Water use efficiency of non-irrigated field crops

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Water use efficiency (WUE) is a measure of plant productivity per unit of water used and must be defined relative to the level of biological organisation - leaf, plant, crop or ecosystem - under consideration. Biochemists and plant physiologists have considered WUE primarily in terms of the function of the leaf where net CO_2 uptake and water loss per unit leaf area define a WUE. Reviews of WUE at this level include (1,2), the role of stomata and their interaction with the environment around the leaf have been accorded particular significance (3,4,5). Isolated plants grown in sealed containers have also contributed to the study of WUE (6), particularly the effects of how water is distributed throughout the plant life cycle and here the appropriate measure is usually the plant dry matter produced per unit of water transpired.

At the other end of the scale, farmers and field agronomists are most interested in WUE of individual crops or of farming systems and the most appropriate definitions of WUE may be in terms of total dry matter or grain yield and the net change in water status over the life of a crop. Reviews at this level are less frequent, but three of note are (7,8,9). Here water is lost through surface runoff, drainage and evaporation from the soil in addition to the water actually transpired by the crop. This may be far removed from the assimilation and transpiration of a single leaf, but there is a unifying theme in the linkage of dry matter production and water use.

Over much of Australia, water is considered the limiting environmental resource for crop production and where this is true, an appropriate measure of WUE indicates the efficiency with which an organ or crop or farming system is using the limiting resource. For farmers, WUE may provide a benchmark against which to measure performance whilst for agronomists WUE provides a means of comparison between environments and farming systems.

In this review, I will consider the field measurements of WUE and attempt to show that studies of WUE at the leaf and plant level can be used to validate and extend the results of field measurements of WUE

Field measurement of WUE

Measurements of WUE on crops have invariably used the water balance equation [1] where SW1 and SW2 are initial and final soil moisture profiles, P the rainfall, RO any surface runoff, D deep drainage, SE soil surface evaporation and T the crop transpiration

$$SW1 + P = RO + D + (SE + T) + SW2 \qquad [1]$$

Making the assumption that RO and D are zero, measurements of soil water content at the start and the end of the crop cycle and of precipitation allow estimation of total evapotranspiration (ET = SE + T) as the residual term in the equation.

Since [I] has been widely used to measure WUE in the field, its limitation warrant consideration. Major problems are -

- Because ET is measured by difference, RO and D are generally assumed to be zero. This may be valid, but should not be assumed for all soils and all circumstance. Drainage may be important on coarse textured soils and RO may occur on soils such as red-brown earths where surface sealing may inhibit infiltration. Any errors of measurement are automatically lumped into the ET term.
- Measurement errors may be significant

- The method does not allow easy separation of the two components of the total evapotranspiration, namely the soil evaporation and crop transpiration.

Table 1 presents WUE measurements of field crops in Australia and selected measurements in similar environments overseas. In each case, water use was measured at least at sowing and crop harvest and in many cases at regular intervals through the lifecycle of the crop.

The measurements in Table 1 are of individual experimental crops. A second measure of WUE may be obtained by plotting a series of individual yields versus water use. Such data may come from irrigation experiments where water supply to the crop is an experimental treatment or where other experimental treatments lead to variation in crop growth and water use. Fig. 1 is an example from Griffiths, N.S.W. (22).

Analysed in this way, the slope of the regression line represents the WUE for biomass or for grain, after subtraction of a proportion of the water use represented by the intercept on the x axis. The positive intercept on the water use axis - at which grain yield is zero - has often been taken as a measure of the soil evaporation component of total ET. Other experimental data obtained over years in a single environment (Fig. 2) or even farm yields (Fig. 3) show a remarkable consistency in WUE as the total water use varies although the actual slope and the intercept value appear to vary between the data sets.

Table 1. Water use efficiency for cereal crops in Australia and overseas.

Location	Biomass kg/ha	WUE	Grain kg/ha	WUE	Comment	Reference
Queensland						
Narayan	8200	42.7	3030	15.8	Brigalow grey-brown and red clays, fallowed	10
Biloela			1950	13.4	4 years. Uncertainty about extraction below 120	11
New South Wales						
Wagga	12000	33.8	3330	9.4	Red-brown earth	12
Victoria						
Horsham	3610		3610	14.1		13
Rutherglen	13650	34.5	4624	11.7	Red-brown earth. 1971 trial	14
Rutherglen	14652	49.5	2994	10.1	red-brown earth. 1972 trial	14
South Australia						
Northfield			1808	4.5	Black earth Ug 5.11, fallow	15
Parafield			1709	4.9	Red-brown earth Dr 2.13, fallow	15
Pinery			949	4.5	Deep sand Uc 1.12, fallowed	15
Adelaide			3200	10.7		16
Kimba	12060	37.1	4120	12.7		17
Western Australia						
Wongan Hills	7590	29	3020	12.5	Deep loamy sand Uc 1.12	18
Merredin	6950	42	1955	11.8	Red-brown earth Dr 2.13	18
Merredin	7600	42	2485	13.8	Red-brown earth Dr 2.13	18
Merredin	8290	37	2775	12.4		18
Merredin	8020	39	3085	14.9		18
Syria						
Tel Hadya	10830	29.1	3560	9.6		19
Breda	4940	22.9	2130	9.9		19
United Kingdom						
Rothamsted		33		15.3	Spring wheat	20
Cambridge		36.4		14.8	Spring barley	21

