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Analysis of the genetic and environmental factors influencing grain quality of oats to meet end-user requirements and increase grower returns

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CONTENTS

1. Abstract

Grain quality of oats is important to meet the requirements of the milling industry and to enhance the value of the crop for the grower. Developing oat varieties with high milling quality is constrained by a lack of detailed information on how genetic differences and environmental and management factors impact on grain quality. Focussing on key milling quality characters, i.e. specific weight, kernel content, hullability and thousand grain weight, four winter oat varieties (Gerald, Mascani, Tardis and Balado) were grown under conventional and organic regimes at six different geographical locations in 2012-13 and 2013-14. In addition, grain yields and oil, protein and β-glucan content of the groat were determined. The length, width, area, roundness and weight of the grain and groat, were measured using non-destructive methods. The influence of environment, management conditions and genetic differences on grain quality parameters, were determined. The results were statistically significant for grain and groat area, length and width, for both environment and genotypes (p-value <0.05). Grain yield however, were only significantly different between environments and not between varieties. Negative and positive correlations were found between grain size and shape with kernel content, hullability and thousand grain weight when studying each of the genotypes, showing the influence of grain and groat area (mm^2), length (mm) and width (mm), over each quality parameter. The variability found in this project, between environments, years and genotypes suggest that locally adapted varieties could perform better. Therefore, niche-matching varieties according to historical performance of local environments rather than overall performance of the variety would allow reaching higher grain quality parameters for end-users and milling industry requirements. Follow on investigations will examine the effect of nitrogen fertilisation on milling quality traits as well as using a mapping population to determine their genetic basis. The results obtained in this research will be used to develop new varieties for the milling industry, by the farmer to assess quality on farm prior to marketing and by the plant breeder in selection programs, where genetic improvements in milling quality may be made more precisely and rapidly than previously.

2. Introduction

One of the challenges for the cereal market, including the oat market, is to optimise grower returns whilst minimising environmental impact. Grain yield and quality contribute to the value of an oat crop to the producer. The most common quality measurement used is specific weight (also known as test or bushel weight). However, it is not a measurement related with any processing trait, and it is not good predicting milling yield (White et al. 2003). Other grain quality traits, i.e. kernel content, thousand grain weight, hullability and grain composition (β-glucan and protein and oil content), are highly desirable for the milling industry, human consumption and for animal feed but these traits are more laborious to measure.

As with other cereals e.g. wheat and barley (Hundal et al. 2017; Pushman & Bingham 2017; Ma et al. 2012; Clarke et al. 2004; Paroda & Hayes 1971; Lehmensiek et al. 2008), knowledge of genotype by environment effects on oat grain quality parameters is important for the understanding of the mechanisms underlying grain quality traits (Cooper 1937). However, previous studies have shown conflicting results, in terms of the effect that both, the genotype and the environment and their interaction have on grain quality traits (Doehlert 2001; Peterson et al. 2005). Therefore, while some results suggest that major variation in specific weight can be explained by variety choice, other researchers have found equal effects from both environment and genotype. These confounding results make it more difficult for the selection and development of new varieties.

To identify the variability that exists for grain quality parameters and yield across environments and years, historical data was obtained from the AHDB Recommended List trials between 2008 and 2013. This allowed the evaluation of the variety performance from standardised field trials at a range of locations across the U.K. (AHDB 2012). These trials are conducted independently each year at a range of sites that represent oat growing areas and are used to both identify superior new varieties and to provide data for users such as farmers to select suitable varieties for their purposes. Successful new varieties must not only have high grain yield and quality but also perform well over a wide range of environments.

The Recommended List for oat varieties, as shown in table 2.1, provides average values for specific quality parameters over six harvest seasons. These average values are obtained when possible, from each site where the AHDB is conducting trials however some trials and years are lacking some quality parameters measurements.

Table 2.1. *Mean yield (t/ha), grain quality and agronomic values of four winter oat varieties used in this research, from 2008 to 2013. Data extracted from Recommended List* (AHDB Cereals & Oilseed, 2008-13).

** = variety no longer in trial from 2012. C = yield control, Gerald from 2008 to 2013 and Mascani for 2012/2013 harvest season. All relative yields from 2008 to 2013 on this table are taken from treated trials receiving a full fungicide programme. On the 1-9 scales high figures indicate that a variety shows the character to a high degree (e.g. disease resistance). # The winter hardiness is measured on a scale where scores above 5 indicate only leaf damage and no plant death.*

Quality Traits	Tardis *	Gerald C	Mascani C	Balado
Scope of Recommendation	UK	UK	UK	UK
UK yield as % treated control (8.3 t/ha)				
Fungicide treated	103	99	99	105
Untreated with fungicide	96	89	95	101
Grain quality				
Kernel content (%)	73	73	78	73
Specific weight (kg/hl)	50	53	54	50
Screenings % through 2.0mm	0	1	0	1
Agronomic features				
Resistance to lodging	7	6	6	7
Straw length (cm)	111	119	117	100
Ripening (days +/- Gerald, -ve = earlier)	-2	-1	-1	-1
Winter hardiness #	8	8	7	8
Disease resistance				
Mildew	8	5	6	6
Crown rust	7	4		5
Year first listed	2007	1993	2004	2010
Treated yields with and without PGR as % treated control				
With PGR (8.2 t/ha)	101	98	98	106
Without PGR (8.1 t/ha)	*106*	*101*	*101*	*112*

The varieties listed in table 2.1 and 2.2 include the four winter oat genotypes from the Aberystwyth University winter oat breeding programme that will be under study in this chapter, i.e. Balado, Gerald, Tardis and Mascani. The data available included among others, grain yield, specific weight and kernel content. Due to the progression of old and new varieties onto and off the *Recommended List* (table 2.2), not all varieties were tested in all years and some missing data was present in the data supplied by AHDB. Therefore, a complete statistical analysis comparing both as factors was not conducted. Despite this, a graphical analysis was applied to the dataset.

Table 2.2. *Average values of lodging (%), height (cm) and ripening days, for the four winter oat varieties, Balado, Gerald, Mascani and Tardis from 2007 to 20013. Data extracted from Recommended List* (AHDB Cereals & Oilseed, n.d.). *N/A, data not available as variety not on Recommended List.*

	Lodging %				Height cm				Ripening Days			
Years	Balado	Gerald	Mascani	Tardis	Balado	Gerald	Mascani	Tardis	Balado	Gerald	Mascani	Tardis
2007	N/A	21.30	19.20	20.40	N/A	121.8	117.1	114.1	N/A	310.3	310.5	310.2
2008	3.30	33.30	33.30	33.90	87.4	110.9	99.7	98.7	292.0	290.7	286.0	288.0
2009	0.00	15.00	0.00	0.00	88.3	106.3	102.3	96.9	293.1	292.9	291.8	289.2
2010	0.00	6.70	3.70	3.00	97.9	120.5	115.5	109.5	312.4	312.4	312.0	311.8
2011	0.00	1.30	1.30	1.70	74.8	93.7	91.9	88.9	286.8	281.7	281.5	282.0
2012	0.60	2.80	0.00	N/A	102.1	119.3	116.9	N/A	317.5	317.2	315.8	N/A
2013	0.00	0.00	0.00	N/A	79.1	96.2	95	N/A	291.0	291.0	291.0	N/A

Although the overall performances of each of the varieties provides a guide to their quality, deconstructing the mean by year and variety, allows the variability between years and within years between sites (table 2.2) to be investigated. The mean for each variety on a yearly basis, regarding lodging (%), height (cm), are indicated in table 2.2, whilst yield (t/ha), kernel content (%) and specific weight (kg/hl) average by year and variety, are represented in the figures 2.1 to 2.6.

The average yield by year, from 2008 to 2013, for four winter oat varieties, Balado, Gerald, Mascani and Tardis is shown in figure 2.1. Although 2009 was the highest in terms of yield, both, specific weight (figure 2.2) and kernel content (figure 2.3), were not as high as in 2008. Mean yields and specific weights were lowest in 2012, whereas mean kernel content was highest in 2008. This variability, was found for all, spring and winter oat variety results from *Recommended List* trials (data not shown). Considerable variation between years was found for all traits reported.

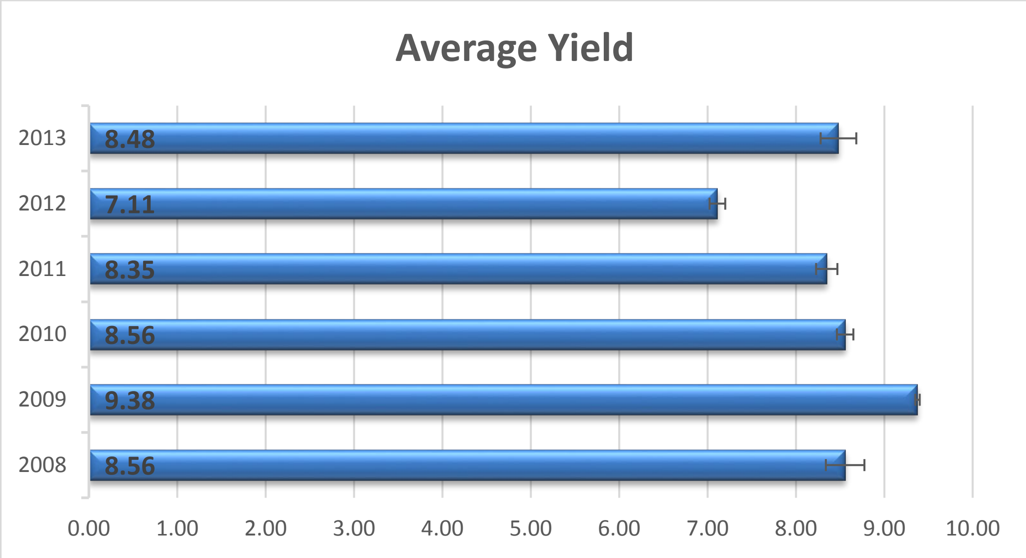


Figure 2.1. *Average yield (t/ha) ± s.e.m. value by year for the four winter oat varieties shown in table 2.1. Data from historical reports of Recommended List trials. AHDB personal communication.*

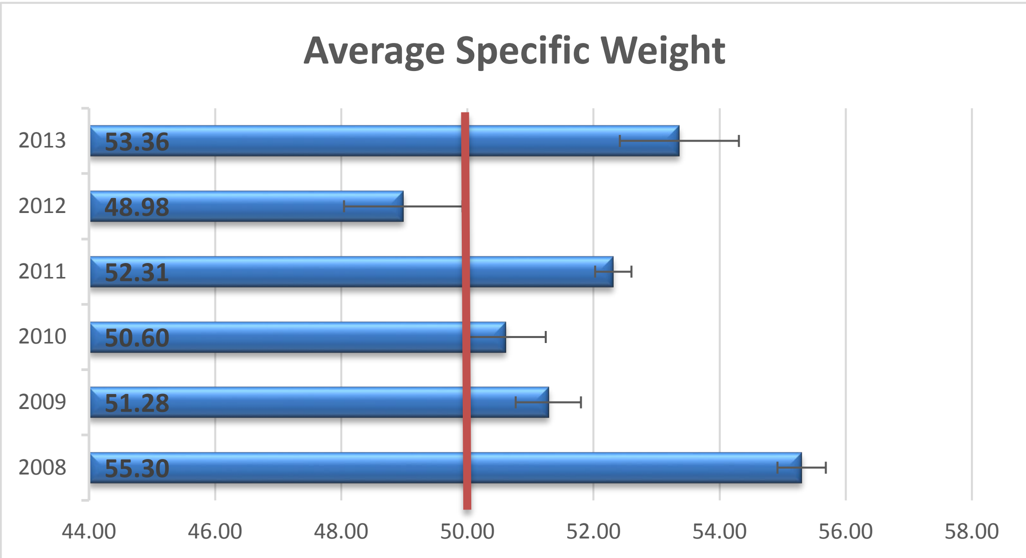


Figure 2.2. *Average Specific Weight (kg/hl) ± s.e.m., for four winter oat varieties, Balado, Gerald, Mascani and Tardis, from 2008 to 2013. The red line represents the minimum value for a variety to be included on the Recommended List at the time of testing (50 kg/hl). Data from historical reports of Recommended List trials. AHDB personal communication.*

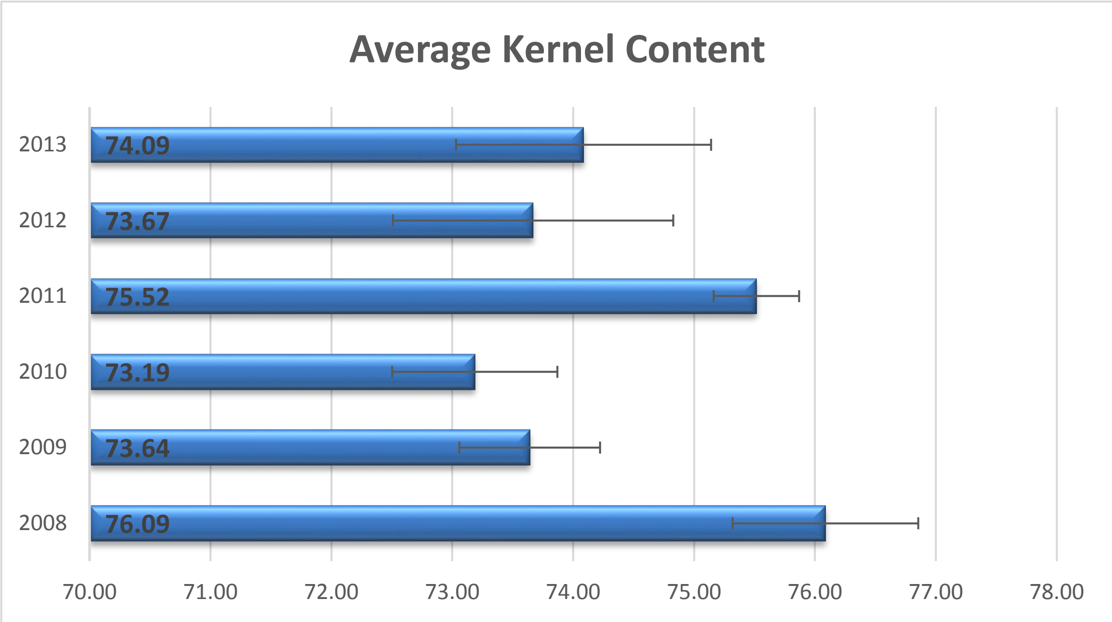


Figure 2.3. *Average kernel content (%) ± s.e.m., for four winter oat varieties, Balado, Gerald, Mascani and Tardis, from 2008 to 2013. Data from historical reports of Recommended List trials. AHDB personal communication.*

Figure 2.4 shows the median grain yield of specific varieties from 2008 to 2013 where it can be seen that are quite similar between varieties. This stability might be explained given the complexity of this trait, with more than a single model explaining its components (Adams & Grafius 1971). Both, specific weight, (figure 2.5) and kernel content (figure 2.6) were, graphically speaking, different between the four varieties. For a variety to be added to the *Recommended List,* it must meet certain criteria including a minimum specific weight of 50 kg/hl (red line figure 2.5). Balado presented the highest levels of variability in terms of specific weight, with values below market specifications in 2010 and 2012, despite having a good yield in almost all years. Tardis showed a similar performance with the specific weight average values falling below 50 kg/hl in 2009 and 2010, but a more consistent outcome in terms of kernel content and yield was found. Mascani and Gerald were more consistent between years and were above the minimum required for all traits under study.

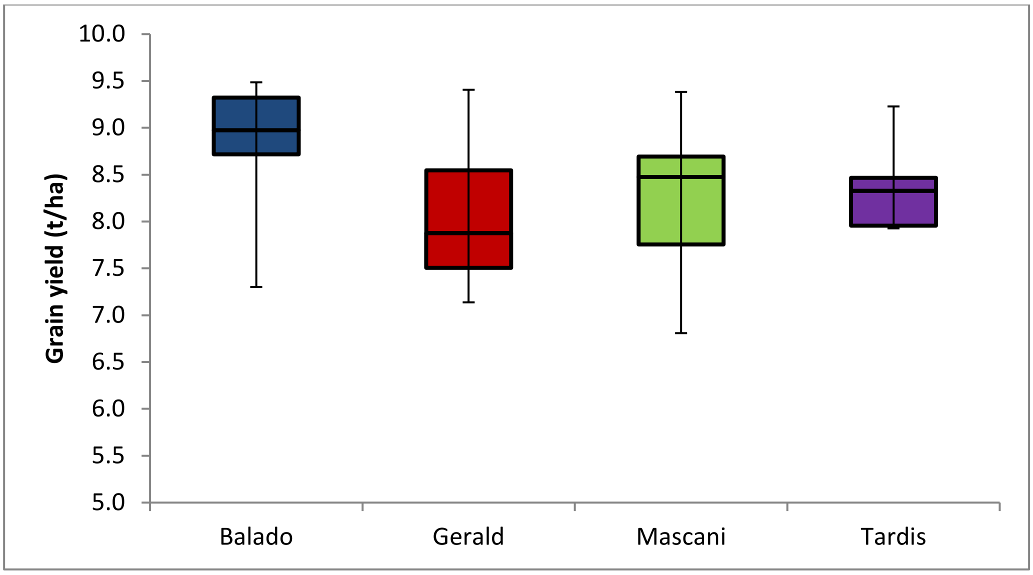


Figure 2.4. *Box plot of yield (t/ha) values of four winter oat varieties, Balado, Gerald, Mascani and Tardis, from 2008 to 2013 historical data reports (AHDB personal communication). The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data 75 %, with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile.*

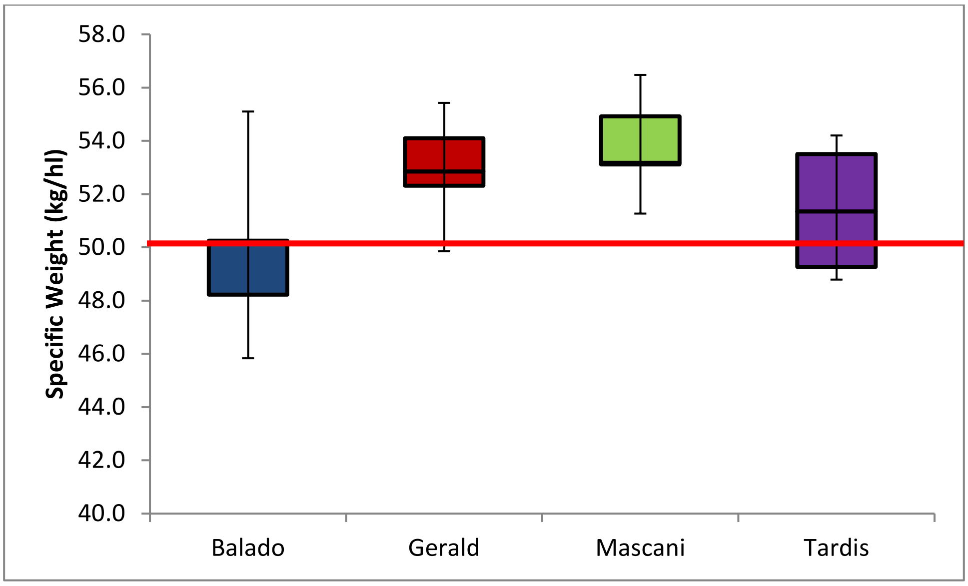


Figure 2.5. *Box plot of specific weight (kg/hl) values of four winter oat varieties, Balado, Gerald, Mascani and Tardis, from 2008 to 2013 historical data reports (AHDB personal communication). The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data 75 %, with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile.*

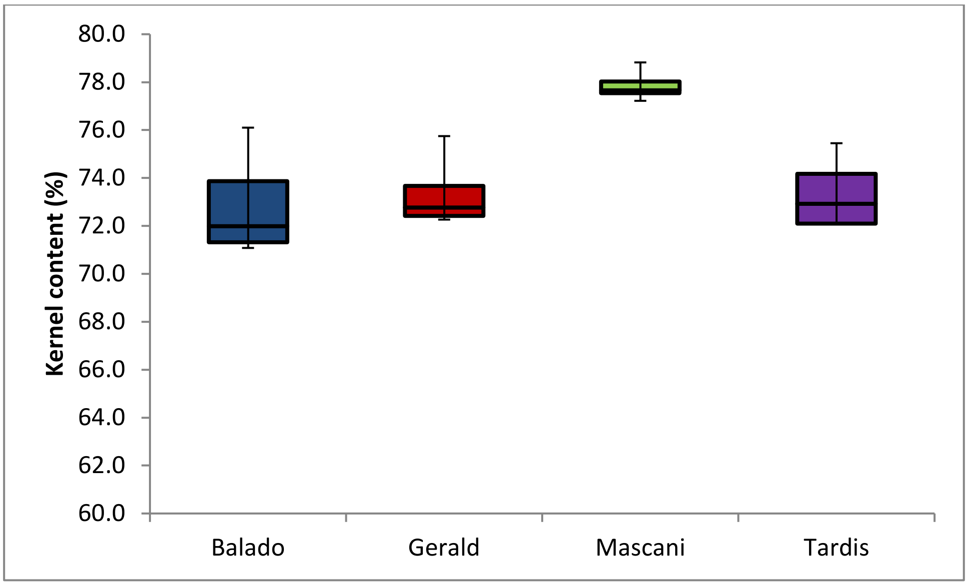


Figure 2.6. *Box plot of kernel content (%) values of four winter oat varieties, Balado, Gerald, Mascani and Tardis, from 2008 to 2013 historical data reports (AHDB personal communication). The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data 75 %, with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile.*

The variability in grain quality that is evident in figures 2.4 and 2.5, might be explained by both genetic differences between varieties and their interactions with the environment. Having established that considerable variation for grain quality traits is present not only between varieties but also across years, this chapter describes the results from multi-site replicated field trial across the major areas of oat production in the United Kingdom (figure 2.7) using the four varieties indicated in table 2.1 and 2.2.

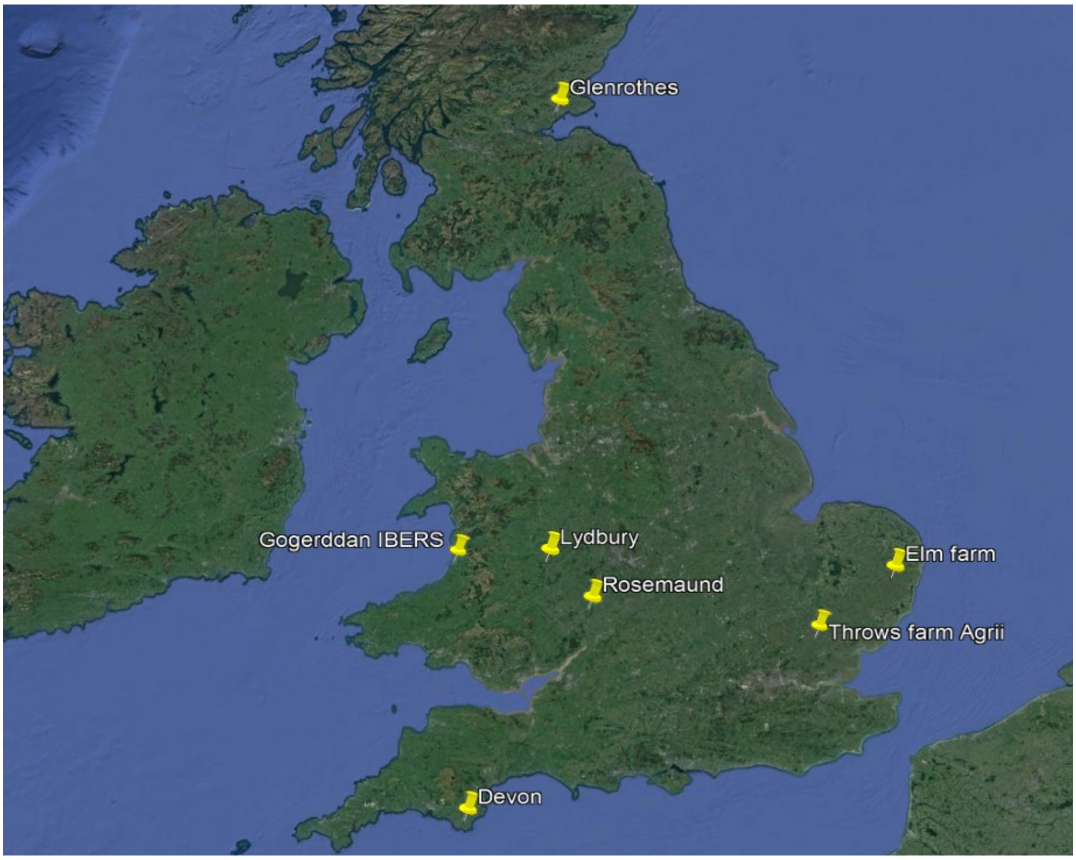


Figure 2.7. *Sites across the country where field trials were in 2012-2013 and 2013-2014 harvest seasons.*

A clear knowledge and understanding of the relationship between the genetic factors and the environment will benefit variety selection methods in breeding programs. This knowledge could have an important economic impact on the milling industry, accelerating selection methods of variety breeding, and focus on grain quality traits through the development of new and more suitable varieties of oats. For arable producers, it will help to develop agronomic practises that maximise the use of land and while diminishing the environmental impact, without comprising grain quality.

The objective of this study was first, to establish the genetic differences between varieties and the effect of different environmental growing sites on grain quality parameters and yields. Secondly, to determine whether there are genetic and environmental interactions for the grain quality traits under study. Thirdly, to determine whether there is any kind of relationship between grain quality parameters. And fourth, to investigate the physical basis that determines grain quality parameters through grain and groat size and shape dissected by the non-destructive analysis of grain.

3. Materials and methods

Details of field trials

The four winter oat varieties were grown in replicated field trials at 7 sites across the United Kingdom (figure 2.7, table 3.3) over two harvest years (2012/2013 and 2013/2014). Sites were chosen to represent contrasting environmental conditions within the UK and included the geographical areas where oats are grown in arable rotations.

Table 3.3. *Site codes, longitude and latitude, site codes, sowing dates and harvest dates at each site. The site codes were assigned to identify, graphically, the site within each year where samples were taken to analyse for the present research.*

Site	*Site code*	*Longitude/ Latitude*	*Year*	*Sowing date*	*Harvest date*
Gogerddan	1	-4.02/52.43	2013	23/10/2012	18/8/2013
Glenrothes	2	-3.11/56.19	2013	02/10/2012	14/8/2013
Devon	3	-3.76/50.27	2013	20/10/2012	13/8/2013
Rosemaund	4	-2.39/52.09	2013	06/02/2013	03/9/2013
Elm farm	5	1.35/52.36	2013	16/10/2012	24/8/2013
Gogerddan	6	-4.02/52.43	2014	25/09/2013	24/7/2014
Lydbury	7	-2.94/52.45	2014	08/10/2013	20/8/2014
Glenrothes	8	-3.11/56.19	2014	26/09/2013	04/8/2014
Devon	9	-3.76/50.27	2014	07/10/2013	31/7/2014
Rosemaund	10	-2.39/52.09	2014	30/09/2013	31/7/2014
Throws farm	11	0.41/51.58	2014	05/10/2013	22/7/2014

Each trial included at least three replicate plots (1.8 x 6 m) of each variety, sown in a randomised block design, planted at a sowing rate of 300 seeds/m^2 except for the Elm farm 2013 (site 5), where a sowing rate of 425 seeds/m^2 was used. Winter oats were sown between September and October at all sites except for Rosemaund at 2013. At this site, a particular wet autumn in 2012 led to a very wet soil preventing earlier sowing. Fertiliser application to the seedbed and top dressing applied was according to established conventional management protocols used for Recommend List testing of varieties in the UK considering previous crop, type of soil and levels of nitrogen present in the soil ("Section 4 Arable crops Nutrient Management Guide (RB209)," 2016) except for site 5. Site 5 was grown at an organically managed site as described in Fradgley *et al.,* 2017 (Gibson et al. 2007) with no synthetic chemicals, i.e. pesticides and fertilizers, applied. Nutrient levels in the soil, were established by growing grass and clover for three years and then ploughing it in to the soil. Semi-natural and boundary vegetation, i.e. hedges and field margins, and a crop-weed competitive interaction was also stablished as a mechanism to avoid herbicide use against weeds as in conventional management conditions.

