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Crop & Pasture Science

Supplementary Material

Water use efficiency in Western Australian cropping systems

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Supplementary material

S1. Details of the calculation of water use (WU)

Water use efficiency (WUE), can be expressed as per Equation 1:

$$WUE = \frac{Y/T}{1+(Es+R+D)/T} \qquad \text{Equation S1}$$

Where Y is grain yield, T is the amount of water transpired, Es is the amount of water evaporated from soil, R is the amount of water lost due to run-off, and D is water amount of water lost due to drainage below roots. Assuming R and D are equal to zero, total water used (WU) to produce Y is equal to Es + T. Thus, equation S1 is simplified to Equation S2:

$$WUE = \frac{Y}{Es+T} \qquad \text{Equation S2}$$

Water use (WU), which is also commonly called evapotranspiration (ET), is similar to the amount of rain received in the growing season in the semi-arid southern Australian climate (French and Schultz 1984).

Furthermore, benchmarking achieved yields to estimate water-limited yield potential is commonly reported using variations of the frontier method applied by French and Schultz; actual yields achieved were plotted by water use, within a defined agroecological zone, and a linear frontier or boundary function fitted against the instances with the greatest WUE.

$$Y_{wl} = TE_{max} \times (Es + T - Es) \qquad \text{Equation S3}$$

Where Y_{wl} is water-limited yield potential, TE_{max} is maximum mean transpiration efficiency for the lifecycle of the crop, T is transpiration and Es is soil evaporation. This was expressed more succinctly as:

$$Y_{wl} = TE_{max} \times (WU - Es),$$

or simply Y_{wl} = TE_{max} x mm water transpired

Values for TE_{max} of 20 kg grain/ha.mm of water transpired, and Es of 110 mm were commonly used based on French and Schultz (1984);

$$Y_{wl} = 20 \times (WU - 110)$$

S2.

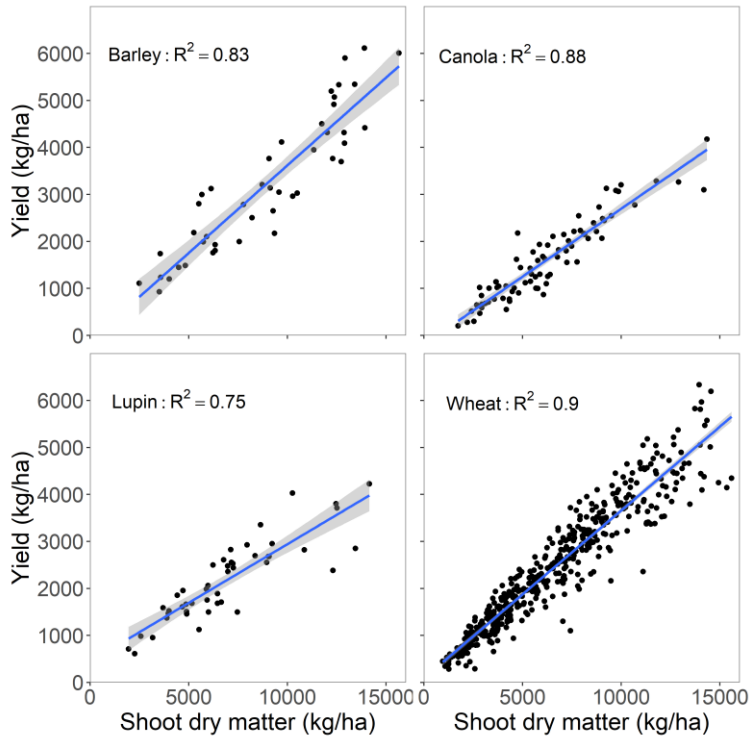

Fig. S2. Relationships between shoot dry biomass and yield for barley, canola, lupin and wheat, the shaded area around the fitted line is 95% confidence interval.

S3.