French & Schultz (17) have used the same method to analyse an extensive set of water use and wheat yield data collected from experiments in South Australia between 1964 and 1975. This data, collected from many locations is much more variable than the more restricted sets presented in Figs 2 & 3. French & Schultz interpret their results by stating '----we have drawn an arbitrary line which encloses almost all the highest yielding crops at different levels of water use and thereby defines a linear relationship between potential yield and water use. The spread of data below this line indicates sites where yield was limited by factors such as extremes of temperature, agronomic deficiencies, the effect of pests and diseases and possibly soil erosion'.

The slope of the potential WUE line is 20 kg/ grain/mm of water use above an intercept value of about 110 mm. Both of these are greater than values in Figs 1-3 and although the authors extend and qualify their analysis, the figures of 20 kg/mm and 110 mm have been widely used in extension material as a means of defining potential yield for cereal crops.

The data presented in Table 1 and Figs 1-4 are all field measurements of WUE. Can theory now help to understand and interpret those measurements and particularly to understand the underlying causes of variation in WUE between environments?

Pathways of vapour and CO_2 movement.

The linkage of dry matter production and water use arises from the shared pathways of water vapour and CO_2 movement between the bulk atmosphere and the sites of CO_2 assimilation in the leaf.

Movement along the pathway occurs in response to differences in vapour of CO_2 concentration and the pathway can be segmented into steps with a concentration difference and associated resistance. Modern theory (4) favours the use of molar fluxes and conductances to analyse vapour and CO_2 movement, however the resistance model is intuitively easier to follow and is adequate in this analysis. For vapour, the major resistances are those at the leaf boundary layer (rb) and the stomatal pore (rs). Movement of CO_2 faces these resistances (r'b and r's) plus a resistance (r'm) associated with its movement in the mesophyll cells to the sites of CO2 assimilation. The stomatal and boundary layer resistances for vapour and CO_2 are not identical, because of differing molecular size but are related by r'= 1.6r (4).

More complex analyses of the diffusion pathways can be developed including aerodynamic and intercellular space resistance and the segmentation of the mesophyll resistance into components representing the biochemical steps in CO2 assimilation.

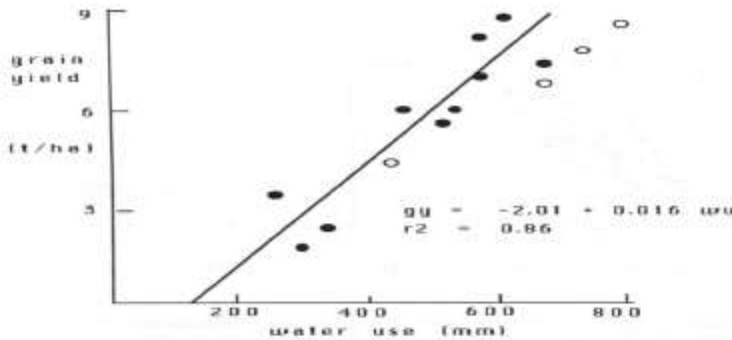


Fig. 1. Grain yield and water use for irrigated wheat
● Griffiths, ○ Leeton. Redrawn from (22).

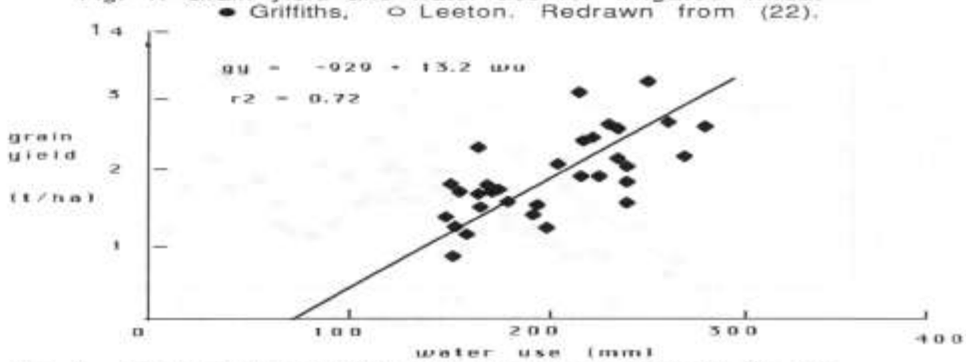
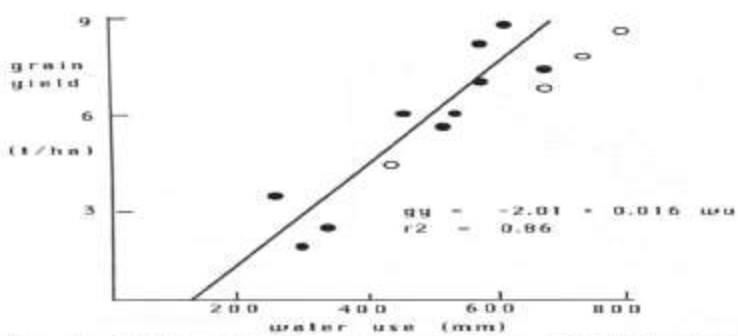


Fig. 2. Grain yield and water use from experiments in the wheatbelt of Western Australia., 1979 - 1985 .



