A national benchmark for the Australian wheat industry: accounting for overlooked climate drivers

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Abstract

In Australia wheat is produced in environments of predominantly winter rainfall (Victoria, South Australia and Western Australia), summer rainfall (central and northern New South Wales, and Queensland), and a transition region (central New South Wales) where rainfall is more evenly distributed throughout the year. Regional differences in rainfall patterns (seasonality and size of events) vapour pressure deficit (VPD), mean temperature (T) photosynthetically active radiation (PAR) and fraction of diffuse radiation (FDR) during critical stages in wheat, can dramatically affect potential values of water use efficiency (WUE) across Australia. Models that do not account for these factors, e.g. French and Schultz with fixed parameters, are therefore bound to be biased. In this work we analysed wheat WUE at the shire level for the whole of Australia during the period 1975-2006; we used (a) actual census yields from the Australian Bureau of Statistics, and (b) modelled water use (*Oz-Wheat* model) to derive WUE = yield/water use, and (c) a climate index accounting for T, VPD, PAR and FDR to produce a measure of actual water use efficiency normalised by these climate drivers (nWUE). The newly developed nWUE index can be used to more fairly compare the regional performance of wheat production across Australia, irrespective of important differences in environmental potential. In general, nWUE from the northern GRDC region is as high as that from the southern or western GRDC regions. Potential causes for lower nWUE values in underperforming regions include the presence of subsoil constraints (e.g. South Australian and Victorian Mallee, south eastern Queensland, southern Western Australia), water logging (e.g. high rainfall zones of Victoria, and southern Western Australia), and management issues in regions with high proportion of mixed grain and livestock farm businesses (e.g. the Western Downs and Maranoa regions in Queensland, and central and eastern New South Wales).

Introduction

Crop production is a function of the ability of crops to capture resources, chiefly radiation and water, and the efficiency in the use of resources to produce dry matter and grain (Monteith et al., 1994). Both water availability and the efficiency in the use of water restrict grain production in the Australian wheat-belt. Much research on these efficiencies has benefited from up-scaling gas exchange principles from leaf to canopy (Rodriguez and Sadras, 2007). Theoretical and empirical evidence indicate that potential water-use efficiency of wheat is an inverse function of vapour pressure deficit and temperature, and a direct function of photosynthetically active radiation and proportion of diffuse radiation (Rodriguez and Sadras, 2007). However, actual water use efficiency is also influenced by seasonality and size structure of rainfall events (Sadras and Rodriguez, 2007). It is also clear that across the Australian wheat belt the mean, variance and seasonal dynamics of these climatic variables vary significantly affecting both potential and attainable yields across regions and seasons. Calculations of biomass and yield production in up-to date dynamic simulation models, e.g. APSIM and its derived products, are soundly based on these principles. In contraposition, empirical estimates of potential yield (French and Schultz, 1984) improperly extrapolated across Australia (Walcott et al., 2006) fail to account for fundamental climate drivers (Rodriguez and Sadras, 2007), and ignore the dynamics of seasons i.e. soil water losses, and rainfall distribution in relation to crop water demand. In a context of current water scarcity and projected deterioration associated with hotter and dryer climates, a more comprehensive temporal and spatial characterisation of the environmental potential and limitations to water use efficiency for wheat production in Australia is highly relevant. In this paper we have combined recent advances in the understanding of key drivers of crop performance across Australia (Rodriguez and Sadras, 2007; Sadras and Rodriguez, 2007) with outputs from a shire level dynamic model (Potgieter et al., 2006) to (i) benchmark the performance of 245 wheat-producing shires across Australia, and (ii) identify potential causes underpinning low performances.

Methods

All variables, including yield, water use and climate drivers, were analysed at the shire level.

Water use and water use efficiency

The *Oz-Wheat* model (Potgieter et al., 2006) is a shire-level production model which uses daily-step climate records as main input from 245 of the major wheat producing shires around Australia. In *Oz-Wheat* wheat yields are derived after calculating a crop water stress index during a narrow window around anthesis (Fischer 1985), given a typical sowing date, and an assumed soil depth for each shire. The model was developed using actual wheat yields from the census data collated by The Australian Bureau of Statistics (ABS) for the seasons 1975 through to 1999 (training data set), and validated against the census data for the years 2000 and 2005-2006.