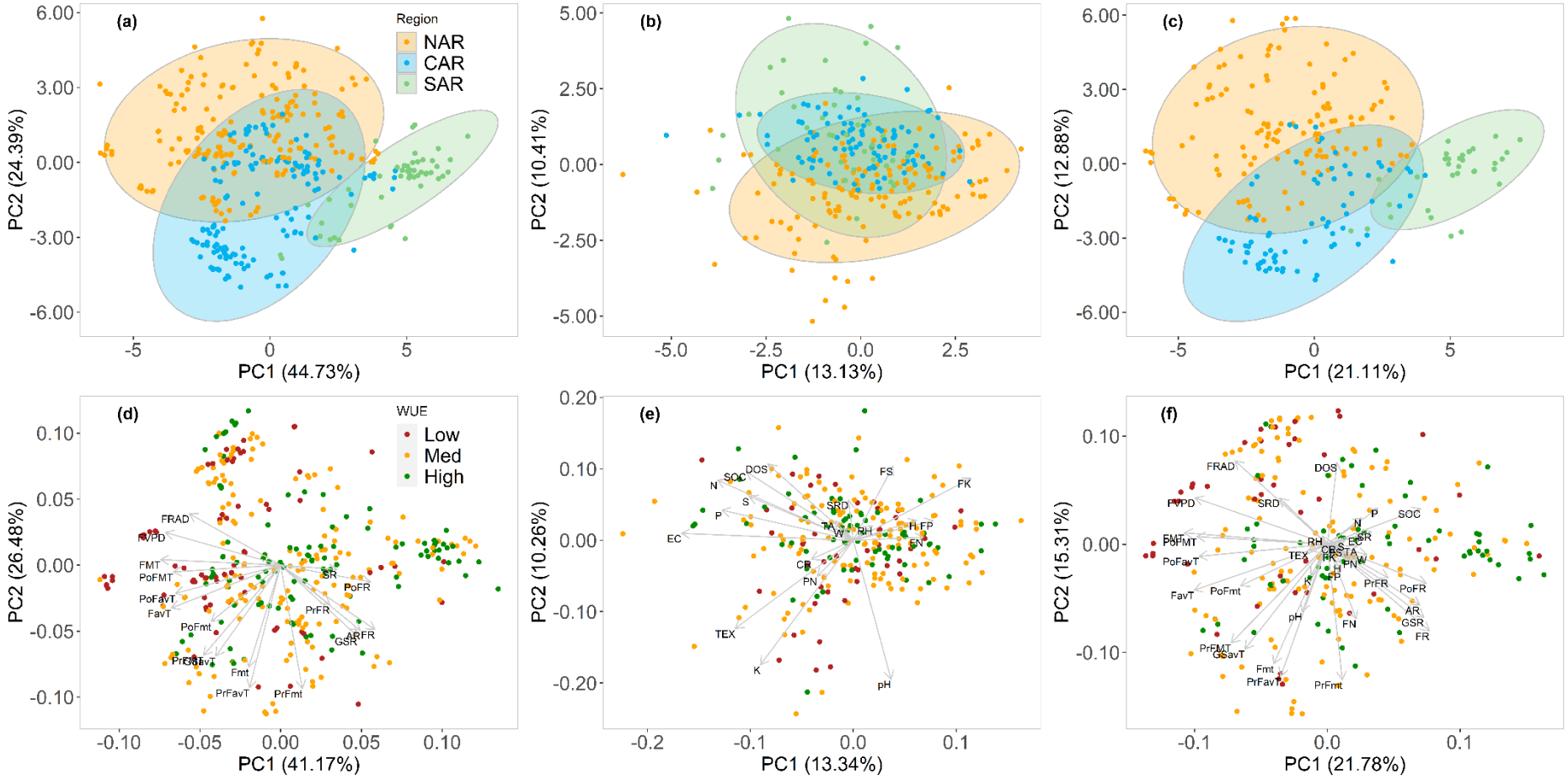

Fig S2. Meteorological variates accounted for 69% of the variation in the data and regions separated along principal component axes (Fig. S2a), which is consistent with the differences in rainfall and temperature presented in (Fig. 3). A lower proportion of the variability in the data was explained by management, soil and biotic variates (PC1 + PC2 = 23%), and there was less segregation by region (Figure S2b), which is consistent with findings of similar management practices and moderate variations in soil and biotic constraints across regions (Harries *et al.* 2020). Inclusion of all variates increased regional segregation, enabling better distinction of

regional differences in management and soil variates, i.e. PC1 Eigen vectors (not shown in figure) for soil $pHCaCl_2$ and SOC were -0.16 and 0.21 respectively, indicating lower soil $pHCaCl_2$ and greater SOC in 0–10 soil layer in SAR paddocks compared to NAR paddocks (Figure S2c), as reported in (Harries *et al.* 2021).

