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Evapotranspiration measurement and estimation using modified Priestley–Taylor model in an irrigated maize field with mulching

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ABSTRACT

Accurate measurement or estimation of crop evapotranspiration (ET) is important to develop exact irrigation scheduling and reasonably use water resources. ET of an irrigated maize field mulched with plastic film was measured using eddy covariance technique over two growing seasons in an arid region of northwest China. A modified Priestley–Taylor (PT) model was developed, incorporating the effect of leaf area, soil moisture, mulching fraction and leaf senescence on ET. The model was parameterized by field measurements in 2008 and validated by those in 2009. Results indicate that diurnal variation of ET was bell-shaped curve for all the growing stages. During the two growing seasons, total ET was 503.1 and 562.4 mm, and mean daily ET 3.47 and 3.54 mm d^{-1}, respectively. ET was mainly controlled by solar radiation, and significantly affected by influential factors below the thresholds, which were leaf area index of 3.0 m^2 m^{-2}, and soil relative extractable water of 0.5, and canopy conductance of 20 mm s^{-1}, respectively. A good agreement was found between ET estimated by the modified PT model with observations, with linear slope of 0.99 and R^2 of 0.94 and 0.96 for half-hourly and daily time scale, respectively. Thus the modified PT model can be used to estimate ET or quantify the effect of controlling factors on ET in similar agricultural fields.

1. Introduction

More than 90% of water used in agriculture is lost by soil evaporation and crop transpiration (Rana and Katerji, 2000). Thus accurate measurement or estimation of crop evapotranspiration (ET) is important to develop exact irrigation scheduling and reasonably use water resources (Kang et al., 2008). However, direct measurement of ET is difficult, cost and not available in many regions, so different models are developed to estimate ET (Stannard, 1993; Sumner and Jacobs, 2005; Utset et al., 2004). ET is significantly affected by weather condition, crop species, irrigation scheduling and field management (e.g. surface mulching) (Allen et al., 1998; Kang et al., 2003; Tolk et al., 1998; Zhao et al., 2010). Therefore, determination of major factors affecting ET is needed to provide information to establish the ET model.

The Priestley and Taylor (PT) model is a simplification of Penman equation (Agam et al., 2010; Priestley and Taylor, 1972; Utset et al., 2004). In this model, ET is a product of the equilibrium evaporation (ET_{eq}) and PT coefficient (α), where ET_{eq} can be obtained from meteorological data (net radiation, soil heat flux, and air temperature). The successful use of PT model depends on accurate determination of α (De Bruin, 1983; Pereira and Villa Nova, 1992; Priestley and Taylor, 1972). De Bruin (1983) developed the PT coefficient model as a function of surface resistance. Pereira and Villa Nova (1992) showed that α was linearly related to sensible heat flux at either hourly or daily time scales. In addition, some studies indicated that α = 1.26 could be applied to many vegetated areas (Brutsaert, 1982; Lhomme, 1997; Parlange and Katul, 1992). Conversely, other studies indicated that α was not constant over whole growing season and varied greatly with crop species, soil moisture availability and climate condition (Lei and Yang, 2010; Pereira, 2004). They suggested that the main factors controlling α included leaf area index (LAI), vapor pressure deficit (VPD) and soil moisture content (θ). However, a unique functional form for the response of α to the factors has not been defined yet.

Maize is one of main food crops in Shiyanghe basin of arid region in northwest China, where has larger population density and higher exploitation of water resources (Kang et al., 2008). Because of low precipitation in this region, water requirement of maize is mainly supplied by irrigation. To reduce soil evaporation in the field, ground is mulched with plastic film, which is a well established management strategy (Hou et al., 2010). Many studies indicated that plastic mulching not only reduced water loss from soil evaporation, but also accelerated crop development in the early stage by increasing soil temperature and controlling weed, which would enhance crop yield (Allen et al., 1998; Hou et al., 2010).

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Table 1
Crop management and irrigation scheduling over the whole growing seasons of maize in 2008–2009.

Year	Sowing date	Emergence date	Harvest date	Irrigation scheduling	
				Irrigation date	Irrigation quota (mm)
2008	May 2	May 11	September 25	June 12	100
				July 7	100
				July 27	100
				August 23	95
2009	April 21	May 1	September 28	June 15	105
				July 6	105
				July 29	105
				August 20	105

Irrigation water amount was measured by pump meter in each event.

However, fewer attempts have been made to investigate long-term variation in ET and its controlling factors with this management practice.

In this study, to investigate the variability and magnitude of ET and the controlling factors, ET of an irrigated maize field with mulching was measured by eddy covariance technique over the whole growing seasons in 2008 and 2009. Leaf area, meteorological factor and soil water content were also measured. After incorporating the effects of leaf area, soil moisture, ground mulch and leaf senescence on ET, a modified PT model was developed to estimate ET.

