10.1071/CP23320

Crop & Pasture Science

Supplementary Material

Rain and potential evapotranspiration are the main drivers of yield for wheat and barley in southern Australia: insights from 12 years of National Variety Trials

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Supplementary material

Testing relationships between climatic and fertiliser variables on highest yield per site

These notes summarise: (a) how we tested the effects on highest grain yield per site of climatic and fertiliser variables for wheat and barley, (b) the process in which we narrowed-down the range of variables tested as we progressed from 1- and 2- to 3-variable relationships, and (c) the statistics of the best relationship involving each combination of x-variables, and the interval of months over which the adjusted R^2 was maximised. Relationships with climatic variables alone are reported in Tables S1 (one *x*-variable), S2 (two *x*-variables) and S3 (three *x*-variables). Relationships incorporating non-climatic variables are reported in Table S4 (one *x*-variable), S5 (two *x*-variables) and S6 (three *x*-variables)

Single *x*-variable relationships

With single *x*-variable relationships, we tested the value of the 10 climatic variables listed in Table 2 of the main paper for both crops (Table S1). For climatic variables involving rain and aridity index we tested all combinations of adjacent months between November of the previous year (abbreviated as Nov*) and December of the cropped year (105 options); for other climatic variables we tested all options of adjacent months between January and December of the cropped year (78 options).

For both crops, the climatic variables accounting for most of the variation were aridity index (rain/ET_o), rain, ET_o, av max T, max maxT and av T (with adjusted R^2 values between 54.5 and 21.6%).

Analyses were also conducted to test the effects of a wide range of non-climatic variables on the highest grain yield per trial of wheat and barley (Table S4). These included: the application of N, P and S fertilisers, soil pH, $EC_{1:5}$, ESP and the concentrations of N, P and organic carbon in the soil at two soil depths (0-10 and 10-60 cm), and the dates of sowing and harvest. In these analyses, no non-climatic factors were more important than fertilisers. The 5 fertiliser application variables examined were total N fertiliser (N fert), N fertiliser applied at or before sowing or after sowing (N fert start and N fert later respectively), P fert and S fert. In single *x*-variable relationships the first 4 of these accounted for between 22.5 and 7.2% of the variation in each crop (Table S4).

An important theme of the paper is that fertiliser responses were confounded with improved agronomic management of the trials and the use of better adapted varieties. The value of fertilisers in these relationships therefore needs to be treated cautiously.

Two *x*-variable relationships

In 2 *x*-variable relationships we focused on aridity index, rain, ET_o, and temperature (av maxT, max maxT, av minT, min minT, and av T) as climatic variables of interest, and on N fert, N fert later, N fert start and P fert as fertiliser variables.

The best families of solutions for 2 *x*-variable relationships are summarised in Table S2 (climatic variables alone) and Table S5 (climatic with fertiliser variables).

With 2 variable relationships, we tested effects of: (a) rain (*x1*) combined with ET_o, max maxT, av max T, min minT or av minT (x2), and (b) aridity index (*x1*) combined with max maxT, av max T, av minT, or min minT (*x2*). As noted previously, rain and aridity index were tested over 105 combinations of monthly intervals and the other climatic variables were tested over 78 combinations of monthly intervals. In addition, we also tested: (c) the value of splitting aridity index or rain into the pre-seasonal period (from November of the previous year to April of the cropped year – 21 monthly intervals – *x1*) and the seasonal period (from May to December of the cropped year – 36 monthly intervals – *x2*). In relationships incorporating fertilisers we tested rain or aridity index (*x1*) (105 combinations of monthly intervals) with N fert, N fert later, N fert start or P fert (*x2*).

With wheat, the best relationship with 2 climatic variables was rain (*x1*) combined with ET_o (*x2*), (adjusted R^2 = 61.8%; Table S2A). With barley, the best relationship with 2 climatic variables was aridity index separated into pre-seasonal (*x1*) and seasonal components (*x2*) (adjusted R^2 = 50.6; Table S2B). Compared with single variable relationships, these 2-variable relationships increased the amount of variation accounted for by 7.3% for wheat and 9.2% for barley (c.f. Table S2A with Table S1A; c.f. Table S2B with Table S1B). N or P fertilisers were important additional variables with aridity index or rain (Table S5).

Three *x*-variable relationships

In light of these results, we examined in 3 *x*-variable relationships the effects of aridity index (or rain with ET_o) coupled with four temperature variables (max maxT, av maxT min minT and av minT) as climatic variables, and N and P as fertiliser variables.

As noted in the Materials and Methods, when it came to 3 climatic variable relationships, it was not possible for us to run 105 x 78^2 GAM options in reasonable periods of time on desktop computers, so when it came to relationships involving 3 climatic variables, we constrained the number of options examined. Single *x*-variable, 2 *x*-variable, and preliminary runs with 3 climatic variable analyses showed that the best solutions involving aridity index or rain were determined over 5- to 12-month intervals between November of the previous year and October (36 options), best solutions involving Σ ET_o were determined over 1- to 4-month intervals between July and October (10 options), and best solutions involving min minT, av minT, max maxT and av maxT were determined over 1- to 4-month intervals between April and October (22 options). Where aridity index was divided into pre-seasonal and seasonal

months (*x1*, *x2*), and these were coupled with temperature variables (*x3*), we filtered 21 x 36 x 22 (= 16,632 options).

The best families of solutions for 3 *x*-variable relationships, with the number of relationships tested, are summarised in Table S3 (for climatic variables alone) and Table S6 (for climatic with fertiliser variables).

For wheat, the best 3 *x*-variable relationship involved aridity index split into pre-seasonal and seasonal components (*x*1 and x*2*) coupled with av maxT (*x*3) with an adjusted R^2 for the best relationship of 65.7%. This accounted for 3.9% more of the variation than the best 2 *x*-variable relationship for wheat (c.f. Table S3A with Table S2A). For barley, the best 3 *x*-variable relationship also involved aridity index split into pre-seasonal and seasonal components (*x*1 and x*2*) but coupled with min minT (*x*3), with an adjusted R^2 for the best relationship of 58.1%. This accounted for 7.5% more of the variation than the best 2 *x*-variable relationship for barley (c.f. Table S3B with Table S2A).

A range of 3-variable relationships were tested involving combinations of climatic with fertiliser variables (Table S5). As noted previously, we view these results with caution. For wheat, the highest ranked combination of climatic with fertiliser variables was Σ rain (*x1*) x Σ ET_o (*x2*) x N fert later (*x3*), with an adjusted R^2 of 66.6% (Table S6A). For barley, the highest ranked combination of climatic with fertiliser variables was Σ rain (*x1*) x Σ ET_o (*x2*) x P fert (*x3*) with an adjusted R^2 of 59.3% (Table S6B).