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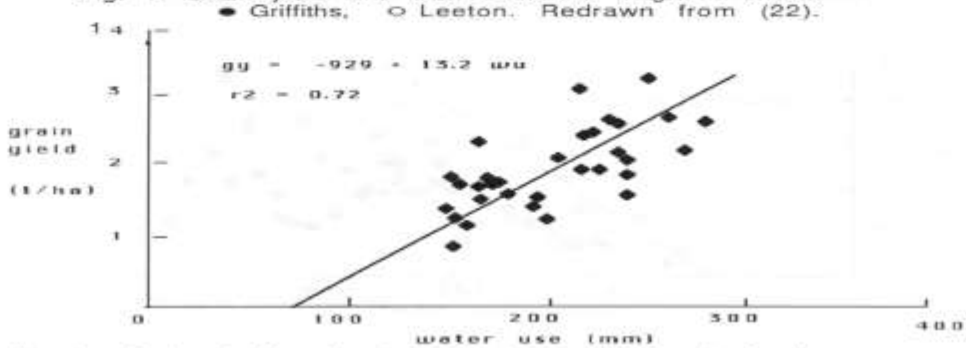

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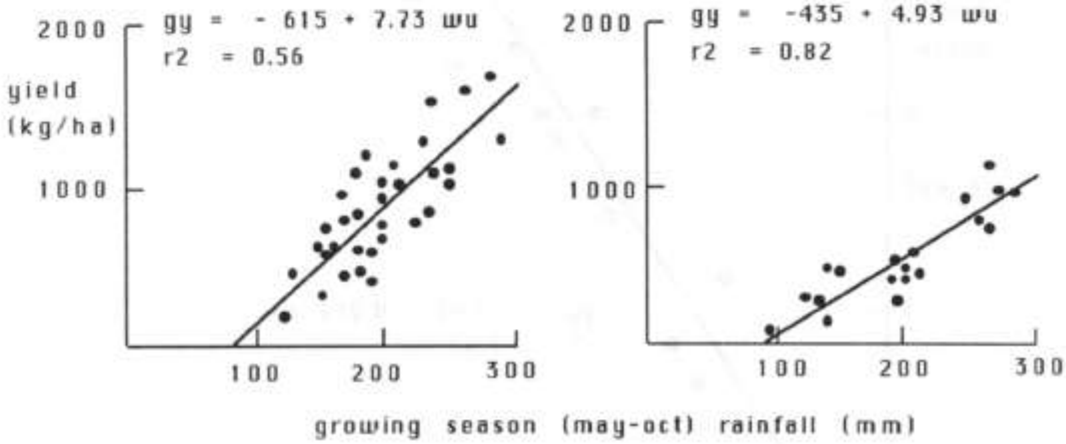

Fig 3. Grain yield and growing season rainfall relationships for (a) Merredin Research Station, W.A. and (b) Kummel property Morawa, W.A. (Data kindly supplied by Mr. N. Fallon).

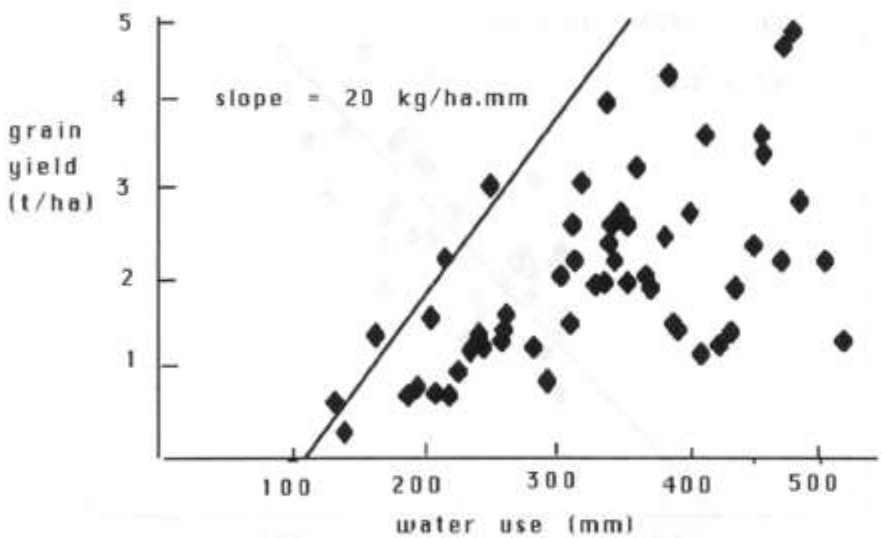

Fig. 4. Grain yield and water use in South Australia. Redrawn from French & Schultz (17).

