Project Report No. 517 August 2013

Adding value to variety trial data: a performance rating for wheat varieties for dry conditions

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Adding value to variety trial data: a performance rating for wheat varieties for dry conditions

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CONTENTS

1. Abstract

The wet conditions of 2012 notwithstanding, on average 10% of the UK wheat yield is lost each year due to insufficient soil moisture. Record-breaking dry conditions, most recently in 2011, reinforce the need to find ways to maximise productivity when water is limiting. Growers want to know what variety to plant on light land, which varieties are more likely to yield better in dry conditions, and which varieties show better stability of yield across a range of conditions. The aim of this project was to provide quantitative data to help guide these decisions by mining the information contained in the multi-location variety trials conducted each year for the Recommended List (RL). The objectives of this project were to evaluate the 2011 RL trial yield data by assigning a drought stress index to each test site using site-specific soil and weather data, then to score each variety according to how well it performed relative to other varieties along a gradient of sites from unstressed to stressed. In addition, using various statistical methods, the data were analysed to show which varieties tend to be more stable than others across locations, and which varieties show the best combination of yield potential and yield stability.

In 2011, test sites varied in the level of drought stress, and variety rankings changed from site to site. A regression analysis showed that some varieties showed relatively better yields as conditions became drier (Cocoon, Delphi, SY-Epson, KWS-Gator), while others showed greater sensitivity to water availability (Chilton, Denman, Gallant, Grafton) and yielded poorly compared with the tolerant varieties at the stressed sites. Other varieties showed little response to changing water availability, and also yielded well across all sites (e.g. Conqueror). There were small differences in the stability of varieties across sites, and variety rankings for yield, adjusted for stability, changed little. It is important to note that the data were from only one year, and therefore insufficient to provide a robust picture of variety performance. Nevertheless, the results show how stability, yield potential and drought tolerance can be evaluated to provide more information on variety performance. The real stability of varieties would have to be judged from a larger dataset drawn from multiple years and sites. Drought symptoms of different varieties were scored in a survey of 300 random fields, but did not reveal strong varietal differences, and therefore could not be used to corroborate drought rankings derived from the RL trial data.

The results show that there is valuable, untapped information inherent in multi-location variety trial data that can be used to add value to those data and current variety recommendation procedures. Furthermore, when these data are combined with specific environmental variables for each trial, additional information about varieties and test locations can be obtained with little extra cost.

2. Introduction

In the UK, it is estimated that approximately 30% of the wheat acreage is grown on drought-prone soils and at least 10% of the wheat yield is lost each year due to insufficient soil moisture, with greater losses in very dry years (Foulkes *et al*., 2007). Therefore, crops frequently fail to attain their potential output because water supply cannot keep pace with demand, often during critical stages of yield formation. Research has shown that wheat varieties can be fundamentally different in their susceptibility to dry conditions (HGCA-funded LINK project RD-2005-3233; Foulkes *et al*., 2007; Ober *et al*., 2010). However, growers have little guidance on which of the current varieties are best suited for dry conditions. The main aim of this work is to help enable the identification of superior wheat varieties for water-limited conditions.

Choosing the best variety is one of important decisions growers make in an effort to maximise productivity. Breeders have been successful in improving the yield potential of varieties, but there is variation in the stability of performance of these varieties. The ranking of varieties changes from location to location and from year to year; sometimes a 'good' variety performs poorly for some unknown reason. The year- or site-specific environmental conditions that cause unstable performance in some varieties are rarely identified. Therefore, selections and recommendations are made largely on the basis of mean relative yield across a series of multi-location trials. In general, this is a robust approach; however, two varieties with similar mean yields can often differ substantially in yield stability. In the past, studies quantified the level of these genotype x environment interactions, but took this no further. There is a need by growers and breeders to know not only the yield potential, but also the yield stability of a variety. Currently, there is no mechanism to obtain or to convey this information.

Earlier efforts by Welham *et al*. (2005) incorporated site characteristics into the RL *Plus* system aimed at classifying varieties according to soil type. However, this approach was limited by the accuracy of weather and soil data held in the system. In recent years, new statistical software tools have become available that allow computation and visualisation of genotype performance (yield and stability), and genotype x environment interactions. There are now many examples worldwide of variety evaluation programs that are beginning to use these methods in conjunction with site-specific environmental data such as soil water holding capacity and rainfall (Chapman *et al*., 2002; Chapuis *et al*., 2012; Fan *et al*., 2007; Mathews *et al.,* 2011; Rizza *et al.,* 2004). We have used these approaches to analyse RL variety trial data for sugar beet (Pidgeon *et al.,* 2006) and winter wheat (HGCA-LINK project RD-2005-3323) to identify varieties that are relatively more drought tolerant or drought susceptible. Each trial or test environment is characterised by a drought stress index (DSI). This index quantifies the stress experienced by the crop by combining soil and weather data to compute how much water deficit accumulated over the course of the growing season. The drought tolerance or susceptibility of an individual variety can be judged by examining its performance relative to the trial mean as water becomes more limiting (along a range of increasing DSI). Briefly, the approach was to assign a DSI to each trial, and then plot the regression of relative yield performance of each variety against the range of DSI. This is similar to the Finlay-Wilkinson technique (1963), except that an actual weather-based factor was used as an environmental descriptor instead of the overall trial mean. The DSI for each site was derived using the Sirius wheat growth model (Lawless *et al*., 2005) to simulate the water use of a variety given the actual conditions of the trial, and water use in the absence of any water limitation. The summed ratio of these two values over the course of the season provided a simple, robust index describing the trial environment. Varieties were ranked according to their intercept (yield potential under low-stress conditions) their slope, which indicates relative drought tolerance or susceptibility, and scatter (yield stability) (Pidgeon *et al.*, 2006).This work was cited as an example of a useful approach to improving productivity (Cattivelli *et al*., 2008).

Currently, information on yield stability is not published as part of the HGCA Recommended Lists (RL), but growers frequently say that this is an important consideration for at least some of their planting. Stability can be derived easily from RL trial data. There are many indices that have been used to describe yield stability (e.g. Baxevanos *et al.,* 2008; Flores *et al*., 1998; Ober *et al.*, 2004). However, there is often a trade-off between yield stability and yield potential: a low-yielding variety frequently is able to maintain that yield under most conditions (Hohls, 2001). This is of limited value. It is more helpful to combine the yield potential and stability, which can be derived from statistical tools such as genotype and genotype x environment (GGE) biplots (Yan and Kang, 2003). GGE biplot-derived yield stability was found to be the most reliable indicator of yield and stability across years (Baxevanos *et al*., 2008).

The location and number of test sites is an important consideration in variety evaluation. Choosing the appropriate locations can reduce costs and increase the quality and usefulness of the information gained at each site. The same statistical tools described above can be used to provide a quantitative measure to aid the evaluation of test site value to the RL process, as done recently in oat breeding trials (Yan and Holland, 2010). Two parameters that can be derived are test site discrimination power (the ability to distinguish between varieties) and similarity with other environments (avoiding duplication of the same information at more than one site). We propose that these calculations can be performed in parallel with the variety performance analysis. These data should be useful for variety trial managers. The objectives of the study were to:

1. Evaluate the 2011 RL trial yield data by assigning a drought stress index to each test site using site-specific soil and weather data.
2. Provide scores for each variety indicating relative drought susceptibility and yield potential in the absence of stress.

3. Compare different yield stability statistics that combine information on yield potential, yield stability, and sensitivity to environmental characteristics such as water availability to determine which indices provide the most useful information growers need.
4. Use statistical tools to quantify and visually portray the relationships between test sites and variety performance, and to characterise test sites in terms of ability to discriminate between varieties, and similarity to other test sites.
5. Explore ways that this additional information gleaned from variety trial data can be used routinely in the RL.
6. Use 2011 crop survey data as auxiliary information to judge variety performance in conjunction with RL trial data.

3. Materials and methods

3.1. Calculation of drought stress indices for RL trial sites in 2011

Twenty trial sites were chosen from the set of 2011 Recommended List (RL) trial sites. Of these, six sites where ‘second wheat’ sites where the previous crop was also wheat (Table 1). There were 34 varieties tested at each of the 20 sites, while an additional three varieties were tested at only 13 of the 20 sites (Table 2).

Each trial or test environment (an environment is any site x year combination) was characterised by a stress index, as described previously (Pidgeon *et al*., 2006; HGCA Project Report 476). The stress index quantifies the stress experienced by the crop by combining soil and weather data to compute how much water deficit accumulated over the course of the growing season. The stress index is small on sites with deep water retentive soil and sufficient rainfall, whereas on lighter soils with inadequate rainfall, stress index values are larger. The drought tolerance or susceptibility of an individual variety can be illustrated by examining its performance relative to the trial mean as water becomes more limiting along a range of sites with increasing stress index. The Sirius wheat growth model (Lawless *et al*., 2005) was used to derive a stress index for each site either based on simulated yields (DSI), or calculated evapotranspiration rates (TSI). The steps involved in this process are shown in Fig. 1. Model-based approaches to test environment characterisation are superior to simple climate-based indices (e.g. accumulated soil moisture deficit based on soil water balance) because crop developmental stages and stress level of the crop are taken into account. The drought stress index (DSI) was based on a simulated yield given the actual conditions of the trial, and a yield in the absence of any water limitation, using Mercia as the variety calibrated in the model. The ratio of these two yields provided a robust index describing the environment, and did not require Mercia as one of the actual trial entries, nor did it depend on how well the simulated yield matched the observed yields. The DSI is a function of the modelled yield (Y’) of the calibration variety using actual weather and soil conditions (Y’a) for each environment (a year, trial site combination), and the modelled yield of the calibration variety using weather inputs that eliminate any stress by supplying as much water as the crop demanded (the yield potential, Y’p; Eqn. 1).

1) $$DSI = 100 \times \left(1 - \frac{Y'_a}{Y'_p}\right)$$

The transpiration-based stress index (TSI) used the accumulated ratio of the simulated crop evapotranspiration (ET'_a) to potential evapotranspiration in the absence of any stress (ET'_p; Eqn 2). The DSI and TSI are directly related (Fig. 2).

2) $$TSI = \sum \left(1 - \frac{ET'_a}{ET'_p}\right)$$

However, the indices differ slightly in that the DSI, being yield-based, is affected more by the biomass partitioning characteristics of the calibration variety. Therefore, to avoid this potential complication, the TSI was used for the variety evaluations in this project, but the same conclusions can be drawn using either index.

To express the performance of a variety (i) within a location (j), the relative yield (RY) was calculated, which is the mean yield of a given variety (Y_i) divided by yield averaged across all varieties tested in the trial (Y_j; Eqn. 3). Other denominators could be used (e.g. Y’p, or yield of check varieties), but with greater than 30 entries in a trial, there is little chance that the performance of a check variety (which changes over time) in a particular trial would have a significant influence on the value of the denominator.

3) $$RY_{ij} = \frac{\overline{\overline{Y_i}}}{Y_j}$$

Although there is already a rough characterisation of soil type for each test location, this has been shown to be inadequate for an accurate calculation of DSI (Welham *et al*., 2005). Even digital soil survey maps are not sufficiently reliable (Fortin and Moon, 1999). In order to calculate the DSI for the trials in this study, physical soil samples were taken from the field in which trials were located at each selected location. Some sites may have been sampled in previous work and soil characteristics were already in our database. Soils were sampled at four horizons: 0 –25 cm, 25–50 cm, 50–70 cm and 70+ cm.

Table 1. The 2011 RL test sites that were used in the analysis, and the abbreviations used in the Figures.

Trial ID	Site Abbrev	Nearest Settlement	County	TSI	DSI	Site Mean Yield
						t ha^{-1}
WW2011HH106T	EYorks	Barthorpe	North Yorkshire	2.47	2.87	10.04
WW2011AN108T	Nrthum	Croft-on-Tees	North Yorkshire	0.00	0.00	13.34
WW2011SU109T	Lincs3	Ulceby	Lincolnshire	1.11	0.11	10.96
WW2011SY111T	Lincs4	Great Sturton	Lincolnshire	5.24	3.10	7.34
WW2011AN112T	Lincs1	Welbourn	Lincolnshire	13.77	8.72	7.22
WW2011LM114T	Norfk	Wolferton	Norfolk	11.85	10.58	9.47
WW2011CA115T	Cambs	Girton	Cambridgeshire	21.85	14.97	8.67
WW2011SL116T	Sufflk3	Stetchworth	Cambridgeshire	25.77	24.89	6.05
WW2011LM117T	Sufflk2	Elsmwell	Suffolk	22.81	19.15	6.97
WW2011EL119T	Lincs2	Moulton Seas End	Lincolnshire	11.82	5.80	10.7
WW2011KW120T	Sufflk1	Framlingham	Suffolk	13.47	9.14	9.95
WW2011MA121T	Essex	Great Dunmow	Essex	19.56	14.35	9.16
WW2011WY122T	Kent	Newchurch	Kent	13.11	14.27	13.69
WW2011HA123T	Shrops	Newport	Shropshire	4.46	2.07	9.79
WW2011KW124T	Leics	Frisby	Leicestershire	12.72	10.46	11.57
WW2011DL125T	Gloucs	Didbrook	Gloucestershire	5.31	1.59	10.62
WW2011AS126T	Warwick	Haseley	Warwickshire	10.17	4.69	10.8
WW2011IS127T	Hants	Crawley	Hampshire	2.13	1.03	9.47
WW2011SH128T	Devon	West Charleton	Devon	1.87	1.60	9.77
WW2011AS129T	Somset	Huntworth	Somerset	9.46	10.18	11.58

Three to four replicate sets are taken and bulked together for each depth. The samples were then air-dried, milled in a rotary grinder and the weights of dried soil and stones were recorded. Soft chalk in the samples milled down but harder chalks remained and were treated as stone. All samples were then finger-textured over a period of a few days by one trained person using comparison soil standards (National Soil Resources Institute, Silsoe, UK) to determine the soil particle size class. Stone content was calculated by volume, assuming a standard soil bulk density of 1.40g ml^{-1} and a stone density of 2.65 g ml^{-1}. Using the standard tables for available water (Hall *et al.,* 1977), and correcting for stone content, the available water capacity of soil at each site was determined and used as an input for the Sirius growth simulation model (Table A2). A shallower rooting depth was used in the model when soil samples indicated physical barriers to root penetration at a given depth.

Table 2. List of varieties from the 2011 RL trial dataset that were evaluated.

Entry code	Breeder ref	Variety name	No. of trials
WW1564	Alchemy	Alchemy	20
WW2023	BA-W10	Delphi	20
WW2022	BA-W9	Monterey	20
WW1885	Beluga	Beluga	20
WW1922	Cocoon	Cocoon	20
WW1813	Conqueror	Conqueror	20
WW1388	Cordiale	Cordiale	20
WW2009	Crusoe	Crusoe	20
WW1895	Denman	Denman	20
WW1980	DSV-80113	Chilton	20
WW1725	Duxford	Duxford	13
WW1376	Einstein	Einstein	20
WW1766	Gallant	Gallant	20
WW1811	Grafton	Grafton	13
WW1940	Gravitas	Gravitas	20
WW2018	Horatio	Horatio	20
WW1853	Invicta	Invicta	20
WW1737	JB-Diego	JB-Diego	13
WW1837	Kingdom	Kingdom	20
WW1907	KWS-Podium	KWS-Podium	20
WW1916	KWS-Santiago	KWS-Santiago	20
WW1880	KWS-Sterling	KWS-Sterling	20
WW1911	KWS-Target	KWS-Target	20
WW1971	KWS-W174	KWS-Saxtead	20
WW1975	KWS-W178	KWS-Mammoth	20
WW1977	KWS-W180	KWS-Gator	20
WW1658	Oakley	Oakley	20
WW1986	RW40834	Torch	20
WW1987	RW40837	Trident	20
WW1988	RW40847	Relay	20
WW1787	Scout	Scout	20
WW1282	Solstice	Solstice	20
WW1941	Stigg	Stigg	20
WW2001	SY-Epson	SY-Epson	20
WW1954	Tuxedo	Tuxedo	20
WW1812	Viscount	Viscount	20
WW1865	Warrior	Warrior	20

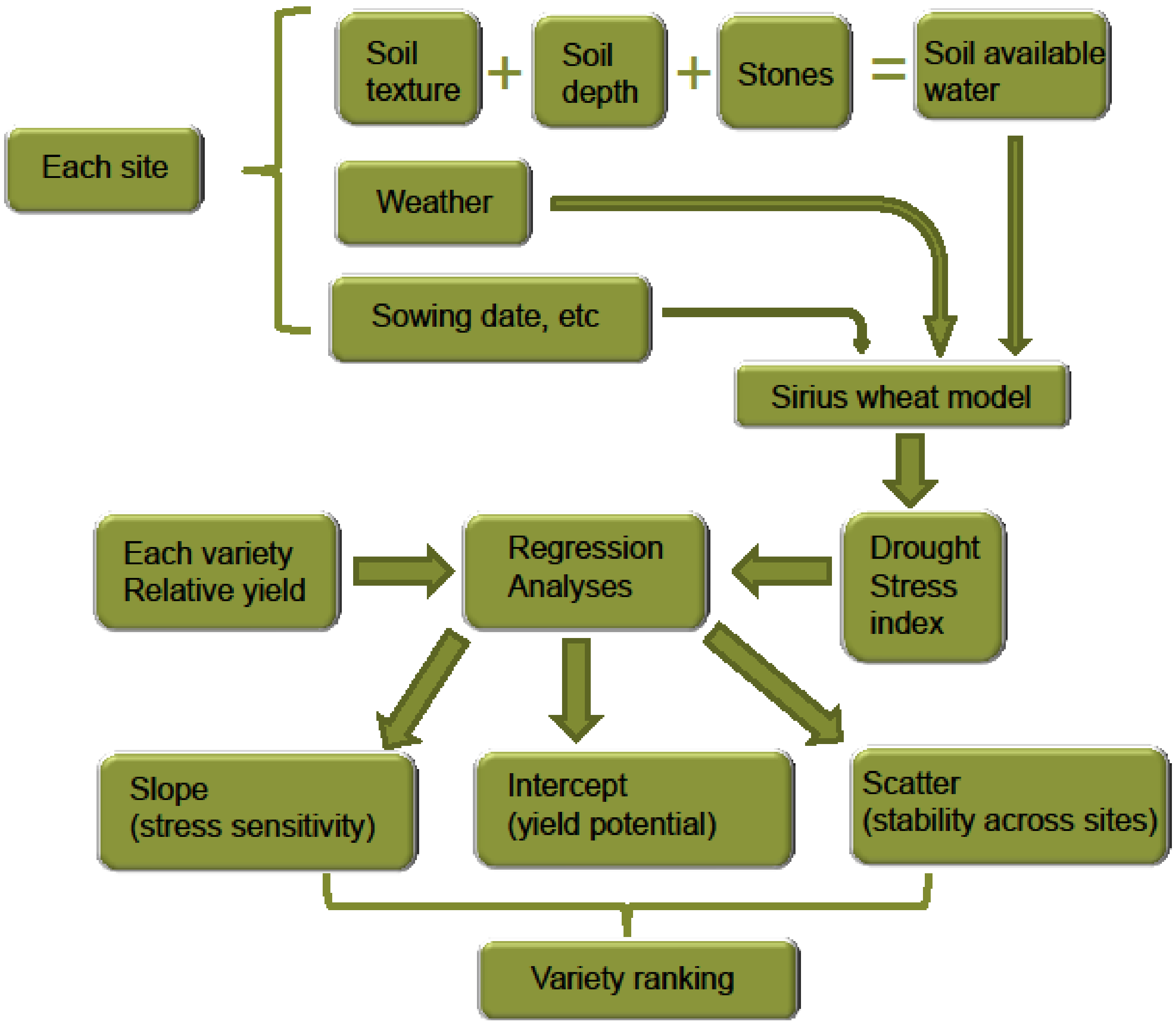


Figure 1. A schematic diagram of steps involved in calculating the drought stress index (DSI or TSI).

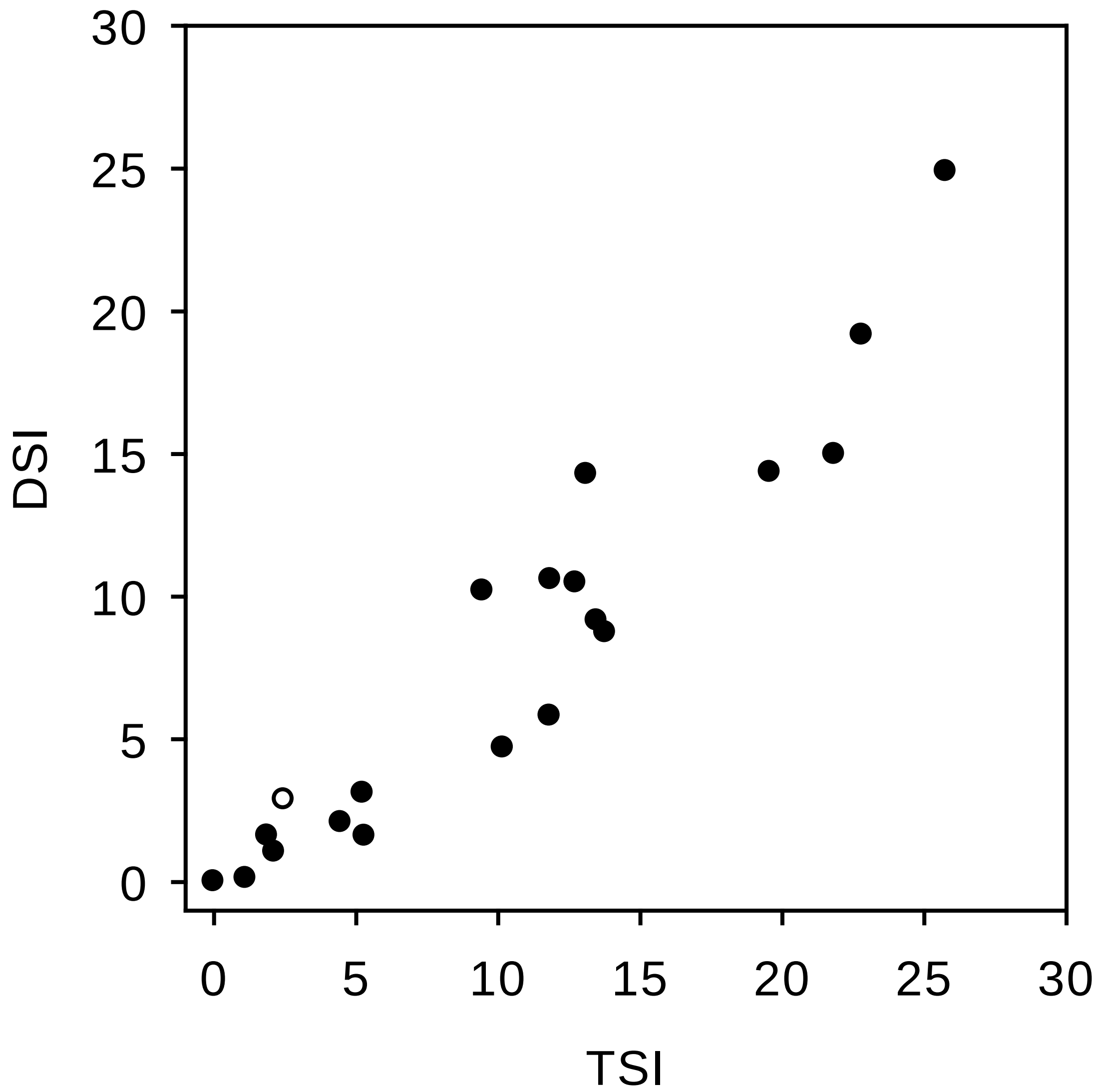


Figure 2. The relationship between two slightly different ways to calculate the stress index at each site (circles). The TSI is based on simulated crop transpiration, while the DSI is based on simulated yield.