Table S1. Best single *x*-variable relationships (climatic factors only) accounting for variation in the highest grain yield per site (*y*-variable) for: (A) wheat, and (B) barley. These have been ranked in order of best relationship (i.e. from highest to lowest adjusted R^2). Also shown is the significance (*P*-value) of the variable in the best relationship.

A. Wheat (n = 918)

Relationship	Number of relationships tested in family	Adjusted R^2 (%) of best relationship	Monthly interval of best relationship	*P*-value of best relationship†
Aridity index (Σ rain/Σ ET_o)	105	54.5	Feb–Oct	***
Σ rain	105	49.7	Feb–Oct	***
Σ ET_o	78	42.1	Sep–Oct	***
Av maxT	78	34.8	Sep–Oct	***
Max maxT	78	32.8	Sep–Oct	***
Av T	78	29.1	Sep-Nov	***
Range T	78	28.5	Jul–Oct	***
Av minT	78	16.8	Oct–Dec	***
Min minT	78	9.7	Nov–Dec	***

B. Barley (n = 551)

Relationship	Number of relationships tested in family	Adjusted R^2 (%) of best relationship	Monthly interval of best relationship	*P*-value of best relationship†
Aridity index (Σ rain/Σ ET_o)	105	41.4	May–Sep	***
Σ rain	105	36.4	Nov*–Oct	***
Σ ET_o	78	32.3	Sep	***
Av maxT	78	27.4	Sep–Oct	***
Max maxT	78	22.4	Sep–Oct	***
Av T	78	21.6	Oct	***
Range T	78	20.2	Sep	***
Av minT	78	12.7	Oct–Dec	***
Min minT	78	8.9	Oct–Nov	***

* Denotes month of previous year

† Significance: *** *P* < 0.001.

Table S2. Best two *x*-variable relationships (climatic factors only) accounting for variation in the highest grain yield per site (*y*-variable) for: (A) wheat, and (B) barley. These have been ranked in order of best relationship (i.e. from highest to lowest adjusted R^2). Also shown is the significance (*P*-values) of the variables (main effects and interactions) in the best relationship.

A. Wheat (*n* = 918)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship		*P*-values of variables in best relationship †		
			x1	x2	x1	x2	x1.x2
1. *Σ rain (x1) x ΣET_o (x2)*							
	105 x 78	61.8	Jan–Sep	Jul–Oct	***	***	**
2. *Aridity index – pre-seasonal (Σ rain/ ΣET_o – x1) x Aridity index – seasonal (Σ rain/ ΣET_o – x2)*							
	21 x 36	60.6	Feb–Apr	May–Sep	***	***	***
3. *Aridity index (Σ rain/ ΣET_o – x1) x av maxT (x2)*							
	105 x 78	60.0	Feb–Oct	Apr–Jul	***	***	***
4. *Σ rain (x1) x av T (x2)*							
	105 x 78	59.7	Jan–Sep	Sep–Nov	***	***	*
5. *Aridity index (Σ rain/ ΣET_o – x1) x min minT (x2)*							
	105 x 78	59.6	Feb–Oct	Jun–Jul	***	*	***
6. *Aridity index (Σ rain/ ΣET_o – x1) x max maxT (x2)*							
	105 x 78	58.8	Feb–Sep	Sep–Oct	***	**	*
7. *Aridity index (Σ rain/ ΣET_o – x1) x av T (x2)*							
	105 x 78	58.5	Feb–Oct	May–Jun	***	***	***
8. *Σ rain (x1) x av max T (x2)*							
	105 x 78	58.4	Jan–Sep	May–Nov	***	***	*
9. *Aridity index (Σ rain/ ΣET_o – x1) x av minT (x2)*							
	105 x 78	58.3	Feb–Oct	Jun	***	***	***
10. *Σ rain (x1) x min minT (x2)*							
	105 x 78	57.9	Feb–Oct	Oct–Dec	***	***	***
11. *Σ rain (x1) x av minT (x2)*							
	105 x 78	57.7	Jan–Sep	Oct–Nov	***	***	**
12. *Σ rain (x1) x max maxT (x2)*							
	105 x 78	56.8	Feb–Sep	Sep–Oct	***	***	*
13. *Σ rain – pre-seasonal (x1) x Σ rain – seasonal (x2)*							

	21 x 36	53.6	Nov*–Apr	May–Oct	***	***	***

B. Barley (*n* = 551)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship		*P*-values of variables in best relationship †		
			x1	x2	x1	x2	x1.x2
1. Aridity index – pre-seasonal (Σ rain/ ΣET_o – x1) x Aridity index – seasonal (Σ rain/ ΣET_o – x2)							
	21 x 36	50.6	Apr	May–Sep	**	***	***
2. Aridity index (Σ rain/ ΣET_o – x1) x av maxT (x2)							
	105 x 78	49.3	May–Oct	Dec	***	***	***
3. Aridity index (Σ rain/ ΣET_o – x1) x min minT (x2)							
	105 x 78	49.1	May–Oct	Aug–Nov	***	***	*
4. Aridity index (Σ rain/ ΣET_o – x1) x av minT (x2)							
	105 x 78	48.5	May–Oct	Aug–Nov	***	***	***
5. Aridity index (Σ rain/ ΣET_o – x1) x max maxT (x2)							
	105 x 78	48.2	May–Oct	Aug–Dec	***	ns	***
6. Σ rain (x1) x ΣET_o (x2)							
	105 x 78	47.5	Dec*–Aug	Sep	***	***	ns
7. Aridity index (Σ rain/ ΣET_o – x1) x av T (x2)							
	105 x 78	47.5	Feb–Oct	Aug	***	***	**
8. Σ rain (x1) x min minT (x2)							
	105 x 78	47.4	Mar–Oct	Aug–Nov	***	***	*
9. Σ rain (x1) x av minT (x2)							
	105 x 78	47.2	Feb–Oct	Aug–Nov	***	***	**
10. Σ rain (x1) x av T (x2)							
	105 x 78	46.7	Feb–Oct	Aug–Sep	***	***	***
11. Σ rain (x1) x av max T (x2)							
	105 x 78	45.8	Dec*–Oct	Aug–Sep	***	***	ns
12. Σ rain (x1) x max maxT (x2)							
	105 x 78	43.2	Apr–Sep	Aug–Oct	***	***	***
13. Σ rain – pre-seasonal (x1) x Σ rain – seasonal (x2)							
	21 x 36	42.0	Nov*–Apr	May–Oct	***	***	***

Table S3. Selected three variable relationships (climatic factors only) accounting for variation in the highest grain yield per site (*y*-variable). These have been ranked in order of best relationship (i.e. from highest to lowest adjusted R^2 value) for: (A) wheat, and (B) barley. Also shown is the significance (*P*-values) of the variables (main effects and interactions) in the best relationship.

