, and soil texture on crop ET to provide valuable information for irrigation system management and new insights into the mechanisms of water transmission.

MATERIALS AND METHODS

Description of the experimental facility and WTDPED

The experiment was conducted at the Key Laboratory of Water Cycle and Related Land Surface Processes, IGSNRR, CAS, Beijing, China. The size of the experimental facility was 7 m long, 5 m wide, 4.5 m above the soil surface, and 3 m deep below the soil surface. The net volume was 140 m³. Air-conditioners were used for heating, cooling, and dehumidifying internal circulation. Two centrifugal humidifiers were utilized to increase humidity. Sodium lamps and metal halide lamps served as light sources (24 in total), which were divided into three groups to modify light intensity. When all the lamps were turned on, the light intensity reached the maximum value of 30,000 Lux. A CO₂ gas storage cylinder was filled with highly purified CO₂ and controlled by a system comprising a sensor transmitter, a solenoid valve, a reducing valve, and a flow velocity meter. Sensors for AT, RH, and CO₂ concentration, light intensity, and photosynthetic quantum flux density were installed in the same position. All environmental elements were controlled by the AT, RH, light, and CO₂ automatic control system (Figure 1).

WTDPED consists of three controlled subsystems (Figure 1): the environmental element control, the soil moisture dynamic and transformation observation, and the groundwater control subsystems. The environmental element control subsystem (Figure 2(a) and 2(c)) was used to simulate and monitor environmental factors such as AT, RH, light, and CO₂ concentration.

Figure 1 | Schematic diagram of the Water Transformation Dynamical Processes Experimental Device, showing the environmental element control subsystem, the soil moisture dynamic and transformation observation subsystem, and the groundwater control subsystem. AT, air temperature; RH, relative humidity.
The soil moisture dynamic and transformation observation subsystem (Figure 2(b)) is composed of two large-scale weighing lysimeters with a surface area of 6 m² and a height of 3 m, which quantified the input and output of water. Each lysimeter was filled with either homogeneous or layered soil. The 5TE soil moisture, temperature, and electrical conductivity sensor (Decagon Devices, Pullman, WA, USA), the MPS-2 soil–water matrix potential sensor (Decagon Devices), and the DLS-II-type tensiometer (Institute of Geographical Sciences and Natural Resources Research, Beijing, China) were installed into each lysimeter at depths of 20, 43, 53, 73, 83, 92.5, 110.5, 130.5, 150.5, 180.5, 210.5, 240.5, and 275.5 cm to monitor the moisture dynamics and transformation of the soil. The 5TE soil moisture, temperature, and electrical conductivity sensor monitored the volumetric water content, temperature, and bulk electrical conductivity of the soil; the MPS-2 soil–water matrix potential sensor monitored the water potential and temperature of the soil; and the DLS-II-type tensiometer device was used to extract the soil solution from soil layers through a vacuum. The maximal load of each weighing lysimeter was 81 t, and the resolution of the weighing lysimeter system was 180 g.

The groundwater control subsystem (Figure 2(b)) was composed of a water storage tank, water pipes, and a water supply or drainage device. The controlled electric circuit for the entire water supply and drainage process was made up of a fixed storage tube, a needle for measuring the liquid level, and the corresponding controlled software. Related control information was transferred to a computer.
monitoring system to check the data at any time. The groundwater level was controlled with a precision of 0.1 cm.

**Experimental design**

The average values of 10-year (2000–2010) meteorological data (AT, RH, CO\(_2\) concentration, photosynthetically active radiation, etc.) collected in Beijing were used to simulate the whole growing period of summer maize. AT was modified every 3 h based on the average values at 01:00, 04:00, 07:00, 10:00, 13:00, 16:00, 19:00, and 22:00 to fully reflect the normal diurnal variation. RH was set as the average value of daily RH over the 10-year period. We measured the photosynthetically active radiation at different heights in the experimental facility, and the lamps were arranged according to the average value of photosynthetically active radiation over the 10-year period. Lights were turned on from 06:00 to 18:00 with three groups on. CO\(_2\) concentration was set to 376 ppm, which was the average value over the 10-year period. The groundwater table depth was set to 2.5 m. The measurement frequency of meteorological data, soil volumetric water content, soil temperature, and soil bulk electrical conductivity was set to 1 h.