3.2. Regression method to evaluate relative drought susceptibility

For each variety, relative yield was plotted against TSI to obtain a slope and intercept using a simple Finlay-Wilkinson regression approach (Finlay and Wilkinson, 1963). A negative slope indicates drought susceptibility i.e. the relative performance of a variety decreases as conditions become drier, while a positive slope indicates relative drought tolerance. The intercept indicates yield potential in the absence of stress, and the scatter in the data indicates the relative yield stability. The statistical significance of the slope was tested by comparing the correlation coefficient r value with Table values at $P < 0.05$.

3.3. Multivariate approaches: principal component and biplot analyses

Various multivariate approaches have been used to understand variety x environment interactions, which define stability (Flores *et al*., 1998). AMMI (additive main effect and multiplicative interaction) and principal component analyses (PCA) are two of these methods. AMMI combines ANOVA and PCA models (Gauch *et al*., 2008). Genotype and genotype x environment interaction (GGE) biplots based on the principal components that capture variation in genotype and genotype interactions were plotted to portray the interactions between variety performance and location (Yan and Kang, 2003). Other information that can be gleaned from these biplots allow the comparison of test sites in terms of ability to discriminate between varieties, and how different sites can be grouped to represent a similar test environment. Similarly, interactions between varieties, environments and grain quality traits were visualised using GGE biplots. The GGE biplot analyses were conducted using GGE software (http://www.ggebiplot.com) and AMMI analysis was done using Genstat (v.14, VSN International).

3.4. Calculation of yield stability indices

There are several published yield stability indices that quantify the meaning of 'stability' in different ways, and others that combine information on yield potential, yield stability, and sensitivity to environmental characteristics such as water availability (Table A3, Appendix). As a static 'Type-I' (Lin and Binn, 1988) stability index, we calculated the environmental variance (S_i^2), which is the variance in yields across locations (Becker and Léon, 1988). For variety (i):

$$S_i{}^2 = \frac{\sum(R_{ij} - m_i)^2}{e - 1}$$

where R_{ij} = observed yield (across all replicates) of variety i at location *j*, m_i = genotype mean yield across environments, and *e* = number of test locations. Greatest stability is $S_i^2 = 0$. As an example of dynamic, Type-II stability indices, we calculated Wricke's ecovalence (Wricke, 1962):

$$W_i{}^2 = \sum\left(R_{ij} - m_i - m_j + m\right)^2$$

where m_i and m_j are as above and m is the grand mean. The S_i^2 computed on the basis of relative yields becomes effectively a Type-II index, and numerically provides the same variety ranking as W_i^2. Finlay-Wilkinson regressions of variety yield against an environmental index for each site can be used as a static measure of stability, but using relative yields instead of absolute yields, as we have done here, makes this regression approach a dynamic descriptor of stability, as it eliminates the environment main effect (Yau and Hamblin, 1994).

It has been observed that varieties with the greatest static stability (the same yield in any environment) are often those with the smallest yields, which is of little use to growers (Calderini and Slafer, 1999). A more comprehensive view of variety performance should include a combination of both stability and yield, and there are several indices that attempt to quantify this. The performance index P_i) (Lin and Binn, 1988) for a variety expresses the deviations in yield from the maximum yielding variety in each environment:

$$P_i = \sum(R_{ij} - M_j)^2 / 2n$$

where M_j is the maximum yield in environment j and n is the number of trials. The Pi assumes that the benchmark variety is one that shows the best yield in every environment, and a good variety measured against that benchmark is one that shows the smallest deviation from the benchmark across all locations (a low Pi value). Other methods use a stability statistic to adjust variety rankings based on yield. Kang's (1993) yield stability statistic (YS_i) combines Shukla's environmental variance with weighted yield rankings adjusted by experimental error (the LSD value). Similarly, Yan's heritability-adjusted superiority index (HASI), which combines heritability (repeatability) with relative yield rankings uses the same approach. Another straightforward method is to plot stability against yield for each environment, and visually select those varieties that fall into the quadrant that expresses high yield and high stability (Gauch *et al*,. 2008). The advantage of this approach is that it captures 100% of the genotype effect on the x-axis and 100% of the GxE effect on the Y-axis, whereas AMMI and GGE biplots approximate these effects.

Purchase *et al*., (2000) described the AMMI stability value (ASV), derived from the interaction principal component axes (IPCA):

$$ASV = \sqrt{\left[\frac{IPCA1ss}{IPCA2ss}(IPCA1)\right]^2 + (IPCA2)^2}$$

where IPCA1ss and IPCA2ss are the sum of squares for the first two scores, IPCA1 and IPCA2. As with univariate methods above, AMMI scores or biplot values can be used to adjust yield rankings, for instance a yield stability index sums variety rankings for ASV and yield (Farshadfar *et al.,* 2011).

3.5. Crop Survey data from the CropMonitor programme

The Food and Environment Research Agency (FERA) made observations and collected samples as part of the Defra-funded pest and disease surveys in the 'CropMonitor' programme. The objective was to use these auxiliary data in parallel with variety ratings derived from RL trial data evaluation, to possibly enhance or corroborate the variety performance rankings for susceptibility to water deficit. Additional measurements to the usual survey procedure were taken in response to the record dry conditions in 2011.

The annual survey was undertaken on 300 winter wheat crop samples from fields selected at random from a list of farms stratified by region and arable area size from annual returns to Defra Census Branch. Farmers were contacted in late spring to confirm their participation and to select a single wheat crop on each farm for assessment. A questionnaire was used to obtain details of cultivar, tillage practice, sowing date, previous cropping and pesticide use. Crops were sampled at GS73–75 (July) by collecting 50 fertile tillers at random from a diagonal transect of the field. Samples were collected by ADAS and NIAB-TAG and sent to FERA for assessment. Field scale assessments were made in the field at the time of sample collection. Each crop was assessed for incidence of stunting and senescence, and in the laboratory a sub-sample of 25 plants was measured for plant height and visually assessed for degree of senescence, ear sterility and drought spotting. Leaf necrotic spots were tested to differentiate between drought-induced necrosis and tan-spot. Drought-induced reduction in stem extension was calculated by dividing the plant height measured in lab samples by the mean height of the variety measured in the 2011 RL trials (without added growth regulator). RL mean heights of varieties were similar in 2011 and 2012, a year without water deficit during the main growing season.

All assessment and agronomic data were entered onto an Informix database, which holds all national survey data from winter wheat collected since 1970. Data were scrutinised for logical errors prior to entry and the electronic data were cross-referenced with the original paper records to check for transcription errors.

4. Results

4.1. Analysis of variation and calculation of drought stress indices

There was significant variation in grain yield between varieties (Fig. 3) and between sites (Fig. 4). Analysis of variance by ANOVA showed that there was significant variety x site interaction (Table 3), indicating that the ranking of variety performance depended on the site (similar results were obtained with REML analysis). The proportion of total variation accounted for by the interaction was small compared with the effect of variety and site. The change in variety ranking depending on site is also shown in the illustration of the crossover behaviour (Fig. 5).

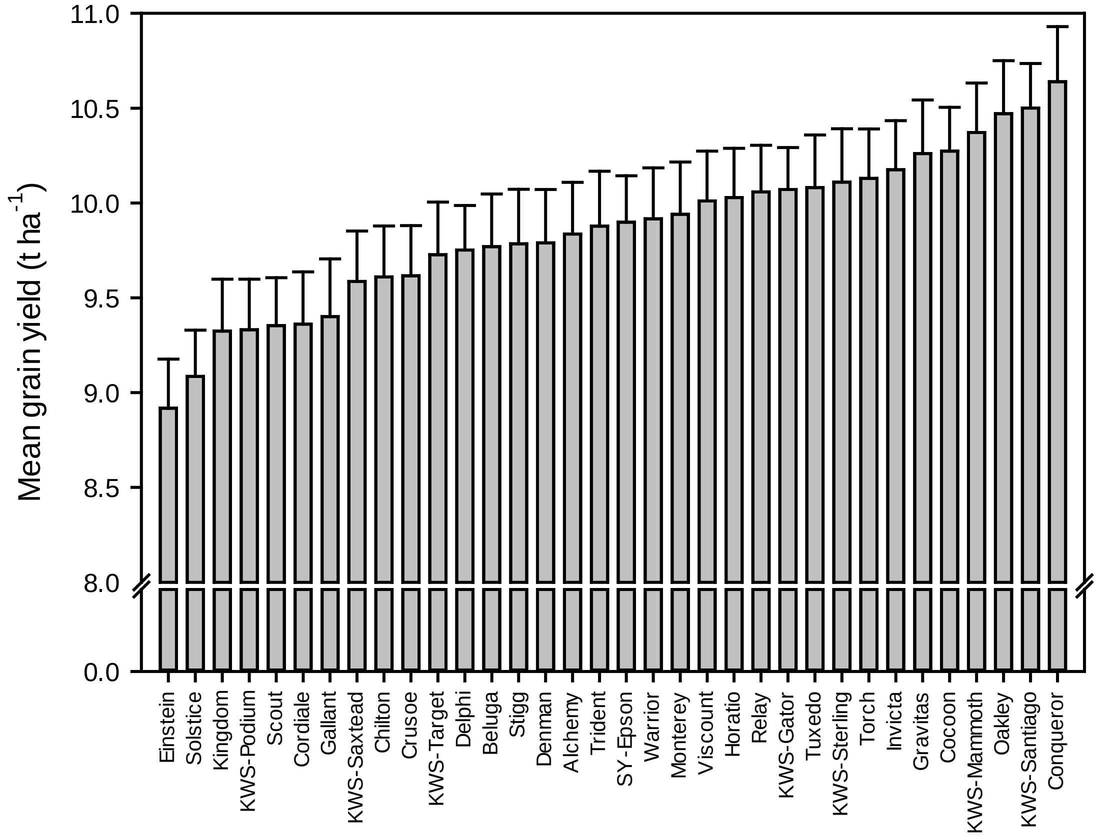


Figure 3. Grain yields for 34 varieties tested on 20 sites in 2011. Bars indicate the mean ± se (n = 20).

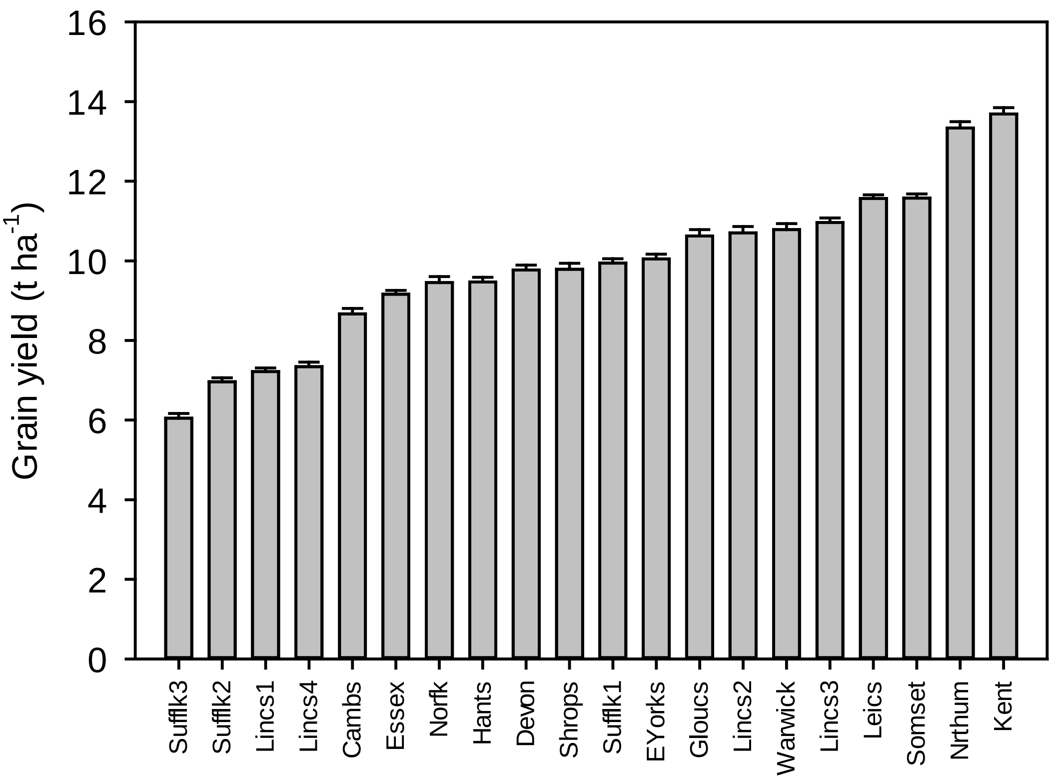


Figure 4. Grain yield averaged across 34 varieties at the 20 selected sites in 2011. Bars are mean ± se (n = 34). See Table 1 for the corresponding site codes for these abbreviations.

Table 3. Analysis of variance (ANOVA) of the 2011 RL trials results for grain yield. Variance is partitioned into factors for variety (GENO), test location (ENV), and the interaction between variety and location (GxE). All sources of variation were highly significant (F Prob < 0.001).

Source	DF	SS	MS	F	F Prob
TOTAL	2039	8751			
GENO	33	331	10.03	38.50	<.001
ENV	19	7599	400	1537	<.001
GxE	627	365	0.58	2.20	<.001
BLK(ENV)	40	113	2.83	10.90	<.001
Error	1320	344	0.26		
Grand Mean	9.86				
LSD(0.05)	0.83				

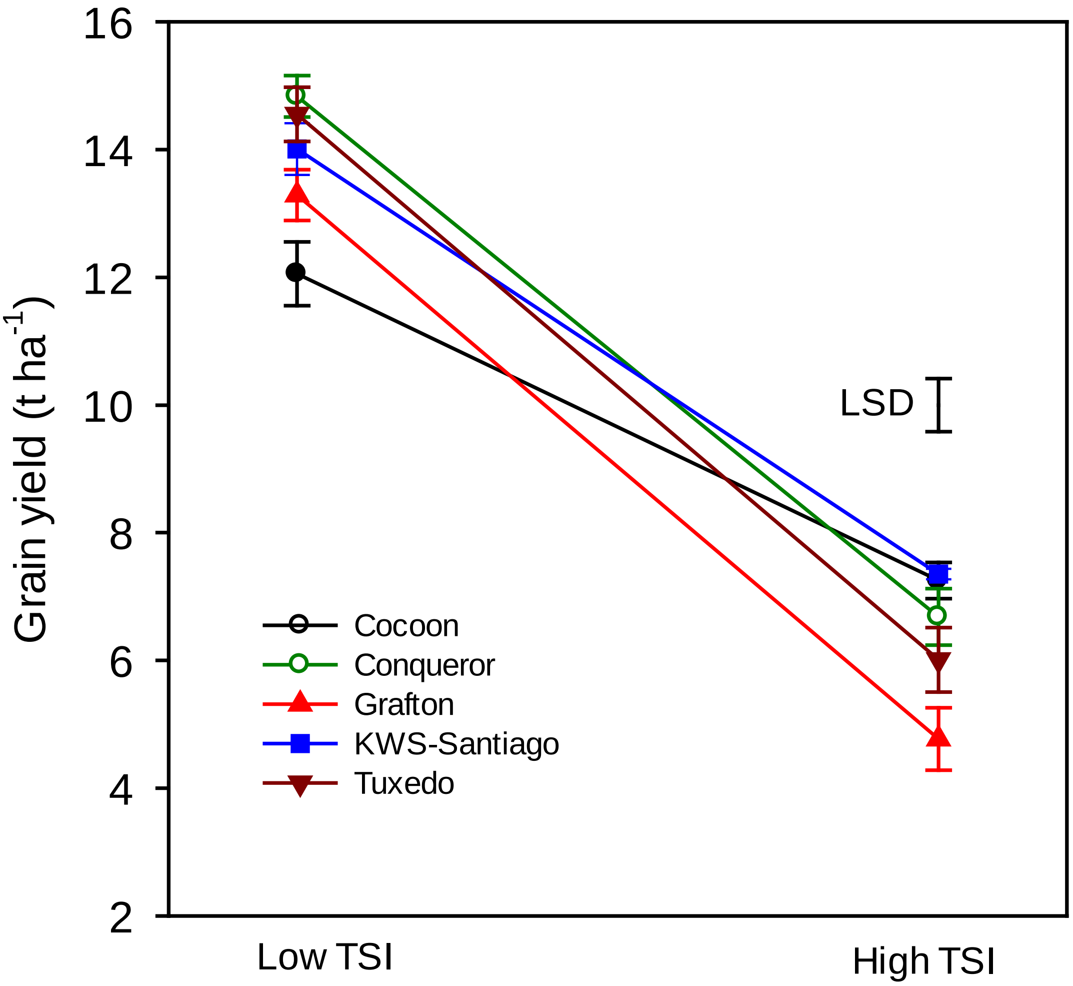


Figure 5. Varieties that show significant ‘crossover’ behaviour, illustrating the change in variety ranking between a site with plentiful moisture (low TSI) and one that was stressed (high TSI). Symbols are the mean ± se (n = 3). The bar shows the LSD for the variety x site interaction term from ANOVA. In this example, only five of the 34 varieties are shown for clarity; the low TSI site was Northumberland (AN108), and the high TSI site was Stetchworth (Sufflk3; SL116).

The DSI and TSI calculated for the 20 sites used in the evaluation are shown in Table 1. The range in TSI values were similar to those observed in RL trials in 2006 and 2009 (HGCA Report 476). There was a negative correlation between TSI and site mean yield, indicating that a significant proportion of the variability in yields could be explained by water availability in 2011 (Fig. 6).

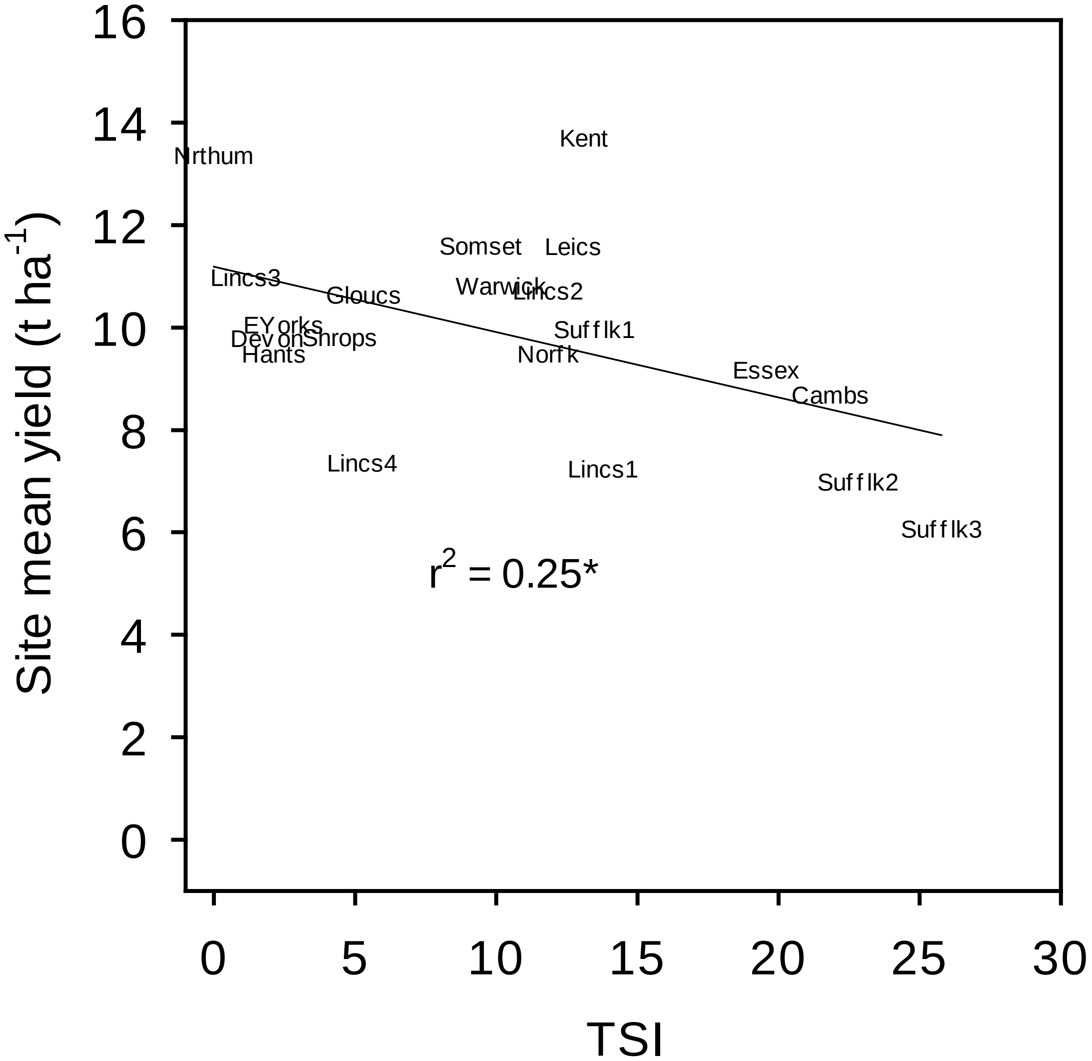


Figure 6. The relationship between the mean grain yield at each site (indicated by the site abbreviation; see Table 1) and the stress index (TSI) computed for each site. The regression indicates that in 2011, 25% of the variation in site yields can be explained by the variation in stress level between sites. Correlations, of course, do not prove cause and effect.