Grain from each replicate at each site was harvested using a combine and subsampled for analysis in this study. Traits measured included specific weight (t/hl), kernel content (%), hullability (%), thousand grain weight (g), yield (t/ha), grain number, oil, protein and *β-glucan* content (%), and grain and groat size and shape.

Statistical analysis

The mean and the standard error of the mean of each trait were calculated for each variety at each site along with the overall mean for each site, by harvest season. The statistical methods were chosen to be suitable to study an unbalanced experimental design where the number and location of sites used for field trails may differ between seasons. These included: two-way ANOVA with variety and site as factors, to determine the significance of both and Pearson´s correlations between all traits under study, by both site and variety.

To evaluate the stability of a genotype across environments, a number of different indices were compared, including joint regression analysis (Finlay & Wilkinson 1963). In this analysis a modified joint regression was performed on data classified by two factors, i.e. variety and environments, at which experiments were grown. The regression, following therefore, a non linear model (equation 1), characterizes the sensitivity or inversely, the stability, of each variety to environmental effects.

$$y_{ij} = v_i + b_i \; x \; e_j + error \qquad (1)$$

where v_i are variety means, e_j are environment effects and b_i are the sensitivity parameters or the slope of the regression.

The analysis fits a regression of the environment means for a variety on the average environment means. The regression slope (b_i) describes the general response pattern among all cultivars. When b_i is less than 0.7 means that the cultivar is better adapted to low-yielding locations, whilst b_i above 1.3 means that the cultivar is better adapted to high yield locations. Therefore, high values of b_i reflects high sensitivity to the environment whereas low values of b_i indicate that a variety is less affected by the environment.

In addition, three non-parametric measures were calculated to determine the effect of genotype, environment and their interaction, i.e. cultivar superiority and static stability, and sensitivity (Huehn 1990). This enabled the assessment of the stability of each variety for all the traits under study and to determine the existence of local adaptation.

Cultivar superiority (*P*) (equation 2) (Lin & Binns 1991a; Lin & Binns 1991b). It measures the mathematical distance, i.e. difference, between the cultivars response and the maximum response averaged over all locations. The maximum response is the upper boundary in each location, therefore, small values imply the closeness of the trait for the corresponding genotype to the maximum and therefore, a superior overall response.

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

Where P_i represents the superiority measure of the i_{th} test cultivar, X_{ij} represents the yield of the i_{th} cultivar grown at the j_{th} location and M_j is the maximum response among all cultivars in the j_{th} location. It can be defined as the mean square of the difference between the i_{th} cultivar and the maximum responses. Since P_i is measured over all locations, it represents superiority in the sense of general adaptability.

Static stability (Lin & Binns 1991a; Lin & Binns 1991b) defines a stable genotype as one that possesses an unchanged performance regardless of any variation of the environmental conditions, i.e. its variance between its means in the various environments is zero. It provides a measure of the consistency of the genotype, but without taking account of how good it is.

When looking at the non parametric stability parameters mentioned above, and joint regression sensitivity values, the mean deviations for the observations about the line fitted for each genotype were also considered. A genotype with smaller mean square deviations gives the more predictable responses (Finlay & Wilkinson 1963).

The relative performances of each cultivar at each site was also determined by removing the effect of the environment. This was done by subtracting the mean over all genotypes at each site from the mean of each genotype at that site. This allows a graphical representation of the relative performance of the genotypes at each site, removing environment variation, and therefore, enables to see which environments really discriminate between genotype performances.

To complete the analysis, the bimodality of the individual grain size traits was determined following frequency distribution analysis. Grain size parameters were considered mixture of two normal distributions (Symons & Fulcher 1988). A MATLAB script (MathWorks 2013) was used to find the maximum likelihood estimation of means and variances of each distribution. In addition to the mean grain length, width and area of each sample, the individual grain and groat data were analysed to establish the frequency of the distribution of the grain population according to those dimensions. Where appropriate, this included determination of the bimodality of the population of grains analysed. Grain and groat size parameters were considered mixture of two normal distributions.

$$d = v \int_{npd} (\mu_1, \sigma_1) + (1 - v) \int_{npd} (\mu_2, \sigma_2) \qquad (3)$$

Where μ is the mean and σ the standard deviation of the normal probability density function ($\int_{npd}$) for the component distributions (subscripts 1 and 2) and v is the proportion in population 1 (Wychowaniec et al. 2013).

The bimodal distribution was fitted iteratively with initial values for μ_1 and μ_2 set to 25% (μ_1) and 75% (μ_2) quartiles of the overall distribution of grain size (x). Initial values for σ_1 and σ_2 were both set to $\sqrt{}$ *(var (x) – 0.25($\mu_1 - \mu_2$))^2* where *var (x)* is the variance of *x* , and *v* was always set to 0.5 (Alan Gay, personal communication).

A MATLAB script (MathWorks 2013) was used to find the maximum likelihood estimation of means and variances of each distribution. Comparative graphical analysis is presented at each chapter where this analysis was performed.

3.1. Weather conditions

Meteorological data was obtained either by the use of on-site weather stations or using locally located publicly availed Met Office sites. Weather conditions measured included temperature minimum and maximum (°C), relative humidity (%) and rainfall (mm) on a daily basis. These parameters allowed to calculate, where possible, the growing degree days (GDD).

Growing degree days *(GDD)* is a weather-based indicator for assessing crop development, used by crop producers. It is a measurement of heat accumulation used to predict plant development and the date that a crop reaches maturity. When there are no extreme conditions such as drought or disease, plants grow in a cumulative stepwise manner which is strongly influenced by the ambient temperature. Many developmental events of plants and insects depend on the accumulation of specific quantities of heat, thus, it is possible to predict when these events should occur during the growing season regardless of differences in temperatures from year to year. GDD units can be used to assess the suitability of a region for production of a crop, estimate the growth stages of crops, weeds or even life stages of insects, predict maturity and cutting dates of forage crops. Daily growing degree day values are added together from the beginning of the season, providing an indication of the energy available for the plant growth. GDD totals are used to compare progression of a growing season to the long-term average.

Growing degrees (*GD*) is defined as the mean daily temperature (average of daily maximum and minimum temperatures) above a certain threshold base temperature accumulated daily in time. The base temperature varies between crops and the value is derived from the growth habits of each specific crop. It is that temperature below which plant growth is zero. In oats, similarly to barley, rye and wheat, it is 0 ^oC or 32 ^oF (Miller et al. 1997).

GDs were calculated each day as described in equation (4) in which the maximum temperature (T_{max}) plus the minimum temperature (T_{min}) is divided by 2 (i.e. the mean temperature), minus the base temperature (T_{base}). GDDs are accumulated by adding each day´s GDs contribution as the season progresses. If the average temperature is below the base temperature, the growing degree day value for that day is zero. GDDs are typically calculated from the time of sowing.

$$GDD = (T_{max} + T_{min}) / 2 - T_{base} \tag{4}$$

3.2. Yield and cleaning

Grain from all traits described in subsequent chapters was harvested using a small plot combine and harvested yields corrected to 15% moisture content. Harvested grain was cleaned through a 3.5 mm to get rid of straw, double grains, and a 2 mm sieve to get rid of undesirable particles, etc., for subsequent analysis of grain quality.

3.3. Specific Weight

Specific weight (kg/hl), also known as hectolitre weight or test weight, is defined as the weight of grain which fills a specified volume under standard packing conditions. Cheap and easy to perform, and with little technical training required, it is the standard method used by the grain trade to determine the market value of oats as it affects the weight of grain contained in each lorry load transported. Previous studies however, have shown that it is not related to key milling quality parameters such as kernel content or hullability (Burke et al. 2001; Manley et al. 2009).

It was measured using a chondrometer (Nileme, C288) on three replicate samples (approximately 500 ml) per field plot. Chondrometers are cylindrical devices containing a column in which grains are isolated from the cylinder of known volume underneath by means of a level blade or metal bar (Manley et al., 2009). The blade separates a precise volume of grain (below the blade) from excess grains above the blade (ISO 1986). The upper part, the forerunner, was filled with the sample to the top. Then a little trap door allowed the sample to drop into the bottom container. With a cut off slide, the excess of sample was removed from the rest. This known volume of grain was weighed and the mass converted to kg/hl.

3.4. Thousand Grain Weight. Kernel Content and Hullability determination

From each location and variety, thousand grain weight was also calculated (TGW). A 30 g sample, from each of the three replicates per variety from each location and harvest season, was counted out by a seed counter (Data technologies model number data count S-25) and weight on a precision scale. The data obtained were used to calculate TGW following the equation below.

$$Thousand\ Grain\ Weight = \left(\frac{Weight\ of\ the\ sample}{Number\ of\ grains\ in\ the\ sample}\right) x\ 1000 \tag{5}$$

Kernel content (KC) is the mass of groat or kernel relative to the mass of the grain. It represents the highest priority in selection programs for the milling industry as the groat is the fraction used for human consumption. The hullability is the easiness with which the husk is removed to get the kernel/groat. This parameter is highly important as it affects the efficiency with which the oats are milled without causing groat breakage which would result in economic losses. It is influenced by the method and conditions of dehulling used and the different size of the grain (White & Watson 2010).

All kernel content and hullability determinations were assessed using 30 g of each sample using a *Codema impact dehuller*; Model LH5095 (set at 100 bar for 45 seconds), and then separating the output into husks, groats and whole grain. Each fraction obtained was weight using a precision scale and the kernel content and hullability determined using the equations below.

$$KC = \left(\frac{Groat\ weight}{Initial\ weight - Whole\ grain}\right)\ x\ 100 \tag{6}$$

$$Hullability = \left(100 - \frac{Groat}{Initial\ weight}\right) x\ 100 \tag{7}$$

3.5. Grain composition

Approximately 20 grams of each sample of husked oats and whole groats were scanned at 2 nm intervals over the wavelength range from 400 to 2498 in reflectance mode, by a FOSS NIR (Near-Infrared Spectroscopy), Systems 6500 spectrophotometer, a non-destructive technique. NIR uses an electromagnetic spectrum that implies the vibrational response of molecular bonds O-H, C-H, C-O and N-H, and the specific vibration pattern in these bonds. Biological molecules within these bonds are present, e.g. oil, protein, starch and fibre, absorb vibrational energy in a specific way generating a characteristic spectrum that behaves as a fingerprint of the sample. Husked and dehulled oats were scanned at 2nm intervals over the wavelength range from 400 to 2498 in reflectance mode, by a NIR (Near-Infrared Spectroscopy). The general method consists in spectral data acquisitions, data pre-processing to reduce the noise and baseline shift, from the instrument and the background, to build the calibration models using samples of known concentration by well referenced methods and finally validate the model. Quantification of oil, protein, β-glucan were determined using a calibration curve developed internally at IBERS and built up on the basis of the analysis of spring and winter oat samples harvested between 1998 and 2016. Wet chemistry analyses were completed on selected samples to validate the NIR screening. Samples were presented as whole oat (dried and undried) and milled (dried and undried). Calibrations were developed using modified partial least squares (MPLS) regression plus scatter corrections applied. Equations were developed using standard normal variate and detrend and second derivative transformations using modified partial least squares (mPLS) regression. The methods used included total N analysis on ground groat samples which was performed using the Kieldahl method (AOAC method 945.18) (199) using a LCEO FL-48 analyser (LECO Corp, ST. Joseph, MI). Oil calibration data was obtained by extraction using petroleum ether and the Soxtec system (FOSS UK, Warrington, UK). The β-glucan content was determined in parallel using the Megazyme ™ kit (McCleary method) (AOAC method 995.16) (Megazyme and Ireland, 1991) (1999) on all samples (Megazyme and Ireland, 1991). NIR scans from the whole oats were used to develop a calibration for kernel content.

3.6. Grain and groat size and shape

Physical analysis of grain size and shape, including area, length and width of the grain and the groats once they were dehulled, were determined by a non-destructive method, using a Digital Seed Analyser, *MARVIN* (Sensorik GmbH 2001). The same 30 g sample that was used for thousand grain weight, kernel content and hullability determination was used at all times. Seeds were placed on the analysing tray and spread out so that no seeds were touching. All seeds in the sample were measured requiring several scans with MARVIN. Special software evaluated the captured image on the basis of digital image processing. The output gave the number of seeds analysed and the individual grain length, width and area. The grain sample was then dehulled and the process repeated with the groats.

Grain and groat area, length and width, were also used to determine shape descriptors as described below:

$$Grain\ or\ Groat\ Ratio = \left(\frac{Width\ of\ the\ grain\ or\ groat}{Length\ of\ the\ grain\ or\ the\ groat}\right) \tag{8}$$

$$Circularity = \sqrt{\left(\frac{Area\ of\ the\ grain\ or\ the\ groat}{\pi\ x\left(\frac{Length\ \text{of the grain or groat}}{2}\right)^2}\right)} \tag{9}$$

$$Grain\ or\ Groat\ Density = \left(\frac{Thousand\ grain\ weight\ of\ the\ grain\ or\ the\ groat}{Area\ \times Width\ of\ the\ grain\ or\ the\ groat}\right) \quad (10)$$

Other determinations and shape descriptors will be explained in detail in the appropriated section where they are calculated.

4. Results

4.1. Weather conditions.

Autumn 2012, was wet leading to difficult planting conditions (figure 4.8) resulting for one site that it was not possible to sown until spring (table 3.3, Rosemaund, site 4). Overall, 2013 was characterized by exceptionally cold spring, leading into a warm and sunny summer (Anon 2015). The mean summer temperature was 0.8 ºC above the 1981-2010 average, the summer rainfall total was 187 mm (78% of average), and the summer sunshine total was 578 hours. In 2014, the winter was warm and wet (rainfall 165% of average) leading into a warm but wet spring and a sunny summer (113% of average).

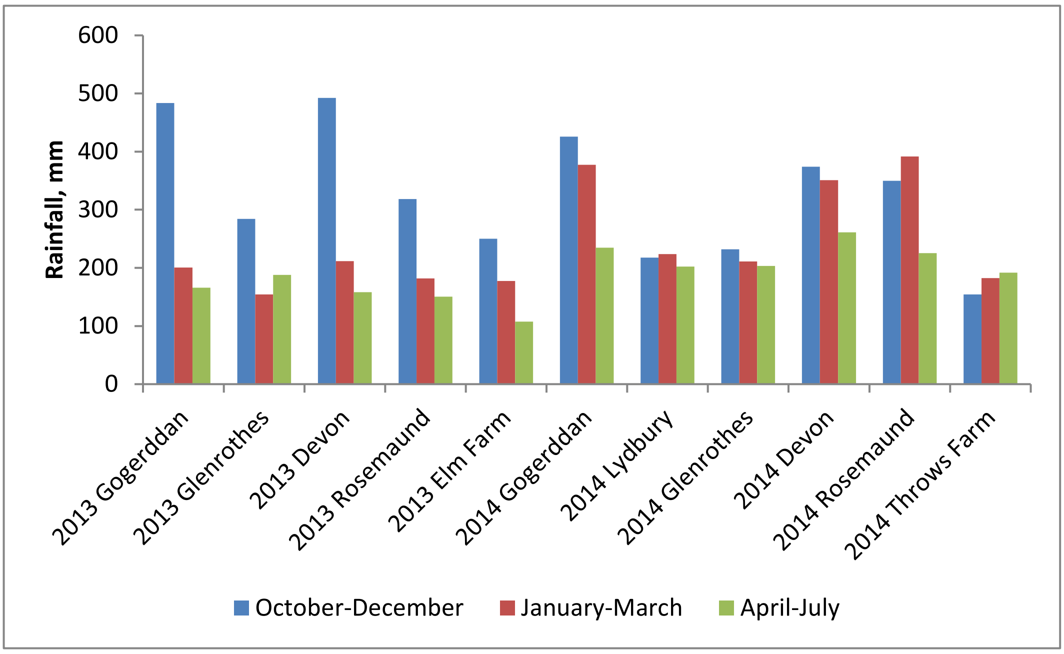


Figure 4.8. *Average rainfall (mm) values at each of the eleven sites across UK during both harvest seasons, 2012/2013 and 2013/2014, used in this research.*

Detailed weather data (daily maximum and minimum temperature (ºC), rainfall (mm) and relative humidity (%)) were only available from Gogerddan site for both the 2012/2013 and 2013/2014 harvest seasons. From the temperature data, Growing Degree Days (GDD). GDD were calculated using as 0 ºC as the base temperature (figure 4.9). The data from both harvest seasons coincide in the amount of days between sowing and harvesting dates, giving a total of 302 days for both seasons. However, the curve of GDD (figure 4.9) shows the difference in the amount of thermal time accumulated in the two seasons. In 2013/2014, daily mean temperatures were higher in the autumn and summer than in 2012/2013. At the same time, cumulative rainfall during the season was similar for the first 120 days in 2012/2013 and 2013/2014 at Gogerddan but thereafter, it was much drier in 2012/2013 (figure 4.10). Although it is needed to consider other weather parameters, such as humidity, wind as well as previous soil conditions and crop, these differences might explain some results obtained in terms of grain and groat quality parameters.

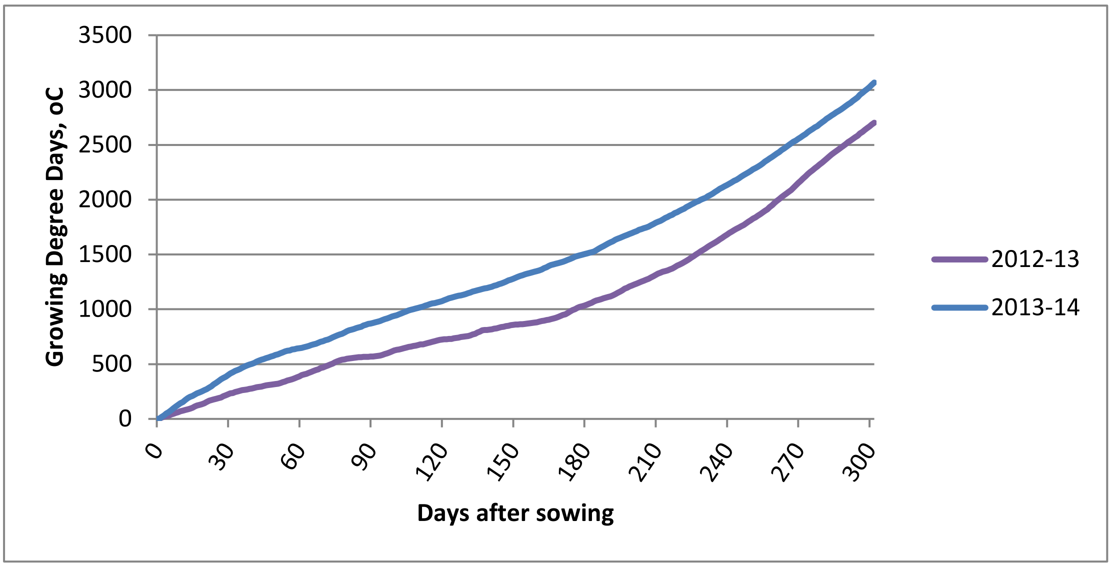


Figure 4.9. *Growing Degree Days (GDD) ºC, at both 2012/2013 and 2013/2014 harvests seasons, for Gogerddan (Catherine Howarth, personal communication).*

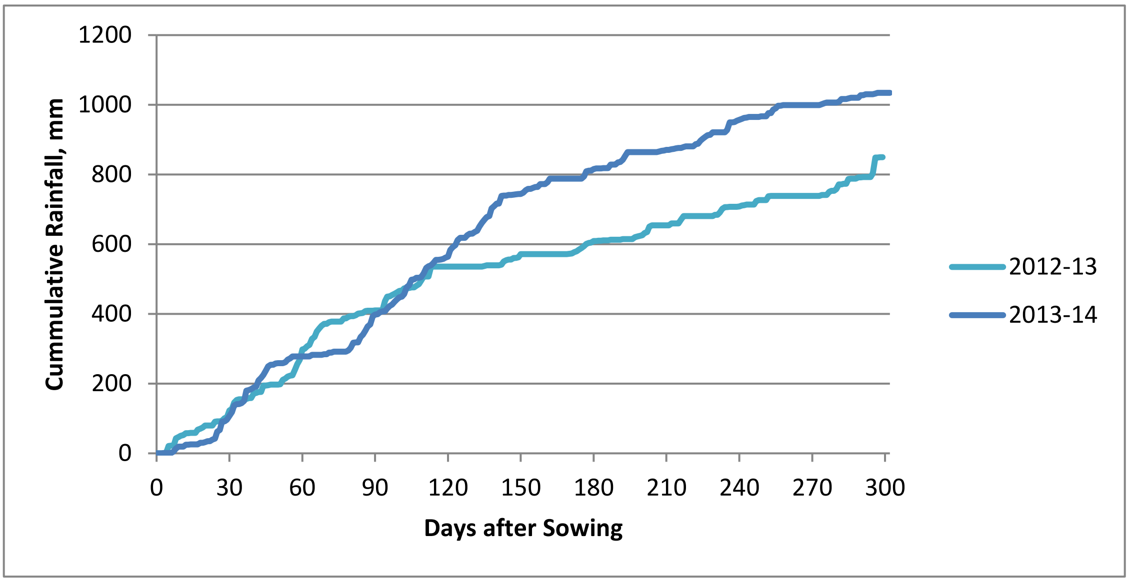


Figure 4.10. *Cumulative rainfall (mm) at both 2012/2013 and 2013/2014 harvests seasons, for Gogerddan (Data from Gogerddan met station).*

Table 4.4. Effect of the environment on the mean ± s.e.m. values for yield (t/ha), grain number (n^o/m^2) kernel content (%), specific weight (kg/hl), hullability (%) and thousand grain weight (g) of four winter oat varieties at 11 sites and both harvest seasons.

Site	*Site code*	*Year*	*Yield (t/ha)*	*s.e.m.*	*Grain n^o/m^2*	*s.e.m.*	*Kernel content (%)*	*s.e.m.*	*Specific weight (kg/hl)*	*s.e.m.*	*Hullability(%)*	*s.e.m.*	*Thousand Grain Weight (g)*	*s.e.m.*
Gogerddan	1	2013	8.3	0.1	19846.0	237.6	73.1	0.2	50.2	0.3	77.5	1.6	42.0	0.3
Glenrothes	2	2013	8.8	0.1	21900.7	276.7	73.1	0.2	52.1	0.2	84.9	1.1	40.2	0.3
Devon	3	2013	10.5	0.1	26824.1	309.7	72.2	0.3	51.8	0.2	75.9	1.6	39.4	0.3
Rosemaund	4	2013	5.0	0.1	12622.1	422.8	75.7	0.2	50.8	0.1	92.4	0.7	40.6	0.4
Elm farm	5	2013	9.7	0.1	23142.1	279.6	72.7	0.2	51.9	0.3	76.3	1.6	42.1	0.4
Gogerddan	6	2014	9.3	0.1	24630.7	387.8	69.7	0.7	50.3	0.3	84.1	1.3	38.5	0.7
Lydbury	7	2014	7.9	0.1	16514.3	213.3	75.2	0.2	53.7	0.2	91.4	0.7	48.2	0.4
Glenrothes	8	2014	9.7	0.1	22457.2	178.3	72.9	0.3	53.2	0.2	80.6	1.3	43.2	0.3
Devon	9	2014	9.9	0.1	22789.2	312.5	72.8	0.3	50.9	0.3	83.7	1.2	43.7	0.3
Rosemaund	10	2014	7.1	0.1	17227.6	227.5	73.9	0.3	49.2	0.2	86.9	0.9	41.5	0.4
Throws farm	11	2014	9.4	0.0	26769.6	318.0	70.5	0.5	49.2	0.4	83.1	1.1	35.4	0.4
Overall mean			8.7	0.9	21338.5	590.3	72.9	1.6	51.2	1.1	83.3	2.0	41.3	0.9
Significance Site			<0.05		<0.05		<0.001		<0.001		<0.001		<0.001	
Significance Genotype			Non significant		<0.05		<0.001		<0.001		<0.001		<0.001	
Significance Interaction			<0.05		Non significant		<0.001		Non significant		<0.001		<0.001	

4.2. Yield

Analysis of variance (two way ANOVA) showed significant differences (p-value <0.05) for grain yield between sites. The lowest average value 5.0 t/ha (table 4.4) was obtained at Rosemaund in 2013 (site code 4), whilst Devon in 2013 (site 3) yielded the highest value of 10.5 t/ha (table 4.4, figure 4.11). The overall average value was 8.7 t/ha. Interestingly, Rosemaund 2013 (site code 4), with the lowest yield performance, was the only site where the grain was sown in the spring because weather conditions prevented earlier sowing. This late sowing might have meant a shorter maturation period in plant development and lower tillering when compared to the other sites, but this data is not available.

At the same time, yield showed statistical significant interactions between environment and variety (p-value <0.05, two-way ANOVA). However, there was non-significant differences between varieties (table 3.5). Grain number per m^2 also was significantly different (p-value <0.05) between sites and between varieties and no significant interaction with the environment.

