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Quantification of wheat water-use efficiency at the shire-level in Australia

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Abstract. In eastern Australia, latitudinal gradients in vapour pressure deficit (VPD), mean temperature (T), photosynthetically active radiation (PAR), and fraction of diffuse radiation (FDR) around the critical stage for yield formation affect wheat yield and crop water-use efficiency (WUE = yield per unit evapotranspiration). In this paper we combine our current understanding of these climate factors aggregated in a normalised photothermal coefficient, NPq = (PAR· FDR)/(T · VPD), with a shire-level dynamic model of crop yield and water use to quantify WUE of wheat in 245 shires across Australia. Three measures of WUE were compared: WUE, the ratio of measured yield and modelled evapotranspiration; $\mathrm{WUE}_{\mathrm{VPD}}$, i.e. WUE corrected by VPD; and $\mathrm{WUE}_{\mathrm{NPq}}$, i.e. WUE corrected by NPq. Our aim is to test the hypothesis that $\mathrm{WUE}_{\mathrm{NPq}}$ suits regional comparisons better than WUE or $\mathrm{WUE}_{\mathrm{VPD}}$.

Actual median yield at the shire level (1975–2000) varied from 0.5 to 2.8 t/ha and the coefficient of variation ranged from 18 to 92%. Modelled median evapotranspiration varied from 106 to 620 mm and it accounted for 42% of the variation in yield among regions. The relationship was non-linear, and yield stabilised at ~2 t/ha for evapotranspiration above 343 mm. There were no associations between WUE and rainfall. The associations were weak ($R^2 = 0.09$) but in the expected direction for $\mathrm{WUE}_{\mathrm{VPD}}$, i.e. inverse with seasonal rainfall and direct with off-season rainfall, and strongest for $\mathrm{WUE}_{\mathrm{NPq}}$ ($R^2 = 0.40$). We suggest that the effects of VPD, PAR, FDR, and T, can be integrated to improve the regional quantification of WUE defined in terms of grain yield and seasonal water use.

Additional keywords: vapour pressure deficit, diffuse radiation, photothermal quotient, regional production modelling, yield, evapotranspiration.

Introduction

In Australia, wheat is grown in environments of predominant winter rainfall in Victoria, South Australia, and Western Australia, in environments of predominant summer rainfall in northern New South Wales and Queensland, and in a transition region in central New South Wales where rainfall is more evenly distributed throughout the year (Gentilli 1971). Prevalent size and frequency of rainfall events also vary widely, with typically larger and less frequent events in summer-rainfall regions and smaller, more frequent events in winter-rainfall regions (Sadras and Rodriguez 2007). Seasonality, size, and frequency of rainfall events strongly influence the dynamics of water in these agroecosystems; e.g. a higher proportion of rainfall loss through soil evaporation is associated with winter rainfall and small and more frequent rainfall events (Sadras 2003; Sadras and Rodriguez 2007). In the eastern wheat-growing region, there are strong gradients in fraction of diffuse radiation (FDR), vapour pressure deficit (VPD), mean temperature (T), and photosynthetically active radiation (PAR) during the critical phenological window of kernel set (Rodriguez and Sadras 2007). Owing to this gradient, wheat yield in a transect between Horsham (36°S) and Emerald (23°S) was unrelated to the photothermal quotient (Fischer 1985) defined as the ratio between radiation and temperature in this phenological window (Rodriguez and Sadras 2007). However, yield was related to NPq, a photothermal quotient normalised to account for VPD and FDR (Rodriguez and Sadras 2007).

Availability and efficiency in the use of water constrain wheat yield over much of Australia (Fischer 2009). For this reason, it is common to predict wheat yield using linear models relating yield and seasonal evapotranspiration (Angus *et al*. 1980; French and Schultz 1984*a*, 1984*b*; Cornish and Murray 1989; Angus and van Herwaarden 2001; Sadras and Angus 2006; Walcott *et al*. 2006). This model assumes an *x*-intercept representing seasonal soil evaporation and a slope representing an upper limit of the yield-to-transpiration ratio. Shire-level comparisons in Australia have been used to identify districts with high and low efficiencies under the assumption of a constant yield-to-transpiration ratio (Beeston *et al*. 2005; Walcott *et al*. 2006). But at this spatial scale this assumption does not hold: the ratio is affected by T, PAR, FDR, and VPD (Rodriguez and Sadras 2007; Sadras and Rodriguez 2007).

A comprehensive spatial characterisation of the environmental potential and limitations to yield and water-use efficiency is relevant in a context of water constraints for food production (Falkenmark *et al*. 2009). The objective of this paper