4.2. Varietal differences in drought susceptibility

4.2.1. Regression analysis using TSI and relative yields

Regressions of relative yield against TSI were calculated for each of the 37 varieties (Table A1, Appendix). In eight cases, the regressions were statistically significant. The results show that some varieties showed a positive slope (Fig. 7; Cocoon, Delphi, SY-Epson, KWS-Gator), while others showed a negative slope (Fig. 8; Chilton, Denman, Gallant, Grafton). Positive slopes indicate that these varieties tended to perform better than the trial mean as conditions became drier, while negative slopes indicate a tendency to perform poorer than the trial mean as less water becomes available. It is important to convey at the outset that these data are from only one year, and a more robust comparison of varieties requires combination of data from several seasons. Nevertheless, the significant positive correlation between the stress index of the site and the relative yield indicates relative drought tolerance, compared with relative drought susceptibility in varieties showing significant negative slopes. The majority of varieties showed no significant slope, so it is impossible to categorise these in terms of sensitivity to stress. It is possible that with data from additional test seasons, slopes will reach statistical significance.

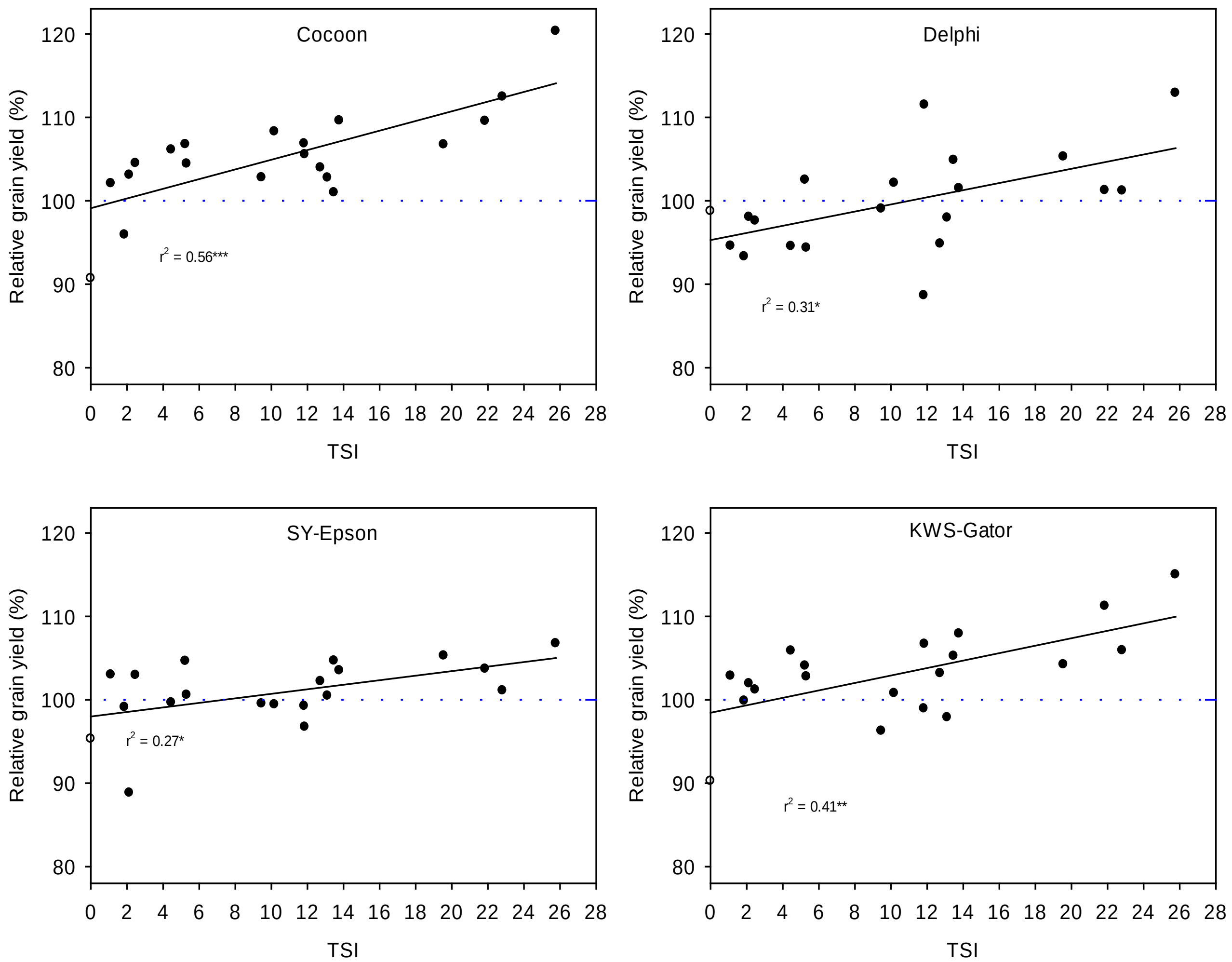


Figure 7. Finlay-Wilkinson-type regressions of relative grain yield against the TSI stress index at each test location. Positive slopes indicate that these varieties tended to perform better than the trial mean (dotted line) as conditions became drier. The r^2 value indicates that a significant proportion of the variance in relative yield is explained by the variation in TSI.

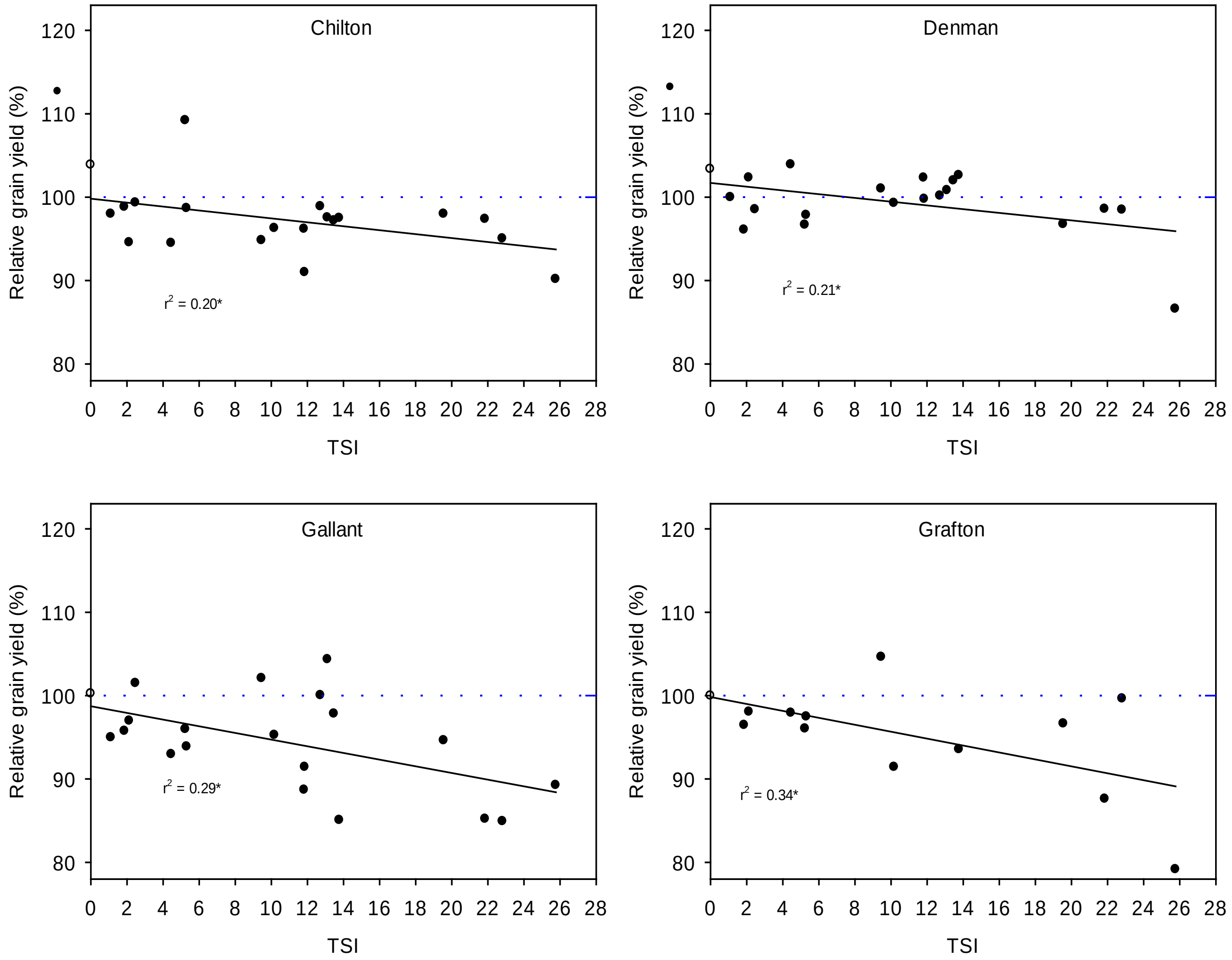
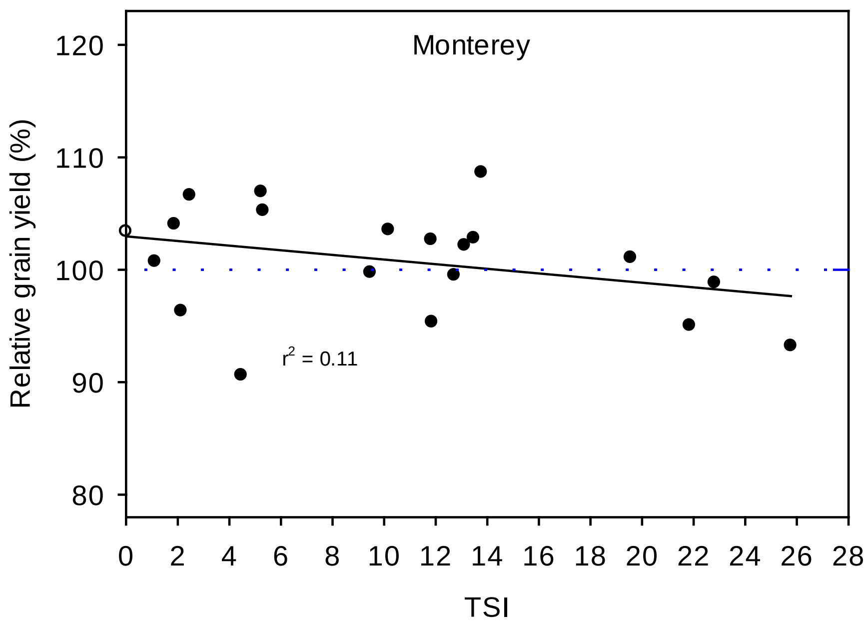


Figure 8. Finlay-Wilkinson-type regressions of relative grain yield against the TSI stress index at each test location. Negative slopes indicate that these varieties tended to perform worse than the trial mean (dotted line) as conditions became drier. The r^2 value indicates that a significant proportion of the variance in relative yield is explained by the variation in TSI.

The regression plots portray additional varietal information that is not apparent when only the overall means averaged across sites are considered. For instance, the varieties Monterey and SY-Epson both had a mean relative yield of 101.8% suggesting that there were no differences in yield performance of these varieties (Fig. 9). However, Monterey showed a slightly negative slope, while SY-Epson had a positive slope, and relative yields at the driest site were significantly different (Monterey: 93%; SY-Epson, 107%), but ranking was reversed on the less-stressed site (Monterey: 104%; SY-Epson, 95%).



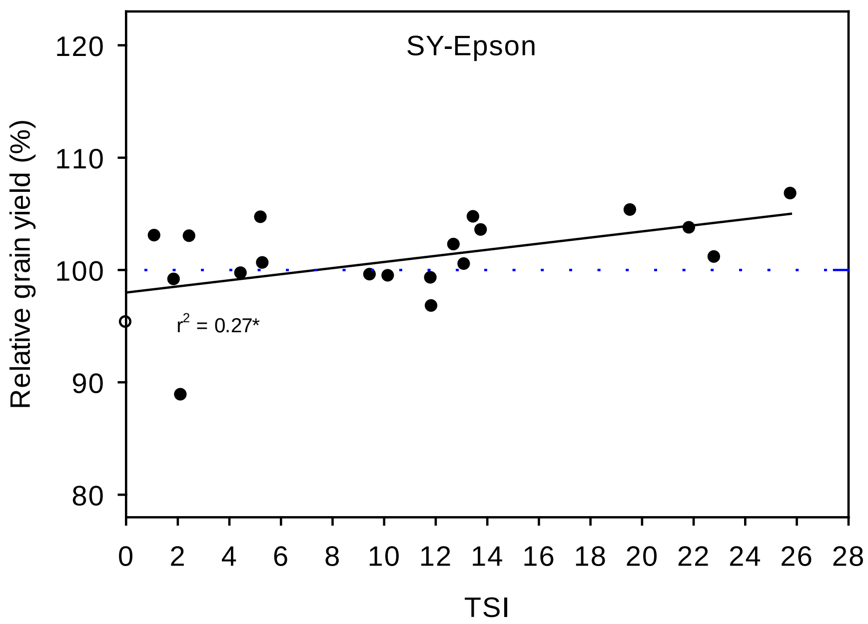
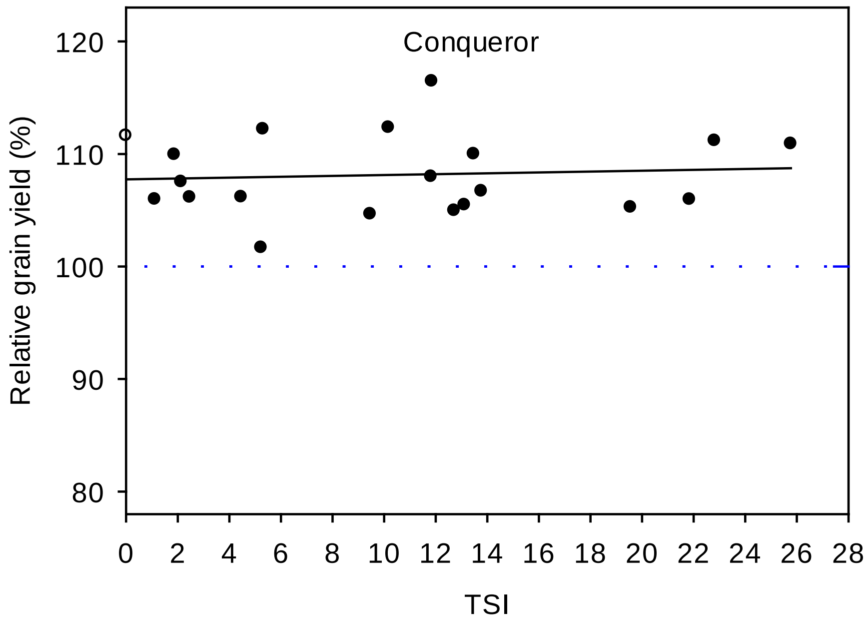


Figure 9. Both varieties have an overall mean yield of 101.8%, but different performance across a range of sites differing in water availability. Does use of the overall mean hide important performance characteristics, or does it also avoid over-interpretation of performance based on the results at a small number of sites, biasing the picture?

A third category of varieties showed no slope, which indicates that the varieties were not responsive to the prevailing water supply at the test locations (Fig. 10). This could be interpreted as a positive trait, indicating that yield was maintained even as conditions became drier, or as a negative trait, indicating that varieties were unable to take advantage of greater water availability. However, varieties with *above-average* yield potential, *combined* with zero slope (e.g. Conqueror and Invicta, Fig. 10), would provide good yield at any site. This desirable performance characteristic is only apparent when yields are plotted in this way.



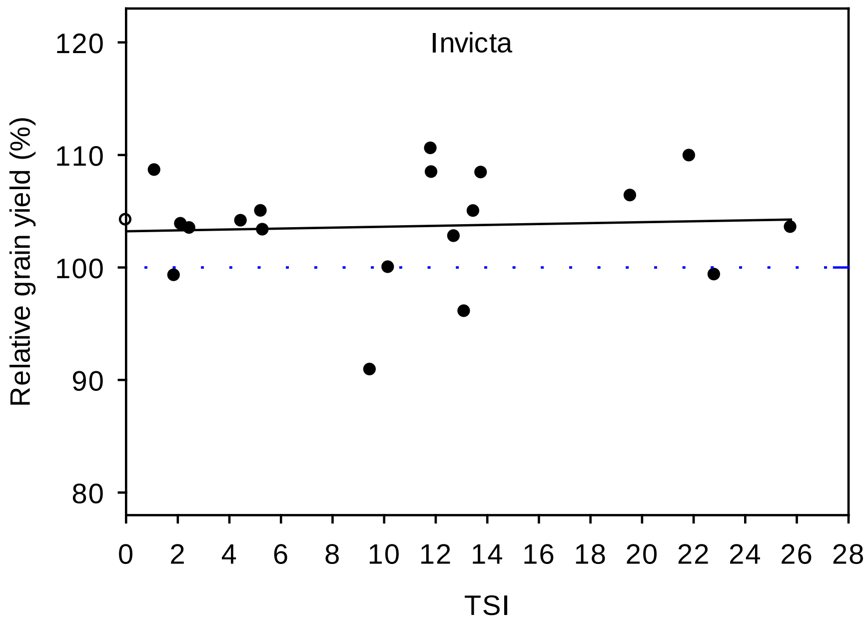


Figure 10. Two varieties with no slope, but above-average yield across sites.

The regression Figures also illustrate the yield potential of varieties, indicated by the intercept on the y-axis. The yield potential is the yield that can be obtained in the absence of any environmental limitations, illustrated here by a TSI value of zero, or complete water sufficiency. In some seasons there may be no test sites that experienced zero water deficit. Therefore, the extrapolation of the regression line to zero TSI may be a good way to convey the yield potential of varieties.

A third piece of information conveyed by the regression plots is the degree of scatter in the datapoints around the regression line. Greater scatter indicates more variability in yields from site to site. For example, KWS-Mammoth showed greater scatter and variability in yields than Solstice

(Fig. 11). There are other methods of quantifying this yield variability, which will be discussed below.

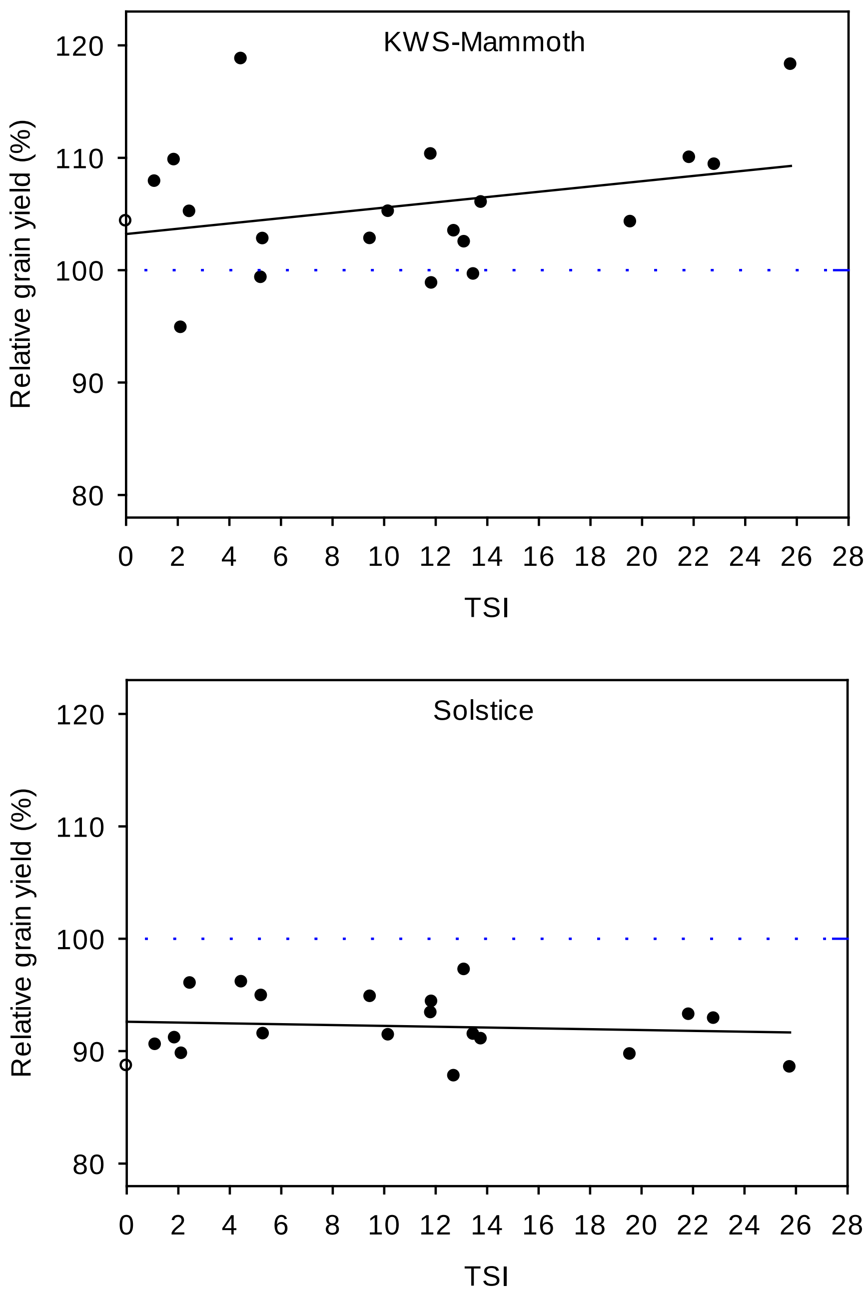
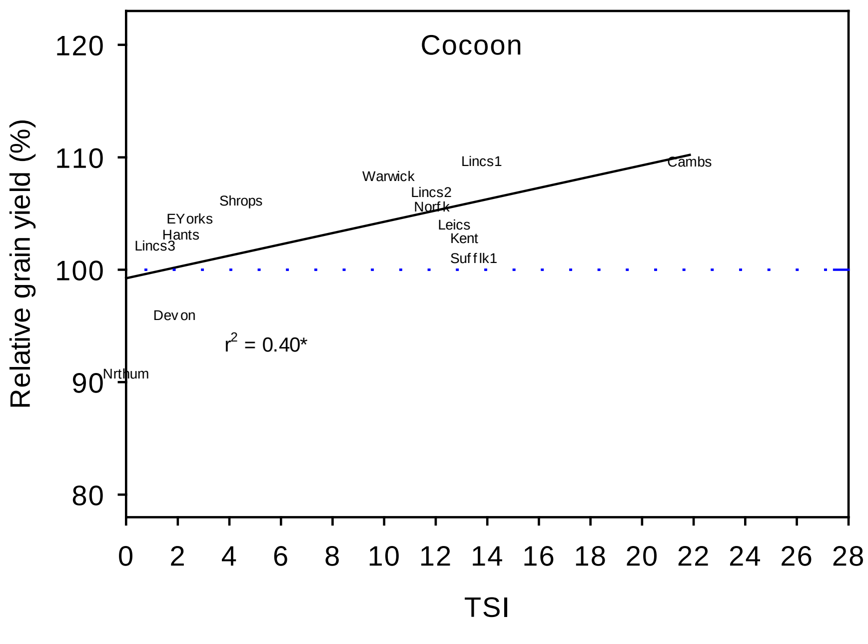


Figure 11. Two varieties that differ in the degree of scatter, or how far individual datapoints deviate from the regression line, which illustrates the yield variability across sites. It is often observed that static yield stability is associated with low yield potential (as with Solstice), but this was not always the case in the 2011 dataset.