Experimental soil samples were collected from a common farmland in Huangcun Town, Daxing District, Beijing, China. Soil type was fluvo-aquic, which is the representative soil type in Beijing. Soil samples were backfilled with homogeneous soil and layered soils. The physical properties of soil in the 0–300 cm layer are listed in Table 1.

Seeds of the summer maize hybrid ZhengDan958 were planted at 5 cm depth. The planting density was 4,000 plants ha\(^{-1}\) with 63 cm space between rows and 37 cm between plants within each row to achieve optimum irrigation conditions during the whole growing period. The irrigation amount was determined as follows:

\[ I = (\theta_{fc} - \theta_m) \times H \]  

where \( I \) is the net irrigation water (mm); \( \theta_{fc} \) is the soil volumetric water contents at field capacity, \( \theta_m \) is the average of measured soil moisture content above 100 cm soil depth (m\(^3\) m\(^{-3}\)); \( H \) is planned moist layer in soil, which was defined as 100 cm in this experiment. The irrigation time was determined by the average of soil moisture content above 100 cm soil depth equal to 75% of the field capacity. Irrigation dates were May 13, June 3, July 1, July 30, and September 5, and the total irrigation was 300 mm. A compound fertilizer (N–P\(_2\)O\(_5\)–K\(_2\)O, 15–15–15) was applied on May 13 and June 3, and urea was applied on July 30. The amount of water and fertilizer applied each time is listed in Table 2.

Maize was planted on May 17, 2014 and harvested on September 19, 2014. The whole growing period of summer maize (126 d) was divided into six stages: planting time to third leaf stage (PT–V3), third leaf to sixth leaf stage (V3–V6), sixth leaf to 12th leaf stage (V6–V12), 12th leaf to tasseling-silking stage (V12–VT), tasseling-silking stage to milk stage (VT–R3), and milk stage to physiological maturity stage (R3–R6).

**ET calculation**

The ET at time \( t \) (mm) was calculated as follows:

\[ ET = \frac{M_t - M_{t-1}}{\rho \times S} + 1,000 \]  

where \( M_t \) is the weight of the system at the time \( t \) (kg), \( M_{t-1} \) is the weight of the system at the time \( t - 1 \) (kg), \( S \) is the experimental area (m\(^2\)), and \( \rho \) is the density of water.

**Table 1 | Physical properties of soil used in this study**

<table>
<thead>
<tr>
<th>Soil</th>
<th>Depth (cm)</th>
<th>Bulk density (g cm(^{-3}))</th>
<th>Field capacity (cm(^3) cm(^{-3}))</th>
<th>Saturated water content (cm(^3) cm(^{-3}))</th>
<th>Soil texture</th>
<th>Particle fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layered</td>
<td>0–100</td>
<td>1.48</td>
<td>0.24</td>
<td>0.50</td>
<td>Silt sandy-loam</td>
<td>61.53 37.47 1.00</td>
</tr>
<tr>
<td></td>
<td>100–210</td>
<td>1.63</td>
<td>0.27</td>
<td>0.44</td>
<td>Loam</td>
<td>64.50 23.50 12.00</td>
</tr>
<tr>
<td></td>
<td>210–300</td>
<td>1.55</td>
<td>0.25</td>
<td>0.45</td>
<td>Loam</td>
<td>69.00 19.70 11.30</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>0–300</td>
<td>1.55</td>
<td>0.26</td>
<td>0.45</td>
<td>Silt sandy-loam</td>
<td>58.90 40.71 0.39</td>
</tr>
</tbody>
</table>

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Statistical analysis

One-way analysis of variance (ANOVA) in conjunction with the least significant difference method was used to compare the daily ET between homogeneous and layered soils at \( p < 0.05 \). Correlations between ET and AT or RH were tested using Spearman’s rank correlation at \( p < 0.01 \) and \( p < 0.05 \) (two-tailed). All analyses were conducted using SPSS 16.0 (IBM Corp., Chicago, Illinois, USA).

