An alternative method for simulating crop water use

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Abstract

An alternative to current methods of predicting transpiration (T) is to predict it as a factorial function of intercepted radiation (R_i) and daytime vapour pressure deficit (VPD'). The aim of this paper was to quantify the transpiration coefficient (Θ_T) and to validate potential of this factorial coefficient (FC) approach to simulate T from a lucerne crop in New Zealand. Observations from dryland and irrigated treatments of two experiments recorded throughout two years were used to quantify Θ_T. Transpiration showed a strong linear relationship with both R_i and VPD' and gave a Θ_T of 0.47?mm MJ^{-1} m^{-2} kPa^{-1}. Observations of T from another three years of measurement were used to validate simulations of T using the FC method compared with predictions made using the transpiration efficiency (TE) method. The FC method gave accurate predictions of T, whereas TE underestimated T. The RMSD was also lower for FC predictions showing this method is a suitable alternative for simulating crop water use.

Keywords

Transpiration, Radiation, Vapor pressure deficit, Transpiration efficiency, Lucerne, *Medicago Sativa* L.

Introduction

Transpiration (T) of well watered crops is often simulated using the transpiration efficiency (TE) method (Wang *et al.* 2004) developed by Tanner and Sinclair (1983). Daily T is calculated from the product of the daily growth increment and daytime vapor pressure deficit (VPD'). The first step is to calculate daily biomass production as the product of intercepted radiation (R_i) and a radiation use efficiency (RUE) adjusted for temperature and nitrogen limitations. Biomass production is then multiplied by a constant transpiration efficiency coefficient (ω) and corrected for VPD' to estimate potential T (Equation 1).

Equation 1

$$T = R_i \times RUE \times VPD'/\omega$$

This method is dependant on three assumptions; biomass is linearly related to R_i, T is linearly related to VPD' and T/VPD' is linearly related to biomass production (i.e. TE?VPD' is constant). Thus, it follows that T/VPD' must be linearly related to R_i. A simpler, alternative approach for predicting potential T would be directly from R_i and VPD' using a constant transpiration coefficient (Θ_T, Equation 2).

Equation 2

$$T = \Theta_T \times R_i \times VPD'$$

This is similar to the radiation use efficiency approach of predicting biomass production. It predicts the rate directly from its main environmental drivers in a factorial combination with an empirical coefficient. This direct factorial coefficient (FC) method is simpler than the TE approach and removes the possibility for errors in RUE to be translated into errors in T. It also removes the questionable assumption (Brown *et al.* 2004; Zhang and Nobel 1996) that TE?VPD' is constant. The FC approach assumes that T increases linearly with R_i and VPD' (also implicit in the TE approach) and needs to be validated. Thus, the objective of this paper is to quantify the relationship of T with R_i and VPD' for lucerne crops grown in New Zealand and validate predictions of T using the FC method compared with those predicted using the TE method.

Materials and methods

This research is based on data collected from two experiments conducted in adjacent paddocks (Iversen 8 and 9) at Lincoln University, Canterbury, New Zealand. Both experiments were randomised complete blocks with three replicates of dryland (unirrigated) and fully irrigated treatments. The experiment in Iversen 8 (I8) was sown on 30 November of 1996 and measurements were made from 1 July 1997–30 June 2002. The experiment in Iversen 9 (I9) was established on 24 October 2000 and measurements made from then until 30 June 2002. Both experiments were grazed with sheep and had 6–7 regrowth periods per year. Defoliations occurred prior to or soon after lucerne began to flower. Irrigation was applied to ensure the soil water deficit in the top 2.3 m of soil did not exceed 200?mm in irrigated treatments. Further details on the establishment and management of this experiment were given by Brown *et al.* (2005).

Volumetric soil water content (VWC) was measured at 5–20?d intervals throughout the duration of both experiments. Measurements in the top 0.2?m were made with a TDR and below that with a neutron probe at 0.1?m intervals from 0.2–2.3?m depth. Dry matter production was measured at 7–14?d intervals throughout by cutting a 0.2?m^2 quadrat to crown level. Fractional radiation interception (R_i/R_o) was measured at 5–10?d intervals between 1 July 2000 and 30 June 2002 using a canopy analyser and estimated from its relationship with standing biomass (Brown *et al.* 2006) in the 1997-98, 1998-99 and 1999-00 years. T was calculated throughout each experiment as WU less E. WU was calculated from a soil moisture balance (Brown *et al.* 2005) and E was calculated as the product of WU from the top 0.2?m of soil and 1- R_i/R_o.

