Field validation of empirical functions used to estimate crop water use

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Abstract

Water use (WU) of lucerne crops was measured over a two-year period at Lincoln University (43?38'S, 172?28'E, 11?m?a.m.s.l.) and used to validate empirical methods of estimating soil evaporation (E_S) and crop transpiration demand (E_T demand). The most realistic estimation of E_S was given by a modified form of the Ritchie E_S calculation. Modifications included calculating second stage E_S as a function of accumulated Penman potential evapotranspiration (PE) and a crop cover (I/I_o) factor that reduced E_S to account for crop roots drying the soil. Unmodified Ritchie E_S overestimated E_S by >45?mm over a 300?d continuous drying cycle. The product of transpiration efficiency and vapour pressure deficit (E_T_eff*VPD) was variable throughout the season, indicating estimates of E_T demand based on a constant E_T_eff*VPD may be erroneous. However, the seasonal variation of E_T_eff*VPD could be explained by a linear increase (R^2 = 0.81) from 7 to 22?kg?DM?ha^{-1}?mm^{-1}?kPa^{-1} as temperature increased from 7 to 14?C. The E_T_eff*VPD decreased below this relationship in autumn when increased partitioning of DM to roots reduced shoot DM production.

Media summary

Soil evaporation could be accurately estimated from the Ritchie calculation adjusted for potential evapotranspiration and root extraction. Transpiration efficiency*VPD increased with air temperature.

Key words

soil evaporation, transpiration demand, transpiration efficiency, vapour pressure deficit

Introduction

An accurate estimation of crop water use (WU) is vital for simulation of crop growth and soil water dynamics. Crop WU consists of E_S and E_T. Ritchie (1972) presented functions for calculating E_S that consisted of an initial energy limited phase (E_S1) and a second diffusion limited phase (E_S2). Additional improvements have been suggested including calculating E_S2 as a function of PE (rather than time) to improve estimations in a cool climate (Boesten and Stroosnijder 1986). The Ritchie (1972) calculations also fail to account for soil drying by crop roots that decreases E_S (Eastham and Gregory 2000). In spite of suggested improvements it is difficult to accurately measure E_S from an area of crop in a field situation so there are few suitable comparisons of different methods.

Crop E_T is the lessor of supply or demand and E_T demand can be calculated from the product of E_T_eff and VPD (Monteith 1986). This method assumes that an increase in VPD causes a linear increase in E_T with no effect on photosynthesis so the product of E_T_eff and VPD is constant and has been widely adopted because it requires fewer data inputs than alternatives (Meinke et al. 2002). However, recent studies have shown E_T_eff*VPD is not constant (Zhang and Nobel 1996) and simulation models using E_T_eff*VPD to predict E_T demand may be erroneous.

The objectives of this study were to assess methods of calculating E_S and E_T demand by comparing calculations with WU of lucerne measured over two years in the field at Lincoln University, New Zealand.

Materials and Methods

General

Measurements were conducted in two experiments in adjacent fields (Iversen 8 and 9) at the Lincoln University Field Service Centre. Each lucerne field had three replicates of full and nil irrigation treatments and full details of establishment and design were given in Brown (2004). Lucerne crops were rotationally grazed throughout each year. Mean monthly temperature ranged from 6??C in June/July to 17?C in January/February with mean daily solar radiation of 5–23?MJ?m^{-2} and VPD of 0.3-1.3?kPa over the same period. The 00/01 season (I July 2000 – 30 June 2001) had an annual rainfall of 587?mm, 1058?mm PE with 281 and 325?mm of irrigation applied to treatments in I8 and I9 respectively. The 01/02 season (1 July 2001 – 30 June 2002) had an annual rainfall of 785?mm, 943?mm PE with 65 and 220?mm of irrigation applied to treatments in I8 and I9 respectively.

Measurements are reported for a two-year period (1 July 2000 – 30 June 2002). Soil water content was measured at 5–14?d intervals in 22 layers of the soil profile to a depth of 2.3 m at each measurement date. The top layer (0-0.2?m) was measured with a time domain reflectometer and the other 21 layers (0.1?m layers from 0.2–2.3?m) were measured at their mid depth with a neutron probe. Dry matter (DM) production was measured at 7–10?d intervals from a single 0.2?m quadrat. The radiation interception (I/I_o) was recorded at 3–7?d intervals using a LI-COR LAI-2000 canopy analyser.

Data analysis

Soil evaporation was calculated using three methods, full details were given in Brown (2004). Method 1 was Ritchie E_S (Ritchie 1972), which calculated E_S in two phases following rewetting of the soil (Equation 1).

