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Review

Field measurements of bare soil evaporation and crop transpiration, and transpiration efficiency, for rainfed grain crops in Australia – A review

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ABSTRACT

Australian agriculture is dominated by rainfed cropping in environments where evaporative demand greatly exceeds annual rainfall. In this paper we review field measurements of crop transpiration and bare soil evaporation under rainfed grain crops, and crop transpiration efficiencies. Crop transpiration is typically calculated from the difference between evapotranspiration and bare soil evaporation, however, while the former is readily measured, the latter is difficult to obtain. For wheat we found only 19 studies which measured the critical water balance parameters of bare soil evaporation and crop transpiration in Australia, and very many fewer for other crops. From the studies reported for wheat, on average 38% of evapotranspiration was lost to direct soil evaporation. Data for other crops are insufficient to ascertain whether they are similar or different to wheat in terms of the relative contributions of Es and T to the water balance. Although it may have occurred in practice, we can find no field measurements of the crop water balance to demonstrate an increase in crop transpiration at the expense of bare soil evaporation as a function of improvements in agronomic practices in recent decades.

Although it is thought that crop transpiration efficiencies are primarily a function of vapour pressure deficit, transpiration efficiencies reported in the literature vary considerably within crops, even after accounting for vapour pressure deficit. We conclude that more reliable estimates of crop transpiration efficiency would be highly valuable for calculating seasonal transpiration of field grown crops from shoot biomass measurement, and provide an fruitful avenue for exploring water use efficiency of grain crops.

1. Introduction

The majority of grain cropping in Australia is dependent on rainfall for its source of water and occurs in environments where the atmospheric demand for water greatly exceeds annual rainfall. The ratio of annual rainfall to annual open pan evaporation is < 1 over $> 98\%$ of the continent. Grain crop production and improved pastures are confined to areas in the south and east of the country $> 28^\circ$ of latitude (Unkovich et al., 2009) where rain falls during the cooler months and exceeds 25% of the annual evaporation (Nidumolu et al., 2012). The northern fraction of the country where rainfall exceeds 25% of the annual evaporation is a summer rainfall region, with exceptionally high evaporative demand during the wet season (Nix, 1975) and less grain cropping (Unkovich et al., 2009). The potential productivity of agriculture in Australia is thus determined primarily by rainfall, with greater rainfall generally resulting in greater productivity of crops (Fitzpatrick and Nix, 1970; Hutchinson et al., 1992; Nix, 1975; van Rees et al., 2014).

The strong correlation between rainfall and crop productivity in Australia underpins a useful conceptual framework (Fig. 1A), relating crop growth to water use (evapotranspiration, ET), split into evaporation directly from soil (Es) and crop transpiration (T). Graphical representations of this type of crop water use probably first appeared in Arkley (1963) and Hanks et al. (1969), although de Wit (1958) had earlier presented the relationship between transpiration and crop growth. Working in Australia, Doyle and Fischer (1979) plotted water use against dry matter production for rainfed wheat at Tamworth in NSW and suggested that such an approach might prove fruitful for exploring crop production efficiency.

While bare soil evaporation forms part of the total crop water use it is unproductive. Diverting Es to T (moving from point a to b in Fig. 1B) increases crop growth without necessarily increasing ET. Since Fig. 1 defines the X axis as evapotranspiration, rather than rainfall + stored soil water as is often done, drainage and run off can be ignored.

When grain yield is plotted on the Y axis of Fig. 1, the slope of the line should not be considered as a transpiration efficiency alone, but a product of transpiration efficiency for dry matter, flowering capacity and flowering success, grain development and effects of pests, diseases

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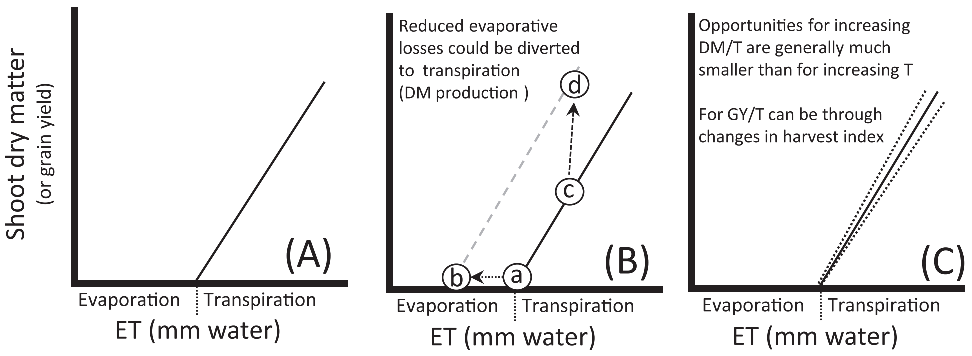

Fig. 1. The relationship between crop dry matter production or grain yield (Y axis) and crop evapotranspiration (X axis) can be represented as in (A), with the slope of the line representing transpiration efficiency. Crop water use efficiency could be improved where soil evaporative losses can be reduced and crop transpiration increased, as illustrated by moving from the solid to broken line in (B). Opportunities for improving the transpiration efficiency, the slope of the line are much more limited (C) but would be apparent where grain yield is plotted on the Y axis and harvesting efficiency or crop harvest index are improved.

and frost on grain weight (see e.g. van Herwaarden and Passioura, 2001), and finally, the effectiveness of grain harvest. Shattering losses during harvesting, particularly for broadleaf crops, can have a significant impact on apparent crop water use efficiency where grain yield is plotted on the Y axis. Therefore to avoid misleading interpretations it is preferable to examine water use in terms of dry matter production. Grain yield efficiency analysis is best conducted after an independent water use efficiency assessment. We thus restrict the present analysis to relationships between crop evapotranspiration and crop shoot dry matter production.