Here we used *Oz-Wheat* to calculate an average shire level crop-water use, assuming a 10% full soil water profile at the end of the previous years' crop and simulating fallow water balance from rainfall and predicted evaporation (from Ritchie's (1972) equations). Initial soil water (ISW, mm), final soil water (FSW, mm) and in-crop rain (ICR, mm) were modelled over the same period as the ABS census data (1975 – 2000) and crop water use (WU, mm) was calculated for each season by using the following equation:

$$WU = ISW + ICR - FSW \qquad \text{eq. 1}$$

Water use efficiency (WUE, kg/mm.ha) was then calculated for each year and shire as the ratio between actual yield (kg/ha) and modelled water use.

$$WUE = Yield / WU \qquad \text{eq. 2}$$

Normalised photo-thermal quotient

Building up on Fischer's (1985) photothermal coefficient, Rodriguez and Sadras (2007) demonstrated the importance of temperature (T, ^oC), vapour pressure deficit (VPD, kPa), total (PAR, MJ/m^2.day) and fraction of diffuse radiation (FDR) as sources of variation in yield potential across Australia. They integrated these four factors in a new climatic index, the normalised photothermal quotient, NPq:

$$NPq = (PAR * FDR) / (VPD * T) \qquad \text{eq. 3}$$

This index showed an improved capacity to explain observed variability in grain yield across wide range of environments in relation to the original photothermal quotient = PAR/T. Here we estimated NPq over a narrow window around anthesis for each shire and season using equation 3.

Normalised crop water use efficiency

Normalised crop water use efficiency (nWUE, kg ha^{-1} mm^{-1} MJ^{-1} m^2 ?C kPa) for each season and shire was calculated by the following equation:

$$nWUE = WUE / NPq \qquad \text{eq. 4}$$

Results and discussion

The long term median (1975-2000) ABS shire level wheat yields (Fig 1a) varied from 0.5 to 2.8t/ha, with highest values recorded in south New South Wales and south and central Victoria. Long term median predicted water use (Fig 1b) varied from about 106mm in the northern Mallee and Western wheat belt to as high as 620mm along the eastern New South Wales wheat belt. Water use efficiency seems to increase southwards from southern and central Queensland to maximum values in Victoria. When other key climatic factors were ignored, this has been interpreted as the northern grains region lagging behind, in terms of crop performance, with respect to the southern and western regions (Walcott et al., 2006).

Lower total and diffuse radiation together with higher vapour pressure deficit and day time temperatures around anthesis lead to lower NPq in the northern region compared to the southern or western grain regions (Fig 2a). For the eastern Australian wheat belt, Rodriguez and Sadras (2007) found a significant positive correlation ($p<0.001$, $n=51$) between NPq around anthesis and actual yield measured in field trials from south Australia to central Queensland. In that work the authors concluded that this newly developed climatic index (NPq) showed a good capacity to explain observed variability in grain yield across environments characterised by contrasting day time vapour pressure deficit, total and fraction of diffuse radiation and temperature. This suggests that the NPq index could be used to more fairly compare the performance of crops across contrasting agro-ecological zones. Here, in Fig 2b we plotted WUE from Fig 1c normalised (i.e. divided) by NPq in Fig 2a.

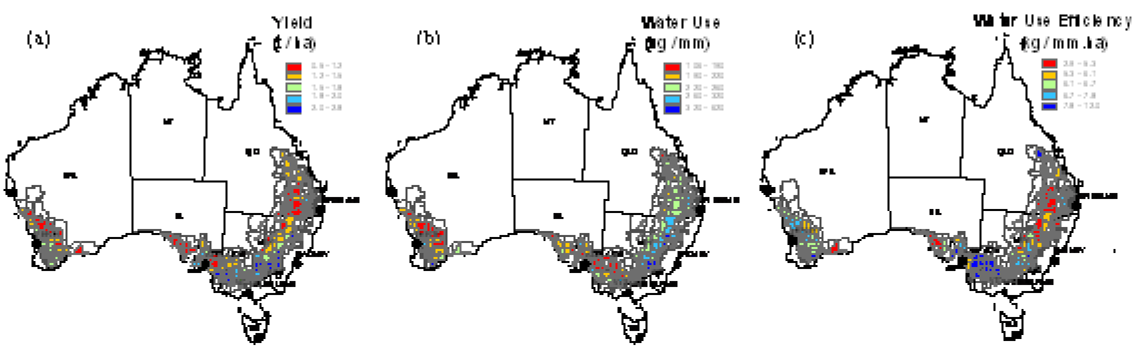

Fig 1. (a) Median wheat yields from ABS; (b) median crop water use modelled with Oz-Wheat; and (c) median water use efficiency calculated as the ratio between values in map (a) and map (b). Period 1975-2000.