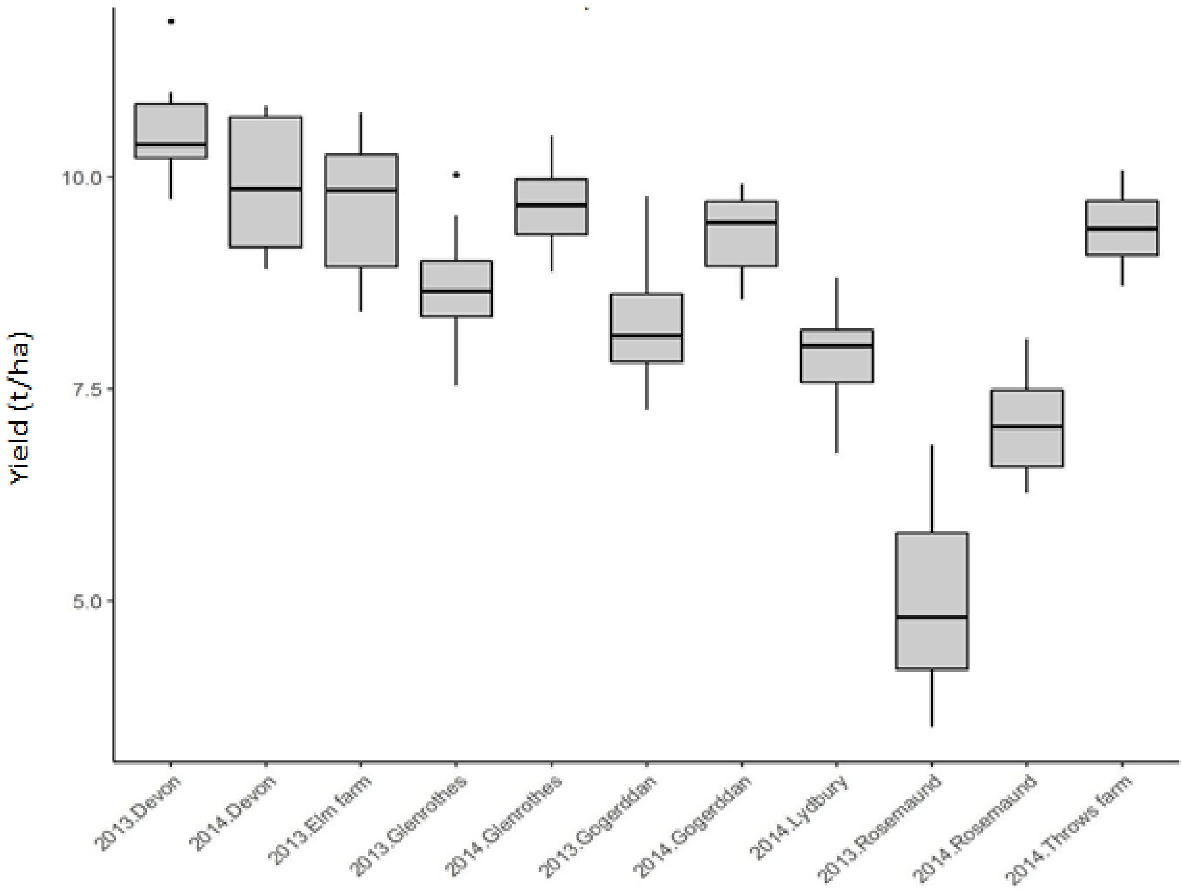


Figure 4.11. *Box plot of yield (t/ha) values of four winter oat varieties, Balado, Gerald, Mascani and Tardis, from each site and harvest season (2012/2013 and 2013/2014). The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data 75 %, with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

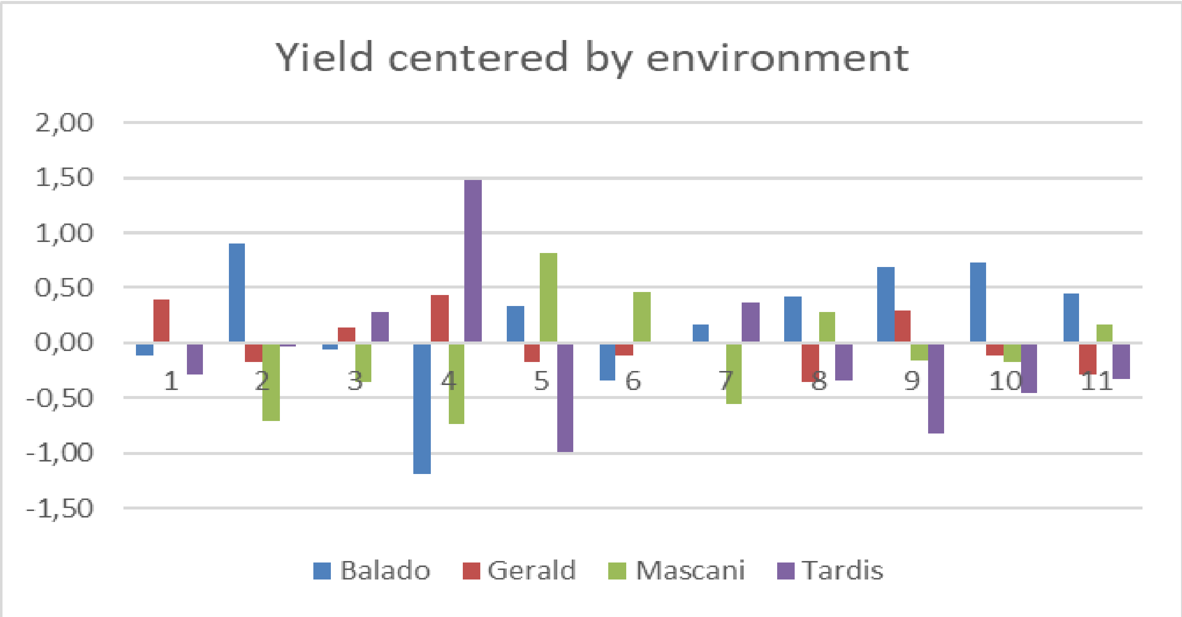


Figure 4.12. *Grain yield (t/ha) centred by environment of the four varieties, i.e. Balado, Gerald, Mascani and Tardis, at each site (see Table 3.3), for both 2013 and 2014 harvest seasons. This graph was developed by subtracting the mean yield over all genotypes at each location from the yield of each genotype at that location.This gives a mean yield at all environments of zero allowing to remove the effect of the environments and comparing genotypes performances.*

Figure 4.12, shows the relative performance of the genotypes at each location and removes the environment to environment variation. This visualises which genotypes are yielding above and below average at a given environment, as well as the ranking of genotypes by yield at each environment. The range of yield values found graphically, by variety, reflects the sites that would be more interesting to discriminate between varieties´ performances, i.e. to investigate further in which sites a genotype yields well, and in which it performs poorly. Therefore, site 2, Glenrothes 2013, site 4, Rosemaund 2012/2013, site 5, Elm farm 2013, site 9, Devon 2014, and site 10, Rosemaund 2014, showing a wider range of values are the best environment to discriminate between the four varieties. However, the rest of the sites did not have visible differences in the performance of the different genotypes and therefore are less useful to discriminate between genotypes. There was not a consistent effect of genotype apparent across environments and no genotype performed consistently better at all sites.

Joint regression analysis (Finlay & Wilkinson 1963), was also used to determine phenotypic stability and the sensitivity of trait performance to the environment (figure 4.13, table 4.5). In this analysis, the variety performance is plotted against the environment mean at each site and a linear regression is performed. This regression of the genotypic response on an environmental index, such as the average of all phenotypes in an environment, is defined as the difference between the marginal mean of the environment and the overall mean. The slope of the regression line represents the sensitivity of a variety to the environment. A phenotype with a regression coefficient of 1 and minimum deviations from the regression will be considered as most stable. The general stability (Lin & Binns 1991b), is a cultivars homeostatic ability to withstand unpredictable environmental variation.

The sensitivity and static stability values obtained (table 4.5), indicated that across environments, Tardis was the more stable variety, i.e. an unchanged performance regardless of any changes on the environmental conditions, meaning its variance between environments is the closest to zero (Lin & Binns 1991b), whereas Balado had the highest sensitivity to the environment. Gerald however, was the highest in cultivar superiority ranking, i.e. it was superior in general response across changing conditions across environments (table 4.5).

It is also interesting to consider the mean of the square deviations of the observations about the line fitted for each genotype. Gerald had the highest values in cultivar superiority in general terms and with a value of 0.219 mean square deviation (figure 4.13), is giving the most predictable responses, in agreement with previous results (figure 4.12) when removing the effect of the environment. However, static stability values showed Tardis as the genotype with an unchanged performance regardless of any changes on the environmental conditions, i.e. its variance between environments is zero, which might lead to the idea of a lower effect of the genetic by environment interaction in terms of Tardis' yield performance.

Table 4.5. *Average yield (t/ha) over all sites, cultivar superiority, static stability and sensitivity of the four winter oat varieties. *Numbers in brackets indicated the ranking positions of each variety, as best cultivar.*

Yield t/ha	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Varieties					
Balado	8.874	0.381 (2)	3.737 (4)	1.200(4)	0.346(4)
Gerald	8.696	0.259 (1)	2.160 (2)	0.923(2)	0.219(1)
Mascani	8.604	0.478 (4)	3.481 (3)	1.167(3)	0.418(3)
Tardis	8.589	0.438 (3)	1.492 (1)	0.700(1)	0.407(2)
Significance	n.s.	*p-value<0.05*	*p-value<0.05*	*p-value<0.001*	*p-value<0.001*

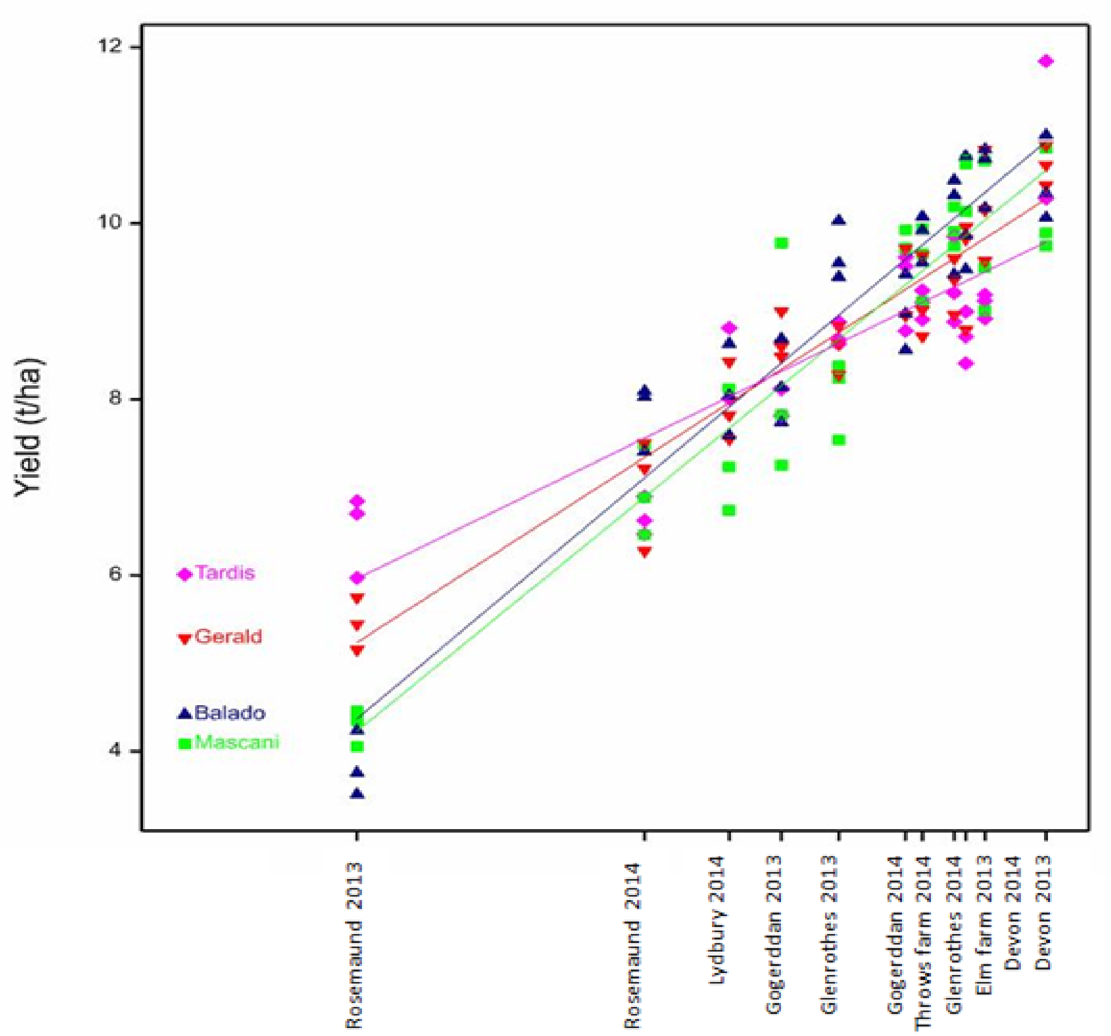


Figure 4.13. *Joint regression plot (Finlay & Wilkinson, 1963), of four winter oat varieties 'yield performance against sites for both harvest seasons 2013 and 2014.*

4.3. Kernel content

Mean kernel content (table 4.4) was statistically significantly different (p-value < 0.001, two-way ANOVA) for both varieties and sites, as well as showing a significant genetic by environment interaction (p-value <0.001).

Between varieties, Balado had the lowest mean kernel content with a value of 70.4% whilst Mascani showed the highest with 76.6% (table 4.6, figure 4.14). Interestingly, a wider range of values was found for Balado in 2014 in comparison with the 2013 harvest season (figure 4.14), while the rest of the varieties did not show differences between years.

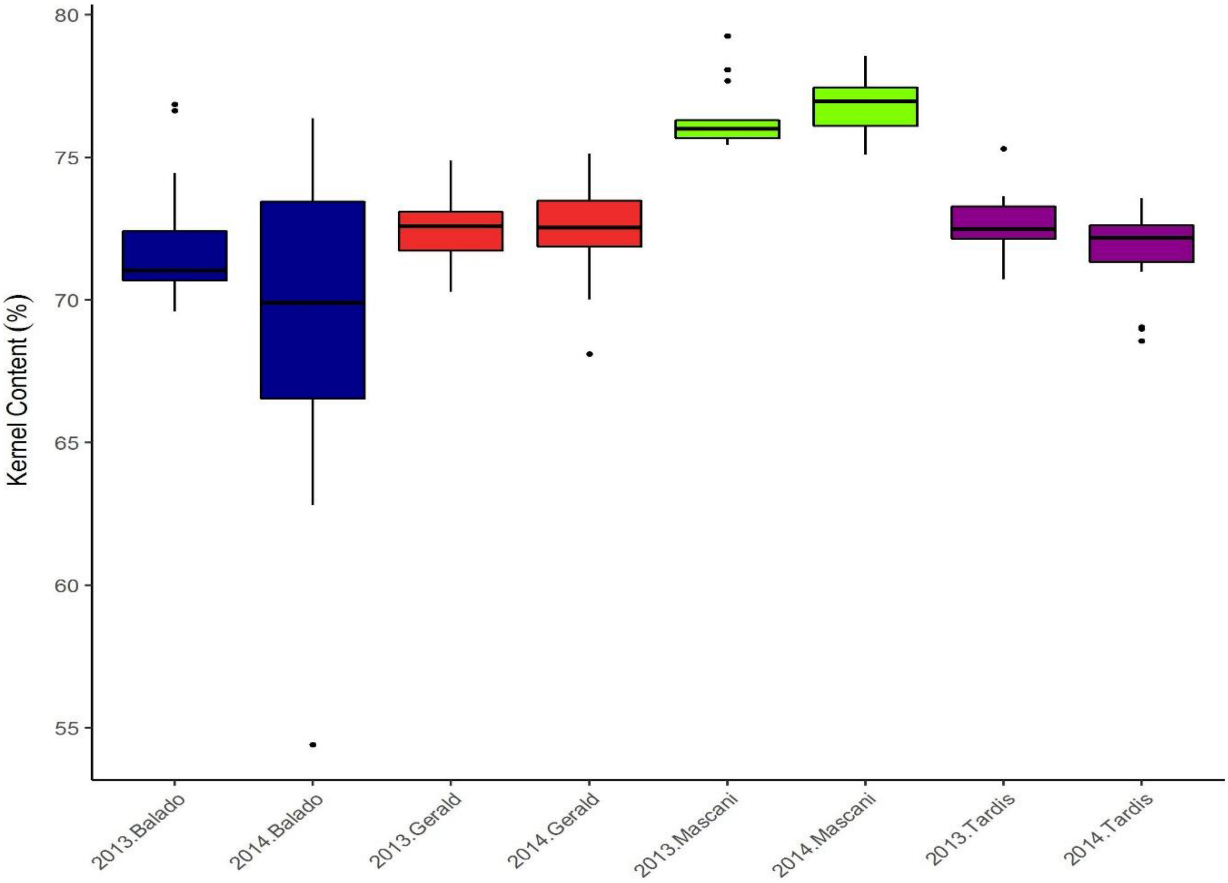


Figure 4.14. Box plot of k*ernel content (%) by variety and year of the four winter oat varieties, Balado (blue), Gerald (red), Mascani (green) and Tardis (purple), for both harvest seasons, 2013 and 2014. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

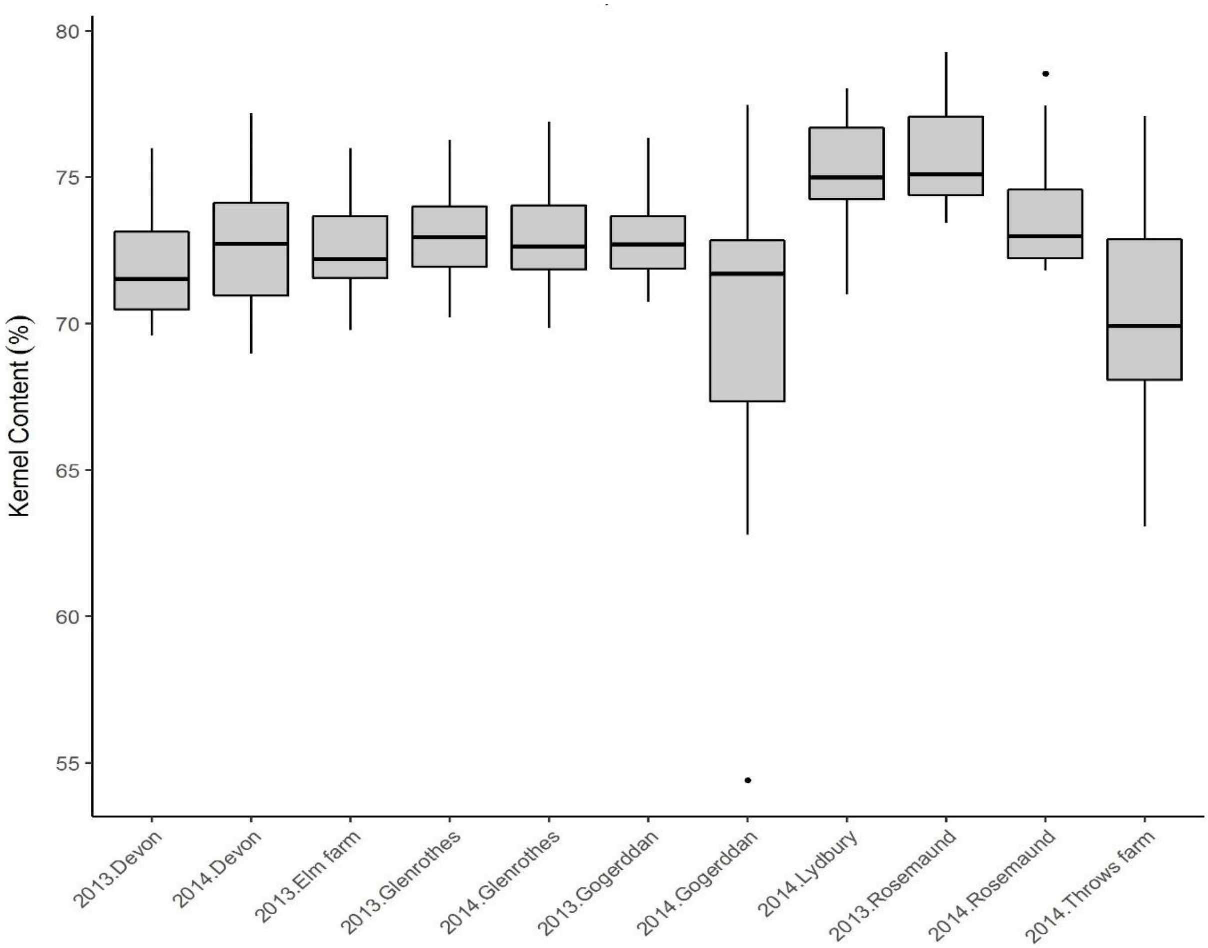


Figure 4.15. Box plot of k*ernel content (%) of the four winter oat varieties, Balado, Gerald, Mascani and Tardis, for each environment. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

By locations (table 4.4, figure 4.15) the highest values for kernel content were obtained at Rosemaund 2013 and Lydbury 2014 (site 4 and 7, respectively) whereas the lowest values were obtained at Gogerddan and Throws farm in 2014. At the same time, the range of values obtained for kernel content was widest in Gogerddan 2014 and Throws farm 2014. This is also reflected in the joint regression analysis presented in figure 4.16. Balado reached the lowest values (mean of 60.8%) at Gogerddan 2014 (site 6) which is far below the minimum required for the milling industry and end-user, and at Throws farm-2014 (site 11) with a mean of 65.4%. Gerald also had the lowest kernel contents at Gogerddan-2014.

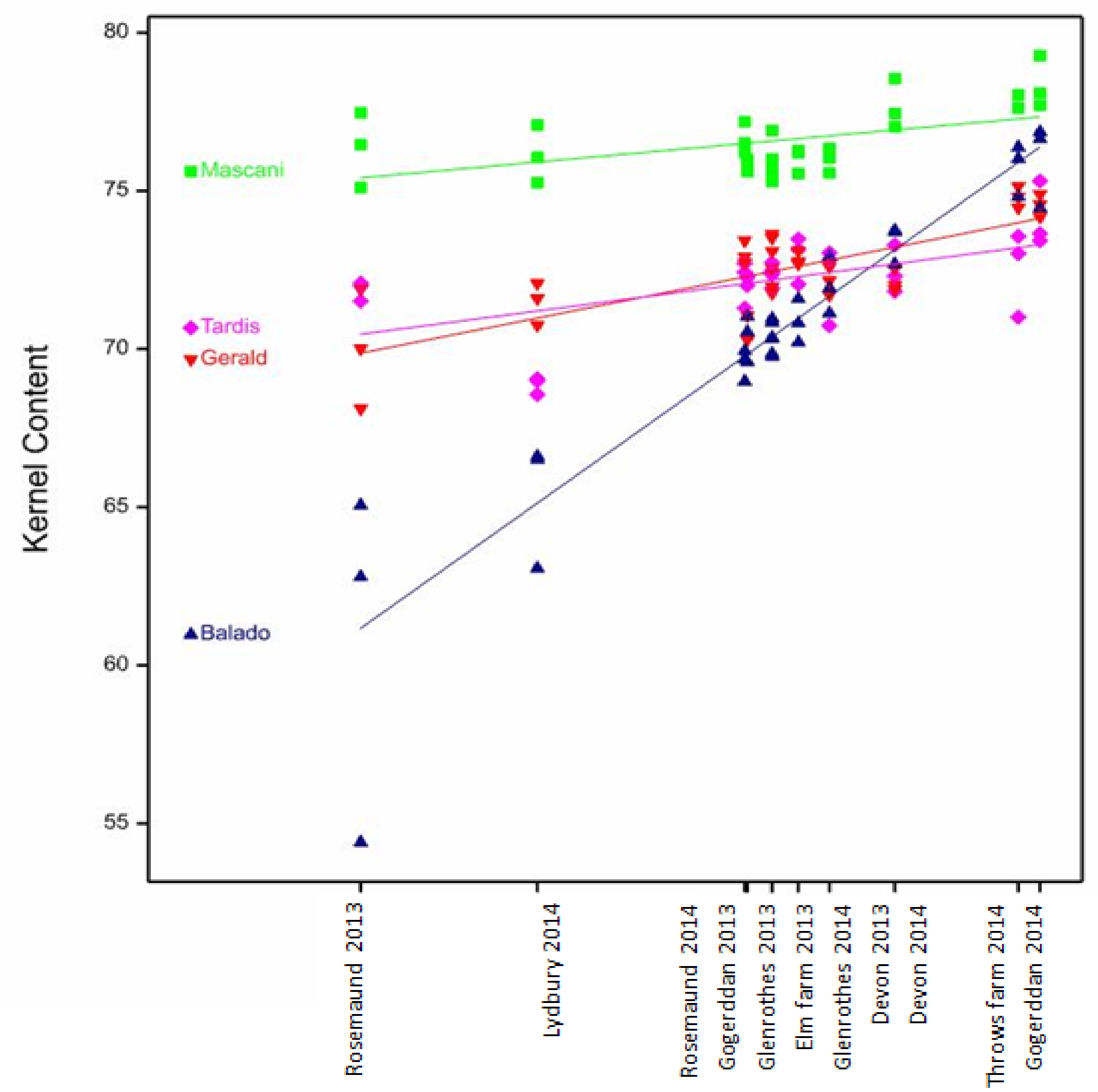


Figure 4.16. *Joint regression plot (Finlay & Wilkinson, 1963), of four winter oat varieties' kernel content values against sites for both harvest seasons 2013 and 2014.*

Joint regression analysis (figure 4.16), showed Mascani as the most stable between environments, with a sensitivity value of 0.308 (table 4.6), also shown in the graph by the joint regression line and by the mean square deviation value (0.834), i.e. a more predictable response. The highest sensitivity to the environment was obtained for Balado indicating that it had the lowest stability and the least predictable response to the environments. These results are in accordance with the values on the ranking (numbers between brackets in the table), table 4.6, which also shows that Mascani is the cultivar with the highest superiority (0.00) and static stability (0.836), whilst Balado has the lowest values for these measures.

Table 4.6. *Average kernel content (%) over all seasons and sites, cultivar superiority, static stability and mean square deviation of the four winter oat varieties. *Numbers in brackets refers to the position on the ranking of best cultivar.*

Kernel Content (%)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviation
Varieties					
Balado	70.43	25.86(4)	19.013(4)	2.435(2)	2.742(4)
Gerald	72.46	9.090(2)	2.175(3)	0.681(4)	1.044(3)
Mascani	76.58	0.000(1)	0.836(1)	0.308(1)	0.834(1)
Tardis	72.19	10.29(3)	1.566(2)	0.452(3)	1.032(2)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

4.4. Specific weight

Environment had a significant (p-value <0.001 two way ANOVA) effect on specific weight (table 4.4) which ranged from 49.2 kg/hl at Rosemaund and Throws Farm (site 10 and 11), both in 2014, to 53.7 kg/hl at Lydbury 2014 (site 7). A significant (p-value <0.001) difference was also found between varieties averaged over all environments. The specific weight of Mascani and Gerald was greater than Balado and Tardis for both harvest seasons. Balado had the lowest values in both harvest seasons, with a mean of 49.1 kg/hl in 2013 and 48.5 kg/hl in 2014 (figure 4.17). There was no significant difference between varieties in their sensitivity to environment as shown by joint regression analysis (table 4.7, figure 4.18).