The framework presented in Fig. 1 has been used in many studies examining the productivity of Australian farming systems (see e.g. Oliver et al., 2009; Robertson and Kirkegaard, 2005; Siddique et al., 2001), but the X intercept (Es) and slope (transpiration efficiency) parameters do not appear to have been very well defined, especially for non-cereal crops. Interestingly, the seminal paper on which most of the Australian work has been based (French and Schultz, 1984b), measured neither bare soil evaporation nor transpiration efficiency.

Many excellent reviews have been written about crop water use and water use efficiency in rainfed environments and it is not our purpose to repeat such reviews. Readers are referred to Angus and van Herwaarden (2001), Condon et al. (2002), Cooper and Gregory (1987), Passioura (2006), Sinclair et al. (1984), Turner and Asseng (2005) and Turner (2004). The key elements which emerge from these reviews of the crop water balance in water-limited environments are summarised in Table 1. In this paper we review published field measurements of the partitioning of total seasonal evapotranspiration between bare soil evaporation and crop transpiration, and published values for crop transpiration efficiency in environments relevant to the Australian grain cropping zone. We do not review techniques for estimating total seasonal ET, but assume that, in the absence of drainage and run-off, total seasonal ET can be suitably estimated from the difference between water in the soil at sowing and at harvest, plus in crop rainfall.

2. Separating total seasonal ET into Es and T

Evaporation of water directly from soils can be measured using mini lysimeters (e.g. Eastham and Gregory, 2002; Eberbach and Pala, 2005), but if this technique excludes plant roots and therefore plant water uptake, it is not a direct measure of Es in the presence of a crop. Villalobos and Fereres (1990) developed a perforated mini-lysimeter technique to virtually eliminate this problem. Nevertheless this difficulty typically means that estimates of soil evaporation in the presence of a crop are made using combinations of measurement and modelling (Denmead et al., 1996; Tallec et al., 2012; Young et al., 2008).

In-crop management of well established rainfed crops tends to have only a minor influence on total seasonal ET (Ritchie and Burnett, 1971; Ward et al., 2007), but could effect changes in the ratio between Es and T (Ritchie, 1983). While increasing N application has been shown to lead to greater early vigour, crop transpiration, grain yield and total water use (e.g. Norton and Wachsmann, 2006), this seems to be the exception rather than the rule for winter crops dependent on in-crop rainfall (Unkovich et al., 2010, Cooper et al., 1983).

In Australia, C3 grain crops are primarily sown in late autumn/early

Table 1
Principal factors influencing soil water fluxes (exempla in brackets).

Water availability (Allen et al., 1998; Hamblin et al., 1987; Verburg et al., 2012)	● for rainfed agriculture water supply is the key variable in the crop water balance ● water recently added to the soil will be near the surface and more prone to direct evaporation than water held in deeper soil layers ● small rainfall events are likely to lead to greater evaporation from soil than larger rainfall events
Radiation (Horton et al., 1996)	● radiation determines the potential (demand) for evaporation of water from soils and for transpiration by crops
Vapour pressure deficit (Rawson et al., 1977; Stockle and Kiniry, 1990)	● if the atmosphere already holds a lot of water (high humidity) then the atmospheric (evaporative) demand for water is lower
Soil texture (O'Leary and Connor, 1997)	● finer textured soils are able to store more water, but they hold it more tightly and closer to the surface, leaving it more susceptible to evaporation. It is more difficult for crops to extract water from fine than coarse textured soils ● deep drainage below the crop rooting depth is more likely on coarse textured soils
Soil cover (stubble, mulch) (Hamblin et al., 1987; Lascano and Baumhardt, 1996)	● soil cover increases rainfall infiltration ● soil cover intercepts radiation, reducing soil temperature and direct evaporation (in the short term only)
Crop cover (Ritchie and Burnett, 1971) (Kleeman and Gill, 2010) (Ritchie, 1983)	● crop cover drives water loss through transpiration, reduces both radiation and rainfall reaching soil and thus reduces evaporation directly from soil ● the greater the crop cover (leaf area) the greater is the demand for water by crop roots ● wide row spacing of crops tends to reduce crop cover and increase soil evaporation ● increased heat flux from the bare soil (sensible heat) between rows serves to increase transpiration in wider rows
Tillage (Silburn et al., 2007)	● reduced tillage, in conjunction with crop residue (mulch) management, can increase infiltration of water to the soil, and therefore reduce run off
Early sowing (Anderson, 1992)	● across most of the southern Australian cropping belt earlier development of crop leaf area when surface soils are often wetter, and temperatures lower, might increase transpiration at the expense of soil evaporation (relative to a later sown crop) ● a similar effect may result from high nitrogen fertility

winter, coincident with increasing rainfall and declining temperatures (Nix, 1975). Evaporation of water directly from soil might thus account for a higher fraction of ET earlier in the growing season when surface soils are moist and crop leaf area low (Eastham and Gregory, 2000; Ritchie and Burnett, 1971), and be much lower later in the growing season (late spring) when the soil surface is usually drier and crop leaf area is higher. For soils near or above field capacity, Es may still account for 15% of ET under full canopy cover (Tanner and Sinclair, 1983) but with dry surface soils, transpiration can account for virtually all of the water flux from the soil under full crop canopy cover. While the split between Es and T will be influenced by crop leaf area index and the wetness of the soil, the period of low leaf area index for much of the Australian grain cropping region tends to coincide with the period of low evaporative demand in winter and contributions of both Es and T to the total seasonal water balance at this time tend to be low. Nevertheless, where surface soils have a high water content and there is a low crop leaf area, Es will most likely make up a greater fraction of ET. The depth to which water penetrates the profile can also influence the extent of direct evaporation from soils under a crop (Verburg et al., 2012).

