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Modeling sprinkler efficiency with consideration of microclimate modification effects

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ABSTRACT

Irrigation efficiency is an important consideration for selecting a suitable irrigation method in arid and semiarid regions. Crop canopy interception and wind drift may reduce sprinkler efficiency. However, the evapotranspiration suppression resulting from temperature reduction and humidity increase in sprinkler-irrigated fields versus non-irrigated fields, defined as microclimate modification in this article, imposed a positive effect on sprinkler efficiency. In this study, a sprinkler efficiency model based on the Cupid program was proposed for considering the effects of microclimate modification. The air temperature, relative humidity, plant transpiration, soil evaporation and sprinkler efficiency during the irrigation season of corn in the North China Plain were simulated using the model. The results indicated that the microclimate within the sprinkler-irrigated field could be modified during irrigation, and the effects continued for 10–20 h after the application finished. When evapotranspiration suppression was considered, sprinkler efficiency could be improved by 5 percentiles versus non-irrigated fields. A sensitivity analysis of sprinkler efficiency was conducted by classifying the input variables of the model into three categories: constant, hourly and daily variables. It was found that the sprinkler efficiency was only generally sensitive to the leaf thermal emissivity for all constant and daily variables investigated. The sensitivity to hourly variables was greatly dependent upon the specific soil, plant and weather conditions during an irrigation event.

1. Introduction

Irrigation is one of the practices used to increase and stabilize crop yield. The application efficiency plays an important role in selecting a suitable irrigation method in arid and semiarid regions. Sprinkler irrigation supplies water to crops in a manner similar to natural rainfall. Sprinkler water losses are mainly caused by crop canopy interception, wind drift and evaporation. However, these losses can reduce temperature and increase humidity in the fields and consequently suppress plant transpiration and soil evaporation by microclimate modification (Wang et al., 2006; Cavero et al., 2009). McNaughtom (1981) believed that any "savings", or decline, in crop transpiration from the wetted area compared with a non-irrigated field can be subtracted from gross interception losses for a reduced, or net, interception loss. Thompson et al. (1993b) reported that both soil evaporation and crop transpiration reduction led to effective water losses for sprinkler application.

The influence of sprinkler irrigation on evapotranspiration mainly depends on the amount of water intercepted by the crop canopy and the recovery time for the microclimate modification. Different researchers determined the recovery time for different temporal scales. Tolk et al. (1995) determined the transpiration suppression of corn during and after an irrigation event. Thompson et al. (1993b) calculated the effective loss of sprinkler water in a field during the process of irrigation, relative to a non-irrigated field. Liu and Kang (2006) reported that field microclimate modification continued throughout two consecutive sprinkler irrigations intervals. Through measurements of plant transpiration rate and microclimate in fields of winter wheat and corn, Wang et al. (2007) found that temperature and humidity had an approximately similar recovery time. They estimated the net interception loss by crop canopy from the beginning of sprinkler application to the point when the plant transpiration rate increased to the rate in the reference fields receiving surface irrigation. Playán et al. (2005) and Cavero et al. (2009) reported that daytime sprinkler irrigation strongly modified field microclimate during the irrigation and for a short period after the irrigation finished, while this modification was minimal for a nighttime irrigation.

The Cupid package is a comprehensive soil–plant–atmosphere model in which many of the essential physical and physiological

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processes that describe plant–environment interactions had been incorporated. To accomplish the structure of Cupid, the canopy, soil and atmosphere are divided into layers and leaves within each layer are divided into leaf-angle classes. This enables the boundary conditions for the soil and atmosphere to be defined so that profiles of air and soil temperature, relative humidity, leaf temperature, soil water content, intercepted rainfall or irrigation, dew formation and thus leaf wetness duration can be generated from the input information. The input data requirements for the model Cupid include five classes: initial conditions, ambient environment, soil characteristics, plant characteristics and site factors. The measurement of these data can be found in Norman and Campbell (1983). This detailed knowledge of crop energy and water balance produced by Cupid has permitted its applications to micrometeorology (Inclán and Forkel, 1995; Kustas et al., 2007), remote sensing (Huang et al., 2007) and integrated pest management (Norman, 1982). Since combining equations governing water droplet evaporation and droplet ballistics with the Cupid program (Thompson et al., 1993a), Cupid has become a useful tool to estimate the microclimate modification and evapotranspiration suppression from sprinkler irrigation (Thompson et al., 1993b, 1997).

The objectives of this study were to develop a sprinkler efficiency model based on the Cupid program that considers the effects of microclimate modification, to verify the model using the accessible field data of temperature and humidity for sprinkler-irrigated corn and to find parameters that have a relatively important influence on sprinkler efficiency from among a huge number of input variables.