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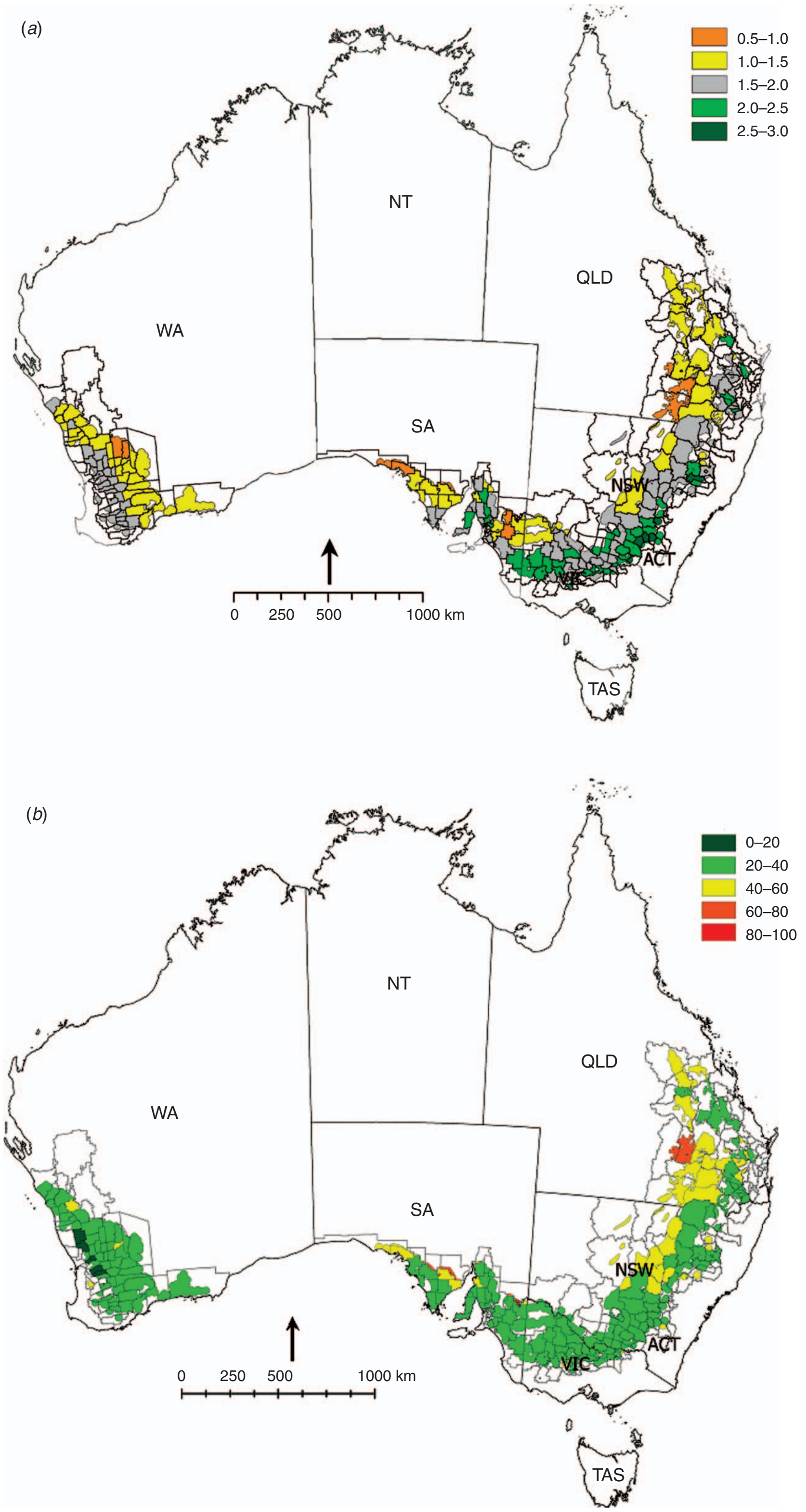

Fig. 1. (*a*) Actual median wheat yield (t/ha), (*b*) coefficient of variation of yield (%), and (*c*) (facing page) modelled median seasonal evapotranspiration (mm) in wheat-producing shires of Australia. All variables are for the period 1975–2000.

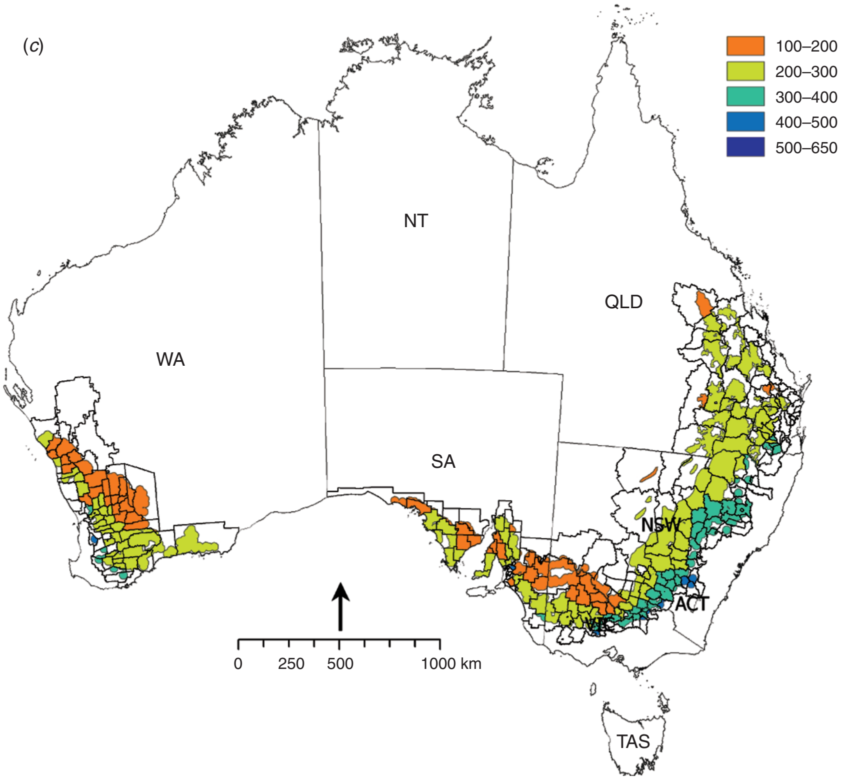

Fig. 1. (*continued*)

is to quantify water-use efficiency of wheat in 245 shires across Australia. To capture the spatial variation in climate, we combined recent advances in the understanding of climatic drivers of crop yield and water-use efficiency (Rodriguez and Sadras 2007), with outputs from a shire-level dynamic model (Potgieter *et al*. 2006). Three measures of water-use efficiency were compared: WUE, the ratio of actual yield and modelled evapotranspiration; WUE_{VPD}, i.e. WUE corrected by VPD (Tanner 1981; Abbate *et al*. 2004; Kemanian *et al*. 2005); and WUE_{NPq}, i.e. WUE corrected by NPq. Our aim is to test the hypothesis that WUE_{NPq} suits regional comparisons better than WUE or WUE_{VPD}.