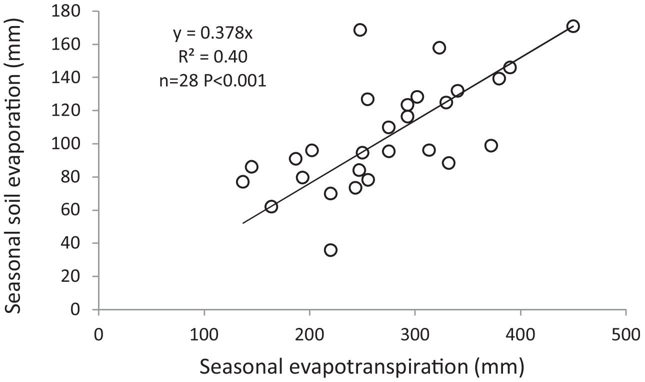

Fig. 2. Correlation between seasonal evaporation from soil and seasonal evapotranspiration for wheat crops in Australia. Data sources are given in Table 2, averaged site x year. The orthogonal least squares regression is forced through the origin since by definition evaporation from soil must be nil when evapotranspiration is nil. Regardless, the analysis indicated that the intercept (27 mm) was not significant (P = 0.15).

2.1. Seasonal soil evaporation estimates for wheat

We searched the literature and compiled published seasonal estimates of the fractional contribution of Es to ET for rainfed wheat crops in Australia (Table 2), each obtained by a combination of field measurement and modelling. We have not included estimates derived wholly from crop simulation modelling. We found only 15 publications reporting a modest total of 28 site x year field estimates of total seasonal Es and T for rainfed wheat crops in Australia. Plotting seasonal evaporation from soil against seasonal evapotranspiration for the data of Table 2, it can be seen that total seasonal ET accounts for 40% of the variance in seasonal evaporation from soil (Fig. 2), indicating that factors other than water supply are also important. The coefficient of variation for the fraction of ET lost as bare soil evaporation (28%) is slightly less than that for the amount of water lost to direct soil evaporation (31%). Thus using a fractional water loss to evaporation across locations and years for Fig. 1 might be marginally more reliable than using a fixed amount.

Some published studies provide Es/ET but not Es and T and hence were not included in Table 2. For example, at Loxton in South Australia, Sadras et al. (2005) found Es/ET for wheat ranged from 0.33–0.59, depending on the extent of soil compaction. Soils which had been ripped tended to have a lower fraction of ET lost as bare soil

Table 2

Field estimates of seasonal evapotranspiration (ET), evaporation from soil (Es) and crop transpiration (T) for rainfed wheat in Australia. ET, Es, T and growing season rainfall (GSR) are provided in mm of water, and year is the year crops were harvested. Values are averaged by site x year x data source.

Location	Year	ET	Es	T	Es/ET	GSR	Source
Bodallin	2000	250	95	156	0.38	230	Simpson and Siddique (1994)
Condobolin	2001	293	117	177	0.40	537	Condon et al. (2002)
Condobolin	2002	244	74	170	0.30	253	López-Castañeda and Richards (1994)
East Beverley	1991	255	127	129	0.50	248	Gregory et al. (1992a)
Lever Gully	1990	248	169	79	0.68	242	Young et al. (2008)
Merredin	1973	202	96	106	0.49	185	Hamblin et al. (1987)
Merredin	1974	164	62	102	0.38	102	Perry (1987)
Merredin	1975	194	80	114	0.41	185	Siddique et al. (1990b)
Merredin	1982	145	86	59	0.59	127	Yunusa et al. (1993) soil 1
Merredin	1984	187	91	96	0.49	127	Yunusa et al. (1993) soil 2
Merredin	1985	275	110	165	0.40	255	Hamblin et al. (1987)
Merredin	1988	256	78	177	0.31	224	Simpson and Siddique (1994)
Merredin	1989	220	70	150	0.33	197	Hamblin et al. (1987)
Moombooldool	1983	293	124	170	0.42	253	López-Castañeda and Richards (1994)
Moombooldool	1985	275	96	180	0.35	241	Condon et al. (1993)
Moombooldool	1991	341	132	209	0.39	373	López-Castañeda and Richards (1994)
Pucawan	1989	330	125	205	0.38	280	Angus and van Herwaarden (2001)
Rudall	1984	137	77	60	0.56	181	Adcock (2006)
Rudall	1989	313	96	217	0.31	301	Adcock (2006)
Rudall	1990	220	36	184	0.16	213	Adcock (2006)
Tamworth	1983	380	139	240	0.37	233	Doyle and Fischer (1979)
Tamworth	1987	372	99	273	0.27	187	Doyle and Fischer (1979)
Tamworth	1998	332	89	244	0.27	139	Doyle and Fischer (1979)
Wagga Wagga	1998	390	146	244	0.38	418	Condon et al. (2002)
Wagga Wagga	2001	323	158	165	0.49	514	Leuning et al. (1994)
Windy Creek	2001	450	171	279	0.38	242	Young et al. (2008)
Wongan Hills	1989	247	84	163	0.34	359	Hamblin et al. (1987
Wongan Hills	1989	302	128	174	0.42	359	Perry (1987)
means		273	106	167	0.40	257	
standard deviation		76	33	60	0.11	107	
minimum		137	36	59	0.16	102	
maximum		450	171	279	0.68	537	
coefficient of variation (%)		28	31	36	28	42	

evaporation, presumably because crop growth (and thus root length, leaf area and T) was improved with deep ripping of soils.

