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Water use efficiency in Western Australian cropping systems

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ABSTRACT

Rotations and associated management practices in rainfed farming systems of southwest Australia have shifted towards intensified cropping. Survey data from 184 fields spanning 14 Mha of southwest Australia were used to document water use efficiency (WUE) and water-limited yield potential (WLYP) of commercial crops and crop sequences and identify biophysical variables influencing WUE. WUE achieved in commercial wheat crops was 10.7 kg grain/ha.mm. Using a boundary function Ywl = 25 × (WU − 45), farmers achieved 54% of WLYP. Climate variables affected WUE more than management and biotic variates, the highest latitude region having WUE of 9.0 kg grain/ha.mm, compared to 11.8 kg grain/ha.mm for regions further south. Increased soil nitrogen and nitrogen fertiliser increased WUE, as did sowing earlier; in keeping with farmers in southern Australia sowing crops earlier and trebling fertiliser nitrogen usage since 1990. Wheat yield and WUE increased a small amount after break crop or pasture (12.5 kg grain/ha.mm) compared to wheat grown after wheat (11.2 kg grain/ha.mm), due to good weed and root pathogen control, and high fertiliser nitrogen application. However, WUE of wheat declined to 8.4 kg grain/ha.mm when more than three wheat crops were grown in succession. Farmers continue to improve WUE with increased inputs and new technologies replacing some traditional functions of break crops and pasture. However, break crops and pastures are still required within the rotation to maintain WUE and break effects need to be measured over several years.

Keywords: agronomy, break crop, canola, legumes, rotation, water use efficiency, wheat, yield potential.

Introduction

Western Australia has a Mediterranean-type climate, with water availability frequently limiting yield. The efficiency of converting water to grain is commonly termed water use efficiency (WUE) and is reported as the ratio of grain yield to total water used (Angus and van Herwaarden 2001). Mean WUE for wheat (*Triticum aestivum*) in southern Australia has been estimated at 9.9 kg grain/ha.mm which is equal to, or above, comparable dryland farming environments: China Loess Plateau 9.8, northern Great Plains 8.9, Mediterranean Basin 7.6 and southern-central Great Plains 5.3 (Sadras and Angus 2006).

It is estimated that wheat yields from dryland farms in southern Australia increased from ~35% of maximum attainable water-limited yield in 1980 to ~60% of attainable yield by 2021 (Hochman *et al.* 2016; Anderson *et al.* 2017; Hochman and Horan 2018; Hunt *et al.* 2021). Growers have closed the gap between achieved and water-limited yields through improved agronomic management practices, varieties and technological gains (Fischer *et al.* 2014; Hochman *et al.* 2017). These gains are evidenced by increased transpiration efficiency, from 20 to 24 kg grain per mm transpired, and reduced lowest theoretical soil evaporation, from 110 mm to 60 mm, in southern Australia over the period 1984–2006 (French and Schultz 1984*a*; Sadras and Angus 2006; Sadras and Lawson 2013).

Hence, there have been two mechanisms by which WUE has increased: greater transpiration efficiency and increasing the proportion of rainfall transpired (reducing soil evaporation and or losses to run-off and drainage below the root zone). These mechanisms are intrinsically linked (Fischer 2009), i.e. simultaneous breeding for high harvest index (Perry and D'Antuono 1989; Slafer and Andrade 1991; Sadras and Lawson 2011), combined with implementation of conservation agriculture methods to minimise soil evaporation (French and Schultz 1984*b*; Siddique *et al.* 1990; Blum 2009; Llewellyn *et al.* 2012; Llewellyn and Ouzman 2019) facilitate earlier sowing (Stephens and Lyons 1998; Fletcher *et al.* 2016; Anderson *et al.* 2017) and maximise water for the period around flowering when wheat sets seed number (Fischer 1985) and transpiration efficiency for grain production is greatest (Angus and van Herwaarden 2001).

Studies benchmarking the yield of wheat in southern Australia report a wide variation in water-limited yield compared to farm yield achieved, which is commonly termed the yield gap. For example, recent field surveys reported leading farmers were achieving ~80% of water-limited yield potential (van Rees *et al.* 2014; Lawes *et al.* 2021) compared to estimates of 50–60% based on mean industry level data and simulation analyses (Hochman *et al.* 2016; Anderson *et al.* 2017; Hochman and Horan 2018) and estimates ranging ~35–70% at the local government level (Hochman *et al.* 2021).

The concept of the yield gap has been applied widely (van Ittersum *et al.* 2013) to determine the extent of yield improvements that are achievable, with four methods commonly employed: (1) field experiments, (2) yield contests (farmer yield competitions), (3) maximum farmer yields based on surveys, and (4) crop model simulations. Instances of highest WUE give an estimate of the highest yields attainable through best practice implementation of technologies to mitigate constraints other than water availability (Fischer *et al.* 2014). The magnitude of the yield gap gives an indication of yield lost due to constraints other than water (French and Schultz 1984*b*; Sadras and Angus 2006). In south-eastern Australian farming systems, commonly identified constraints limiting WUE include: climate variables (frost, heat stress and high vapour pressure deficit), plant nutrition (particularly nitrogen), delays in seeding, competition from weeds both in fallow and crop, root disease, soil constraints (pH, salinity, sodicity, nutrient toxicities) and low seeding density (French and Schultz 1984*b*; Sadras *et al.* 2002; Hochman *et al.* 2009; Kirkegaard *et al.* 2014; Hochman and Horan 2018; Hunt *et al.* 2020).

Traditionally crop and pasture rotations have been used to manage some of these constraints, in particular nitrogen, diseases and weeds, with break crops or pastures employed to reduce diseases and weeds building up or nitrogen depleting in continuous sequences of wheat (Liebman and Dyck 1993; Krupinsky *et al.* 2002; Kirkegaard and Hunt 2010; Lin and Chen 2014). The increase in WUE in the subsequent wheat after a break crop or pasture compared to monoculture wheat is dependent on the extent of the mitigation of production constraints. For example, van Rees *et al.* (2014) concluded that leading farmers effectively controlled weeds and diseases to obtain WUE of up to 82%. However, this study only included wheat grown after break crops and the role of break crops in controlling weeds and disease was not discussed. Similarly Lawes *et al.* (2021) reported farmers achieved 80% WUE across southern Australia, with yield potential of the crop and nitrogen nutrition being the most prominent contributors to the yield gap, followed by biotic stresses. Kirkegaard *et al.* (2014) analysed a wider set of farm data, concluding that improvements to WUE of between 16 and 83% could be achieved by including more break crops within Australian dryland farming systems. Experimental data also provides many examples of increased yield and WUE when wheat is sown after a break crop or pasture, compared to when sown after wheat (Kirkegaard *et al.* 2008; Seymour *et al.* 2012; Angus *et al.* 2015; Gan *et al.* 2015).

In recent decades there have been substantial changes in rotations throughout southern Australia, with an intensification of cropping and a decline in legume pasture production (Kirkegaard *et al.* 2011). Within southwest Australia, farm area dedicated to pasture declined by up to 30% in some agroecological zones between 2000 and 2015 (Planfarm and Bankwest 2016) and sheep numbers decreased from 26 to 14 million head between 2005 and 2015 (ABS 2016). The increased area sown to crop has been accompanied by a move towards cereal and oilseed crops across most agroecological zones of southwest Australia (Harries *et al.* 2015; Planfarm and Bankwest 2016), with grain legume production declining by 0.7 million hectares from 2000 to 2015 (ABS 2016). Assessments of WUE under these new cropping systems are constrained by a scarcity of field data sets containing both biophysical measurements and management actions (Lacoste 2017).

Our research objective was to investigate WUE of different crops and crop sequences in the growing regions of southwest Australia and to identify which biophysical variables had the greatest influence on WUE of wheat, the most commonly grown crop. We do this by studying relationships between crop WUE and a wide range of biotic and abiotic constraints measured from a series of selected fields over the period 2010–2015. Additionally we use this set of data to update boundary functions of water-limited yield potential for southwest Australia, as originally proposed by French and Schultz (French and Schultz 1984*a*).

Materials and methods

Data sources

Data were obtained from the 'Focus Paddocks' database (Harries *et al.* 2015), which pairs records of biophysical measurements of weeds, soil borne diseases and soil chemical and physical properties to land management actions from the same fields over the period 2010–2015. This comprised 184 fields across southwest Australia (Fig. 1). Field measurements were from a geo-referenced one hectare area within each field. Farmers who managed the Focus Paddocks were interviewed annually, providing information on land use, agronomic inputs and insights into management rationale. Wheat was grown in all fields in the first year of monitoring, followed by farmer-specified land uses in the following years. Climate data were obtained for each field using the SILO (Scientific Information for Land Owners) database (Jeffrey *et al.* 2001). Mean daily air temperature was calculated for each field-year as (maximum daily temperature + minimum daily temperature)/2. Soil classification data appear in Harries *et al.* (2015).