Methods

Oz-Wheat model

Oz-Wheat is a shire-level production model that has been fully described in Potgieter *et al*. (2006). Briefly, the model generates a final water-limited stress index by integrating (*i*) a daily water balance during fallow and crop growth periods, (*ii*) daily weather records, and (*iii*) crop-specific parameters. The model accounts for spatial variability of rainfall, crop cultivar and phenology, timing of sowing, soil depth, and plant-available water. It was developed using yield from data collated by the Australian Bureau of Statistics (ABS) between 1975 and 1999 (training dataset), and validated against data for 2000. ABS data were adjusted to fit the shire local area boundaries of 2000–01, and variations in area associated with shifts in shire boundaries were $\leq$10% for the shires included in the study. Thermal time to anthesis was calculated with APSIM (Keating *et al*. 2003) for early, medium, and late cultivars, and one of the 3 simulated cultivars was selected, depending on when the sowing event happened inside a region-specific sowing window. The model showed a significant ability to mimic actual shire-scale wheat yield across the Australian wheatbelt and its suitability for climate studies at regional level has been highlighted (Potgieter *et al*. 2006).

Shire level yield, water use, and water-use efficiency

We combined actual shire yields and crop evapotranspiration from Oz-Wheat to derive a series of measures of water-use efficiency. Oz-Wheat was run for each wheat-growing shire in Australia using daily weather data for the time series 1975–2000. To avoid artificial skill derived from grid data points, we only used actual long-term climate stations that had the highest quality data. Climate data for 927 recording stations were obtained from the Australian Bureau of Meteorology SILO patch-point dataset (www.bom.gov.au/silo/). When more than one weather station was available within each shire, data were weighted by the relative area of the shire they represented using Thiessen polygons (de Berg *et al*. 2000). Crop evapotranspiration was calculated assuming a 10%-full soil water profile at the end of the previous year's crop and simulating the fallow water balance with Ritchie's (1972) equations. Initial soil water (ISW, mm), final soil water (FSW, mm), and in-crop rain (ICR, mm) were calculated, and crop evapotranspiration (ET, mm) derived as:

$$\mathrm{ET} = \mathrm{ISW} + \mathrm{ICR} - \mathrm{FSW} \qquad (1)$$

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

$$\mathrm{WUE} = \frac{\mathrm{Yield}}{\mathrm{ET}} \tag{2}$$

and it was normalised by VPD (from 20 days before to 14 days after anthesis) to derive $\mathrm{WUE}_{\mathrm{VPD}}$ (kg.kPa/ha.mm):

$$\mathrm{WUE}_{\mathrm{VPD}} = \frac{\mathrm{Yield}}{\mathrm{ET}/\mathrm{VPD}} \tag{3}$$

Building up on Fischer's (1985) photothermal coefficient relating temperature (T, °C) and photosynthetically active radiation (PAR, $\mathrm{MJ/m^2}$.day), Rodriguez and Sadras (2007) demonstrated the importance of vapour pressure deficit (VPD, kPa), and the fraction of diffuse radiation (FDR) as sources of variation in yield across a latitudinal gradient in eastern Australia. They integrated these 4 factors in a normalised photothermal coefficient, NPq ($\mathrm{MJ/m^2}$.day.°C.kPa):

$$\mathrm{NPq} = \frac{\mathrm{PAR} \times \mathrm{FDR}}{\mathrm{VPD} \times \mathrm{T}} \tag{4}$$

Here we calculated NPq over a window from 20 days before to 14 days after anthesis for each shire and season. VPD and FDR were calculated using vapour pressure, temperature, and incoming radiation from the Australian Bureau of Meteorology, and the algorithms in Monteith and Unsworth (1990). WUE normalised by NPq ($\mathrm{WUE}_{\mathrm{NPq}}$, kg/ha.mm per $\mathrm{MJ/m^2}$.day.°C. kPa) for each season and shire was calculated as:

$$\mathrm{WUE}_{\mathrm{NPq}} = \frac{\mathrm{Yield}}{\mathrm{ET} \times \mathrm{NPq}} \tag{5}$$

Comparison of different measures of water-use efficiency at shire level: associations with the proportions of in-season and off-season rainfall

We compared shire-level WUE, $\mathrm{WUE}_{\mathrm{VPD}}$, and $\mathrm{WUE}_{\mathrm{NPq}}$ against expected relationships with rainfall, namely:

(*1*) water-use efficiency decreases with increasing proportion of seasonal rainfall as expected from unproductive water losses (deep drainage, runoff), and reductions in yield associated with transient water-logging and nutrient deficiencies (French and Schultz 1984*a*, 1984*b*; Sadras and Roget 2004; Sadras and Angus 2006);

(*2*) water-use efficiency increases with increasing fraction of off-season rainfall, as deep-stored water contributes proportionally more to grain yield (Kirkegaard *et al.* 2007).

Sources of bias

Ozwheat (Potgieter *et al.* 2006) and the approach described above make a series of assumptions that may bias our results. In addition, we highlight the following potential sources of bias.