In the studies of French and Schultz (1984a) the authors postulated that 33% of water use might be lost as direct evaporation from soil under wheat crops. From the data of Table 2, where more specific measurements of the crop water balance have been made, a marginally higher average value of 38% of ET as direct soil water evaporation emerges. A Students *t*-test indicates that this value of 0.38 is significantly higher than the 0.33 proposed by French and Schultz. In studies of the water balance of wheat by Adcock (2006) on the Eyre Peninsula South Australia, Es varied from 36 to 102 mm at one location over three years. Clearly the amount of water evaporated from soil under a crop varies widely between locations, and between years within a location.

Since potential ET is much higher than actual ET in the grain cropping regions of Australia it would be anticipated that bare soil evaporation might be strongly correlated with rainfall. However when we plot the growing season rainfall against the bare soil evaporation in the studies of Table 2 we find that rainfall explained only 22% of the variance in soil evaporation from under the crops, much less than for ET. This might be because drainage and runoff are not accounted for and because the frequency and intensity of rainfall events can have a large bearing on soil evaporation (Monzon et al., 2006; Sadras, 2003). Where one uses ET as the measure of water use, these elements can be ignored.

Higher water use efficiencies have been reported for water used from deep in the profile after anthesis if there is no surface soil water available (e.g. Angus et al., 1980; Kirkegaard et al., 2007; Young et al., 2008). This is because evaporation of soil water is slower from deeper soil layers and crop uptake (transpiration) can become the dominant pathway for water loss from depth. In Queensland where winter sown crops are much more dependent on stored soil water than in more southern cropping regions, Es accounted for only 14% of ET (Angus et al., 1980). Interestingly this study, from crops sown in 1972, is the only published measurement of direct soil evaporation under a winter cereal crop that we can find for this region. Although French and Schultz (1984a) suggested that crops grown predominantly on stored soil water, such as the northern grain belt in Queensland, would have lesser fractions of ET lost as Es, we could not find suitable datasets from north eastern Australia to be able to do a comparative analysis between crop water balances in summer, equiseasonal and winter dominant rainfall regions.

We recognise an element of ‘autocorrelation’ in Fig. 2, with soil evaporation inherent in both the X and Y axes. In practice we would expect that as ET declines below values observed in this dataset (150 mm), the slope of the line might change and Es could become an increasing fraction of ET. This is because at very low ET (low rainfall), crops are not able to produce enough leaf area to intercept radiation and therefore crops will grow slower and transpire less. Nevertheless, the slope of the regression in Fig. 2 should provide a convenient scaling for the X axis intercept of Fig. 1A. The slope (0.38) is close to what has been considered typical (0.4) for well managed wheat crops in Australia (Richards, 1991). In an earlier review of water balance research in Western Australia (Hamblin et al., 1987), Es/ET for wheat crops grown in the early 1980’s was reported to range 0.28–0.62, averaging 0.42. These data included only indirect estimates of Es.

Table 3

Field estimates of seasonal evapotranspiration (ET), evaporation from soil (Es) and crop transpiration (T) for rainfed crops other than wheat in Australia. ET, Es and T values are mm, and year is year of crop harvest. Where there is more than one measurement in a year for a single study, values are averaged site x year x data source.

Crop	Location	Year	ET	Es	T	Es/ET	Data source
Barley	East Beverley	1988	251	111	140	0.44	Gregory et al. (1992a)
	Condobolin	1989	239	55	184	0.23	López-Castañeda and Richards (1994)
	Moombooldool	1990	319	112	206	0.35	
	Moombooldool	1989	283	103	179	0.36	
	Bodallin	1998	236	90	146	0.38	Simpson and Siddique (1994)
	Merredin	1998	235	78	156	0.33	
mean						*0. 35*	
Canola	Longerenong	1988	333	104	229	0.31	Norton and Wachsmann (2006)
	Longerenong	1989	302	118	184	0.40	
mean						*0.36*	
Chickpea	Merredin	1982	222	115	106	0.51	Siddique and Sedgley (1987)
	Merredin	1983	186	96	90	0.52	
mean						*0.52*	
Oat	Condobolin	1989	239	70	169	0.29	López-Castañeda and Richards (1994)
	Moombooldool	1990	321	140	181	0.43	
	Moombooldool	1989	272	120	152	0.44	
mean						*0.39*	
Sorghum	Windy Creek	2002	442	194	247	0.44	Young et al. (2008)
Triticale	Condobolin	1989	243	76	167	0.31	López-Castañeda and Richards (1994)
	Moombooldool	1990	318	129	189	0.40	
	Moombooldool	1989	270	120	150	0.44	
mean						*0.39*	

2.2. Seasonal soil evaporation estimates for other crops

Soil water evaporation under a barley crop might be expected to be lower than for wheat, because it develops leaf area more quickly and has a slightly more prostrate habit (higher radiation extinction coefficient), possibly enabling it to fix more carbon early when the vapour pressure deficit (VPD) is lower (Sadras and Rodriguez, 2010). Simpson and Siddique (1994) observed higher apparent water use efficiency of barley than wheat and López-Castañeda and Richards (1994) reported Es for barley to be 5–10% less than for wheat grown under the same conditions. Although Reuter et al. (1996) suggested lower seasonal soil water evaporation under barley (90 mm) than wheat (110 mm) in South Australia and Victoria, they used the same values for both crop species in Western Australian, but no data were provided in support of these crop and region specific differences. From the available data (Table 3) we cannot distinguish barley from wheat in this respect. There are not sufficient data available to be able to repeat the analyses of Fig. 2 for other crops (Table 3).