Part A. Wheat (*n* = 918)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship			*P*-values of variables in best relationship[†]						
			x1	x2	x3	x1	x2	x3	x1.x3	x1.x2	x2.x3	x1.x2 .x3
1. *Aridity index – pre-seasonal ($\Sigma rain/ \Sigma ET_o$ – x1) x Aridity index – seasonal ($\Sigma rain/ \Sigma ET_o$ – x2) x av maxT (x3)*												
	21 x 36 x 22	65.7	Jan–Apr	May–Sep	Apr–Jul	***	***	***	**	***	***	ns
2. *Aridity index – pre-seasonal ($\Sigma rain/ \Sigma ET_o$ – x1) x Aridity index – seasonal ($\Sigma rain/ \Sigma ET_o$ – x2) x max maxT (x3)*												
	21 x 36 x 22	65.2	Jan–Apr	May–Sep	May–Jun	***	***	***	***	***	ns	ns
3. *$\Sigma rain$ (x1) x ΣET_o (x2) x av maxT (x3)*												
	36 x 10 x 22	64.7	Feb–Sep	Jul–Oct	Apr–Jul	***	***	***	ns	ns	ns	ns
4. *$\Sigma rain$ (x1) x ΣET_o (x2) x max maxT (x3)*												
	36 x 10 x 22	64.6	Feb–Sep	Jul–Oct	May	***	***	***	ns	**	ns	ns
5. *Aridity index – pre-seasonal ($\Sigma rain/ \Sigma ET_o$ – x1) x Aridity index – seasonal ($\Sigma rain/ \Sigma ET_o$ – x2) x min minT (x3)*												
	21 x 36 x 22	64.3	Jan–Apr	May–Sep	Apr	***	***	ns	***	***	***	ns
6. *Aridity index – pre-seasonal ($\Sigma rain/ \Sigma ET_o$ – x1) x Aridity index – seasonal ($\Sigma rain/ \Sigma ET_o$ – x2) x av minT (x3)*												
	21 x 36 x 22	64.2	Jan–Apr	May–Oct	Jun	***	***	***	**	***	***	ns
7. *$\Sigma rain$ (x1) x ΣET_o (x2) x min minT (x3)*												
	36 x 10 x 22	64.1	Feb–Oct	Jul–Sep	May–Jun	***	***	ns	ns	ns	***	ns
8. *$\Sigma rain$ (x1) x ΣET_o (x2) x av minT (x3)*												
	36 x 10 x 22	63.9	Dec*-Aug	Sep	Apr	***	***	**	ns	ns	***	ns

Table S3 – Part A – wheat continued

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship			*P*-values of variables in best relationship†						
			x1	x2	x3	x1	x2	x3	x1.x3	x1.x2	x2.x3	x1.x2.x3
9. *Σrain – pre-seasonal (x1) x Σrain – seasonal (x2) x av maxT (x3)*												
	21 x 36 x 22	62.2	Jan–Apr	May–Oct	May–Jul	***	***	***	**	***	***	ns
10. *Σrain – pre-seasonal (x1) x Σrain – seasonal (x2) x av minT (x3)*												
	21 x 36 x 22	61.2	Jan–Apr	May–Oct	Oct	***	***	***	**	***	***	ns
11. *Σrain – pre-seasonal (x1) x Σrain – seasonal (x2) x max maxT (x3)*												
	21 x 36 x 22	60.8	Jan–Apr	May–Sep	Apr–Jun	***	***	***	***	***	**	ns
12. *Σrain – pre-seasonal (x1) x Σrain – seasonal (x2) x min minT (x3)*												
	21 x 36 x 22	60.2	Feb–Apr	May–Oct	Aug–Oct	***	***	***	*	***	***	ns

Part B. Barley (n = 551)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship			*P*-values of variables in best relationship†						
			x1	x2	x3	x1	x2	x3	x1.x3	x1.x2	x2.x3	x1.x2.x3
1. *Aridity index – pre-seasonal (Σrain/ $ΣET_o$ – x1) x Aridity index – seasonal (Σrain/ $ΣET_o$ – x2) x min minT (x3)*												
	21 x 36 x 22	58.1	Jan–Apr	May–Oct	Jul–Oct	***	***	***	ns	***	ns	*
2. *Aridity index – pre-seasonal (Σrain/ $ΣET_o$ – x1) x Aridity index – seasonal (Σrain/ $ΣET_o$ – x2) x av minT (x3)*												
	21 x 36 x 22	57.2	Feb–Apr	May–Sep	May-Jun	**	***	***	ns	***	ns	**
3. *Σrain (x1) x $ΣET_o$ (x2) x max maxT (x3)*												
	36 x 10 x 22	56.8	Dec*–Aug	Sep	Aug	***	***	ns	*	ns	***	***

4. *Aridity index – pre-seasonal (Σ rain/ ΣET_o – x1) x Aridity index – seasonal (Σ rain/ ΣET_o – x2) x max maxT (x3)*												
	21 x 36 x 22	56.7	Feb–Apr	May–Sep	Sep–Oct	**	***	ns	**	ns	ns	***

Table S3 – Part B – barley continued

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship			*P*-values of variables in best relationship[†]						
			x1	x2	x3	x1	x2	x3	x1.x3	x1.x2	x2.x3	x1.x2 .x3
5. *Aridity index – pre-seasonal (Σ rain/ ΣET_o – x1) x Aridity index – seasonal (Σ rain/ ΣET_o – x2) x av maxT (x3)*												
	21 x 36 x 22	55.9	Jan–Apr	May–Oct	Sep	***	*	ns	ns	ns	***	**
6. *Σ rain (x1) x ΣET_o (x2) x min minT (x3)*												
	36 x 10 x 22	54.6	Apr–Sep	Oct	Sep–Oct	***	*	***	ns	*	ns	***
7. *Σ rain (x1) x ΣET_o (x2) x av maxT (x3)*												
	36 x 10 x 22	55.6	Jan–Oct	Jul–Oct	Aug–Sep	ns	***	***	***	***	***	*
8. *Σ rain (x1) x ΣET_o (x2) x av minT (x3)*												
	36 x 10 x 22	54.4	Jan–Sep	Aug–Oct	Sep	***	*	***	**	**	**	***
9. *Σ rain – pre-seasonal (x1) x Σ rain – seasonal (x2) x av minT (x3)*												
	21 x 36 x 22	54.1	Nov*–Apr	May–Sep	Jun	***	***	***	*	***	**	ns
10. *Σ rain – pre-seasonal (x1) x Σ rain – seasonal (x2) x av maxT (x3)*												
	21 x 36 x 22	54.0	Feb–Mar	May–Oct	Sep	ns	***	***	ns	**	ns	***
11. *Σ rain – pre-seasonal (x1) x Σ rain – seasonal (x2) x min minT (x3)*												
	21 x 36 x 22	53.6	Jan–Apr	May–Oct	Aug–Sep	**	***	***	***	***	***	ns
12. *Σ rain – pre-seasonal (x1) x Σ rain – seasonal (x2) x max maxT (x3)*												
	21 x 36 x 22	52.0	Jan–Apr	May–Sep	Aug–Sep	*	***	***	***	ns	***	***

Table S4. Single-factor relationships between fertiliser, agronomic or soil variables (*x*), and variation in grain yield (*y*) for: (A) wheat, and (B) barley. The variables have been ranked in order from highest to lowest adjusted R^2. Also shown is the significance (*P*-value) of the relationship.

