PENMAN-MONTEITH FORMULATION FOR DIRECT ESTIMATION OF MAIZE EVAPOTRANSPIRATION IN WELL WATERED CONDITIONS WITH FULL CANOPY

by

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An efficient use of water resources for irrigation requires an accurate estimation of crop water requirements. The traditional approach to estimate crop evapotranspiration (ET) requires the use of a crop coefficient and an estimate of a reference ET. However, crop coefficients depend on crop type, management, and weather conditions and they sometimes lead to large errors in crop ET estimates. The Penman-Monteith (PM) formulation can be used to estimate crop ET without using a crop coefficient if the crop surface and aerodynamic resistances are known. PM formulation application also requires weather measurements from above the crop in question; however, this is not possible in everyday applications. This study analyzed the feasibility of using the PM formulation in maize ET estimation and characterized the uncertainties introduced when the weather data are measured above grass. Expressions to estimate aerodynamic and canopy surface resistances were evaluated. Weather measurements from above the maize canopy and above grass were compared. Techniques to translate weather measurements from a nearby weather station with grass cover to a maize canopy were evaluated. Maize ET was estimated

separately using measurements taken above the maize canopy and measurements taken above grass and translated to the maize canopy. Eddy covariance measured and estimated maize ET were compared. The results show that the PM formulation can be used to estimate the maize ET. The approach worked reasonably well for a full crop cover under well watered conditions. The critical point was to estimate the surface resistance as a function of climatic variables. Maize ET was estimated with $RMSE$ values that varied between 0.3 and 0.78 mm/day when the ET was estimated using weather data measured above the maize canopy. The uncertainty introduced when the maize ET was estimated using weather data measured above the grass was relatively small, the $RMSE$ increased between 0.12 and 0.2 mm/day. A different crop management system introduced larger ET estimation differences than the uncertainty introduced when the ET was estimated using weather data measured above the grass.

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Introduction

Accelerated population growth places a high demand on food supply. As a result of this exigency, the optimal use of available natural resources is essential. Water resources are very important in the production of food; plant growth and productivity are directly related to the availability of water (Rosenberg et al., 1983).

Irrigation is the largest use of water resources in many agricultural regions. An efficient use of water resources for irrigation requires an accurate estimation of crop water requirements. Timely applications of water, based on robust irrigation scheduling tools, can optimize yields while minimizing frequency and amount of water application (De Oliveira, 2002).

Evapotranspiration (ET) estimates are required for agricultural and environmental management applications, such as hydrologic studies, crop modeling and irrigation scheduling (Rana et al., 1997). The traditional approach to estimate crop ET is to first estimate reference ET from a standard surface and to apply an appropriate empirical crop coefficient such as those presented by Doorenbos and Pruitt (1977), and Wright (1981, 1982). However, several types and forms of reference ET have been presented in the literature, each of which provides estimates of reference ET that differ from the others (Allen et al., 1989).

The Food and Agriculture Organization of the United Nations (FAO) organized a group of experts and researchers in collaboration with the

International Commission for Irrigation and Drainage and the World Meteorological Organization, to review the FAO methodologies on crop water requirements and to advise on a revision and update of procedures. After deliberation, the panel of experts recommended the adoption of the Penman-Monteith (PM) formulation as a new standard for reference ET and advised on procedures for calculating the various parameters (Allen et al., 1998).

Several studies have shown the applicability of the PM formulation to a wide variety of climates. Allen et al. (1989) compared the PM and other forms of the Penman equation at eleven international lysimeter sites; the PM formulation provided best estimates of daily and monthly average reference ET and was the most consistent across all locations evaluated. A similar study was made by Yoder et al. (2005) where eight different approaches were used to estimate daily reference ET at a site in the humid southeast United States. The results indicated that the PM formulation is the best method for this humid site. Temesgen et al. (2005) conducted a study using weather stations across the state of California that demonstrated the robustness of the PM formulation in that all versions of the equation do not require local calibrations as other approaches used to estimate the reference ET.

Past research on ET has provided sound theoretical knowledge and practical applications that have been validated through field measurements; however, the transfer of theoretical advances into field practice remains far short of its potential (Pereira et al., 1999).

Current operational approaches to estimate ET for an agricultural crop require use of crop coefficients; worldwide research provides data for most existing crops. However, crop coefficients have long been considered empirical and several researchers have mentioned variations in the accuracy of estimation of crop ET due to the use of fixed values of crop coefficients (Ritchie, 1972; Jagtap and Jones, 1989; Ritchie and Johnson, 1990; Allen et al., 1996a). Differences as large as 40% between the crop coefficient values reported by Allen et al. (1998) and values experimentally obtained have been found (Katerji and Rana, 2006).

Allen et al. (1996a, b, 1998) have proposed corrections for standard crop coefficients to account for varying roughness of crops relative to the grass reference as a function of crop height, wind speed, and relative humidity. Ritchie (1972, 1974) proposed the use of a functional relationship that considers the stage of crop development and canopy density, as represented by a function of the leaf area index and a second function that represents the water availability in the soil to generate the value of the crop coefficient.