Thomas and Fukai (1995) compared evaporative losses of water under barley and chickpea crops for part of the growing season in Queensland. In those studies bare soil evaporation during the period of measurement accounted for > 50% of ET in chickpea but generally much less than 30% in barley. The total seasonal water losses to soil evaporation were not given. In studies of debranched chickpea (Siddique and Sedgley, 1987), debranching did not result in reduced dry matter production and a reduction in T and increased Es did not occur. In sunflower there was no difference in Es/ET in different statured crops and Es accounted for about 45% of ET for both fully and partially irrigated crops (Sadras et al., 1991).

There are very few reports for other crops in Australia. In Syria (Zhang et al., 2000), where the cropping environment is very similar to much of the Australian grain belt, soil evaporation under lentil (28%) was lower than that for chickpea (35%) or for wheat. For rainfed wheat in Syria, Es accounted for 40% of crop ET of N fertilised wheat, and 44% for unfertilised wheat (Zhang et al., 1998, averaged across five years).

The studies listed in Tables 2 and 3 are primarily for crops grown before the widespread adoption of conservation tillage, earlier sowing, improved rotations with lower disease loads, and increased nitrogen application (Passioura, 2002). Together these management improvements may have increased the rate of leaf area development and increased crop transpiration relative to evaporation from soil. If this were the case then the fractional contribution of evaporative soil water loss to the crop water balance may have decreased and be less than that described in Fig. 2. However we can find no water balance measurements to assess any such trend. Further work is required to better define the intercept term of Fig. 1, and whether there are significant differences between crop species and or Australian grain producing regions.

3. Transpiration efficiency

Transpiration efficiency is the ratio between net shoot dry matter gain and water transpired by the crop, represented in Fig. 1 as the slope of the line. Gas exchange (CO_2 and H_2O) of leaves can be measured directly using porometry, with results expressed as mmol carbon assimilated per mol H_2O transpired $m^{-2} s^{-1}$. It is effectively a measure of the ratio of stomatal conductance to CO_2 and water vapour. This physiological measure of transpiration efficiency is not very useful at the field scale because fixed C lost to respiration elsewhere in the plant (typically 30–50% of photosynthesis (Amthor, 2010; McCree, 1986)) or allocated to root growth, is not captured in the leaf scale porometry, and scaling up from leaf to canopy across time from such measures requires many assumptions (De Pury and Farquhar, 1997; Hoyaux et al., 2008; Jarvis and McNaughton, 1986).

At the shoot or whole plant level, TE can be measured in pots in the glasshouse (e.g. Armstrong et al., 1994; Condon et al., 1993; Mortlock and Hammer, 2000) or indeed in pots in the field (e.g. Wright et al., 1988). In pots, direct evaporative water loss from the soil can be eliminated, or nearly so, allowing water use to be ascribed to plant transpiration. Net transpiration efficiency is then calculated by dividing shoot or whole plant dry matter by total water use. For the purpose of this paper, TE is expressed as the ratio of net shoot dry matter gain to the amount of water transpired. In Table 4 (cereal crops) and Table 5 (broadleaf crops), we compile published estimates of such values for the principal Australian crops, and the geometric mean values are provided in Table 6.

3.1. *Crop species effects on transpiration efficiency*

Between crop species the biggest difference in TE is between plants with the C4 photosynthetic pathway and those with the C3 photosynthetic pathway, with the latter about 30% lower in TE than C4 species (Howell, 1990). The primary reasons for this are that C4 crops such as sugarcane, sorghum, maize and millet, have both higher photosynthetic rates and lower respiratory losses of CO_2 compared to C3 species (Ludlow, 1985). Loomis and Connor, (1992) give transpiration efficiencies of 73–105 kg/ha/mm for C4 species and 34–55 kg/ha/mm for C3 species, however the data of Table 4 indicates overlap between the ranges of TE's for some C3 and C4 species. Comparison of TE's of C3 and C4 crops needs to be done with care because these crops are often grown in different environments under different atmospheric conditions. Transpiration efficiency is also known to vary as a function of leaf area index (Ehlers, 1991), as interception of radiation by the crop canopy changes the energy and water balance of the system, typically lowering the vapour pressure deficit within the canopy (Tanner and Sinclair, 1983).

In their seminal paper French and Schultz (1984a) estimated TE for wheat crops to range from 16 to 60 kg/ha/mm, and attributed this range to variation in evaporative demand. Their TE estimates varied by more than two fold between sites even after variations in VPD were taken into account. This large variation may have been because their TE estimates were based on an assumed bare soil evaporation of 110 mm (for sites with > 150 mm rain) or 60% of growing season rainfall (for

Table 4
Estimates of transpiration efficiency (kg shoot dry matter/ha/mm water transpired) for cereal crops important in Australia. Most reported values not corrected for VPD.