- Over-estimates of ET can be expected in high-rainfall areas of south-eastern Australia and sandy soils in Western Australia where episodic runoff or deep drainage occurs (e.g. Asseng *et al.* 2001*a*).
- Weed control during fallow can be more effective in cropping-intensive regions compared with shires where weeds may be used as a resource for animal production, hence biasing our estimates of initial soil water.
- Residual water from irrigation is unaccounted for, and may bias our estimates of wheat WUE in shires of eastern Australia where wheat is grown in rotations with irrigated cotton or rice.
- Region-specific sowing windows may not reflect recent changes in practices, such as 'dry sowing', i.e. sowing before opening rains (Fulwood 2009).
- Our estimates are based on a static view of long-term (1975–2000) yields. In this period, wheat yield has increased but at different rates across regions (Stephens 2003; Turner and Asseng 2005; Fischer 2009).
- We assumed a stationary climate over this period, but there were definite trends in climatic elements of relevance for crop production, i.e. reduced rainfall in Western Australia and increased temperature across the Australian wheatbelt (Sadras and Monzon 2006; Asseng *et al.* 2009).

Results

Spatial variation in yield and evapotranspiration

The actual median wheat yield varied from 0.5 to 2.8 t/ha across shires. It was higher in southern New South Wales and southern and central Victoria (Fig. 1*a*). The coefficient of variation for yield between 1975 and 2000 in each shire ranged from 18 to 92% and increased inland and northwards in eastern Australia (Fig. 1*b*). Modelled median water use varied from ~106 mm in south-eastern Australia and the western wheatbelt to ~620 mm in eastern New South Wales (Fig. 1*c*). For the pooled data, i.e. all wheat-growing shires, ET accounted for 42% of the variation in yield (Fig. 2*a*, Table 1). While a continuous model (dashed line in Fig. 2*a*) describes the relationship between yield and ET more realistically, i.e. yield response to ET is gradual, a piece-wise model (solid line in Fig. 2*a*) allowed estimation of agronomically meaningful parameters: yield increased with ET at an average rate of 4.3 kg/ha.mm and stabilised at ~2 t/ha for ET above a breakpoint of ~343 mm. Piece-wise regressions for each state returned slopes in a range from 13 kg/ha.mm in Victoria to 3 kg/ha.mm in New South Wales (Table 1). The slope and the breakpoint ET were inversely related ($R^2 = 0.84$, $P < 0.001$, $n = 5$; Table 1).

Climate factors and water-use efficiency

Yield was inversely related to median VPD around anthesis (Fig. 2*b*), which ranged from 0.5 to 1.4 kPa (Fig. 3*a*). Median NPq around anthesis varied 5.6-fold. It decreased northwards in both the western and eastern regions (Fig. 3*b*). In eastern Australia, the northward decline in NPq is explained by the northward decline in both total and diffuse radiation, and the northward increase in both VPD and daytime temperature around anthesis (Rodriguez and Sadras 2007). Actual yield increased non-linearly with NPq, reaching a plateau of ~2 t/ha (Fig. 2*c*).

In eastern Australia, WUE decreased northwards from central Victoria to Queensland (Fig. 4*a*). In Western Australia, it was largely between 6 and 9 kg/ha.mm, with a patchy distribution of districts with lower (<6 kg/ha.mm) and higher efficiencies

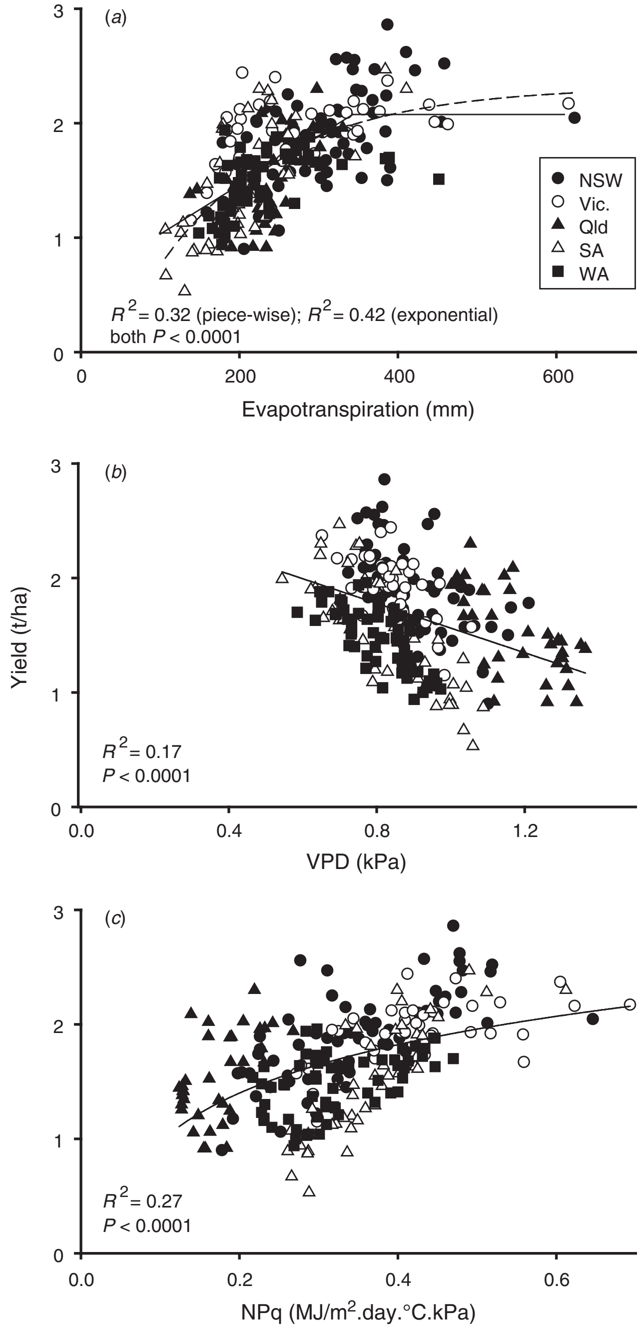

Fig. 2. Relationship between actual wheat yield and (*a*) seasonal evapotranspiration, (*b*) vapour pressure deficit, and (*c*) normalised photothermal quotient, NPq (Eqn 4). In (*a*) exponential rise to maximum, i.e. $y = a + b[(1 - e^{-cx})]$ (dashed line) and piece-wise (solid line) models were fitted for comparison. Vapour pressure deficit and NPq correspond to a window from 20 days before to 14 days after anthesis. All variables are medians for the period 1975–2000.