2. Material and methods

2.1. Definition of sprinkler efficiency

Irrigation efficiency ($E1$, %) is defined as the ratio of total water stored in the root zone for plant use (W_s, mm) to the total amount of water applied (I, mm) (Hansen, 1960):

$$E1 = \frac{W_s}{I} \times 100\%. \quad (1)$$

The total water stored in the root zone in the Cupid program included two components. One is the stem flow (S, mm), and the other is the drip-off water (D, mm). The sum of stem flow (S) and the drip-off water (D) is an output parameter for the Cupid program. The stem flow (S) in the Cupid program is determined by

$$S = \sum_{j=2}^{n} f_s(P_j - e_j - p_{\max} \times 2.0 \times df), \quad (2)$$

where n is the total number of sublayers, f_s is the fraction of intercepted application that runs down the stem, P_j (mm) is the intercepted application by sublayer j, e_j (mm) is the evaporated water in sublayer j, $p_{\max}$ (mm) is the maximum effective thickness of water on one side of a leaf and df is the leaf area index for sublayer j.

The drip-off water (D) in the Cupid program is described as

$$D = P_1 + \sum_{j=2}^{n} d_j \times \exp\{-0.5 \times [(j-2) \times df]\}, \quad (3)$$

where d_j (mm) is the drip-off water from sublayer j and P_1 (mm) is the intercepted application by layer between the soil surface and canopy, namely, the part of the application water passing the canopy directly.

The contribution of microclimate modification to sprinkler efficiency was based on the comparison of evapotranspiration between a sprinkler-irrigated field and a non-irrigated field. The Cupid model was able to simulate the evapotranspiration under these two scenarios. Both plant transpiration (T_p, mm) and soil evaporation (E_s, mm) were two of the model outputs. Note that the plant transpiration and soil evaporation in the sprinkler-irrigated field were T_{p1} and E_{s1}, while they were T_{p2} and E_{s2} in the non-irrigated field. The sprinkler efficiency model was defined as

$$E2 = \frac{W_s + (T_{p2} - T_{p1}) + (E_{s2} - E_{s1})}{I} \times 100\% = \frac{W_s + \Delta T_p + \Delta E_s}{I} \times 100\%, \quad (4)$$

where ΔT_p (mm) and ΔE_s (mm) are the plant transpiration suppression and soil evaporation suppression relative to a non-irrigated field, respectively.

Because the air vapor deficit, which is a function of air temperature and humidity, is the main force for plant transpiration and soil evaporation, the calculation duration of the sprinkler efficiency model (t) was selected to span from the beginning of application to the point at which both air temperature and humidity recovered to the contrast level after the irrigation finished (Eq. (5)). To minimize the influence of the time step of the model simulation on the stability of ΔT_p and ΔE_s, the convergence criterion for the calculation duration t(h) was defined as

$$t = \max\{t(\Delta T \geq -0.01), t(\Delta RH \leq 0.01)\}, \quad (5)$$

where ΔT (°C) is the decrease in the air temperature in a sprinkler-irrigated field versus a non-irrigated field, ΔRH (%) is the increasing amount of relative humidity in a sprinkler-irrigated field versus a non-irrigated field, $t(\Delta T \geq -0.01)$ (h) is the time when ΔT is equal to or larger than −0.01 and $t(\Delta RH \leq 0.01)$ (h) is the time when ΔRH is equal to or smaller than 0.01.

2.2. Field experiments

The field experiment was conducted at the Experimental Station of the Agrometeorology Institute, Chinese Academy of Agricultural Science in Beijing, North China Plains (39°48′N, 116°28′E, 31.3 m above sea level) to provide the data related to the input variables and to verify the Cupid model. The experimental area, located in the temperate monsoon climate zone, is in a dry, subhumid region with an annual mean precipitation of 550 mm. The soil was sandy clay loam with a bulk density of 1.3 g/cm^3 and a field capacity of 0.30 cm^3/cm^3. An automated weather station was installed 80 m from the experimental field to measure the hourly ambient environment.

Impact sprinklers (80B2, LEGO Israel) with a nozzle diameter of 4 mm were used for irrigation. The flow rate for an individual sprinkler was 0.8 m^3/h at 0.3 MPa. The nozzle height of the solid-set system was 2.4 m above the soil surface. The entire irrigated plot was 15 × 45 m. Sprinklers were spaced in a square grid of 15 × 15 m. Twenty-seven TDR access tubes were uniformly distributed in the irrigated plot with an equal grid of 5 × 5 m. Normally, the soil–water contents at each access tube from depths of 10–100 cm were measured by time domain reflectometry (TDR) (TRIME-T3, IMKO Germany) with an interval of 10 cm. The initial soil–water contents for each irrigation event were also measured prior to the irrigation event. Irrigation was applied when the average soil–water content within the top 50 cm layers was depleted to approximately 75% of the field capacity. The soil–water content was measured before the sprinkler application and at the same time after the application finished for seven consecutive days.

Summer corn cultivar Zhongnuo No. 1 (*Zea mays* L.) was sown on 24 June with rows 0.6 m apart, with 0.4 m of spacing between plants and harvested on 15 September 2005. A 4 m high mast with three layers of sensors (U23-002, HOBO America) was installed in the