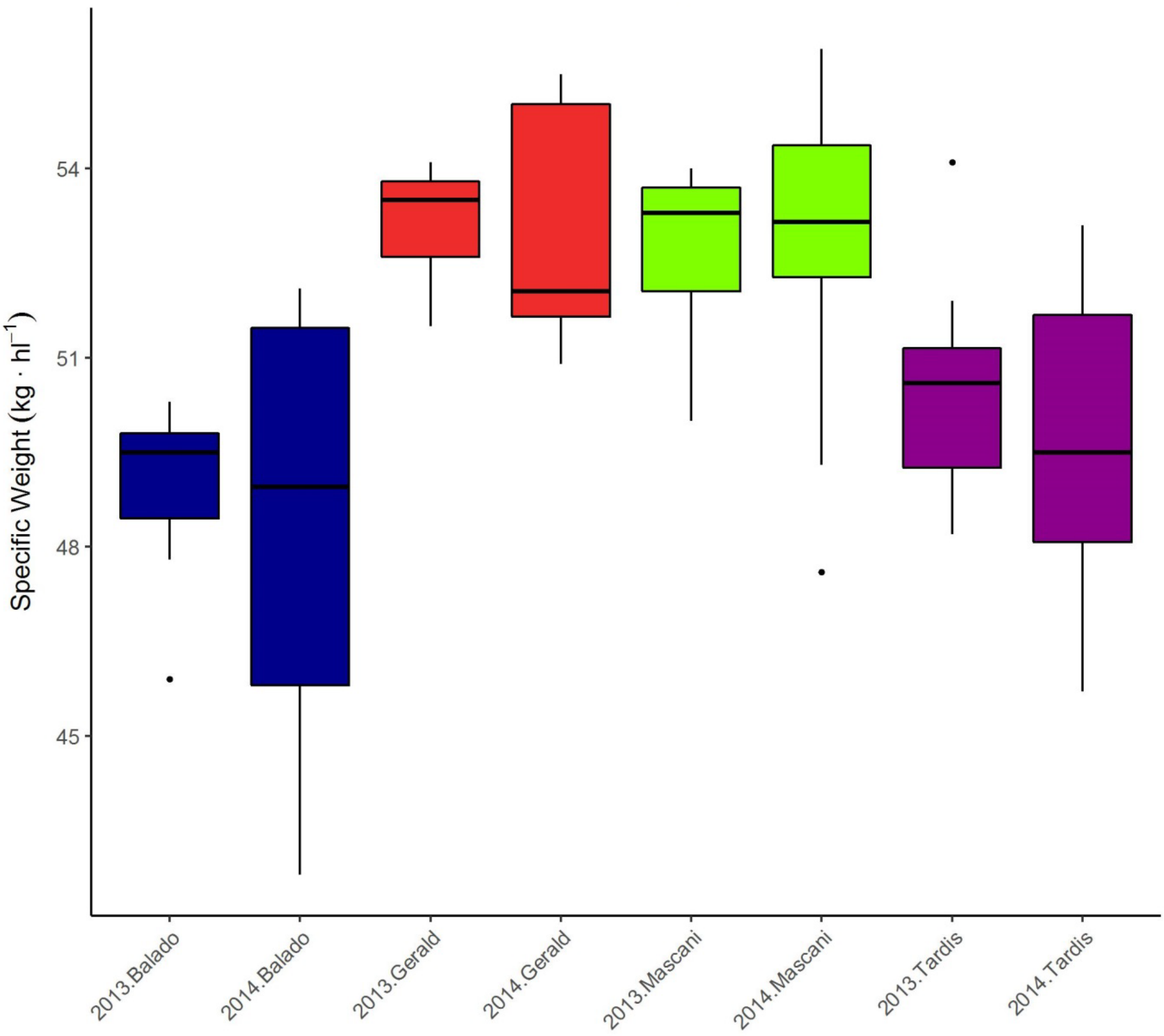


Figure 4.17. *Box plot of grain specific weight (kg/hl) of Balado, Gerald, Mascani and Tardis, average values for 2012-2013 and 2013-2014 harvest seasons. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

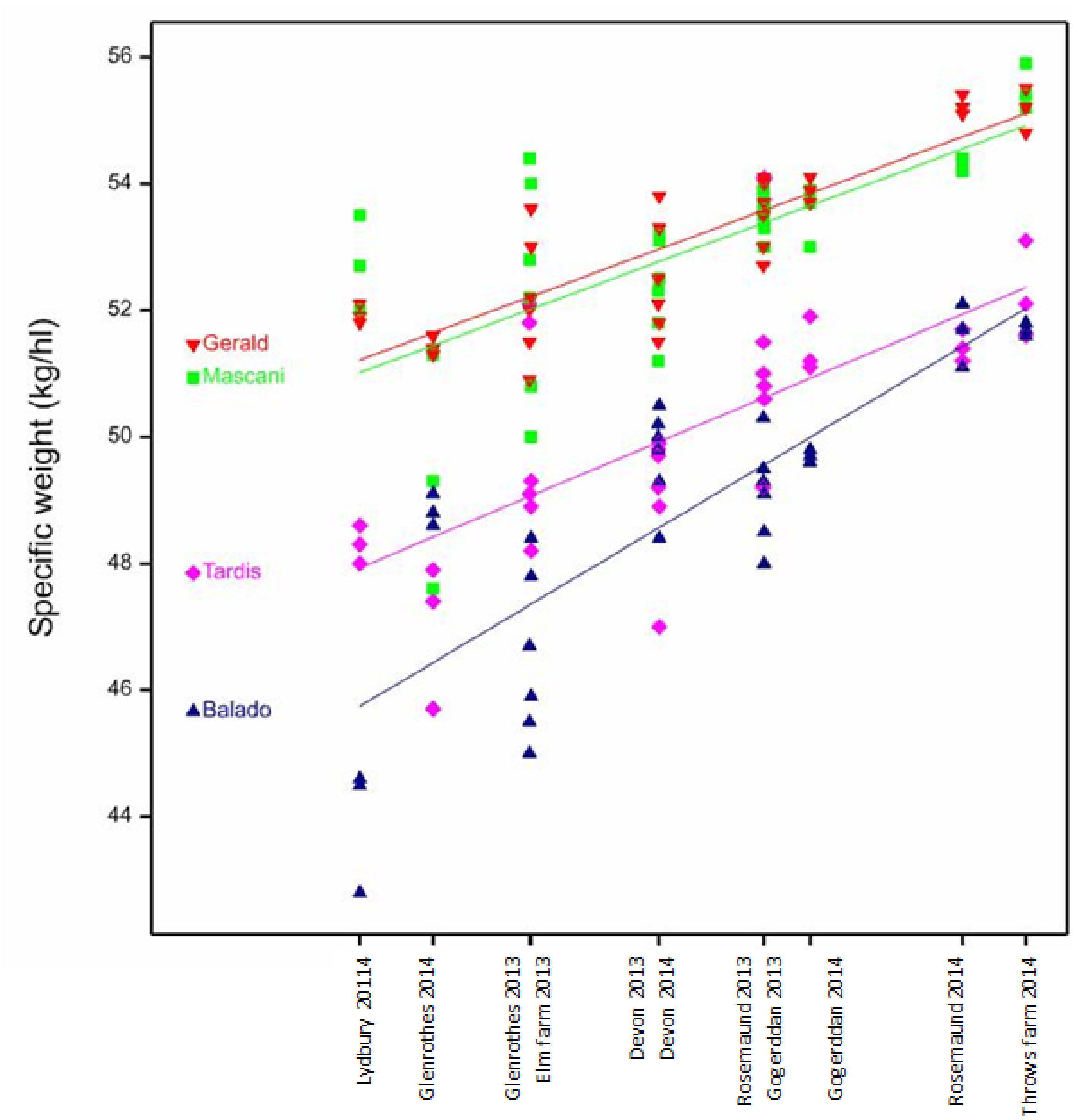


Figure 4.18. *Joint regression plot (Finlay & Wilkinson, 1963) of four winter oat varieties' specific weight values against sites for both harvest seasons 2013 and 2014.*

Balado had the lowest specific weight at all environments. Gerald and Mascani presented the higher cultivar superiority (0.179 and 0.336), and static stability (1.815 and 2.535) (figure 4.18 and table 4.7). Balado and Tardis, had always poorer values ranking the lowest.

Table 4.7. *Average specific weight (t/hl) overall seasons and site, cultivar superiority, static stability and ranks of the four winter oat varieties. *Numbers in brackets refers to the position on the ranking of best cultivar.*

Specific Weight (t/hl)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviation
Varieties					
Balado	48.78	12.564(4)	5.475(4)	1.345(4)	1.867(4)
Gerald	53.10	0.179(1)	1.815(1)	0.834(1)	0.467(1)
Mascani	52.90	0.336(2)	2.523(2)	0.836(2)	1.669(2)
Tardis	50.07	5.976(3)	2.926(3)	0.948(3)	1.783(3)
Significance	*p-value*<0.001	*p-value*<0.001	*p-value*<0.001	*p-value*=0.158	*p-value*<0.001

4.5. Hullability

Regarding percentage hullability, genotypes were significantly different (p-value <0.001, two way ANOVA) (table 4.7, figure 4.19). Mascani displayed very little variation in both harvest years (figure 4.19) remaining the highest at all sites with no value below 95% obtained for any environment. Balado, Gerald and Tardis, showed a wide range in results from 60% to 90% in both harvest years (figure 4.19). There were significant statistical differences (p-value <0.001) between sites, table 4.4 and the lowest values were obtained in the 2013 harvest season, regardless of the variety (figure 4.19). Rosemaund 2013 and Lydbury 2014 gave the highest values, while Elm Farm 2013 and Devon 2013 had the lowest hullabilities. Genotype by site interaction were also statistically significant (p-value <0.001).

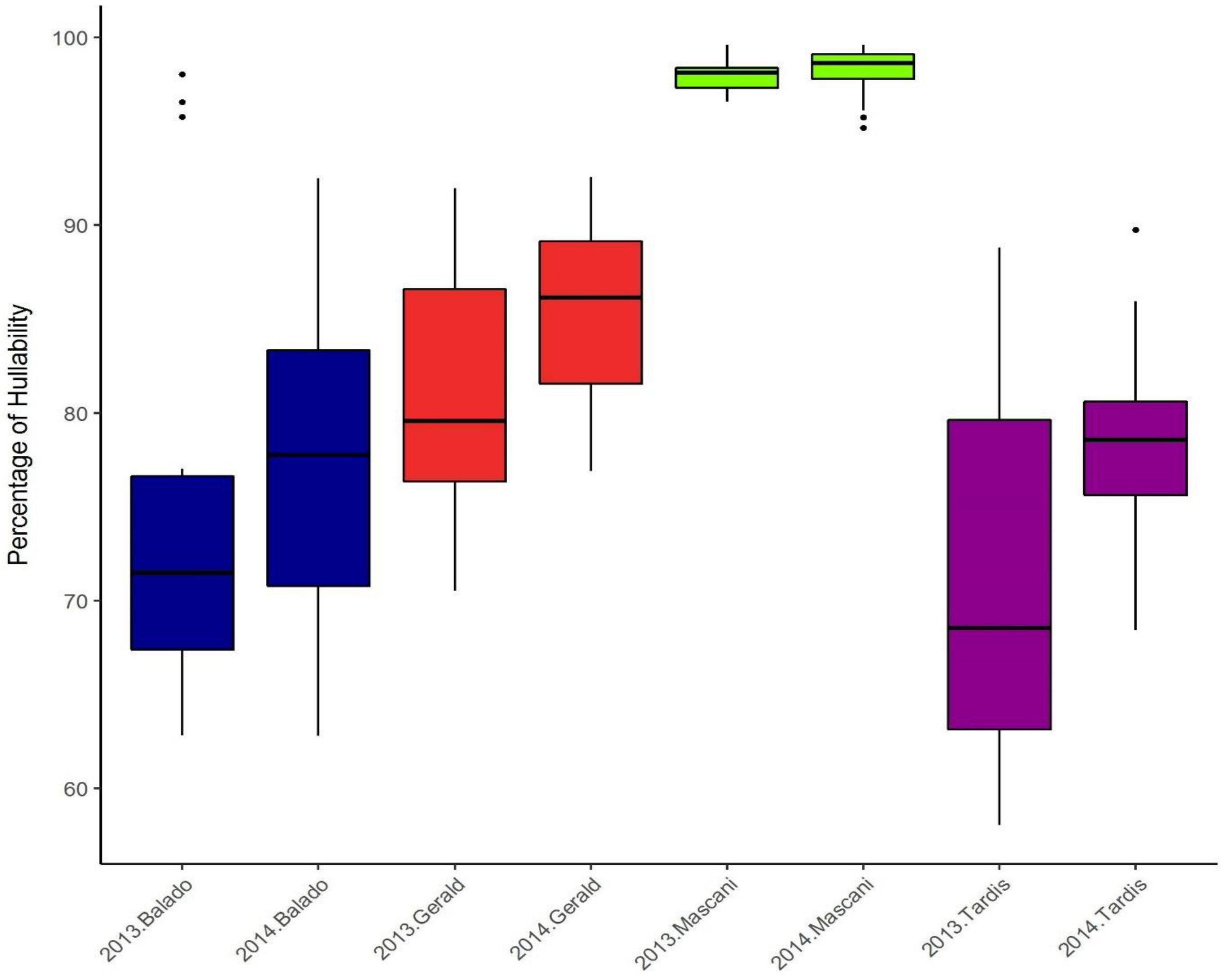


***Figure 4.19**. Box plot of hullability (%) values for each of the four winter oat varieties, i.e. Balado, Gerald, Mascani and Tardis, at each harvest season (2012/2013 and 2013/2014). The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

By removing the effect of the environment, in an environment centred analysis (figure 4.20), the range of hullability performances at each site is apparent. Thus, site 4 (Rosemaund 2013) and site 7 (Lydbury 2014), displayed the lowest range in hullability values, meaning that at those sites, the genotype effect was lower when compared to other sites, where varieties displayed higher values. Mascani with a hullability higher than the overall mean when compared with the rest of varieties, was less affected by the environment. Gerald displayed hullabilities in all environments similar to the mean of those environments whilst Balado displayed a higher interaction with the environment for hullability and reached a maximum of 98.72%, at Rosemaund 2013 (site 4) and the lowest of 66.53%, at Devon 2013 (site 3). Gerald gave the best results at Lydbury 2014 (89.8% site 7) and its lowest value at Devon 2013 (73.1% site 3). Finally, Tardis achieved the highest value at Lydbury 2014, (83.8% site 7) whilst the lowest was at Elm farm 2013 (62.9% site 5).

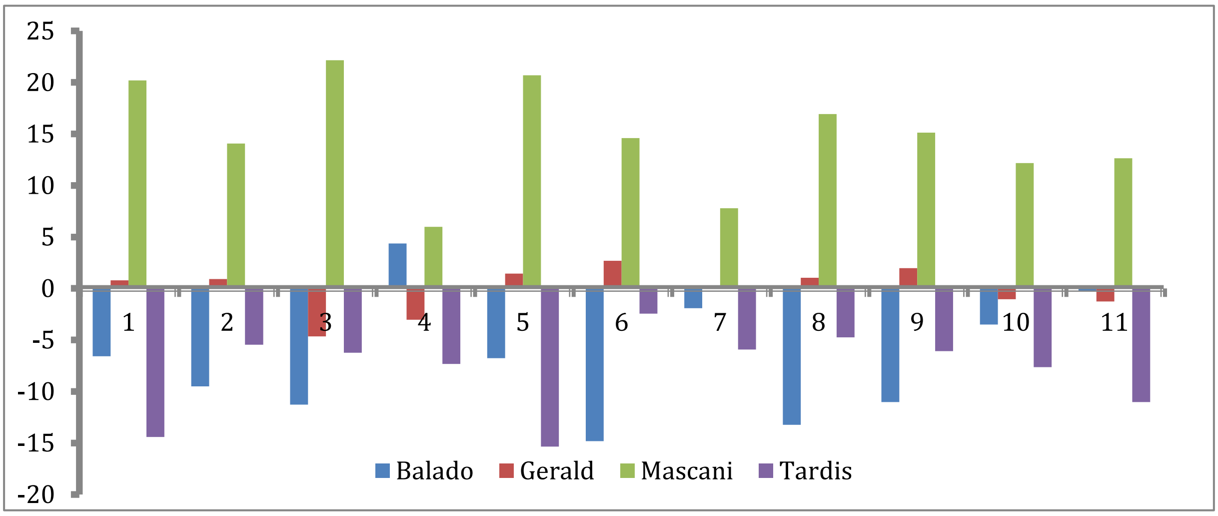


Figure 4.20. *Environment centred genotype hullability (%) by environment*

Joint regression analysis (figure 4.21) showed no interaction with the environment (table 4.8) for Mascani with also higher stability and superiority values. The mean square deviation values for Mascani of 1.13, indicates that it is giving a more predictable response to the environment. This, along with the lowest variance between environments, makes Mascani the first in the ranking. Balado, Gerald and Tardis, showed more variable results. Sensitivity values for Balado (1.683), indicates a higher interaction with the environment (figure 4.20), lower values of stability performance and therefore, a more unpredictable behaviour. Tardis, although more stable than Balado in terms of sensitivity value (1.261), gave a higher mean square deviation value (table 4.8), i.e. a more unpredictable response to the environment.

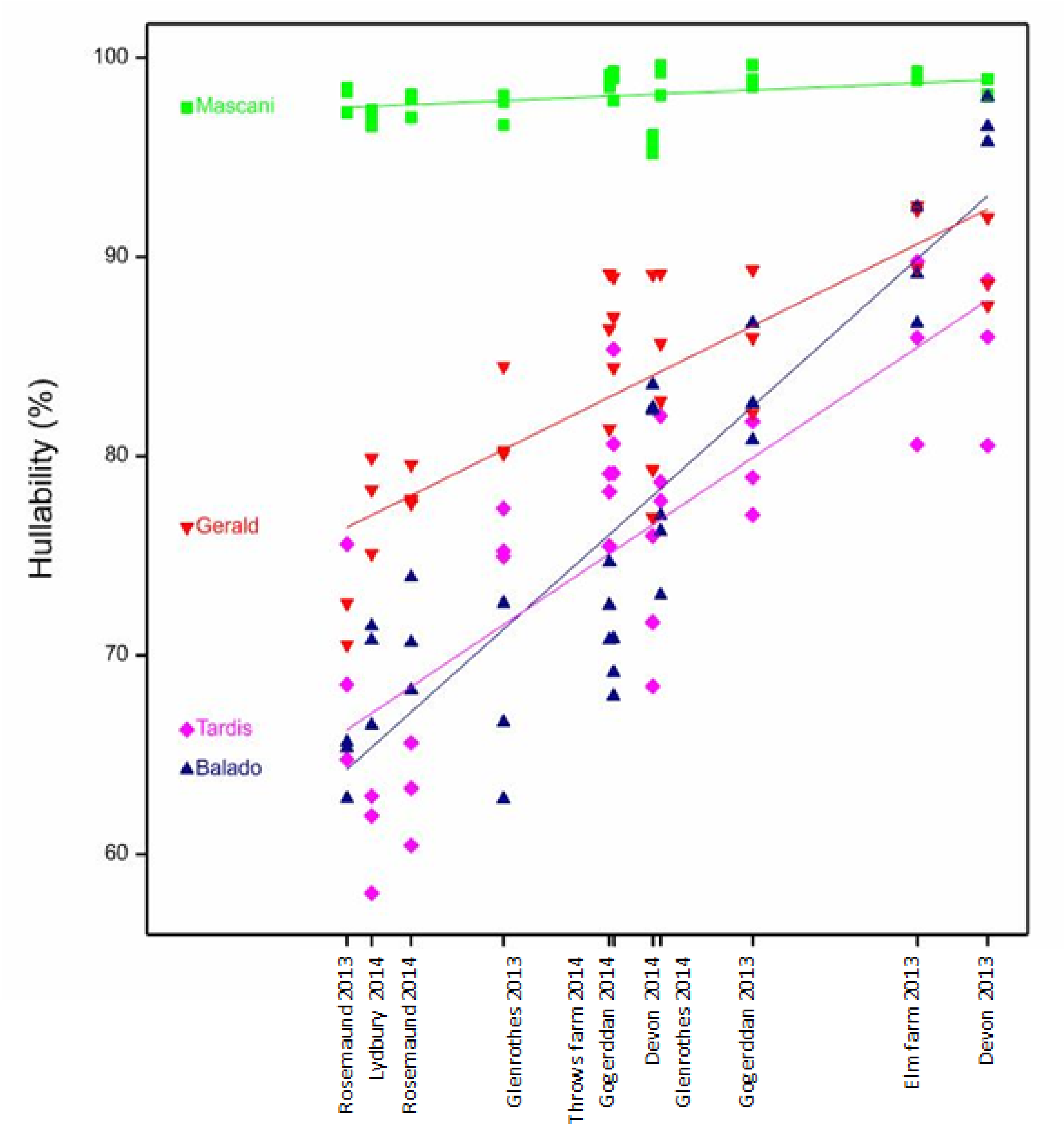


***Figure 4.21**. Joint regression analysis of hullability (%) values for each of the four winter oat varieties at each of the eleven sites across UK at each harvest season (2012/2013 and 2013/2014).*

Table 4.8. *Average hullability (%) overall seasons and site, cultivar superiority, static stability and ranks of the four winter oat varieties over all environments. *Numbers in brackets refers to the position on the ranking of best cultivar.*

Hullability (%)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviation
Varieties					
Balado	76.57	277.7(3)	103.77(4)	1.683(4)	19.54(3)
Gerald	83.24	123.3(2)	34.04(2)	0.934(2)	13.64(2)
Mascani	98.09	0.000(1)	1.120(1)	0.080(1)	1.13(1)
Tardis	75.47	282.2(4)	67.48(3)	1.261(3)	25.28(4)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

4.6. Thousand grain weight

There was a significant (p-value <0.001, two way ANOVA) effect of environment on thousand grain weight (TGW) which ranged from 35.4 g (Throws Farm 2014) to 48.2 g (Lydbury 2014) across the 11 environments (table 4.4) and a significant effect (p-value <0.001) of variety with the mean TGW of Mascani (45.1 g) significantly greater than Gerald (36.9 g) with Balado and Tardis intermediate (table 4.9). The results observed in 2013, for all varieties except Gerald, had a higher variance, (figure 4.22), in comparison with the 2014 harvest season.

There was also a significant (p-value <0.001) difference between varieties in their sensitivity to environment as shown by joint regression (table 4.9, figure 4.23). Mascani showed a higher stability (8.971), superiority value (1.008) and with a sensitivity value of 0.718, it was the most stable variety, being therefore, the first in the ranking (table 3.9). However, the mean square deviation of 4.092 for Mascani suggests that it does not display a predictable response to the environment, while Tardis, the second in the ranking and with a higher sensitivity value (0.887) gives the most predictable response.

Balado on the other hand, is the fourth in the ranking, and therefore, the least stable, (table 4.9). In environments where the mean TGW was high, Balado performed better (figure 4.23) with its regression line intersecting that for Tardis. However, its TGW was lower than Tardis in environments with a low mean TGW. Gerald, although more stable than Balado in terms of sensitivity value, 1.261, gave a higher mean square deviation value, which means that it has a more unpredictable response to the environment.

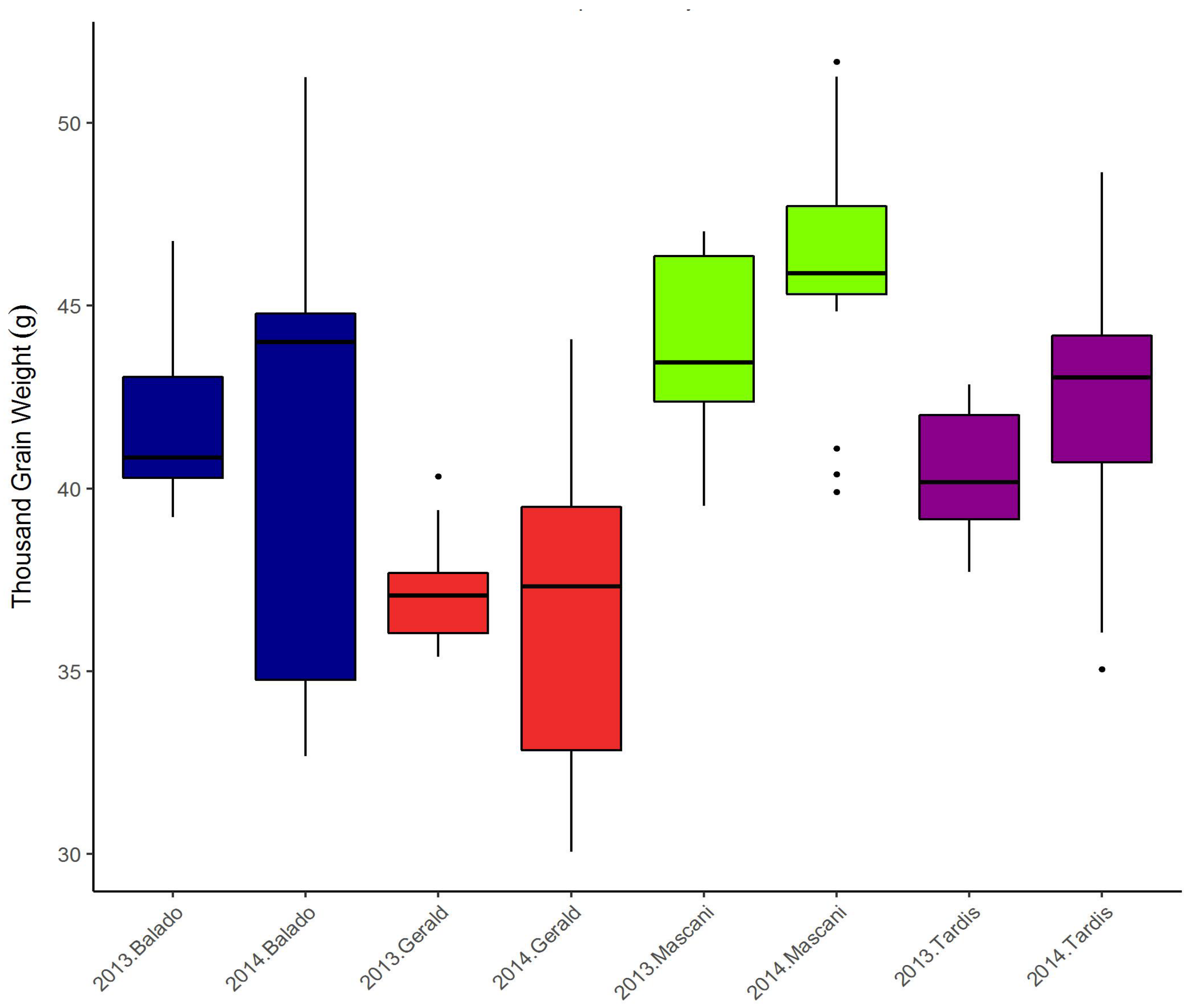


Figure 4.22. *Box plot for thousand Grain Weight (g) values of the four winter oat varieties, Balado, Gerald, Mascani and Tardis for 2012- 2013 and 2013-2014 harvest seasons. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