A. Wheat

Variable	Adj. R^2 of relationship (%)	*n*	*P*-value of relationship†
• N fert later	22.5	909	***
• Org. C (0-10 cm)	14.8	906	***
• N fert	14.5	909	***
• Harvest day	12.7	918	***
• P fert	11.2	909	***
• Org. C (10-60 cm)	9.7	596	***
• N fert start	7.2	909	***
• pH_{H2O} (0-10 cm)	6.3	903	***
• pH_{CaCl2} (10-60 cm)	4.5	894	***
• pH_{CaCl2} (0-10 cm)	4.5	903	***
• Soil N (0-10 cm)	4.2	742	***
• Soil N (10-60 cm)	4.2	742	***
• Soil P (0-10 cm)	4.1	905	***
• pH_{H2O} (10-60 cm)	3.9	884	***
• Sowing day	3.2	918	***
• ESP (10-60 cm)	3.0	442	***
• S fert	2.5	909	**
• $EC_{1:5}$ (0-10 cm)	2.6	902	***
• $EC_{1:5}$ (10-60 cm)	2.1	896	***
• Soil P (10-60 cm)	0.6	599	*
• ESP (0-10 cm)	0.5	428	ns

Table S4 – continued

B. Barley

Variable	Adj. R^2 of relationship (%)	*n*	*P*-value of relationship†
• N fert later	18.3	545	***
• P fert	16.3	545	***
• N fert	9.4	545	***
• N fert start	8.1	545	***
• Org. C (0-10 cm)	5.9	532	***
• Org. C (10-60 cm)	5.8	279	***
• pH_{H2O} (10-60 cm)	5.4	514	***
• $EC_{1:5}$ (0-10 cm)	4.9	533	***
• pH_{CaCl2} (10-60 cm)	4.9	519	***
• Harvest day	4.7	551	***
• S fert	3.6	545	**
• pH_{H2O} (0-10 cm)	2.6	530	*
• pH_{CaCl2} (0-10 cm)	2.3	531	*
• Soil N (0-10 cm)	1.9	442	*
• Soil P (10-60 cm)	1.7	279	ns
• $EC_{1:5}$ (10-60 cm)	1.2	521	ns
• Soil P (0-10 cm)	1.2	532	**
• Soil N (10-60 cm)	0.9	403	ns
• ESP (10-60 cm)	0.9	326	ns
• Sowing day	0.2	551	ns
• ESP (0-10 cm)	-0.2	330	ns

† Significance: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table S5. Two-factor relationships between climatic and fertiliser variables (*x*-variables), and variation in grain yield (*y*) for: (A) wheat, and (B) barley. The variables have been ranked in order from highest to lowest adjusted R^2. Also shown is the significance (*P*-value) of the relationship.

A. Wheat (*n* = 909)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship		*P*-values of variables in best relationship †		
			x1	x2	x1	x2	x1.x2
1. Aridity index (Σ rain/ ΣET_o – x1) x N fert later (x2)							
	105 x 1	61.3	Feb–Oct	-	***	***	***
2. Aridity index (Σ rain/ ΣET_o – x1) x N fert (x2)							
	105 x 1	60.1	Feb–Oct	-	***	***	***
3. Aridity index (Σ rain/ ΣET_o – x1) x N fert start (x2)							
	105 x 1	59.7	Feb–Oct	-	***	***	***
4. Σ rain (x1) x N fert later (x2)							
	105 x 1	59.5	Jan–Oct	-	***	***	***
5. Aridity index (Σ rain/ ΣET_o – x1) x P fert (x2)							
	105 x 1	58.7	Feb–Oct	-	***	***	***
6. Σ rain (x1) x P fert (x2)							
	105 x 1	57.6	Jan–Oct	-	***	***	***
7. Σ rain (x1) x N fert start (x2)							
	105 x 1	57.1	Jan–Oct	-	***	***	***
8. Σ rain (x1) x N fert (x2)							
	105 x 1	55.1	Jan–Oct	-	***	***	***

† Significance: *** $P < 0.001$

B. Barley (*n* = 545)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship		*P*-values of variables in best relationship †		
			x1	x2	x1	x2	x1.x2
1. Aridity index (Σ rain/ ΣET_o – x1) x P fert (x2)							
	105 x 1	49.6	Nov*–Oct	-	***	***	***
2. Σ rain (x1) x P fert (x2)							
	105 x 1	49.0	Nov*–Oct	-	***	***	***
3. Aridity index (Σ rain/ ΣET_o – x1) x N fert later (x2)							
	105 x 1	48.6	Mar–Nov	-	***	***	ns
4. Σ rain (x1) x N fert later (x2)							
	105 x 1	47.8	Nov*–Oct	-	***	***	*
5. Aridity index (Σ rain/ ΣET_o – x1) x N fert start (x2)							
	105 x 1	47.4	May–Oct	-	***	***	***
6. Aridity index (Σ rain/ ΣET_o – x1) x N fert (x2)							
	105 x 1	46.0	Mar–Oct	-	***	***	**
7. Σ rain (x1) x N fert start (x2)							
	105 x 1	44.4	Nov*–Oct	-	***	***	***
8. Σ rain (x1) x N fert (x2)							
	105 x 1	41.5	Nov*–Oct	-	***	***	ns

* Denotes month of previous year

† Significance: ns = not significant or P>0.05; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table S6. Selected three variable relationships (combinations of climatic and fertiliser factors) accounting for variation in the highest grain yield per site (*y*-variable). These have been ranked in order of best relationship (i.e. from highest to lowest adjusted R^2 value) for: (A) wheat, and (B) barley. Also shown is the significance (*P*-values) of the variables (main effects and interactions) in the best relationship.

