Estimation of the daily water consumption by maize under Atlantic climatic conditions (A Coruña, NW Spain) using Frequency Domain Reflectometry – a case study

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Received: 16 September 2011 – Revised: 12 December 2011 – Accepted: 23 January 2012 – Published: 23 March 2012

Abstract. Climatic variables and soil present a high spatio-temporal variability. Evapotranspiration estimations based on climatic variables may be inadequate for assessing soil water content in the root-influenced zone and/or soil water consumption by plants. Other methods may provide better estimates of this water consumption. The aim of this study was to quantify the soil moisture dynamics in the root-influenced zone and to assess the daily water consumption by the crop using Frequency Domain Reflectometry (FDR). The studied site is located in A Coruña (Spain). The study was carried out from June to October in 2008 and 2009, in a maize (Zea mays, L.) field on a silt-clay textured soil. Evapotranspiration was estimated by the Penman-Monteith equation using meteorological data from a station located on the experimental site. Soil water content in the root-influenced zone (0–60 cm depth) was hourly monitored each 20 cm (0–20 cm, 20–40 cm, and 40–60 cm) using FDR. Evaluations were performed on days with slight or no rainfall. During the study period, the magnitude of the diurnal soil water loss was more evident in the first layer (0–20 cm depth) and less important in the subsequent soil layers. The greatest consumption occurred between 14 and 19 h, up to 53.64 % of the total. Overall, daily water consumption increased significantly with soil water content (p-value < 0.001). In general, water losses from the 0–20 cm soil layer were greater than in subsoil horizons due to maize water-uptake and evaporation. In contrast, water content in the deepest part of the soil profile was close to saturation, even on the driest days of the studied period. Evapotranspiration overestimate maize water requirements as its values were greater than those measured with the probe. In conclusion, FDR allows a more accurate estimation of the soil water balance. Therefore, monitoring soil water content would be useful in the assessment of saturation risks or water stress (drought), thus aiding in the decision making, for instance, in irrigation management. Results from this study may help to improve irrigation practices in humid zones.

1 Introduction

Evapotranspiration is the combination of two different processes where water is lost from the soil surface and from the surface leaves by evaporation and from plants by transpiration. It constitutes one of the main components of the hydrological cycle and its estimation demands auxiliary meteorological data. The FAO Penman-Monteith method has recently been recommended as the sole standard method. It is a method with a strong likelihood of correctly predicting the potential evapotranspiration in a wide range of locations and climates (Aaron et al., 1996; Allen et al., 1998; D’Urso and Menenti, 1995).

Crop water requirements are affected by climatic parameters such as rainfall, wind speed or solar radiation. Hence, crop water requirements vary from year to year and so does water availability. On the one hand, some of these climatic variables are changing due to global warming (IPCC, 2007) and on the other hand, they present great spatial and temporal variability (e.g. Alsamamra et al., 2009; Mirás-Avalos et al., 2009). The latter reason has made them inadequate for indicating soil water consumption by plants, which is an essential parameter for assessing water availability. Thus, soil water content measurements are thought to be more useful in the assessment of crop water requirements (e.g. Vera

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Table 1. Soil characteristics at the experimental site.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Texture analysis</th>
<th>Chemical properties</th>
<th>Physical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand (2-0.05 mm)</td>
<td>Total carbon (%)</td>
<td>Bulk density g cm⁻³</td>
</tr>
<tr>
<td></td>
<td>Silt (0.05-0.002 mm)</td>
<td>Total nitrogen (%)</td>
<td>Field capacity %</td>
</tr>
<tr>
<td></td>
<td>Clay (&lt;0.002 mm)</td>
<td>C/N</td>
<td>Permanent wilting point %</td>
</tr>
<tr>
<td>0-15</td>
<td>24.85</td>
<td>3.27</td>
<td>1.28</td>
</tr>
<tr>
<td>15-30</td>
<td>24.78</td>
<td>0.25</td>
<td>31.16</td>
</tr>
<tr>
<td>30-60</td>
<td>27.05</td>
<td>10.18</td>
<td>13.04</td>
</tr>
<tr>
<td>60-90</td>
<td>31.13</td>
<td>5.38</td>
<td></td>
</tr>
</tbody>
</table>
where ET$_0$ is the reference evapotranspiration (mm day$^{-1}$), $R_n$ is the net radiation at the surface (MJ m$^{-2}$ day$^{-1}$), $G$ is the ground heat flux density (MJ m$^{-2}$ day$^{-1}$), $T$ is the mean daily air temperature at 2 m height ($^\circ$C), $u_2$ is the wind speed at 2 m height (m s$^{-1}$), $e_s$ is the saturation vapour pressure (kPa), $e_a$ is the actual vapour pressure (kPa), $\Delta$ is the slope of the saturation vapour pressure curve (kPa $^\circ$C$^{-1}$), and $\gamma$ is the psychrometric constant (kPa $^\circ$C$^{-1}$).