Table 1. Parameters from the split-line regression (slope and plateau) between actual wheat yield and modelled crop evapotranspiration

a is the intercept (t/ha), *b* is the slope (t/ha.mm), and $ET^{\#}$ is the evapotranspiration at the breakpoint between the slope and plateau (mm). All regressions are significant at $P < 0.0001$. Yield and evapotranspiration are medians for the period 1975–2000

State	*a*	*b*	$ET^{\#}$	R^2	*n*
Victoria	–0.66	0.013 ± 0.002	203 ± 2	0.52	38
Western Australia	–0.19	0.008 ± 0.001	229 ± 10	0.44	60
South Australia	0.16	0.006 ± 0.001	308 ± 38	0.46	45
Queensland	0.24	0.005 ± 0.001	323 ± 62	0.31	35
New South Wales	0.90	0.003 ± 0.001	410 ± 5	0.29	67
All	0.60	0.004 ± 0.0003	343 ± 9	0.41	245

(>9 kg/ha.mm). Comparison of Fig. 4*a* with 4*b* and 4*c* highlights climatic influences on the geographical gradients of WUE. For example, the pattern of declining WUE from central Victoria to central Queensland (Fig. 4*a*) is smoothed when correcting by VPD (Fig. 4*b*) and is partially reversed when correcting by NPq (Fig. 4*c*). Most shires had WUE_{NPq} in a range from 10 to 30 kg/ha. mm per MJ/m^2.day.°C.kPa, with higher efficiencies in central Victoria and northern Queensland.

Relationships between water-use efficiency and rainfall

We expected WUE to be inversely associated with seasonal rainfall and positively related to off-season rainfall. There were no associations between WUE defined as the ratio of yield and water use and rainfall (Fig. 5*a*, *d*). The associations with rainfall were weak but in the expected direction for WUE normalised by VPD (Fig. 5*b*, *e*), and strongest for WUE normalised by NPq (Fig. 5*c*, *f*).

Discussion

Where water availability constrains crop yield, benchmarks of yield against water use are widely applied (Angus *et al.* 1980; French and Schultz 1984*a*, 1984*b*; Cornish and Murray 1989; Sadras and Angus 2006; Walcott *et al.* 2006; Grassini *et al.* 2009*a*, 2009*b*). The need to correct WUE by VPD or other measures of evaporative demand is well established (de Wit 1958; Tanner and Sinclair 1983; Sadras *et al.* 1991; Chen *et al.* 2003; Abbate *et al.* 2004; Kemanian *et al.* 2005). Our approach to correcting WUE (Eqns 4 and 5) further incorporates two robust physiological concepts, namely (*i*) the notion of a critical window for grain yield determination (Fischer 1985; Foulkes *et al.* 2009; Sadras and Denison 2009), and (*ii*) the enhancing effect of diffuse radiation on canopy photosynthesis (Spitters 1986; Stockle and Kemanian 2009).

Theoretical justification of WUE_{NPq}

Direct comparison of WUE_{VPD} and WUE_{NPq} (Fig. 4*b v. c*) and the differential ability of these efficiencies to capture agriculturally meaningful patterns (Fig. 5) indicated that normalisation by NPq improved on raw WUE or the generalised normalisation by VPD. This improvement can be interpreted physiologically as follows. Consider the expression of WUE relating biomass (B), and the components of ET, i.e. crop transpiration (T) and soil evaporation (Es) (Cooper *et al.* 1987):