Field measurements

The one hectare area was divided into four replicates of 25 m by 100 m and sampling was conducted in a zig-zag transect through each. Detailed descriptions of sampling and analytical methods are available in Harries *et al.* (2020, 2021). Soil was taken prior to seeding each year with 990 field-years sampled at 0–10 cm from 2010 to 2015 inclusive. In brief, chemical analyses included the Rayment and Lyons (2011) method 7C2b, nitrate and ammonium, 9B, $P_{Colwell}$ and $K_{Colwell}$; 10D1, S_{KCl40}; 4B41, pH_{CaCl2}; 3A1, EC and 6A1, soil organic carbon (SOC) (Walkley-Black), with nitrate and ammonium added together to give soil mineral nitrogen (N) content. Texture was assessed using a bolus ribbon technique (Schoknecht and Pathan 2013). Soil for PreDictaB assays (Ophel-Keller *et al.* 2008), which measures pathogen DNA and nematode eggs, was taken near anthesis (August–October) from 804 field-years from 2010 to 2015 inclusive. Visual scores of plant root damage at anthesis (Zadoks 65) (Zadoks *et al.* 1974) were made from 40 plants within the one hectare area, with 10 per replicate. An overall rating (0–5) of percentage severity of root damage (SRD) caused by root pathogens was given: 0 = (no disease), 1 = 1–5% (trace disease), 2 = 6–25% (low amount of brown lesions), 3 = 26–50% (medium amount of brown lesions, similar amounts of healthy and necrotic), 4 = 51–75% (most of the roots covered in brown lesions, little healthy root left) and

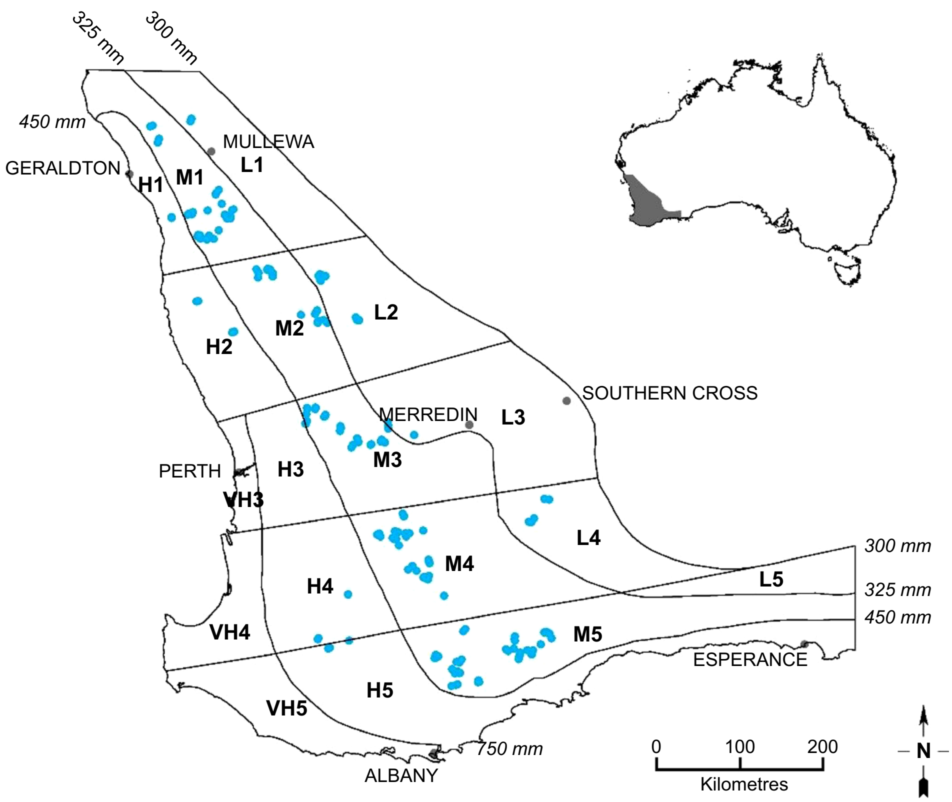

Fig. 1. Location of 184 survey paddocks (blue dots) from 2010 to 2015 in the south-west of WA. Boundaries depict Western Australian Department of Primary Industries and Regional Development (DPIRD) agroecological zones according to rainfall. Letters refer to rainfall zones: VH, very high; H, high; M, medium; L, low. Numbers refer to regions: Northern (1 and 2), Central (3 and 4) and Southern (5) Agricultural Regions.

5 = 75–100% (all or nearly all roots covered in brown lesions or short brown stumps), similar to the method of McDonald and Rovira (1985). Grass weed density was measured near anthesis, with 752 field-years of data accumulated from 2010 to 2014 inclusive. Farmer records of fertiliser and herbicide inputs were collated from 644 and 614 field-years respectively, spanning 2010–2014 inclusive. Grain or seed yield and above ground biomass was measured for 648 field-years, from one hand cut of 1.0 m of row per replicate, with grain air-dried to ~10.5% moisture content; this comprised 45 field-years of barley (*Hordeum vulgare*), 79 canola (*Brassica napus*), 48 lupin (*Lupinus angustifolius*), 465 wheat and 11 other crops, which included chickpea (*Cicer arietinum*), faba bean (*Vicia faba*) and field pea (*Pisum sativum*). Nitrogen fixation was estimated from above ground biomass of grain legumes and pasture species, as described in detail in Harries *et al.* (2021). Dates of field observations at seedling, flowering and maturity stages were used to divide plant development into three periods for the analysis of temperature and rainfall effects on WUE: (1) 'pre-flowering period' – Zadoks 1 (seedling) to 14 days prior to Zadoks 65 (flowering); (2) 'flowering period' – 14 days prior to the start of flowering to 14 days after the start of flowering; (3) 'post-flowering period' – 14 days after flowering to Zadoks 89 (maturity). Variates used for analyses are presented in Table 1.

Water use efficiency

Water use efficiency (WUE) can be expressed as:

$$\mathrm{WUE} = \frac{Y}{\mathrm{Es} + T}, \tag{1}$$

where Y = yield, Es = evaporation and T = transpiration (Tennant 2000). This assumes that there is no run-off or drainage, as assumed in previous calculations of crop water use in semi-arid agroecosystems (French and Schultz 1984*a*; Tennant 2000; Angus and van Herwaarden 2001; Hochman *et al.* 2009). Furthermore, French and Schultz (1984*a*) showed that in South Australia Es + T, which is commonly referred to as water use (WU) and/or evapotranspiration (ET), is similar to the amount of rain received in the growing season, April–October. This approximation of rainfall to WU has subsequently been refined across southern Australia by adding a proportion of 'fallow season' (summer) rainfall to growing season rain to estimate WU (Tennant 2000; Oliver *et al.* 2009; Hunt and Kirkegaard 2012). Because farmers and agronomists readily emulate this method to produce 'French and Schultz' type equations, we used this approach to estimate WU for each field-year, as (0.25 × January–April rainfall + growing season rainfall), and for calculations of WUE. We compared this estimate of WU with inclusion of previous November and December rainfall, to check if rain in these months affected WUE, and checked against model-simulated estimates of ET for each paddock-year obtained by running APSIM 7.9 (Holzworth *et al.* 2014). APSIM simulations used daily gridded SILO rainfall data for each paddock coordinate with WU calculated as evaporation + transpiration over the growing period of each crop. A simulation for each paddock was run over the period of the study. Sowing date was as per actual sowing date, nitrogen was non-limiting and soils were selected from the APSOIL database. Soils were categorised for plant available water holding capacity (PAWC) based on soil characterisations; high APSOIL# 512 (135 mm PAWC), medium APSOIL# 510 (90 mm PAWC), and low APSOIL# 507 (57 mm PAWC). This method was used because soils were not characterised for water holding capacity, and for this reason we did not undertake more detailed APSIM modelling analysis. We also present WUE corrected for vapour pressure deficit (VPD) within the flowering period ($\mathrm{WUE_{VPD}}$), because this has previously been used to compare between regions (Doherty *et al.* 2009):

$$\mathrm{WUE_{VPD}} = \frac{Y}{\mathrm{WU/VPD}} \tag{2}$$

For a more detailed description of WU calculations, see Supplementary material (S1).

Maximum water use efficiency and associated water-limited yield potential

Water-limited yield potential was estimated by fitting a linear frontier or boundary function against the instances of greatest WUE from the survey, based on farmer yield and WU (Webb 1972; Casanova *et al.* 2002; Sadras and Angus 2006; Lobell *et al.* 2009; van Loon *et al.* 2018; Houshmandfar *et al.* 2019; Sadras 2020). For wheat, a method modified from Casanova *et al.* (2002) was used: yields were plotted in WU deciles from 0 to 300 mm and a linear regression fitted using the upper 95% confidence limit of the normal distribution of yield in each decile. This regression equation was used to calculate water-limited potential yield and yield gaps from observed yields. For other crop species there was not enough data to use the aforementioned method, hence frontier lines were visually fitted to high WUE crops, an approach used by French and Schultz (1984*a*).

Statistical analysis

Relationships between variates in Table 1 and WUE of wheat were investigated using several analyses. Firstly principal component analyses (PCA) were conducted using data from all regions combined. This approach was limited by data gaps in farmer records and field monitoring, hence three analyses were undertaken: (1) meteorological variates, (2) management and biotic variates and (3) all variates

Table 1. Variates used to investigate WUE; abbreviated variate name, description and unit.

Variate	Description	Unit
Reg	Region	NAR, CAR, SAR
T	Daily temperature	°C
R	Cumulative sum of daily rainfall	mm
VPD	Vapour pressure deficit	kPa
RAD	Solar radiation	MJ/m^2
DOS	Day of sowing	Julian day of year
H	Number of herbicides applied	n
W	Weed density	m^2
FN	Fertiliser nitrogen applied	kg/ha
FP	Fertiliser phosphorous applied	kg/ha
FK	Fertiliser potassium applied	kg/ha
FS	Fertiliser sulfur applied	kg/ha
N	Soil N concentration (NO_3^- + NH_4^+) prior to sowing (0–10 cm)	mg/kg
P	Soil phosphorus concentration prior to sowing (0–10 cm)	mg/kg
K	Soil potassium concentration prior to sowing (0–10 cm)	mg/kg
S	Soil sulfur concentration prior to sowing (0–10 cm)	mg/kg
SOC	Soil organic carbon (0–10 cm)	%
EC	Soil electrical conductivity (0–10 cm)	dS/m
pH	Soil pH (0–10 cm)	$CaCl_2$
TEX	Soil texture; bolus ribbon length	mm
TA	*Gaeumannomyces graminis* var. *tritici* (take-all)	pg DNA/gram soil
RH	*Rhizoctonia solani AG-8*	pg DNA/gram soil
PN	*Pratylenchus neglectus*	nematodes/gram soil
CR	*Fusarium culmorum* and *F. pseudograminearum* (crown rot)	pg DNA/gram soil
SRD	Visual root damage score	% severity
Nin	Nitrogen balance in year prior + fertiliser nitrogen applied current year	kg/ha

Note: temperature and rainfall data were assessed within the three plant development periods described above, denoted as PrF (pre-flowering), F (flowering), PoF (post-flowering). Rain was also assessed for the calendar year (AR) and summer fallow period (SR). Rain and mean temperature were assessed for the growing season (GSR, GSavT respectively). Temperature data were stratified into daily maximum, minimum and mean (max + min)/2. Monthly average mean temperature and total rainfall data were used to investigate regional climate effects on WUE. Variates other than T, R, VPD, RAD and Nin are referred to collectively as management and biotic variates.