Crop evapotranspiration (ET$_c$) was calculated by multiplying ET$_0$ and a crop coefficient ($K_c$) for maize. This crop coefficient depends on the phenological stage of maize. We worked with “yield maize” and the final stage of crop development was very short (around 15 days), therefore, in our case, three phenological stages were considered: initial, middle and final (Table 2). Their corresponding $K_c$ values were 0.3, 1.2, and 1.0, respectively (Allen et al., 1998).

2.3 Soil water content measurements

The volumetric soil water content was monitored continuously by a multi-depth capacitance probe (EnviroSCAN SOLO, Sentek, Australia). These measurements are based on frequency domain reflectometry (FDR) yielded by a series of coil capacitor circuits. Mid-points of the sensors were sited at 20, 40 and 60 cm depth and connected to a datalogger which stored an average value every hour. The probe was installed in a representative location within the plot. The spot within the plot where the probe was installed was selected after a previous study in the same area using a non-continuous measuring probe in several locations within the plot (Mestas-Valero et al., 2009).

Each sensor inside the PVC access tube was previously normalized taking readings exposed to air and water before being installed in the field following the manufacturer’s guidelines. The accuracy of the data obtained by this equipment depends on the installation procedure since the radius of influence of the sensors’ electric field is relatively small (Evett et al., 2002). In the absence of air gaps between sensor and soil, its precision can be as good as $\pm 0.01$ m$^3$m$^{-3}$ (Muñoz-Carpena, 2004).

A total of 46 days were surveyed per year, between 29 June and 4 October in 2008 and between 16 June and 13 September in 2009. On those days, slight or no rainfall was observed; therefore, water loss from soils was considered to be consumed by maize, although it included evaporation from the soil, drainage and uptake of water by the crop.

To estimate the soil water balance, we used the method described by Arauzo et al. (2003). For each period between two rainfalls, we calculated the evapotranspiration and drainage, and also the variation in soil water content. Soil water balance is commonly represented as $\Delta S = I + R - D - ET_c$, where $\Delta S$ is the variation in soil water content, $I$ is irrigation, $R$ is rainfall, $D$ is drainage, and ET$_c$ is crop evapotranspiration (Vera et al., 2009). In our case, since the maize was not irrigated and we only used data from days with no rainfall, soil water balance was simplified to $\Delta S = D + ET_c$. Furthermore, we considered drainage as negligible and variations in soil water content were accounted for as crop water uptake. $\Delta S$ values were calculated as the difference in the soil water content between two consecutive days.

2.4 Data analysis

Crop evapotranspiration (ET$_c$) values were compared to those of soil water content and water consumption by the crop determined by FDR using regression analysis. Data were analysed using R software version 2.12.1 (R Development Core Team, 2010).

3 Results

Maize growing dynamics followed a sigmoidal curve due to different growing rates during its development cycle. The maximum development was observed at 50 days after sowing, approximately until the end of blooming and beginning of grain formation. After these periods, the growth rate was negligible. Knowledge of the different phenological stages and crop growing processes may help to determine crop water requirements and avoid water stress during critical phases that may considerably affect the quantity and quality of the final yield.

The average daily ET$_0$ was 4.16 mm day$^{-1}$ in 2008 and 4.64 mm day$^{-1}$ in 2009. These values ranged between 2 and 6.5 mm day$^{-1}$ in both years studied (Fig. 1). The crop water uptake was mainly produced during the day and, significantly, from 12 h. The highest values were observed between 15 and 17 h. In contrast, this water uptake at night or at dawn was low. These observations are in accordance with the daily dynamics of water content in the soil profile (Fig. 2), when a greater decrease of water content is produced from noon in

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**Table 2.** Crop developmental stages for both years. Note: $K_c$ denotes crop coefficient.

<table>
<thead>
<tr>
<th>Year</th>
<th>Planting date</th>
<th>Crop development stages</th>
<th>Period length (days)</th>
<th>$K_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>24 June</td>
<td>Initial, Middle, Final</td>
<td>35, 47, 14</td>
<td>0.3, 1.2, 1</td>
</tr>
<tr>
<td>2009</td>
<td>21 June</td>
<td>Initial, Middle, Final</td>
<td>32, 54, 18</td>
<td>0.3, 1.2, 1</td>
</tr>
</tbody>
</table>
Fig. 1. Rainfall and daily potential evapotranspiration estimated during the two study periods.

both years studied. This decreasing is rapid till 18 h, approximately, and then it reduces its velocity.

