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Simulation of the evaporation of soil water beneath a wheat crop canopy

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ABSTRACT

The evaporation of soil water (E_s) is an important component of the water balance in cropping systems. Although E_s is considered to be non-beneficial (not directly related to crop production), it may indirectly influence water availability for transpiration which is directly related to crop growth and thus yield. Due to the difficulty in measuring E_s, empirical models are usually used, especially Ritchie's two stage model. Ritchie's model assumes that stage 1 evaporation is dependent on radiant energy at the soil surface, and that during stage 2, E_s is independent of radiant energy. During stage 2, the model assumes that E_s is only dependent on soil hydraulic properties, and that cumulative stage 2 E_s is proportional to the square root of time. To evaluate the model, we measured E_s under the canopy of wheat grown on a clay loam soil in Punjab, India, using mini-lysimeters. Soil evaporation during three different potential evaporation (E_o) periods (1.5, 3.0, 6.0 mm d^{-1}) was compared during the 2006–2007 and 2007–2008 wheat seasons. The results suggested that stage 2 E_s was affected by E_o, and cumulative E_s was not described well by a square root of time function. An exponential decay function which describes the decrease in E_s/E_o as a function of a soil dependent constant (b), whose value is directly related to E_o, was developed. Using this function, calculated cumulative E_s for two independent drying periods was close to the observed E_s values with coefficients of determination of 0.82 and 0.95.

1. Introduction

Soil evaporation (E_s) accounts for 30% to 70% of total crop evapotranspiration (ET) in semi-arid regions (Balwinder-Singh et al., 2011b; Cooper et al., 1983). It is an important component of the water balance, particularly in irrigated cropping systems where the soil is frequently subjected to wetting and drying cycles. The movement of water vapour from the soil surface to the atmosphere i.e. E_s is considered to be largely a non-beneficial loss of water, but it may influence transpiration in a number of ways. Directly, E_s reduces the amount of water available to the crop for transpiration, but a more subtle indirect effect is moderation of the canopy atmosphere, influencing both air and canopy temperature and humidifying the air (Leuning et al., 1994). Soil moisture affects ground temperature, which affects vertical air temperature profile, loss of water from the soil surface, and the surface energy balance. Through these direct and indirect effects, E_s reduces the passive water loss from the plants i.e. transpiration, perhaps without affecting total crop ET. Due to this compensation effect, there is a need to understand the interaction between E_s and transpiration as components of ET.

Several approaches have been used to separate E_s from ET (Wallace, 1991). In measuring E_s beneath the crop canopy, researchers normally use mini-lysimeters located between the crop rows (Allen, 1990; Eberbach and Pala, 2005; Yunusa et al., 1993), and ascribe the gravimetric loss of water from these containers to E_s. But, this method is time consuming and labour intensive, and cannot be used to measure evaporation during rainy periods. Therefore, researchers often prefer to model evaporation. Several approaches which require minimal data input have been developed to model E_s (Boesten and Stroosnijder, 1986; Cooper et al., 1983; Ritchie, 1972). The approach of Ritchie (1972) has been used extensively and has been widely incorporated into sophisticated crop growth models such as the DSSAT series and APSIM.

Ritchie's model is based on the concept of Philip (1957) which separates E_s between soil wetting events into two stages. Stage 1 evaporation occurs immediately after soil wetting and is determined by the amount of radiant energy received at the soil/evaporative surface (the 'energy dependent' stage). The amount of evaporation during stage 1 is directly related to the drying potential of the air and is theorised to last until a specified volume of water has evaporated (Ritchie, 1972). In contrast, stage 2

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evaporation is postulated to occur at a rate determined only by soil hydraulic properties (Philip, 1957), and the rate declines as a function of the square root of time (Hillel, 1980; Monteith, 1981; Ritchie, 1972) (the 'falling rate' stage). The total evaporative loss that occurs between wetting events is sum of the two stages. Ritchie's model has previously been described in detail by others (Aydin et al., 2005; Ritchie, 1972; Wallace et al., 1999).

Despite the principles of evaporation being conceptualised, applying the model is more difficult. Several laboratory and field studies have shown that the two stage concept of evaporation does not easily fit the empirically determined data in three ways. (1) The change from the energy dependent to the soil limited stage of evaporation is not abrupt, but occurs gradually, and it has been postulated that during the transition period, evaporation is sensitive to both the drying potential of the air and the hydraulic properties of the soil (Jalota and Prihar, 1991; Yunusa et al., 1994). (2) Stage 1 drying does not always last for an integral number of days and could be less than 1 day in very sandy soils (Eberbach and Pala, 2005; Wallace and Holwill, 1997) or even non-detectable during periods of high evaporation (Johns, 1982), which makes it difficult to define the beginning of stage 2 drying accurately. (3) The assumption of a decline in cumulative stage 2 evaporation as a function of the square root of time (Hillel, 1980; Monteith, 1981; Ritchie, 1972) appears to have little empirical support. Several studies have shown a lack of fit of empirical data to stage 2 evaporation when using the square root of time function (Jalota and Prihar, 1986; Jalota and Prihar, 1991; Prihar et al., 1996; Jackson et al., 1976; Yunusa et al., 1994). Indeed, our inability to match our empirically derived E_s data with APSIM-wheat-simulated data in an allied study (Balwinder-Singh et al., 2011a) led us to the conclusion that some further revision of the concept may be justified. In this manuscript we compare our empirically derived data obtained over several periods of the 2007–2008 winter cropping season, each with characteristically different levels of evaporative demand, to simulated evaporation using the Ritchie model with the particular aim of examining the appropriateness of the stage 2 square root decline function in comparison with an alternative, derived function.

