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Quantifying and predicting soil water evaporation as influenced by runoff strip lengths and mulch cover

Weldemichael A. Tesfuhuney[a,*], Leon D. Van Rensburg[a], Sue Walker[a,b], James Allemann[a]

[a] Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa
[b] Crops for the Future, The University of Nottingham Malaysia Campus, Semenyih, Malaysia

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ABSTRACT

Soil water evaporation from the cropping surface is a wasteful loss of potentially productive rainwater, thus efficient use of rainwater can help to sustain dryland production. The purpose of this study was to quantify the effect of canopy shading (CS) and mulch levels (ML) on soil water evaporation (*Es*) from each 1 m section of in-field rainwater harvesting (IRWH) and to evaluate the Ritchie (α') and Stroosnijder (β') soil evaporation models on the effect of surface treatments. A microlysimetric method was used to measure *Es* from beneath maize (*Zea mays L.*) canopy for three consecutive drying cycles across the basin and runoff sections of IRWH on fine sandy loam soil of Bainsvlei Kenilworth ecotope. First, main effects of four runoff strip lengths (RSL) and three ML treatments were statistically analysed on the weighted *Es* values. Second, the ML treatments were allocated to the main plots and four levels of CS allocated according to lengths of the runoff sections. Third, cumulative *Es* ($\sum Es$) measurements were used to evaluate empirical equations related to time (α') and potential evaporation (β'). The two models for *Es* were compared by considering the effects of surface treatments. A significantly higher *Es* was observed from a bare (ML0%) treatment compared with either of two mulched treatments *viz.* mulch level 39% and 96% cover (ML39% and ML96%); no significant differences were found between the mulched treatments. The insignificant effect of RSL treatments on *Es* implied the dynamics of spatial distribution of soil water and energy that influenced evaporation were as a result of green mulch or shading cover (CS) on *Es* beneath the canopy. Less suppressive *Es* properties were developed from bare surface and efficient *Es* restriction was found under high mulch and shading cover treatments. The α' and β' values ranged from 2.34 to 4.26 mm d$^{-0.5}$ and from 1.38 to 2.06 mm d$^{-0.5}$, respectively. In all the treatments the simulated $\sum Es$ was underestimated by the Ritchie model and overestimated by the Stroosnijder model. The main effect of shading was due to the dominant effect of energy limited evaporation (stage-1), while the mulched treatments were mainly driven by soil limited stage (stage-2) of evaporation. The Ritchie model performed well to estimate $\sum Es$ from the basin area and the potential Stroosnijder model from the unshaded runoff strips. The microclimate of the cropping system changed according to surface treatments that highly influenced the *Es* losses in IRWH of dryland production.

1. Introduction

The amount of soil water lost to the atmosphere via soil water evaporation (*Es*) from beneath a crop canopy daily as well as during growth stages is highly variable. In dryland environments, soil evaporation accounts for 30–50% of rainfall loss (Cooper et al., 1987; Wallace, 1991), a value that can exceed 50% in sparsely cropped farming systems in semi-arid regions (Allen, 1990). Thus a considerable proportion of the rainwater that could be used for growth and development is lost. This unproductive loss of rainwater can be reduced by a variety of management practices of which mulching practices (Hensley et al., 2000; Botha et al., 2003) and optimum runoff to basin area ratio are most feasible to enhance rainwater harvesting into the root zone (van Rensburg, 2010). IRWH uses the soil surface crusting as an advantage to enhance runoff collected from the runoff strip length to be stored in a 1 m wide basin. The function of the basin area is to stop ex-field runoff to increase infiltration and to store harvested water while runoff is designed to promote in-field runoff and to act as a storage medium for water (van Rensburg, 2010). Addition of mulch on the runoff area decreases in-field runoff to the basin and presumably

* Corresponding author. Tel.: +270514012222; fax: +270514012217.
E-mail addresses: weldit78@yahoo.com, tesfuhuneyw@ufs.co.za (W.A. Tesfuhuney).

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increases infiltration across the runoff area. Thus, reduction of *Es* for improved water use efficiency depends on the length of the runoff strip and degree of much cover on the runoff area. Studies in in-field rainwater harvesting (IRWH) techniques spanning two decades, considered *Es* a major component in the evaluation of different management practices (Hensley et al., 2000; Nhlabathi, 2010; Botha et al., 2012; van Rensburg et al., 2012; Tesfuhuney et al., 2012). However, more investigations concerning the effect of shading ("*green-mulch*") and stover mulch ("*dry-mulch*") in suppressing *Es* are required to improve water management practices.

A number of models have been proposed and developed to estimate evaporation from soils beneath the crop (Ritchie, 1972; Shuttleworth and Wallace, 1985; Boesten and Stroosnijder, 1986). However, their application is limited. Several mechanistic models have also been reported to estimate *Es* using the general flow of water (Rose, 1968; van Bavel and Hillel, 1976). Ritchie (1972) developed a simple functional model to estimate daily *Es* under second stage evaporation, based on the diffusivity theory. This model has been widely used to estimate *Es* because of its validity and simplicity (Shouse et al., 1982; Jury et al., 1991; Yunusa et al., 1994; van Rensburg et al., 2012; Nhlabathi, 2010). Ritchie's model assumes a linear relationship with a zero intercept between cumulative soil evaporation ($\sum Es$) and the square root of time ($t^{0.5}$). The value of the slope (α') characterizes the evaporation process (mm d$^{-0.5}$) and t is time (days) after rainfall. According to modified Ritchie (1972) soil evaporation in stages-1 and 2 can therefore be expressed mathematically as:

$$\sum Es_1 = \sum_{t=0}^{t} Es_0 \quad \text{for } t < t_1 \qquad (1)$$

$$\sum \mathrm{Es}_2 = \alpha'(t)^{0.5} \quad \text{for } t > t_1 \qquad (2)$$

where $\sum Es_1$ and $\sum Es_2$ are the cumulative amount of soil evaporation in the first and second drying stages.