NAR, northern agricultural region; CAR, central agricultural region; SAR, southern agricultural region.

TEX: 1 = sand little ribbon coherence, 1.5 = loamy sand 5–15 mm ribbon, 2.0 = loam 20–25 mm ribbon, 2.5 = clay loam 45–50 mm ribbon, 3.0 = clay 60–65 mm ribbon, 3.5 = heavy clay 75 mm + ribbon (Schoknecht and Pathan 2013).

Nin: nitrogen balance from previous year = fertiliser and legume inputs − grain exports. See Harries *et al.* (2021) for calculation method.

together. The PCA analysis of all variates is presented in this manuscript; results of all three PCA analyses are provided in Supplementary material S3. Relationships with WUE were investigated visually by categorising all points on the biplot by their WUE (categorised as high, medium or low). Secondly regional differences in variate relationships to WUE were explored using univariate regression and chi-squared goodness of fit tests. Thirdly, three regression tree analyses were conducted using the r.part package within R (Therneau and Atkinson 2019): first with all variates in Table 1; second excluding meteorological variates, to examine management and biotic effects; and third with weeds, plant root damage and nitrogen inputs (Nin) and wheat crops sown in the year after canola, lupin and pasture, to examine break effects.

Analyses were conducted using R statistics software version 3.6.0. (The R Foundation 2019). Shapiro–Wilk tests and QQ plots were used to test normality and transformations applied prior to ANOVA if required. If significantly different ($P \leq 0.05$), appropriate tests such as unpaired *t*-tests and their pairwise comparisons or Tukey HSD tests were applied. Correlation coefficients were calculated using the Pearson method. All data presented were back transformed if relevant.

Results

Land use

Regionally, more fields were sown to wheat and lupin in the northern agricultural region (NAR), while more fields were used for pasture and barley in the southern agricultural region (SAR). Canola accounted for around 12% of field-years in each region, (Fig. 2) and pastures and grain legumes combined accounted for 21% of field-years. Notably, barley was seldom grown prior to wheat, with only five occurrences within the dataset; there were only two records of five wheat crops in succession; ~5% of fields had four wheat crops in succession; and ~20% of fields had three wheat crops in succession. These results are similar to industry level data (ABS 2016; Planfarm and Bankwest 2016); for more detail on land use see Harries *et al.* (2020).

Climatic conditions and comparison of WU estimation methods

There were large differences in rainfall between years and regions, with annual rainfall ranging 196–546 mm (Fig. 3*a*). Growing season rainfall was < 300 mm in 83% of paddock-years. Analysis of mean daily air temperature, °C (max + min)/2, of each field over the years 2010–2015, showed temperature increased with latitude (Fig. 3*b*). There were more days within the growing season with maximum air temperature > 30°C in the NAR (9.7) and the central agricultural region (CAR) (9.4) compared to the SAR (4.1) (Fig. 3*c*) and more days with minimum air temperature < 0°C in the CAR (4.8) compared to the NAR (0.03) and SAR (0.28) (Fig. 3*d*). Mean observed flowering (Zadoks 65) dates by region were: NAR 14 September (s.d. 14 days), CAR 3 October (s.d. 9), SAR 18 September (s.d. 15). The late flowering date in the CAR was due to limited sowing opportunities in some seasons, particularly 2010, when the mean sowing date in this region was 27 May (s.d. 19 days). Inclusion of November and December rain increased mean WU by 5 mm, making little difference to WUE. There was a strong correlation (*r* = 0.85) between our estimated WU and model-APSIM simulated ET. This correlation increased to 0.90 when data was restricted to paddock-years in which wheat was grown, with APSIM predicting a mean ET of 211 mm compared to our estimate of 221 mm.

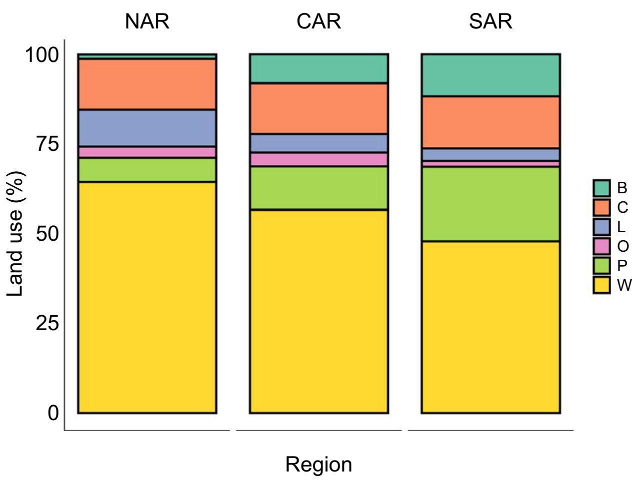

Fig. 2. The proportion of each land use category within the Focus Paddock database grouped by DPIRD Region; (B, barley; C, canola; L, lupin; O, other; P, pasture; W, wheat).

Yield, dry matter and water use efficiency by land use and region

For barley, canola, lupin and wheat there were strong positive relationships between plant biomass and yield ($r \geq 0.87$) (Figure S2 supplementary material). The mean yield of barley was greater than all other land uses ($P < 0.001$), conversely canola yielded less than wheat and barley ($P < 0.001$) and lupin ($P = 0.003$) (Table 2). Mean yields from each region were different ($P < 0.001$). Mean WUE was greatest for barley ($P < 0.006$), followed by wheat and then lowest for canola and lupin, which were different from each other ($P = 0.019$). Water use efficiency was lower in the NAR compared to the other regions ($P < 0.001$) (Table 2); for wheat 9.0, 11.8 and 11.9 kg grain/ha.mm for the NAR, CAR and SAR respectively. WUE_{VPD} was lower than WUE in the SAR, due to low VPD at flowering, but WUE and WUE_{VPD} were similar in the NAR and CAR, such that each region had different WUE_{VPD} ($P < 0.05$, Table 2).

Analysis of main constraints impacting WUE of wheat

We sequentially report the analyses including all variates, then temperature and rain variates, then management and biotic variates and finally the impacts of rotation and break crops.

Multivariate analyses

Principal components (PC) 1 and 2 accounted for 69% of the variability in the data when using meteorological variates and 23% of the variability in the data when using management and biotic variates, with regions segregating on meteorological variates but not on management and biotic variates (Fig. 4, see Supplementary material S3 for more detail). PCA including all variates (meteorological, management and biotic), had PC1 and PC2 accounting for 34% of the variability in the data and regional segregation (Fig. 4*a*).

Biplots showed WUE (categorised as high, med and low) segregated strongly based on meteorological variates and weakly based on management and biotic variates (see Supplementary material S3 for more detail). When meteorological and management and biotic variates were

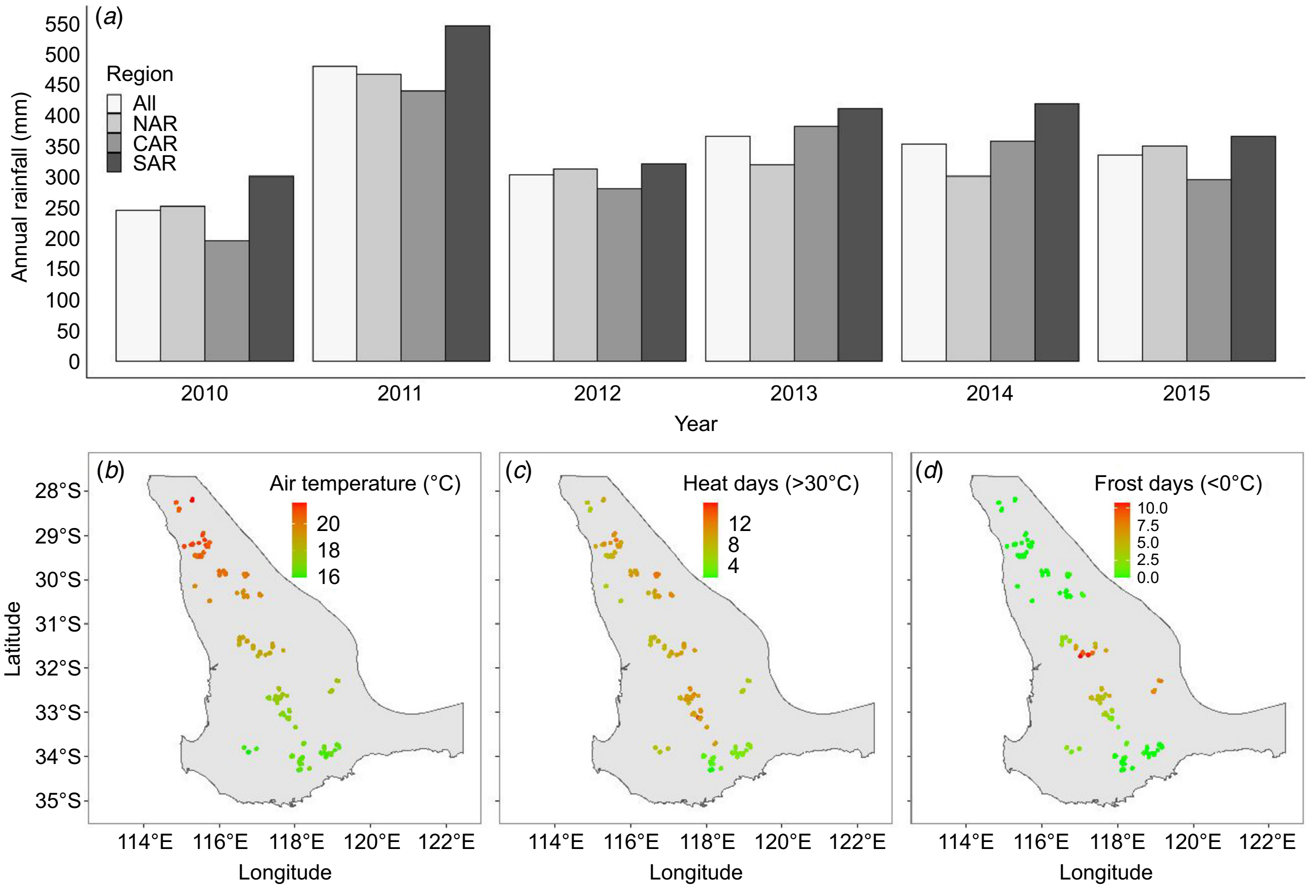

Fig. 3. Climatic data for southwest Australia averaged across 2010–2015 for all paddocks (points in figures *b*–*d*) in the study, including: (*a*) annual rainfall (mm) for the Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR); (*b*) mean daily air temperature °C (max + min)/2; (*c*) heat days, or the number of days with maximum temperature > 30°C within the growing season; and (*d*) frost days, or the number of days with minimum temperature < 0°C within the growing season.