A. Wheat (*n* = 909)

Relationship	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship			*P*-values of variables in best relationship†						
			x1	x2	x3	x1	x2	x3	x1.x3	x1.x2	x2.x3	x1.x2 .x3
1. Σrain (x1) x ΣET_o (x2) x N fert later (x3)												
	105 x 78 x 1	66.6	Dec*–Oct	Sep	-	***	***	***	**	ns	ns	ns
2. *Aridity index (Σrain/ ΣET_o – x1) x N fert later (x2) x N fert start (x3)*												
	105 x 1 x 1	66.5	Feb–Oct	-	-	***	***	*	***	***	ns	**
3. *Aridity index – pre-seasonal (Σrain/ ΣET_o – x1) x Aridity index – seasonal (Σrain/ ΣET_o – x2) x N fert later (x3)*												
	21 x 36 x 1	65.9	Jan–Apr	May–Oct	-	***	***	***	ns	***	*	ns
4. *Aridity index (Σrain/ ΣET_o – x1) x av maxT (x2) x N fert later (x3)*												
	105 x 78 x 1	65.8	Feb–Oct	May–Jul	-	***	***	***	ns	***	ns	*
5. *Σrain (x1) x ΣET_o (x2) x N fert start (x3)*												
	105 x 78 x 1	65.4	Feb–Sep	Aug–Oct	-	***	***	***	ns	*	***	ns
6. *Aridity index – pre-seasonal (Σrain/ ΣET_o – x1) x Aridity index – seasonal (Σrain/ ΣET_o – x2) x N fert start (x3)*												
	21 x 36 x 1	65.2	Feb–Apr	May–Sep	-	***	***	ns	**	***	***	**
7. Σrain (x1) x ΣET_o (x2) x P fert (x3)												
	105 x 78 x 1	64.6	Jan–Sep	Sep–Oct	-	***	***	***	ns	**	ns	**
8. Aridity index – pre-seasonal (Σrain/ ΣET_o – x1) x Aridity index – seasonal (Σrain/ ΣET_o – x2) x P fert (x3)												
	21 x 36 x 1	64.3	Jan–Apr	May–Oct	-	***	***	***	ns	***	***	ns

B. Barley (*n* = 545)

Variables/ crop	Number of relationships tested in family	Adj. R^2 (%) of best relationship	Monthly interval of variables in best relationship			*P*-values of variables in best relationship†						
			x1	x2	x3	x1	x2	x3	x1.x3	x1.x2	x2.x3	x1.x2 .x3
1. Σrain (x1) x ΣET$_o$ (x2) x P fert (x3)												
	105 x 78 x 1	59.3	Dec*–Aug	Sep	-	***	***	***	*	*	ns	***
2. Aridity index – pre-seasonal (Σrain/ ΣET$_o$ – x1) x Aridity index – seasonal (Σrain/ ΣET$_o$ – x2) x P fert (x3)												
	21 x 36 x 1	58.0	Jan–Apr	May–Sep	-	***	***	***	ns	***	ns	*
3. Aridity index (Σrain/ ΣET$_o$ – x1) x av maxT (x2) x N fert later (x3)												
	105 x 78 x 1	57.2	Mar–Nov	Jan	-	***	***	***	**	ns	*	*
4. Aridity index (Σrain/ ΣET$_o$ – x1) x P fert (x2) x N fert start (x3)												
	105 x 1 x 1	57.0	Feb–Oct	-	-	***	***	ns	ns	**	ns	***
5. *Σrain (x1) x ΣET$_o$ (x2) x N fert later (x3)*												
	105 x 78 x 1	56.9	Feb–Sep	Sep	-	***	**	***	***	ns	**	***
6. Aridity index – pre-seasonal (Σ rain/ Σ ET$_o$ – *x*1) x Aridity index – seasonal (Σ rain/ Σ ET$_o$ – *x*2) x N fert later (*x*3)												
	21 x 36 x 1	56.4	Dec*–Apr	May–Oct	-	***	***	***	ns	***	ns	ns
7. Σrain (x1) x ΣET$_o$ (x2) x N fert start (x3)												
	105 x 78 x 1	55.9	Jan–Oct	Sep	-	**	***	**	**	***	**	**
8. Aridity index (Σrain/ ΣET$_o$ – x1) x N fert later (x2) x N fert start (x3)												
	105 x 1 x 1	55.6	Mar–Oct	-	-	***	***	*	**	ns	**	*
9. Aridity index – pre-seasonal (Σrain/ ΣET$_o$ – x1) x Aridity index – seasonal (Σrain/ ΣET$_o$ – x2) x N fert start (x3)												
	21 x 36 x 1	55.5	Feb–Apr	May–Sep	-	***	***	ns	**	***	ns	***