$$\mathrm{WUE_B} = \frac{\mathrm{B/T}}{1 + \mathrm{E_s/T}} \tag{6a}$$

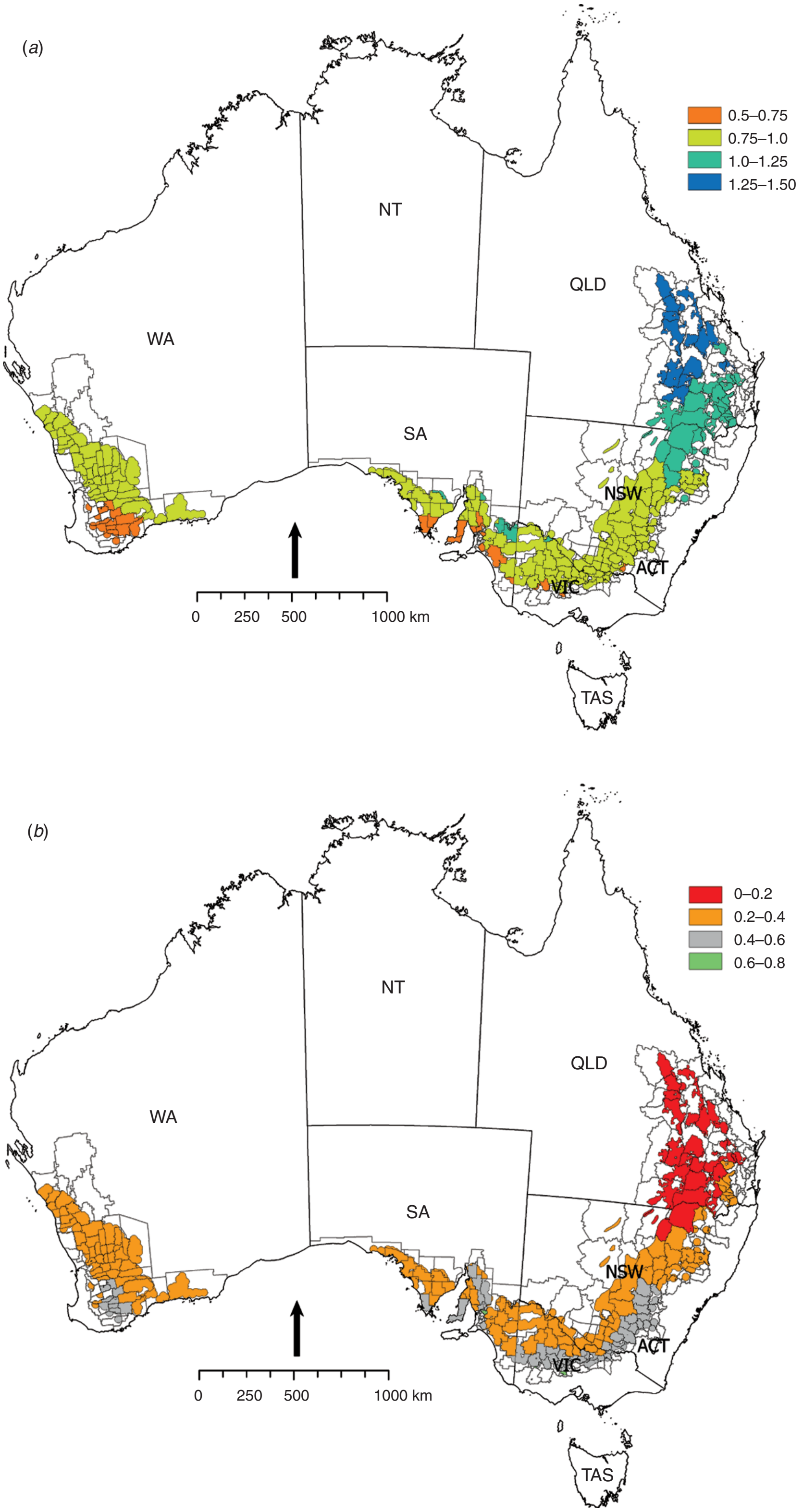

Fig. 3. (*a*) Vapour pressure deficit (kPa) and (*b*) normalised photothermal quotient (MJ/m^2.day.°C.kPa) in wheat-producing shires of Australia. Both variables are medians for the period 1975–2000 and correspond to a window from 20 days before to 14 days after anthesis.