Species	n	min	max	Mean	Treatments	Data source
Barley	6	42.8	60.0	50.1	N rate x year	Cooper et al. (1983)
	3	43.8	51.1	47.8	three cultivars	Gregory et al. (1992b)
	24	25.8	56.8	42.7	water x cultivar	Hubick and Farquhar (1989)
	2	29.9	46.7	38.3	two years	Kemanian et al. (2005)
	1			53.8		Leuning et al. (1994)
	5	34.6	68.0	51.9	cultivar x year	López-Castañeda and Richards (1994)
Oat	6	39.0	70.0	55.7	year	Ehlers (1989)
	3	39.8	52.8	48.3	cultivar x year	López-Castañeda and Richards (1994)
Triticale	3	48.3	65.5	55.6	cultivar x year	López-Castañeda and Richards (1994)
Wheat	2	36.5	39.1	37.8	water availability	Bolger and Turner (1998)
	11	40.6	61.1	51.9	genotype	Condon et al. (1990)
	2	43.0	43.0	43.0	N rate x year	Cooper et al. (1983)
	6	33.0	49.0	42.2	sow date x year	Doyle and Fischer (1979)
	2	29.3	35.3	32.3	row spacing	Eberbach and Pala (2005)
	1			38.5		Gregory et al. (1992b)
	1			46.0		Hamblin et al. (1987)
	1			55.0		Kirkegaard et al. (2007)
	1			59.0		Leuning et al. (1994)
	6	37.3	62.6	50.1	cultivar x year	López-Castañeda and Richards (1994)
	10	45.0	52.2	48.7	ten cultivars	Matus et al. (1996)
	2	39.0	43.0	41.0	water availability	Meinke et al. (1997)
	1			50.0		Passioura and Angus (2010)
	8	44.7	73.4	60.2	soil compaction	Sadras et al. (2005)
	8	38.6	52.3	46.5	eight cultivars	Siddique et al. (1990b)
	2	52.4	63.0	57.7	site	Tallec et al. (2012)
	2	52.0	73.0	62.5	site	Young et al. (2008)
	2	52.1	55.8	54.0	soil type	Yunusa et al. (1993)
	2	21.7	46.1	38.5	water availability	Zhang et al. (1998)
Maize	1			74.3		Tallec et al. (2012)
	1			71.1		Yu et al. (2004)
Sorghum	1	68.2	68.2	68.2		Hammer et al. (1997)
	17	57.8	90.5	75.9	cultivar	Mortlock and Hammer (2000)
	14	50.0	69.0	58.8	cultivar	Xin et al. (2008)
	1			43.0		Young et al. (2008)

Table 5
Estimates of transpiration efficiency (kg shoot dry matter/ha/mm water transpired) for broad-leafed crops important in Australia.

Species	n	min.	max.	mean	Treatments	Data source
Cotton	1			30.0		Slatyer and Bierhuizen (1964)
Canola	10	39.3	42.7	41.2	ten cultivars	Matus et al. (1996)
Sunflower	5	18.7	24.3	21.5	cultivars x years	Connor et al. (1985)
	6	35.2	49.7	40.7	irrigation x cultivar	Sadras et al. (1991)
	1			42.9		Tallec et al. (2012)
Chickpea	2	18.9	23.3	21.1	sowing season	Cooper and Gregory (1987)
	1			35.0		Kashiwagi et al. (2006)
	2	17.0	25.0	21.0	irrigation	Singh and Sri Rama (1989)
	8	40.4	57.1	49.4	water availability	Zaman-Allah et al. (2011)
Field pea	6	31.0	41.5	35.1	six cultivars	Armstrong et al. (1994)
				34.0		de Wit (1958)
Lentil	10	33.7	42.7	39.2	ten cultivars	Matus et al. (1996)
Soybean	1	43.0	43.0	43.0		Yu et al. (2004)

Table 6
Mean transpiration efficiency (kg shoot dry matter/ha/mm water transpired) for crops from Table 5 and Table 4. Values are not corrected for differences in vapour pressure deficit because this was not generally reported.

Crop	Species	TE
Barley	*Hordeum vulgare*	45.3
Canola	*Brassica napus*	41.2
Chickpea	*Cicer arietinum*	39.5
Cotton	*Gossypium*	30.0
Field pea	*Pisum sativum*	34.5
Lentil	*Lens culinaris*	39.2
Maize	*Zea mays*	72.7
Oat	*Avena sativa*	53.2
Sorghum	*Sorghum bicolor*	67.4
Soybean	*Glycine max*	43.0
Sunflower	*Helianthus annuus*	32.9
Triticale	*Triticosecale*	55.6
Wheat	*Triticum aestivum*	48.7

Table 7
Calculated transpiration efficiency constants (kc) relating transpiration efficiency to vapour pressure deficit. Units resolve to Pascals.

Species	TE constant (kc)	Data source	notes
Chickpea	2.81	Thomas and Fukai (1995)	
Field pea	3.78	Wilson et al. (1985)	
Peanut	3.5	Hammer et al. (1995)	
Soybean	4.0	Tanner and Sinclair (1983)	
Sunflower	4.7, 3.64	Sadras et al. (1991)	
Oat	3.3	Ehlers (1989)	
Wheat	4.7	Meinke et al. (1997)	
	5.2	Young et al. (2008)	field estimate
Barley	6.82	Kemanian et al. (2005)	
Sorghum	13.8	Tanner and Sinclair (1983)	
	8.1	Young et al. (2008)	field estimate
	8.5	Hammer et al. (1997)	
Maize	9.5	Tanner and Sinclair (1983)	
	7.4	Walker (1986)	

sites with < 150 mm rainfall), rather than a measured Es and hence much of the variance in their calculated TE could have been due to variance in Es rather than TE.