Table 2. Mean yield, growing season rainfall and water use efficiency for main land uses and regions; Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR).

Land use or region	Yield (kg/ha)	GSR (mm)	WU (mm)	WUE (kg/ha.mm)	WUE_{VPD} (kg.kPa/ha.mm)
Barley	3217a	236 (68)	259 (66)	12.4a	10.1a
Canola	1646d	274 (87)	295 (90)	5.6d	4.6b
Lupin	2210c	291 (79)	312 (82)	7.1c	5.7b
Wheat	2460b	213 (73)	231 (77)	10.7b	9.7a
NAR	1865c	221 (75)	238 (79)	7.8b	8.0b
CAR	2393b	205 (71)	224 (74)	10.7a	10.9a
SAR	3397a	294 (74)	318 (74)	10.7a	7.2c

Values in parenthesis are standard deviations. Different letters indicate differences at $P < 0.05$.

plotted together, WUE did segregate into low and high WUE (Fig. 4*a*, *b* – low WUE towards the top left and high WUE towards the bottom right). The biplot and the associated eigenvectors (Table 3) showed that as PC1 increases towards higher WUE there is increased soil organic carbon, flowering and post-flowering rain and decreasing vapour pressure deficit, solar radiation and temperatures, which are associated with the SAR (Fig. 4*a*, *b*). As PC2 increases towards lower WUE there is a decrease in the rain at flowering, fertiliser nitrogen, pH and an increase in

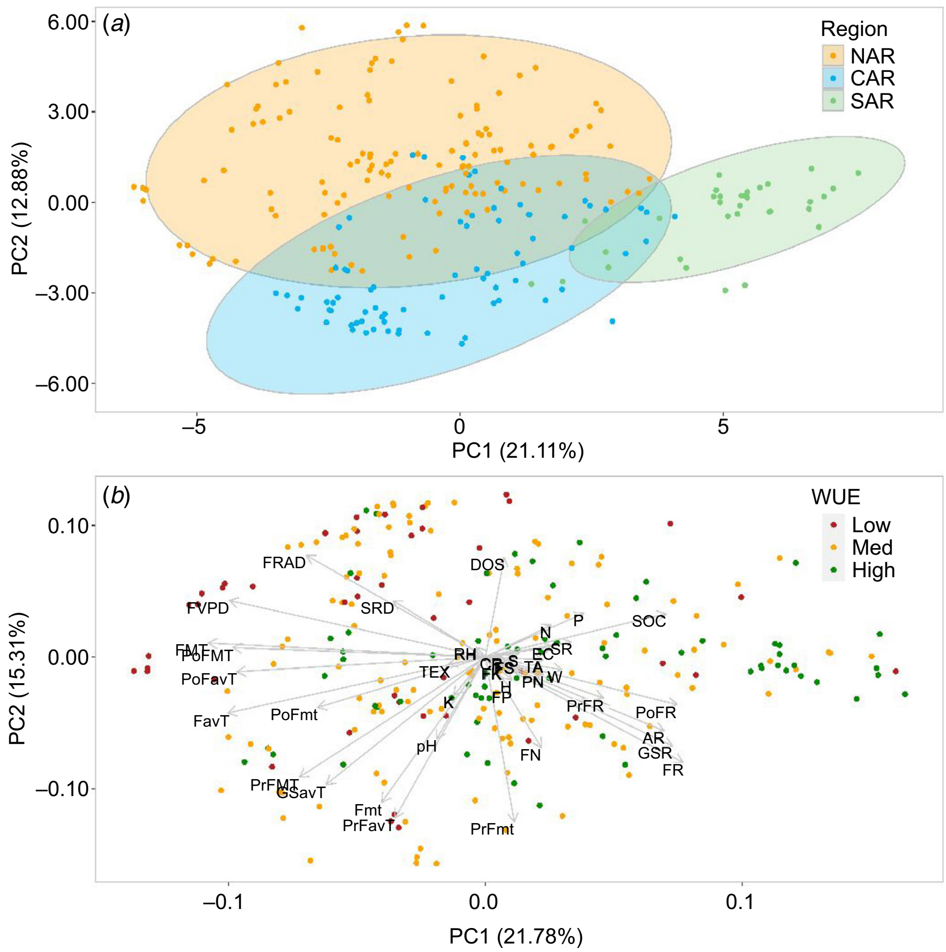

Fig. 4. Principal component analyses of (*a*) meteorological and management/biotic variates combined grouped by region [Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR)], ellipses at 95% confidence interval and (*b*) biplot of meteorological and management variates combined grouped by WUE (Low $\leq$ 6.4 kg/mm, Med = 6.4–12.5 kg/mm, High $\geq$ 12.5 kg/mm). Variates include pre-flowering maximum air temperature (PrFMT), pre-flowering minimum air temperature (PrFmt), pre-flowering mean air temperature (PrFavT), pre-flowering rain (PrFR), flowering maximum air temperature (FMT), flowering minimum air temperature (Fmt), flowering mean air temperature (FavT), flowering rain (FR), post-flowering maximum air temperature (PoFMT), post-flowering minimum air temperature (PoFmt), post-flowering mean air temperature (PoFavT), post-flowering rain (PoFR), vapour pressure deficit at flowering (VPD), solar radiation at flowering (FRAD), annual rain (AR), summer rain (SR), growing season rain (GSR), day of sowing (DOS), number of herbicides applied (H), grass weed density (W), fertiliser nitrogen applied (FN), fertiliser phosphorus applied (FP), fertiliser potassium applied (FK), fertiliser sulfur applied (FS), soil test concentrations of mineral (N), phosphorus (P), potassium (K) and sulfur (S) in 0–10 cm layer, soil texture (TEX), *Gaeumannomyces graminis* var. *tritici* (take-all, TA), *R. solani AG-8* (rhizoctonia, RH), *P. neglectus* (nematode, PN), *Fusarium* sp. (crown rot, CR) and severity of root damaged (SRD).

vapour pressure deficit, solar radiation, severity of plant root damage, sowing date (later sowing) and most flowering and post-flowering temperature variates.

Regression tree analysis using all variates (Table 1) had a relative error of the regression of 0.41 and an R^2 of 0.59. As with the PCA, climate variables were better predictors of WUE than management or biotic variates, contributing 18 of the 19 most important predictors. For most splits within the tree lower WUE was associated with variates associated with high evaporative demand, although this was countered by rain at and after flowering at some nodes. Hence, both the PCA and regression tree analyses indicate warmer dryer conditions,

Table 3. Eigenvectors for principal components of meteorological and management/biotic constraints on WUE (from Fig. 4).

Component	Variate	Eigenvectors	
		PC1	PC2
Environment	AR	0.21	−0.17
	GSR	0.22	−0.20
	GSavT	−0.19	−0.29
	PrFMT	−0.22	−0.28
	PrFmt	0.03	−0.38
	PrFavT	−0.11	−0.37
	PrFR	0.14	−0.09
	FMT	−0.33	0.03
	Fmt	−0.12	−0.33
	FavT	−0.30	−0.13
	FR	0.23	−0.24
	FRAD	−0.21	0.23
	FVPD	−0.30	0.13
	PoFMT	−0.30	0.02
	PoFmt	−0.20	−0.12
	PoFavT	−0.29	−0.03
	PoFR	0.23	−0.11
Management	SR	0.10	0.03
	DOS	0.02	0.23
	H	0.03	−0.05
	FN	0.07	−0.21
	FP	0.03	−0.08
	FK	0.02	−0.02
Soil	FS	0.03	−0.01
	N	0.08	0.07
	P	0.12	0.10
	K	−0.04	−0.09
	S	0.04	0.01
	SOC	0.21	0.10
	EC	0.08	0.02
	pH	−0.06	−0.19
Biotic	TEX	−0.04	−0.02
	W	0.09	−0.03
	TA	0.07	−0.01
	RH	−0.01	0.02
	PN	0.07	−0.04
	CR	0.02	0.00
	SRD	−0.11	0.13

PC, principal component, see Table 1 for descriptions of variate acronyms.

particularly around flowering, were most important in reducing WUE. See Supplementary material S4 for a more detailed description of this regression tree analysis.

Regional temperature and rainfall effects

For months early in the year (January–May) in NAR fields, more rain and higher temperatures were related to increased WUE (Table 4). For later months the results were less clear, with increased temperatures reducing WUE in some months (August and November) and rainfall coefficients negative for most months, except September (Table 4). Analyses of mean maximum air temperature and rainfall in the flowering period provided additional evidence of the effects of these variables on WUE. From the chi-squared goodness of fit tests the likelihood of achieving high WUE (top quartile, ≥ 11.2 kg grain/ha.mm) was 11 times greater when mean maximum air temperature in the flowering period was < 25°C than when it was > 25°C ($P = 0.035$); the 32 paddock-years > 25°C with a mean WUE of 5.3 kg grain/ha.mm compared to 8.6 kg grain/ha.mm for those < 25°C. For rainfall, 22% of paddock-years received < 15 mm of rain in the flowering period and these were 7.5 times less likely to achieve high, ≥ 11.2 kg grain/ha.mm, WUE ($P = 0.025$).

For CAR, fields' monthly data indicated more rain and higher average monthly mean (daily min + max)/2 temperatures increased WUE, with few negative coefficients (Table 4). Analysis of air temperature during the growing season supported the monthly data results; increased minimum growing season temperature increased WUE ($P < 0.001$) and goodness of fit tests of mean growing season temperature indicated < 17.2°C resulted in 4.6 times less chance of achieving high WUE, in the top quartile ≥ 13 kg grain/ha.mm ($P = 0.030$). There was a noticeable decline in WUE when maximum air temperatures at flowering decreased to < 22.8°C ($P < 0.001$), with paddocks below this temperature six times less likely to achieve high WUE.