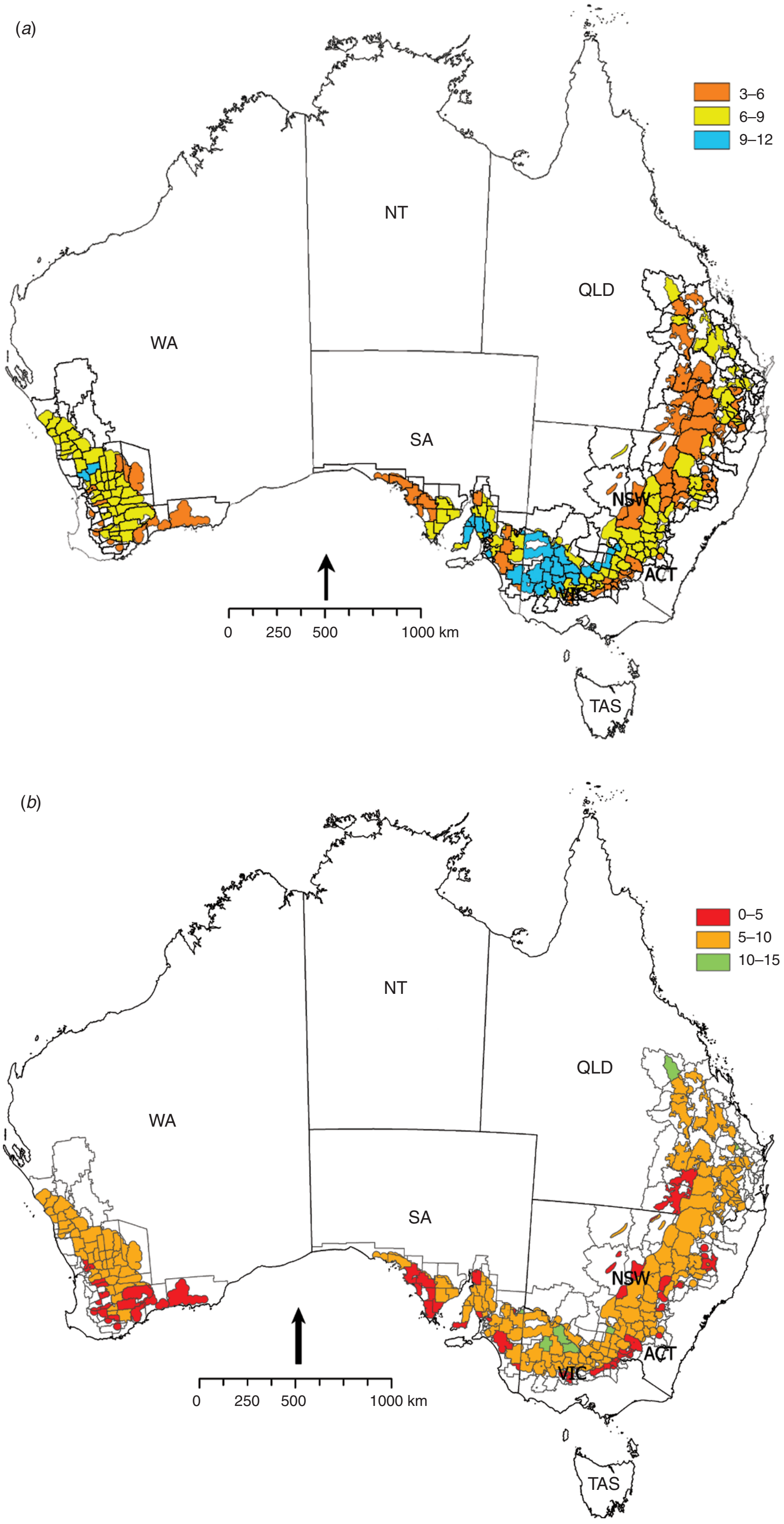

Fig. 4. (*a*) Water-use efficiency (kg/ha.mm), (*b*) water-use efficiency corrected by vapour pressure deficit (kg kPa/ha.mm), and (*c*) (facing page) water-use efficiency corrected by normalised photothermal quotient (kg/ha.mm per MJ/m^2.day.°C.kPa) in wheat-producing shires of Australia. All variables are medians for the period 1975–2000. Information contained in the variables increases from WUE to WUE$_{\mathrm{VPD}}$ to WUE$_{\mathrm{NPq}}$; hence, the need for an increasing number of categories in this sequence of maps.

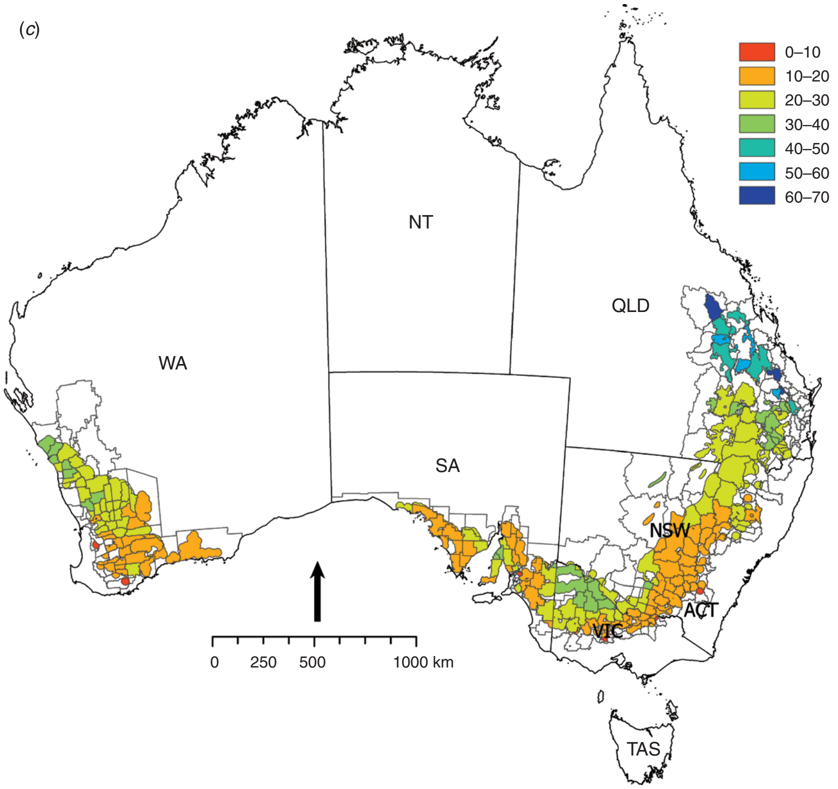

Fig. 4. (*continued*)

and the derived expression of WUE on a grain yield basis equivalent to Eqn 2:

$$\mathrm{WUE} = \frac{(\mathrm{B/T}) \cdot [(\mathrm{KN} \cdot \mathrm{KS})/\mathrm{B}]}{1 + \mathrm{E_s/T}} \qquad (6b)$$

where KN is kernel number and KS is average kernel mass. Biomass per unit transpiration is an inverse function of VPD (Tanner 1981; Sadras *et al.* 1991; Gregory *et al.* 1992; Kemanian *et al.* 2005; Haefele *et al.* 2009). Thus, for WUE defined on a biomass basis (Eqn 6a), correction by VPD is necessary and sufficient. However, for a definition of WUE on a grain yield basis (Eqns 2 and 6b), we also need to account for climatic factors that influence kernel number and size. Fischer (1985) demonstrated that wheat kernel number is proportional to a photothermal quotient in a window bracketing flowering, and Rodriguez and Sadras (2007) have expanded this index to account for VPD and fraction of diffuse radiation (Eqn 4). Furthermore, physiological and evolutionary evidence support the notion that not only kernel number but also potential kernel size are determined in this narrow phenological window (Sadras 2007; Sadras and Denison 2009; Yang *et al.* 2009). Collectively, these considerations provide a theoretical justification for using NPq to correct yield-based measures of WUE. For WUE on a biomass basis, correcting by NPq is theoretically unjustified. Limitations of NPq that stem from correlations between its components, e.g. high VPD is often associated with lower FDR and lower rainfall, have been discussed in detail (Rodriguez and Sadras 2007).

Application of WUE_{NPq}

The measure of WUE in Fig. 4*a*, where yield is divided by water use, has led to the conclusion that south-eastern and western regions perform better than the north-eastern grain region in Australia (Beeston *et al.* 2005; Walcott *et al.* 2006). For the eastern Australian wheatbelt, a positive correlation between NPq around anthesis and actual yield has been reported (Rodriguez and Sadras 2007). In contrast to the conclusions of Walcott *et al.* (2006), the normalisation of WUE with NPq indicates that the north-eastern region has WUEs as high as or even higher than those observed in the southern region. Among other factors, this might reflect the high degree of specialisation in the northern production systems where cropping land is less often shared with livestock enterprises. Of the 3 efficiencies compared in this study, only $\mathrm{WUE_{NPq}}$ captured the expected associations with rainfall, i.e. negative with seasonal rain and positive with off-season rain (Fig. 5).