Bierhuizen & Slatyer (24) formalized the description of the vapour and CO_2 transfer using the equations :

$$N_L = dC / (r'b + r's + r'm) \qquad [2]$$

and

$$T_L = (p\varepsilon/P)\ (e^*L - e)/rb + rs) \qquad [3]$$

where NL and TL are the CO_2 assimilation and transpiration per unit leaf area, dC is the CO_2 concentration difference between bulk air and the compensation point, e*L the saturation vapour pressure (at leaf temperature) and e the vapour pressure of the atmosphere, p the air density, e the ratio of the mole weight of water vapour to air and P the atmospheric pressure. The resistances are as defined previously.

Combining [2] and [3] and taking constant values for P, dC, p and E and by assuming that leaf and air temperature are the same, (i.e. $e^*L = e^*$) gives equation [4].

$$N_L/T_L = [\, k' / (e^*-e) \,]\, [\, (rb + rs)/(r'b + r's + r'm) \,] \qquad [4]$$

Bierhuizen and Slatyer argued that the ratio of the resistance (rb + rs) to (r'b + r's + r'm) would remain relatively constant during the day and that the WUE of the leaf was relatively constant when adjusted for the vapour pressure deficit (VPD) of the atmosphere.

Tanner and Sinclair (25) have shown that [4] can be modified and extended, using simplifying assumptions, to a whole canopy, Their expression for the transpiration efficiency (TE) of a closed canopy is -

$$TE = k/(e^*-e) \qquad [5]$$

where k is a species specific constant and (e*-e) the vapour pressure deficit of the atmosphere for the daylight period during which gas exchange occurs. The limitations and simplifying assumptions of [5] have been discussed (25), but despite these, the equation represents a theoretically based approach to the water use efficiency of field crops. Its major features are -

- k represents a species specific coefficient which may be calculated from theory and which depends primarily on the photosynthetic pathway (C3 or C4 species) and the chemical composition of the crop biomass. The latter is significant because 1 g of primary photosynthate is equivalent to about 0.83 g of carbohydrate, 0.40 g of protein and 0.33 g of lipid (26). Conversion coefficients for seed range from 0.42 for sesame to 0.75 for the grain of temperate cereals (27) depending on the proportions of lipid, protein and carbohydrate in the seed and this is one of the main reasons for

$$TE = m/E_0 \qquad [6]$$

Crop	C_3/C_4	Experimental k (mbar)	Calculated k (mbar)
Zea mays	C4	0.082-0.12	0.118
Sorghum bicolor	C4	0.138	0.118
Medicago sativa	C3	0.043	0.050
Glycine max	C3	0.040	0.035
Triticum aestivum	C3	-	0.051

$$Y/ET = [k/(e^*-e)]\, [1 - SE/ET] \qquad [7]$$

lower seed yield (and WUE) in protein and oilseed crops compared to the temperate cereals.

- (e*-e), the vapour pressure deficit (VPD) represents the influence of environment on WUE. Variations in VPD occur on a daily and on a seasonal basis and will vary between environments.

Equation [5] is similar in form to the empirical relationship deduced from the analysis of data on water use of plants grown in sealed containers (28).

where m is an empirical constant and E0 pan evaporation. The similarity of [5] and [6] is not unexpected, however the later analysis (7) shows that vapour pressure deficit rather than pan evaporation is the sounder normalizing factor and that k has a theoretical basis compared to the empirical 'm'. Reasonable agreement has been found between calculated and measured values of k (Table 2).

Table 2. Measured and calculated values of k in equation [5] for various field crops (25).

Analysing water use of a field crop

Direct application of [5] in the field is difficult because water balance measurements estimate ET not T. Equation [5] may be rewritten for ET as Equation [7] would be useful to us if SE/ET were constant, for example under a perennial crop with good groundcover, however for an annual field crop the ratio SE/ET will clearly vary from close to 0 to close to 1 through the life of the crop. We might also speculate that SE/ET may vary with other factors such as soil type and rainfall pattern. Separation of SE and T thus appears to be a key step in the further understanding of crop water use and WUE.

One approach is to analyse in more detail the patterns of crop growth and water use through the life cycle of a crop. Many of the measurements of WUE (Table 1) come from experiments where dry matter and soil water were measured at intervals from sowing to harvest. One such set of data was collected at Merredin W.A. in 1984 (18). The soil was a red-brown earth and crop dry matter, leaf area and soil profile water were collected fortnightly (Fig. 5). Soil water profiles were also measured on an ajacent unsown, weed free, fallow plot. Moisture profiles confirmed that water did not move below 120 cm and as sowing to harvest rainfall was only 102 mm there was no runoff and all water use was as ET.