Research must continue to provide a better understanding of the sources of variation in crop coefficients, not only related to the characteristics of crop varieties and crop management, including salinity, but also considering the climatic factors such as net radiation, vapor pressure deficit, temperature, and wind velocity (Pereira et al., 1999). In an attempt to explain the variations found in the crop coefficients, Hubbard (1992), Pereira et al. (1999) and Shuttleworth

(2006), developed theoretical expressions for the crop coefficients based on the PM formulation. The expressions show that the crop coefficients are a function of surface resistance, aerodynamic resistance and climate conditions.

Crop ET can be estimated directly (without using a crop coefficient) from the PM formulation if the crop specific surface and aerodynamic resistances are known (Shuttleworth, 2006). Direct estimation of ET from agricultural crops avoids the uncertainty associated with the use of crop coefficients.

Several studies have attempted a direct estimation of crop ET using the PM formulation. Hatfield and Allen (1996) found consistent ET estimations of cotton, grain sorghum and grass forage, using an empirical surface resistance. Katerji and Perrier (1983) proposed to simulate the surface resistance as a function of climatic and aerodynamic resistances. This model has been used in several studies to estimate ET of different crops such as alfalfa, rice, grass, lettuce, sweet sorghum, grain sorghum, soybean, tomato and wheat (Alves and Pereira, 2000; Katerji and Rana, 2006).

At present, data on crop specific surface resistances are insufficient, but it is expected that appropriate characterization of primary crops will be available for wide use in the next decade (Pereira et al., 1999). Shuttleworth (2006) provides theoretical analyses that facilitate the use of the PM formulation to make a direct estimation of crop water requirements.

In addition to the necessity of estimating canopy and aerodynamic resistances of the crops, the direct application of the PM formulation presumes

that the measurement of wind speed, humidity, and temperature are made above the crop in question (Pereira et al., 1999).

In everyday applications measurements over the crop surface are not feasible. However, data from weather stations at nearby sites over a reference surface are available. Direct estimation of crop ET, using the PM formulation for areas where these parameters are not measured over the canopy, requires procedures that permit the translation of weather measurements from nearby reference surfaces to crop surfaces (Allen et al., 1997).

This study analyzes the feasibility of using the PM formulation in the direct estimation of maize ET and characterizes the uncertainties introduced when the weather data for estimating the ET come from a fixed site over grass as opposed to using weather data measured over the crop. Specific objectives of this study are to:

1) Evaluate expressions to estimate aerodynamic and canopy resistances of a maize crop, which along with weather data measured over the maize crop permit the direct estimation of ET.
2) Compare estimated maize ET, using the PM formulation, to measured maize ET using an eddy covariance flux system.
3) Compare direct maize ET estimates that use weather parameters measured above the maize crop to maize ET estimates that use measurements from a nearby weather station.

4) Compare techniques that translate weather parameters from a nearby weather station to those of an irrigated maize canopy.
5) Compare maize ET estimates that use weather parameters measured above the maize crop to maize ET estimates that use translated measurements from a nearby weather station.

Methodology

Study area

The study was conducted in two production fields, which are referred to as site 1 and site 2, located at the University of Nebraska Agricultural Research and Development Center near Ithaca, Nebraska. The sites are part of the Carbon Sequestration Program (CSP); details of this program are provided in Verma et al. (2005). Site 1 (41° 09′ 54.2″ N, 96° 28′ 35.9″ W, 361 m) is 47 ha in size, has a center pivot irrigation system and is planted in continuous maize; the growing seasons of 2002 through 2004 at this site were used in the study. Site 2 (41° 09′ 53.5″ N, 96° 28′ 12.3″ W, 362 m) is 52.4 ha, also has a center pivot irrigation system, and is under a maize-soybean rotation; the growing season of 2003 was used in this study, during this season the site was planted in maize.

The study sites provide sufficient upwind fetch over a uniform cover to adequately measure mass and energy fluxes using eddy covariance systems. The soils are deep silty clay loams consisting of four soil series: Yutan, Tomek, Filbert and Filmore. Prior to initiation of the study, the sites had a 10-year history of maize-soybean rotation under no till. The study sites were uniformly tilled by disking prior to initiation of the CSP in 2001 and during the years used in this study, they have been under no-till management.

Seeds were planted below the crop residue from previous years. Standard best management practices for maize were followed. The crops used in this

study were maize, Pioneer 33P67 in 2002 and Pioneer 33B51 in 2003, with a planting population of 84,015 seeds per hectare. Water was applied in the irrigated fields to maintain a minimum of 50% available soil moisture.

Field measurements

Hourly maize ET rates from eddy covariance measurements were collected as part of the CSP. Net radiation, soil heat flux, sensible heat flux, temperature, relative humidity, wind speed, solar radiation, soil water, leaf area index and crop height were also measured (see Verma et al. 2005 for details).