RESULTS AND DISCUSSION

Variation in ET per hour

The ET per hour started to increase at V6 and reached the maximum value of 0.32 mm in homogeneous soil and 0.33 mm in layered soil at V12–VT (Figures 3 and 4). From V12 to middle R3, the ET per hour was maintained at a relatively high level for both homogeneous and layered soils and then decreased at VT–R6. Therefore, during the entire growing period, an increase first and then a decrease in hourly ET occurred by the linear fitting line. During the whole growing period, the ET peaked at 14:00–15:00 on a daily basis both in homogeneous and layered soils. The hourly AT changed moderately during the course of PT–V12 with the average value of 26.26 °C (Figures 3 and 4). However, a significantly decreased trend was observed in hourly AT during V12–R6 ranging from 9.72 °C to 36.15 °C, with the average value of 21.42 °C. Therefore, a peak of hourly AT occurred at V12–VT along the linear fitting line. An increased trend of RH was found at PT–V12 ranging from 42.00% to 84.10%, and the hourly RH did not change significantly with the average value 68.51% at V12–R6 along the linear fitting line. From the above it can be seen that ET was positively correlated with AT during V12–R6 to some extent, while the correlation between ET and RH was not so obvious by the linear fitting line.

Variation in daily ET

The variation in daily ET followed a bell curve during the entire growing period of summer maize (Figure 5), and it varied from 2.01 mm to 3.26 mm in homogeneous soil and from 2.17 mm to 3.43 mm in layered soil. At V12–R3, the daily ET reached the maximum value of 3.26 mm at 75 days in homogeneous soil and 3.45 mm at 61 days post-planting in layered soil, and then it declined gradually. The average daily ET at PT–V3 was 2.39 mm in homogeneous soil and 2.42 mm in layered soil, that at V3–V6, was 2.44 mm and 2.62 mm, respectively, and that at V6–V12, was 2.59 mm and 2.78 mm, respectively. The average daily ET reached the maximum value of 2.88 mm in homogeneous soil and 3.14 mm in layered soil at V12–VT. At VT–R3, the average daily ET was 2.79 mm in homogeneous soil and 3.05 mm in layered soil, and then it declined to 2.37 mm and 2.51 mm, respectively, at R3–R6. The variation in daily AT followed a bell curve during the entire growing period and reached its maximum value at V12–VT. The mean daily AT was 23.32 °C, with a maximum value of 30.37 °C at 58 days after sowing and minimum value of 14.28 °C at 116 days post-planting. However, the daily RH changed moderately during the entire growing period, especially after V12–VT, and it ranged from 44.54% to 79.04% with an average of 64.24% during the entire growth period of summer maize. There was a positive correlation between daily ET and AT during the entire growth period of summer maize, especially at 40 days post-planting. However, the correlation between daily ET and RH was uncertain during PT–V12.

Variation in 5-day ET

The variation in 5-day ET followed a bell curve (Figure 6) and varied from 11.49 mm to 14.98 mm in homogeneous soil and from 11.67 mm to 15.02 mm in layered soil. At V12–R3, the 5-day ET reached the maximum value of 14.98 mm in homogeneous soil and 15.02 mm in layered soil at V12–VT. At VT–R3, the average 5-day ET was 13.79 mm in homogeneous soil and 14.05 mm in layered soil, at R3–R6, the average 5-day ET was 13.03 mm in homogeneous soil and 13.31 mm in layered soil, and then it decreased to 12.79 mm and 12.97 mm, respectively. The variation in 5-day ET followed a bell curve during the entire growing period and reached its maximum value at V12–VT.
soil and from 11.79 mm to 16.26 mm in layered soil. The average 5-day ET was 11.60 mm in homogeneous soil and 11.79 mm in layered soil at 5 days post-planting, 12.22 mm and 13.49 mm at 30 days post-planting (V3–V6), respectively, and 13.74 mm and 14.96 mm at 55 days post-planting (V12–VT), respectively. At V12–R3, the 5-day ET reached the maximum value of 14.98 mm in homogeneous soil and 16.26 mm in layered soil. At R3–R6, the average 5-day ET was 12.17 mm in homogeneous soil and 12.92 mm in layered soil.

Variation in ET at different growth stages

The ET at PT–V3 showed minimum values and accounted for 7.9% and 7.7% of the total ET in homogeneous and layered soils (Figure 7), respectively; at V3–V6, it accounted for 16.0% of the total ET both in homogeneous and layered soils; at V6–V12, it accounted for 13.7% of the total ET both in homogeneous and layered soils; and at V12–VT, it accounted for 13.5% and 13.7% of the total ET in homogeneous soil and layered soil, respectively. At VT–R3, the
ET reached the maximum value of 80.86 mm (25.2% of total ET) in homogeneous soil and 87.73 mm (25.5% of total ET) in layered soil. The ET at VT–R6 accounted for more than 50% of the total ET both in homogeneous and layered soils. Therefore, it is necessary for irrigation at VT–R6 for summer maize from our study.