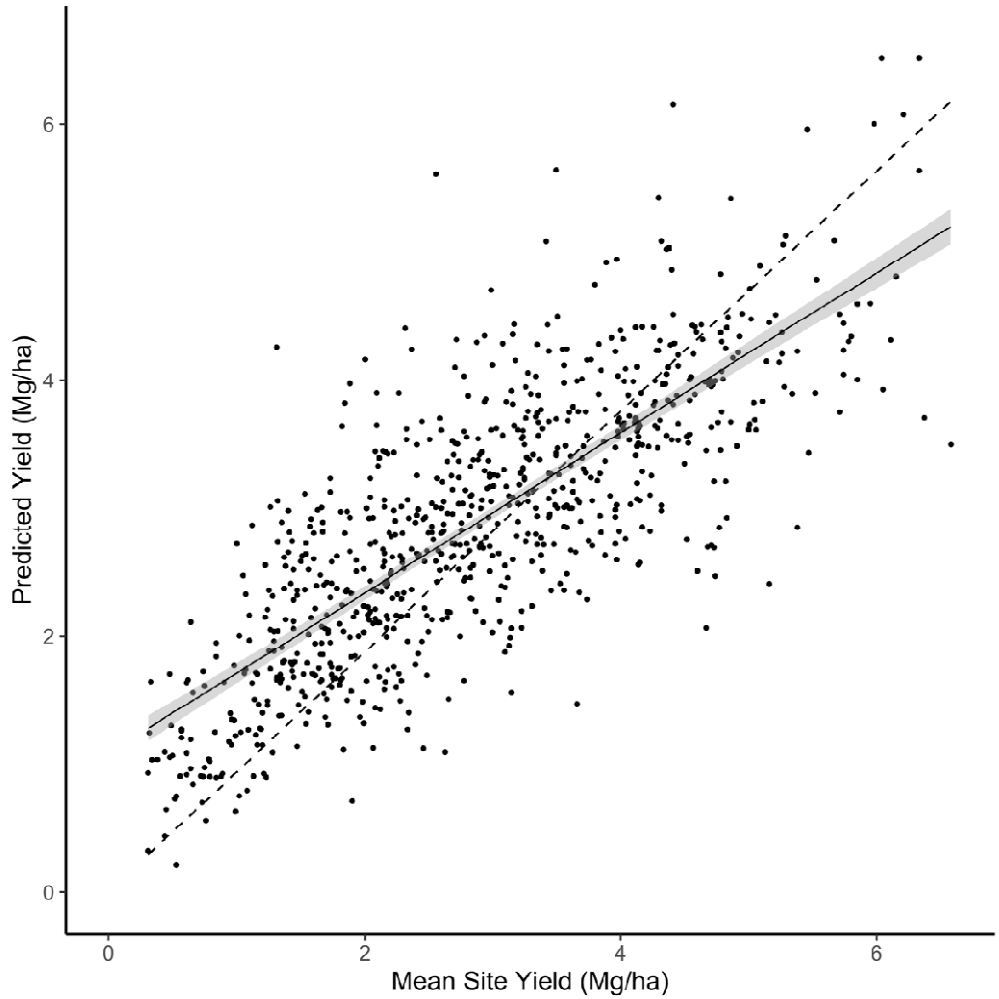

Fig. S1. A comparison between observed and predicted values from the final GAM model for wheat. The summary statistics for the cross-validated linear fit are presented in Table 4.

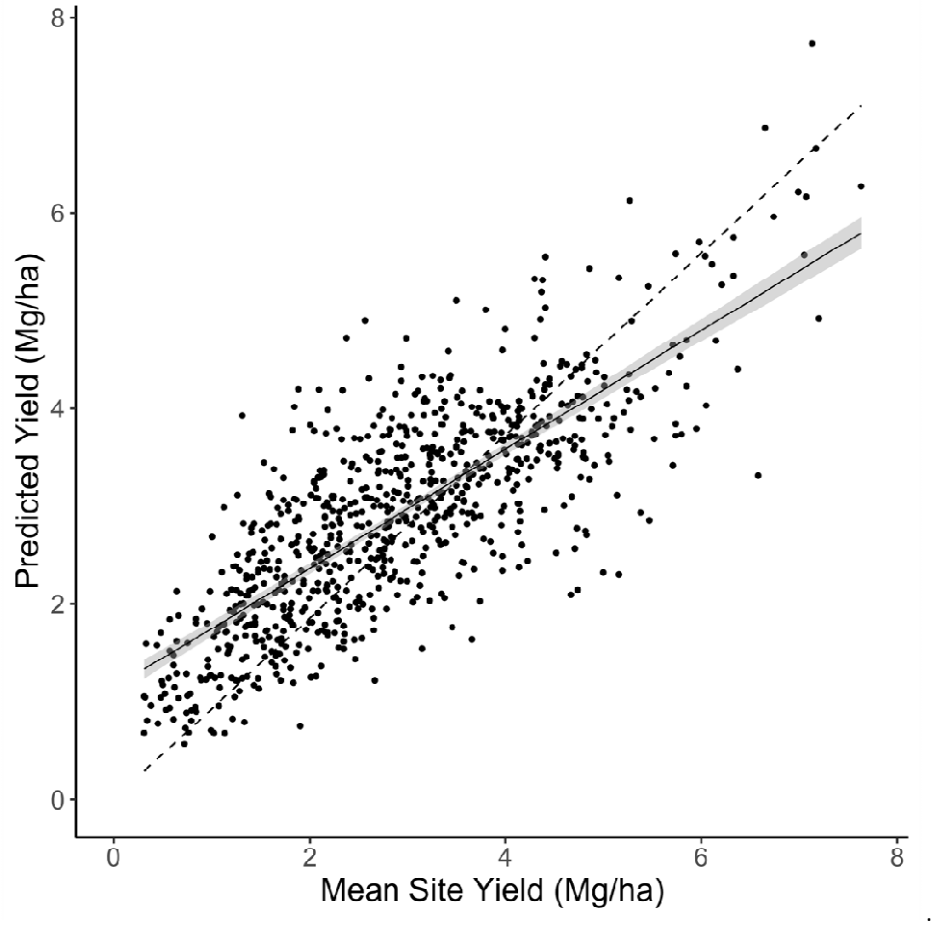

Fig. S2. A comparison between observed and predicted values from the final GAM model for barley. The summary statistics for the cross-validated linear fit are presented in Table 5.

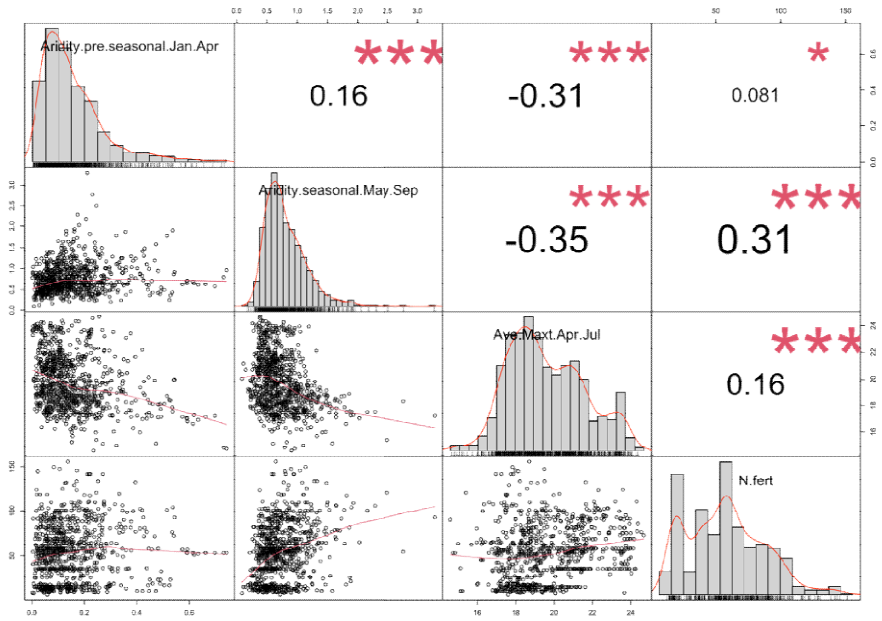

Fig. S3. Correlation statistics between the variables chosen for the final GAM model for wheat (pre-seasonal aridity index (Jan-Apr), seasonal aridity index (May-Sep), and average maximum temperature (Apr-Jul)). The total nitrogen fertilizer applied is also shown for comparison. The present number is the Pearson correlation of the relationship with the font size scaled based on the strength of the correlation.