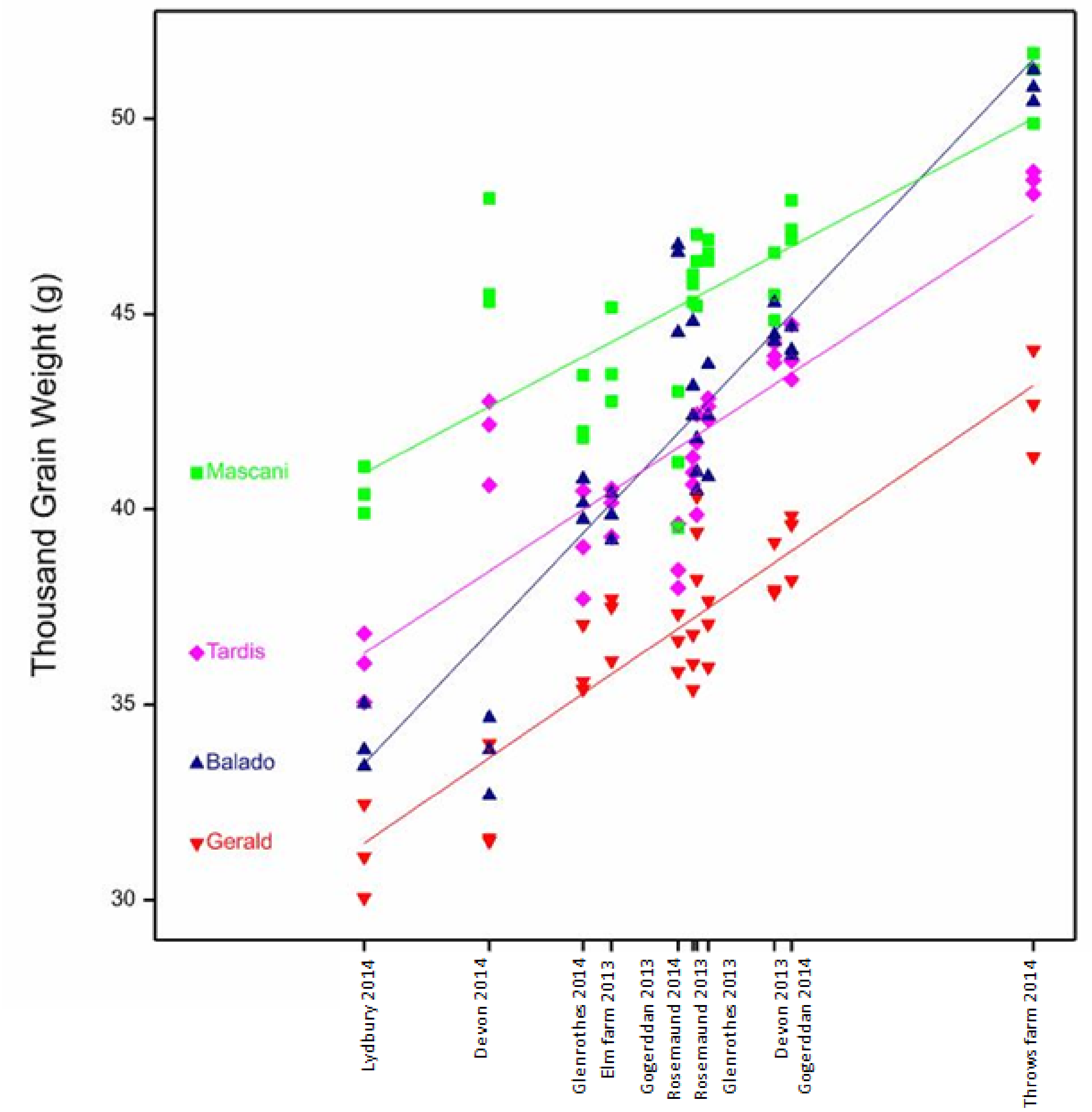


Figure 4.23. *Joint regression analysis of Thousand Grain Weight (g) from the four winter oat varieties and of the eleven sites across UK for 2012- 2013 and 2013-2014 harvest seasons.*

Table 4.9. *Average Thousand Grain Weight (g) overall seasons and site, cultivar superiority, static stability and ranks of the four winter oat varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Thousand Grain Weight (g)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviation
Varieties					
Balado	41.86	12.639(3)	24.733(4)	1.427(4)	3.594(3)
Gerald	36.89	39.735(4)	10.150(2)	0.927(3)	1.715(1)
Mascani	45.15	1.008(1)	8.971(1)	0.718(1)	4.092(4)
Tardis	41.53	9.134(2)	10.776(3)	0.888(2)	2.833(2)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Grain chemical composition traits

Table 4.10. *Groat oil, protein and groat β-glucan content (%), average values ± s.e.m by site, i.e. eleven locations across the country and at each harvest season.*

Site	Site code	Year	Oil content	s.e.m	Protein content	s.e.m	β-Glucan content	s.e.m
Gogerddan	1	2013	6.96	0.06	12.12	0.07	4.15	0.04
Glenrothes	2	2013	6.91	0.06	11.60	0.06	4.18	0.04
Devon	3	2013	7.53	0.06	10.27	0.07	3.78	0.04
Rosemaund	4	2013	6.49	0.05	14.11	0.12	4.40	0.06
Elm farm	5	2013	7.32	0.05	11.33	0.05	3.87	0.05
Gogerddan	6	2014	7.91	0.07	8.92	0.03	3.33	0.07
Lydbury	7	2014	7.37	0.03	11.01	0.06	3.40	0.06
Glenrothes	8	2014	7.82	0.05	9.79	0.06	3.15	0.05
Devon	9	2014	7.33	0.04	9.06	0.06	3.53	0.07
Rosemaund	10	2014	7.40	0.05	9.66	0.03	3.40	0.06
Throws farm	11	2014	7.91	0.05	14.29	0.05	3.44	0.07
Overall average			7.36	0.16	11.11	0.27	3.69	0.09
Significance Genotype			*p-value<0.001*		*p-value<0.001*		*p-value<0.001*	
Significance Site			*p-value<0.001*		*p-value<0.001*		*p-value<0.001*	
Significance Interaction			*p-value<0.001*		*p-value<0.001*		*p-value<0.001*	

4.7. Oil content

Significant differences (p-value <0.001, two way ANOVA) were obtained both between genotypes and between sites regarding grain oil content (%) (table 4.10). There was statistical significant interaction between the two factors, as well. Average values by variety and of each year (figure 4.24), shows that Mascani has the lowest value between varieties, reaching a minimum in 2013 of 6.4%, and an overall mean of 6.7% (table 4.10). On the other hand, Tardis gave the highest overall value, 7.7%, similar to Balado at 7.6%. At the same time, Tardis was more stable (figure 4.24), in terms of variance around the average, although with higher differences between seasons than Balado.

By sites (table 4.10), the lowest result was from Rosemaund 2013 (site 3), with a value of 6.49%, while Gogerddan and Throws Farm both in 2014, were the highest in oil content with 7.91%. 2012/2013 harvest season had lower results in comparison with 2013/2014 harvest season by varieties and by sites.

Table 4.11. *Average oil content (g) overall seasons and site, cultivar superiority, static stability and ranks of the four winter oat varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Oil Content (%)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviation
Varieties					
Balado	7.5	0.048(2)	0.376(4)	1.250(4)	0.082(4)
Gerald	7.3	0.142(3)	0.163(1)	0.848(1)	0.033(1)
Mascani	6.7	0.649(4)	0.208(3)	0.950(3)	0.048(3)
Tardis	7.6	0.033(1)	0.196(2)	0.943(2)	0.043(2)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value=0.041*	*p-value<0.001*

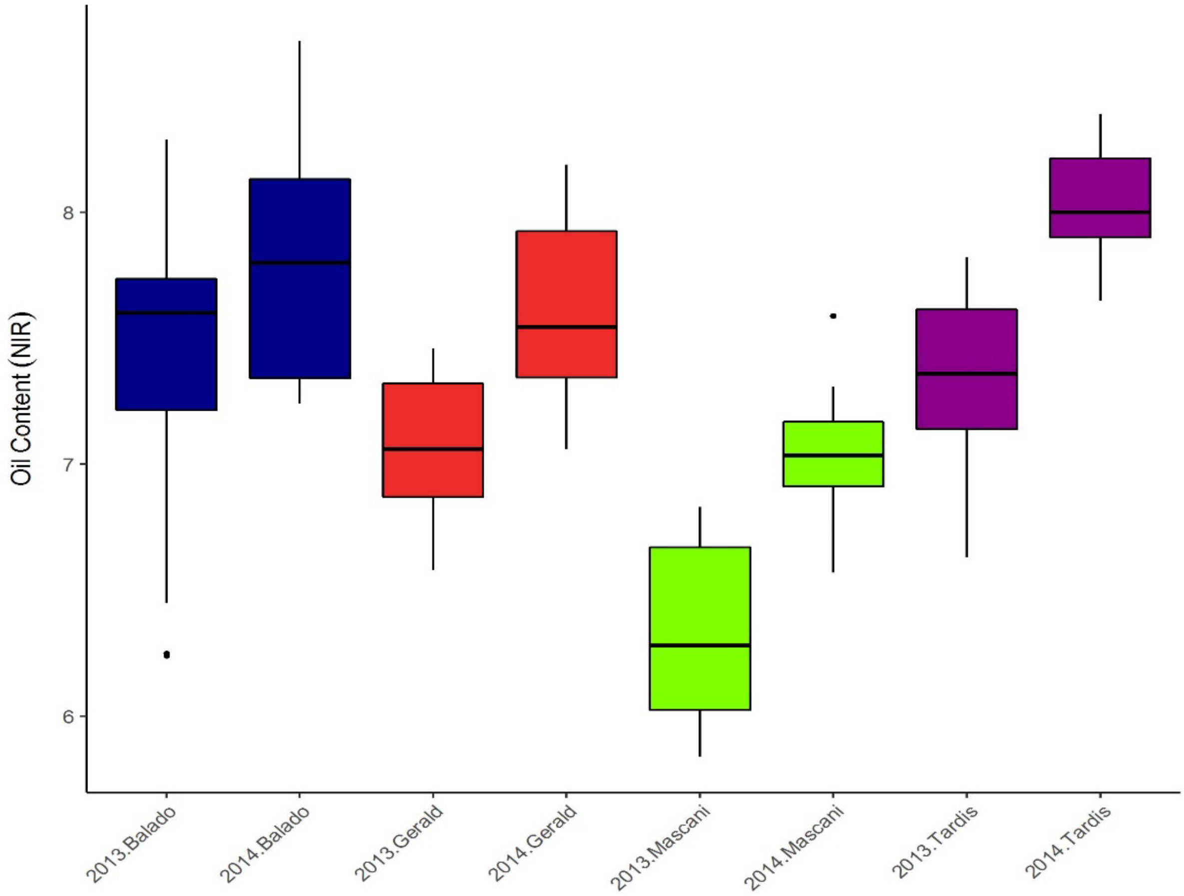


Figure 4.24. *Box plot of grain oil content (%) values of the four winter oat varieties, Balado, Gerald, Mascani and Tardis for 2012- 2013 and 2013-2014 harvest seasons. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

There was also a significant (p-value<0.004) difference between varieties in their sensitivity to environment (figure 4.25). Balado (sensitivity 1.25) was the most sensitive to environment with Gerald (slope 0.85) the least sensitive to environment, with Mascani and Tardis intermediate (table 4.11). Tardis with the highest average oil content, 7.6%, had the highest superiority value. Gerald with an average oil content of 7.3% had the best static stability, meaning that it was the most stable between varieties. The mean square deviation values also show that Gerald with the lowest value, indicating that it gave the most predictable response to the environment. Balado, on the other hand, having higher average oil content (7.5%), than Gerald (7.3%) and Mascani (6.7%), was the worst in terms of static stability. It also, had the highest mean square deviation so was the least stable and the most unpredictable of the four varieties.

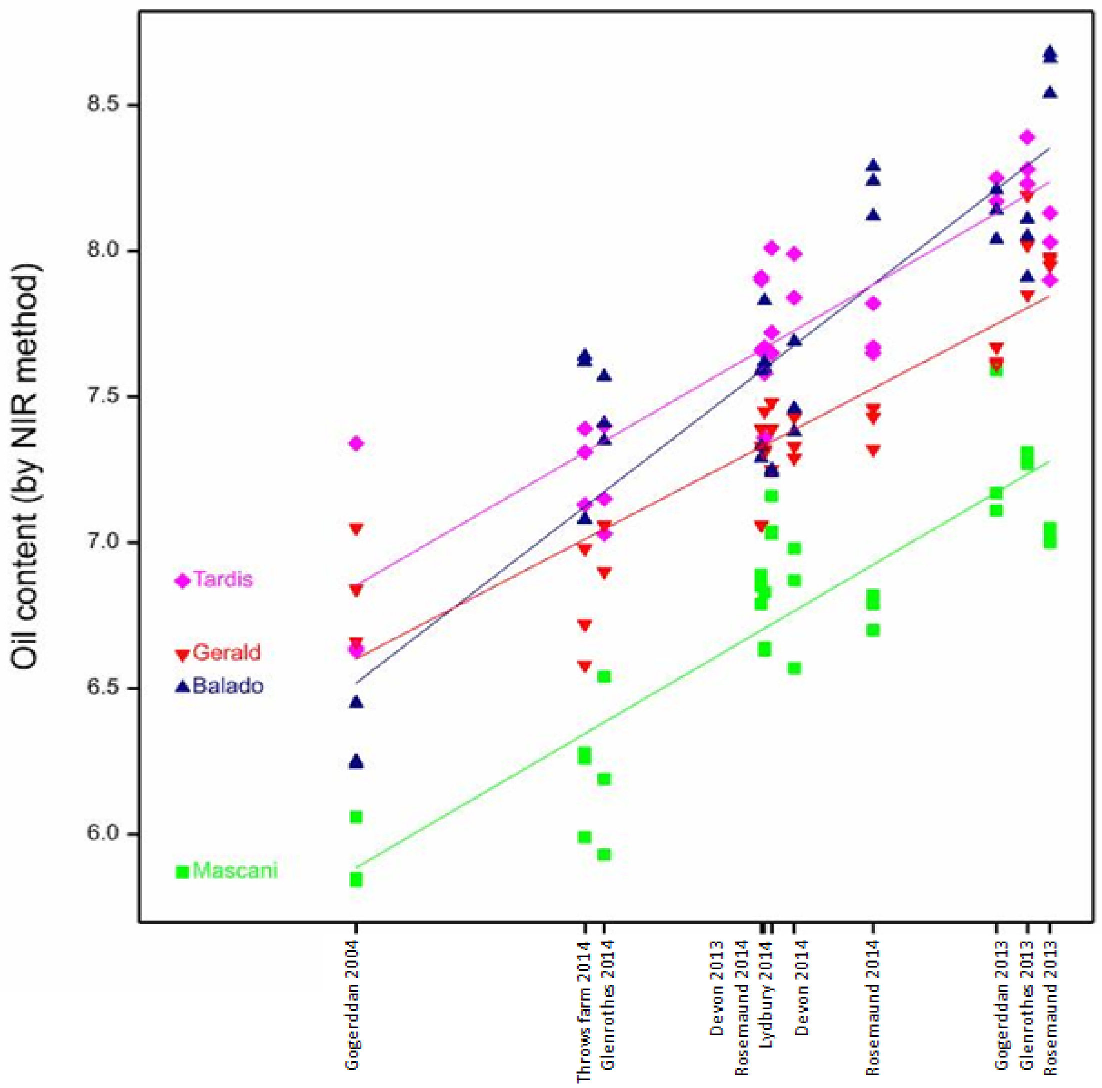


Figure 4.25. *Joint regression analysis of oil content (g) from the four winter oat varieties and of the eleven sites across UK for 2012- 2013 and 2013-2014 harvest seasons.*

4.8. Protein content

There were significant statistical differences between genotypes, sites and significant interaction between the two factors (p-value<0.001 two way ANOVA, table 4.10). The mean protein content (table 4.10 and figure 4.26) in 2013 was higher than

2014. Although Tardis had an overall average protein content higher than Balado with 12.2% in 2013, it was Balado that was the highest variety, followed by Gerald and Tardis, with 11.8% protein content. By sites (table 4.10), Rosemaund 2013 had the highest results for all varieties, with a minimum value of 12.5% from Gerald and a maximum value of 14.8% from Balado. Gogerddan 2014, with 8.94% was the lowest mean site protein content.

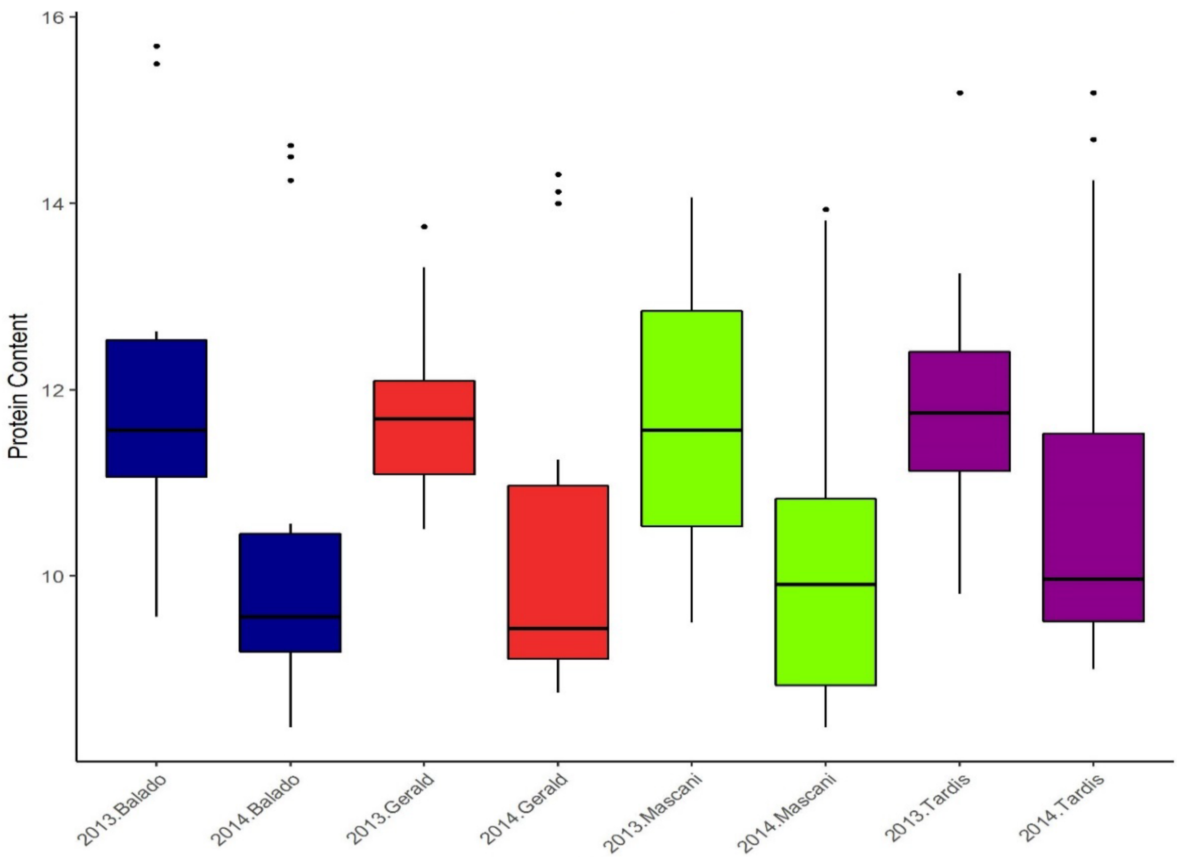


Figure 4.26. *Grain protein content (%) average value of the four winter oat varieties, Balado, Gerald, Mascani and Tardis for 2012- 2013 and 2013-2014 harvest seasons. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile*

The range of protein values as displayed in figure 4.27 reflects the sites that have the potential to discriminate between varieties´ performances, i.e. to investigate further in which sites a genotype protein values are better in comparison with the rest of sites. Therefore, site 4, Rosemaund 2012/2013, site 7, Lydbury 2014, and site 9, Devon 2014, showing a wider range of values suggest that these are the best environments to discriminate between the four varieties. However, the rest of the sites did not have visible differences in the performance of the different genotypes and therefore they are not useful to discriminate between genotypes.

Joint regression analysis (table 4.12 and figure 4.28), showed statistical significance for sensitivity to the environment (p-value <0.001). The ranking showed Tardis in the first place (table 4.12) in terms of static stability and sensitivity, despite having lower protein content. It however, had the highest mean square deviation. Balado was the first in ranking in terms of cultivar superiority but also had the lowest stability and sensitivity across environments.

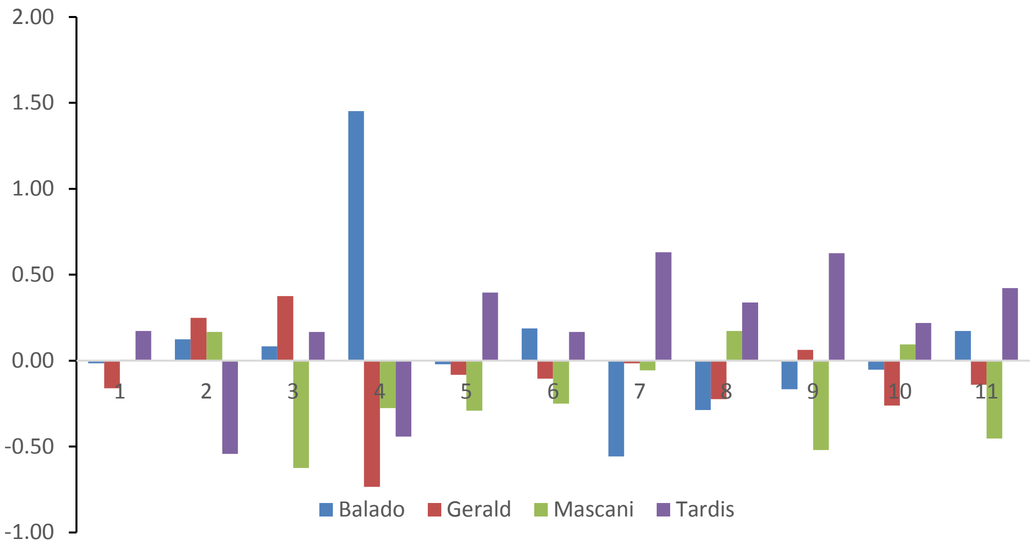


Figure 4.27. *Environment centred genotype grain protein content (%) by environment of the four winter oat varieties, Balado, Gerald, Mascani and Tardis, for 2012- 2013 and 2013-2014 harvest seasons*

Table 4.12. *Average protein content (g) overall seasons and site, cultivar superiority, static stability and ranks of the four winter oat varieties.*

Protein Content (%)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviations
Varieties					
Balado	11.6	0.130(1)	4.716(4)	1.159(4)	0.284(2)
Gerald	11.2	0.309(3)	3.031(2)	0.933(2)	0.122(1)
Mascani	11.2	0.331(4)	3.381(3)	0.986(3)	0.315(3)
Tardis	11.5	0.193(2)	3.023(1)	0.922(1)	0.357(4)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

4.9. β-Glucan content

There were significant statistical significant differences (p-value <0.001, two way ANOVA) between genotypes, sites and interaction between the two factors. Balado had the highest β-glucan content (table 4.13 and figure 4.29), in both harvest seasons with an overall average value of 4.6% (table 4.13), whilst Gerald had the lowest of 3.6%. Tardis, with an overall average value of 3.7%, showed a wider range of values than the rest of varieties. By sites (table 4.10), Rosemaund 2013 had the highest values (4.4%), whilst Devon in 2013 had the lowest value, 3.8%.

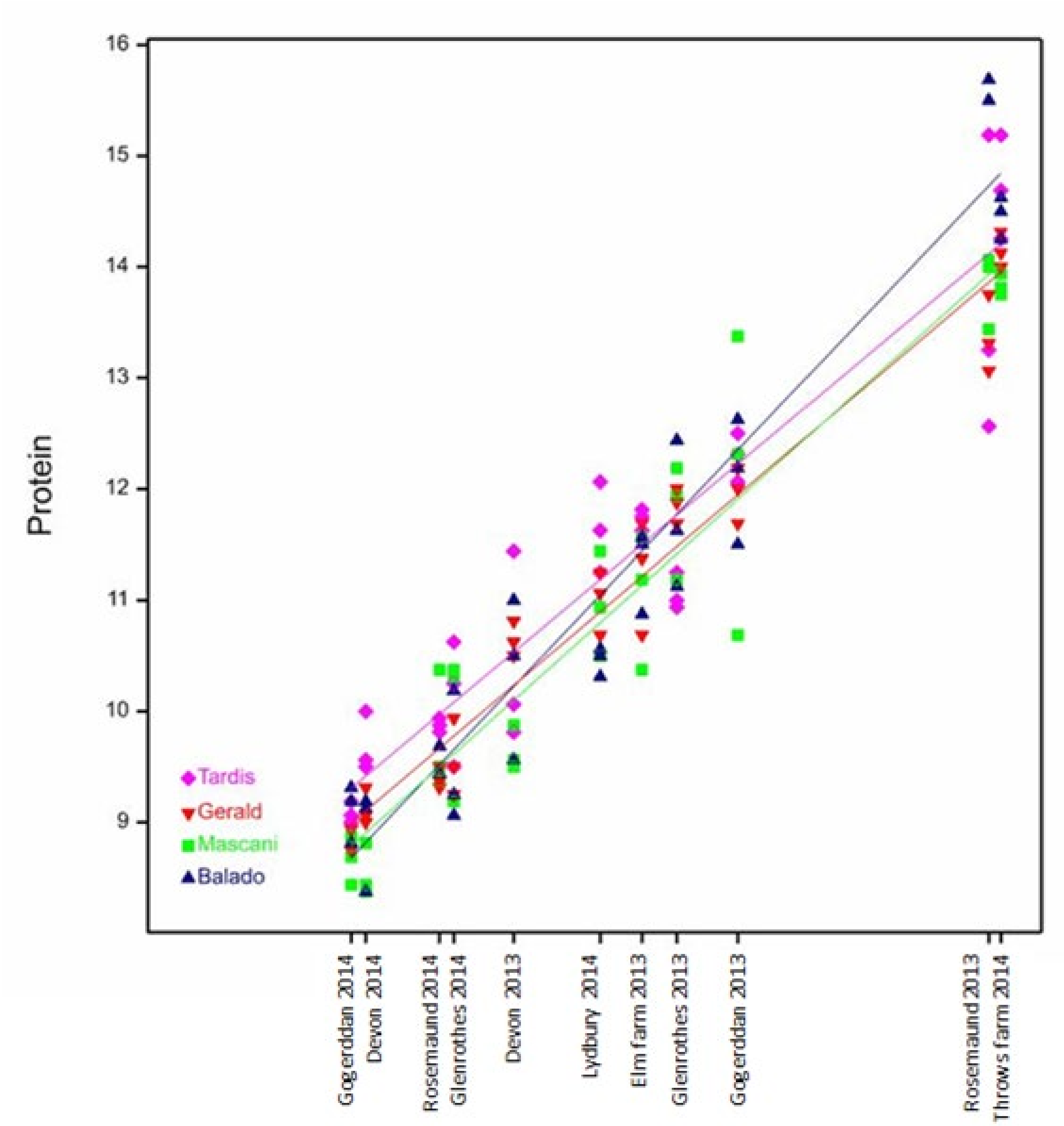


Figure 4.28. *Joint regression graph for grain protein content (%) values of the four winter oat varieties and the eleven sites across UK, for 2012- 2013 and 2013-2014 harvest seasons*.