2. Materials and methods

2.1. Study area

The experiments were conducted at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University, located in Gansu Province of northwest China (N 37°52′, E 102°50′, altitude 1581 m) during 2008–2009. The site has high sunlight hours with a mean annual sunshine duration over 3000 h, mean annual temperature of 8 °C and frost-free days of 150 d. The region is limited in water resources with a mean annual precipitation of 164 mm and a mean annual pan evaporation of 2000 mm measured by a cylinder Class A evaporation pan with a diameter of 120.7 cm and a depth of 25.0 cm. Average groundwater table is below 30 m.

Spring maize was sown in the experimental field with a north-south length of 700 m and a west-east width of 300 m on May 3 2008 and April 21 2009, and harvested on September 25 2008 and September 28 2009. Plastic film was mulched with the width of 100 cm and bare soil of 65 cm between two plastic films. Maize was sown in hole of 5.0 cm diameter under plastic film, with a row spacing of 50 cm and a plant spacing of 23.8 cm, so the planting density was approximately 76,300 plants ha^{-1}. Actual mulching fraction was about 0.5 for the two years. The experimental soil is light sandy loam texture, with a dry bulk density of 1.45 g cm^{-3}, field capacity (θ_F) of 0.32 cm^3 cm^{-3} and wilting point (θ_W) of 0.10 cm^3 cm^{-3} at the 0–100 cm layer. The irrigation regime and crop management are listed in Table 1. The different growing stages were divided by our local visual observations of maize development characteristics and phenology, combined with changes of maize height and leaf area (Allen et al., 1998; Xu et al., 2002).

2.2. Evapotranspiration measurements

Evapotranspiration was measured using an eddy covariance system, which was installed in the center of maize field. The eddy covariance (EC) system consists of a fast response 3D sonic anemometer, a Krypton hygrometer and a temperature and humidity sensor. The sensors were installed at a 3.5 m height above ground level. Net radiation (R_n) was measured by a net radiometer which was installed at a height of 3.5 m. Two soil heat fluxes were installed below 8.0 cm soil depth under the plastic film and the bare soil, respectively. Temperature above the soil heat flux plates was measured with thermocouples at depths of 2.0 cm and 6.0 cm in line with each soil heat flux plate, and soil moisture at 0–10.0 cm was measured by an EnviroSMART soil moisture reflectometer. Surface soil heat flux is estimated by correcting the heat flux at 8.0 cm for heat storage above the transducers; the storage above 8.0 cm is determined from changes in soil temperature and volumetric moisture content above the heat flux transducers. The instrumentation and fluxes correction was described in Ding et al. (2010).

Soil evaporation (E_s) was measured by micro-lysimeters in 2009 (Ritchie, 1972). Eight micro-lysimeters cylinders, made from PVC tubes with a diameter of 10 cm and height of 20 cm, were installed within bare soil between two plastic films. The cylinders were weighted in the evening every day by the electric scale with the precision of 0.1 g. The micro-lysimeters were reinstalled within one day after each irrigation and heavy rain.

2.3. Other measurements

Solar radiation, precipitation, air temperature, relative humidity and wind speed were measured with a standard automatic weather station at a height of 2.0 m above the ground. Volumetric soil moisture at root zone (0–100 cm) was measured with eight PVC access tubes at the experimental field using portable device Diviner 2000 (Sentek Pty. Ltd., Australia). Measurements were made at an interval of 10 cm with maximal soil depth of 100 cm at intervals of 3–5 days. Extra samplings were conducted before and after irrigation events, and after rainfall. The measurements were calibrated by oven drying method. Interpolation is applied between consecutive irrigations to determine the θ at each day of the growing season.

Ten maize plants were randomly selected to measure leaf length and width at intervals of approximately 10 days during the growing period. Leaf area was calculated by summing rectangular area of each leaf (product of leaf length and maximum width) multiplied by a factor of 0.74, which was obtained by analyzing the ratio of rectangular area to real area, measured by an AM300 (ADC BioScientific Ltd., UK). Leaf area index (LAI) is defined as maize green leaf area per unit area (Allen et al., 1998). Continuous LAI was obtained by fitting observations with the days after sowing (DAS) using a single equation ($\mathrm{LAI} = a \cdot t^b \exp(-r \cdot t)$, where t is DAS, r is rate of LAI change with the value of 0.077 d^{-1}, a and b are fitted coefficients) (Hashimoto, 1990).

Maize leaf chlorophyll content (C_c) was measured by SPAD-502 meter (Konica Minolta Optics, Inc., Japan). SPAD readings, which are relative values of chlorophyll content and dimensionless, were taken three times during the growing season in 2009, at the shooting stage (June 30), filling stage (August 20), and maturity stage