A measure of WUE accounting for known climate drivers around a narrow critical window of grain yield determination is, we propose, a more robust means to identify low efficiencies and probe for causes (Fig. 4*c*). The south-western and western wheatbelt have been characterised by decline in soil nutrients and biological activity, soil acidification, surface soil structural decline, surface water logging, subsoil compaction, and

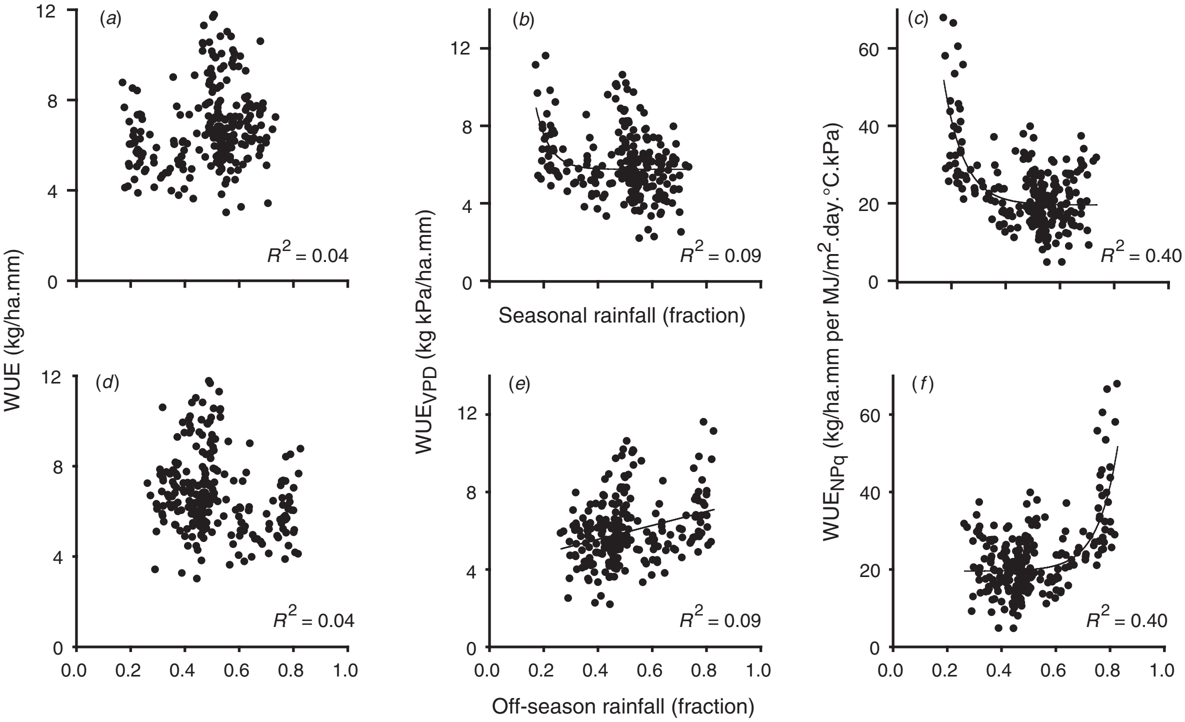

Fig. 5. Shire-level relationship between (*a*, *d*) water-use efficiency (WUE, Eqn 2), (*b*, *e*) water-use efficiency corrected by vapour pressure deficit (WUE$_{VPD}$, Eqn 3), and (*c*,*f*) water-use efficiency corrected by normalised photothermal quotient (WUE$_{NPq}$, Eqn 5) and (*a*–*c*) seasonal or (*d*–*f*) off-season rainfall expressed as fractions of annual rain. All variables are medians for the period 1975–2000.

secondary salinity from rising ground-water (Rengasamy 2002; Williams *et al*. 2002). Stephens (2003) suggested that high rates of drainage and water-logging on duplex soils reduce WUE in wetter districts of Western Australia. Similarly, low efficiencies 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). In the South Australian Eyre Peninsula, subsoil chemical constraints, i.e. salinity and sodicity, are widespread (Rengasamy 2002). Subsoil chemical constraints and water repellency have been invoked as factors reducing WUE in this region (Stephens 2003). Low WUE in south-eastern Queensland can be partially related to subsoil salinity (Dang *et al*. 2006). Soil acidification and decline in soil nutrients and biological activity (Williams *et al*. 2002) are likely sources of inefficiencies in shires from the central, Northern Tablelands and Granite Belt, Western Downs, and New South Wales Slopes and Plains.

Shire-level yield tended to level off at around 2 t/ha in relation to both water use and normalised photothermal quotient (Fig. 2*a*, *c*). This is consistent with crop-level modelling and measurements in central Western Australia (Asseng *et al*. 2001*b*), the Mallee region of south-eastern Australia (Sadras and Roget 2004; Sadras 2005), and more broadly across diverse agro-climatic zones of the Australian wheatbelt (Hochman *et al*. 2009), where shortage of nitrogen contributes to a comparable ceiling at around 2 t/ha.

Conclusions

The effects of major climate drivers, namely vapour pressure deficit, radiation, diffuse radiation, and temperature, can be integrated to improve the quantification of water use efficiency. This is particularly important for regional characterisations or where these climatic factors vary substantially for other reasons. We further propose a focus on the critical period of grain yield determination, rather than on the whole season.

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