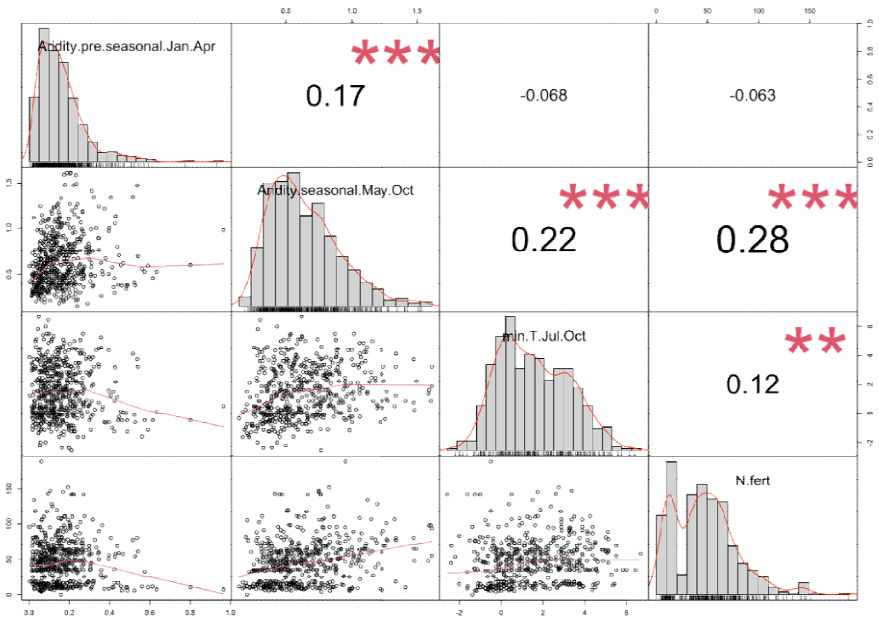

Fig. S4. Correlation statistics between the variables chosen for the final GAM model for barley (Σ rain (pre-seasonal Feb-Apr), Σ rain (seasonal May-Oct), ET_o (Aug-Sep)). The total nitrogen fertilizer applied is also shown for comparison. The present number is the Pearson correlation of the relationship with the font size scaled based on the strength of the correlation.

Table S7. The "estimate" measure of concurvity between terms in the final GAM model for wheat (Part A) and barley (Part B). The measure is bounded between 0 and 1, with 0 indicating no problem, and 1 indicating a total lack of identifiability.

A. Wheat

	para	Aridity (pre-seasonal Jan-Apr)	Aridity (seasonal May-Sep)	Max temp (Jun-Apr)	X1.X2	X2.X3	X1.X3	X1.X2.X3
para	1	0.00	0.00	0.00	0.01	0.04	0.01	0.00
Aridity (pre-seasonal Jan-Apr)	0.00	1	0.05	0.10	0.06	0.03	0.08	0.07
Aridity (seasonal May-Sep)	0.00	0.02	1	0.11	0.04	0.20	0.01	0.05
Max temp (Jun-Apr)	0.00	0.12	0.09	1	0.02	0.06	0.04	0.02
X1.X2	0.08	0.21	0.53	0.05	1	0.15	0.11	0.21
X2.X3	0.20	0.12	0.59	0.39	0.09	1	0.05	0.07
X1.X3	0.11	0.55	0.04	0.30	0.16	0.07	1	0.10
X1.X2.X3	0.17	0.63	0.63	0.37	0.55	0.38	0.36	1

B. Barley

	para	Aridity (pre-seasonal Jan-Apr)	Aridity (seasonal May-Oct)	Min temp (Jul-Oct)	X1.X2	X2.X3	X1.X3	X1.X2.X3
para	1	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Aridity (pre-seasonal Jan-Apr)	0.00	1	0.07	0.03	0.08	0.02	0.11	0.09
Aridity (seasonal May-Oct)	0.00	0.03	1	0.08	0.04	0.05	0.02	0.03
Min temp (Jul-Oct)	0.00	0.02	0.07	1	0.01	0.04	0.02	0.02
X1.X2	0.13	0.46	0.38	0.08	1	0.06	0.17	0.15
X2.X3	0.11	0.04	0.33	0.17	0.05	1	0.05	0.05
X1.X3	0.04	0.51	0.05	0.14	0.12	0.06	1	0.13
X1.X2.X3	0.18	0.66	0.41	0.33	0.33	0.30	0.36	1

Table S8. Critical dates, soil conditions and fertilising conditions for the different crops – percentiles and *n*.

Factor	Measurement	Wheat	Barley
Sowing day (in year)	5th percentile	126	127
	15th percentile	130	131
	25th percentile	134	135
	35th percentile	137	138
	45th percentile	140	141
	55th percentile	145	145
	65th percentile	147	148
	75th percentile	151	152
	85th percentile	157	158
	95th percentile	163	164
	n	918	551
Harvest day (in year)	5th percentile	309	305
	15th percentile	316	314
	25th percentile	321	317
	35th percentile	326	321
	45th percentile	331	325
	55th percentile	335	330
	65th percentile	338	334
	75th percentile	342	339
	85th percentile	347	345
	95th percentile	355	355
	n	918	551
Soil texture† (0-10 cm)	5th percentile	1	1
	15th percentile	1.5	1.5
	25th percentile	2	1.5
	35th percentile	2	2
	45th percentile	2	2
	55th percentile	2	2.5
	65th percentile	3	3
	75th percentile	3	3
	85th percentile	4	4
	95th percentile	5	5
	n	822	465
Soil texture† (10-60 cm)	5th percentile	1	1
	15th percentile	1.5	1.5
	25th percentile	2	2
	35th percentile	2	2
	45th percentile	2.5	2.5
	55th percentile	3	3
	65th percentile	3	3
	75th percentile	3.5	3.5
	85th percentile	4	5
	95th percentile	5	5
	n	715	376
Soil N (mg kg^{-1}; 0-10 cm)	5th percentile	8	9
	15th percentile	12	13
	25th percentile	16	17
	35th percentile	19	21
	45th percentile	22	25
	55th percentile	27	28
	65th percentile	32	33
	75th percentile	39	42
	85th percentile	49	51
	95th percentile	79	76
	n	785	442

† Texture scores were: 1 = sand, 2 = sandy loam, 3 = loam, 4 = loamy clay, and 5 = clay.