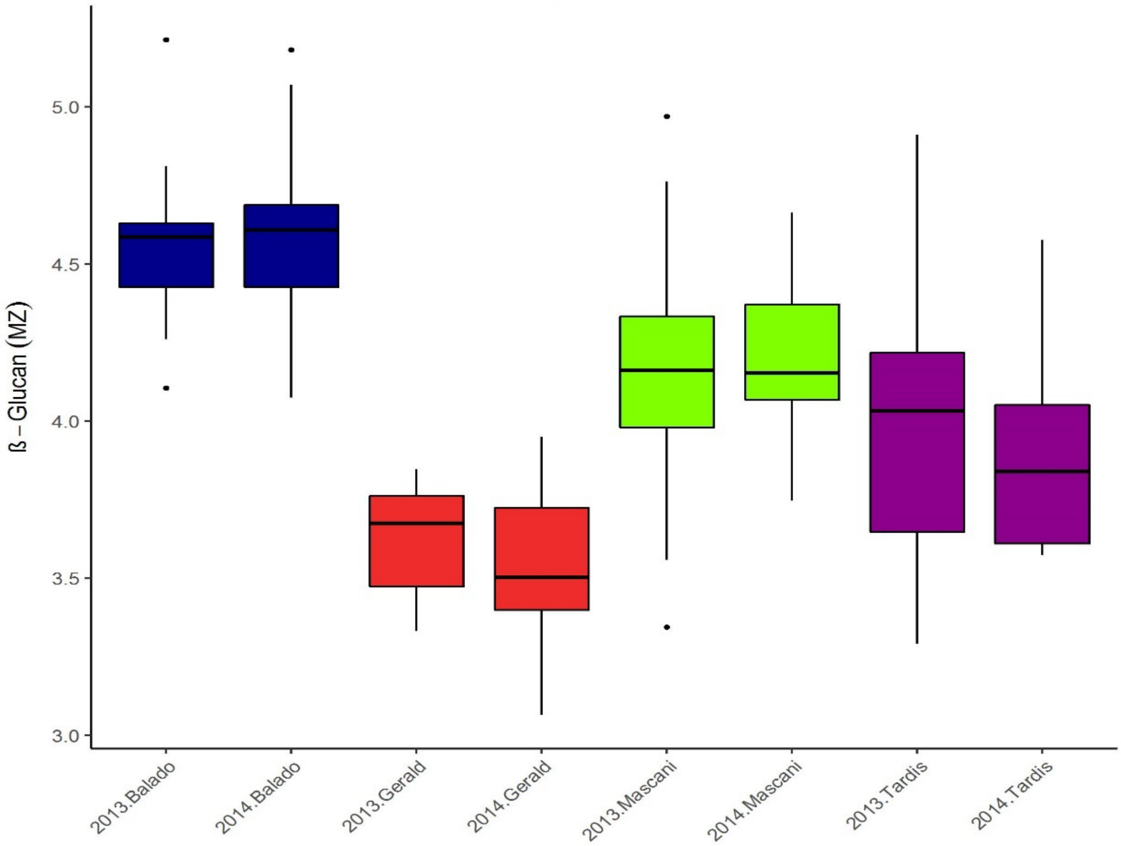


Figure 4.29. *Box plot of grain β-glucan content (%) values of the four winter oat varieties for 2012-2013 and 2013-2014 harvest seasons. The box plot* (Weisstein 2018) *represents between first quartile (25 %) and the third quartile of the data (75 %), with the horizontal line inside the box indicating the median. The whiskers represents the data within 1.5 times the interquartile range of the first quartile and the third quartile. Data points represented by stars are outliers, i.e. they are more than farthest from 1.5 times the interquartile range of the first quartile and the third quartile.*

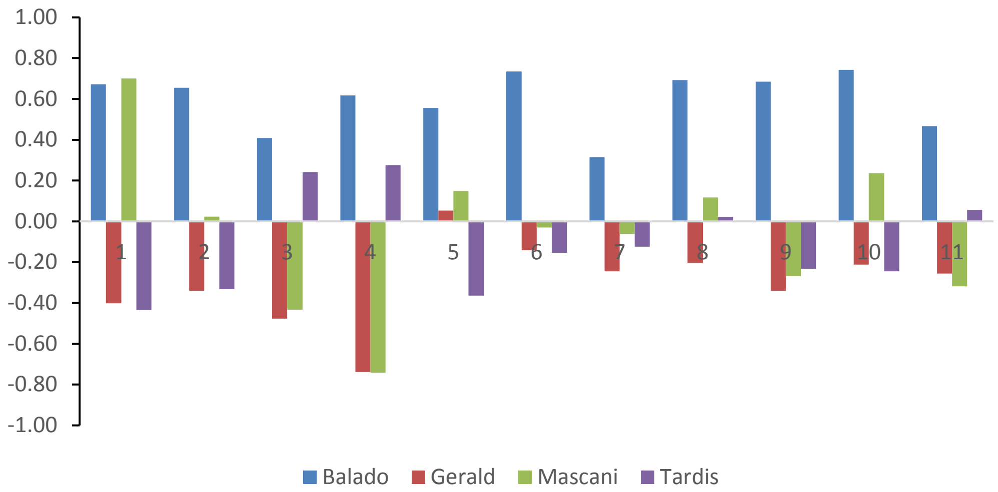


Figure 4.30. *Environment centred genotype grain β-glucan content (%) by environment of the four winter oat varieties, Balado, Gerald, Mascani and Tardis, for 2012-2013 and 2013-2014 harvest seasons.*

The effect of environment on β-glucan (figure 4.30), indicates that at almost all sites, Balado had the highest values. This analysis also indicates the sites that would be more interesting to discriminate between varieties´ performances. However, all sites showed similar results, with no visible differences in the performance of the different genotypes and therefore, no site was identified that was useful to discriminate between genotypes.

Joint regression analysis showed statistically significant sensitivity values (p-value <0.05) (table 4.13 and figure 4.31), indicating that there is variation in genotypes behaviour with changing environments. Cultivar superiority, table 4.13 and figure 4.31, shows Balado with the highest β-glucan content, 4.6%. The most stable across environments is Gerald, 0.032 static stability and the lower mean square deviation, 0.045, but it had also the lowest mean value (table 4.13). The variety with the highest sensitivity (1.645), was Tardis.

Table 4.13. *Average β-glucan content (%), cultivar superiority, static stability and mean square deviation values of the four winter varieties. *Numbers in brackets refers to the position on the ranking of best cultivar.*

β-Glucan Content (%)	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square deviation
Varieties					
Balado	4.3	3.6e-6(1)	0.037(2)	0.645(2)	0.059(3)
Gerald	3.6	0.559(4)	0.032(1)	0.377(1)	0.045(1)
Mascani	3.9	0.130(2)	0.078(3)	1.200(3)	0.069(4)
Tardis	3.7	0.257(3)	0.109(4)	1.645(4)	0.049(2)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value=0.003*	*p-value<0.001*

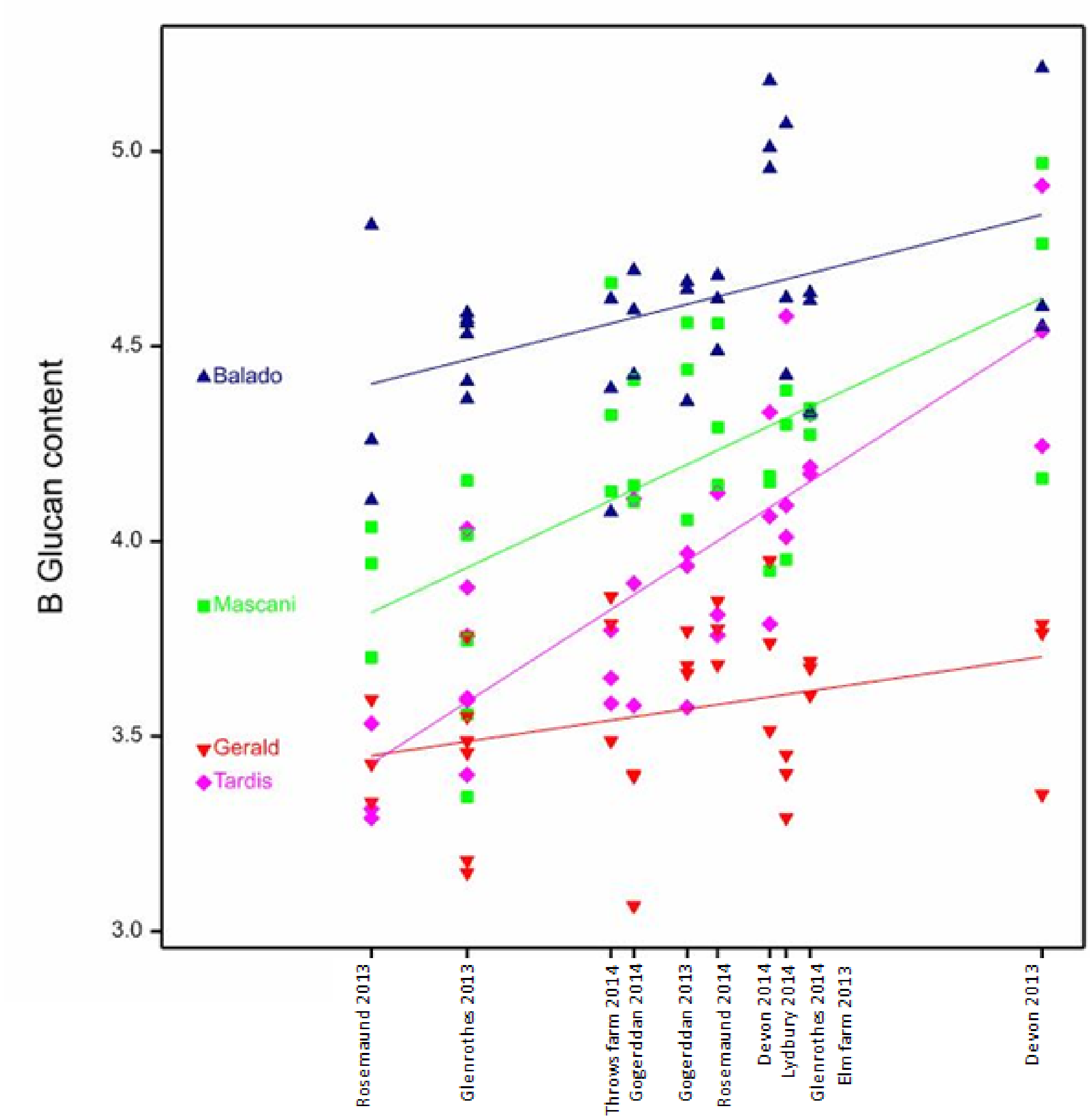


Figure 4.31. *Joint regression graph for grain β-glucan content (%) as measured using the megazyme (MZ) method for the four winter oat varieties and the eleven sites across UK, for 2012- 2013 and 2013-2014 harvest seasons*.

4.10. Grain size and shape

MARVIN image analysis was conducted on the grain prior to de-hulling and on the de-hulled groats of the same sample used for kernel content and hullability determination. From the results obtained, a mean value for a range of grain and groat dimensions were determined for each sample, i.e. width, length, area and grain and groat ratio (equation 8, section 3.6) and shape descriptors, i.e. circularity, and grain density (equations 9 and 10, section 3.6). Two way ANOVA showed statistical significance differences between genotypes (p-value <0.001), environments (p-value <0.001) and significant interactions between them (p-value<0.001), table 4.14 and 4.15, for all grain size and shape traits under study.

Gerald had the lowest mean grain and groat area values (table 4.15 and 4.16.a and 4.16.b), but the lowest mean square deviation in both cases, meaning that it was the more stable in grain and groat area performance. The variety with the highest sensitivity to the environment and the highest static stability grain area value however was Balado (table 4.16.a). The highest mean grain area was found in Balado at Rosemaund in 2013 with a value of 30 mm^2 whereas the lowest value was obtained for Gerald at Throws Farm 2014 (22 mm^2). In terms of groat area, Mascani displayed the highest mean value (table 4.16.b) with also the best cultivar superiority and static stability performance. Interestingly, Gerald in terms of groat area, had the lowest cultivar superiority value.

Table 4.14. *Mean grain and groat area (mm^2), width (mm) and length (mm) of each site at both harvest seasons, 2012/2013 and 2013/2014, of the four winter varieties.*

Site	*Site code*	*Year*	*Area mm^2*	*s.e.m*	*Width mm*	*s.e.m*	*Length mm*	*s.e.m*	*Grain Ratio*	*s.e.m*	*Area Groat mm^2*	*s.e.m*	*Width Groat mm*	*s.e.m*	*Length Groat mm*	*s.e.m*	*Groat Ratio*	*s.e.m*
Gogerddan	1	2013	28.5	1.7	3.1	0.0	12.8	0.8	0.25	0.3	15.5	1.0	2.6	0.0	7.1	0.4	0.36	0.2
Glenrothes	2	2013	26.7	1.3	3.1	0.0	11.9	0.6	0.26	0.2	15.1	0.8	2.5	0.0	7.1	0.3	0.36	0.1
Devon	3	2013	27.3	1.3	3.1	0.0	12.5	0.7	0.25	0.2	14.3	0.9	2.5	0.0	6.8	0.3	0.36	0.1
Rosemaund	4	2013	28.0	1.5	3.1	0.1	12.6	0.5	0.24	0.2	15.5	1.5	2.5	0.1	7.3	0.5	0.34	0.1
Elm farm	5	2013	27.2	1.6	3.1	0.0	12.2	0.7	0.26	0.2	15.3	1.1	2.6	0.1	7.1	0.4	0.37	0.1
Gogerddan	6	2014	24.8	1.8	3.1	0.1	10.7	0.5	0.29	0.2	13.8	1.5	2.5	0.1	6.6	0.4	0.38	0.1
Lydbury	7	2014	26.6	1.5	3.4	0.1	10.7	0.5	0.31	0.1	16.3	1.0	2.7	0.1	7.1	0.3	0.38	0.1
Glenrothes	8	2014	25.8	1.5	3.2	0.0	10.8	0.6	0.30	0.2	14.9	0.9	2.6	0.0	6.8	0.3	0.38	0.1
Devon	9	2014	26.4	1.4	3.2	0.0	11.0	0.6	0.29	0.2	15.1	0.9	2.6	0.0	6.8	0.3	0.39	0.1
Rosemaund	10	2014	25.6	1.5	3.1	0.1	11.1	0.6	0.28	0.2	14.7	1.2	2.5	0.1	6.9	0.4	0.37	0.1
Throws farm	11	2014	23.9	1.4	2.9	0.1	10.7	0.5	0.28	0.1	13.7	1.1	2.4	0.1	6.8	0.3	0.36	0.1
Overall Mean			26.46	0.59	3.09	0.01	11.54	0.26	0.27	0.01	14.94	0.34	2.55	0.06	6.95	0.15	0.37	0.01
Significance Genotype			*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*	
Significance Site			*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*	
Significance Interaction			*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*		*p-value<0.001*	

Table 4.15. *Grain and groat size and shape, i.e. area (mm²), length (mm), width (mm), and grain and groat ratio average values ± s.e.m. by variety, at each location and harvest season*

Selection	Site	Site code	Year	Area	s.e.m	Width	s.e.m	Length	s.e.m	Grain ratio	s.e.m	Area Groat	s.e.m	Width Groat	s.e.m	Length Groat	s.e.m	Groat ratio	s.e.m
Balado	Gogerddan	1	2013	28.5	0.6	3.1	0.0	12.9	0.5	0.24	0.0	15.4	0.1	2.5	0.0	7.2	0.1	0.35	0.0
	Glenrothes	2	2013	27.7	0.3	3.0	0.0	12.5	0.0	0.24	0.0	15.0	0.4	2.5	0.0	7.2	0.1	0.34	0.0
	Devon	3	2013	28.5	0.5	3.1	0.0	13.2	0.2	0.23	0.0	14.1	0.1	2.4	0.0	6.9	0.0	0.35	0.0
	Rosemaund	4	2013	30.0	0.2	3.2	0.0	13.0	0.1	0.24	0.0	17.5	0.3	2.6	0.0	8.0	0.0	0.32	0.0
	Elm farm	5	2013	28.0	0.5	3.1	0.0	12.6	0.1	0.25	0.0	15.4	0.2	2.5	0.0	7.3	0.1	0.34	0.0
	Gogerddan	6	2014	24.4	0.4	2.9	0.0	10.9	0.2	0.27	0.0	12.5	0.2	2.3	0.0	6.5	0.1	0.36	0.0
	Lydbury	7	2014	28.0	0.3	3.5	0.0	11.0	0.2	0.31	0.0	17.0	0.1	2.8	0.0	7.4	0.0	0.38	0.0
	Glenrothes	8	2014	27.3	0.2	3.2	0.0	11.4	0.1	0.28	0.0	15.3	0.2	2.6	0.0	7.0	0.0	0.37	0.0
	Devon	9	2014	27.5	0.6	3.2	0.0	11.6	0.4	0.28	0.0	15.6	0.3	2.6	0.0	7.0	0.1	0.37	0.0
	Rosemaund	10	2014	26.5	0.3	3.1	0.0	11.3	0.1	0.28	0.0	15.1	0.3	2.5	0.0	7.1	0.0	0.36	0.0
	Throws farm	11	2014	23.8	0.1	2.9	0.0	10.8	0.0	0.27	0.0	13.6	0.2	2.3	0.0	6.9	0.1	0.34	0.0
	Overall Mean			27.5	1.8	3.1	0.2	12.0	0.9	0.3	0.0	15.4	1.4	2.5	0.1	7.2	0.4	0.3	0.0
Gerald	Gogerddan	1	2013	26.2	0.7	3.1	0.0	11.6	0.2	0.27	0.0	14.2	0.4	2.6	0.0	6.6	0.1	0.39	0.0
	Glenrothes	2	2013	24.8	0.2	3.1	0.0	10.9	0.0	0.28	0.0	14.0	0.3	2.5	0.0	6.6	0.1	0.38	0.0
	Devon	3	2013	25.4	0.1	3.0	0.0	11.6	0.0	0.26	0.0	13.3	0.3	2.5	0.0	6.4	0.1	0.39	0.0
	Rosemaund	4	2013	26.2	0.1	3.0	0.0	11.8	0.2	0.26	0.0	13.9	0.2	2.4	0.0	6.7	0.1	0.36	0.0
	Elm farm	5	2013	24.6	0.4	3.1	0.0	11.0	0.1	0.28	0.0	13.7	0.1	2.6	0.0	6.4	0.0	0.40	0.0
	Gogerddan	6	2014	22.4	0.8	2.9	0.0	10.0	0.3	0.29	0.0	12.5	0.5	2.5	0.0	6.0	0.2	0.41	0.0
	Lydbury	7	2014	24.3	0.6	3.2	0.0	10.0	0.2	0.32	0.2	14.6	0.5	2.7	0.1	6.6	0.1	0.40	0.0
	Glenrothes	8	2014	23.7	0.3	3.1	0.0	10.0	0.1	0.31	0.0	13.4	0.4	2.6	0.0	6.3	0.1	0.41	0.0
	Devon	9	2014	24.2	0.2	3.1	0.0	10.2	0.1	0.31	0.0	14.3	1.0	2.6	0.0	6.5	0.4	0.40	0.0

	Rosemaund	10	2014	23.2	0.5	3.0	0.0	10.3	0.2	0.29	0.0	12.9	0.3	2.5	0.0	6.2	0.1	0.40	0.0
	Throws farm	11	2014	22.0	0.4	2.9	0.0	9.9	0.0	0.29	0.0	12.5	0.2	2.4	0.0	6.2	0.0	0.38	0.0
	Overall Mean			24.4	1.4	3.1	0.1	10.8	0.7	0.3	0.0	13.6	0.7	2.5	0.1	6.5	0.2	0.4	0.0
Mascani	Gogerddan	1	2013	29.8	1.4	3.2	0.0	13.2	0.6	0.24	0.0	16.9	0.3	2.6	0.0	7.5	0.2	0.35	0.0
	Glenrothes	2	2013	27.7	0.7	3.1	0.0	12.0	0.3	0.26	0.0	16.1	0.3	2.6	0.0	7.3	0.0	0.35	0.0
	Devon	3	2013	27.6	0.7	3.1	0.0	12.3	0.2	0.25	0.0	15.5	0.2	2.5	0.0	7.1	0.1	0.36	0.0
	Rosemaund	4	2013	28.2	1.0	3.1	0.0	12.6	0.4	0.24	0.0	15.7	0.4	2.4	0.1	7.5	0.0	0.32	0.0
	Elm farm	5	2013	28.2	0.2	3.2	0.0	12.4	0.1	0.26	0.0	16.6	0.1	2.7	0.0	7.3	0.0	0.36	0.0
	Gogerddan	6	2014	26.1	0.5	3.2	0.0	10.7	0.2	0.30	0.0	15.8	0.3	2.7	0.0	7.0	0.1	0.38	0.0
	Lydbury	7	2014	26.7	0.5	3.3	0.1	10.6	0.1	0.31	0.0	16.9	0.2	2.8	0.0	7.2	0.1	0.39	0.0
	Glenrothes	8	2014	25.7	0.7	3.2	0.0	10.5	0.3	0.31	0.0	15.8	0.4	2.7	0.0	6.9	0.2	0.39	0.0
	Devon	9	2014	26.5	0.2	3.3	0.0	10.6	0.1	0.31	0.0	15.4	1.4	2.7	0.1	6.8	0.4	0.37	0.0
	Rosemaund	10	2014	26.1	0.2	3.2	0.0	10.9	0.1	0.29	0.0	16.0	0.2	2.6	0.0	7.1	0.0	0.36	0.0
	Throws farm	11	2014	25.0	0.4	3.0	0.0	10.8	0.1	0.28	0.0	15.4	0.1	2.6	0.0	7.1	0.0	0.36	0.0
	Overall Mean			27.2	1.4	3.2	0.1	11.6	1.0	0.3	0.0	16.0	0.5	2.6	0.1	7.2	0.2	0.4	0.0
Tardis	Gogerddan	1	2013	29.4	0.6	3.1	0.0	13.4	0.2	0.23	0.0	15.4	0.5	2.6	0.0	7.2	0.1	0.36	0.0
	Glenrothes	2	2013	26.6	0.1	3.1	0.0	12.1	0.1	0.25	0.0	15.1	0.5	2.5	0.0	7.1	0.1	0.35	0.0
	Devon	3	2013	27.8	0.4	3.0	0.0	13.1	0.2	0.23	0.0	14.2	0.3	2.5	0.0	6.8	0.1	0.36	0.0
	Rosemaund	4	2013	27.7	0.4	3.0	0.0	12.9	0.3	0.23	0.0	14.7	1.0	2.4	0.1	7.2	0.3	0.33	0.0
	Elm farm	5	2013	27.9	0.1	3.1	0.0	12.7	0.1	0.25	0.0	15.4	0.2	2.6	0.0	7.2	0.1	0.36	0.0
	Gogerddan	6	2014	26.5	0.3	3.2	0.0	11.3	0.2	0.28	0.0	14.6	0.5	2.5	0.1	6.9	0.1	0.36	0.0
	Lydbury	7	2014	27.5	0.1	3.3	0.0	11.1	0.1	0.30	0.0	16.7	0.1	2.7	0.0	7.4	0.0	0.37	0.0
	Glenrothes	8	2014	26.6	0.3	3.2	0.0	11.2	0.1	0.29	0.0	15.2	0.1	2.6	0.0	7.0	0.0	0.37	0.0
	Devon	9	2014	27.3	0.1	3.2	0.0	11.4	0.1	0.28	0.0	15.1	0.3	2.6	0.0	6.9	0.0	0.38	0.0
	Rosemaund	10	2014	26.6	0.8	3.1	0.0	11.8	0.4	0.26	0.0	14.8	0.2	2.5	0.0	7.0	0.0	0.36	0.0
	Throws farm	11	2014	25.0	0.4	3.0	0.0	11.1	0.1	0.27	0.0	13.9	0.1	2.4	0.0	6.9	0.0	0.35	0.0
	Overall Mean			27.2	1.1	3.1	0.1	12.1	0.3	0.3	0.0	15.0	0.7	2.5	0.1	7.1	0.2	0.4	0.0

Table 4.16.a *Mean grain area (mm^2), cultivar superiority, static stability and mean square deviation values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Balado	27.43	0.370(2)	3.000(4)	1.314(4)	0.098(2)
Gerald	24.35	6.343(4)	1.725(3)	1.041(3)	0.000(1)
Mascani	27.22	0.443(3)	1.588(2)	0.887(2)	1.054(4)
Tardis	27.34	0.368(1)	1.123(1)	0.741(1)	0.764(3)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Table 4.16.b *Mean groat area (mm^2), cultivar superiority, static stability and ranks values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean square Deviation
Balado	15.15	1.015(3)	2.005(4)	1.824(4)	0.982(4)
Gerald	13.59	3.644(4)	0.520(2)	0.852(3)	0.000(1)
Mascani	16.02	0.156(1)	0.297(1)	0.388(1)	0.436(2)
Tardis	15.01	0.932(2)	0.557(3)	0.776(2)	0.545(3)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Mean grain length also differed significantly between environments (p-value <0.001, two way ANOVA), which averaged over all varieties ranged from 10.7 mm to 12.8 mm across the 11 environments (table 4.14). Gerald (10.57 mm) not only had shorter grains than the other 3 varieties but also was the most stable across environments (table 4.17.a). Gerald also had the shortest groats (table 4.15 and 4.17.b). Tardis not only had the longest grains (13.44 mm) but was the most sensitive to the environment (table 4.17.a). Mascani and Balado however had the longest groats across environments.

Table 4.17.a *Mean grain length (mm), cultivar superiority, static stability and ranks values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Balado	11.94	0.038(2)	0.842(3)	1.039(3)	0.873(4)
Gerald	10.68	1.070(4)	0.538(1)	0.841(1)	0.000(1)
Mascani	11.52	0.211(3)	0.971(4)	1.124(4)	0.327(2)
Tardis	12.03	0.013(1)	0.753(2)	0.996(2)	0.545(3)
Significance	*p-value <0.001*	*p-value <0.001*	*p-value <0.001*	*p-value <0.001*	*p-value <0.001*

Table 4.17.b *Mean groat length (mm), cultivar superiority, static stability and ranks values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Balado	7.141	0.021(2)	0.137(4)	1.664(4)	0.691(3)
Gerald	6.429	0.373(4)	0.045(2)	0.850(3)	0.000(1)
Mascani	7.180	0.017(1)	0.049(3)	0.777(2)	0.945(4)
Tardis	7.056	0.043(3)	0.031(1)	0.656(1)	0.509(2)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Mean grain and groat width differed significantly (p-value <0.001, two ways ANOVA) between environments. Grain width ranged from 2.94 mm at Throws Farm to 3.43 mm at Lydbury 2014 across environments (table 4.14). There was also a significant (p-value <0.001) difference between varieties with Mascani (3.23 mm) having wider grain than Tardis and Balado and all greater than Gerald (3.09 mm) (table 4.15). There was also a significant difference between varieties in their sensitivity to environment (table 4.18.a and 4.18b) for both grain and groat width. Balado was more sensitive to the environment than the other three varieties, whilst Mascani and Tardis were the most stable. Gerald had the lowest values in all grain size traits with means of 24.8 mm^2 area, width 3.00 mm and length, 10.95 mm.

Table 4.18.a *Mean width (mm), cultivar superiority, static stability and ranks values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Balado	3.121	0.007(3)	0.024(4)	1.435(4)	1.382(4)
Gerald	3.057	0.013(4)	0.010(2)	0.931(3)	0.545(2)
Mascani	3.183	0.001(1)	0.007(1)	0.699(1)	0.327(1)
Tardis	3.118	0.005(2)	0.011(3)	0.902(2)	0.727(3)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Table 4.18.b *Mean groat width (mm), cultivar superiority, static stability and ranks values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Balado	2.514	0.013(4)	0.021(4)	1.403(4)	1.691(3)
Gerald	2.533	0.007(3)	0.007(1)	0.834(2)	0.564(2)
Mascani	2.624	0.001(1)	0.008(2)	0.733(1)	0.418(1)
Tardis	2.536	0.006(2)	0.009(3)	0.990(3)	0.564(2)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Table 4.19. *Mean grain ratio, cultivar superiority, static stability and ranks values of the four winter varieties. *Numbers in brackets refers to the position in the ranking of the cultivars.*

Variety	Mean	Cultivar Superiority	Static Stability	Sensitivity	Mean Square Deviation
Balado	0.263	0.0003(3)	0.0005(3)	1.061(3)	0.00007(2)
Gerald	0.288	0.0000(1)	0.0004(1)	0.805(1)	0.00003(1)
Mascani	0.278	0.0001(2)	0.0008(4)	1.312(4)	0.00005(4)
Tardis	0.261	0.0004(4)	0.0005(2)	0.816(2)	0.00002(3)
Significance	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*	*p-value<0.001*

Grain ratio was calculated using width and length values and provides a measure of grain roundness (equation 8, section 3.6). Joint regression analysis of grain ratio showed statistically significant sensitivity values (p-value <0.001) (figure

4.32), indicating that there is variation in genotypes performances with changing environments. Cultivar coefficient, static stability and sensitivity values (table 4.19) showed Gerald with the highest mean and most stable to the environment, whilst Mascani had the highest interaction with the environment.