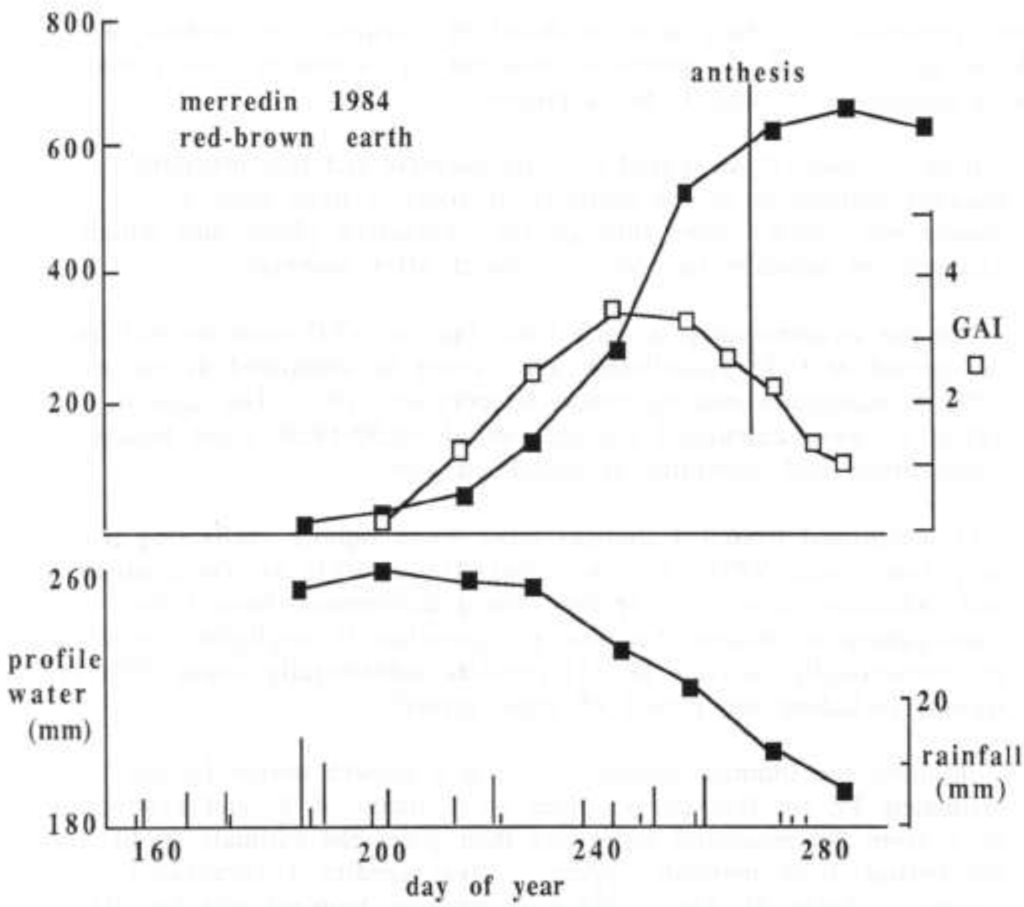

Fig. 5. Crop dry weight, green area index and soil profile water content for a red-brown earth at Merredin, W.A. The crop was sown on 11 June 1984 (day 163) and flowered on 23 September (day 267).

Separating ET into its components requires either direct measurement or estimation of SE or T. Fischer (7) used a relationship between transpiration efficiency and pan evaporation derived from pot experiments at Wagga, N.S.W.

$$TE = 10.2 - 1.3E_{pan} + 0.053\ E_{pan}^2 \quad [8]$$

By dividing a measured biomass increment over a growth period by the TE for the same period, it is possible to estimate T and, by subtraction from total ET, the SE for the period. Equation [5] can be used in exactly the same way.

Table 3 illustrates the calculation of T and SE from the data presented in Fig. 5 and for a similar trial conducted at Wongan Hills, W.A. in 1983 (18).

I have presented this data in some detail to illustrate the method of analysis and some of the problems inherent in estimating rather than directly measuring SE and T. Some points are -

- Both [5] and [7] are based on total biomass and this invariably requires estimation of the quantity of roots. I have used a conversion which varies through the vegetative phase and which assumes no increase in root dry matter after anthesis.
- The pan evaporation is a daily total, but the VPD must be that for the period of CO_2 assimilation and cannot be estimated as the mean VPD at maximum and minimum temperature (29) . The data in Table 3 were calculated for the period 08.30-18.30 from hourly temperature and humidity recorded on site.
- TE calculated from [5] changes much more rapidly reflecting the very low winter VPD's and the rapid rise of VPD as temperature and radiation increase in spring. These differences have little consequence in winter, because transpiration is negligible, however the theoretically derived TE [5] predicts substantially lower TE's in spring, including the period of grain growth.
- dividing the biomass produced during a growth period by the estimated TE for that period gives an estimate of T, and subtraction of T from the measured water use then gives the estimate of SE for the period. Both methods appear to over predict T (bracketed figures in Table 3). This could arise because biomass was too high or because TE was too low. The latter would arise if the measured daytime integral of VPD were higher than the effective VPD when the crop was assimilating carbon. Midday stomatal closure due to lowered leaf water potential (2) or a direct effect of low atmospheric humidity (30) is a possible cause.

Table 3. Calculation of transpiration efficiency (TE), transpiration (T) and soil evaporation (SE).