4.2.2. Regression analysis using TSI and relative yields – 1st wheat sites only

One of the assumptions of the regression analysis is that the main factor that determines site to site differences in yield is due to water availability, which is quantified using the TSI. This presumes that other yield-limiting factors have been minimised, such as weeds, pest and diseases, nutrients, etc. As all trials were conducted according to the rigorous agronomic and husbandry protocols established for official variety trials, it was deemed safe to assume that these were not major factors. For instance, if diseases were not controlled sufficiently by the fungicide programme, the trials would have been eliminated from the analysis, and perhaps not even harvested. The results of the regressions could be misinterpreted if other factors, such as N limitation, occurred in parallel with water limitation (there was significant co-variation), but all the varietal differences were attributed solely to response to water, ignoring the other variable. However, the statistical analysis of the data did not reveal any significant co-variation that needed to be taken into account. Furthermore, notebooks kept by the trial managers did not reveal any cause for considering other factors. The analysis is simplified by the fact that disease pressure in 2011 was very low.

One factor that is important to consider in detail is whether or not the trial was a 1st wheat (the preceding crop was not wheat). Trials that were 2nd wheat or continuous wheat may have sustained greater take-all pressure or had smaller site yield potential for other reasons. Therefore, we also analysed the varieties using only the 1st wheat sites to eliminate this potential confounding factor. This eliminated six sites, reducing the number of sites from 34 to 28. However, analysis of this smaller dataset did not alter the varietal comparisons or the conclusions obtained using the full dataset. For example, the variety Cocoon showed a similar response with or without the 2nd wheat sites (Fig. 12). Because of the reduced number of sites in the analysis, only four varieties showed statistically significant slopes (Fig. 13). In the 1st wheat-only dataset, KWS-Saxstead gained statistical significance, showing a negative slope (Fig. 13). An ANOVA comparing 1st wheat sites vs. 2nd wheat sites did not show any statistically significant differences in yield, indicating that inclusion of 2nd wheat sites in the overall analysis did not introduce a systematic bias that would affect conclusions drawn from the analysis.



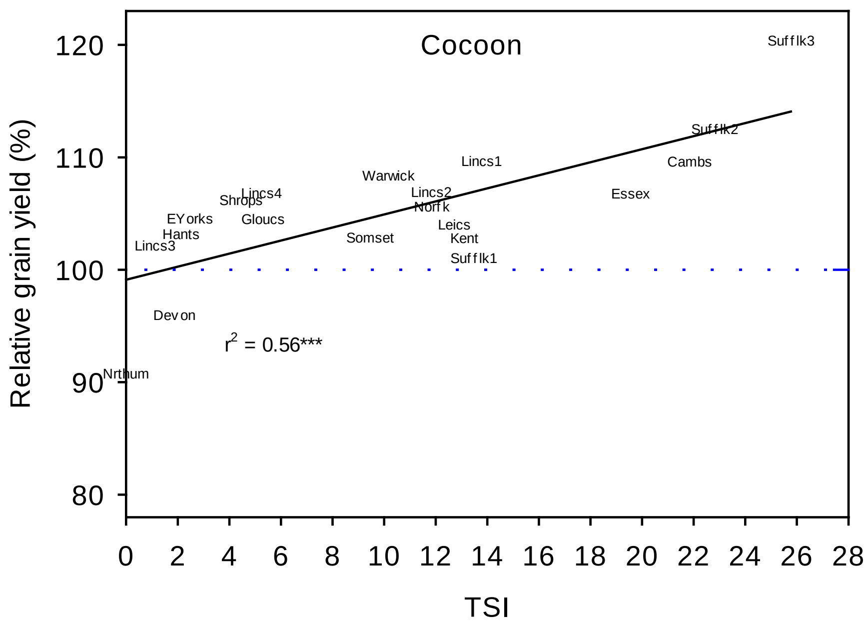


Figure 12. Comparison of the regressions for cv. Cocoon based on only first wheat sites (top panel) and the regression using the additional six second wheat sites. The inclusion of second wheat sites did not significantly alter the portrayal of this variety.

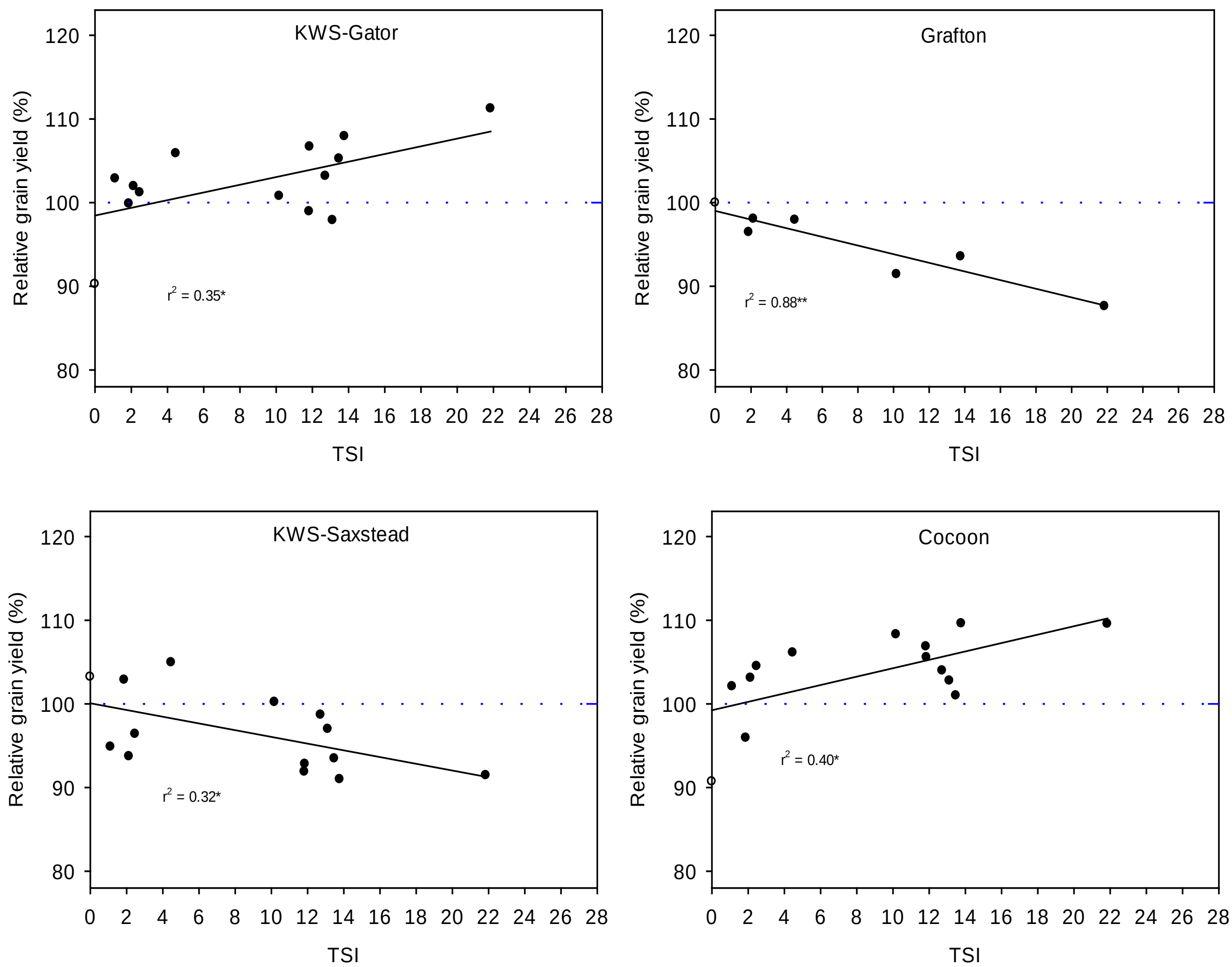


Figure 13. Varieties that showed significant regressions using the dataset that excluded second wheat sites.

4.2.3. Ranking varieties for drought tolerance

It was shown above that judging the performance of a variety based solely on the across-site mean yield can be inaccurate for individual locations differing in the availability of water. The regression analyses provide further data to compare varieties, but these plots would be cumbersome to use as part of the RL description. It would be possible to rank varieties according to the slope of regression, ordering varieties according to drought tolerance. However, this single value does not convey any information about whether yields tend to be relatively large or small in the absence of stress. Two varieties, for instance, could have the same slope (responsiveness to water supply), but one could depart from a point of good yield potential (a y-intercept greater than 100%), while another variety could depart from a very small yield potential. This is an important distinction. What value or values should then be used?

A compromise between displaying the regression plot for each variety showing yield response across all locations (too much information) and a single yield value (too little information) is to express performance for a situation with no stress (TSI = 0), a situation with severe stress (TSI = 25) , and an intermediate situation with some stress (TSI = 10). By using the regression equation that captures yield performance across all locations, the yields that could be expected under these three discrete environmental conditions can be calculated (Fig. 14). In this way, the performance of a variety can be judged for the most relevant conditions. For instance, for a field with shallow, sandy soil, the rankings based on TSI = 25 may be more predictive of variety performance that those at TSI=0.

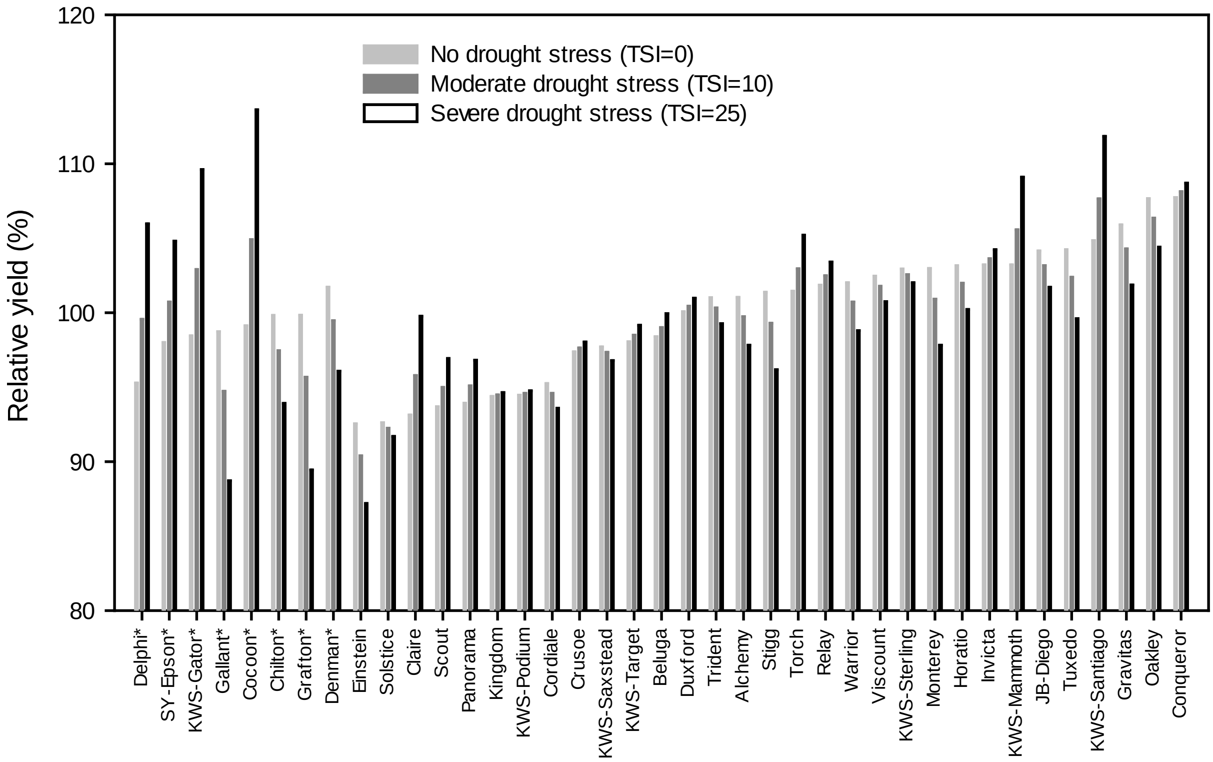


Figure 14. Calculated relative yields for three different levels of stress using the equation derived from the regression of relative yield against TSI (using the full dataset including 2nd wheat sites). Variety names with asterisks denote those that showed statistically significant regressions. The ranking of varieties changes depending on the drought scenario chosen. This allows the performance of a variety to be anticipated for sites that are rarely stressed and for sites that are relatively drought-prone.

4.2.4. Characteristics of varieties differing in drought rankings

It is useful to consider which plant characteristics might differentiate drought-tolerant varieties from the drought-susceptible lines. This would help growers and breeders identify other potentially drought tolerant varieties that have not been analysed in multi-location trials. Detailed measurements of many different kinds of anatomical and physiological traits were measured on a large number of UK varieties (RD-2005-3233), but very few of those lines remain on the RL studied here. The RL dataset has some supplementary information about varieties, but this is limited in scope. However, one important trait is flowering time, or related measures of crop development and maturity. This is important because the timing of water deficits in relation to sensitive stages of yield formation can be a critical determinant of drought susceptibility.

One illustration of this can be seen in the differences between varieties in days to maturity (Fig. 15). Cocoon clearly stands out as a relatively late variety in 2011. Interestingly, Cocoon also showed the greatest level of drought-tolerance. The connection may be that rainfall in early June 2011, which broke the developing drought, allowed varieties to recover. However, early-maturing varieties, such as drought-susceptible Gallant, may have been less able to take advantage of this late rainfall than a later-maturing variety such as Cocoon. Except for these two extremes, amongst the remaining varieties there was little correlation between days to maturity and slope from the regression.

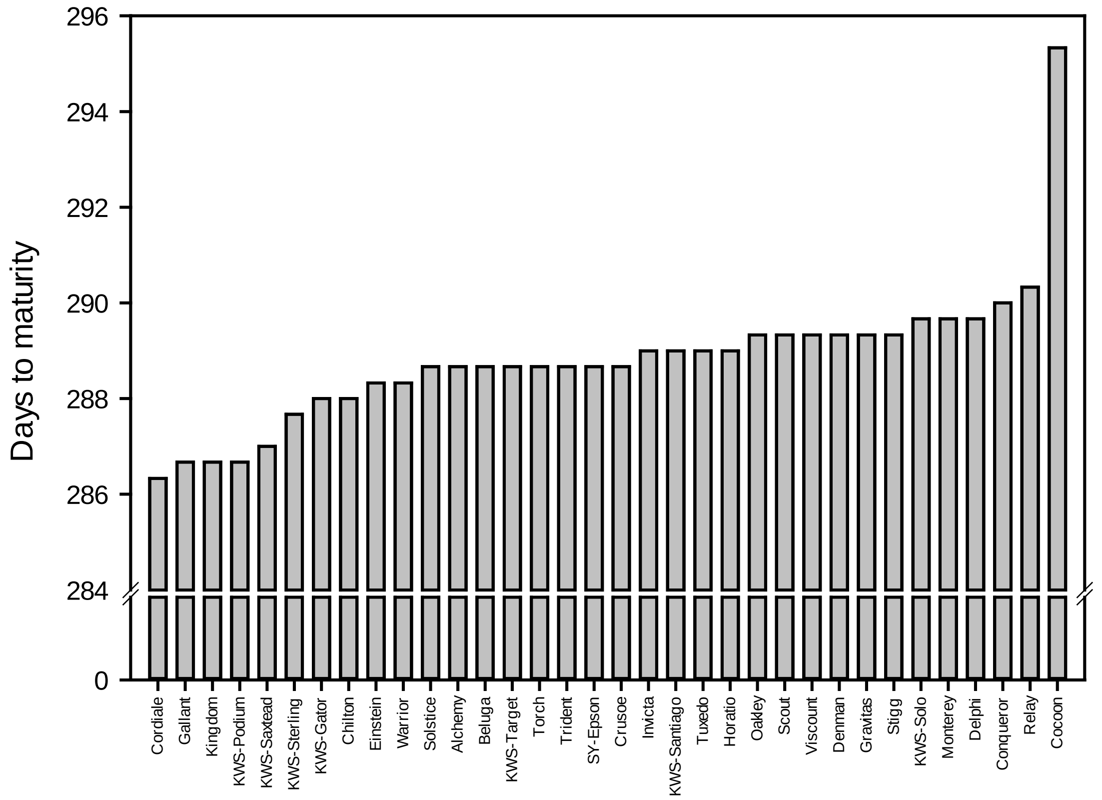


Figure 15. Days to maturity measured at Framlingham (1KW120T).

4.3. Varietal differences in yield stability

4.3.1. Classical stability indices

The coefficient of variation (cv%)

Several stability indices that have been reported in the literature were calculated and compared. Though slightly different in mathematical derivation, many such indices are inter-related, and variety rankings based on these are similar (Baxevanos *et al.,* 2008). Therefore, only the indices that describe stability in different ways are shown in Table 4. The correlations between the parameters are shown in Table 5. Stability indices are primarily used as descriptive statistics and not for drawing inferences or hypothesis testing. However, while methods are available for making statistical comparisons of stability calculated for different varieties (Annichiarico, 2002; Eskridge and Mumm, 1992), this is of limited use from single-year data, hence these were not attempted here.

Table 4. Yield stability statistics calculated for each variety. Legend: cv%, coefficient of variation; Si^2, Lin's environmental variance; Wi^2, Wricke's ecovalence; Si^2 (RY) computed on the basis or relative yield; Pi, performance index; HASI, heritability-adjusted superiority index

Variety	CV%	%CV (RelY)	Si^2	Wi^2	Si^2 (RY)	AMMI Stability Value (ASV)	Pi	Mean Yield (t ha^{-1})	Relative Yield (%)	Stability Deviation	HASI%
Alchemy	21.49	6.74	4.37	2.79	16.93	0.14	0.77	9.84	99.7	0.359	56
Delphi	18.50	7.56	3.23	5.62	35.36	0.59	0.97	9.77	99.8	0.499	52
Monterey	21.45	5.77	4.47	3.47	23.05	0.61	0.73	9.94	100.8	0.443	61
Beluga	21.95	7.96	4.33	5.12	23.62	0.45	0.96	9.77	99.0	0.497	52
Cocoon	17.44	5.73	3.00	5.13	35.80	0.93	0.46	10.27	105.2	0.506	79
Conqueror	20.78	6.05	4.67	2.57	12.55	0.38	0.13	10.65	108.1	0.449	100
Cordiale	22.57	7.52	4.40	3.29	19.52	0.23	1.48	9.34	94.6	0.488	28
Crusoe	21.33	6.48	4.06	4.55	24.83	0.32	1.10	9.62	97.7	0.347	43
Denman	22.15	6.02	4.64	1.58	14.20	0.28	0.76	9.82	99.4	0.445	55
Chilton	21.43	8.37	4.17	2.35	16.68	0.33	1.08	9.60	97.4	0.416	43
Einstein	22.49	7.49	3.84	4.47	26.55	0.60	2.37	8.92	90.3	0.493	6
Gallant	24.87	5.56	5.41	4.92	33.14	1.05	1.49	9.39	94.5	0.401	31
Gravitas	21.18	6.70	4.65	4.04	19.15	0.74	0.34	10.27	104.2	0.323	79
Horatio	20.05	7.20	3.77	2.09	12.04	0.55	0.55	10.03	101.9	0.320	66
Invicta	19.64	6.86	3.74	4.77	23.20	0.91	0.44	10.18	103.6	0.417	75
Kingdom	22.75	7.67	4.45	4.21	20.97	0.77	1.56	9.33	94.5	0.346	28
KWS-Podium	21.90	6.58	4.08	2.45	16.95	0.33	1.48	9.33	94.6	0.460	28
KWS-Santiago	17.22	6.10	3.05	4.98	36.71	0.77	0.26	10.53	107.8	0.374	93
KWS-Sterling	21.36	7.34	4.58	3.96	20.23	0.53	0.51	10.11	102.6	0.374	71
KWS-Target	22.09	6.67	4.53	2.75	17.90	0.47	0.97	9.73	98.5	0.281	50
KWS-Saxstead	21.42	6.30	4.17	3.63	23.25	0.67	1.11	9.59	97.3	0.430	43
KWS-Mammoth	19.47	6.84	4.07	4.94	35.94	0.37	0.31	10.37	105.7	0.506	85
KWS-Gator	17.03	6.82	2.73	4.85	28.61	1.05	0.61	10.07	103.1	0.530	69
Oakley	20.71	5.26	4.72	3.92	15.71	0.70	0.23	10.47	106.3	0.371	91
Torch	19.96	5.83	4.04	2.40	13.86	0.46	0.51	10.13	103.0	0.477	72
Trident	22.56	6.65	4.97	2.39	11.84	0.56	0.72	9.92	100.3	0.343	60
Relay	18.89	5.94	3.56	3.21	17.42	0.57	0.52	10.06	102.5	0.426	68
Scout	20.89	6.97	3.70	2.78	13.43	0.30	1.54	9.35	95.0	0.496	29
Solstice	20.81	5.58	3.52	2.04	7.43	0.28	1.91	9.09	92.2	0.373	15
Stigg	22.35	5.88	4.57	3.70	24.42	0.29	0.87	9.80	99.2	0.406	54
SY-Epson	19.18	5.53	3.58	2.79	16.45	0.34	0.76	9.90	100.8	0.350	59
Tuxedo	21.34	7.22	4.37	3.46	14.42	0.23	0.51	10.08	102.3	0.459	69
Viscount	20.30	5.84	4.03	2.04	11.36	0.31	0.58	10.01	101.7	0.320	65
Warrior	20.96	6.83	4.22	4.23	20.32	0.36	0.78	9.92	100.7	0.473	60

Table 5. Pearson correlation coefficients showing the relationships between various measures of stability, and between stability and yield. See Table 4 for abbreviations. Values in boldface are significant at P<0.01.