The magnitude of the diurnal soil water loss was more evident in the first layer (0–20 cm depth) and less important in the subsequent soil layers (Table 3). In fact, water consumption in the first soil layer was almost 4 times greater than that in the deepest range considered (40–60 cm depth) for both years studied. Water loss from the top horizon included evaporation losses.

During daytime and in absence of rainfall or any other water supply, soil water content varies (Fig. 2) due to the bioclimatic demand of the crop (ET\(_c\)). This soil water loss progressively diminishes from one day to the following due to the progressive consumption by the crop of available water.

Daily ET\(_c\) values and crop water consumption were significantly correlated (Fig. 3). A potential relation was observed with regression values of 0.56 and 0.54 for 2008 and 2009, respectively. Although significant, these regressions do not explain data spread. However, ET\(_c\) was always greater than crop water consumption determined by FDR. Similar relations were observed between evapotranspiration and soil water content (data not shown).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>0–60</th>
<th>0–20</th>
<th>20–40</th>
<th>40–60</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop water consumption</td>
<td>2.13</td>
<td>1.13</td>
<td>0.58</td>
<td>0.42</td>
</tr>
<tr>
<td>Soil water content</td>
<td>23.12</td>
<td>18.72</td>
<td>22.98</td>
<td>24.36</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop water consumption</td>
<td>2.95</td>
<td>1.88</td>
<td>0.67</td>
<td>0.40</td>
</tr>
<tr>
<td>Soil water content</td>
<td>25.59</td>
<td>22.32</td>
<td>23.68</td>
<td>30.78</td>
</tr>
</tbody>
</table>

4 Discussion

In the humid zone of Spain, climate change may increase the water requirements of crops as suggested by Moratiel et al. (2011) for other regions in Spain. In this context, the use of a methodology that accurately estimates crop water consumption is of paramount importance in order to make a wise use of water resources. In this study, we observed that estimating ET\(_c\) using the Penman-Monteith approach overestimates crop water requirements in the case of maize, whereas FDR provided a more accurate prediction. This may be due to a lack of adjustment of the \(K_c\) values for our study area; therefore, it may indicate that measuring soil water content is preferable to relying on models from meteorological data.

However, decreases in soil water content may be due to crop evapotranspiration, drainage, and moisture redistribution within the soil profile. Our results showed that crop evapotranspiration was mainly produced during the day. In contrast, ET\(_c\) values at night or at dawn were low. Therefore, water loss in the soil profile at night and dawn was considered to be caused by drainage, as we observed a certain decline in soil water content during this time of the day.

However, as also reported by Vera et al. (2009), the FDR probes explore a small soil volume and, for agricultural purposes, several probes should be installed in the field to achieve a high representativeness of the culture water requirements. For instance, the fact that most of the soil water loss was produced in the shallowest soil layer indicates the high root concentration in this first layer, which may also prove the potential use of these sensors as a biological indicator.

In conclusion, FDR probes are useful for calculating crop water consumption and estimating the evolution through time of soil water content, being accurate in assessing crop water requirements. Furthermore, they would be useful in the assessment of saturation risks or water stress (drought), thus aiding in the decision making, for instance, in irrigation management. Results from this study can be used for crop water
Fig. 2. Hourly evolution of soil water content in the root zone (0–60 cm depth). Data are averaged from the analyzed days, namely 46 days in 2008 and 2009.

requirement modelling purposes employing such models as ISAREG (Pereira et al., 2003), which has been successfully applied to maize crops in Galicia (Cancela et al., 2006) and may help to improve irrigation practices in humid zones.

5 Conclusions

Monitoring water content within the soil profile (each 10 cm depth) and with a high data acquisition frequency (every hour) allowed us to estimate the real evapotranspiration of maize crop. Measuring soil water content within the rooting zone (0–60 cm depth) revealed the dynamics of soil moisture due to root water uptake. This information is valuable for irrigation purposes. In addition, the estimation of crop water uptake by FDR was more accurate than the use of the FAO Penman-Monteith equation, which overestimates crop water requirements.

Acknowledgements. This work was funded in part by Spanish Ministry of Science and Innovation (MICINN) within the framework of the project reference CGL2009-13700-C02. Roger M. Mestas-Valero was supported by the Programme AlBan, the European Union Programme of High Level Scholarships for Latin America, scholarship no. E07D403924PE. José Manuel Mirás Avalos thanks Xunta de Galicia for funding his contract within the framework of the program “Isidro Parga Pondal”. Useful comments from two reviewers are gratefully acknowledged.

Edited by: A. M. Tarquis
Reviewed by: two anonymous referees

Fig. 3. Relation between daily crop evapotranspiration (ETc) and daily crop water consumption determined by FDR during the two years studied: 2008 and 2009.
References