Biplots grouping WUE as high, med and low showed WUE segregating strongly along PC1 axis with Eigenvectors of temperature at all plant stages decreasing as PC1 increased and rain at all plant stages increasing with PC1, the most highly correlated variate to PC1 being mean temperature at flowering, Pearson correlation of 0.92 (Fig. S2d).

Conversely, levels of WUE did not segregate based on management and soil variates when assessed without meteorological variates (Fig. S2e). However, when management and soil variates were plotted with meteorological data, WUE did segregate; low in the top left and high at the bottom right of Fig. S2f variates toward the top right are maximum temperature at flowering and post-flowering, and post-flowering mean temperature, as well as the proportion of root diseased. Soil organic carbon, post flower rain, flowering rain, and fertiliser nitrogen are all in the lower left quadrant. For example, the Eigenvector of PC2 for fertiliser nitrogen (FN) is -0.21, hence as PC2 increased (towards lower WUE data points) the amount of applied fertiliser N decreased. Eigenvectors for Figures S2f are presented in Table 3.

S4. Regression tree analysis with all variates within Table 1

The regression and classification analysis tree using all variates (Table 1) had a relative error of the regression of 0.41, an R^2 of 0.59. Inspection of variable importance output showed 18 of the 19 most important variables in predicting WUE of wheat were climate variables. Below we describe the regression tree nodes, including variables that would provide similar primary splits and variables that could act as surrogate splits in the absence of the node variable.

The first node, and best predictor of WUE, was amount of rain post flowering which split at ≥0.25 mm post flowering rain. Alternative variables for this split included post flowering vapour pressure deficit (2.1 kPa), pre flowering vapour pressure deficit (0.69 kPa), flowering average vapour pressure (1.6 kPa) and growing season temperature (26.9°C). Surrogates included post flowering vapour pressure deficit (2.1 kPa), flowering average vapour pressure (1.6 kPa) and growing season temperature (26.9°C) as well as rain at flowering (0.15 mm) and maximum temperature at flowering (26.4°C). Hence a warmer, dryer climate, particularly around flowering, was the most important factor in reducing WUE.

The second node, which came from paddocks receiving <0.25 mm of post flowering rain, contained 17% of the data with a WUE of 6.3 kg grain/ha.mm. Because this is a terminal node no further assessment of this data was possible.

The third node, coming from paddocks receiving >0.25 mm post flowering rainfall, contained 83% of the data with WUE at (11 kg grain/ha.mm) and split based on pre flowering radiation at 11 (23.0 MJ/m^2). Alternative variables for this split included, flowering radiation (23.0 MJ/m^2), pre flowering vapour pressure deficit (0.7 kPa), growing season minimum temperature (9.7°C), pre flowering rain (33.7 mm). Surrogate variables included average max flowering temperature (19.6°C), average mean flowering temperature (13.8°C), pre flowering average max temperature (16.5°C), flowering radiation (14.6 MJ/m^2) and paddock (#146, mostly SAR paddocks). Hence even for paddocks that did receive post flowering rain higher temperatures, vapour pressure deficit, solar radiation and lower rain and minimum temperature resulted in lower WUE.

The fourth node contained 68% of the data with a WUE of 11 kg grain/ha.mm and split based on radiation at flowering (23 MJ/m^2). Alternative variables for this split included growing season minimum temperature (9.7°C), Pre flowering rain (34 mm), pre flowering vapour pressure deficit (0.7 kPa), flowering vapour pressure deficit (1.5 kPa). Surrogate splits included growing season minimum temperature, pre flowering rain (33 °C), flowering vapour pressure deficit (1.5 kPa), growing season rain (107 mm), pre flowering radiation (16.7 MJ/m^2). At this split low pre flower or growing season rain or high amounts of radiation and vapour pressure deficit had a large impact on WUE.

The fifth node contained 12% of the data with A WUE of 12 kg grain/ha.mm and split on annual rain (491 mm). Alternative split variates included minimum average temperature at flowering (7.4°C), post flowering vapour pressure deficit (1.1 kPa), post flowering rain (123 mm) and flowering rain (36.4 mm). Surrogate splits included radiation at flowering (15.9 MJ/m^2), growing season temperature (18.7°C), post flowering rain (131 mm) and crown rot DNA (7 pg/g soil). This split differed from previous splits in that lower temperature vapour pressure deficit and more rain split to the left (lower WUE). The reason for this difference is that a surrogate split to node 5, from node 3, is paddock >146 (mostly SAR paddocks). It is possible that for these paddocks waterlogging or drainage occurred. This is the only split for which a biotic variate was a surrogate, crown rot.