	CV%	%CV (RelY)	Si^2	Wi^2	Si^2 (RY)	ASV	Pi	Yield	Relative Yield	Stability Deviation
CV%	1.00									
%CV (RelY)	0.06	1.00								
Si^2	**0.86**	-0.29	1.00							
Wi^2	-0.26	**0.63**	-0.25	1.00						
Si^2 (RY)	-0.30	**0.63**	-0.31	**0.87**	1.00					
AMMI Stability Value (ASV)	-0.26	0.37	-0.19	**0.59**	**0.54**	1.00				
Pi	**0.52**	0.28	0.03	-0.06	-0.05	-0.14	1.00			
Yield	**-0.56**	-0.22	-0.08	0.14	0.12	0.21	**-0.98**	1.00		
Relative Yield	**-0.62**	-0.19	-0.15	0.17	0.15	0.22	**-0.97**	**1.00**	1.00	
Stability Deviation	-0.23	0.33	-0.33	0.36	0.38	0.05	0.12	-0.06	-0.03	1.00
HASI%	**-0.56**	-0.22	-0.08	0.14	0.12	0.21	**-0.98**	**1.00**	**1.00**	-0.06

A common measure of variability is the coefficient of variation (cv%), which is popular because: it is simple to calculate (the standard deviation divided by the mean); the tendency of standard deviation and mean to change in proportion; and that cv% is unitless, so cv% values can be compared across datasets measured in different units. However, despite the assumption of proportional scaling of variance and the mean, in field trials the cv% is often negatively correlated with yield (Taylor *et al.,* 1999), as shown here (r = -0.56*; Table 5). As yield is strongly influenced by the environment, cv% is also and, therefore, not entirely suitable as an indicator of variety variability. In other words, high cv% values tend to be biased towards low-yielding varieties, which may be explained in biological terms, but is also affected by the mathematical derivation of the cv% ratio (Atchley *et al*., 1976). Use of the error variance partitioned in analysis of variance (ANOVA) is independent of this potential bias, and therefore may be a fairer basis for estimating yield stability of varieties (Annichiarico, 2002; Taylor *et al*., 1992). The cv% provides rankings similar to the environmental variance (S_i^2; see below), another indicator of 'static' stability (Table A3), but is unrelated to measures of dynamic stability (W_i^2). On the other hand, the cv% based on relative yields, as would be expected, is unrelated to S_i^2, but shows greater correlation with W_i^2.

The environmental variance (S_i^2) and ecovalence (W_i^2)

In general, the differences in yield stability between varieties were relatively small, which would be expected for lines that have reached the RL stage (highly unstable varieties, in most cases, would have been eliminated at earlier stages in the breeding process). Nevertheless, it can be seen from the scatterplots (Fig. 11) that varieties were not uniform in the stability of yields across sites (Table 4). For instance, KWS-Gator and Gallant show, respectively, the smallest and largest static stability based on S_i^2, whereas Denman and Delphi had, respectively, the smallest and largest dynamic stability based on W_i^2. Another dynamic stability measure, S_i^2 computed on the basis of relative yields, shows the largest contrast between Solstice and KWS-Santiago.

4.3.2. Stability indices combined with yield

Most growers would not be interested in a variety with exceptional stability if the yield potential of that variety was below average. Likewise, a variety that had potential for high yield, but only delivered in some cases and not others, might be considered too risky to plant. Therefore, it is valuable to combine measures of stability and yield as a performance indicator. Calculations of the Performance index (Pi), Kang's yield stability statistic (YSi) and the heritability (repeatability)-adjusted superiority index (HASI) showed similar rankings of varieties. All the indices were dominated by varietal differences in yield, as differences in stability were comparatively small (Table 4). Rankings of varieties based on yield shifted little when expressed on the basis of Pi or HASI. For instance, KWS-Gator was ranked 11/34 for mean yield, but moved up one place to 10/34 based on rankings for HASI.

4.3.3. Multivariate methods to quantify stability

Evaluation of variety performance using biplot analysis assists in the visualisation of genotype and environment interactions. The 2011 RL data, subjected to principle component analysis and plotted as a biplot revealed several pieces of information (Fig. 16). The plot is divided into sectors defined by groups of locations, and lines are drawn between varieties showing the greatest values in each sector. For instance, Conqueror showed the best performance in the sector defined by Northum, Devon, EYorks, etc, while KWS-Santiago was greatest in the sector defined by Sufflk3, Cambs, Essex, etc. Einstein, Solstice, Scout were together in a sector that was differentiated from the sector led by Gallant. More information on how to interpret biplots can be found in Yan and Kang (2003) and in similar examples (Sandhu *et al*., 2012; Yan *et al*., 2011).

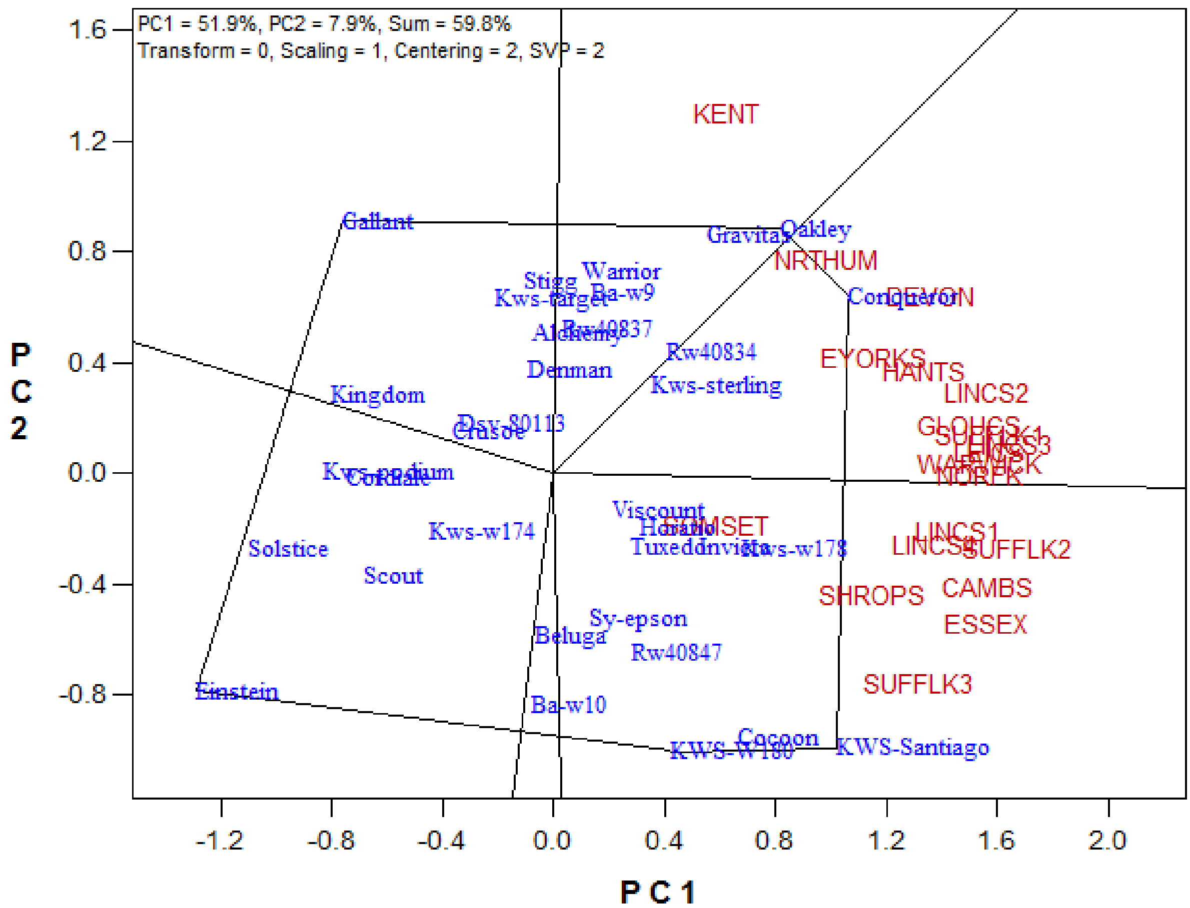


Figure 16. A biplot showing the first two principle components (PC) derived from the 2011 RL dataset that captures 60% of the total variation. Varieties are shown in blue (see Table 2 for variety names of breeder line references), and locations are show in red caps (see Table 1 for abbreviations). The plot is divided into sectors defined by groups of locations, and lines are drawn between varieties showing the greatest values in each sector. For instance, Conqueror showed the best performance in the sector defined by Northum, Devon, EYorks, etc, while KWS-Santiago was greatest in the sector defined by Sufflk3, Cambs, Essex, etc. Einstein, Solstice, Scout were together in a sector that was differentiated from the sector led by Gallant.

Plotted slightly differently, the biplot can portray the site value, or the ability of sites to discriminate between varieties (Fig. 17). The length of the vector is proportional to the variation between varieties captured at a site: a long vector indicates a site with greater discriminating power. The angle between vectors that connect the location (in red caps) with the origin of the plot is related to the correlation between sites. For instance, an angle of nearly 90° between Kent and Sufflk3 indicates no correlation between the sites: variety performance evaluated in Kent has little relationship to that in Sufflk3. (If the angle approached 180°, the ranking of varieties would be completely reversed at the two site, but fortunately this does not exist here). In contrast, the narrow angle between Cambs and Essex shows that similar information about varieties is provided at both locations. Site vectors that practically overlay each other indicate that the same information about varieties is supplied by both sites. This may be desired for replication, or it may suggest that one site is redundant and can be eliminated without any loss in information.

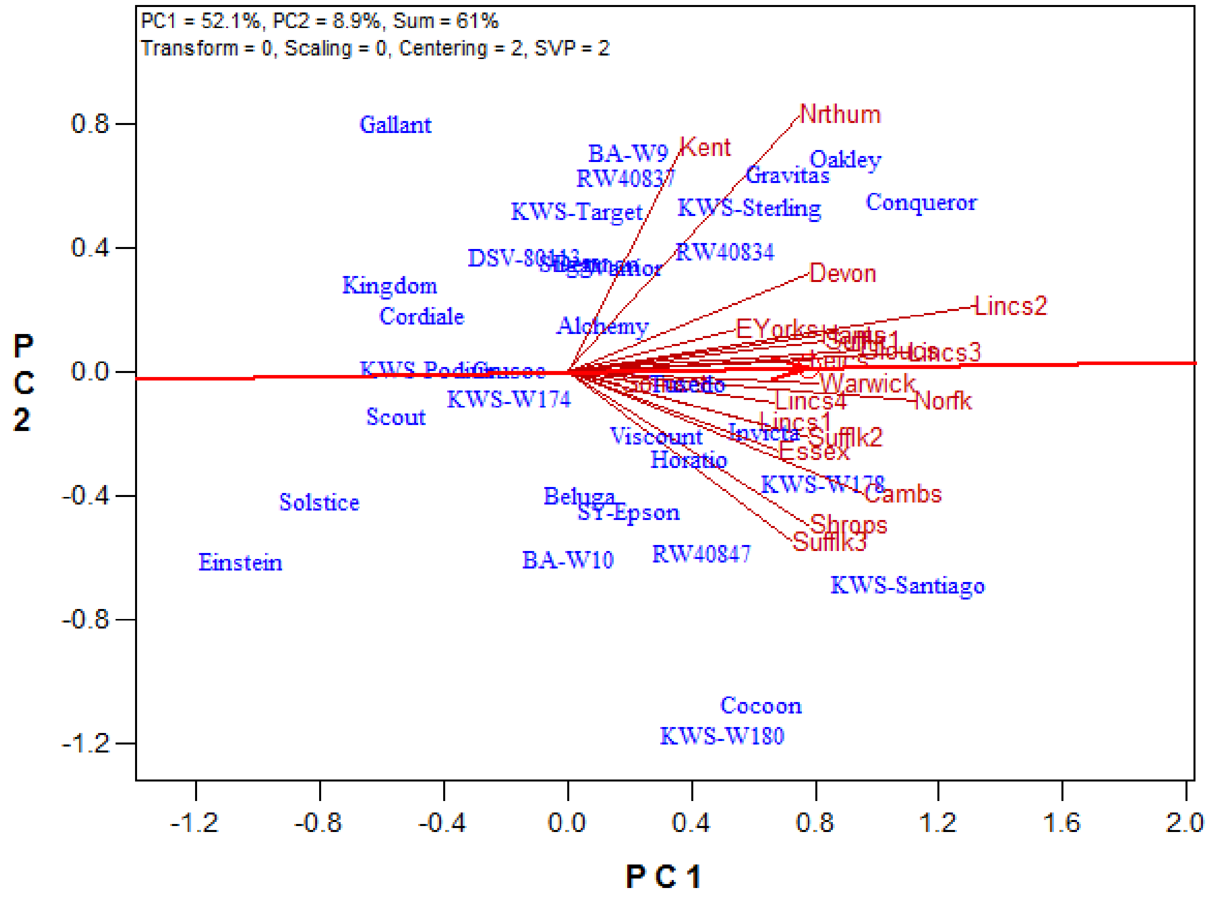


Figure 17. A biplot that portrays the relationships between locations. The angle between vectors (red lines) that connect the location (in red caps) with the origin of the plot is related to the correlation between sites. For instance, an angle of nearly 90° between Kent and Sufflk3 indicates no correlation between the sites: variety performance evaluated in Kent has little relationship to that in Sufflk3. In contrast, the narrow angle between Cambs and Essex shows that similar information about varieties is provided at both locations. The length of the vector is proportional to the power of the location to discriminate between varieties.

The data can be analysed in a biplot that portrays both yield and stability (Fig. 18). Varieties are separated along the horizontal, red arrow, with greater yields in the direction of the arrow, and stability along the blue, vertical arrow, with greater variability in the direction of the arrows (greater or smaller variability than the mean). A variety that lies close to the red arrow, further to the right (e.g. Conqueror) shows greater yield and stability than a variety at greater vertical distance from the red line, and further to the left (e.g. Gallant). The same information portrayed in the biplot can be derived from multiple rows and columns of raw data, but the biplot is a more efficient device for communicating this complex information.

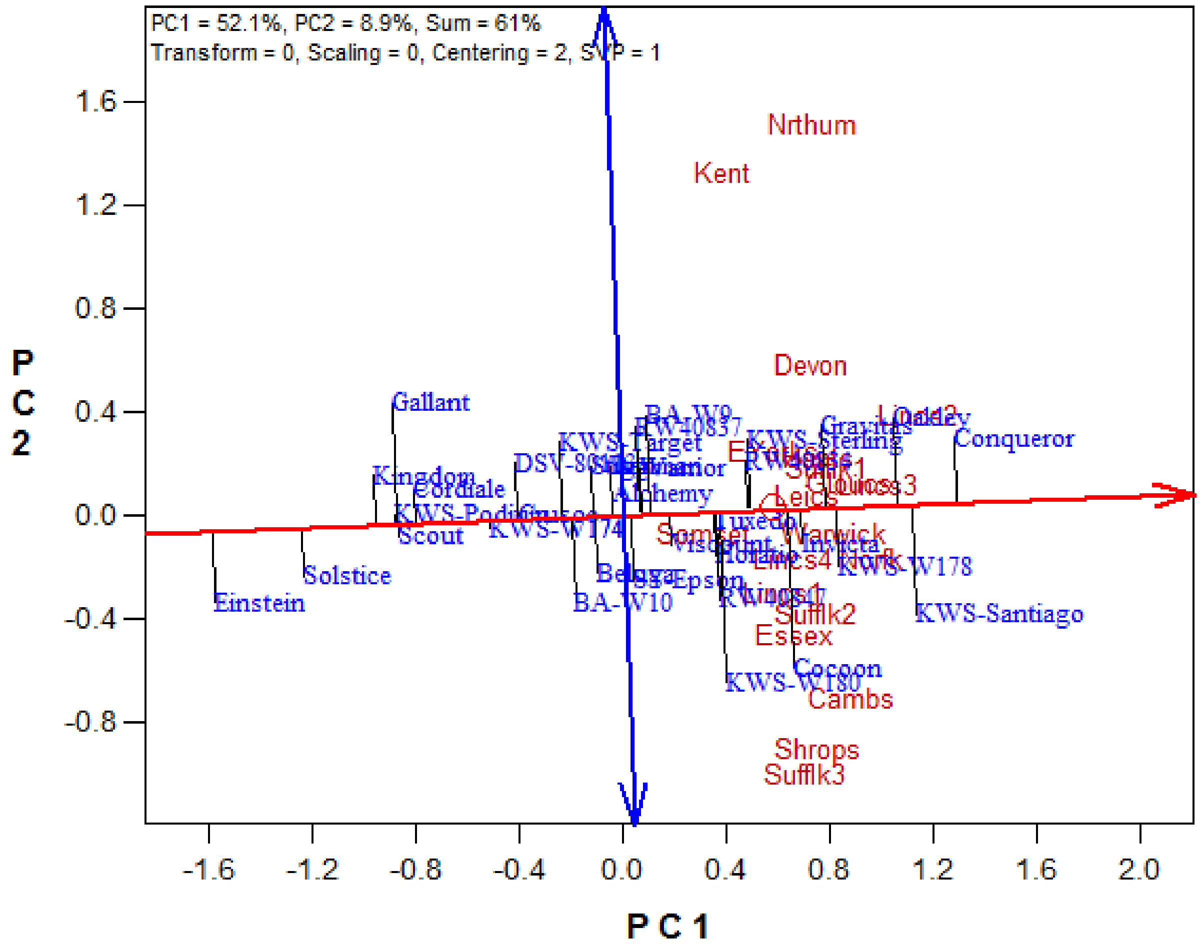


Figure 18. A biplot that portrays yield across locations (greater yield in the direction of the red horizontal arrow) and yield variability (greater instability in the direction of the vertical blue arrows).

4.3.4. Stability vs Yield scatterplots

A potential drawback of GGE biplots, and AMMI plots as well, is that they only approximate the genotype x environment variation and, depending on the dataset, some varieties or locations may not be well represented (located close to the origin). Simple scatterplots of stability against yield permit the straightforward visualisation of both aspects of variety performance, which captures 100% of the genotype x variety interaction (Gauch *et al*., 2008). A scatterplot of instability, computed as the ecovalence of relative yields (the sum of squares contribution to GxE for each variety) versus the grain yield is shown (Fig. 20). Although the varietal differences in stability were small, varieties located in the lower right-hand quadrant (low instability, high yield) would be more desirable over those with less stability or smaller yields. A plot based on the AMMI stability value (ASV; Fig. 21) shows similar information to Fig. 20, although there are slight differences due to the different approaches to deriving stability values. Both plots show Conqueror in the quadrant with good stability and yield, and Gallant in the poor stability and yield quadrant.

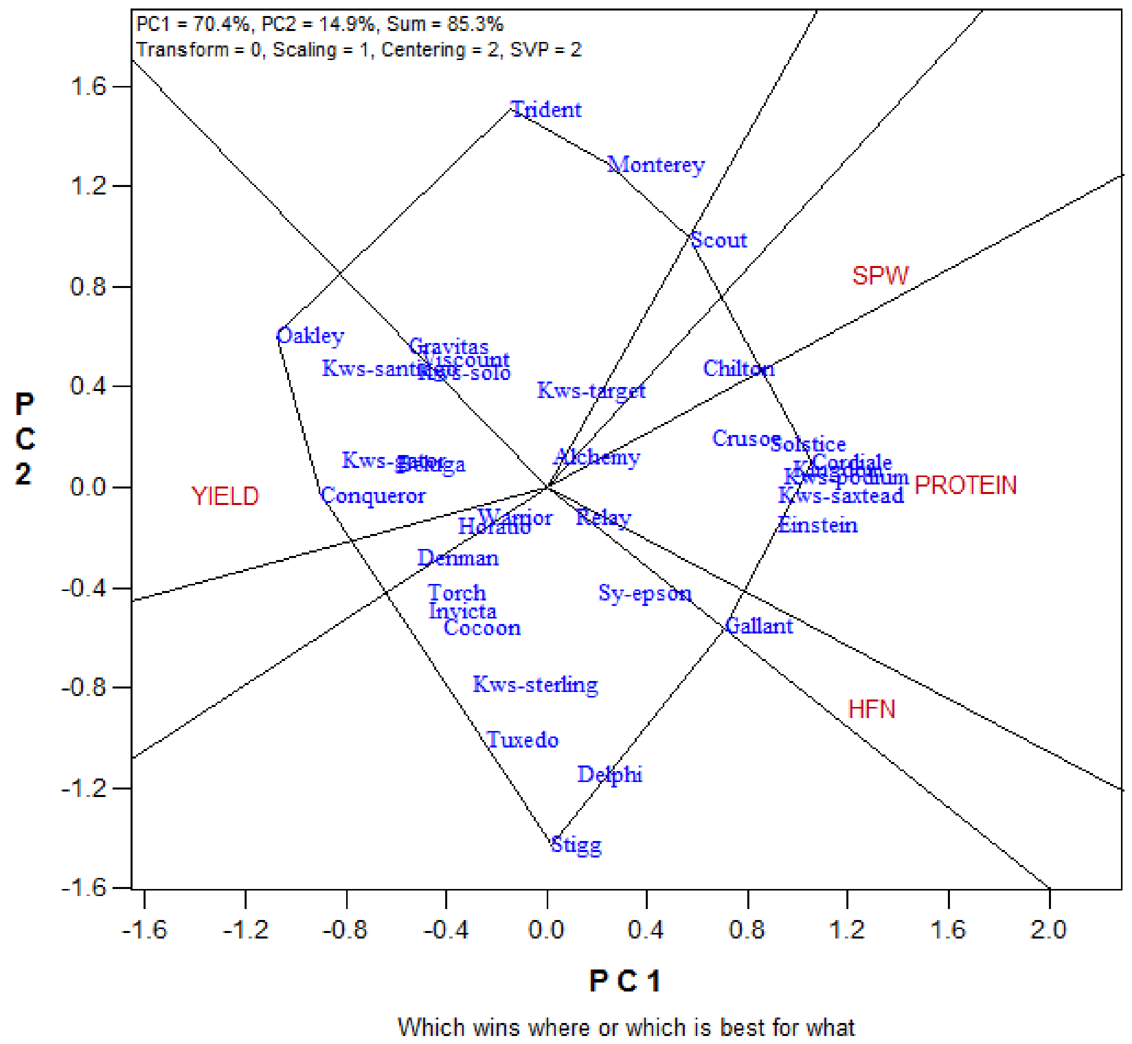


Figure 19. A biplot that portrays the relationships between varieties (in blue), grain quality traits (in red caps), and their interactions. The green dashed arrow indicates greater expression of both protein and yield, with smaller HFN. Abbreviations: SPW, specific grain weight; HFN, Hagberg Falling Number.