For SAR fields, monthly data indicated more rain in the growing season reduced WUE, with most months having a negative coefficient (Table 4). Analysis of pre and post-flowering rain provided further evidence of this. A negative response ($r = −0.44$) of WUE was observed to pre-flowering rain; goodness of fit tests showing > 92 mm (top quartile) decreased likelihood of achieving high WUE (top quartile ≥ 14.5 kg grain/ha.mm) by 4.6 times ($P = 0.049$), with the same effect if post-flowering rain exceeded 127 mm ($P < 0.001$). Monthly temperature data had an inconsistent effect on WUE (Table 4). A temperature effect was more apparent from analysis of mean daily air temperature during the growing season with a weak trend ($P < 0.001$), of increased WUE with increasing temperature ($r = 0.30$). The goodness of fit tests for this indicted likelihood of achieving high WUE was four times less likely when mean maximum air temperature over the growing season was < 16.5°C ($P = 0.009$). Conversely, lower maximum temperature at flowering tended to increase WUE ($r = 0.40$), where maximum temperature > 21.2°C resulted in a mean WUE of 6.4 kg grain/ha.mm, and sixteen times less chance ($P = 0.030$) of achieving high WUE of 12.8 kg grain/ha.mm.

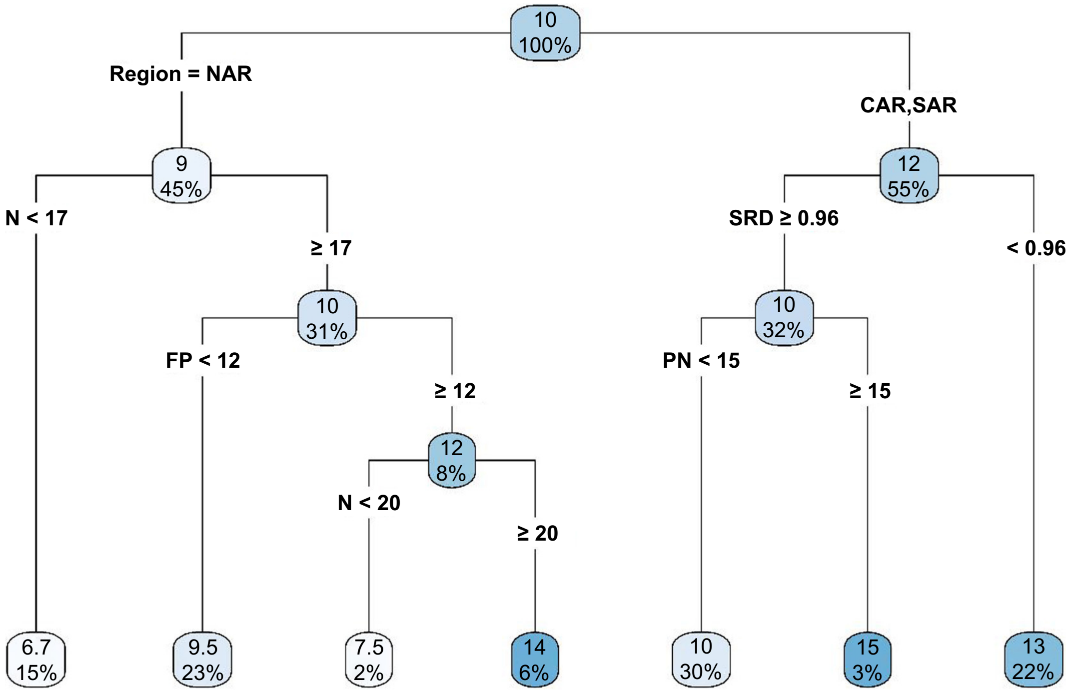

Fig. 5. Classification and regression tree analysis (CART) of WUE including variates in Table 5; Region (Northern, Central and Southern Agricultural Region); N, soil mineral nitrogen concentration in 0–10 cm pre-sowing (mg/kg); SRD, root damage score (% severity). Upper number in box is WUE (kg grain/ha mm) and lower number is percentage of observations. Lighter shading represents lower WUE.

Management and biotic variates

There were regional differences in the management and biotic variates which reduced WUE. Regression tree analysis using all management and biotic variates in Table 5 had a relative error of 0.28 and R^2 of 0.72. The first split, and most important variate in predicting wheat WUE was on region, with lower WUE in the NAR (9 kg grain/ha.mm) compared to the CAR and SAR combined (12 kg grain/ha.mm) (Fig. 5).

Within the NAR split, WUE of terminal nodes ranged 6.7 kg grain/ha.mm to 14 kg grain/ha.mm, with splits, alternatives and surrogates based mainly on parameters associated with soil fertility, soil nutrient concentration and/or fertiliser inputs. Hence, low soil fertility was a cause of low WUE in the NAR (see Supplementary material S5 for detailed description of Fig. 5 nodes and splits). This finding was supported by univariate regressions, with amount of applied fertiliser N, P and K and soil N content having positive effects on WUE in the NAR ($P < 0.001$–0.009, Table 5).

The first split on the CAR/SAR side of the tree was based on the visual score of severity of root damaged; when this was more than 0.96, WUE was reduced by 3 kg grain/ha.mm. Univariate analysis indicated root disease severity had an effect on WUE of wheat ($P < 0.001$), with responses in the NAR and CAR ($P < 0.001$–0.008, Table 5). The next split had less *P. neglectus* DNA in soil resulting in lower WUE, which is counterintuitive. However, alternate splits to the left included fertiliser nitrogen (< 38 kg/ha) and soil sulfur (< 28.0 mg/kg). Hence the terminal node on the CAR/SAR side of the tree containing 3% of data, with WUE of 15 kg grain/ha.mm, represents paddocks with high levels of N and S, which may also provide conditions under which soil pathogen DNA is high. Univariate analyses also captured this effect with positive responses of WUE to *P. neglectus* in the CAR and *P. neglectus*, *R. solani* (AG 8) and *G. graminis* in the SAR (Table 5).

The effect of rotation on yield and water use efficiency of wheat

Mean yield of wheat after canola, lupin and pasture was similar to growing wheat after one previous wheat crop (Fig. 6*a*). Longer sequences of continuous wheat production resulted in reduced yield, with the fourth consecutive wheat yielding 1089 kg/ha less than wheat after one previous wheat crop ($P = 0.019$) (Fig. 6*a*). Water use efficiency of wheat also declined under these longer sequences of wheat monoculture (Fig. 6*b*); WUE efficiency ranged from 13.2 kg grain/ha.mm after pasture to 8.4 kg grain/ha.mm in the fourth consecutive wheat crop. WUE in wheat was not different when the wheat was grown after canola (12.3 kg grain/ha.mm), lupin (12.2 kg grain/ha.mm), pasture and 1 year of wheat (11.2 kg grain/ha.mm) but declined after > 2 years of wheat (Fig. 6*b*) ($P = 0.008$).

Table 4. Linear regression *P*-values and coefficients for the effect of total monthly rainfall (mm) and average monthly mean, (max. – min.)/2, temperature (°C) on WUE within each region; Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR).

Month	Rain (mm) or Temp (°C)	NAR		CAR		SAR	
		P-value	Coeff.	*P*-value	Coeff.	*P*-value	Coeff.
Jan	Rain	0.7250	−1.27	**0.0958**	0.81	0.7750	0.32
	Temp	0.3293	−0.44	**0.0000**	1.15	0.5640	1.24
Feb	Rain	**0.0001**	2.51	0.8570	−0.12	0.2000	2.70
	Temp	0.6490	0.13	0.3750	0.24	0.9260	0.06
Mar	Rain	**0.0387**	0.71	0.9530	−0.01	0.6740	0.50
	Temp	0.3562	−0.36	0.7900	0.11	0.9920	0.02
Apr	Rain	**0.0114**	1.11	**0.0004**	2.30	0.7540	−0.54
	Temp	**0.0001**	1.31	**0.0000**	1.83	0.5940	0.87
May	Rain	0.1641	0.35	0.8572	0.06	**0.0234**	−2.45
	Temp	**0.0095**	1.56	**0.0539**	1.71	0.1208	−6.95
Jun	Rain	0.3125	0.14	0.3619	0.28	**0.0088**	2.99
	Temp	0.1865	−0.54	**0.0058**	3.22	**0.0051**	10.81
Jul	Rain	**0.0121**	−0.49	**0.0183**	0.33	**0.0054**	−1.79
	Temp	0.6801	−0.32	**0.0000**	4.24	0.1763	−4.51
Aug	Rain	**0.0002**	−0.75	0.2116	0.32	**0.0088**	−2.11
	Temp	**0.0131**	−1.35	**0.0089**	1.83	0.2345	−3.72
Sep	Rain	**0.0030**	0.73	**0.0260**	0.51	0.8440	−0.12
	Temp	**0.0202**	1.53	**0.0000**	2.58	0.1020	3.35
Oct	Rain	0.7679	−0.17	**0.0029**	0.89	**0.0000**	−2.98
	Temp	**0.0001**	1.80	**0.0000**	2.49	**0.0020**	−5.63
Nov	Rain	**0.0003**	−1.06	0.1421	0.64	0.0729	−1.47
	Temp	**0.0001**	−0.94	**0.0008**	1.31	0.4269	1.26
Dec	Rain	**0.0272**	−1.38	0.0704	0.65	0.0882	−0.85
	Temp	**0.0126**	1.09	**0.0003**	1.19	**0.0329**	−2.26

Bold indicates a significant effect at $P \leq 0.05$.

