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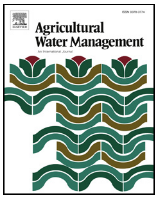

Review

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 ° 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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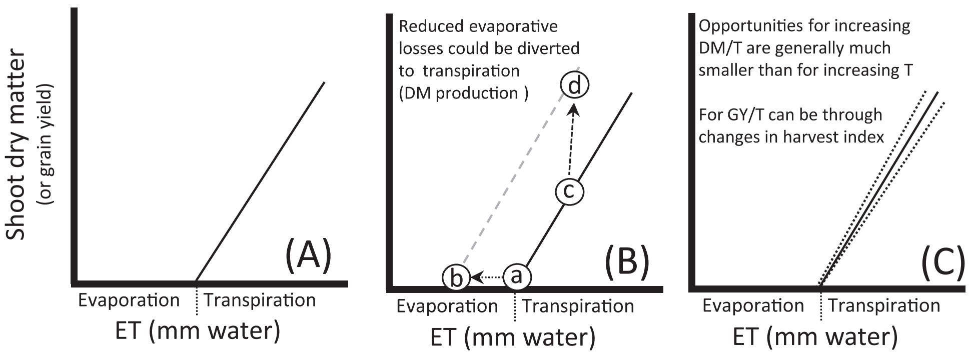

Fig. 1. The relationship between crop dry matter production or grain yield (Y axis) and crop evapotranspiration (X axis) can be represented as in (A), with the slope of the line representing transpiration efficiency. Crop water use efficiency could be improved where soil evaporative losses can be reduced 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