Data from the 2000-01 and 2001-02 years from I8 and I9 were used to quantify Θ_T and TE. Data from the 1997-98, 1998-99 and 1999-00 years from I8 were used as observations to validate simulations of T from the TE (Equation 1) and FC (Equation 2) methods. The TE method used measured DM production (in place of R_i?RUE) to remove the possibility of errors in simulating biomass production giving errors in T and confounding comparisons. Residual mean square deviations (RMSD) were calculated for each method by comparing mean daily predicted and observed T within each measurement period (n = 49) of the three validation years.

Results and Discussion

Transpiration

There was a strong ($R^2 > 0.90$) linear relationship between accumulated T and R_i in all regrowth periods measured in I8 and I9 in 2000-01 and 2001-02. Examples of these relationships are presented in Figure 1 for a year when dryland crops were rain-sheltered and experienced increasing water stress as time progressed. The linear relationship between T and R_i occurs because radiation provides the energy for evaporation of water within the leaf and stimulates stomatal opening (Jarvis and Morison 1981). Overall the dryland and irrigated crops intercepted a similar amount of radiation but the relative difference in the slope of the relationships between T and R_i (T/R_i) increased in subsequent regrowth periods as water stress increased.

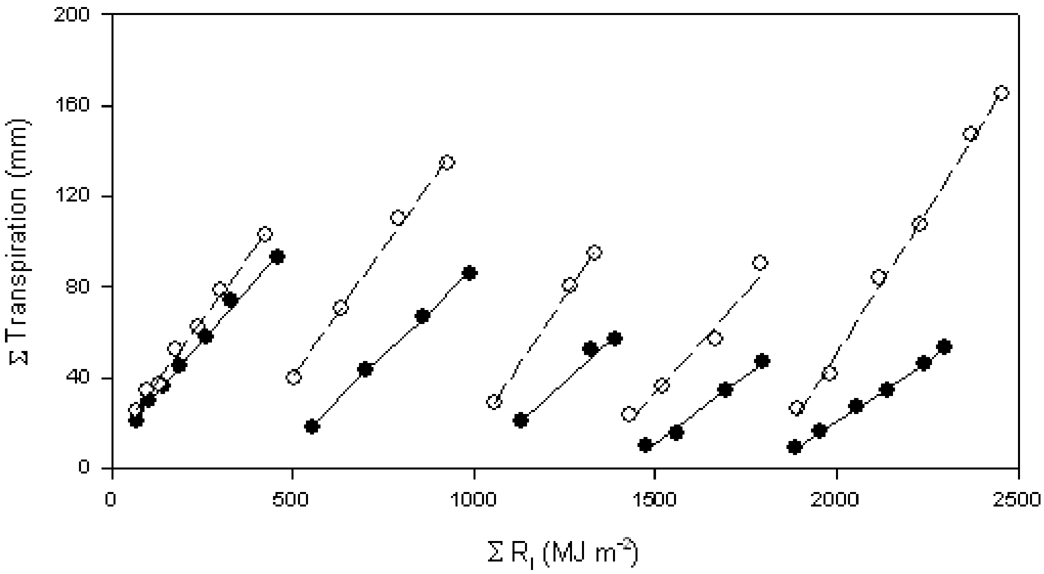

Figure 1. Transpiration accumulated within regrowth periods against accumulated intercepted radiation (R_i) for irrigated (open) and dryland (closed) lucerne crops grown from 1 July 2001 – 30 June 2002 in Iversen 9 at Lincoln University, Canterbury, New Zealand.

The T/R_i of the irrigated treatments varied between 0.12 and 0.31?mm MJ^{-1} m^{-2} throughout the two years of measurement. This variation was explained by a linear relationship (R^2 = 0.71, 18df) between T/R_i and VPD' (Figure 2a). The intercept of the regression (Figure 2a) was not different to zero and the slope (0.47 mm MJ^{-1} m^{-2} kPa^{-1}) represents Θ_T for lucerne. The strong dependency of T on R_i (Figure 1) and VPD' (Figure 2a) suggests the FC approach will give accurate predictions of T when the crop is not water limited.

Some of the T/R_i values from the dryland treatments fitted onto the same relationship as the irrigated treatments but most had a lower T/R_i at any given VPD' (Figure 2a). The T/R_i of dryland crops relative to irrigated crops in the same regrowth period (D/I) showed an exponential decline as the fraction of volumetric water content (FVWC) in the top 1.8?m of soil decreased (Figure 2b). This suggests that root water extraction became limited as the soil dried, reducing T below the potential as indicated by irrigated treatments. Thus, it will be necessary to limit T to the minimum of the predicted potential and the supply predicted from a soil extraction module, to accurately simulate T in water limited situations.