Date (MERREDIN)	Tops g/m2	Biomass g/m2	Change in Biomass	Epan mm/day	TE (1) g/m2.mm	(e*-e) mbar	TE (2) g/m2.mm	Water Use (mm)	Equation [8] T	Equation [8] SE	Equation [5] T	Equation [5] SE	SE algorithm T	SE algorithm SE
11 Jun-21 Jun				1.92	7.9			8.9		8.9		8.9		8.9
22 Jun-5 Jul	2.8	3.6	3.6	2.28	7.5	3.00	17.0	14.2	0.5	13.7	0.2	14.0	(-1.1)	15.3
6 Jul-19 Jul	9.0	12.6	9.0	2.86	6.9	2.78	18.3	12.6	1.3	11.3	0.5	12.1	(-2.8)	15.4
20 Jul-2 Aug	47.2	70.8	58.2	1.89	7.9	4.28	11.9	8.4	7.3	1.1	4.9	3.5	1.2	7.2
3Aug-16 Aug	138.5	193.9	123.1	1.70	8.1	3.58	14.2	19.4	15.1	4.3	8.6	10.8	13.7	5.7
17 Aug-30 Aug	297.0	386.1	192.1	2.14	7.7	5.03	10.1	31.8	25.1	6.7	18.9	12.9	29.1	2.7
31 Aug-13 Sept	516.0	619.2	233.1	3.10	6.7	7.07	7.2	25.6	34.9	(-9.3)	32.3	(-6.7	21.3	4.3
14 Sep-27 Sep	703.0	773.3	154.1	4.20	5.7	9.43	5.4	26.0	27.2	(-1.2)	28.5	(-2.5	20.7	5.3
28 Sep-11 Oct	764.0	834.3	61.0	4.95	5.1	13.52	3.8	16.6	12.1	4.5	16.2	0.4	12.3	4.3
12 Oct-23 Oct	730.0			8.05	3.2	19.31	2.6	0.6	0.0	0.6	0.0	0.6	(-2.2)	2.8
								164.1	113.0	51.1	100.9	63.2	92.2	71.9

Day of Year	Tops g/m2	Biomass g/m2	Change in Biomass	Epan mm/day	TE (1) g/m2.mm	(e*-e) mbar	TE (2) g/m2.mm	Water Use (mm)	Equation [8] T	Equation [8] SE	Equation [5] T	Equation [5] SE	SE algorithm T	SE algorithm SE
15 Jun- 5 Jul								27.2		27.7		27.7		27.7
6 Jul-19 Jul	4.5	5.8	5.8	2.35	7.4	5.86	8.7	16.2	0.8	15.4	0.7	15.5	(-7.6)	(-8.6)
20 Jul- 3 Aug	14.0	18.2	12.4	2.98	6.8	6.35	8.0	14.7	1.8	12.9	1.5	13.2	(-2.2)	(-16.9)
4 Aug-17 Aug	43.3	64.5	46.3	3.06	6.7	5.89	8.7	21.8	6.9	14.9	5.3	16.5	6.5	15.3
18 Aug-31 Aug	99.5	139.3	93.0	2.52	7.3	3.93	13.0	25.5	12.8	12.7	7.2	18.3	11.1	14.4
1 Sep-14 Sep	228.2	296.7	157.4	3.52	6.3	4.07	7.3	50.2	25.1	25.1	21.7	28.5	36.0	14.2
15 Sep-29 Sep	407.7	489.2	192.5	4.28	5.6	9.51	5.4	50.7	34.3	16.4	35.9	14.8	46.9	3.8
30 Sep-12 Oct	619.0	700.5	211.3	5.56	4.6	13.71	3.7	49.4	45.8	3.6	56.8	(-7.4)	47.1	2.3
13 Oct-26 Oct	737.0	818.5	118.0	7.63	3.4	23.24	2.9	38.8	35.0	3.8	40.5	(-1.7)	32.1	6.7
27 Oct- 9 Nov	767.5	849.0	30.5	8.47	3.0	20.27	2.5	7.7	10.2	(-2.5)	12.1	(-4.4)	3.7	4.0
								302.7	170.2	132.5	168.2	134.5	183.4	119.3

Independent measurement of SE would also allow separation of SE and T. Direct measurement of SE is possible (31) however there remains the problem of integrating instantaneous measurements over a 3-6 month crop life cycle. Two phases of moisture loss are recognised for a bare soil surface (32) . An initial phase after the soil is thoroughly wetted allows evaporation to be determined by the daily energy input and daily SE approximates pan evaporation. A second phase begins when the moisture supply to the surface determines water loss and during this phase the cumulative evaporation increases in proportion to the square root of time.

Crop simulation models have used algorithms to simulate this two phase evaporation and these can be used to estimate soil evaporation under a crop canopy by assuming that 'under canopy' SE is proportional to the radiant energy reaching the soil surface.