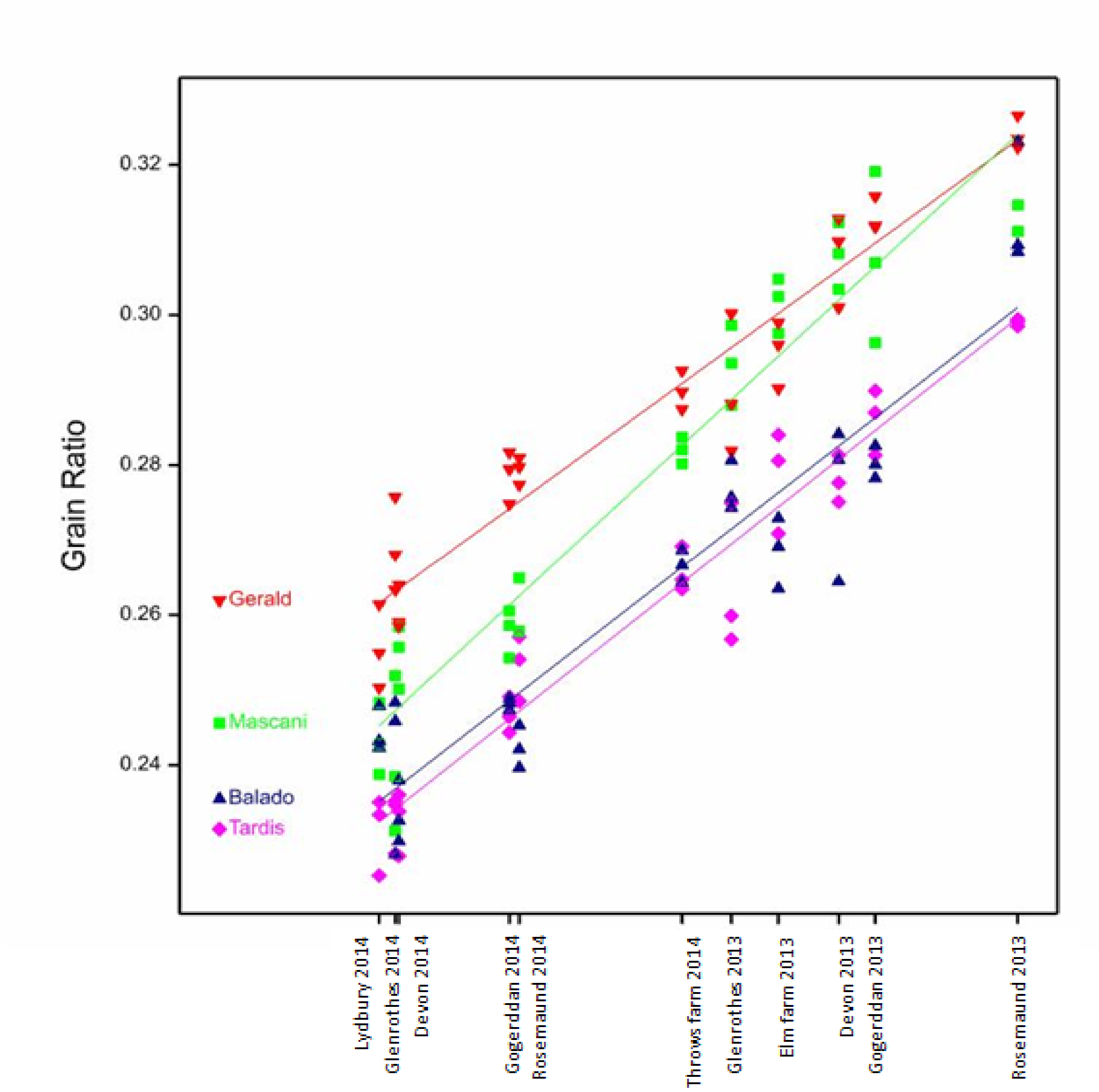
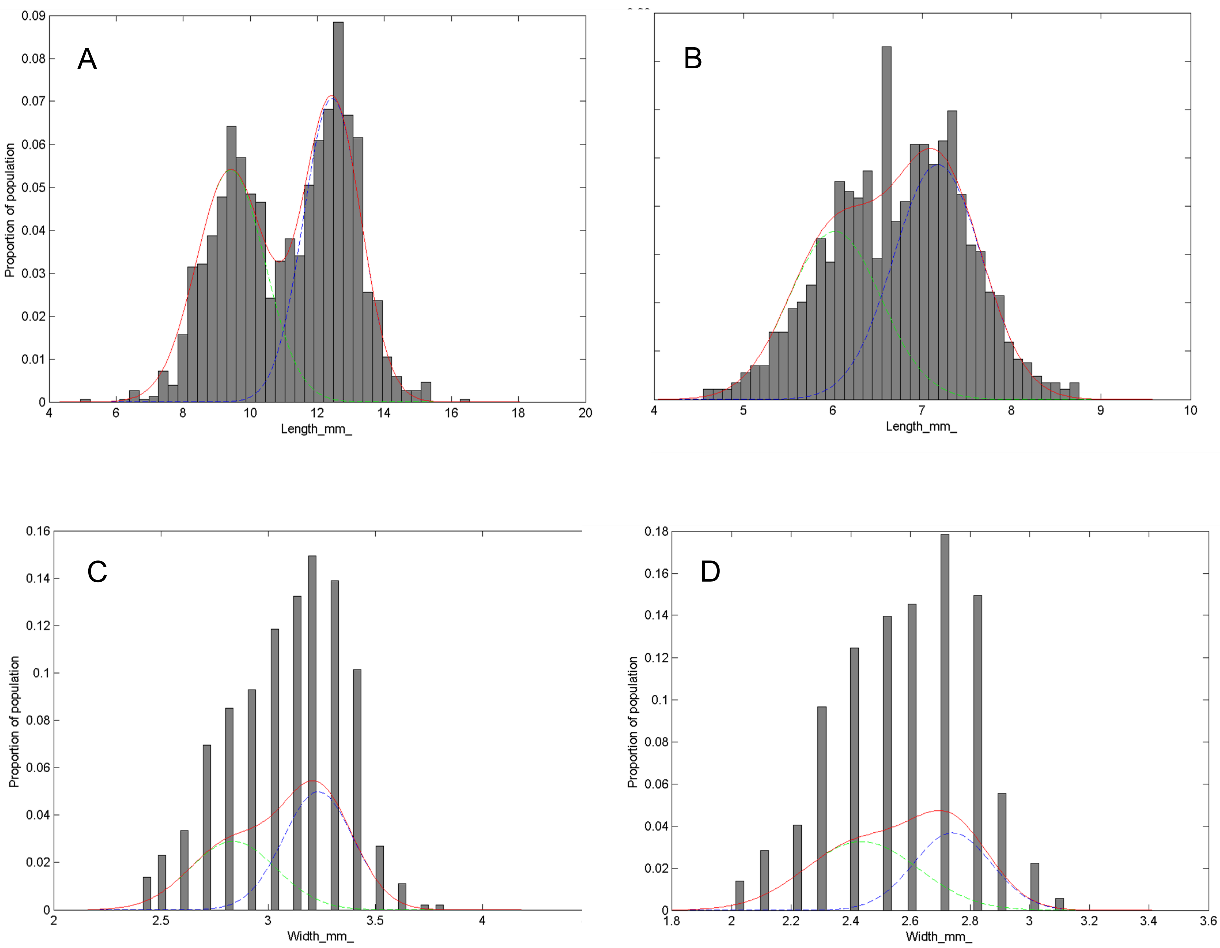
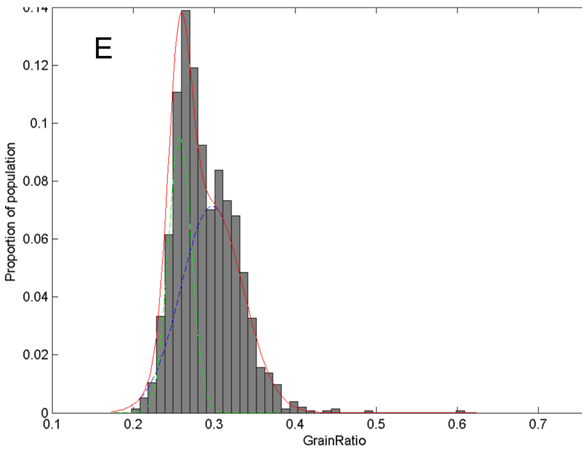


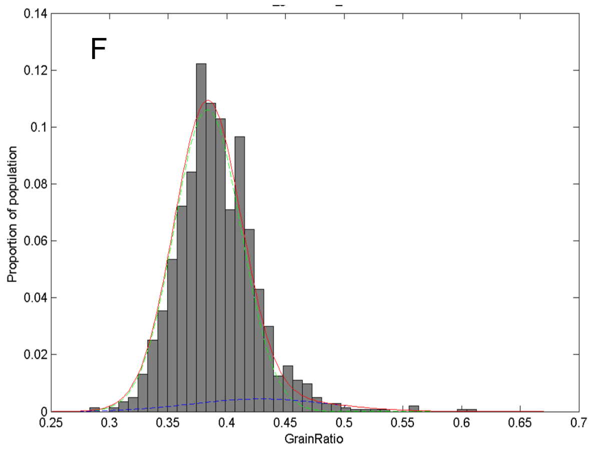
Figure 4.32. *Joint regression graph for grain ratio values of the four winter oat varieties and the eleven sites across UK, for 2012- 2013 and 2013-2014 harvest seasons*.

In addition, frequency distribution analysis of the individual grain and groat data was conducted. These were analysed to determine their bi-modality and to establish the mean, standard deviation and the numerical balance between any sub-populations observed (Symons & Fulcher 1988). A bimodal frequency distribution was found regarding grain and groat area and length representing the primary and secondary grain found in each oat spikelet (figure 4.33 to 4.34). A two-normal distribution was fitted to these curves enabling the calculation of the mean and standard deviation of the primary and secondary grain sub-populations along with the proportions of grain in each (tables 4.20 and 4.23), for all environments.

Figure 4.33. *Frequency of individual grain and groat length, width and ratio for grain and groats of Gerald grown at Glenrothes in 2013. A. grain length; B groat length; C, grain width; D groat width, E grain ratio; F, groat ratio. The fitted bimodal distribution is indicated in red with the primary grain distribution indicated in blue and secondary grain distribution indicated in green.*



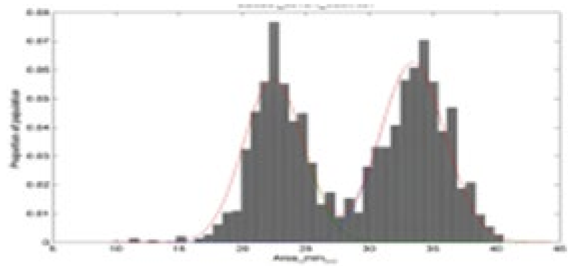




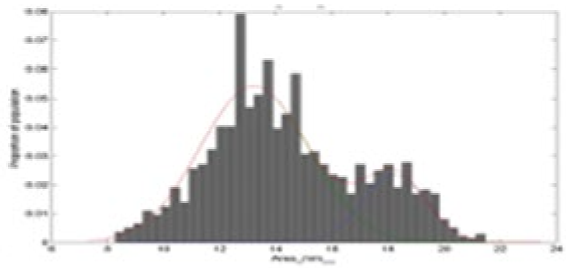
A less clear bimodal distribution was obtained for grain and groat width and grain ratio (figure 4.33). An overlap was found between primary and secondary in terms of width and area for both grain and groat. Circularity and compactness did not show bimodal distribution for any variety or site.

An example of an interesting comparison of the bimodal distribution of grain and groat areas is shown in figure 4.34 for Devon 2013 and in figure 4.35 for Devon 2014. Each variety shows bimodal distribution. However, the proportion of each subpopulation changes between grain and groats, but Mascani. Whereas for the grain area, distribution of all 4 varieties a clear bimodal distribution was obtained, but when the groats are examined it is apparent that for all varieties except for Mascani there is not such a clear distinction between the primary and secondary populations. A far higher proportion of groats were found in the secondary distribution than would be predicted by looking at the distribution of grain size. For Balado, across sites 50% of the grain were in each of the primary and secondary distributions whereas for the groats, only 31 % were in the primary distribution was 53% and of groats it was 48% (table 4.20). This increase in the proportion of grain in the secondary distribution once the husk is removed was highest in Tardis, although for 2 sites this resulted in difficulties in fitting two normal distribution curves (table 4.20).

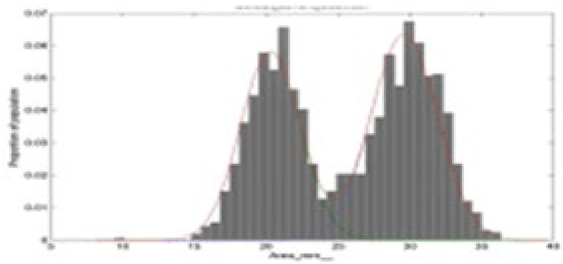
A



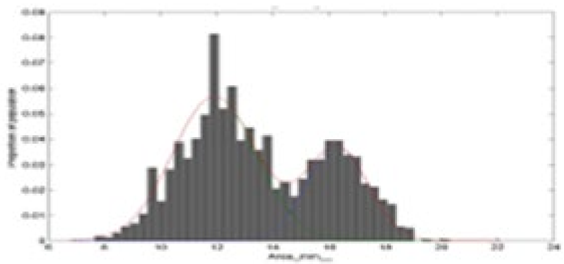
E



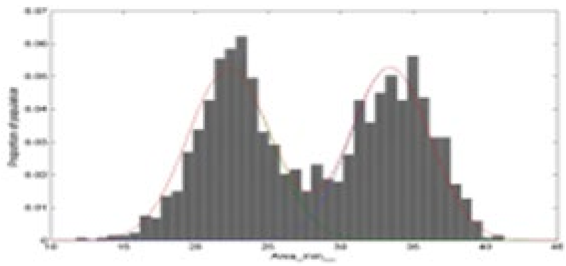
B



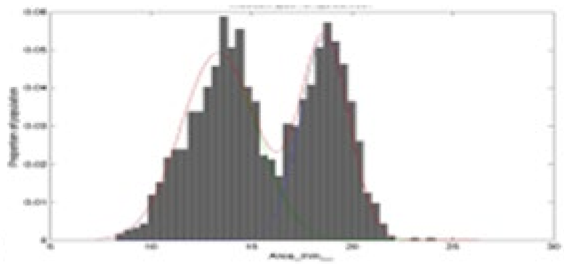
F



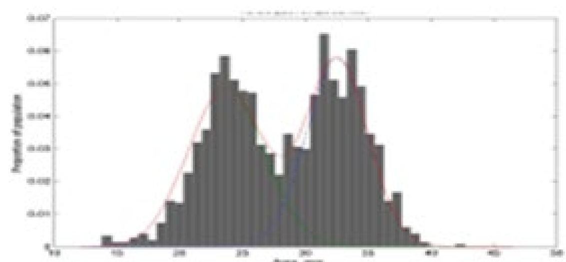
C



G



D



H

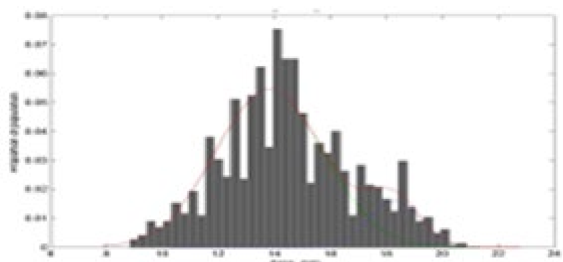


Figure 4.34 Grain (A - D) and groat (E - F) area (mm^2) bimodality graphs from Devon trial 2013 harvest season of Balado (A, E), Gerald (B, F), Mascani (C, G) and Tardis (D, H).

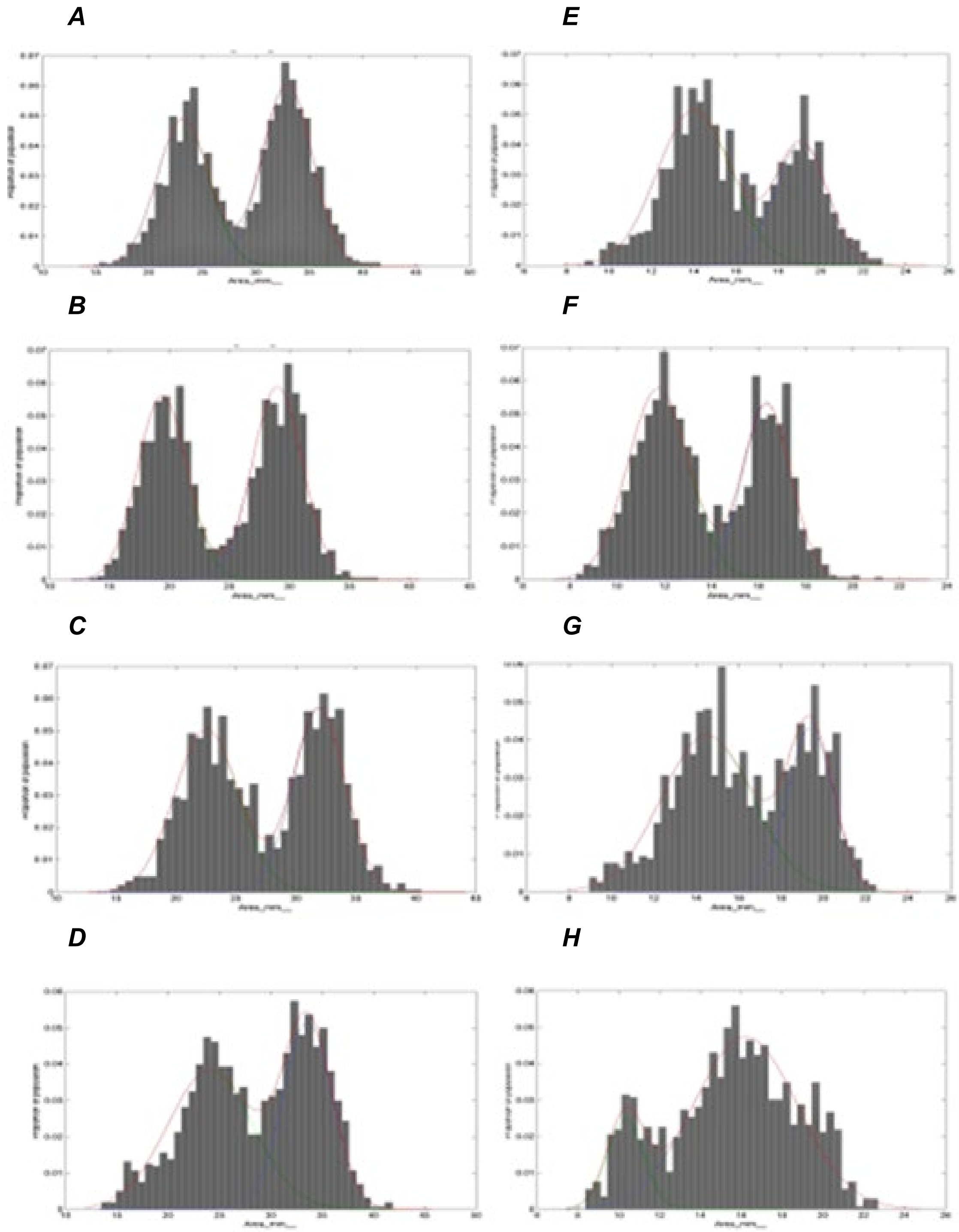


Figure 4.35 Grain (A - D) and groat (E - F) area (mm^2) bimodality graphs from Devon trial 2014 harvest season of Balado (A, E), Gerald (B, F), Mascani (C, G) and Tardis (D,H).

Tables 4.20 *Primary and secondary grain and groat length (mm) bimodality proportions by variety at each location and harvest season*

		Balado				Gerald				Mascani				Tardis			
		Grain		Groat		Grain		Groat		Grain		Groat		Grain		Groat	
		1^0	2^0	1^0	2^0	1^0	2^0	1^0	2^0	1^0	2^0	1^0	2^0	1^0	2^0	1^0	2^0
Gogerddan	2013	0.50	0.51	0.25	0.75	0.55	0.45	0.43	0.57	0.63	0.37	0.50	0.50	0.42	0.58	0.14	0.86
Devon	2013	0.54	0.46	0.36	0.64	0.55	0.45	0.32	0.68	0.49	0.51	0.41	0.59	0.49	0.51	0.12	0.88
Glenrothes	2013	0.48	0.52	0.29	0.71	0.58	0.42	0.53	0.47	0.62	0.39	0.40	0.60	0.38	0.62	0.16	0.84
Rosemaund	2013	0.38	0.62	0.18	0.82	0.64	0.36	0.38	0.62	0.45	0.55	0.70	0.30	0.29	0.71	0.95	0.05
Elm Farm	2013	0.51	0.49	0.34	0.66	0.54	0.46	0.41	0.59	0.51	0.49	0.49	0.51	0.45	0.55	0.23	0.77
Gogerddan	2014	0.66	0.34	0.30	0.70	0.53	0.47	0.47	0.53	0.54	0.46	0.51	0.49	0.38	0.62	0.15	0.85
Devon	2014	0.36	0.64	0.20	0.80	0.51	0.49	0.42	0.58	0.48	0.52	0.34	0.66	0.44	0.56	0.84	0.16
Glenrothes	2014	0.62	0.38	0.47	0.53	0.57	0.43	0.53	0.47	0.59	0.41	0.57	0.43	0.55	0.45	0.21	0.79
Rosemaund	2014	0.48	0.52	0.33	0.67	0.57	0.43	0.51	0.49	0.45	0.56	0.35	0.65	0.43	0.57	0.17	0.83
Lydbury	2014	0.46	0.54	0.39	.61	0.53	0.47	0.39	0.61	0.52	0.49	0.51	0.49	0.49	0.51	0.39	0.61
Throws Farm	2014	0.48	0.52	0.32	0.69	0.52	0.48	0.37	0.63	0.54	0.46	0.48	0.52	0.38	0.63	0.09	0.91
Mean		0.50	0.50	0.31	0.69	0.55	0.45	0.43	0.57	0.53	0.47	0.48	0.52	0.43	0.57	0.31	0.69

4.11. Correlations

Tables 4.21. *Pearson´s correlation coefficients, i.e. r, (p-value <0.05) between quality traits and grain and groat size of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations (p*value <0.05 for a two-tailed Pearson correlation test). Given the size of the table, it is split in three sections.*

	Oil	***Protein***	***B-Glucan***	***Kernel content***	***Hullability***	***Specific weight***	***Yield***	***TGW***
Oil	1.00							
Protein		1.00						
B-Glucan			1.00					
Kernel content	-0.71			1.00				
Hullability	-0.66			0.68	1.00			
Specific weight			-0.52	0.58		1.00		
Yield (t/ha)							1.00	
TGW				0.59				1.00
Grain Density				0.47	0.59	0.48		0.57
Grain nº/m^2	0.56			-0.59			0.85	-0.59
Area								0.66
Width				0.53				0.92
Length								
Circularity Grain								
Compactness								
Grain Ratio						0.46		
Area Groat	-0.53			0.61				0.89
Width Groat				0.60		0.58		0.82
Length Groat			0.50					0.68
Groat Ratio		-0.55	-0.61			0.57		
Circularity Groat		-0.56	-0.59			0.57		

	Grain Density	***Grain n^0/m^2***	***Area***	***Width***	***Length***	***Circularity Grain***	***Compactness***	***Grain Ratio***
Grain Density	1.00							
Grain n^0/m^2		1.00						
Area		-0.52	1.00					
Width	0.58	-0.49	0.48	1.00				
Length	-0.63		0.83		1.00			
Circularity Grain	0.79		-0.61		-0.94	1.00		
Compactness	-0.78		0.62		0.95	-1.00	1.00	
Grain Ratio	0.81		-0.56		-0.91	0.98	-0.97	1.00
Area Groat		-0.64	0.75	0.75				
Width Groat	0.68			0.91				0.54
Length Groat		-0.62	0.83	0.45	0.62			
Groat Ratio			-0.59		-0.72	0.70	-0.69	0.75
Circularity Groat	0.47		-0.59		-0.72	0.70	-0.69	0.74

	Area Groat	***Width Groat***	***Length Groat***	***Groat Ratio***	***Circularity Groat***
Area Groat	1.00				
Width Groat	0.69	1.00			
Length Groat	0.90		1.00		
Groat Ratio			-0.73	1.00	
Circularity Groat			-0.72	0.98	1.00

The physical quality traits, i.e. kernel content (%), thousand grain weight, specific weight (kg/hl) and hullability (%), were significantly correlated (p-value <0.05) with several grain and groat size parameters (table 4.21). Only those physical and chemical quality parameters with a correlation coefficient higher than an absolute value of 0.55 and with a p-value<0.05 are reported.

Thousand grain weight was positively correlated (p-value <0.05), table 4.21 and figure 4.36, with grain area (mm^2) and width (mm). The correlation was higher between grain width and thousand grain weight than with grain area and thousand grain weight. Similar correlations were found between groat dimensions and thousand grain weight.

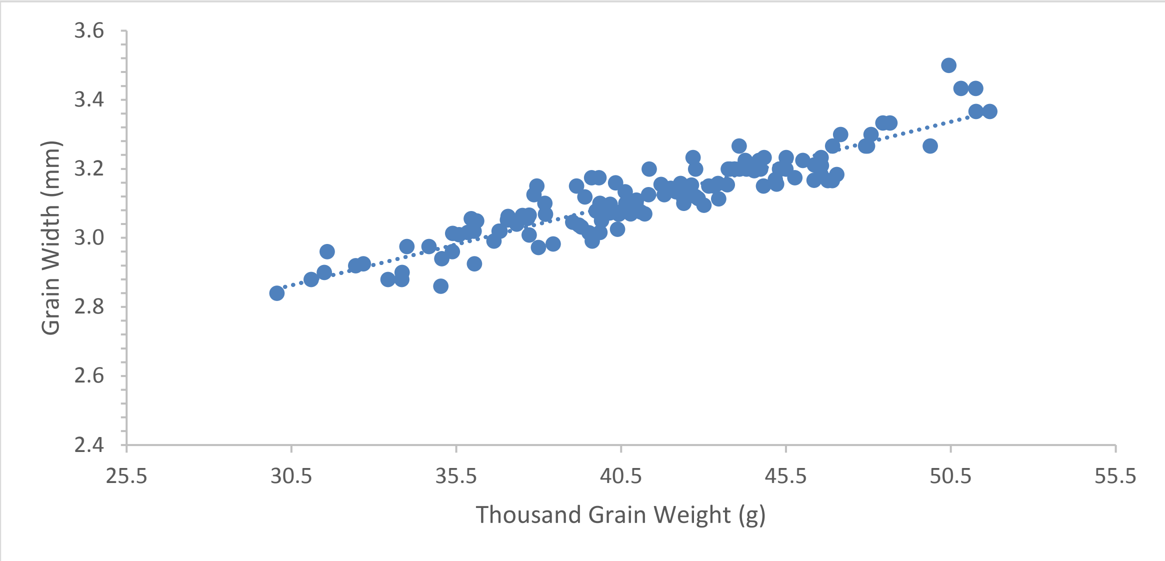


Figure 4.36. *Correlation plot between grain width (mm) and thousand grain weight (g) of the four winter oat varieties and the eleven sites across UK for 2012/2013 and 2013/2014 harvest seasons.*

This positive correlation was also found when varieties were examined individually (see appendix). Balado and Gerald showed consistently positive correlations between thousand grain weight and groat area, width and length, with correlation coefficients above 0.70. However, Mascani only presented this positive correlation in case of groat width. Tardis, on the other hand, showed significant positive correlations between TGW and with groat area, grain and groat width, grain and groat ratio and grain density. Grain density was estimated as described in equation 10 (section 3.6).