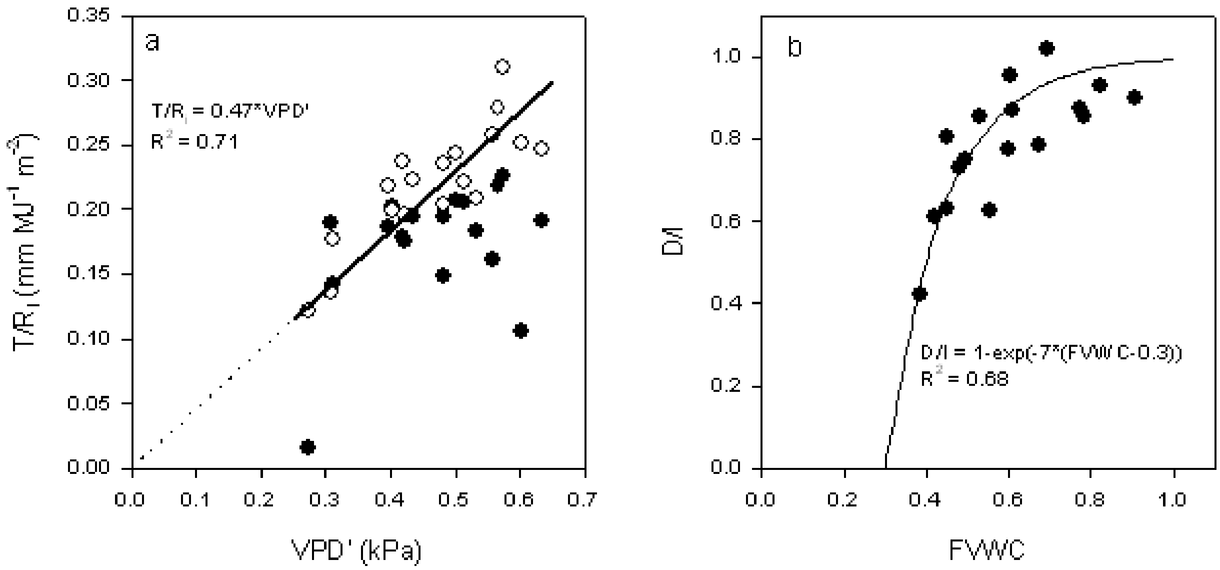

Figure 2. a) Transpiration per unit of intercepted radiation (T/R_i) of irrigated (open symbols) and dryland (closed) lucerne crops in relation to daylight averaged vapour pressure deficit (VPD'). b) Transpiration coefficient of dryland crops relative to irrigated crops (D/I) in relation to fractional volumetric water content in the top 1.8?m of soil (FVWC). Data are from I8 and I9 in the 2000-01 and 2001-02 years.

Validation

T was simulated using Equation 2 and a Θ_T of 0.47?mm MJ^{-1} m^{-2} kPa^{-1}. It was also simulated using the TE method (Equation 1) with a ω of 5.0?g m^{-2} mm kPa (Dolling *et al.* 2005). Both methods predict potential T so simulated T was set as the minimum of the predicted values and the potential water extraction predicted by a water extraction model (Brown, unpublished). Briefly, the soil was split into 6 layers (0-0.2, 0.2-0.5, 0.5-0.9, 0.9-1.3, 1.3-1.8 and 1.8-2.3?m) and potential water extraction was the sum of potential extraction in all layers. Potential daily water extraction in each layer decreased exponentially as FAWC decreased. For example, potential water extraction in the 0-0.2?m soil layer decreased from 1.7?to 1.5 to 0 mm d^{-1} as the FAWC decreased from 1 to 0.65 to 0.3 (lower limit), respectively.

The FC method gave predictions close to observed values in dryland and irrigated treatments in all three validation years (Figure 3) with a residual of 0.04 mm d^{-1} and an RMSD 28% of the observed mean (Table 1). This shows the FC method was suitable for predicting the T of lucerne in New Zealand. The FC method uses standard environmental variables so it should also be suitable for predicting T of lucerne in other environments. It can be adapted to predict T of other crops by determining the appropriate values for Θ_T for the concerned crop. By contrast the TE method consistently under-estimated T in all years and treatments with a residual of -1.41 mm d^{-1}. The actual ω of lucerne measured in the 2000/01 and 2001/02 years (1.6?g?m^{-2} mm kPa) was substantially lower than the 5?g?m^{-2} mm kPa used by Dolling *et al.* (2005) to predict lucerne transpiration in Australia. This explains the large discrepancy between predicted and observed values but also shows that TE?VPD' is not constant. This is consistent with other authors (Jamieson *et al.* 1998; Zhang and Nobel 1996) and suggests this assumption of the TE method is incorrect. Simulating T using a ω of 1.6 g m^{-2} mm kPa improved predictions but the residual and RMSD were still larger than the FC method (Figure 3; Table 1). In actual simulation situations the TE method also depends on predictions of DM production to achieve accurate predictions of T (measured DM was used in simulations in this study) so there is further potential for error in T predictions using the TE method that the FC method is not prone to.