2. Materials and methods

2.1. Soil evaporation

The experimental conditions and the method of measuring E_s are described in detail by Balwinder-Singh et al. (2011b,c). In brief, a replicated field experiment was conducted over two wheat seasons (2006–2007 and 2007–2008) on the experimental farm of Punjab Agricultural University (PAU), Ludhiana (30°56′N, 75°52′E; 247 m above sea level), Punjab, India. The region is characterised by a sub-tropical and semi-arid climate with a hot dry summer (March–June), wet monsoon season (late June–mid September) and a cool, dry winter (December–January). Average annual rainfall is 734 mm (constituting 44% of pan evaporation) of which about 80% is received during the monsoon. Meteorological data, including US Class A pan evaporation (E_o), were collected from the Punjab Agricultural University weather station, located about 1.5 km from the experimental site.

Maximum and minimum temperature and pan evaporation during 2006–2007 and 2007–2008 crop seasons are presented in Fig. 1. The topsoil of the experimental site was clay loam overlying silty clay, with an abrupt change to sandy loam at about 90 cm. Bulk density was 1.50 g cm^{-3} in the topsoil, and there was a hard pan (1.71 g cm^{-3}) at 15–30 cm. The soil was slightly alkaline (pH 7.8–8.3) with low soil organic C content which decreased from (3.7 g C kg^{-1} at 0–15 cm to 2.2 g C kg^{-1} at 15–30 cm). Zero till wheat was sown in early November each year following rice harvest. There were two rice straw mulching treatments (0 and 7.5 t ha^{-1}). Rainfall was supplemented with irrigation (75 mm per event) to replace ET based on cumulative pan evaporation. Throughout each season, soil water content was measured twice weekly in both treatments using a calibrated CPN 2007 hydroprobe (neutron moisture meter).

Soil evaporation below the wheat canopy was measured using mini-lysimeters. Silos were carefully installed between the crop rows immediately after sowing in each of three replicates of the mulched and non-mulched treatments. The purpose of the silos was to provide a location within the crop where evaporation could be regularly measured. Each silo was prepared by excavating a cylindrical hole in the soil using an auger and inserting a PVC cylinder (0.16 m diameter, 0.20 m long) to act as a sleeve to house each mini-lysimeter. Prior to installation, each sleeve was capped at the base, with holes drilled into the cap, to allow for drainage following irrigation or rain.

Each mini-lysimeter consisted of an intact soil core collected in a PVC cylinder 0.20 m long, 0.10 m (outer diameter) with thick walls (2.5 mm). PVC was chosen to minimise heat conduction from the atmosphere to the soil within the core. At each sampling, three cylinders were inserted 0.2 m into the soil, mid-way between the plant rows, in a large buffer area which was managed in exactly the same manner as the respective treatment. The above ground portion of any small weeds that may have been growing in the mini-lysimeters were cut at the soil surface and removed. The mini-lysimeters were carefully removed from the soil so that the soil inside was not disturbed, the bottom was levelled off, the outsides of the cylinders were cleaned and dried, and a clean cap was fitted to the bottom. Each lysimeter was weighed and then placed in a silo in the experimental plot. During the process care was taken to ensure that no damage occurred to the soil surface, nor the mulch layer in the mini-lysimeters, nor the crop surrounding the silos. Over the next five days, each mini-lysimeter was removed from the silo, weighed and returned to the silo. The weighing occurred at the same time each day (around 9 am), using a digital field balance with a resolution of 0.1 g, giving the capacity to resolve evaporation to an accuracy of 0.005 mm. As the soil cores in the mini-lysimeters were not exposed to plant roots, they were replaced with fresh mini-lysimeters after five days so that volumetric water content would be representative of the soil water content in the treatment plot, consistent with the approach of Eberbach and Pala (2005). After five days, the soil was removed from the mini-lysimeters, weighed and dried at 105 °C to determine gravimetric soil water content and bulk density. The soil cores were also changed if rain of more than a few mm occurred because mini-lysimeters can accumulate more water than the actual rainfall amount recorded by rain gauge (Allen, 1990), due to a lack of ability of the lysimeters to drain water.

2.2. Ritchie's model

Stage 1 of Ritchie's model is conceptualised to last for a number of days until a specified amount of water has evaporated (U, stage 1 coefficient). Cumulative soil evaporation during stage 2 is usually expressed as a function of time (Black et al., 1969) and Ritchie (1972) calculated this to be proportional to the square root of time. Soil evaporation in stage 1 and stage 2 can be expressed as below:

$$\sum E_{s1} = \sum_{t=0}^{t1} E_o = \mathrm{U} \quad t < t1 \tag{1}$$

$$\sum E_{s2} = \alpha\sqrt{(t - t1)} \quad t > t1 \tag{2}$$

where, $\sum E_{s1}$ and $\sum E_{s2}$ are the cumulative amounts of E_s in the first and second stages, respectively, t is the number days after the wetting date, $t1$ is the day on which stage 1 evaporation ends, E_o is