In comparative studies of the water balance of old wheat cultivars released between 1860 and 1986 (Siddique et al., 1990b) there was no significant difference in transpiration efficiency between cultivars, but modern cultivars used less water than older cultivars because they grew for a shorter amount of time, and possibly because they also had higher shoot:root ratios (Siddique et al., 1990a). The primary advantages of the later cultivars were more rapid phenological development and increased harvest index. More recent comparative assessments of historical cultivars (1958–2007, Sadras and Lawson, 2011; Sadras and Lawson, 2013; Sadras et al., 2012) demonstrated increased biomass production by post 1982 cultivars, possibly related to increased leaf nitrogen status (Sadras et al., 2012), but there was no evidence for increased transpiration or transpiration efficiency for modern cultivars.

3.2. Transpiration efficiency and vapour pressure deficit

While the concentration of CO_2 in the atmosphere is relatively constant during the life of an annual crop, and therefore also the leaf to air ratio of CO_2, substantial changes occur in the amount of water vapour in the atmosphere and hence also in the ratio of CO_2:H_2O in the atmosphere. Consequently the relative rates of exchange of CO_2 and of H_2O between leaves and the atmosphere vary as a function of the amount of water in the atmosphere. Higher vapour pressure deficit increases the atmospheric demand for water and thus increases plant water loss per unit CO_2 fixed (Forde et al., 1977; Howell, 1990; Pilbeam et al., 1995; Richards, 1991; Stockle and Kiniry, 1990). This means that as the VPD increases, the slope of the line of Fig. 1A also decreases.

Water stress tends to increase TE but not as much as variation in VPD (e.g. Meinke et al., 1997; Mortlock and Hammer, 2000; Rodriguez and Sadras, 2007; Singh and Sri Rama, 1989), although the two are often linked. Across most of the Australian cereal cropping belt VPD is lowest during the early part of the growing season (winter) and then increases rapidly through spring and into early summer when crops are harvested. Greater early crop vigour could thus lead to higher total seasonal TE through the effects of lower VPD early in the life of autumn or winter sown crops. However, it is generally considered that seasonal TE is primarily determined later in the season when leaf area index is higher and the bulk of dry matter accumulation occurs (Tanner and Sinclair, 1983). The effects of VPD on TE are often accounted for using the following equation (Hammer and Muchow, 1994)

$$\mathrm{TE}\ (\mathrm{g\,m^{-2}\,mm^{-1}}) = \mathrm{kc/VPD}\ (\mathrm{kPa})$$

where kc is a crop specific constant, and VPD is mean daylight VPD.

The constant kc provides a means of scaling the leaf to air ratio of water vapour. This is based on the approach of Tanner and Sinclair (1983) which assumed a leaf area index > 3, shaded leaf and air temperatures are the same, a given respiration rate, and the rate of conversion of hexose to plant biomass (Sinclair et al., 1984). We are unsure how critical these assumptions are, however, under Australian conditions leaf area indices often do not exceed 2 during the life of many crops (Sadras et al., 2005, Hamblin et al., 1987). In Table 7 we have compiled published transpiration efficiency constants (kc) for relevant crops. It is somewhat surprising how few estimates have been made.

Only three of the TE values in Tables 4 and 5 were reported to be corrected for VPD. Kemanian et al. (2005) reviewed kc values from studies on barley and wheat. Values for barley ranged from 3.20 to 5.69 and from 3.10 to 7.13 for wheat. Hammer et al. (2010) stated that a kc of 9 for sorghum has been established but these are different to the values reported in Table 7. The use of a fixed crop kc for TE belies substantial variation in the relationship between TE and VPD apparent in the literature and more work is required to establish robust values for the genotypes and growing conditions in Australia. Care should be taken transferring TE values from one climatic regime to another. For example, in radiation limited environments TE will be lower than in environments with high radiation and low crop leaf area. Hence apparently low TE's in some environments (de Wit, 1958) might apply across radiation limited but not water limited environments and *vice versa*.

While this "constant" (kc) is typically used, and indeed transferred between crop varieties, regions and even continents, the relationship between kc and VPD does not appear to be constant for a given crop (Table 7). It has been shown to vary over time during plant growth, even when VPD is constant (e.g. Donatelli et al., 1992), and thus a time integrated TE and VPD for the life of a crop is required. Donatelli et al. (1992) (and others) have also shown that TE can vary as a function of water stress, independent of atmospheric VPD, possibly due to rising leaf temperatures resulting in increased leaf to air VPD (Rawson et al., 1978). It is actually this difference in vapour pressure within the leaf and that in the surrounding air that is critical, rather than atmospheric VPD *per se*, although the latter is typically used because it is more conveniently obtained.

For autumn and winter sown crops average VPD for much of the southern Australian cropping belt is around 0.75–1.0 kPa, higher in northern regions (1.0–1.5 kPa), and lower in more mesic environments nearer to the coast (< 0.75 kPa) (Doherty et al., 2009). Where daytime VPD is known, it could be used to account for temporal, seasonal or spatial variation in plant transpiration efficiency. An analysis of VPD and other climatic parameters illustrated that crop TE might increase by about 2.6% per degree of latitude as one moved from the north eastern to the south eastern parts of the Australian cereal belt as a function of VPD, from ca 40–55 kg/ha/mm (Rodriguez and Sadras, 2007), but corroborating field measurements are not available.

Thomas and Fukai (1995) estimated TE for chickpea and barley for part of the growing season in field and pot experiments in Queensland. Under field conditions TE of chickpea was less than half of that of barley but in the glasshouse the chickpea TE remained essentially the same as those observed in the field, while the barley TE declined to be close to those of chickpea. This may be because chickpea is less sensitive to VPD and/or because the field measurements might have been less accurate.