Equation?1 a) $E_S1 = PE * I/I_o$ when $\Sigma E_S \leq U$

b) $E_S2 = \alpha * t^{1/2}$ when $\Sigma E_S > U$

Where t is time (d) since the wetting event, U = 9?mm and α = 4.4?mm $d^{-1/2}$ (Jamieson et al. 1995). Soil evaporation was limited to E_S1 when $E_S2 > E_S1$. Method 2 was the same as Ritchie E_S, but E_S2 was calculated in response to accumulated E_S1 using Equation 2 (Boesten and Stroosnijder 1986):

Equation?2 $E_S2 = \beta * \Sigma E_S1^{1/2}$

Where β = 2.4 $mm^{1/2}$ and is analogous to α in Equation 1b (Brown 2004) and ΣE_S1 is summed from the end of the wetting event. Method 3 was similar to Method 2 but included a $1-I/I_o$ factor, which reduces E_S when water uptake by crop roots (E_T) speeds the drying of the soil and reduces E_S.

Equation?3 $E_S2 = (1-I/I_o) * \beta * \Sigma E_S1^{1/2}$

This is based on the assumption that the fraction of soil drying caused by E_T will increase and E_S decrease in opposing proportions to increasing I/I_o. This reduction is additional to the shading effects of I/I_o on E_S1.

Comparisons of E_S calculations were made in the dryland treatments in $I9_{01/02}$, where rainfall was excluded (using rain-shelters) for 300?d giving an extended period where cumulative errors in E_S calculations could be assessed. The ΣE_S calculated by the three E_S methods was compared with the change in soil water content (ΔSWC), which displayed actual soil water depletion in the top 0.2?m of soil. The lucerne crop was growing during this period so it was assumed that some of the ΔSWC was due to root extraction for E_T and $\Sigma E_S \geq$ ΔSWC indicated an overestimation in E_S.

The E_T_eff was calculated for dryland and irrigated treatments in each regrowth cycle from all field/season combinations by regressing DM accumulation against accumulated E_T (slope = E_T_eff). The E_T_eff values were multiplied by the mean VPD for each regrowth cycle.

Results

Soil evaporation

The measured ΔSWC in the top 0.2?m of soil showed three distinct phases (Figure 1) and these were arbitrarily defined as Periods 1-3. Period 1 was the first regrowth cycle (1 August 2001 – 29 September 2001) when the soil dried rapidly (ΔSWC increased from 0 to 30?mm). All three E_S calculations were less than ΔSWC indicating reasonable E_S predictions during this period. Period 2 was from 30 September 2001 – 1 February 2002 when drying was slower (ΔSWC increased from 30-45?mm). During this period Method 3 gave the most sensible prediction with an E_S of 8?mm. The other two methods predicted E_S > 15?mm. Period 3 was when SWC was stable at 45?mm (1 February 2001 – 12 June 2001) and Method 3 predicted E_S of 5?mm, Method 2 predicted 10?mm and Ritchie E_S predicted 20?mm.

Transpiration efficiency

The E_T_eff*VPD showed a seasonal pattern increasing from ~14?kg?DM?ha^{-1}?mm^{-1}?kPa^{-1} in September to ~22?kg?DM?ha^{-1}?mm^{-1}?kPa^{-1} in January and then decreasing abruptly between February and May (Figure 2a). Data were examined as a function of the mean temperature, which showed (R^2 = 0.81) an increase in E_T_eff*VPD from ~7?kg?DM?ha^{-1}?mm^{-1}?kPa^{-1} at 7??C, to 22?kg?DM?ha^{-1}?mm^{-1}?kPa^{-1} at ~15??C (Figure 2b). Data from regrowth cycles occurring as temperatures decreased during February–May were omitted from the regression because they had a lower E_T_eff*VPD compared with similar temperatures from earlier in the growth season.

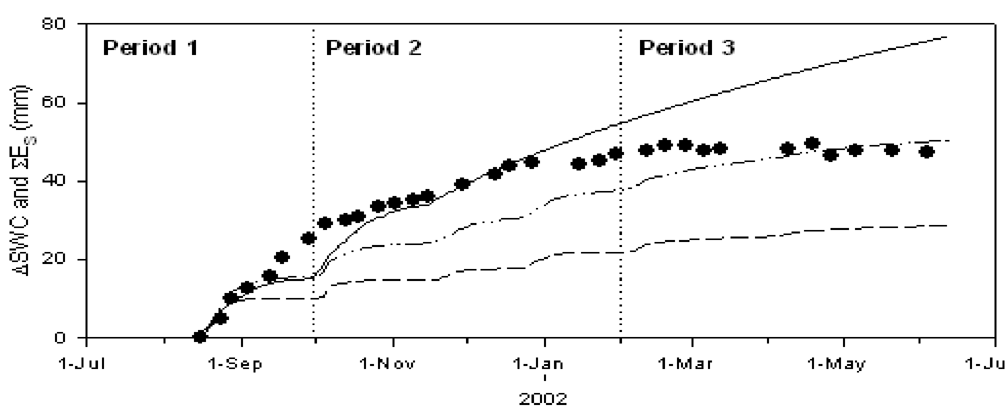

Figure 1. Cumulative Ritchie (——), Method 2 (-?-) Method 3 (--) soil evaporation (ΣE_S) and actual change in soil water content (ΔSWC) from the top 0.2?m of soil (●) for dryland lucerne crops grown under rain-shelters at Lincoln University, Canterbury, New Zealand.