The total ET during the whole growing period was 321.16 mm in homogeneous soil and 344.09 mm in layered soil. These results were similar to those in previous studies. For example, Liu et al. (2010) reported that the total ET of maize was 319–501 mm in the Loess Plateau, China, and Yang et al. (2013) reported the total ET of maize was 335.6 mm in the 1960s and 311.4 mm in the 2000s. Kang et al. (2003) found that the 10-year average seasonal ET was 424 mm in Northwest China.

**Effect of environmental factors on ET**

The ET is significantly affected by crop characteristics (crop type, genotype, growth stage, and plant density),...
soil parameters (salinity, pH, fertility, and management), and environmental conditions (AT, RH, precipitation, solar radiation, sunshine hours, and wind speed) (Jun et al. 2012; Li et al. 2013; Yang et al. 2015). Many studies have investigated the relationship between the ET of summer maize and environmental factors, and suggested that AT, solar radiation, sunshine hours, and wind speed were positively correlated with ET, and RH and

Figure 5 | Variations in daily ET, AT, and RH at different growth stages of summer maize in homogeneous and layered soil. PT-V3, planting time to third leaf stage; V3-V6, third leaf to sixth leaf stage; V6–V12, sixth leaf to 12th leaf stage; V12-VT, 12th leaf to tasseling-silking stage; VT-R3, tasseling-silking stage to milk stage; R3-R6, milk stage to physiological maturity stage.

Figure 6 | Variation in 5-day ET of summer maize at 0–130 days post-planting in homogeneous and layered soils.

Figure 7 | Variation in ET at different growth stages of summer maize in homogeneous and layered soils. PT-V3, planting time to third leaf stage; V3-V6, third leaf to sixth leaf stage; V6-V12, sixth leaf to 12th leaf stage; V12-VT, 12th leaf to tasseling-silking stage; VT-R3, tasseling-silking stage to milk stage; R3-R6, milk stage to physiological maturity stage.
precipitation were negatively correlated with ET (Li et al. 2013; Yang et al. 2013).

To elucidate the effect of environmental factors on ET during the entire growing period of summer maize, the correlation coefficients between ET and AT or RH were calculated in homogeneous and layered soils (Table 3). ET was positively correlated with AT and negatively with RH. These results are consistent with previous studies (Li et al. 2013; Yang et al. 2013). The highest correlation coefficient between ET and AT was 0.70 ($p < 0.01$) in homogeneous and layered soils at PT–V3. At the beginning of the crop growth period, soil evaporation accounted for the larger part of ET, and it was the reason for the highest correlation coefficient between ET and AT occurring at PT–V3 in our study. The transpiration then increased, accompanying the growth of the leaf area (Liu et al. 2002; Kang et al. 2003), during which the minimum correlation coefficient occurred between ET and AT. Therefore, the lowest correlation coefficient observed at V12–VT was 0.55 ($p < 0.01$) and 0.55 ($p < 0.01$), respectively. RH had a negative effect on soil evaporation and transpiration. The highest correlation coefficient between ET and RH was $-0.50$ ($p < 0.01$) in homogeneous soil and $-0.51$ ($p < 0.01$) in layered soil at V12–VT, where ET maintained a relatively high value while RH decreased (Figures 3 and 4). The lowest correlation coefficient observed at V6–V12 was at $-0.11$ ($p < 0.05$) and $-0.14$ ($p < 0.01$), respectively. The correlation coefficient between ET and RH resulted from the integrated effects of AT, leaf area, and their interactions in this experiment.

### Table 3 | Spearman’s correlation coefficients between ET at different growth stages of summer maize and AT or RH in homogeneous and layered soils