Applying plant level estimates of transpiration efficiency to field crops is imperfect because leaves within an annual crop canopy are not exposed to the same environment as individual plants on which TE measurements are typically made. It has been demonstrated (Jarvis and McNaughton, 1986) that the atmosphere within field crop canopies is quite different to that above the crop. Changes in the atmosphere above the crop are thus not directly linked to leaf stomatal openings which instead are driven by a complex series of energy, water vapour and resistance properties of the canopies and leaves themselves. Robust crop or canopy level transpiration modelling may require a more complex approach to the crop water and energy balance than simple transpiration efficiency factors imply.

3.3. *Allocation of fixed CO_2 to roots*

Some of the reported differences in crop TE may be due to real differences between cultivars (e.g. Condon et al., 1990; Hammer et al., 1997; Hubick, 1990; López-Castañeda and Richards, 1994; Sadras et al., 1991). However, inherent in the transpiration efficiency term is a typically unstated assumption about allocation of photosynthate to roots, which might account for some of the difference in apparent TE. While direct effects of nutrient availability on TE are likely to be very small, soil fertility effects on the relative allocation to roots might be important. Increased allocation of photosynthate to root growth under low nutrient conditions or low soil water availability may divert fixed C to roots and reduce apparent TE (Christie, 1978; Cooper et al., 1988). It is not clear, for example, if increased rooting depth in deep sandy soils would result in greater investment in roots and therefore reduced apparent TE. Root pests and diseases might also alter the relative allocation of fixed C to roots. In the glasshouse studies of 17 sorghum genotypes by Mortlock and Hammer, (2000) shoot:root dry matter ratios ranged from 3.6:1 to 1:1 and consequently whole plant TE's (95–180 kg/ha/mm) were 25–100% greater than estimates made on shoots only (58–90 kg/ha/mm). For field grown wheat TE's were estimated to be 18–58% higher when root mass was taken into account (López-Castañeda and Richards, 1994). Clearly assumptions about allocation of C to roots will have a large influence on estimates of crop TE.

4. Summary and conclusions

In the seminal papers of French and Schultz (1984a, b) the relative contributions of bare soil evaporation and crop transpiration to the crop water balance were highlighted as fundamental to an understanding of crop water use efficiency. In more than thirty years since, despite their critical importance in understanding the crop water balance, these two parameters have seldom been measured in Australia, especially for crops other than wheat. From our review of the available published field measurements, the average of 38% of seasonal crop water use lost as bare soil evaporation is marginally higher than the 33% postulated for southern Australia thirty years ago. We have not been able to identify sufficient field data to ascertain whether other crops (C3 cereals, legumes, oilseeds) are inherently different to wheat with respect to the proportional loss of water through bare soil evaporation.

With improved crop agronomy in recent years (better weed control, reduced root diseases, earlier sowing, increased fertiliser application), crop leaf area is likely to develop more quickly and to a greater extent than for crops sown prior to the widespread adoption of conservation tillage (stubble retention + minimum tillage + herbicides + direct sowing, Llewellyn and D'Emden, 2009), and so Es may be expected to be a smaller fraction of ET than it has been historically. Although it is generally thought that rainfed grain crop growth in Australia has become close to the water limited potential (Hochman et al., 2009; Passioura, 2002; van Rees et al., 2014), we have not found any field data to demonstrate that this has been due to increased crop transpiration at the expense of soil evaporation. A key question which is yet to be answered is “has water use efficiency improved over time for rainfed crops in Australia?” If the measure is grain yield, then the answer is yes, but this could be due to an increase in harvest index of crops (about 0.015 per decade, Unkovich et al., 2010), or improved weed and disease management, rather than any fundamental improvement in crop transpiration at the expense of Es or an increased TE. One would assume that improved root health through rotations and resistant crop cultivars may have increased crop transpiration and therefore reduced direct soil evaporation and increased crop production per unit evapotranspiration, however, we have not seen any field data to demonstrate this explicitly. Improved yield (and therefore WUE) over time might also arise from increased total ET (water use) and T through earlier sowing. Sowing of grain crops has moved earlier at about a week per decade since the introduction and then widespread adoption of herbicides (1980 on). A recent national research initiative focusing on crop water use efficiency (Kirkegaard et al., 2014) observed improvement in total crop T and ET through application of management practices that increased soil water storage but there was no reports on the relative importance of reduced Es due to increased T.

This review has highlighted significant gaps in our knowledge of the magnitude of the major components in the crop water balance, and poor definition of some of the physiological constants used in crop modelling, especially for non-cereal crops. While there is no doubt that grain yields per unit area have improved over time, the relative importance of increased ET and T, decreased Es or increased TE is not clear. Improved clarity around these elements might yet highlight opportunities for explicitly improving the way in which water is used by grain crops in rainfed environments and perhaps also provide opportunities for improving simple crop growth modelling in water limited environments.

We recognise that there are serious difficulties in directly measuring evaporation from soil under a crop and so would advocate that attention rather be paid to improving estimates of crop transpiration efficiency and that these be combined with measurement of biomass production to calculate crop transpiration and thus bare soil evaporation by difference. Attention should be paid to the development of regionally relevant, seasonally integrated vapour pressure deficits and the development of more robust transpiration efficiency constants, especially for crops other than wheat. Together such approaches could provide new insight into the critical crop water balance components and perhaps test the robustness of some commonly held water use efficiency assumptions. Although such approaches might be considered somewhat naïve against complex modern crop simulation models, simple approaches to benchmarking actual water use will continue to be applied by those involved in crop agronomy at the practical level and efforts to improve such approaches are warranted.

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