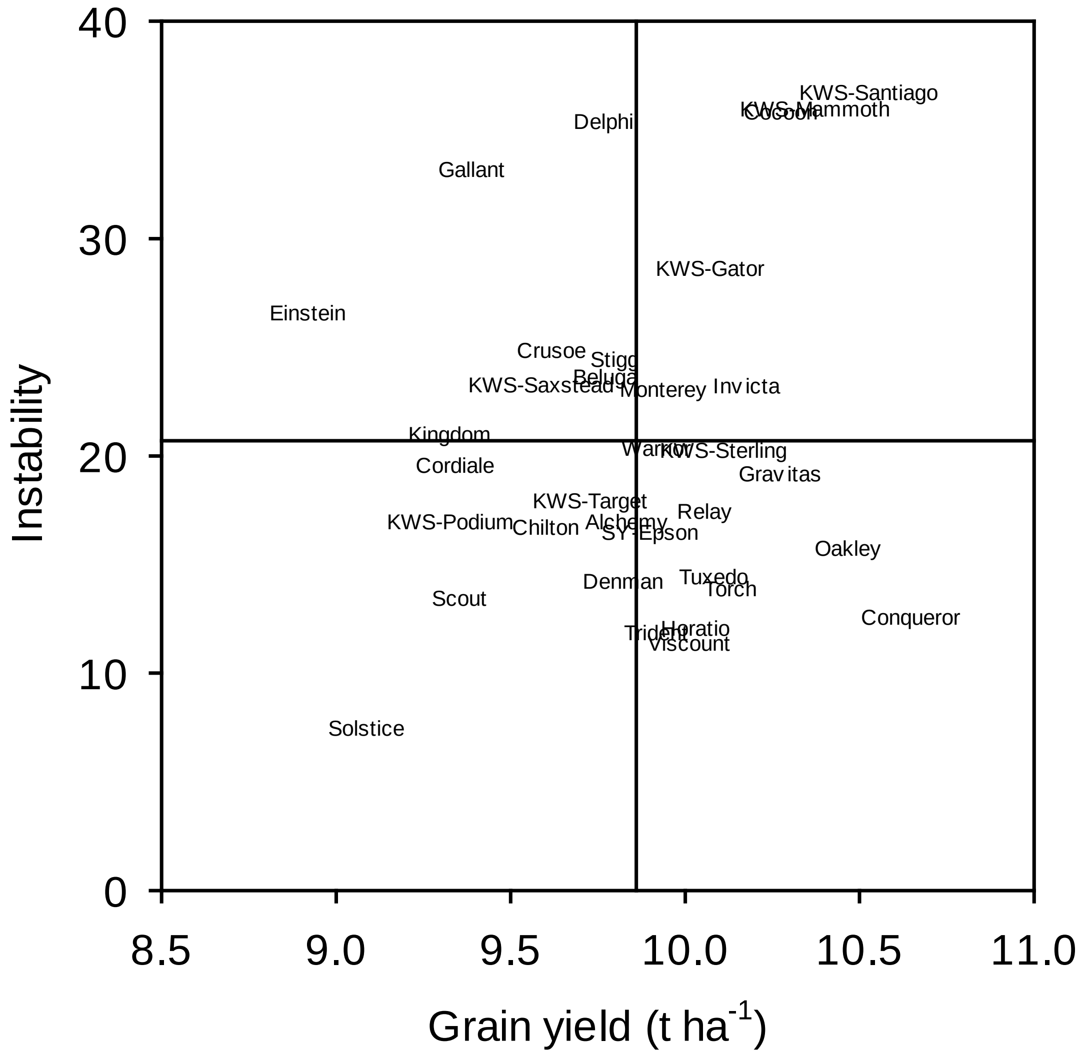


Figure 20. Grain yield of varieties averaged across sites plotted against yield instability calculated as Lin's environmental variance (S_i^2). Varieties that fall in the lower right-hand quadrant show the best combination of yield and stability.

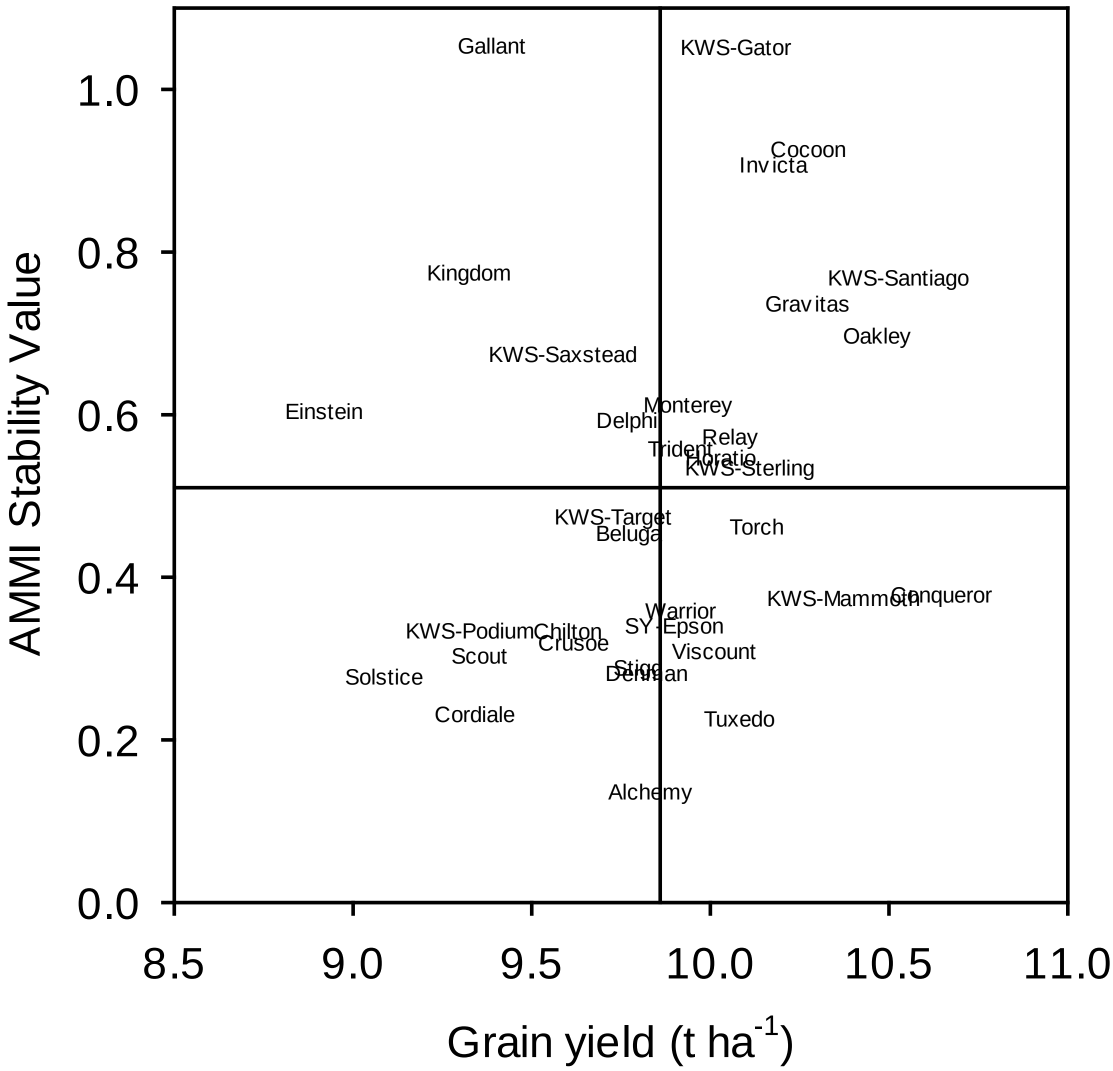


Figure 21. Grain yield for each variety, averaged across sites, plotted against the AMMI stability value derived from IPCA1 vs IPCA2 plots. Varieties that fall in the upper right hand quadrant show the best combination of yield and stability.

4.3.5. Grain quality biplots

By replacing locations with traits, it is also possible to portray the interaction between varieties and quality parameters (Fig. 19). As above, the plot shows that protein is inversely related to yield (vectors connecting traits to plot origin are at 180°), as expected. It also shows that the varieties Cordiale and Solstice, which are clustered around the protein trait (and within the sector dominated by protein), show greater expression of that trait than varieties that are plotted far from ‘protein’ (e.g. Oakley). Gallant showed high expression of Hagberg Falling Number (HFN) compared with Trident, whereas Chilton showed greater expression of specific grain weight (SPW), which was unrelated to HFN. Varieties that show the best combination of traits fall along a new vector that can be drawn that bisects the vectors of two traits (green arrow, Fig. 19). Both Stigg and Trident show balanced expression of yield and protein, but Stigg showed greater HFN. The quality characteristics of Alchemy, which fall near the plot origin, were not well represented in the biplot, probably because of little variation in the expression of the quality traits.

4.4. Crop survey data on drought symptoms

A summary of field and lab assessments is shown in Table 6, and a more detailed analysis is attached as an Appendix. There was high variability in observed symptoms from field to field, probably due to soil type, and between regions, but differences between varieties did not reach statistical significance, except for ear sterility. Hereward showed greater sterility symptoms than other varieties (Table 6). Grafton showed slightly less height reductions than Gallant in the field surveys, but both showed drought susceptibility according to the regression analysis of RL trial yields (Fig. 8).

Table 6. Summary of REML analysis of Crop Monitor field assessments conducted in 2011. Fields were assessed for senescence and stunting, then 25 random plants were sampled and scored further in the lab for ear sterility, leaf senescence, drought-induced leaf necrotic spotting and height. The F probability and average standard error of the differences are shown for each variate. Only varieties that were represented in at least nine fields were analysed.

	Field		Lab				
Variety	Senescence	Stunting	Height	Sterility	Senescence	Spotting	Height loss
	% of crop		cm	% of plants		No. leaves	% of RL
Alchemy	6.4	5.8	78.0	0.04	1.04	0.07	17.9
Claire	14.0	8.5	77.0	0.00	17.14	0.00	16.3
Cordiale	11.0	11.6	70.5	0.18	9.55	0.09	15.1
Duxford	2.3	8.4	75.4	0.10	6.40	0.00	19.8
Einstein	3.6	0.0	74.0	0.00	0.11	0.00	16.9
Gallant	11.4	10.2	68.8	0.14	7.00	0.00	20.0
Grafton	17.5	9.0	68.8	0.00	3.86	0.43	14.0
Hereward	5.1	27.5	70.8	5.58	5.58	0.00	20.4
JB Diego	6.9	14.1	75.3	0.00	4.53	0.07	18.2
Oakley	9.0	15.3	71.0	0.04	5.40	0.00	19.3
Scout	6.6	1.3	75.9	0.25	2.88	0.00	16.6
Solstice	12.5	8.0	78.2	0.22	4.59	0.00	19.4
Viscount	8.4	14.1	68.5	0.00	0.59	0.00	19.5
F pr	0.804	0.539	<0.001	<0.001	0.207	0.232	0.708
avg s.e.d.	7.40	9.85	2.90	0.84	5.25	0.14	3.2

5. Discussion

5.1.1. Ranking varieties for drought tolerance and yield stability

Even though 2011 provided a limited dataset to evaluate variety performance, it was shown that some varieties appeared to yield significantly better than others as conditions became more stressed. It is important to know if this behaviour was particular to the timing and severity of the stress in 2011, or is an indication of general resilience in those varieties that can be relied on in different situations. This can be evaluated only by expanding the analysis to further years, retrospectively where possible, and into the future.

The RL yield data from 2011 showed significant genotype x environment interactions, which means that the ranking of varieties changed, depending on which location was considered. By definition, this means that one number (e.g. the overall trial mean) cannot capture all the information about variety performance. Likewise, ranking varieties according to a single value that would attempt to encapsulate relative drought tolerance would be crude and, potentially, misleading. In contrast, while presenting the entire picture of variety performance would be more informative—for instance as a GGE biplot shown here—it is too much information and would be cumbersome to handle and interpret by the average reader of the RL. A compromise maybe something like the bar graph we have showed with projected yields for three different water availabilities (Fig. 14).

One of the inherent assumptions of the regression analysis was that there was no significant covariate in the genotype x environment interaction other than water availability. Although water availability explained only a portion of the site-to-site variation, we did not find any evidence that other factors played a major, systematic role. Precipitation was the environmental covariate that could explain a large proportion of QTL x location interactions for agronomic traits in wheat (Campbell *et al.,* 2004). Thus, the regressions appear to be a reasonably accurate reflection of variety response to water availability.

Various approaches to quantifying yield stability were explored, but with emphasis on indices or methods that portrayed both yield potential and stability, as both are important considerations. The differences in stability between varieties was small in 2011, which reflected the variation only between locations. It is the year-to-year variability that introduces much larger yield variations and, therefore, the most useful evaluation of stability differences will need to incorporate multiple years in the analysis.

An interesting question is whether or not varieties that show greater relative performance on second wheat sites also show greater yield stability across environments. The basis of such an association may be that varieties with larger and more robust root systems can better withstand the pest and disease pressure of continuous wheat, and such root systems would also provide a benefit when limited rainfall increased dependency on the ability to mine more water from the soil. Unfortunately, this question could not be adequately addressed from the 2011 dataset because there was no variety interaction between first and second wheat sites (no varieties stood out better as second wheats), perhaps because there were only six non first-wheat sites. With larger datasets that included more second wheat sites this idea may be better tested.

5.1.2. Benefits to identifying varieties with improved drought tolerance

For growers and millers

Except for 2008 and 2012, five seasons from 2006–2012 have had dry spells that decreased yields on most farms, except perhaps those on the heaviest land with deep, water-retentive soils. Farmers must rely on experience and unsubstantiated anecdotal reports to guess which variety will stand up to hot, dry conditions better than others. However, there is little general agreement what these varieties are, as each farm has different soils and each year different weather conditions. Furthermore, there is little or no experience with the newest varieties to know how they perform under stressed conditions. Most farmers will put the best varieties on the best land to maximise returns; but on the lightest land and fields with shallow soils, farmers are asking for some kind of guide to help them decide which varieties to sow to get the best out of what that land can offer. Farmers understand that variety performance has complex interactions with environmental conditions that vary from site to site and year to year, and accept that a definitive characterisation of a variety as ‘drought tolerant’ or ‘drought susceptible’ may be difficult to achieve; and yet, they stress that *some* sound information—even if it is based on one season—is better than none at all.

Farmers will benefit from knowing which varieties would tend to perform better on drought-prone land, and which varieties do best when water is plentiful. By ensuring that some of the farm acreage is planted with a stable variety (rather than a high yielding but perhaps unstable variety), some risk is removed due to unpredictable weather conditions. By knowledge-based tailoring the drilling of varieties according to soil texture and the local likelihood of dry conditions, potential profits can be maximised.

Millers and other end-users will benefit from higher quality grain (e.g. less small, shrivelled grain due to drought stress) and a more stable supply in terms of quality and quantity.

For the environment and the public

The environment and general public will benefit from increased input use efficiency on better yielding crops in suboptimal conditions. The level of pesticide and fertiliser applications are rarely reduced significantly on a crop that eventually yields poorly (e.g. due to water limitation).

Therefore, the nutrient use efficiency is also poor, nutrients not taken up by the crop are liable to leaching into groundwater, and returns on input investments are diminished.

N applied to soils in early spring is not fully utilised when crop development is reduced as a result of dry weather. This N is then leached from the soil in winter. ~£231M p.a. is spent on water treatment costs for removing N and P from municipal water supplies; most of these elements originate from arable agriculture (Pretty, 2011). Improved varieties that can continue growing during a water deficit will remove more of the applied N from the soil. Root systems of more stress resilient varieties would take up more water and N per unit of biomass than current varieties. Less N leaching from winter wheat will produce a savings of ~£40M p.a. in water treatment costs (Pretty, 2011). Savings are based on the estimation that N leaching could be decreased by 10% as a result of improved growth in dry seasons (the worst for winter leaching), and wheat comprises approximately 12% of the total arable acreage (DEFRA statistics, 2002), which contributes to most of the water treatment costs for N and P removal.

Only a relatively small wheat acreage is irrigated in a dry year, but the practice may increase as increased pressure on the heaviest land pushes more wheat onto marginal light land. Climate change scenarios predict increased occurrence and severity of dry conditions, so more water resources in future may be diverted to irrigate wheat–sometimes under severe conditions just to ‘save’ the crop or to ‘water in’ the N. Knowledge of which varieties can best handle dry conditions without irrigation will save water resources for other uses.

For variety trial managers

Conducting a large number of variety trials across a range of geographical locations representing different growing conditions is a vital but costly exercise. Therefore, levy payers and trial managers want to see maximum efficiency in the trial system, extracting as much useful data as possible, with the highest quality. Therefore, if for example two test locations provide essentially the same information, only one of those sites is required and the second trial can be moved to another environment that is under-represented, or eliminated to provide a saving.

For breeders and scientists

Identification of varieties that show consistent differences in drought susceptibility (depending on the timing and severity of dry conditions from year to year) can aid research into the biological mechanisms of resilience to stressful growing conditions. Information on key traits that confer improved drought tolerance can be used by breeders to eliminate drought-susceptible types during the process of selecting which lines to cross to create new varieties. Breeders may also adopt these analysis approaches to evaluate drought susceptibility and yield stability in-house multi-environment variety trials.

5.1.3. Relevance of rating variety performance

This was a pilot project to see what kind of analyses can be done with RL data, and which outputs provide the most useful information for growers and trial managers. The analysis looked only at 2011 and, as such, is insufficient to provide a robust indication of variety performance; more years are needed to create a larger database. Confidence in the variety rankings will increase with data added from additional years. RL data from 2006 to 2009 were analysed using similar regression approach in a previous LINK project (RD-2005-3233). These data, along with a new analysis of 2010 data, can be combined together to create a dataset of six years' yield data 2006–2011. Varieties that are represented in this dataset, and remain on the RL, can be analysed to provide a robust picture of drought susceptibility and yield stability.

In future, if this process of analysis is adopted as a routine assessment of variety performance, as new varieties join the RL, information from the previous years' National List (NL), by Fera and BSPB, data could be used so that for the first year on the RL, there should be three years' data available for analysis. Then, with each year on the RL, additional data can be added to the dataset for each variety. The longer an individual variety stays in the NL/RL system, the more data (years + locations) can be gathered to increase the confidence of its characterisation in terms of yield responsiveness to water availability.

5.1.4. Benefits to identifying varieties with improved drought tolerance

It is estimated that 30% of the UK wheat acreage is planted on drought-prone land (Foulkes *et al.,* 2007). In managed drought experiments, not dissimilar to conditions in 2011, yields of RL varieties differed by 15% (1.3 t ha^{-1}) (HGCA Project RD-2005-3233). For a maximum savings scenario, if all 30% of the affected acreage was stressed equally and planted with the most tolerant variety rather than the most susceptible variety, an extra 1.3 t ha^{-1} on 582,000 ha (approximately) at £140/tonne would have produced an extra £105M in gross returns to growers. Actual savings realised in practice will be less, as a smaller proportion of area would experience this level of stress, and a proportion of this area will already be planted with a tolerant variety.

6. Acknowledgements

The valuable help of several people who made this project possible is gratefully acknowledged: Dr. Aiming Qi calculated the TSI values and collated the weather and soil data needed to run the Sirius wheat model. Anne Perry milled the soil samples and did the texture analysis. The trial managers aided access to sites for soil sampling and provided additional information about the trials. Dr Paul Gosling (HGCA) was instrumental in providing the raw data and trial information necessary for the study.

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Appendix

Table A1. A summary of the regression information for each variety. The intercept (a) indicates yield potential in the absence of stress; the slope (b) indicates relative drought susceptibility; the number of trials analysed (n); the regression coefficient (r^2) and correlation coefficient (r) are shown, with Table values for r at P < 0.05. The slope of the regression was significant where r > Table r, indicated by an asterisk. See Table 2 for variety name references.