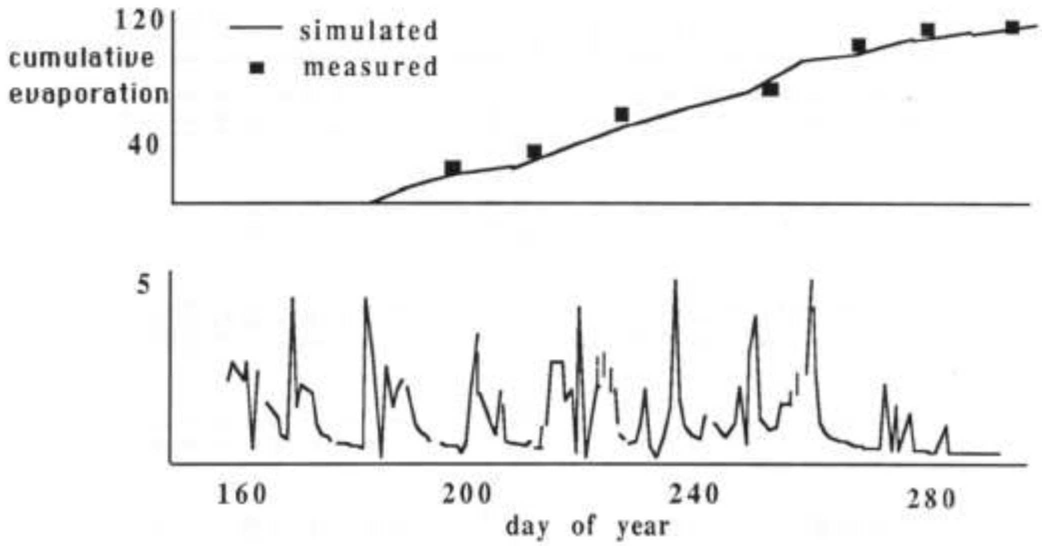

Fig. 6. Simulated daily bare soil evaporation. Simulated cumulative evaporation ,and measured bare plot water use n . simulated daily bare soil evaporation.

I have used one of these algorithms to simulate SE for a bare soil surface (Fig. 6). the algorithm was calibrated by adjusting the coefficients which govern the length of phase 1 and the rate of mositure loss in phase 2 of bare soil evaporation and Fig. 6 shows the simulated daily SE and the cumulative SE with the measured water use from the bare plot. An estimate of SE under the crop was then obatained by reducing bare soil SE by the proportion of radiant energy reaching the ground surface. The latter was calculated as exp(-0.45*GAI) where GAI is the green area index of the crop. Estimates of SE and T (obtained by subtraction of SE from measured water use) are given in the final two columns of Table 3.

Clearly in this case I could have used the measured SE (as was done by (19)),but the simulation procedure has the advantage of generality and can be used to extend the analysis by changing the rainfall patterns or soil properties.

Table 4 summarises the results of the three methods of separating SE and T. Given the uncertainties in each of the methods, there is reasonable agreement that SE was about 60 mm or 40% of water use at Merredin and about 130 mm or 44% at Wongan Hills. Other estimates of SE in Australia include those of Doyle and Fischer (33) who estimated SE values of 73 to 162 mm under a range of experimental treatments at Tamworth. The average SE was 112 mm or 30% of ET. Other estimates are of 27 mm or 14% of ET at Narayan and 162 mm or 35% of ET at Rutherglen (10); and of 60-150 mm (17) depending upon soil type

Table 4. Estimates of transpiration, and soil evaporation (SE) for trials at Merredin and Wongan Hills, W.A.

Method	Merredin T	Merredin SE	Wongan Hills T	Wongan Hills SE
Equation [7]	113.0	51.1 (31%)	170.2	132.5 (44%)
Equation [5]	100.9	63.2 (38%)	168.2	134.5 (44%)
SE algorithm	92.2	71.9 (44%)	183.4	119.3 (39%)
Total Water Use	164.1		302.7	

Partition of water use through the life cycle

Because grain dry matter is mainly formed in the post-anthesis period with only a small contribution from pre-anthesis material, grain yield and thus the WUE (for grain) are largely determined by the post-anthesis water use and the WUE in that period. This, we have seen, is determined by the ambient VPD. Table 5 re-analyses the data of Table 3 to allow calculation of 'potential' grain yield by partitioning the pre-and post-anthesis water use and estimating post-anthesis biomass production from equation [5].

For these trials, post-anthesis water use was 15% and 28% respectively of ET. A ratio of pre- to post-anthesis water use of 2:1 has been suggested where water limits grain yield (34) and a figure of 28% post-anthesis water use is given for both high and low yielding crops in South Australia (17).

Table 5. Calculation of grain yield from post-anthesis water use

Location	Pre-anthesis T (mm)	Post-anthesis T (mm)	Post-anthesis TE (g/m2.mm)	Biomass (g/m2)
Merredin	141	7.4	5.4	40.1
	85%	16.2	3.8	61.6
		675 g/m2 10% =		65.6
				169.2
				(Measured = 195.5)
Wongan Hills	217.3	38.9	3.72	144.7
	72%	38.8	2.19	85.0
		7.7	2.96	22.8
		514 g/m2 10 % =		51.1
				303.6
				(Measured = 300.6)

Calculation of grain yield using [5] and adding 10% of anthesis biomass gave yield estimates quite close to those measured in the field. French and Schultz (17) were unable to relate grain yield to any combination of post-anthesis water use and pan evaporation, but this may have been because they were using evaporation rather that VPD and because they were integrating over the whole period from anthesis to maturity.

Generalization to field measurements of WUE

This analysis, although restricted to only two trials, illustrates how the theoretical basis of WUE can be used to dissect and add meaning to individual experiments. Can we now extend this to a more general analysis of WUE in the field?

Some important conclusions we have drawn are -

- Soil evaporation is a major component of ET and appears to vary greatly both as an absolute amount and as a proportion of Et. This variation is due to differences in soil properties, rainfall distribution and canopy cover.
- The value of the vapour pressure deficit (e*-e) determines WUE on a daily basis.
- The amount of water used post-anthesis is of equal significance because grain yield is largly determined by post-anthesis water use and the ambient VPD.