The sixth node was a terminal node, accounting for 6% of the data with WUE of 7 kg grain/ha.mm. The WUE at this node was considerably less than it's parent node, node 4, indicating low pre flower or growing season rain or high amounts of radiation and vapour pressure deficit had a large impact on WUE.

The seventh node contained 62% of the data with A WUE of 12 kg grain/ha.mm and split on growing season average temperature (21°C). Alternative split variates included region (NAR left, CAR and SAR Right), flowering average minimum temperature (8.6°C), flowering rain (37 mm), growing season minimum temperature (13.6°C). Surrogate variates included growing season minimum temperature (13.8°C), flowering average mean temperature (17.7°C), flowering average minimum temperature (10.0°C), pre flowering average minimum temperature (8.3°C) and pre flowering average mean temperature (14.6°C). Hence this split separated NAR paddocks based mainly on the higher temperatures in that region compared to the CAR and SAR.

The eighth node contained 6% of the data with a WUE of 8.3 kg grain/ha.mm, the left split from node 5.

The nineth node contained 15% of the data with a WUE of 15 kg grain/ha.mm, the right split from node 5.

The tenth node contained 7% of the data with a WUE of 8.6 kg grain/ha.mm, the left split from node 7

The eleventh node contained 55% of the data with A WUE of 12 kg grain/ha.mm and split on flowering vapour pressure deficit (0.8 kPa). Alternative split variates included, flowering average maximum temperature (22.8°C), post flowering vapour pressure deficit (1.3 kPa), post flowering average mean temperature (16.7°C) and flowering rain (34 mm). Surrogates included flowering average maximum temperature (20.8°C), flowering rain (54 mm), growing season rainfall (336 mm) and growing season temperature (19.8°C). This is an unexpected split with lower vapour pressure deficit and temperature reducing WUE but this is countered by rain at flowering increasing WUE. This highlights the importance of the timing of rainfall around the flowering period.

The twelfth node contained 6% of the data with a WUE of 8.9 kg grain/ha.mm, the left split from node 11.

The thirteenth node contained 49% of the data with a WUE of 12 kg grain/ha.mm, the right split from node 11.