Regression tree analysis assessing crop sequence, plant pathogen, weed and nitrogen identified variates affecting WUE of wheat grown in the year after canola, lupin or pasture. Prior land use (canola, lupin or pasture) was not a prominent split in the tree but these preceding crops were identified as alternate variables at some nodes. The first split was made on severity of visual plant root damage (SRD); 9% of wheat crops after break crops with SRD ≥1.8 had WUE of 9.7 kg grain/ha.mm compared to 13.0 kg grain/ha.mm for those with less root damage. Alternate split variates to the left, lower WUE, included fertiliser nitrogen (<14 kg grain/ha.mm) and canola or lupin compared to pasture. After plant root damage, the tree split on nitrogen supply (Nin); 5% of crops with ≥126 kg/ha supplied N had WUE of 17.0 kg grain/ha.mm compared to a mean of 13.0 kg grain/ha.mm for paddocks receiving less. Crop or pasture grown prior to wheat was also an alternate split here, with canola and lupin splitting to the left (13.0 kg grain/ha.mm) compared to pasture to the right (17.0 kg grain/ha.mm). Hence, for a small number of pasture paddocks a large amount of nitrogen was provided to the following wheat crop, which increased WUE. The weed density effect was a lower split which included 38% of the data, where 5% of crops with ≥37 weeds/m^2 in spring had a WUE of 8.9 kg grain/ha.mm compared to 13.0 kg grain/ha.mm for crops with fewer weeds. Crop grown prior to wheat was also an alternate split here with lupin and pasture splitting to the left (8.9 kg grain/ha.mm) compared to canola to the right (13.0 kg grain/ha.mm), indicating these wheat crops benefited from a lower density of weeds following canola. A detailed description of the regression tree is given in Supplementary material S6. In summary it indicates that while break crop effects were low overall (Fig. 6*b*), for the small number of paddocks where weeds, disease or nitrogen limited WUE, break crops could increase WUE substantially. These conditions became more likely when wheat was grown in successive years.

Table 5. Linear regression *P*-values for the effect of soil or management/biotic constraint on WUE by region.

Component	Variate	NAR		CAR		SAR	
		P-value	Coeff.	*P*-value	Coeff.	*P*-value	Coeff.
Management	FN	**0.005**	1.26	0.236	0.48	0.672	0.13
	FP	**0.000**	0.34	0.850	0.01	0.656	0.03
	FK	**0.009**	0.43	0.825	−0.03	0.314	−0.21
	FS	0.484	0.07	0.210	−0.14	0.315	0.11
	H	**0.001**	0.18	0.395	0.04	0.335	0.06
Soil	N	**0.001**	0.89	0.389	0.30	0.604	0.35
	P	0.435	−0.16	0.758	0.10	0.567	−0.37
	K	0.190	2.38	**0.002**	5.71	0.880	−0.44
	S	0.096	0.23	0.057	0.39	0.653	0.16
	EC	**0.013**	0.00	0.269	0.00	0.619	0.00
	SOC	0.417	−0.01	0.953	0.00	0.756	−0.01
	pH	0.055	0.02	0.101	0.01	0.818	−0.01
	TEX	0.803	0.00	0.913	0.00	0.804	0.00
Disease	CR	0.399	30.53	0.462	5.42	0.117	39.67
	PN	0.190	0.12	**0.023**	0.25	**0.000**	0.70
	RH	0.993	−0.01	0.472	−0.88	**0.019**	2.51
	TA	0.424	−0.03	0.298	−0.04	**0.000**	0.25
	SRD	**0.008**	−0.48	**0.000**	−0.86	0.216	−0.34
	W	0.538	−0.22	0.792	0.07	0.696	−0.37

Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR). Bold indicates a significant effect at $P \leq 0.05$. See Table 1 for descriptions of variate acronyms.

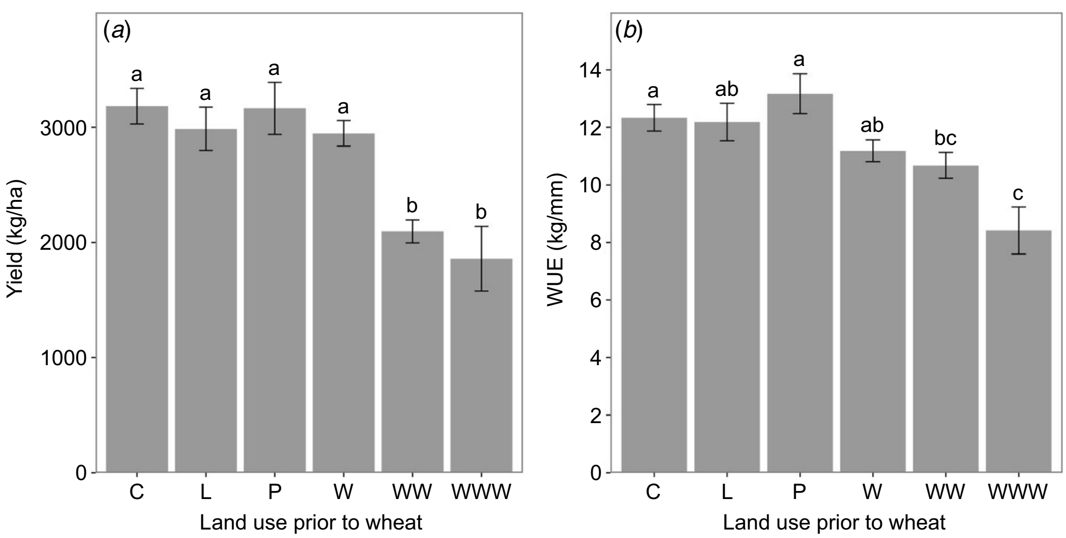

Fig. 6. (*a*) Yield and (*b*) water use efficiency (WUE) of wheat grown after other land uses; C, canola; L, lupin; P, pasture; W, wheat; WW, wheat/wheat; WWW, wheat/wheat/wheat. Error bars show ± s.e., different letters above error bars indicate differences at $P \leq 0.05$.

Grass weed density (plants/m^2) increased when more than two wheat crops were grown in succession, with the first wheat having 11.6 (± 1.2), second wheat 10.4 (± 1.4), third wheat 22.4 (± 6.8) and fourth wheat crop 35.2 (±23.6) and mean density was lowest in wheat crops grown after canola at 8.1 (± 1.0). Similarly, *P. neglectus* eggs per gram of soil, sampled in spring, increased when wheat was grown in succession; 6.4 (± 0.9), 8.3 (± 1.8), 11.1

(± 2.8) and 19.9 (± 12.3) in the first, second, third and fourth successive wheat crop respectively and were lowest in wheat crops grown after lupin (1.7 ± 0.6).

Water-limited yield potential and the gap between water-limited and achieved yield

For wheat, the slope of the frontier equation was 25 kg grain/ha.mm with the *x*-intercept at 45 mm (Fig. 7*a*). The slope of the frontier equation using wheat crops grown after either canola, lupin, or pasture was 26 kg grain/ha.mm, but maximum WUE was not associated with any one of these land uses (Fig. 7*b*).

Transpiration efficiencies for canola and lupin were less, and soil evaporation (*x*-intercept) was greater than the cereals at the water-limited yield frontier (Figs 7*a*, 8). The average wheat crop achieved 54% of the calculated water-limited yield potential; lupin 67%, canola 57%; and wheat crops after canola, lupin or pasture 62%.

Discussion

Break effects on wheat yield and WUE

The importance of including break crops and pastures in the rotation was demonstrated by large declines in yield and WUE when paddocks were sown to long sequences of wheat. But the small yield and WUE boost to a wheat crop sown after canola (0.24 t/ha, 1.1 kg grain/ha.mm), lupin (0.05 t/ha, 1.0 kg grain/ha.mm) or pasture (0.22 t/ha, 2.0 kg grain/ha.mm) compared to wheat sown after wheat (second wheat crop in succession) was contrary to many previously reported responses of wheat to break crops and pastures. A review of > 900 comparisons of wheat grown the season after break crops, compared to wheat grown after wheat, from Australia, Europe, and North America reported mean increases in wheat yield after break crops of 0.5–1.2 t/ha, with wheat after canola having responses at the lower end of this range and wheat after lupins at the upper end (Angus *et al.* 2015). Within southwest Australia, Seymour *et al.* (2012) used data from 167 crop sequence experiments conducted between 1974 and 2007 to determine a mean yield benefit to wheat following canola of 0.4 t/ha and lupin of 0.6 t/ha, compared to wheat grown after wheat. However, a more recent study using farm data from 1997 to 2007 only found a 0.13 t/ha hectare boost to wheat after lupin (Lawes 2010). Using the same dataset, Robertson *et al.* (2010) concluded that lower on-farm use of break crops (~20%) compared to theoretical modelled profit maximising area (23–38%) could possibly be explained by lower break crop yields and/or lower yield boosts to wheat from break crops and pastures being realised than assumed in the models.