A first approach can be to model yield based on some simple assumptions.

Model I	Model II
ET variable 160-320 mm	ET variable 160-320mm
SE = 80 mm	SE = 40,42.5,45,47.5 and 50% of ET
Post-anthesis T = 30% of T	Post-anthesis T = 30% of T
(e*-e) = 10,15 or 20 mbar	(e*-e) = 10,15 or 20 mbar

Fig. 7a shows the results for Model I. Here SE is a constant 80 mm and post-anthesis transpiration is assumed to be 30% of total T. The slopes of the three lines represent the WUE's in the different VPD environments, the lines cross the water use axis at 80 mm.

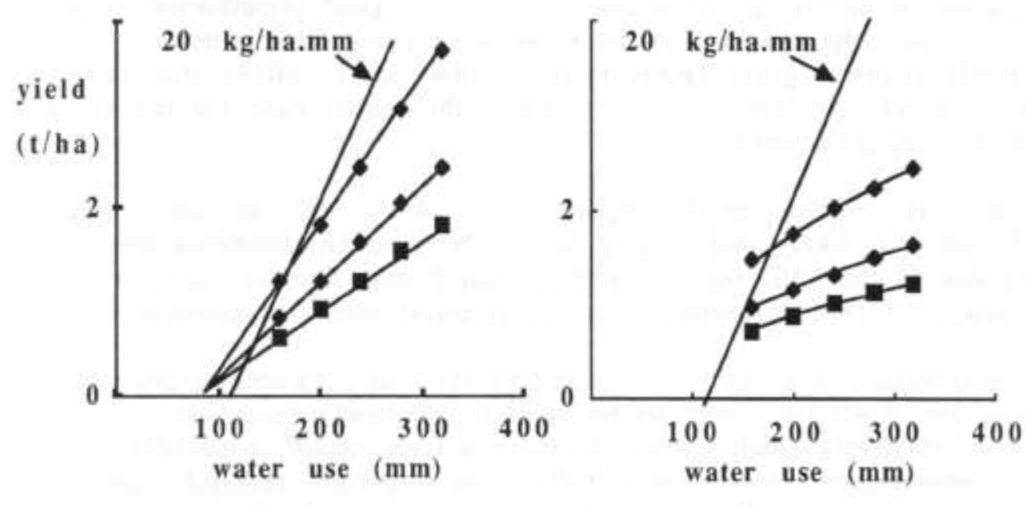

Fig. 7. Predicted yield-water use relationships for Model I and Model II.

An equally naive assumption is that SE increases as a proportion of ET as ET itself increases (Model II). In this case (Fig. 7b) the WUE decreases with increasing water supply. Neither model represents true reality, however the resemblance of Fig. 7a to Figs 1-4 is striking. The different slopes (WUE's) are generated by the differing VPD environments during grain filling. Comparing Figs. 4 and 7, I see the 20 kg/ha.mm 'potential' WUE line as only one of many 'potential' yield lines, albeit one appropriate to an environment with very low VPD and high TE. Where a crop WUE falls below this line it may be because sub-optimal management or detrimental biotic influences (weeds, diseases nutrition etc) reduce yield, or it may be that the best possible yield in that season and at that location was less than 20 kg/ha.mm due to the seasonally determined pattern of water use and TE.

The term 'potential' thus needs careful qualification. I believe that the most appropriate measure against which to judge field crops is not some absolute potential, but the WUE achievable in that environment and that season, and this may be substantially less than 20 kg/ha.mm. The consistent WUE seen in a given environment (Figs 1-3) arises from the consistency of seasonal trends in VPD at a given location whilst grain yield itself varies because of year to year variation in rainfall and therefore in total water supply.

Conclusions

I have attempted to show that water use measurements on field crops in Australia can be interpreted and understood by developing the theory of vapour transfer and CO_2 assimilation of a leaf. The upward integration of knowledge from one level of biological organisation - the leaf - to the crop and then to the level of cropping environments inevitably requires gross approximations, however I believe that the analysis developed here provides a useful theoretical base for the study of WUE and grain yield.

The analysis emphasises the important role of the VPD in determining WUE and it is likely that varying WUE's between environments are largely due to the VPD regimes during grain filling. Greater attention to this aspect of the environment in experimental work is desirable.

Soil evaporation is a major component of the water balance, especially in southern Australia where winter rainfall is often received as frequent, relatively small events. Further analysis of SE, especially direct measurement, would be valuable, as important research topics such as conservation tillage and trash retention modify the soil surface and have the potential to change SE with flow on effects on other components of the water balance.

For grain growers and agricultural scientists, the comparative WUE's in Table 1 are evidence that Australian cereal crops are as efficient in using water as cereal crops in other countries with a technically advanced agriculture. For grain growers, WUE calculations based on growing season rainfall can provide an important benchmark and focus for analysis of their crop enterprise. However, for this to be useful, the analysis of the benchmark 'potential' must be appropriate to that environment taking into account the likely SE given soil type and rainfall pattern, and the VPD regime during grain filling.

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