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Growth stages</th>
<th>AT Homogeneous soil</th>
<th>AT Layered soil</th>
<th>RH Homogeneous soil</th>
<th>RH Layered soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET</td>
<td>PT–V3</td>
<td>0.70***</td>
<td>0.70***</td>
<td>$-0.47$***</td>
<td>$-0.47$***</td>
</tr>
<tr>
<td></td>
<td>V3–V6</td>
<td>0.66***</td>
<td>0.64***</td>
<td>$-0.36$***</td>
<td>$-0.34$***</td>
</tr>
<tr>
<td></td>
<td>V6–V12</td>
<td>0.60***</td>
<td>0.62***</td>
<td>$-0.11$*</td>
<td>$-0.14$**</td>
</tr>
<tr>
<td></td>
<td>V12–VT</td>
<td>0.55***</td>
<td>0.55***</td>
<td>$-0.50$***</td>
<td>$-0.51$***</td>
</tr>
<tr>
<td></td>
<td>VT–R3</td>
<td>0.60***</td>
<td>0.60***</td>
<td>$-0.46$***</td>
<td>$-0.46$***</td>
</tr>
<tr>
<td></td>
<td>R3–R6</td>
<td>0.56***</td>
<td>0.57***</td>
<td>$-0.39$***</td>
<td>$-0.40$**</td>
</tr>
</tbody>
</table>

PT–V3, planting time to third leaf stage; V3–V6, third leaf to sixth leaf stage; V6–V12, sixth leaf to 12th leaf stage; V12–VT, 12th leaf to tasseling-silking stage; VT–R3, tasseling-silking stage to milk stage; R3–R6, milk stage to physiological maturity stage.

*Significant at $p < 0.05$.
**Significant at $p < 0.01$.

**Effect of groundwater on ET**

Groundwater use can play an important role in contributing to crop water consumption (Yang et al. 2007; Luo & Sophocleous 2010). Both the variations of groundwater drainage and recharge were observed in this experiment during the entire growing period of summer maize in homogeneous and layered soils (Figure 8). Groundwater level remained stable at the beginning of the season, then started to fluctuate when the crop water demand increased, and finally stabilized again at the end of the season. Groundwater recharge occurred from 40 days and 37 days post-planting in homogeneous and layered soils, respectively (Figure 8(a)). However, groundwater drainage occurred accompanied by the irrigation. Daily groundwater recharge ranged from 0.16 mm to 0.26 mm with an average of 0.21 mm in homogeneous soil, while it changed from 0.16 mm to 0.25 mm with an average of 0.22 mm in layered soil. During the whole growth period, daily groundwater recharge showed a sharp increase at about 40 days post-planting, then maintained at a relatively high level at about 40–110 days post-planting, and finally declined gradually until the end of the season (Figure 8(a)). Therefore, there was a similar trend between daily recharge and daily ET (Figure 5). Previous research had also shown that when ET is at a maximum, the percentage of groundwater use is also maximal (Soppe & Ayars 2005; Yang et al. 2007). Five-day groundwater recharge also increased greatly at first, then remained at a relatively high level, and finally declined sharply during the whole growth period (Figure 8(c)). There was a
Figure 8 | Variations of daily (a), 5-day (b), different growth stages (e) in groundwater, and relationships of daily recharge and daily ET (c), 5-day groundwater and 5-day ET (d), groundwater and ET at different growth stages (f) during the entire growing period of summer maize in homogeneous and layered soils.
comparable trend between 5-day recharge and ET (Figure 6). The average 5-day recharge was 0.99 mm in homogeneous soil and 1.00 mm in layered soil. Groundwater recharge increased from V6 to V12, then reached its maximum at VT–R3, and declined gradually (Figure 8(e)). There was an analogous trend between recharge and ET at V6–R6 for summer maize (Figure 7).

Daily recharge was positively correlated to daily ET both in homogeneous and layered soils along the linear fitting lines (Figure 8(b)). The variability between daily recharge and ET was about 45% and 16% by the linear regression in homogeneous and layered soil, respectively. Five-day recharge was also positively correlated to 5-day ET in both homogeneous and layered soils, and the variability between 5-day recharge and ET was interpreted as about 46% and 29% by the linear regression in homogeneous and layered soil, respectively (Figure 8(d)). During the whole growth stages, recharge was significantly correlated to ET, and the variability between recharge and ET was interpreted as about 80% and 98% along the linear regression in homogeneous and layered soil, respectively (Figure 8(f)).

The contribution of daily recharge to daily ET varied from 6.14% to 10.14% with an average of 7.83% in homogeneous soil, while it ranged from 5.88% to 10.00% with an average of 7.63% in layered soil (Figures 5 and 8(a)). The average percentage of 5-day recharge was 7.45% in homogeneous soil and 7.09% in layered soil (Figures 6 and 8(c)). The contribution of groundwater recharge to ET at V6–V12 was 4.59% in homogeneous soil and 5.76% in layered soil (Figures 6 and 8(c)). The contribution of groundwater recharge to daily crop water use was 40%. The reasons for the difference in our study may be the different levels of capillary upflow from the water table due to the different soil texture and crop root system or depletion levels of soil water (Soppe & Ayars 2003; Yang et al. 2007; Luo & Sophocleous 2010).