Variety	a	b	r^2	r	n	Table r (P<0.05)	significance
Alchemy	101.03	-0.13	0.06	0.24	20.00	0.44	
BA-W10	95.28	0.43	0.31	0.55	20.00	0.44	*
BA-W9	102.97	-0.21	0.11	0.33	20.00	0.44	
Beluga	98.39	0.06	0.01	0.10	20.00	0.44	
Claire	93.13	0.27	0.30	0.55	6.00	0.81	
Cocoon	99.12	0.58	0.56	0.75	20.00	0.44	*
Conqueror	107.75	0.04	0.01	0.08	20.00	0.44	
Cordiale	95.25	-0.07	0.01	0.12	20.00	0.44	
Crusoe	97.37	0.03	0.00	0.04	20.00	0.44	
Denman	101.72	-0.23	0.21	0.46	20.00	0.44	*
DSV-80113	99.83	-0.24	0.20	0.45	20.00	0.44	*
Duxford	100.08	0.04	0.01	0.07	13.00	0.55	
Einstein	92.53	-0.21	0.10	0.32	20.00	0.44	
Gallant	98.74	-0.40	0.29	0.54	20.00	0.44	*
Grafton	99.84	-0.42	0.34	0.58	13.00	0.55	*
Gravitas	105.91	-0.16	0.08	0.28	20.00	0.44	
Horatio	103.16	-0.12	0.07	0.26	20.00	0.44	
Invicta	103.22	0.04	0.00	0.06	20.00	0.44	
JB-Diego	104.15	-0.10	0.03	0.18	13.00	0.55	
Kingdom	94.38	0.01	0.00	0.02	20.00	0.44	
KWS-Podium	94.47	0.01	0.00	0.02	20.00	0.44	
KWS-Santiago	104.86	0.28	0.13	0.36	20.00	0.44	
KWS-Sterling	102.94	-0.04	0.00	0.06	20.00	0.44	
KWS-Target	98.05	0.04	0.01	0.08	20.00	0.44	
KWS-W174	97.71	-0.04	0.00	0.06	20.00	0.44	
KWS-W178	103.22	0.24	0.09	0.30	20.00	0.44	
KWS-W180	98.45	0.45	0.41	0.64	20.00	0.44	*
Oakley	107.67	-0.13	0.06	0.25	20.00	0.44	
Panorama	93.94	0.11	0.14	0.37	6.00	0.81	
RW40834	101.45	0.15	0.10	0.31	20.00	0.44	
RW40837	101.03	-0.07	0.02	0.16	20.00	0.44	
RW40847	101.86	0.06	0.01	0.12	20.00	0.44	
Scout	93.69	0.13	0.07	0.27	20.00	0.44	
Solstice	92.61	-0.04	0.01	0.10	20.00	0.44	
Stigg	101.38	-0.21	0.11	0.32	20.00	0.44	
SY-Epson	98.00	0.27	0.27	0.52	20.00	0.44	*
Tuxedo	104.24	-0.19	0.14	0.38	20.00	0.44	
Viscount	102.46	-0.07	0.02	0.16	20.00	0.44	
Warrior	102.01	-0.13	0.05	0.22	20.00	0.44	

Table A2. Soil texture classes for each trial site and the available soil water calculated for an effective rooting depth of 120 cm. *The soil texture is for the A horizon; subsoil texture may differ.

Trial Code	Site Abbrev	Total Available Water (mm)	Soil texture class*
AN108T	Nrthum	212.4	Silt loam
AN112T	Lincs1	164.2	Sandy loam
AS126T	Warwick	199.2	Sandy loam
AS129T	Somset	181.2	Silt loam
CA115T	Cambs	182.3	Silt loam
DL125T	Gloucs	181.2	Silt loam
EL119T	Lincs2	226.5	Silt loam
HA123T	Shrops	203.3	Sandy silt loam
HH106T	EYorks	185.7	Silty clay loam
IS127T	Hants	181.2	Silt loam
KW120T	Sufflk1	210.9	Sandy clay loam
KW124T	Leics	202.6	Silt loam
LM114T	Norfk	202.8	Silty clay loam
LM117T	Sufflk2	165.4	Sandy clay loam
MA121T	Essex	189.5	Clay loam
SH128T	Devon	226.0	Silty clay loam
SL116T	Sufflk3	166.3	Sandy clay loam
SU109T	Lincs3	202.2	Silty clay loam
SY111T	Lincs4	181.2	Sandy clay loam
WY122T	Kent	226.4	Silty clay loam

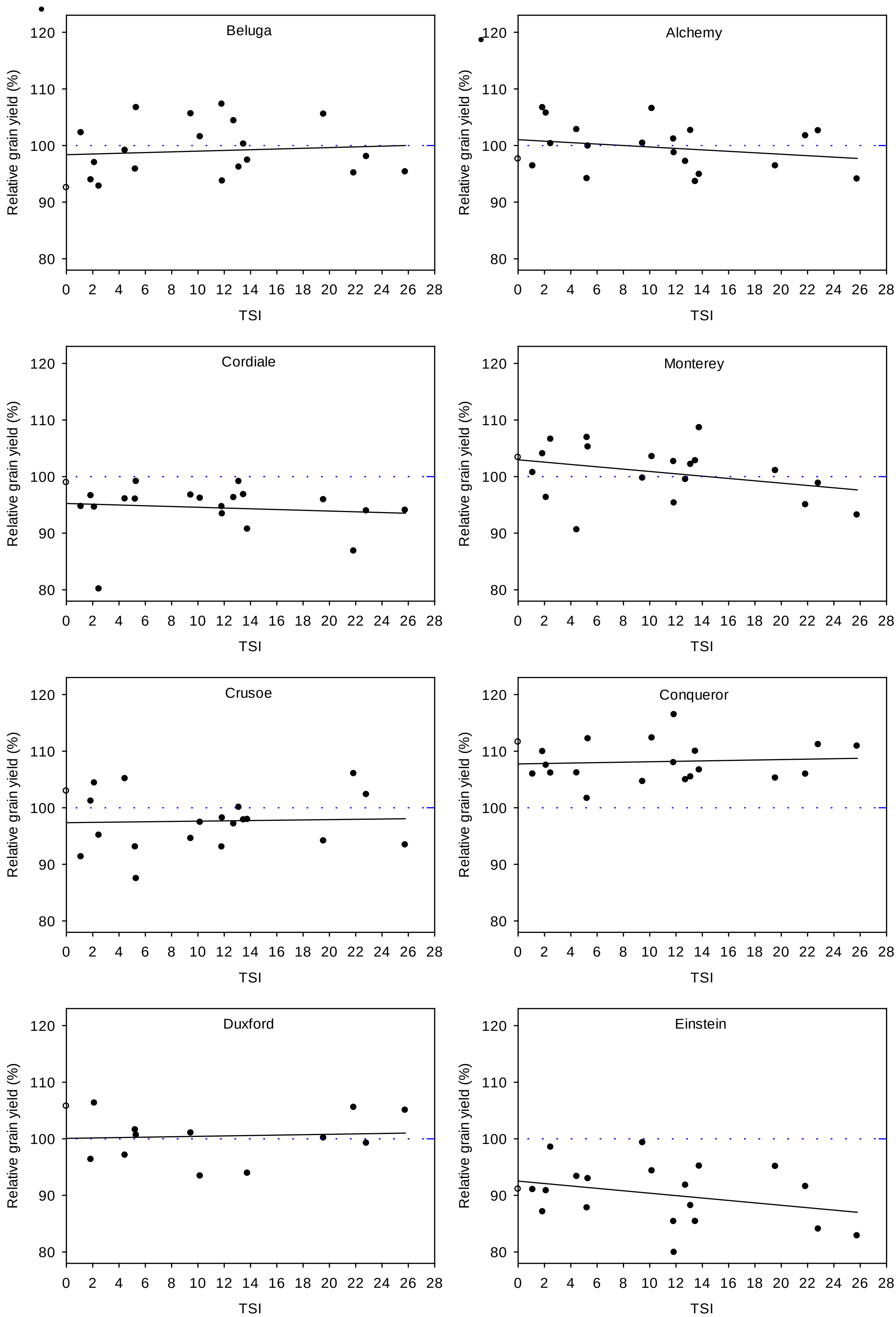

Figure A1. Regressions of relative yield against the transpiration-based stress index (TSI) for each test site in 2011. None of the regressions were statistically significant. Some varieties were tested only on 13 of the 20 sites.

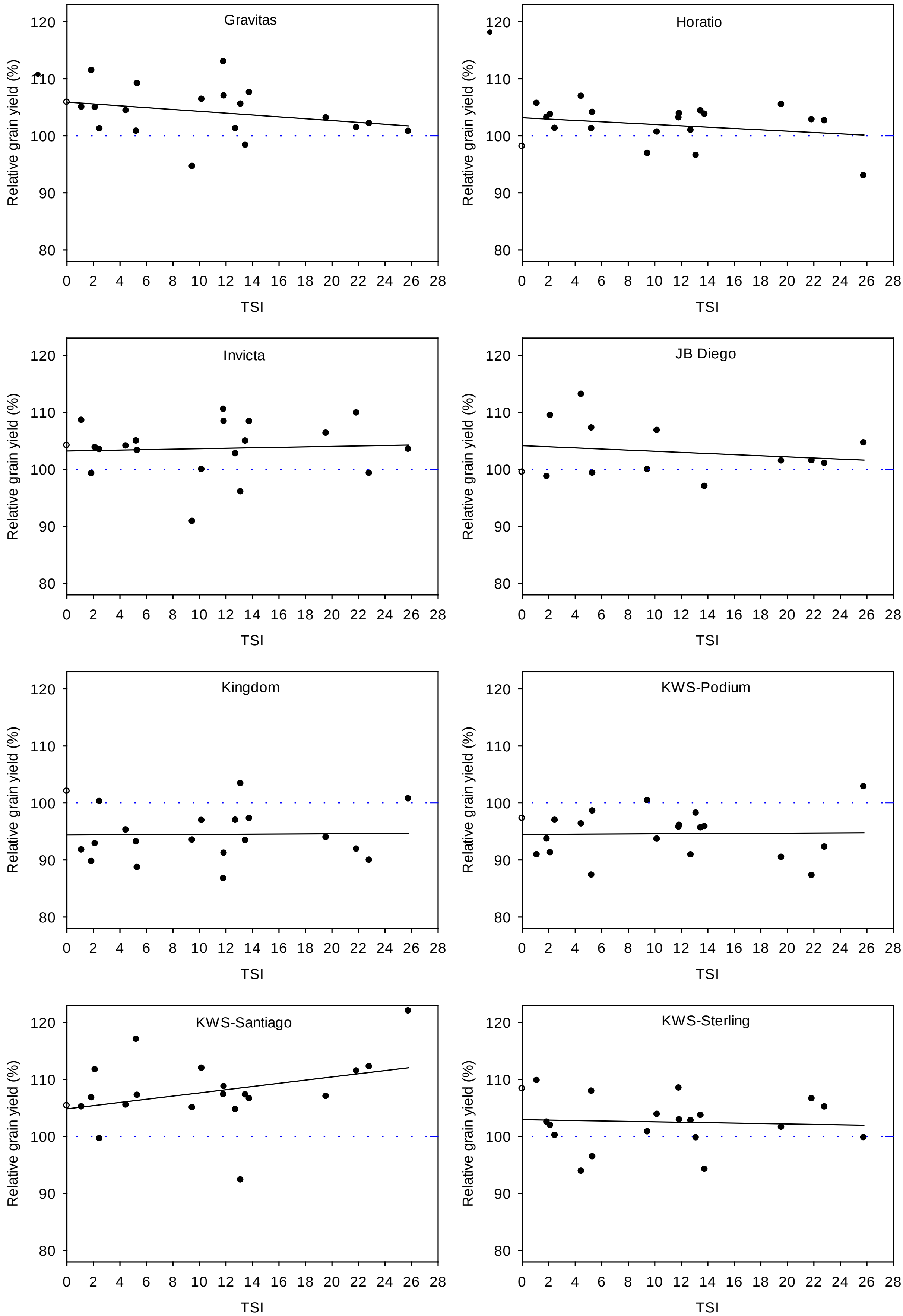

Figure A2, con't. Regressions of relative yield against the transpiration-based stress (TSI) index for each test site in 2011. None of the regressions were statistically significant. Some varieties were tested only on 13 of the 20 sites.

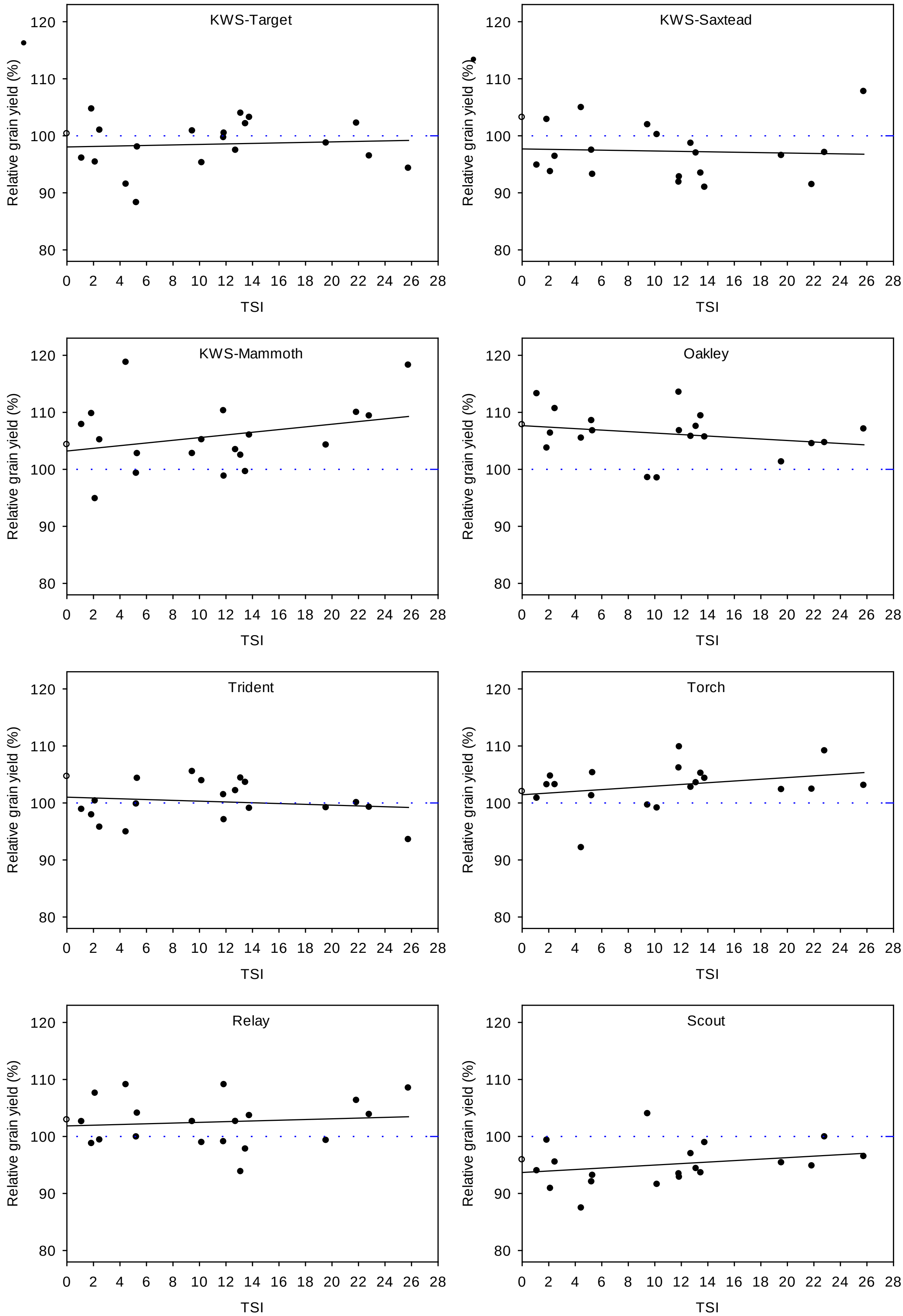

Figure A2,, con't. Regressions of relative yield against the transpiration-based stress index (TSI) for each test site in 2011. None of the regressions were statistically significant. Some varieties were tested only on 13 of the 20 sites.

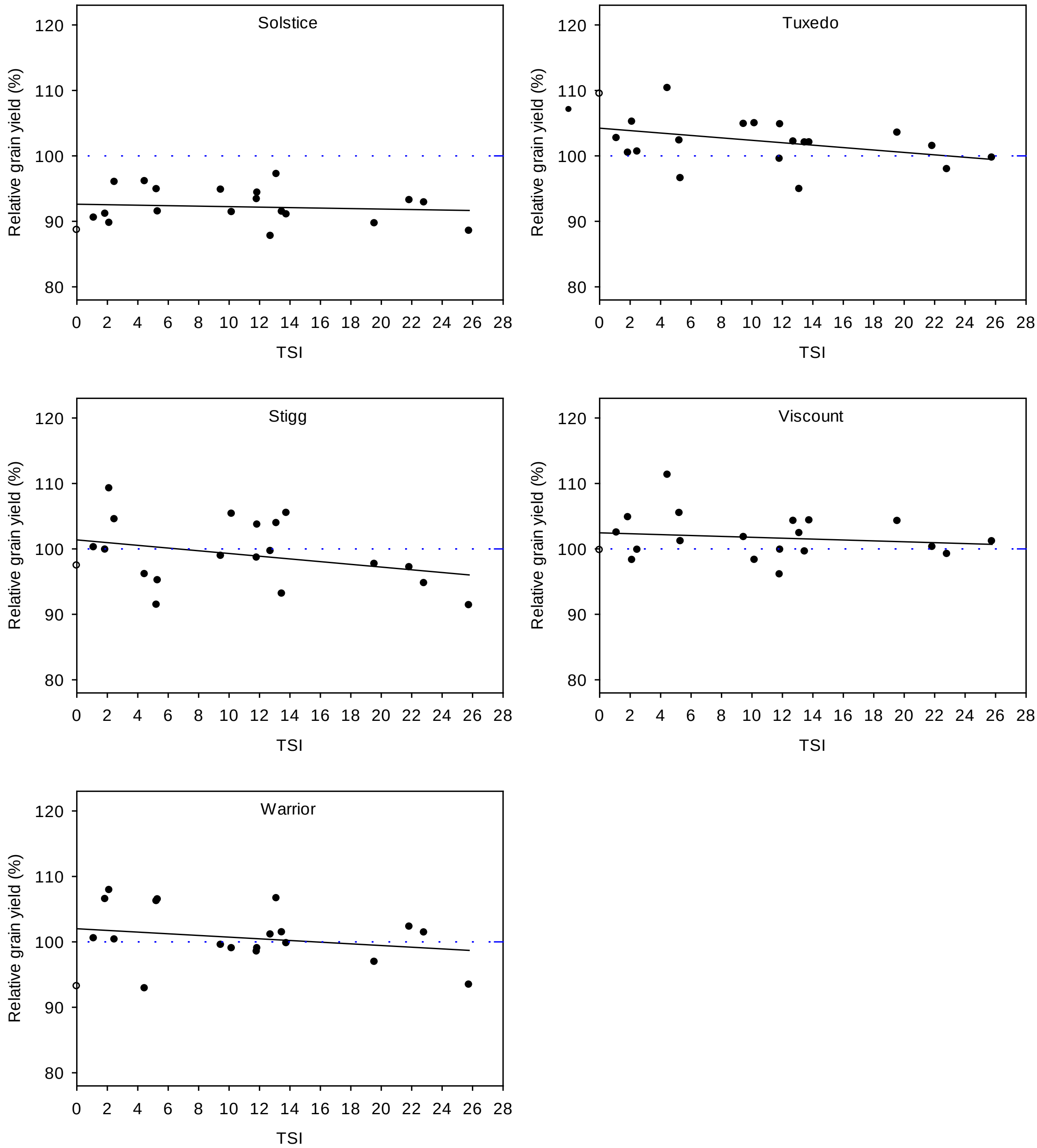

Figure A2, con't. Regressions of relative yield against the transpiration-based stress index (TSI) for each test site in 2011. None of the regressions were statistically significant. Some varieties were tested only on 13 of the 20 sites.

Table A3. A summary of different kinds of stability indices and their classification.

A Summary of different types of stability indices, according to categories described by Linn and Bin (1988).

- Type I: static
    - Stable variety does not change, even if yield potential of location changes
    - Biological stability
    - Examples: cv%, S_i^2
- Type II: dynamic
    - Response of stable variety is parallel to the mean response of all genotypes in the trial, according to expectations at each location
    - Agronomic stability
    - Examples: Shukla's σ_i^2; Finlay-Wilkinson b_i; Wricke's ecovalence W_i^2
- Type III: dynamic
    - Stable variety has small residual mean squares from the regression model on the environmental index
    - Tests goodness of fit to regression model
    - Example: Eberhart and Russel's s_d^2
    - Poor heritability
- Type IV: dynamic
    - Partitions predictable (locations) and non-predictable (years) non-genetic variation (e.g. Lin & Binn's $S_{y \times l}^2$)

1. Fera Survey: Materials and methods

1.1 Defra Winter Wheat Survey Data

The annual survey was undertaken on 300 winter wheat crop samples from fields selected at random from a list of farms stratified by region and arable area size from annual returns to Defra Census Branch. Farmers were contacted in late spring to confirm their participation and to select a single wheat crop on each farm for assessment. Crops were sampled at GS73–75 (July) by collecting 50 fertile tillers at random from a diagonal transect of the field. Samples were collected by ADAS and TAG and sent to The Food and Environment Research Agency (Fera) for assessment. Field scale assessments were made in the field at the time of sample collection. A questionnaire was used to obtain details of cultivar, tillage practice, sowing date, previous cropping and pesticide use.

In 2011, the survey was extended to collect information on the effects of drought on crops following the severe lack of rainfall in spring/summer 2011. At the field scale, each crop was assessed for incidence of stunting and senescence, and in the laboratory a sub-sample of 25 plants was measured for plant height and visually assessed for degree of senescence, ear sterility and drought spotting.

All assessment and agronomic data were entered onto an Informix database, which holds all national survey data from winter wheat collected since 1970. Data were scrutinised for logical errors prior to entry and the electronic data were cross-referenced with the original paper records to check for transcription errors.

2. Results

Survey data were analysed to investigate the influence of variety and geographical location (weather factors and soil type) on degree of drought symptoms exhibited by wheat crops during 2011. The equivalent dataset from 2012 was used as a comparator.

2.1 Range of cultivars surveyed

Thirty-four different varieties of winter wheat were encountered during the 2011 survey and 9 varieties each accounted for at least 4% of the total samples surveyed (Fig. 1). Oakley was the most popular variety, accounting for 16% of the sample in 2011, and was the only variety present in all regions in 2011. The range of varieties encountered in the 2012 survey was very similar with the main trend being increases in popularity of Scout, JB Diego and Gallant and decline in popularity of the other main varieties.