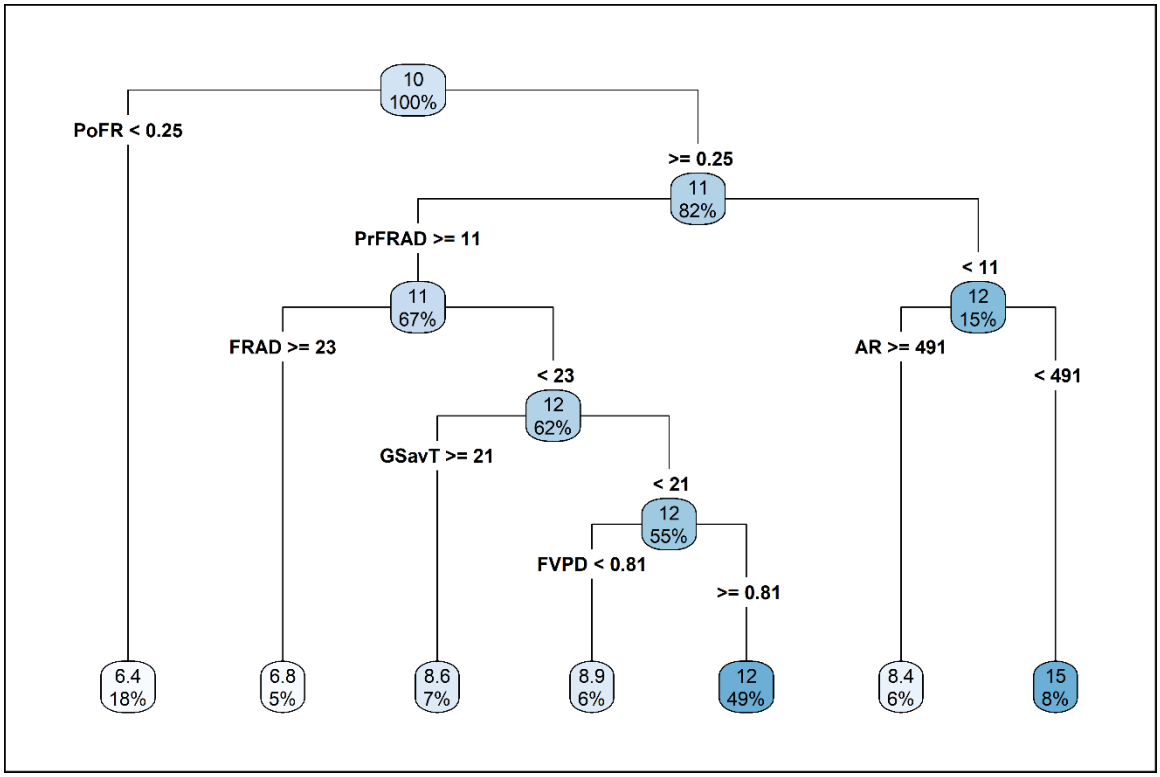

Fig. S4. Classification and regression tree analysis (CART) of WUE including all variates in Table 1. PoFR = post flowering rain, PrFRAD = pre flowering solar radiation, FRAD = flowering radiation, GSavT = growing season average mean temperature, FVPD = flowering vapour pressure deficit, AR = annual rainfall.

S5. Regression tree analysis with all management and biotic variates

The regression and classification analysis tree using management and biotic variates (Table 1) had a relative error of the regression of 0.28, an R^2 of 0.72 (Figure 5). Below we describe the regression tree nodes, including alternate variables, that would provide similar primary splits, and variables that could act as surrogate splits in the absence of the node variable.

The first node, and best predictor of WUE, was Region which split between NAR and the other two regions. Alternative split variates to the left were soil organic carbon (<1.2%), *P. neglectus* (<7.5 pg/gram soil) and soil electrical conductivity (<0.1 dS/m). Surrogate splits to the left included these variates as well as soil phosphorus (<37.5 mg/kg) and crown rot (<0.5 pg/gram soil). This reflects lower values for these variates in the NAR compared to the CAR and SAR. The only alternative split variate to the right was severity of root disease (<1.1) and the only surrogate soil pH 0-10 cm (<5.65). This reflects higher values for these variates in the NAR.

The second node contained 45% of the data with a WUE of 9 kg grain/ha.mm and split on soil N (17 mg/kg). All alternate splits were to the left; soil electrical conductivity (0.1 dS/m), fertiliser P (11.6 kg/ha), soil potassium (56.5 mg/kg), fertiliser nitrogen (25.1 kg/ha). All surrogate splits were to the left and included alternate split variates as well as soil phosphorous (12.5 mg/kg) and soil organic carbon (0.4%). Hence lower soil fertility resulted in lower WUE.

The third node contained 55% of the data with a WUE of 12 kg grain/ha.mm and split on severity of root disease (0.96). All alternate splits were to the left; *P. neglectus* (<8.8 pg/gram soil), crown rot (<105 pg/gram soil), fertiliser nitrogen (<38 kg/ha) and soil sulphur (<28.0 mg/kg). Surrogates also included soil nitrogen (<16.5 mg/kg) and soil pH (<5.25) to the right and region with NAR and CAR left, and SAR right.

The fourth node contained 15% of the data with the lowest WUE of 6.7 kg grain/ha.mm and included paddocks in the NAR with low soil fertility. This was a terminal node, without any further splits.

The fifth node contained 31% of the data with a WUE of 10 kg grain/ha.mm and split on fertiliser phosphorous (11.6 kg/ha). All alternate splits were to the left, lower WUE; less fertiliser N (25.1 kg/ha), K (13.4 kg/ha), S (0.9 kg/ha) and herbicides (7.5 number per season). Soil organic carbon (<1.6%) was also a surrogate to the left. Hence more fertiliser and herbicide inputs increased WUE of these paddocks.

The sixth node contained 32% of the data with a WUE of 10 kg grain/ha.mm and split on *P. neglectus* (15 pg/gram soil). Alternate splits to the left, lower WUE, included fertiliser nitrogen (<38.4 kg/ha), soil sulphur (<9.9 mg/kg) soil electrical conductivity (<0.1 dS/m) and weeds (<29/m^2). Surrogate left splits were crown rot (<358 pg/gram soil) and take all (<63 pg/gram soil).