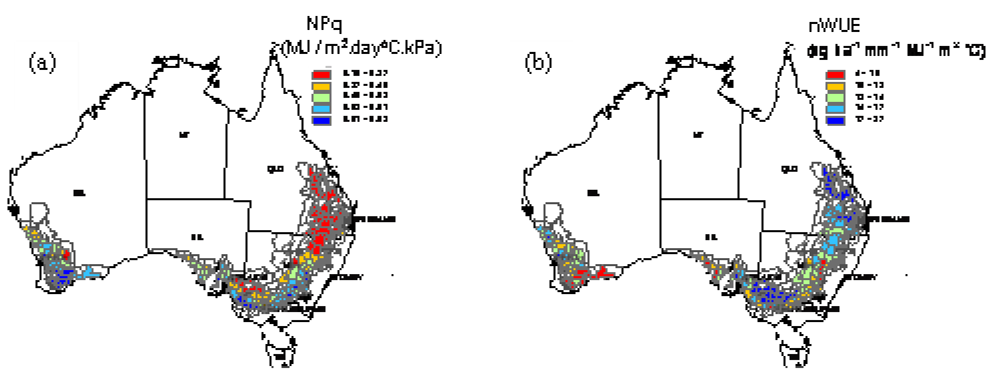

Fig 2. (a) Median normalised photothermal quotient (NPq, MJ/m^2.?C.kPa) as per Rodriguez and Sadras (2007); and (b) Median normalised water use efficiency (nWUE, kg ha^{-1} mm^{-1} MJ^{-1} m^2 ?C kPa). Period 1975-2000.

In contrast to Fig 1c, and the results from Walcott et al., (2006), Figure 2b shows that the northern grains region has water use efficiencies with respect to environmental potential as high as those observed in the southern region. Most important, Figure 2b allows us to more accurately identify under performing regions and shires and hypothesise on potential causes or the underperformance. In Fig 2b, underperforming shires in southern WA, i.e. the south West and Western Wheat Belt, have been characterised as affected by decline in soil nutrients and biological activity, soil acidification, surface soil structural decline, surface water logging, subsoil compaction, and secondary salinity from rising ground-water (Williams et al., 2002; Rengasamy, 2002). Similarly, underperforming shires in the high rainfall areas of southern Victoria can be related to surface water logging, soil acidification and decline in soil nutrients and biological activity (Williams et al., 2002). Underperforming shires in the South Australian Eyre Peninsula have been mostly related to the presence of subsoil constraints such as high levels of salinity and sodicity (Rengasamy, 2002).

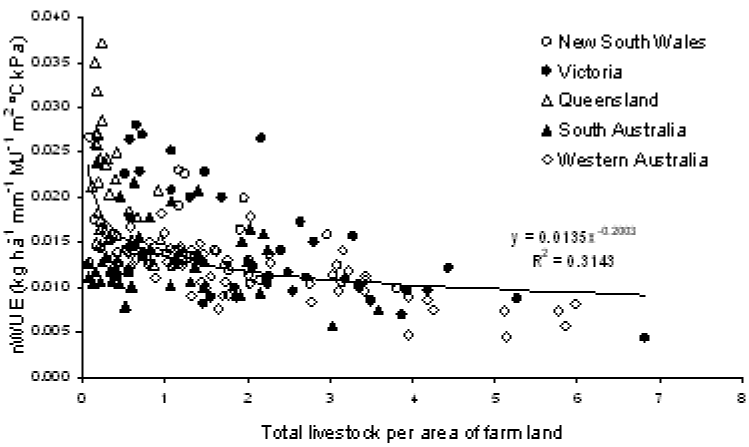

Fig 3. Normalised water use efficiency (nWUE, (kg ha^{-1} mm^{-1} MJ^{-1} m^{2} ?C kPa)) for wheat producing shires across Australia versus the ratio between total number of livestock and area planted to wheat.

Underperforming shires in south eastern Queensland can be related to the presence of high concentration of chloride in the subsoil (Dang et al., 2006) while in shires from the central, Northern Tablelands and Granite Belt and Western Downs and New South Wales Slopes and Planes (Williams et al. 2002) identified decline in soil nutrients and biological activity as well as soil acidification processes as key resource management issues.

In addition to environmental issues we found that land-use patterns may also influence the performance of wheat producing shires. Figure 3 shows that, normalised wheat water use efficiency tended to be low in wheat producing shires having a high density of total livestock (ABS, census data). Interestingly, nWUE was better related to total livestock density than when expressed in dry sheep equivalents (not shown). Here, total livestock density in a shire indicates the likelihood of predominantly mixed grain & graze farm businesses in that shire. Hypothetically, potential causes behind underperforming crops in those shires might be associated to the presence of more complicated management systems where livestock (of any type) has been integrated in cropping land; resulting in reduced stubble retention and ground cover that affect rainfall harvesting, complicating the management of weeds, and the timing of the agricultural operations. We believe this raises questions in regards to R&D programs aiming at promoting the integration of grain and grazing enterprises, before regional whole farm business analyses across Australia are performed to properly answer this question. It is also clear from this analysis that further improvements in systems/whole farm water use efficiency ($/ha.mm of annual rainfall) will be more likely to come from: (i) improved farm business designs i.e. improved enterprise mix and allocation of limited resources across alternative enterprises (land, water, finances, labour, machinery); and (ii) better understanding of the impact of alternative farm business designs on trade-offs between farm profit, economic risk and environmental outcomes.

In this work we have produced a significant step forward towards the development of more realistic and useful national benchmarks for the comparison of regional performances, identification of gaps in understanding and finding potential solutions to increase the amount of Australian grain produced per drop of water.

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