Conclusions

- T was quantified by a linear response to intercepted radiation and VPD' (Θ_T = 0.47 mm MJ^{-1} m^{-2} kPa^{-1}).
- The factorial coefficient approach to simulate crop WU provided an accurate alternative to current methods.
- Analysis indicated ω was neither constant nor 5.0 g m^{-2} mm kPa for lucerne

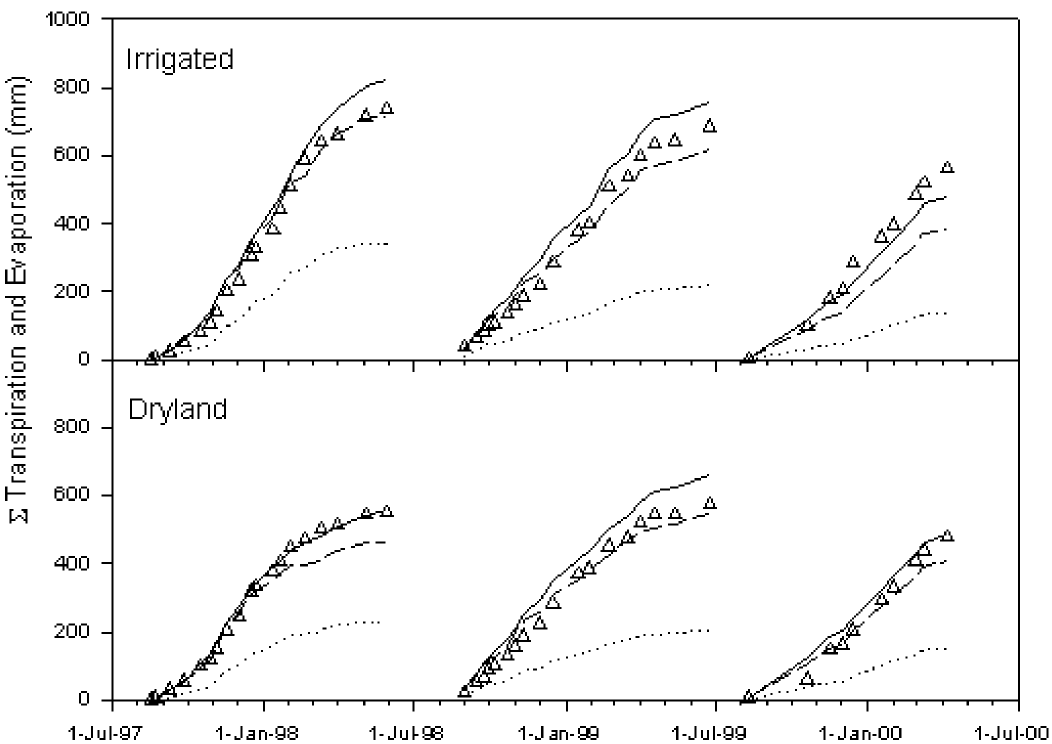

Figure 3. Observed transpiration of lucerne crops (open symbols) compared with transpiration simulated using FC (——) , TE with ω of 5.0 g m^{-2} mm kPa (·········) and TE with ω of 1.6 g m^{-2}mm kPa' (– – –).

Table 1. Residual and residual mean square deviation (RMSD) for daily transpiration of lucerne simulated using factorial coefficient (FC), transpiration efficiency (TE) with a transpiration efficiency coefficient of 1.6 g m^{-2} mm kPa (ω = 1.6) and TE using a ω of 5.0 g m^{-2} mm kPa (ω = 5.0).

		FC		TE (ω = 5.0)		TE (ω = 1.6)	
residual	mm	0.04		-1.41		-0.29	
RMSD	mm (%)*	0.65	(28%)	2.95	(129%)	1.06	(46%)

* Values in parenthesis are RMSD as a percentage of the mean of measured daily transpiration.

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