Effect of homogeneous and layered soils on ET

The average daily ET of summer maize in our study during the entire growing period was 2.57 mm in homogeneous soil and 2.75 mm in layered soil. During the entire growing period, the ET peaked daily at 14:00–15:00 for both homogeneous and layered soils. These results are consistent with previous studies. Li et al. (2008) found that the average daily ET value was 2.96 mm in maize and the corresponding peak time was 13:00, 14:00, 14:00, 14:00, and 13:00 at the seedling, shooting, heading, filling, and maturity stages, respectively, in a semi-arid region of North China under field conditions.

ANOVA results showed that the difference in daily ET between homogeneous and layered soils was significant (Table 4). The daily ET was significantly (p < 0.05) lower in homogeneous soil than in layered soil, and the differences in initial soil moisture content was insignificant. Therefore, the differences in the daily ET of summer maize were mainly due to differences in leaf transpiration area, thus suggesting that the latter was greater in layered soil. Therefore, maize growth in the silt sandy loam–loam layered soil was better than in the silt sandy–loam homogeneous soil because layered soil has higher water and nutrient-holding capacities (He et al. 2013).

CONCLUSIONS

A better understanding of the multi-temporal variation in ET during different crop growth stages is important for determining a reasonable irrigation schedule. In this study, we used WTDPEd to simulate and monitor the growth and water consumption of summer maize in Beijing based on

<table>
<thead>
<tr>
<th>Daily ET</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Significance level (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous soil</td>
<td>2.01</td>
<td>3.26</td>
<td>2.57</td>
<td>0.27</td>
<td>0.00</td>
</tr>
<tr>
<td>Layered soil</td>
<td>2.17</td>
<td>3.43</td>
<td>2.75</td>
<td>0.32</td>
<td></td>
</tr>
</tbody>
</table>
the average meteorological values taken over a 10-year period. Our objective was to illustrate the multi-temporal variation in ET and the effect of environmental and groundwater conditions on it both in homogeneous and layered soils. The main findings are as follows:

1) During the whole growing period, the ET per hour peaked at 14:00–15:00 on a daily basis and reached a maximum value of 0.32 mm in homogeneous soil and 0.33 mm in layered soil at V12–VT.

2) The variation in daily ET followed a bell curve during the entire growing period. The average value was 2.57 mm in homogeneous soil and 2.75 mm in layered soil, thus reaching the maximum value of 3.26 mm at 75 days post-planting and 3.43 mm at 61 days post-planting, respectively.

3) The variation in 5-day ET also followed a bell curve, and it reached the maximum value of 14.98 mm in homogeneous soil and 16.26 mm in layered soil at V12–R3.

4) The ET at VT–R6 accounted for approximately 50% of the total ET during the entire growing period. The ET reached the maximum value of 80.86 mm in homogeneous soil and 87.73 mm in layered soil at VT–R3. The total ET was 321.16 mm and 344.09 mm in homogeneous and layered soils, respectively.

5) During the entire growing period of summer maize, ET was positively correlated with AT and negatively with RH. The daily ET was significantly \( (p < 0.05) \) lower in homogeneous soil than in layered soil because of the larger maize leaf transpiration area in the latter.

6) Daily groundwater recharge showed a sharp increase at about 40 days post-planting, then was maintained at a relatively high level at about 40–110 days post-planting, and finally declined gradually until the end of the season. The average value was 0.22 mm. Recharge was positively correlated to ET both in homogeneous and layered soils. The contribution was up to 10.07% for daily recharge and 7.27% for 5-day recharge.

In this study, WTDPED was used to monitor the multi-temporal variation in water consumption considering the combined effect of climatic factors and groundwater under a controlled standard year, and the results are consistent with several previous studies conducted under field conditions. Some differences between the studies could be attributed to soil conditions, environmental conditions, and growing periods. Further studies are required to investigate the differences in water consumption of summer maize under different controlled environmental conditions (AT, RH, and CO2 concentrations) and groundwater level conditions in homogeneous and layered soils. Overall, studies on the effect of environmental factors and soil structure on multi-temporal ET are important for region-sustainable water planning during crop growing seasons.

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