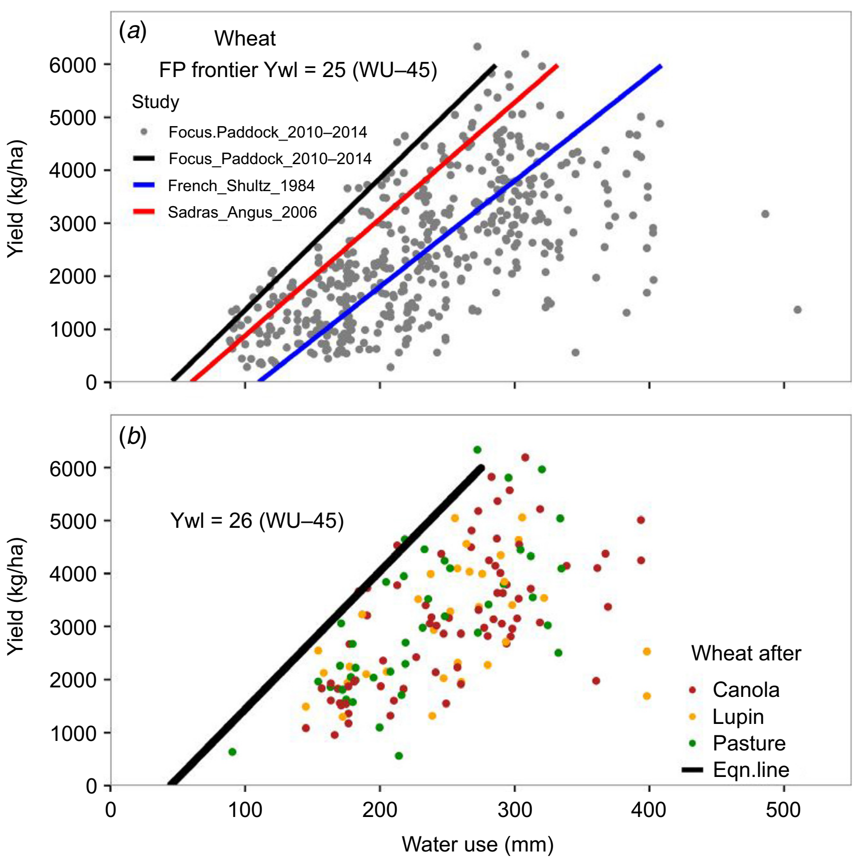

Fig. 7. Wheat yield plotted against water use for the Focus Paddock dataset (southwest Australia 2010–2014). Water use (WU) was calculated from 0.25 × summer rain plus growing season rain. The frontier equations depict water-limited yield (Ywl) potential for (*a*) all wheat crops in the dataset and (*b*) a subset of wheat crops grown after canola, lupin or pasture. The frontier equations were generated using a modification of the method described in Casanova *et al.* (2002). The blue line represents the French and Schultz (1984*a*) frontier, with *x*-intercept (estimated evaporation) = 110 mm and slope = 20 kg grain/ha.mm; the red line represents the Sadras and Angus (2006) frontier, with *x*-intercept 60 mm and slope 22 kg grain/ha.mm; and the black line represents current (Focus Paddock) frontier, with *x*-intercept = 45 mm and slope = 25 kg grain/ha.mm or 26 kg grain/ha.mm. Inset equations are for our Focus Paddock study.

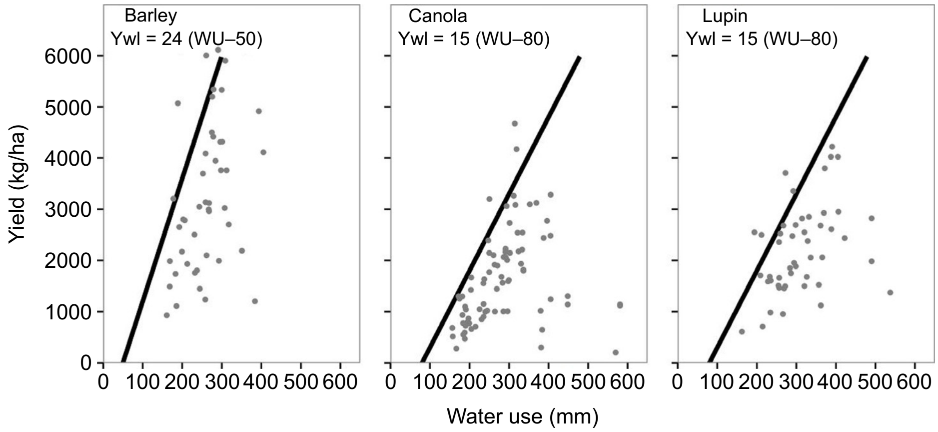

Fig. 8. Relationships between yield and water use for barley, canola and lupin from the Focus Paddock dataset, (southwest Australia, 2010–2014). Water use (WU) was calculated from 0.25 × summer rain + growing season rain. Black lines and accompanying equations presented in each panel represent frontier lines fitted to crops with high water use efficiency.

Occurrences of high densities of grass weeds, more recently herbicide-resistant ryegrass, and associated cereal pathogens have limited the yield response of wheat after break crops and pastures in trials in southwest Australia (Seymour *et al.* 2012; French *et al.* 2015). However, weed (Harries *et al.* 2020) and disease (Harries *et al.* 2015) were at very low levels in the vast majority of the fields we monitored. Additionally, biological nitrogen inputs from legume break crops and pastures were low. This was due to lupins (the most frequently sown grain legume) having a high harvest index, which removed a large proportion of fixed N, and pastures containing a low legume content (Harries *et al.* 2021). Considering these observations, an alternative reason for the low response of wheat to breaks, compared with two or three years of wheat, could be that the majority of fields were well managed through the judicious use of break crops and pastures to avoid the build-up of weeds and diseases throughout the rotation, while the nitrogen contribution from legumes was low. Indeed, we showed that there were few instances of 4 or 5 years of continuous wheat, which confirms the strategic use of break crops and pastures. Furthermore it is possible that the lack of break effect is in part due to intensive agronomic management of wheat crops, with integrated pest management methods used in tandem with large quantities of pesticides (Harries *et al.* 2020) to extend the period of low weed and disease pressure after a break. In support of this we found the use of nitrogen fertiliser increased as the years since a legume break increased (Harries *et al.* 2021). We explore this alternative theory, firstly discussing WUE of canola, lupin and wheat and then which constraints were impacting wheat WUE including the impacts of weeds, disease and soil nitrogen.

Water use efficiency and frontier equations of main crops

The mean WUE of wheat we report (10.7 kg grain/ha.mm) is greater than previous comparable studies, with 9.9 kg grain/ha.mm for south-east Australia and ≤ 9.8 kg grain/ha.mm for dryland farming environments of Asia, northern America and the Mediterranean (Sadras and Angus 2006). Our estimates of transpiration efficiency and soil evaporation from frontier equations are the first to be derived using a substantial dataset of WA farm data. The maximum transpiration efficiency frontier of 25 kg grain/mm.ha for wheat is greater than previously reported for South Australia (French and Schultz 1984*a*), south-eastern Australia (Sadras and Angus 2006), modelled data from southwest Australia (Asseng *et al.* 1998) and a range of other regions within Australia (Hochman *et al.* 2009) and other rainfed wheat production environments (China Loess Plateau, Mediterranean basin, and USA Great Plains) (Sadras and Angus 2006). But, is consistent with experimental plot studies in northern Spain (Cossani *et al.* 2012) and south-eastern Australia, using new genotypes with modern management practices (Sadras and Lawson 2013). The estimated soil evaporation of 45 mm is lower than reported in most of these aforementioned studies, which is likely a result of improved production practices, resulting in faster leaf area production, reducing soil evaporation (Unkovich *et al.* 2018). However, this level of soil evaporation is similar to that reported by Lollato *et al.* (2017), 64 mm southern great plains USA; Schillinger *et al.* (2008), 60 mm Pacific Northwest USA; Zhang *et al.* (2013), 60 mm Loess Plateau China; and Cossani *et al.* (2012), ~50 mm northern Spain.

Using the wheat frontier equation generated from our data, on average, farmers achieved 54% of water-limited yield potential for their wheat crops and average farm yields were at the previous maximum water-limited potential predicted by French and Schultz (1984*a*). This proportion of water-limited yield potential achieved is within ranges previously documented (Hochman *et al.* 2016; Anderson *et al.* 2017; Hochman and Horan 2018). That average yields are now similar to previous estimates of water-limited yield indicates that yield losses caused by constraints other than water have been reduced. Indeed Hochman *et al.* (2017) suggest wheat yields in Australia in the past decade have been maintained by better management in an increasingly dry and hot climate.

The WUE of canola we report is similar to experimental plots in south-eastern Australia (Norton and Wachsmann 2006) and was 52% of wheat WUE. The WUE of lupin was 7.1 kg grain/ha.mm, which was 66% of wheat WUE and was greater than the mean for lupin (5.6 kg grain/ha.mm) from previous studies in southwest Australia (Siddique *et al.* 2001). The lower WUE of break crops is expected, given differences in grain composition and that conversion efficiency of photosynthate to fat and protein are approximately 44% and 75% as efficient as conversion to starch (Sadras and McDonald 2012). The slopes of our frontier equations for lupin and canola (15 kg grain/ha.mm), were the same as previously reported (Siddique *et al.* 2001; Farré *et al.* 2004; Robertson and Kirkegaard 2005). In contrast, more recently, higher transpiration efficiencies have been reported for canola, from New South Wales, Australia (Kirkegaard 2015) and California, USA (16 kg grain/ha.mm) (George *et al.* 2018). Most recently, 17 kg grain/ha.mm and 21 kg grain/ha.mm have been reported for canola and lupin respectively using trial data from Australian national variety trials (2008–2016) (Houshmandfar *et al.* 2019). The greater WUE of the national variety trials could be due to differences in management intensity between trial plots and our farm data, as well as different geographic distributions of the studies. In particular, for lupin, 54% of Focus Paddock crops were sown in the NAR, where we found WUE of wheat was lower than other regions. The amount of soil evaporation we report for canola and lupin crops from frontier equations was similar to recent studies (Kirkegaard 2015; George *et al.* 2018; Houshmandfar *et al.* 2019) and ~50–60 mm/ha less than studies conducted a few decades prior (Siddique *et al.* 2001; Farré *et al.* 2004; Robertson and Kirkegaard 2005). The trend of increasing maximum water-limited yield potential over the past two decades implies that constraints that reduce WUE (weeds, pathogens and low nitrogen in the case of canola) are being managed more effectively compared to previous studies. To our knowledge, our study provides the first frontier equations for canola and lupin derived using WA farm data. However, due to relatively low numbers of paddock-years, these were derived in a similar manner to French and Schultz (1984*a*), and a larger farm yield data set is required to confirm our results with statistically derived frontier functions.

Climate constraints impacting on wheat WUE

Principal component analysis showed climate variables explained 69% of the variability in the data, and dry, warm, conditions 14 days either side of flowering reduced WUE. Variates reducing WUE in the PCA included: increased day of sowing (later sowing date resulting in later flowering), higher flowering and post-flowering temperatures, greater flowering vapour pressure deficit, more solar radiation at flowering, less rain at flowering and increased root disease. This is typical of Mediterranean environments due to hot and dry conditions coinciding with this critical period for determining grain number and yield in wheat (Fischer 1985). In addition, heat shocks post-flowering impede grain filling (Ababaei and Chenu 2020). There were regional differences in this response, with higher temperature around flowering reducing WUE in the NAR and SAR, whereas in the CAR, low mean flowering air temperature decreased WUE. This is likely a consequence of the CAR being a high frost risk area (Zheng *et al.* 2015), as indicated by a greater number of days with minimum temperatures $\leq 0°C$ than other regions. There were also regional differences in the effect of rainfall on WUE. The reduction in WUE in the SAR with high rainfall may indicate that waterlogging, leaching and/or drainage occurred in some paddock-years, and our assumption of no deep drainage used to estimate WU did not hold true in these cases, as noted in previous studies (French and Schultz 1984*a*; Sadras and Angus 2006). If so, our result will be an underestimate of WUE in the SAR.