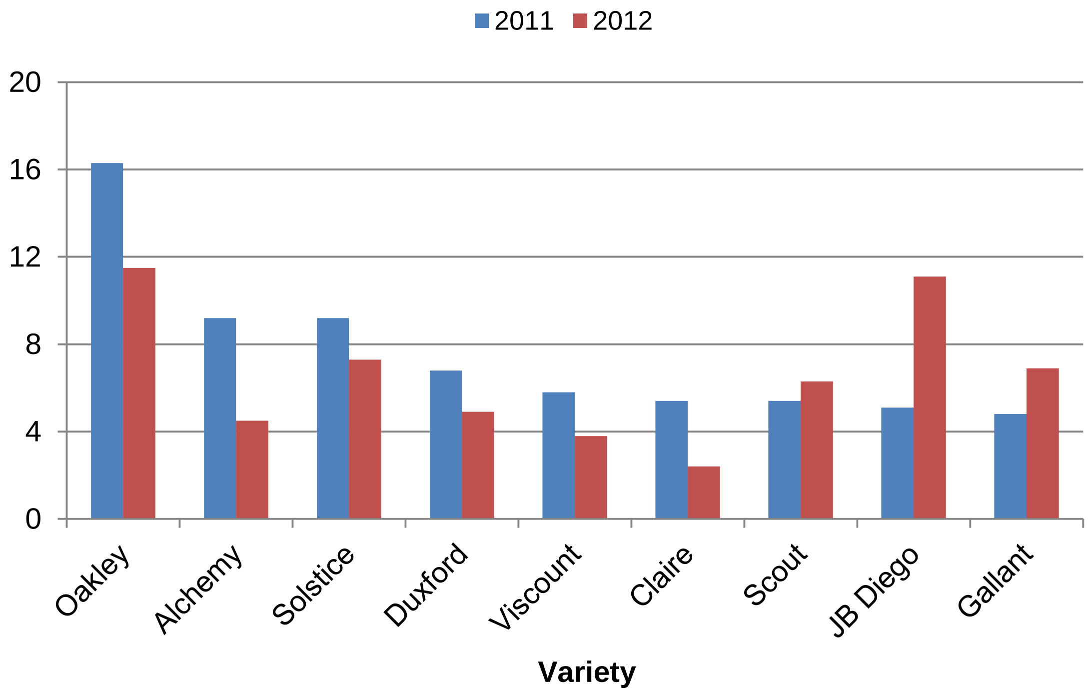

Figure 1. Popularity of varieties in 2011 and 2012 (% crops)

2.2 Effect of variety on drought symptoms

In-field assessments of symptoms of senescence and stunting showed that symptoms of drought were common across all varieties encountered in the survey in 2011, whereas they were almost completely absent in 2012 (Table *). Results indicated that the varieties which were the most severely affected by senescence were Battalion, Solstice, Gallant and Hereward all with over 50% of crops affected. These four varieties also showed the highest prevalence of stunting symptoms with over 45% of crops affected within each variety. The least affected varieties were Einstein, Cordiale, Scout, JB Diego and Duxford. Within this group, Einstein showed the lowest incidence of symptoms with only 14% of crops affected compared to between 30 and 33% for the other four varieties and a national average of 45% of crops. Lowest levels of stunting were in Scout, Invicta, JB Diego and Cordiale with ≤30% of crops showing symptoms; also Einstein, where no symptoms of stunting were found in the seven crops surveyed.

Table *. Incidence of symptoms of drought stress (senescence and stunting) in different varieties* based on assessments in the field (2011 and 2012).

Variety	No. of crops 2011	% crops affected	
		Senes-cence	Stunting
Alchemy	25	48.0	48.0
Battalion	5	100.0	60.0
Claire	13	46.2.0	46.2
Cordiale	10	30.0	30.0
Duxford	15	33.3	40.0
Einstein	7	14.3	0.0
Gallant	12	58.3	50.0
Grafton	12	41.7	25.0
Hereward	11	54.5	72.7
Invicta	8	37.5	25.0
JB Diego	15	33.3	26.7
Oakley	41	46.3	46.3
Scout	16	31.3	25.0
Solstice	22	68.2	45.5
Viscount	17	41.2	29.4
National	**262**	**45.0**	**38.2**

* excludes varieties with < 5 crops within the survey

Variety	No. of crops 2012	% crops affected	
		Senes-cence	Stunting
Alchemy	11	0	0
Battalion	2	0	0
Claire	7	0	0
Cordiale	12	0	0
Duxford	13	0	0
Einstein	2	0	50
Gallant	18	0	0
Grafton	8	0	0
Hereward	5	0	0
Invicta	11	0	0
JB Diego	32	0	0
Oakley	26	0	0
Scout	17	0	0
Solstice	21	0	0
Viscount	11	0	0
National	**282**	**0.4**	**0.7**

Laboratory-based assessments of levels of senescence and stunting showed that an average of 28% of surveyed crops showed symptoms (Table *) of senescence compared to the in-field assessment which indicated that 45% of crops were affected. This reduction will be due to the difference in protocol and that the lab-based assessments were undertaken on a sub-sample of plants in each field. The laboratory assessments identified four varieties which showed the highest incidence of symptoms of senescence: Hereward, Invicta, Batallion and Grafton. Two of these varieties (Battalion and Hereward) were also indicated to be most severely affected in the in-field assessments. Einstein was least affected (11%), also as in the in-field assessment.

Ear sterility symptoms affected 8 of the 15 main varieties with an average of 5.7% of crops affected nationally. By far the worst affected was Hereward with 33% of crops showing symptoms.

Leaf spotting due to drought was not a common symptom affecting only four of the main cultivars in 2011 and only 4% of crops nationally.

In 2012 only one variety showed any symptoms associated with drought (Hereward).

Table *. Incidence of senescence, ear sterility and leaf spotting in different varieties* based on assessments in the laboratory (2011 and 2012).

	2011				2012			
		% crops affected				% crops affected		
Variety	**No. of crops**	**Senes-ecence**	**Ear sterility**	**Leaf spotting**	**No. of crops**	**Senes-ecence**	**Ear sterility**	**Leaf spotting**
Alchemy	27	14.8	3.7	7.4	10	0	0.0	0
Battalion	5	40.0	0.0	0.0	2	0	0.0	0
Claire	14	28.6	0.0	0.0	6	0	0.0	0
Cordiale	11	27.3	9.1	9.1	13	0	0.0	0
Duxford	20	25.0	5.0	0.0	13	0	0.0	0
Einstein	9	11.1	0.0	0.0	2	0	0.0	0
Gallant	14	21.4	7.1	0.0	18	0	0.0	0
Grafton	14	35.7	0.0	7.1	8	0	0.0	0
Hereward	12	58.3	33.3	0.0	5	0	20.0	0
Invicta	8	50.0	0.0	0.0	11	0	0.0	0
JB Diego	15	33.3	0.0	6.7	30	0	0.0	0
Oakley	48	31.3	2.1	0.0	26	0	0.0	0
Scout	16	18.8	12.5	0.0	18	0	0.0	0
Solstice	27	29.6	7.4	0.0	20	0	0.0	0
Viscount	17	17.6	0.0	0.0	11	0	9.1	0
National	**297**	**27.9**	**5.7**	**4.0**	**279**	**0**	**0.72**	**0**

* excludes cultivars with < 5 crops within the survey

Results of measurements of crop height in 2011 showed that the average height of the crops surveyed in 2011 was 73.9 cm compared to 83.5 cm in 2012, a difference of almost 10 cm (Tables * and *). Average height of all the main varieties in 2011 was also reduced when compared to data from the HGCA Recommended lists on crop height for individual varieties without PGR. Crop heights for the main varieties were reduced by an average of 17% compared to the RL data with averages ranging from 13.5% to 20.4%. The least affected varieties were Invicta (13.5%), Grafton (14%) and Cordiale (15.1%) and the most severely affected were Hereward (20.4%), Gallant (20%) and Viscount (20%).

Table *. Average height, height maxima and minima in different varieties* based on assessments in the laboratory (2011).

2011					
	Crop height (from HGCA RL (2010/11))	**Average crop height**	**Reduction in height (%)**	**Max height**	**Min height**
Alchemy	95	78.0	17.9	98	61
Battalion	88	71.6	18.6	81	63
Claire	92	77.0	16.3	87	67
Cordiale	83	70.5	15.1	90	43
Duxford	94	75.4	19.8	92	54
Einstein	89	74.0	16.9	81	60
Gallant	86	68.8	20.0	81	61
Grafton	80	68.8	14.0	81	58
Hereward	89	70.8	20.4	80	54
Invicta	93	80.4	13.5	100	64
JB Diego	92	75.3	18.2	86	55
Oakley	88	71.0	19.3	88	56
Scout	91	75.9	16.6	87	65
Solstice	97	78.0	19.6	98	63
Viscount	85	68.0	20.0	79	54
National	**89.47**	**73.9**	**17.4**	**100**	**43**

* excludes varieties with < 5 crops within the survey

In 2012, crops were also reduced in height compared to the RL data, with an average of 5.9% reduction across the main varieties (Table *). Grafton was the only variety to show an increase in height compared to the RL data. Varieties showing the highest reductions were Solstice (15.9%) and Claire (10.4%) whereas Einstein (2.3%), Alchemy (4.6%), Scout (4.8%) and Cordiale (5.1%) showed the lowest reductions.

Table *. Average height, height maxima and minima in different varieties* based on assessments in the laboratory (2012).

2012					
	Crop height (from HGCA RL (2011/12)	**Average crop height**	**Reduction in height (%)**	**Max height**	**Min height**
Alchemy	95	90.6	4.6	101	79
Battalion	87	79.0	9.2	84	74
Claire	91	81.5	10.4	94	76
Cordiale	82	77.8	5.1	88	69
Duxford	93	83.8	9.9	96	72
Einstein	88	86.0	2.3	92	80
Gallant	86	80.4	6.5	89	73
Grafton	79	85.1	-7.7	98	73
Hereward	89	82.6	7.2	90	75
Invicta	93	87.0	6.5	99	75
JB Diego	91	85.8	5.7	100	69
Oakley	87	80.7	7.2	90	69
Scout	90	85.7	4.8	98	72
Solstice	96	80.7	15.9	93	67
Viscount	84	77.4	7.9	87	67
National	**88.73**	**83.5**	**5.90**	**125**	**64**

* excludes varieties with < 5 crops within the survey

2.3 Regional variation in drought effects on wheat in 2011

There were strong regional differences in the percent crops affected by senescence and/or stunting in 2011. Highest incidence of senescence occurred in crops in the East with 68% of crops affected compared to a national average of 45% (Table *). Similarly the highest incidence of stunting was also in the East with 63% of crops affected compared to the national figure of 38%. The lowest incidence of drought symptoms was in the North East with only 13% of crops affected.

Table *. Regional incidence of symptoms of senescence and stunting in wheat crops based on assessments in the field (2011 and 2012)

Region	**No. of crops**		**% crops affected Senescence**		**% crops affected Stunting**	
	2011	**2012**	**2011**	**2012**	**2011**	**2012**
North East	8	12	12.5	0	0.0	0
North West	7	7	42.9	0	28.6	0
Yorks & Humberside	35	36	45.7	0	5.7	0
East Midlands	51	55	27.5	0	27.5	0
West Midlands	27	27	55.6	0	59.3	0
East	62	75	67.7	0	62.9	2.7
South East	38	38	23.7	0	34.2	0
South West	34	32	52.9	3.2	41.2	0
National	**262**	**282**	**45.0**	**0.4**	**38.2**	**0.7**

Assessments of senescence and stunting in crop samples in the laboratory showed highest levels of senescence were in samples from the East with 46% of samples affected compared to a national average of 28%. Lowest incidence of these symptoms was found in crops from the South West and West Midlands. Incidence of ear sterility was highest in the North West and West Midlands. There was a clear regional difference in the incidence of leaf spotting due to drought with most of the affected crops being in the North of the country.

Table 3. Regional incidence of senescence, ear sterility and drought spotting in surveyed crops based on assessments in the laboratory (2011 and 2012)

Region	No. of crops 2011	No. of crops 2012	Senescence - % crops affected		Ear sterility - % crops affected		Drought leaf spotting - % crops affected	
			2011	2012	2011	2012	2011	2012
North East	12	12	25.0	0	0.0	0.0	33.3	0
North West	7	7	28.6	0	14.3	0.0	28.6	0
Yorks & Humberside	41	38	26.8	0	0.0	5.3	7.3	0
East Midlands	56	57	23.2	0	7.1	0.0	1.8	0
West Midlands	28	25	14.3	0	10.7	0.0	0	0
East	81	76	46.9	0	6.2	0.0	1.2	0
South East	39	35	23.1	0	7.7	0.0	0	0
South West	33	29	9.1	0	3.0	0.0	3	0
National	**297**	**279**	**27.9**	**0**	**5.7**	**0.7**	**4.0**	**0**

As a regional comparison, the ranges of crop heights were less variable than for comparisons across varieties. On average the tallest crops were in the South West, North West and Yorkshire and Humberside and the shortest in the East and North East.

Table *. Regional averages, maxima and minima for crop height of surveyed wheat based on assessments in the laboratory (2011 and 2012)

Region	No. of crops 2011	No. of crops 2012	Average crop height		Max crop height		Min crop height	
			2011	2012	2011	2012	2011	2012
North East	12	12	70.2	86.2	84	98	61	75
North West	7	7	76.3	84.4	88	98	65	74
Yorks and Humberside	41	38	76.5	86.6	100	102	58	67
East Midlands	56	57	74.9	83.1	98	100	60	65
West Midlands	28	25	74.3	87.8	87	100	62	78
East	81	76	70.5	80.4	90	100	54	64
South East	39	35	71.6	79.5	94	92	43	69
South West	33	29	80.2	87.7	98	125	62	73
National	**297**	**279**	**73.9**	**83.5**	**100**	**125**	**43**	**64**

The regional differences in symptoms of drought were investigated in more depth by aligning the data from the survey with information on soil drainage categories. Each of the 300 locations where crops had been sampled were overlaid onto a soil drainage map (Figure *) to assign a soil drainage category to each survey data point. Data were analysed to determine the incidence of symptoms of drought on crops grown on soils of differing drainage categories. Analyses show that symptoms of senescence were most prevalent in crops on soils which had impeded drainage and lowest on crops on soils which were freely draining (Figure *). This is opposite to what might have been expected in a drought year where freely draining soils would be the most affected by lack of rainfall. Data on tiller height indicates that the tallest crops were found on the naturally wet soils which would have been most resilient to water loss during the drought (Figure *).

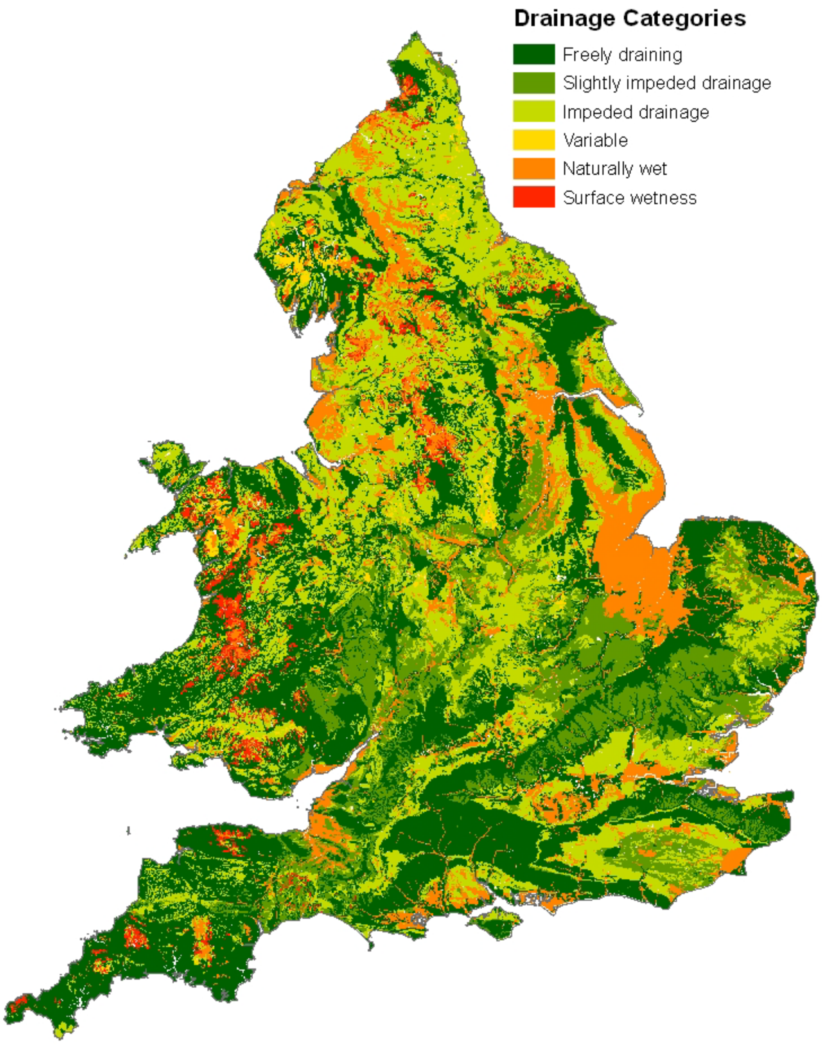

Figure *. Map showing areas of differing soil drainage categories.

Source: The National Soil Map published by the National Soil Resources Institute at Cranfield University.

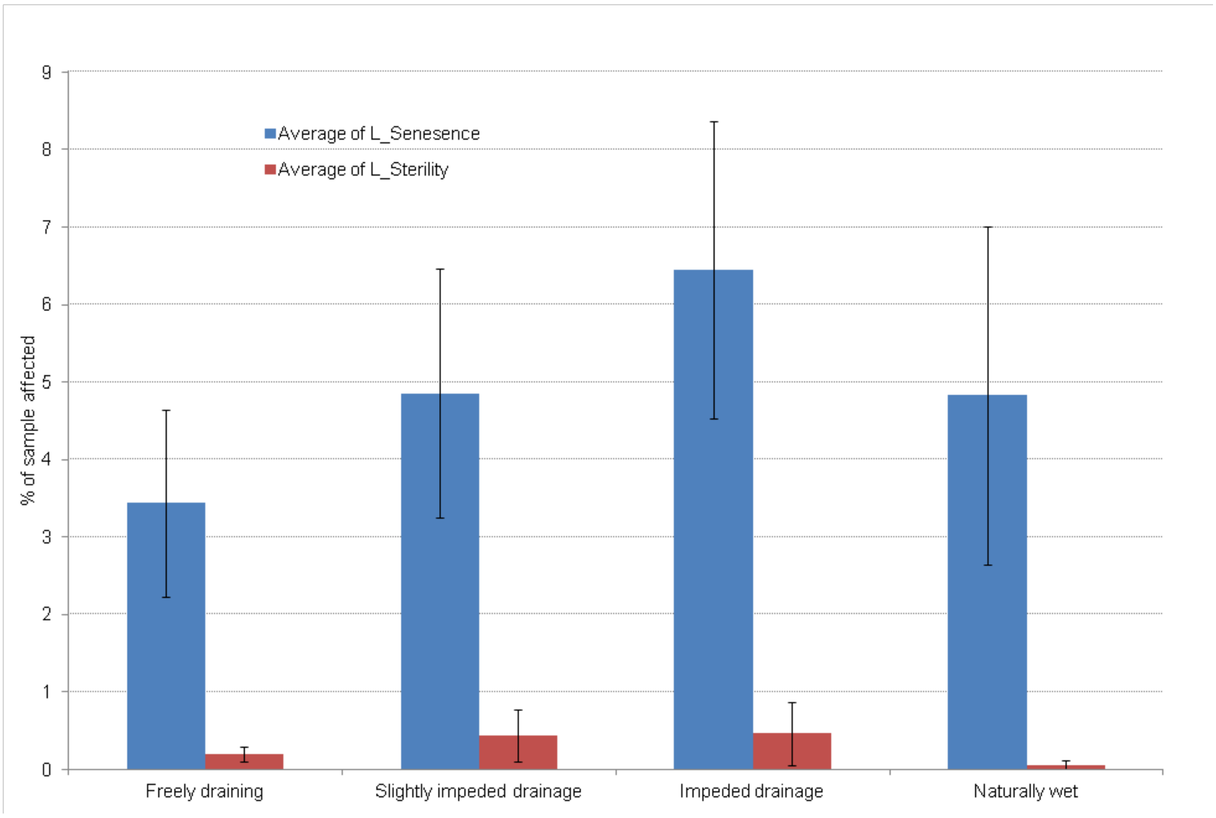

Figure *. Incidence of drought symptoms in wheat grown on different soil types

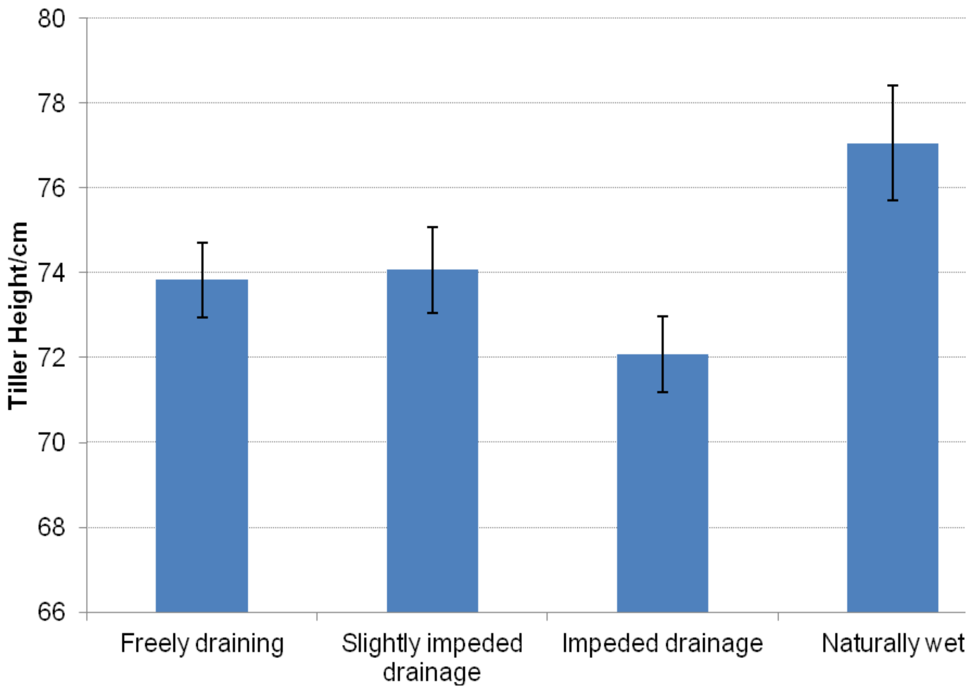

Figure *. Tiller height wheat crops grown on different soil types

3. Discussion

The results from analyses of the survey data indicate that there was considerable variation across the varieties in their response to drought conditions. Although the analyses are based on data from a fully stratified survey of 300 crops, it is often difficult to pinpoint trends in these data based on information from a single year. However, there were varieties which were identified which expressed significant symptoms of drought stress in 2011 (Battalion and Hereward) compared to the national average, and those that were much less affected (Einstein).

On a regional basis, the data show that crops in the East of England were most significantly affected by drought symptoms but this was not well correlated with degree of soil drainage.