Evaporation and crop transpiration; behind the water use efficiency paradigm

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Abstract
We assembled published measurements of wheat water use which included both bare soil evaporation and crop transpiration in Australia in an effort to better define the critical parameters underpinning the "French and Schultz" water use efficiency schema. We found only 19 studies which measured the critical water balance parameters of bare soil evaporation and crop transpiration. Together these studies indicate that on average 38% of crop evapotranspiration is lost to direct soil evaporation under Australian rainfed wheat crops. We can find no data to support an increase in crop productivity due to increased crop transpiration at the expense of bare soil evaporation as a function of improvements in agronomic practices in recent decades.

Key words
Water balance, transpiration efficiency, wheat

Introduction
The strong correlation between rainfall and crop productivity has underpinned a useful conceptual framework (Figure 1A) that describes crop growth as a function of crop transpiration (T). While bare soil evaporation (Es) forms part of total crop water use (evapotranspiration, ET) it is unproductive. Diverting Es to T (Figure 1B) increases crop growth without increasing total water use. The slope of the line in Figure 1 is equivalent to transpiration efficiency (TE), the amount of dry matter produced per unit of water transpired. Where grain yield is plotted on the Y axis, the slope of the line would include effects flowering capacity and flowering success, grain development and effects of pests, diseases and frost on grain weight, and the effectiveness of grain harvest. In that case it does not represent TE.. Since Figure 1 defines the X axis as evapotranspiration, rather than rainfall + stored soil water as is often done, drainage and run off can be ignored. The greatest uncertainty in this framework is the X intercept, variation in Es relative to T, particularly in Australia where low rates of N fertiliser application might lead to slow leaf area development, leaving the soil surface exposed to direct radiation for longer. The application of this framework in Australia has been rather ad hoc, because the parameters have been poorly defined. In the seminal paper of French and Schultz (1984b), neither Es nor transpiration efficiency were actually measured. Here we examine the published measurements of the X axis intercept and the slope of the line of Figure 1 for wheat in Australia.

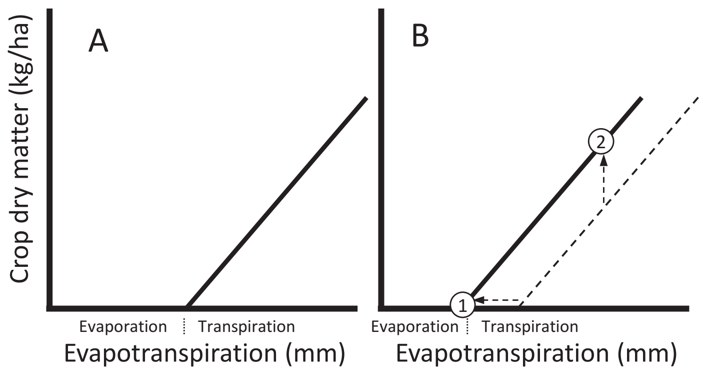

Figure 1(A) Relationship between crop water use (evapotranspiration) and crop dry matter production in a water limited environment. Water which is not transpired but is lost directly to the atmosphere via bare soil evaporation is not productive. (B) Diverting water to transpiration pushes the X intercept to the left (□), increasing dry matter production (□) without changing total evapotranspiration.

Review of available data
We compiled published estimates of the fractional contribution of Es to ET for wheat crops across the Australian cereal belt, each obtained by a combination of field measurement and modelling. We excluded

estimates derived wholly from modelling. From the available measurements, on average 40% of water use over the duration of a wheat crop is attributed to direct evaporation from soil, with values from 16 to 65%, or 36-171 mm evident. In comparison French and Schultz (1984a) concluded that only 33% (110 mm) of water use was lost as Es from soil under wheat crops across 24 sites in South Australia in the years they investigated (1964-1975).

Plotting seasonal evaporation from soil against seasonal evapotranspiration for the data we could find in the literature for 19 different sites across the cereal belt (data sources listed at end), it can be seen that seasonal ET accounted for 44% of the variance in seasonal evaporation from soil (Figure 2). As evaporation from soil must be 0 when ET is 0, we forced the regression through the origin. The slope of the regression in Figure 2 provides a convenient scaling for the X axis intercept of Figure 1A. The slope (0.38) is close to what has been considered typical (0.4) for well managed wheat crops in Australia (Richards 1991). There are insufficient data to examine possible regional differences.