Two additional towers were installed in the vicinity of the study area. One tower was installed over a grass surface (N 41º 09’ 33.9”, W 96º 28’ 33.4”, 372 m), located to the south of the maize field sites. The other tower was installed in the maize field Site 1 (N 41º 09’ 57.7”, W 96º 28’ 38.1, 367 m). Figure 1 shows the approximate positions of the towers.

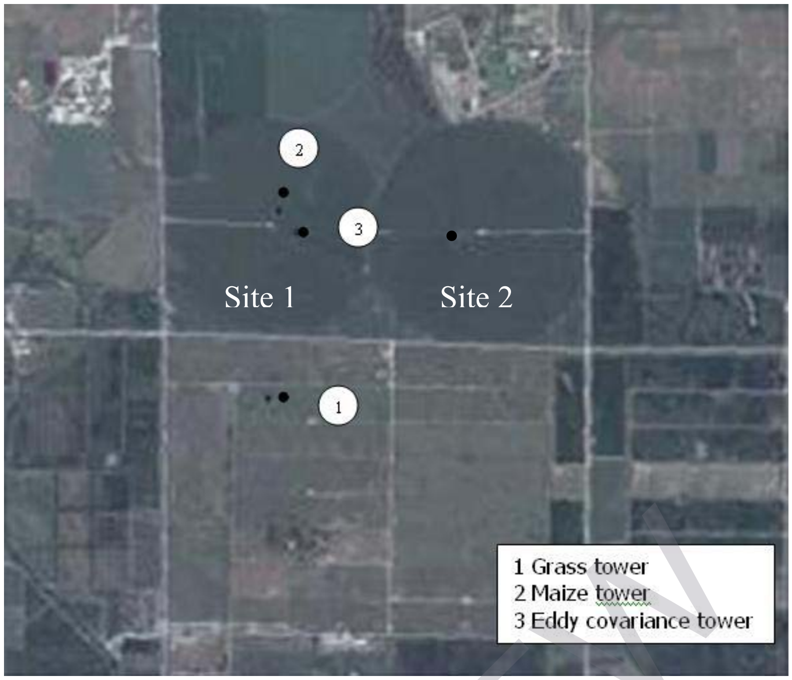

Figure 1. Study location and towers installed during the study.

The following instruments were installed on the towers located in the grass and maize fields: a CR10X Campbell Scientific datalogger, an HMP45C Temperature and relative humidity probe (at 3 m), an LI200X Pyranometer to measure solar radiation (at 3 m), 3 CS800-l Climatronics wind speed and direction sensors (at 3, 6, and 9 m), 3 type E fine wire thermocouples to measure air temperature (.003 inch diameter, at 3, 6, and 9 m), an Airlink CDMA cellular modem and a Texas electronic rain gage. There was no rain gage on the tower located in the maize field and the 3 CS800-l Climatronics wind speed and direction sensors were installed at 3, 4.6, and 6 m instead. The fine wire thermocouples were installed at the same heights as the wind sensors.

Modeling evapotranspiration

Evapotranspiration (ET) can be defined as the combination of two separate processes whereby water vapor is lost from the soil surface by evaporation and from the crop by transpiration. Evaporation is a process where liquid water is converted to water vapor and removed from the evaporating surface. Transpiration consists of the vaporization of liquid water contained in plant tissues and the diffusion of water vapor into the atmosphere. The vaporization occurs within the leaf, namely in the intercellular spaces, and the vapor exchange with the atmosphere is controlled by the stomatal aperture. Weather parameters (such as solar radiation, temperature, wind speed and relative humidity), crop characteristics, management and environmental aspects are factors that affect the ET rate (Allen et al., 1998).

Penman-Monteith formulation

A large number of empirical and semi empirical methods have been developed around the world to estimate ET from different climatic variables. In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface using standard climatological records of sunshine, temperature, humidity and wind speed. Monteith (1965) combined the logarithmic eddy diffusion function and canopy resistance into the PM formulation; it has the form:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (1)$$

where

λET vapor flux density $\left(\frac{MJ}{m^2 t}\right)$

R_n net radiation flux density to the plant canopy $\left(\frac{MJ}{m^2 t}\right)$

G soil heat flux density $\left(\frac{MJ}{m^2 t}\right)$

Δ slope of the saturation vapor pressure curve $\left(\frac{kPa}{°C}\right)$

ρ_a density of the air $\left(\frac{kg}{m^3}\right)$

c_p specific heat of the air $\left(\frac{MJ}{kg°C}\right)$

e_s saturation vapor pressure at the current air temperature (kPa)

e_a actual vapor pressure of the air (kPa)

r_a aerodynamic resistance to vapor diffusion $\left(\frac{t}{m}\right)$

γ psycrometric constant $\left(\frac{kPa}{°C}\right)$

r_s bulk surface resistance $\left(\frac{t}{m}\right)$

λ latent heat of vaporization $\left(\frac{MJ}{kg}\right)$

t time scale for which the vapor flux is to be estimated.

ET in $\left(\frac{mm}{t}\right)$ is calculated by dividing λET by the latent heat of vaporization (λ).

Calculation procedures of the involved variables in the PM formulation are described in Appendix A and follow the methods recommended by Allen et al.