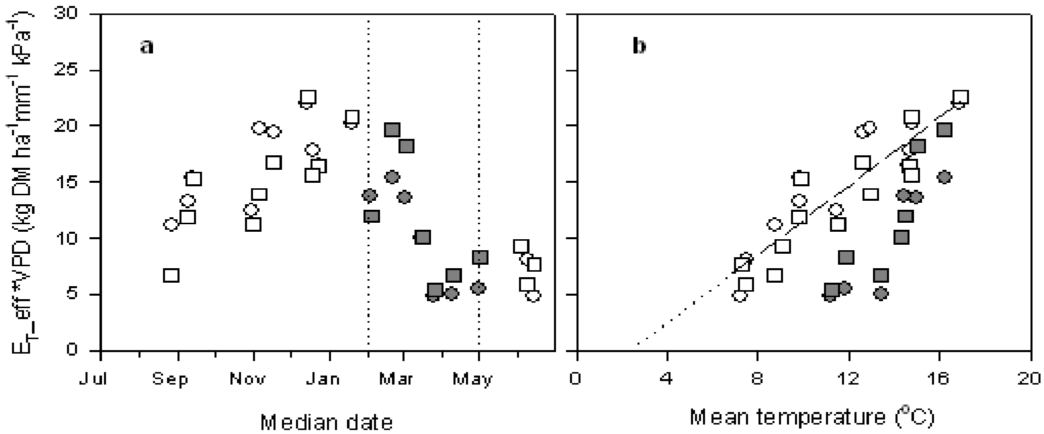

Figure 2. The product of transpiration efficiency (E_T_eff) and vapour pressure deficit (VPD) throughout the growth season (a) and in relation to temperature (b) for dryland (○●) and irrigated (□■) lucerne crops grown at Lincoln University, New Zealand from 1 July 2000 – 30 June 2002. Grey points are those that occurred between 1 February and 1 May which were omitted from the regression, y=-3.7*(1.82)*+1.5*(0.15)*x.

Discussion

Soil evaporation

Method 3 E_S was the most appropriate for estimating E_S based on the assumption that realistic E_S calculations would always give a ΣE_S less than ΔSWC in the top 0.2?m of soil. Errors in E_S calculations were most evident between 1 October and 30 January, when the Ritchie calculation overestimated E_S by more that 25?mm. These errors would have an important influence on WU calculations in sparse crops and perennial forages that are frequently defoliated.

Two reasons were identified for the overestimations by Ritchie E_S. Firstly, E_S2 was calculated in relation to time, assuming diffusion decreases as the soil dries and limits E_S. However, diffusion from the soil is also dependent on temperature gradients in the soil, which may reduce diffusion in cool climates (Boesten and Stroosnijder 1986). This error was corrected by calculating E_S2 as a function of PE (i.e. E_S1) and Method 2 demonstrated the improvement this adjustment made (Figure 1). The second error in Ritchie E_S was the failure to account for drying of the topsoil by crop root extraction (Eastham and Gregory 2000). Method 3 E_S included a factor to reduce E_S to account for E_T drying the soil (Equation 3) and its influence on E_S calculations can be seen by comparing with Method 2. The I/I_o factor is an empirical adjustment that assumes soil drying by roots will increase in proportion to increased canopy cover.

Transpiration efficiency

The product of E_T_eff and VPD was not stable throughout the season (Figure 2a) indicating a single E_T_eff would not give reliable calculations of E_T demand. Some of the seasonal variability in E_T_eff*VPD could be attributed to changes in temperature (Figure 2b) and a temperature response may be used to improve predictions of E_T demand using E_T_eff*VPD. This temperature response may be caused by changes in the ratio of internal leaf to atmosphere CO_2 concentration (Monteith 1988). The effects of temperature on C_i/C_a are recognised in the adjustment of RUE for temperature (Sands 1996) and the link between RUE and E_T_eff has been recognised (Sadras et al. 1991). However, the influence of temperature on E_T_eff has not previously been quantified. The temperature response of E_T_eff*VPD may also be caused by a non-linear response of E_T to increased VPD which generally increases with temperature.

The period in the autumn where E_T_eff*VPD was lower than for similar temperatures at other times of the year (Figure 2b) was likely to have been caused by a change in the partitioning behaviour of the crop. This coincided with the period when the crop was allocating a higher proportion of its DM production to the roots and crowns (Brown 2004) but this was not accounted for in E_T_eff calculations (above ground biomass only). The seasonal decline in E_T_eff is well documented for lucerne (Smeal et al. 1991) and is an additional factor that needs to be considered in the study of perennial crops.

Conclusions

This study provided useful field scale validation of empirical functions used to predict E_S and E_T demand.

- The Ritchie calculation overestimated E_S but predictions could be improved by calculating E_S2 as a function of E_S1 and including a factor to account for soil drying by crop E_T.
- The product of lucerne E_T_eff and VPD was not constant and increased from 7 to 22?kg?DM?ha^{-1}?mm^{-1}?kPa^{-1} as temperatue increased from 7 to 15??C with variation from this relationship in autumn.

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