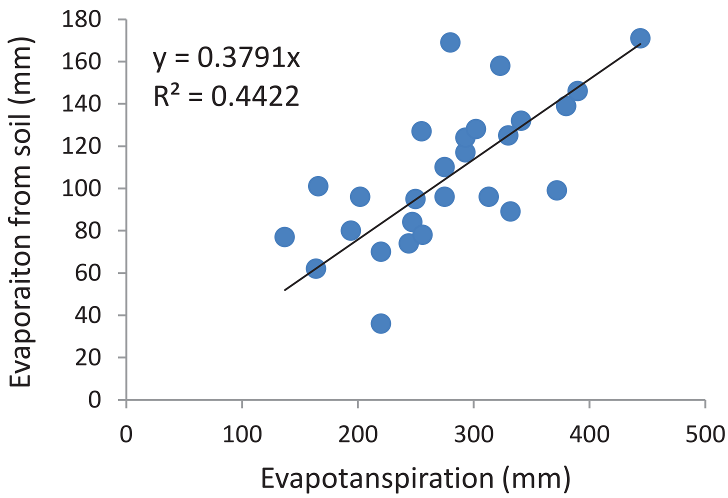

Figure 2Correlation between seasonal evaporation from soil and seasonal evapotranspiration for wheat crops in Australia. Data sources are given in Table 1. The regression is forced through the origin since by definition evaporation from soil must be nil when evapotranspiration is nil.

The studies illustrated in Figure 2 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). These improvements may have increased the rate of leaf area development and thus crop transpiration relative to evaporation from soil. However we can find no water balance data to substantiate any such trend as there appear to be no published studies for crops grown after the year 2002.

The slope of the line in Figure 1 represents transpiration efficiency (TE), the relationship between net shoot dry matter gain and water transpired by the crop. Estimates of TE for wheat in Australia range from 33 (Doyle and Fischer 1979) to 73.4 kg/ha/mm (Sadras *et al*. 2005), averaging 49 across 13 published studies. In a general sense TE is thought to be a conservative parameter, with the largest external influence being the leaf to atmosphere vapour pressure deficit (VPD) (Morison and Gifford 1984). Decreasing VPD, as one moves from the northern to the southern Australian cereal belt, might increase TE by about 2.6% per degree of latitude, or from ca 40 to 55 kg/ha/mm (Rodriguez and Sadras 2007). Such effects of VPD on TE are often accounted for using a crop specific constant (see e.g. Hammer and Muchow 1994,Tanner and Sinclair 1983). Constants scaling TE for wheat to account for VPD of 4.7 (Meinke *et al*. 1997) and 5.2 (Young *et al*. 2008) have been reported. There is large variation in TE apparent in the literature for a given crop, regardless of VPD scaling. Some of this may be due to differences between cultivars (e.g. Condon *et al*. 1990; Hammer *et al*. 1997; Hubick 1990; López-Castañeda and Richards 1994; Sadras *et al*. 1991). Furthermore, inherent in the transpiration efficiency term is an assumption (typically unstated) about allocation of photosynthate to roots which might account for some of the difference in apparent TE. Differences in soil water and nutrient availability, and pests and diseases, may alter the relative allocation of fixed C to roots such that apparent shoot TE may be quite different to actual TE.

Conclusion

The slope of the line in Figure 2 provides a convenient starting point for defining the fraction of seasonal evapotranspiration lost as bare soil evaporation for field application of the water use efficiency schema of Figure 1. However it is based on relatively few measurements and none from the last 13 years. If we were to assume that improved agronomy results in greater crop transpiration at the expense of direct soil evaporation, more contemporary measurements need to be made. Similarly the transpiration efficiency for wheat needs to be better defined as a function of cultivar and VPD environment. Values for transpiration efficiency used in current models are based on very few measurements.

NOTE: data from Figure 2 are sourced from Adcock (2006), Angus and van Herwaarden (2001), Condon *et al*. (2002), Doyle and Fischer (1979), Gregory *et al*. (1992), Hamblin *et al*. (1987), Leuning *et al*. (1994), López-Castañeda and Richards (1994), Condon *et al*. (1993), Perry (1987), Siddique *et al*. (1990), Simpson and Siddique (1994), Young *et al*. (2008), Yunusa *et al*. (1993).

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