The seventh node contained 22% of the data with a WUE of 13 kg grain/ha.mm. These paddocks were NAR and CAR paddocks with low levels of root disease. This was a terminal node, without any further splits.

The eighth node contained 23% of the data with a WUE of 9.5 kg grain/ha.mm. These were NAR paddocks with reasonable soil N concentration but fertiliser P levels <12 kg/ha. This was a terminal node, without any further splits.

The ninth node contained 8% of the data with a WUE of 12 kg grain/ha.mm and split on soil nitrogen (20 mg/kg). All alternate splits were to the left including fertiliser N (<23.5 kg/ha), fertiliser K (<5.5 kg/ha), *P. neglectus* (<1.0 pg/gram soil) and EC (<0.1 dS/m). There were no surrogate variates.

The tenth node contained 30% of the data with a WUE of 10 kg grain/ha.mm. These were CAR and SAR paddocks with high soil root disease and low soil pathogen DNA.

The eleventh node contained 3% of the data with a WUE of 15 kg grain/ha.mm. These were CAR and SAR paddocks with low soil root disease and high soil pathogen DNA. These paddocks received >38.4 kg N fertiliser/ha and had high soil S (>9.9 mg/kg). This was a terminal node, without any further splits. The terminal node represents paddocks with high levels of N and S, which may also provide conditions under which soil pathogen DNA is high.

The twelfth node contained 2% of the data with a WUE of 7.5 kg grain/ha.mm. This represented NAR paddocks with a soil N concentration between 17 and 20 mg/kg. This was a terminal node, without any further splits.

The 13th node contained 6% of the data with a WUE of 14 kg grain/ha.mm. This represented NAR paddocks with a soil N >20 mg/kg. Nodes 4, 12 and 13 show WUE was strongly related to soil N within the NAR.

S6. Regression tree analysis using a sub-set of management and biotic variates

The regression and classification analysis tree using a sub-set of management and biotic variates to examine break effect had a relative error of the regression of 0.25, an R^2 of 0.75. Below we describe the regression tree nodes, including alternate variables, that would provide similar splits.

The first node, and best predictor of WUE, was severity of root disease (<1.78) and mean WUE from break crops was (12.5 kg grain/ha.mm) Alternative split variates to the left were fertiliser nitrogen (< 14), N_in (< 126 kg/ha), and break crop with wheat after lupin or canola to the left (lower WUE) and after pasture to the right. This is consistent with wheat following pasture having a higher WUE (kg grain/ha.mm) than after canola (12.3 kg grain/ha.mm) or lupin (12.2 kg grain/ha.mm).

The second node was the terminal node from node one accounting for 9% of the data with a reduction in WUE from node 1 to 9.7 kg grain/ha.mm due to root disease, less nitrogen or based on previous land use.

The third node contained 91% of the data with a WUE of 12.8 kg grain/ha.mm and was a further split on severity of root disease (0.113). Alternative splits to the left included N_in (< 130 kg/ha), fertiliser nitrogen (<14 kg/ha) and break crop, with wheat after lupin or canola to the left (lower WUE) and after pasture to the right.

The fourth node contained 15.9% of the data with a WUE of 11.2 kg grain/ha.mm resulting from low root disease severity.

The fifth node contained 75.5% of the data with a WUE of 13.1 kg grain/ha.mm and was a further split on severity of root disease (0.213). Alternative splits were to the left, N_in (< 126 kg/ha), fertiliser nitrogen (<14 kg/ha) and break crop, with wheat after lupin (lower WUE) and after canola or pasture to the right.

The sixth node contained 65.6% of the data with a WUE of 12.8 kg grain/ha.mm and was a further split on N_in (126 kg/ha). Alternative split variates to the left were fertiliser nitrogen (<14.8 kg/ha) and break crop, with wheat after lupin and canola (lower WUE) than after pasture to the right. Weeds were an alternative split to the right (<0.75/m^2).

The seventh node contained 9.9% of the data with a WUE of 15.2 kg grain/ha.mm and was the result of various splits on severity of root disease, ending in low levels of root disease.