Table S8 – Continued

Factor	Measurement	Wheat	Barley
Soil N (mg kg^{-1}; 10-60 cm)	5th percentile	3	4
	15th percentile	5	5
	25th percentile	6	6
	35th percentile	7	7
	45th percentile	9	9
	55th percentile	10	10
	65th percentile	12	13
	75th percentile	16	16
	85th percentile	20	21
	95th percentile	29	29
	n	742	403
Soil P (mg kg^{-1}; 0-10 cm)	5th percentile	14	13
	15th percentile	19	20
	25th percentile	23	23
	35th percentile	26	27
	45th percentile	29	30
	55th percentile	34	34
	65th percentile	39	39
	75th percentile	45	46
	85th percentile	52	56
	95th percentile	69	78
	n	905	532
Soil P (mg kg^{-1}; 10-60 cm)	5th percentile	4	3
	15th percentile	5	4
	25th percentile	7	7
	35th percentile	10	8
	45th percentile	12	11
	55th percentile	15	15
	65th percentile	20	19
	75th percentile	24	23
	85th percentile	32	30
	95th percentile	49	50
	n	599	279
Organic C (%; 0-10 cm)	5th percentile	0.4	0.5
	15th percentile	0.7	0.7
	25th percentile	0.8	0.9
	35th percentile	0.9	1.1
	45th percentile	1.1	1.3
	55th percentile	1.2	1.4
	65th percentile	1.3	1.6
	75th percentile	1.5	1.9
	85th percentile	1.8	2.1
	95th percentile	2.5	3.4
	n	906	532
Organic C (%; 10-60 cm)	5th percentile	0.2	0.2
	15th percentile	0.3	0.3
	25th percentile	0.4	0.4
	35th percentile	0.4	0.5
	45th percentile	0.5	0.6
	55th percentile	0.6	0.7
	65th percentile	0.7	0.8
	75th percentile	0.8	0.9
	85th percentile	1.0	1.2
	95th percentile	1.4	2.4
	n	596	279

Table S8 – Continued

Factor	Measurement	Wheat	Barley
pH_{H2O} (0-10 cm)	5th percentile	5.2	5.4
	15th percentile	5.6	5.7
	25th percentile	5.8	6.1
	35th percentile	6.1	6.4
	45th percentile	6.4	7.0
	55th percentile	6.9	7.6
	65th percentile	7.6	8.0
	75th percentile	8.2	8.3
	85th percentile	8.4	8.5
	95th percentile	8.7	8.7
	n	903	530
pH_{H2O} (10-60 cm)	5th percentile	5.2	5.3
	15th percentile	5.5	5.6
	25th percentile	5.9	6.1
	35th percentile	6.2	7.1
	45th percentile	6.8	8.4
	55th percentile	8.1	8.7
	65th percentile	8.6	8.9
	75th percentile	8.9	9.0
	85th percentile	9.1	9.2
	95th percentile	9.4	9.5
	n	884	514
pH_{CaCl2} (0-10 cm)	5th percentile	4.6	4.6
	15th percentile	4.8	5.1
	25th percentile	5.1	5.4
	35th percentile	5.4	5.9
	45th percentile	5.8	6.4
	55th percentile	6.3	6.9
	65th percentile	7.0	7.3
	75th percentile	7.5	7.6
	85th percentile	7.7	7.7
	95th percentile	7.9	7.9
	n	903	531
pH_{CaCl2} (10-60 cm)	5th percentile	4.4	4.5
	15th percentile	4.7	4.8
	25th percentile	5.0	5.3
	35th percentile	5.5	6.2
	45th percentile	6.0	7.6
	55th percentile	7.4	7.8
	65th percentile	7.8	7.9
	75th percentile	8.0	8.1
	85th percentile	8.2	8.2
	95th percentile	8.4	8.5
	n	894	519
$EC_{1:5}$ (dS m^{-1}; 0-10 cm)	5th percentile	0.0	0.0
	15th percentile	0.1	0.1
	25th percentile	0.1	0.1
	35th percentile	0.1	0.1
	45th percentile	0.1	0.1
	55th percentile	0.1	0.2
	65th percentile	0.2	0.2
	75th percentile	0.2	0.2
	85th percentile	0.2	0.2
	95th percentile	0.3	0.3
	n	902	533

Table S8 – Continued

Factor	Measurement	Wheat	Barley
$EC_{1:5}$ (dS m^{-1}; 10-60 cm)	5th percentile	0.0	0.0
	15th percentile	0.0	0.0
	25th percentile	0.0	0.1
	35th percentile	0.1	0.1
	45th percentile	0.1	0.1
	55th percentile	0.1	0.2
	65th percentile	0.2	0.2
	75th percentile	0.2	0.3
	85th percentile	0.3	0.4
	95th percentile	0.5	0.6
	n	896	521
ESP (0-10 cm)	5th percentile	0.4	0.5
	15th percentile	0.7	0.8
	25th percentile	0.9	0.9
	35th percentile	1.1	1.1
	45th percentile	1.3	1.2
	55th percentile	1.6	1.5
	65th percentile	2.0	1.9
	75th percentile	2.7	2.6
	85th percentile	3.8	3.6
	95th percentile	8.8	8.2
	n	428	330
ESP (10-60 cm)	5th percentile	1.0	0.8
	15th percentile	1.6	1.6
	25th percentile	2.3	2.2
	35th percentile	3.3	3.1
	45th percentile	4.5	4.1
	55th percentile	5.7	5.3
	65th percentile	8.5	8.0
	75th percentile	11.3	10.0
	85th percentile	15.1	13.3
	95th percentile	23.1	22.1
	n	442	326
N fert (kg N ha^{-1})	5th percentile	11	9
	15th percentile	15	13
	25th percentile	34	18
	35th percentile	40	35
	45th percentile	51	41
	55th percentile	58	49
	65th percentile	64	58
	75th percentile	76	64
	85th percentile	90	76
	95th percentile	107	106
	n	909	545
N fert start (kg N ha^{-1})	5th percentile	9	7
	15th percentile	11	10
	25th percentile	14	13
	35th percentile	17	14
	45th percentile	19	17
	55th percentile	32	18
	65th percentile	35	19
	75th percentile	37	35
	85th percentile	54	37
	95th percentile	58	58
	n	909	545

* ND = not determined

Table S8 – Continued

Factor	Measurement	Wheat	Barley
N fert later (kg N ha^{-1})	5th percentile	0	0
	15th percentile	0	0
	25th percentile	0	0
	35th percentile	0	0
	45th percentile	21	23
	55th percentile	26	26
	65th percentile	34	32
	75th percentile	42	38
	85th percentile	46	46
	95th percentile	81	71
	n	909	545
P fert (kg N ha^{-1})	5th percentile	10	10
	15th percentile	12	11
	25th percentile	12	12
	35th percentile	13	13
	45th percentile	15	15
	55th percentile	16	16
	65th percentile	16	18
	75th percentile	19	20
	85th percentile	20	20
	95th percentile	22	24
	n	909	545
S fert (kg N ha^{-1})	5th percentile	1	1
	15th percentile	1	1
	25th percentile	2	1
	35th percentile	2	2
	45th percentile	5	2
	55th percentile	5	4
	65th percentile	5	5
	75th percentile	6	6
	85th percentile	10	9
	95th percentile	16	17
	n	909	545