For all regions there were months in autumn and spring, prior to flowering, when higher mean daily air temperature increased WUE. Hence in general, warmer temperatures during the vegetative period and mild conditions around flowering led to high WUE. With warmer vegetative conditions crop leaf area is likely to develop at a faster rate, reducing soil evaporation (Unkovich *et al.* 2018) and flowering will occur earlier, in milder conditions, provided there is no frost. This is consistent with Xiao *et al.* (2013) who reported improved WUE in the semi-arid region of north-western China due to increased temperature, caused by climate warming over the past 50 years.

Increased vapour pressure deficit, particularly around flowering, reduced WUE. There was a similar latitudinal effect of VPD on WUE to that reported for eastern Australia (Rodriguez and Sadras 2007). Consequently, adjusting WUE for VPD around flowering made more difference in the SAR than other regions, due to lower VPD in this region, which is consistent with Doherty *et al.* (2009). It was interesting that there was little difference between WUE and WUE_{VPD} for the NAR and CAR, indicating VPD at flowering was similar for these regions, despite latitudinal differences. Reasons for this are that some of the NAR paddocks are closer to the coast, which would reduce VPD, and in some seasons sowing was delayed significantly in the CAR, due to limited sowing opportunities, which increased VPD at flowering. For example, in the CAR in 2010 mean sowing date was 27 May (s.d. 19), WU 120 mm, wheat yield 1.13 t/ha and WUE was 9.4 kg grain/ha.mm. Consequently, WUE_{VPD} was greater in the CAR than the other regions and some of these paddock-years contributed to the lower soil evaporation in the boundary function compared to previous studies.

Because the responses above are typically observed in Mediterranean environments, farmers in southern Australia have moved to earlier seeding to reduce yield loss caused by heat and drought, and to capture the greatest amount of autumn rain possible. To achieve this, farmers now regularly sow into dry soil prior to autumn rain (Stephens and Lyons 1998; Fletcher *et al.* 2015, 2016; Anderson *et al.* 2017). The early sow strategy was first applied to lupin in the 1980s and has more recently been successfully employed for wheat (Kirkegaard and Hunt 2010; Hunt *et al.* 2015; Flohr *et al.* 2017, 2018; Collins and Chenu 2021), with fast maturing winter wheat types that flower at optimal periods from these early sowing times giving yield increases of 10–20% (Flohr *et al.* 2018; Hunt *et al.* 2019). Canola (Kirkegaard 2019) and pastures (Loi *et al.* 2012) have also been successfully integrated into this early sowing strategy, but not grain legume species, due to poor adaptation of some grain legumes to early sowing. This includes limitations on sowing lupin earlier due to lack of vernalisation requirement and control of flowering time (Berger *et al.* 2012), poor pod set at low temperatures in chickpea and delayed sowing of field pea to reduce the risk of fungal disease and frost (Siddique *et al.* 2013). Yields of broadleaf crops in WA are already lower and more variable than cereals (Fletcher 2019) and it is a concern that fewer legumes will be seeded if their yield gains fall further behind those of the other crops. Additionally, increased heat tolerance at flowering would provide an advantage for all regions of our study, extending the optimal flowering period (Hunt *et al.* 2020), over which transpiration efficacy to grain is greatest (Angus and van Herwaarden 2001; Kirkegaard and Hunt 2010). These efforts to increase WUE will be especially important due to the predicted continuation of reduced in-season rainfall and increased temperatures in southwest Australia (BOM 2018; Scanlon and Doncon 2020). Indeed across Australia, it is estimated that water-limited yield potential of wheat dropped 27% from 1990 to 2015 because of reduced rainfall and rising temperatures, although frontier equations continue to indicate greater water-limited yield potential because of improved management practices and better WUE (Hochman *et al.* 2017).

Management and biotic constraints impacting on wheat WUE

Management and biotic constraints explained 23% of the variability in the data. The low level of variance in WUE, explained by weed, disease and soil nitrogen aspects of management, show that yields of most paddocks were not limited greatly by these constraints. That grass weed density was not strongly related to WUE in any of the regions indicates current weed management practices within wheat crops were, in the main, effective in all regions; although weeds continue to be a significant production constraint across southern Australia (Llewellyn *et al.* 2016). Grass weed density was lowest in wheat crops grown after canola and was also low in the second consecutive wheat crop. Mean grass weed density and variability increased under long wheat sequences, indicating some paddocks had large increases in grass weeds when several wheat crops were grown in succession. These findings are consistent with the high level of weed control obtained in canola fields from autumn to spring and weed levels increasing from low density during the growing season in wheat crops, as reported by Harries *et al.* (2020). The same effect occurred with *P. neglectus*, which is an obligate parasite of wheat, ryegrass and canola, but not lupin, with increased *P. neglectus* in long wheat sequences.

Increasing nitrogen fertiliser rates increased WUE, and the effect was more pronounced in the NAR compared to other regions. Harries *et al.* (2021) showed pre-sowing mineral nitrogen concentration was lower in the NAR (25 mg/kg) compared to CAR and SAR (~32 mg/kg), as was soil organic carbon content. Additionally, there was a greater nitrogen input from legumes in the CAR and SAR compared with the NAR, due to high harvest index of lupin and low legume content of pastures in the NAR; so, logically, there was a greater WUE response to nitrogen fertiliser in the NAR.

Nitrogen is a major limitation to WUE in Australian wheat production (Sadras and Angus 2006; Hochman and Horan 2018), despite nitrogen fertiliser rates trebling in the past 30 years (Angus and Grace 2017). Hunt *et al.* (2020) suggested that adding larger amounts of fertiliser nitrogen to create a pool of residual fertiliser and increased soil organic nitrogen, may close the yield gap, as plants are able to access adequate nitrogen over a wide range of seasonal conditions. These authors note this approach would only work in low rainfall areas with high water holding capacity soils, where nitrogen does not readily leach, and similarly Meier *et al.* (2021) concluded that nitrogen bank targets needed to be closely aligned to water-limited yield potential to avoid environmental losses. Interestingly this nitrogen, and carbon, bank approach is analogous to what was achieved across much of southern Australia using ley farming systems in the 1950s and 1960s (Kirkegaard *et al.* 2011). Recently it has been shown that soil organic carbon can be increased in intensive cereal cropping systems, with C-rich residues, although this does require large amounts of nitrogen fertiliser inputs to obtain C:N ratio and humification rates that lead to a positive C balance (Kirkby *et al.* 2016; Angus and Grace 2017).

Much of the gains that can be expected from in-season water capture and minimised soil evaporation have already been made through the adoption of no-tillage and stubble retention (Freebairn *et al.* 1993) and further improvements may be technically difficult. Nonetheless, there are opportunities such as improved establishment in marginal conditions (Hunt *et al*. 2020), harvesting of micro-water events (Barrett-Lennard *et al*. 2021), use of disc seeders and stripper fronts and more uniform spatial arrangement of crop plants (Harries *et al*. 2018). In addition, efforts should be made to increase plant available water further by reducing physical and chemical root barriers in soil. Indeed, despite a large increase in lime use in WA from 201 000 tonnes in 2004 to 1 425 000 tonnes in 2014 (Metcalfe and Bui 2016), we still found lower pH_{CaCl2} at 0–10 cm associated with low WUE. Another method to improve water extraction is to increase soil water storage capacity. This could become important in WA because rainfall patterns have shifted towards lower in-crop rainfall and greater out of season (summer) rainfall (BOM 2018; Scanlon and Doncon 2020) and the optimal flowering window for wheat is predicted to move 11–29 days earlier under different climate change scenarios (Chen *et al*. 2020). This is not easily achieved in coarse-textured soils and is likely to require a suite of actions, including the addition of stable organic amendments (such as clay, charcoal, biochar, compost) and increased soil organic carbon through greater biomass production and residue retention (i.e. optimum supply of nutrients, cover crops, green manure and use of appropriate rotations with crop and pasture legumes), as described by Hoyle *et al*. (2011). Therefore, the reduction in legume production over recent decades is a concern because improved soil fertility through increased soil N and soil organic carbon via legumes is well documented (Ellington *et al*. 1979; Drinkwater *et al*. 1998; Blair and Crocker 2000; Chan *et al*. 2011; Congreves *et al*. 2015; Kumar *et al*. 2018).

While there are concerns around the reduction in legume use, this change has been made by growers and agronomists to maintain low weed seed banks (Harries *et al*. 2020). This has been essential for effective cropping given the spread of herbicide-resistant weeds across southwest Australia (Walsh and Powles 2014). Low weed seed banks are also a prerequisite for the implementation of earlier and dry sowing, because the entire weed challenge must be managed within the crop and residual herbicide activity is poor under dry conditions. Therefore, it is crucial to improve weed control in legume crops and develop pasture systems that complement intensive cropping to encourage legume production. Furthermore, in farming systems where biotic constraints are well managed it is essential to assess the impact of break crops and pastures over a longer period, rather than expecting large yield responses in the following wheat crop.

Conclusions

Water use efficiency of wheat declined when wheat was sown in the same paddock for more than 2 years in succession. However, farmers seldom used long sequences of wheat, preferring the judicious use of break crops and pastures, at ~20% of the rotation. Consequently, weed and disease levels were low, while legume nitrogen inputs were also low, which explains the small yield response of wheat following break crops and pastures. This indicates that changes in agronomic management, including increased inputs and new technologies, are replacing some of the traditional functions of break crops and pasture and are responsible for the reduction in the yield gap of wheat in recent decades. Despite this, nitrogen remains an important factor in achieving high WUE, and research is required to improve the adaptation of legumes to early sowing systems and to incorporate pastures without compromising in-crop weed control, to facilitate their continued integration into cereal and oilseed dominated rotations.

Supplementary material

Supplementary material is available online.

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