The eighth node contained 60.9% of the data with a WUE of 12.5 kg grain/ha.mm and consisted of paddocks with low root disease without very high nitrogen input. This node split based on N_in (≥ 41 kg/ha) with WUE 13.1 kg grain/ha.mm compared to < 41 kg.N/ha at 12.2 kg grain/ha.mm. The 38% of the data with < 41 kg/ha nitrogen from this split, split further with 32.5% of the data having weeds less than 37.5/m^2 and WUE at 12.7 kg grain/ha.mm compared to a small proportion (5.3%) of weedy

paddocks (>37.5/m^2), with WUE of 9.0 kg grain/ha.mm. An alternative split from this was canola indicating the low weed pressure for wheat after canola.

The ninth node contained 4.6% of the data with a WUE of 16.6 kg grain/ha.mm. This node indicates that a small proportion of pasture paddocks were supplying high amounts of N and this was increasing WUE, and that very low weed density was also associated with very high WUE.

As discussed in the manuscript while break crop effects were low overall (Figure 6b), for the small number of paddocks where weeds, disease or nitrogen limited WUE, break crops could increase WUE substantially.

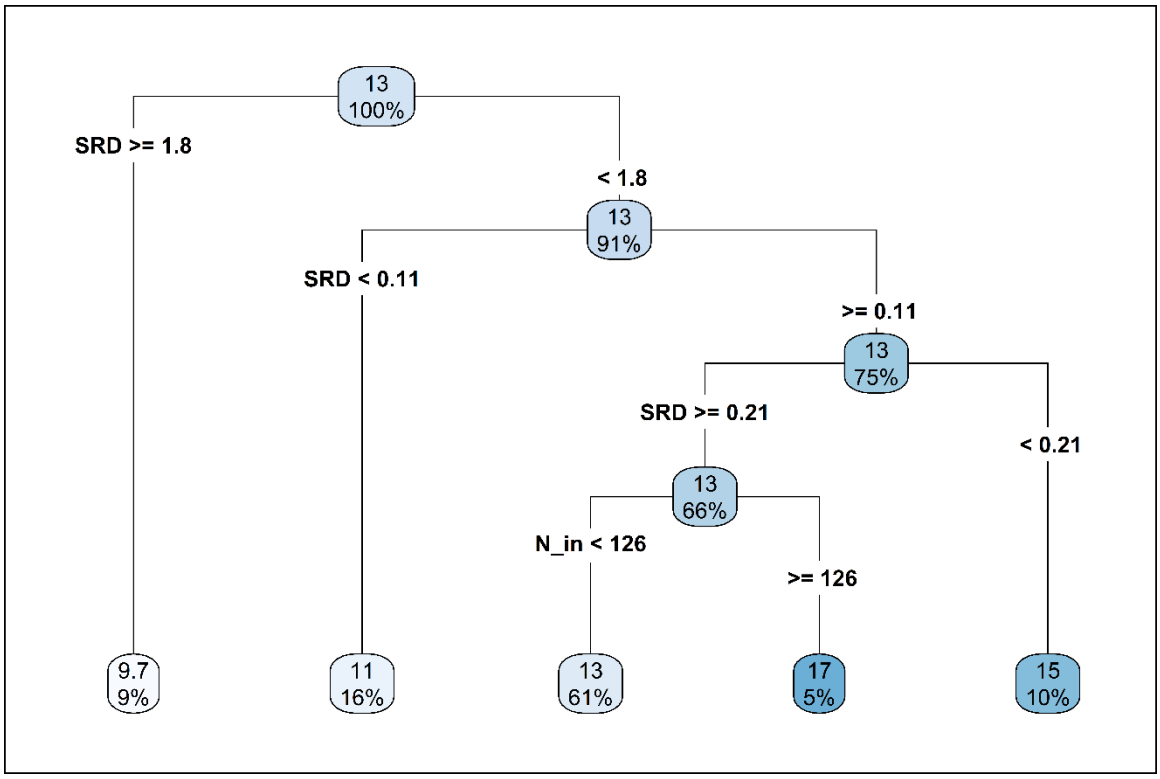

Fig. S6. Classification and regression tree analysis (CART) of WUE including the variates weed, plant root damage and nitrogen inputs (Nin) and wheat crops sown in the year after canola, lupin, and pasture, to examined break effects. SRD = severity of root disease, N_in = nitrogen from previous year + fertiliser nitrogen.

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