Stroosnijder and Kone (1982) assumed that the first stage of *Es* is equivalent to potential evaporation. Boesten and Stroosnijder (1986) proposed a simple parametric model to estimate daily evaporation by using cumulative actual evaporation during a drying cycle as being directly proportional to the square root of potential evaporation. Boesten and Stroosnijder (1986) used potential evaporation (E_{pot}) to calculate actual *Es* for both evaporation stages, proceeding as follows:

$$\sum Es_1 = \sum E_{\mathrm{pot}} \quad \text{for } \sum E_{pot} < \beta'^2 \text{ or } \sum E_{\mathrm{pot}} = \sum E_1 = \beta'^2 \quad \text{(Stage-1)} \qquad (3)$$

$$\sum \mathrm{Es}_2 = \beta'\left(\sum E_{\mathrm{pot}}\right)^{0.5} \quad \sum E_{\mathrm{pot}} \geq \beta'^2 \quad \text{(Stage-2)} \qquad (4)$$

For this model $\sum Es$ depends on cumulative $\sum E_{\mathrm{pot}}$ not on time. The β' (mm$^{0.5}$) value is an evaporation parameter characteristic of the soil, experimentally determined. This implies that *Es* of each day is directly proportional to the atmospheric evaporative demand of that day, which can have large daily variation during the drying cycle. Accurate estimation and modelling of *Es* are needed, to compare management strategies that minimize water losses and can determine management strategies that conserve water in dryland crop production.

The use of 1:2 m basin to runoff strip length in IRWH has been accepted as standard practice for all ecotopes (Botha et al., 2012). This recommendation was made on tacit knowledge for row width and originated from conventional tillage practices. The strip length was not of much importance in the beginning, because the focus was to introduce the new IRWH technique to farmers east of Bloemfontein, South Africa. Today, IRWH is applied across three South African provinces (Free State, Eastern Cape and Limpopo), all with widely differing climate and soil conditions. Thus, the research question was posed whether the 1:2 m basin to runoff strip length represents optimum water harvesting conditions for crop production in all areas. However, in order to understand the effect of different runoff strip lengths, it was important to quantify and evaluate how the soil water evaporates within different basin to runoff strip lengths.

Another cultural practice of huge importance to restrict *Es* in IRWH, is mulching. Hensley et al. (2000) and Botha et al. (2012) introduced mulching to suppress the high *Es* losses that occurred under dryland practices in semi-arid zones. Subsequent research on the effect of mulching on *Es* in IRWH was also implemented on the standard 1:2 m basin to runoff strip length. The effect of mulch on *Es* is crucial to understanding the broader application of IRWH with different runoff strip lengths. However, quantifying the soil water evaporation rate from a crop field with non-homogenous basin and runoff sections within IRWH is not an easy task, especially over long periods. Empirical models of *Es* can help to understand how the soil surface evaporation from the different sections of the IRWH is affected. Therefore, the purpose of this study was to quantify the effect of canopy shading (CS) and mulch levels (ML) on soil water evaporation (*Es*) from each 1 m section of in-field rainwater harvesting (IRWH) and to evaluate the Ritchie (α') and Stroosnijder (β') soil evaporation models on the effect of surface treatments.

2. Materials and methods

2.1. Ecotope characterization

The Bainsvlei Kenilworth ecotope is characterized by a high annual evaporative demand (2294 mm), with a relatively low and erratic rainfall (528 mm), resulting in a semi-arid climate classification on the aridity index (Middleton and Thomas, 1992). The mean annual minimum and maximum temperatures on Kenilworth are 11.0 °C and 25.5 °C, respectively. Topographically, the experimental plots are located in an area with <1% slope falling Northward. The soil is deep (2 m) reddish brown in colour with a fine sandy loam texture and is classified as a Bainsvlei form according to the Soil Classification Working Group (1991). The layers of this soil are characterized by very low silt content, ranging from 4 to 5.3%, more than 67% sand and clay contents of between 8 and 22%. Crust formation on this soil is lower than that found on clay soils. In the upper 0–0.25 m horizon at suction values of 1, 50 and 1500 kPa the water content found in a decreasing order as 0.350, 0.186 and 0.091 mm^3 mm^{-3}, respectively (Chimungu, 2009).

In general, the soil has excellent water storage capacity and drains freely in the top and the upper subsoil due to its soft plinthic horizon property at 1.5 m depth. This helps the profile to store excess drainage within reach of the crop roots. This type of soil therefore can play a significant role in dryland farming due to its water holding capacity, so allowing plant growth during times when evaporation exceeds rainfall.

2.2. Tillage practice and crop parameters

An IRWH experiment using maize hybrid, DKC 80–30R (medium maturing variety) was conducted at the Kenilworth Experimental Farm (29°01′S, 26°09′E, 1354 m a. s. l.) of the University of the Free State near Bloemfontein in South Africa during the 2007/2008 and 2008/2009 seasons. The plots were prepared by a mouldboard plough and disc in the autumn of 2007 in an E–W direction. Basins