Kernel content was also positively correlated (p-value <0.001) with grain width, groat area and width (figure 4.37) and thousand grain weight, although with a lower correlation coefficient (table 4.21).

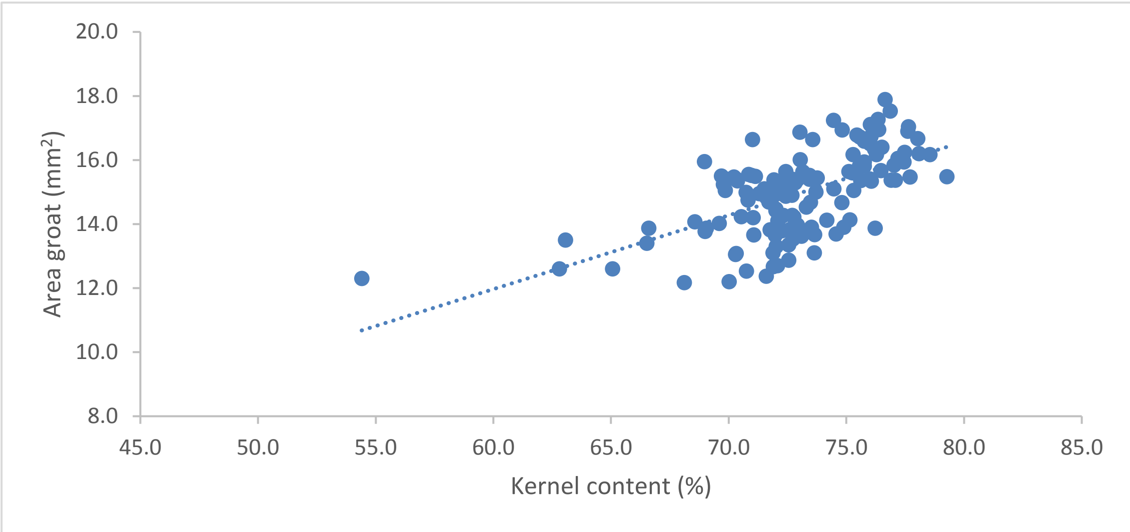


Figure 4.37. *Correlation plot between kernel content (%) and groat area (mm^2) of the four winter oat varieties values in eleven sites*

When varieties were examined individually, Balado presented the same results mentioned above. Gerald showed a positive correlation between kernel content and thousand grain weight and groat area and a negative correlation with grain number per metre square. Mascani´s kernel content, on the other hand, had a significant negative correlation with yield and grain number per meter square. Tardis however, did not display significant correlations, either positive or negative, between grain size parameters and kernel content.

Hullability displayed a positive significant correlation (p-value <0.05), with grain density (table 4.21, figure 4.38). When varieties were examined individually, the hullability of Balado was positively correlated with groat length and negatively with yield and grain number per metre square. No statistically significant correlations were found with the hullability of Gerald, Mascani and Tardis when examined on a variety basis with any trait measured.

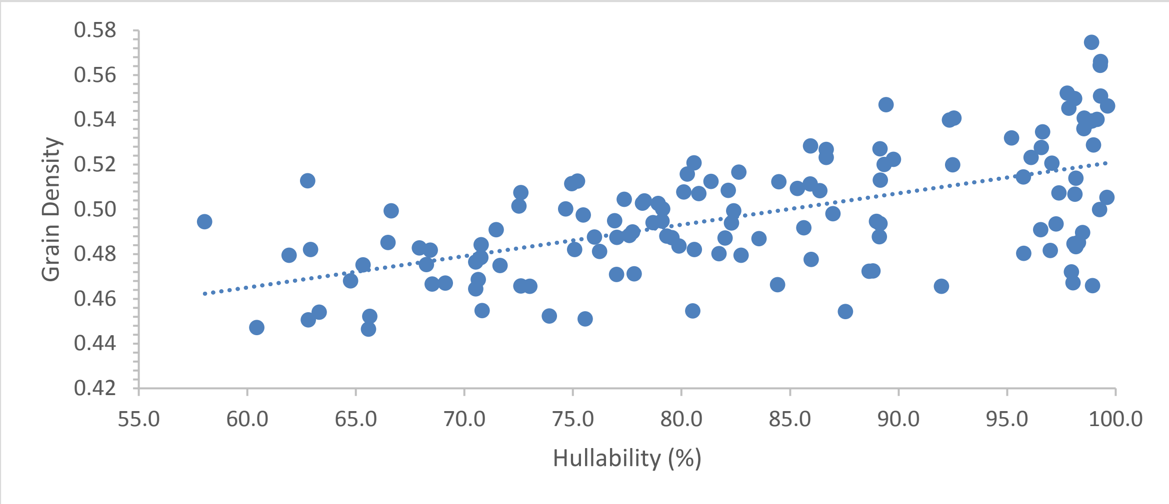


Figure 4.38. *Correlation plot between hullability (%) and grain density of the four winter oat varieties values in eleven sites.*

Specific weight was significantly (p-value <0.05) correlated with grain density, grain ratio and groat width, groat ratio and circularity of the groat. However, the strongest correlation (table 4.21 and figure 4.39) was found between specific weight and groat width.

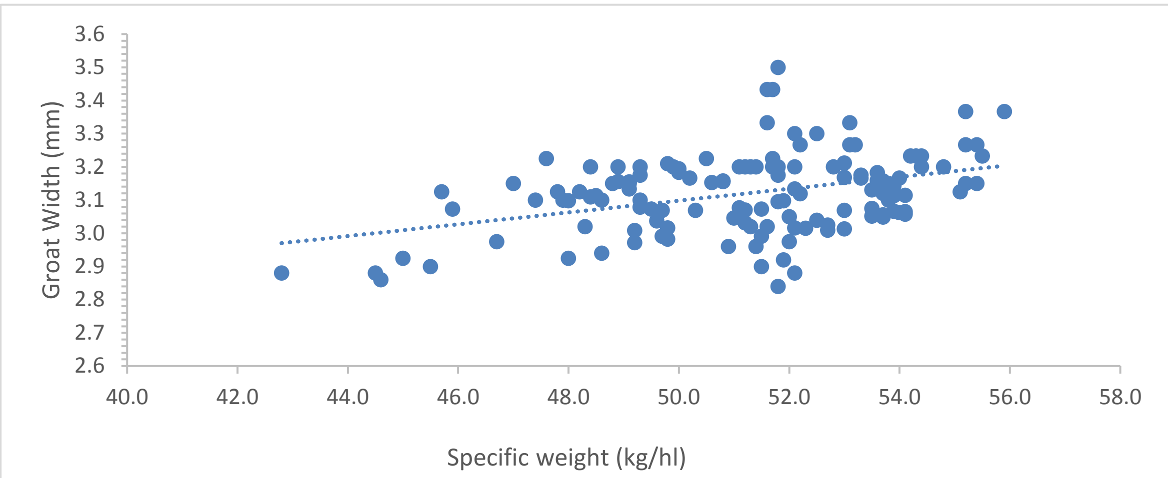


Figure 4.39. *Correlation plot between specific weight (kg/hl) and groat width of all varieties´ values in eleven sites.*

When examined by varieties, Gerald showed significant positive correlations between specific weight and thousand grain weight and grain and groat width, with values above 0.67 in all cases (see appendix). Thousand grain weight was positively correlated with specific weight values for Balado. Neither Mascani nor Tardis presented statistically significant correlations between specific weight and any other quality parameter or grain groat size and shape trait.

Chemical composition traits, i.e. oil, protein and *β-glucan* content, had diverse results (table 4.21). Oil content was significantly and negatively correlated with kernel content (%) and hullability (%) (p-value <0.001). By varieties Balado, Mascani and Tardis´s oil content showed a negative correlation with β-glucan content (%) (p-value <0.001), whilst Gerald along with Mascani and Tardis´ oil content was negatively correlated with grain length (p-value <0.001, see appendix). The four varieties showed a negative correlation between oil content and grain area (p-value <0.001), figure 4.40.

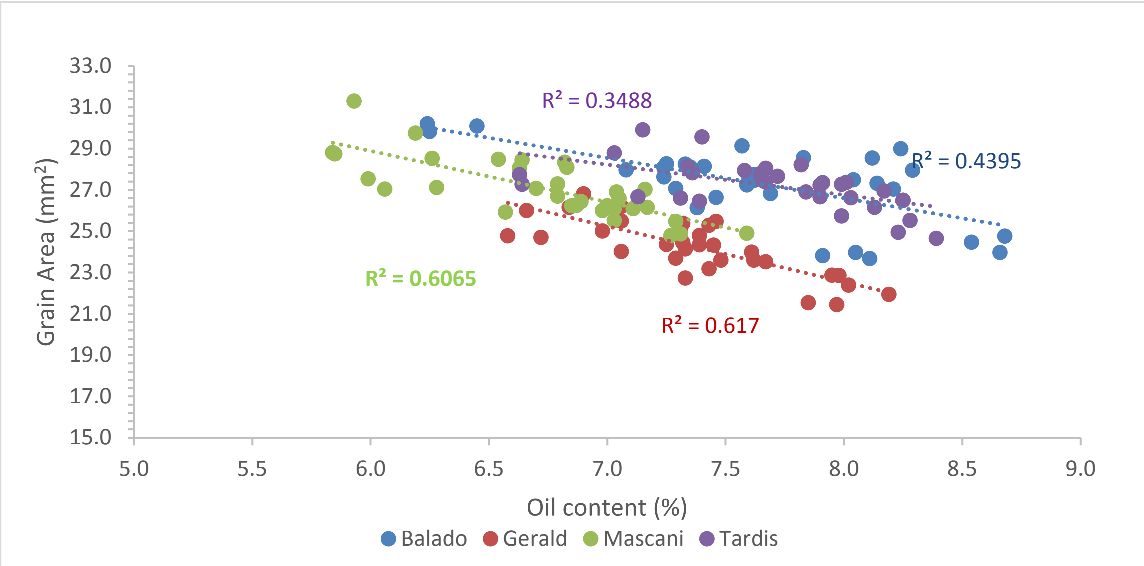


Figure 4.40. *Correlation plot between oil content (%) and grain area (mm^2) of all varieties´ values in eleven sites.*

Protein content had significant negative correlations (p-value >0.05) (table 4.21), with groat ratio and circularity of the groat. When analysed by varieties, all of them showed a significant (p-value <0.05) negative correlation with groat ratio, figure 4.41. Mascani, also presented a significant (p-value <0.05) positive correlation with grain width.

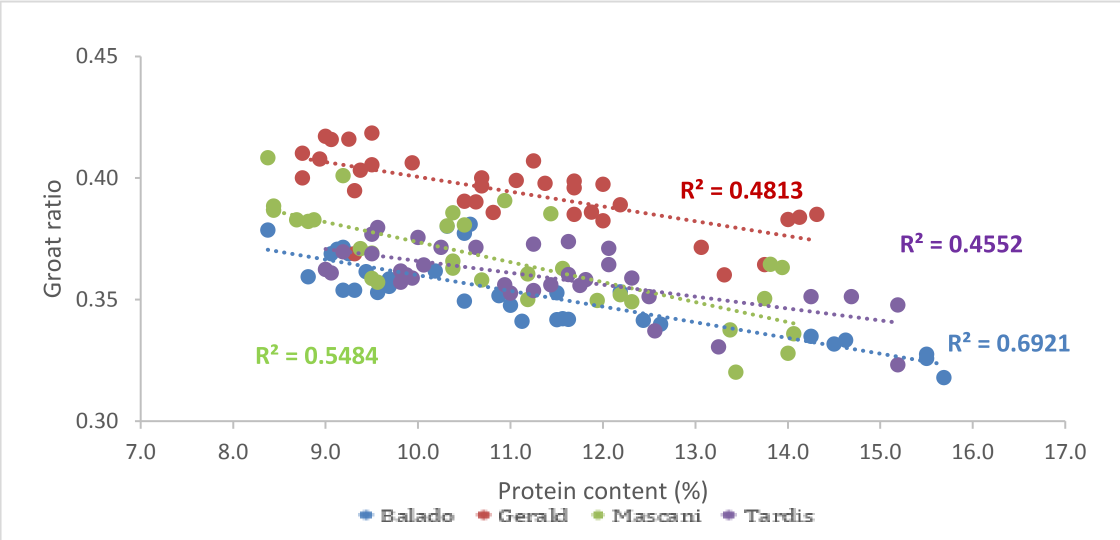


Figure 4.41. *Correlation plot between protein content (%) and groat ratio of all varieties´ values in eleven sites.*

β-glucan content (%), presented a significant (p-value <0.05) negative correlation (table 4.21) with groat ratio (figure 4.42), similar to the negative correlation found for protein content by varieties. Gerald did not show any significant (p-value <0.05) correlation, neither positive nor negative, with any of the quality traits.

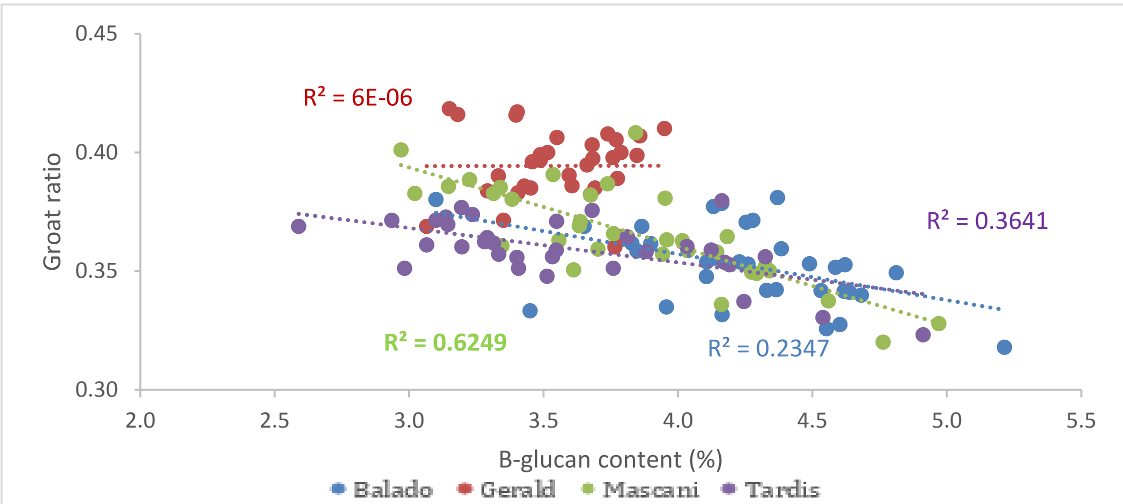


Figure 4.42. *Correlation plot between β-glucan content (%) and groat ratio of all varieties´ values in eleven sites.*

On the other hand, β-glucan content was significantly (p-value <0.001) and positively correlated with hullability (%), grain length and groat area (mm^2) for Balado. Mascani also showed β-glucan content negatively (p-value<0.001) correlated with grain width (mm) and grain and groat ratio (green line, figure 4.42), while positive with grain length (mm) (see appendix).

5. Discussion

Plant breeders aim to develop improved crop varieties that are adapted to produce high yields of quality grain over a wide range of environments (Doehlert 2001) with the adaptability of a variety usually tested by the degree of interaction with different environments under which it is planted (Sial et al. 2000; Asif et al. 2003; Ashraf et al. 2001). Analysis of the genotype by environment interaction on grain yield and quality is therefore, essential in variety evaluation (Becker & Leon 1988; Subira et al. 2015) and to understand the adaptability and stability of varieties (Hongyu et al. 2014) for different environments. The GxE effects on selected oat grain quality traits (Doehlert 2001) and on β-glucan content in commercially available varieties (Andersson & Börjesdotter 2011) and within related wild species (Redaelli et al. 2013) have been studied, but limited information exists for other grain components or on milling quality traits.

Historical data analysed graphically showed that a high degree of variability is apparent between years and between trial sites as well as between varieties. All the historical data was obtained from *Recommended List* trials which all received a similar agronomy suggesting that this variability might be explained by the different environments where the different varieties were grown and by the climate variability between sites.

In this study, none of the varieties displayed a superior performance in all quality traits, neither did one site show superior performance over all values for all varieties. However, there were statistical significant differences between varieties and across the eleven environments over the two harvest seasons, and significant interactions of genotype by environment, when analysing yield, specific weight, kernel content, hullability, thousand grain weight, grain and groat composition and grain and groat size. Yield was significantly different across sites but not between varieties showing more environmental influence on yield than genotype, but displayed a non-significant correlation with any other quality trait nor with grain or groat size and shape parameter. Other studies have found strong correlations between kernel content and yield (Doehlert 2001; Achleitner et al. 2008). However, the weak correlation found in this current study is in accordance with those reported by Forsberg and Reeves (1995).

By sites and traits, Rosemaund yielded the highest hullability, kernel content and β-glucan content for both harvest seasons and the lowest oil content. However, it showed the lowest specific weight in 2014 harvest season. Rosemaund 2013 field trial was sown in February. This might have meant a shorter period of plant development in comparison with the rest of the field trials and seasons, affecting therefore, grain and groat size and shape. This might explain the differences found in specific weight, oil, β-glucan content and kernel content, between harvest seasons at Rosemaund. Devon 2013 performed lowest for hullability, however, its value in 2014 was above 80 %. Gogerddan 2013 and 2014 showed the lowest protein content but the highest oil content. Throws Farm 2014 reached the lowest kernel content and the smallest grain, whilst Lydbury 2014 yielded the highest specific weight and thousand grain weight. Elm Farm, Glenrothes 2013 and 2014, showed variable levels in terms of hullability, kernel content, specific weight, thousand grain weight, oil and protein content. While Elm Farm had low hullability, kernel and oil content, Glenrothes showed high hullability, kernel content, specific weight and oil content. The differences in traits values might allow us to think that these sites are more suitable to investigate differences in terms of genotype by environment interactions, considering at the same time, the differences in management conditions between both sites. However, given that only one season of data from Elm farm 2012/2013 trial under organic management conditions were available no conclusions can be drawn from this result. Glenrothes in both harvest seasons showed variable quality traits values, with low specific weight and kernel content in 2013, opposite to results from 2014. This allows us to conclude a higher effect of the year, i.e. climate/weather conditions and a different size in the interaction with the environment.

Table 5.1 *Summary table of genotype, environment and genotype by environment interactions effects on grain and groat quality parameters for the milling industry and end-users.*

Quality parameter	*Genotype by Environment Interaction*	*Genotype*	*Environment*
Yield (t/ha)	<0.001	non significant	<0.001
Kernel content (%)	<0.001	<0.001	<0.001
Specific Weight (kg/hl)	non significant	<0.001	<0.001
Hullability (%)	<0.001	<0.001	<0.001
Thousand Grain Weight (g)	<0.001	<0.001	<0.001
Oil content	<0.001	<0.001	<0.001
Protein content	<0.001	<0.001	<0.001
β-Glucan content	<0.001	<0.001	<0.001
Grain area (mm2)	<0.001	<0.001	<0.001
Grain length (mm)	<0.001	<0.001	<0.001
Grain width (mm)	<0.001	<0.001	<0.001

Specific weight is a controversial trait. Some studies have found it highly heritable and positively correlated with kernel content (Doehlert et al. 1999; Doehlert 2001; Forsberg & Reeves 1995). However, some other studies conducted in wheat have been proved a poor relationship between specific weight and other quality traits (Wilkinson et al. 2003; Owens et al. 2007). The results from this present study, regarding specific weight values, were statistically significant between environments and between varieties (table 5.1), Mascani being the most stable and with the highest values across sites. However, the grains with the highest specific weight were those that were smallest, i.e. Gerald, in accordance with previous research (Peterson & Wood 1997). There was no significant difference for interaction of genotype with the environment for specific weight. Thus, the significant variation found in specific weight values, might be explained because of the differences between genotypes under study rather than because of the interaction of the genotype with the environment. There was also a significant positive correlation between specific weight and kernel content, therefore, it could be possible to select for varieties or genotypes with the best values of both traits.

Varieties´ hullability (%) and kernel content (%), showed also variable results. Mascani showed the highest values in kernel content, hullability and thousand grain weight, with superior cultivar values and static stability and the lowest sensitivity to the environment. These remarkable superiority and stability values suggest Mascani (Griffiths et al. 2008; White & Watson 2010) as the most suitable variety to continue further investigations including more sites and harvest seasons to find out differences between Mascani and others varieties and therefore, allow to select by breeding for those quality characteristics. Tardis had the highest protein content (%), whilst Gerald, although had highest specific weight (t/hl), it showed the lowest thousand grain weight (g) and β-glucan content (%). Overall by seasons and sites Balado showed the highest β-glucan content (%).

To evaluate the stability of a genotype across environments, a number of different indices were calculated using the data obtained here. Regarding stability, the static concept refers to the ability of a genotype to perform consistently across different environmental conditions while the dynamic (or agronomic) concept of stability implies that a stable genotype shows a yield response in each environment that is always parallel to the mean response of the tested genotypes (Becker and Leon, 1988). Joint regression analysis (Finlay and Wilkinson, 1963) enables the calculation of both the sensitivity of a genotype to the environment and also the mean square deviation from that regression line. Although non-parametric phenotypic parameters, i.e. cultivar superiority, ranks and static stability, provided a useful alternative, reducing outliers, being easy to use and interpret, and with no requirement of normal distribution assumptions, it is still needed to elaborate efficient tests of significance for all parameters and determine relationships between all these parameters and the classic regression approach (Finlay & Wilkinson 1963; Huehn 1990). In general, the ranking of the superiority index matched that of the mean values obtained for each trait. The static stability, sensitivity and mean-square values also provided similar rankings to each other. This was not always the case as shown by the values for protein content for Tardis which had the lowest stability and sensitivity values, but the highest mean square value, indicating that although it had low sensitivity to the environment, it gave the least predictable response. For any given trait, a stable variety does not necessarily also have a high mean performance although for many traits this was found in this study. For 2 traits (β-glucan content and grain length), the most stable variety was Gerald but it had the lowest mean values.

Kernel content, hullability and thousand grain weight displayed a statistical significant interaction with the environment (table 5.1). Lydbury in 2014, was the better site for the three quality traits (table 4.4). However, removing the environmental effect (figures 4.12 and 4.20) the range of yield and hullability values displayed, allow us to discard this site as the most effective to find out in which environments each of the genotype performs better.

Chemical composition suggest Throws Farm 2014 as the best site for maximising oil and protein content, although with not the overall mean highest β-glucan content. Rosemaund in 2013, displayed the highest β-glucan content overall mean, and good levels of protein content and low oil content. This groat composition at Rosemaund 2013, might be explained by the late sowing of this trial, although the lack of more data to compare late sowing time as a factor affecting the physiology and development of the grain, prevent further conclusions. All of the three chemical traits showed significant interaction with all the eleven sites under study as previously reported (table 5.1) (Doehlert 2001; Brunner & Freed 1994; Peterson 1991). Tardis was superior in comparison with the other three varieties in terms of oil and protein content, although Balado displayed the highest β-glucan content. All varieties were statistically sensitive to the environment and according to non-parametric stability values Gerald is the most stable and giving predictable responses in terms of oil and protein content. This along with the interaction between genotype and environment suggest a potential for niche-matching varieties according to the quality trait of interest.

Image analysis of grain and groat size and shape confirmed a bimodality distribution frequency (Doehlert et al. 2005; Wychowaniec et al. 2013). Primary and secondary grain and groat showed for all traits and varieties bimodal distributions regarding size and shape although the most apparent was in terms of length. Area, width, circularity and roundness showed a higher overlap of the two sub-populations. Grain and groat area and length. Grain and groat area showed a stronger variation along length, meaning a stronger correlation than area with width, for all harvest seasons and varieties. This result was also observed regarding grain and groat ratio, although the effect was not so strong. The highest specific weight grains were the smallest and shortest varieties, i.e. Gerald (Peterson & Wood 1997).

Bimodality parameters were confirmed by image analysis of grain and groat size and shape. Primary and secondary grain and groat displayed for all traits and varieties bimodal (Mannerstedt Fogelfors & Peterson 2004) distributions regarding size and shape. These results might be explained by panicle development in oats. In oats, spikelets comprise usually two to three grains (Welch 1995), the primary one being larger in comparison with the secondary and the tertiary grains being at the same time poorer in kernel content and hullability (Browne et al. 2002). Because of this particular structure, the sub-population under the curve in the bimodality graph and proportions calculated does not include exclusively primary or secondary grain but also a certain number of grains that should belong to one or another category, making difficult to establish the limits between them. On the other hand, some of the results in the bimodality proportions calculated showed odd values, allowing to conclude that further development in the mathematical method to assess those parameters is needed. Although further research is needed, the study of bimodality characteristics of grain and groat sub-populations in oats has been proved to lead to a new quality parameter that would allow to select in future breeding programs, varieties with more homogeneous grain subpopulations (Symons & Fulcher 1988).

The positive and negative correlations found between oil, β-glucan and protein content are in accordance with previous research reported. Interestingly, there was a mirror effect between oil and protein content, confirmed by the negative correlation found between them. These results are not conclusive and do not allow establishing a causal relationship between the two parameters. Some reports suggest high variability in the effect that both, genotype and environment, have on chemical quality traits. However, a positive correlation was found by Youngs and Forsberg, 1979, with cultivars with high protein and oil content being developed. On the other hand, consistent genotype differences on b-glucan content have been reported (Peterson 1991; Peterson et al. 1995), whilst genotype by environment interactions have been reported to have variable effect on b-glucan concentration (Brunner & Freed 1994; Humphreys et al. 1994; Jackson et al. 1994). These contrasting results make difficult to establish causal relationships between traits. Similarities in grain size between Balado and Gerald and between Mascani and Tardis, i.e. length, area and width, could explain the similarities in correlation coefficients. The negative and positive correlations found between grain size and shape when studying each of the varieties, showed the influence of area (mm^2), length (mm) and width (mm), over each quality parameter under study.

The variability found between sites and years suggest that locally adapted varieties could perform better, i.e. niche-matching, therefore, choosing varieties according to the historical performance of the site rather than the overall performance of the variety. On the other hand, sites with good overall performance in quality traits under study should be considered, to discriminate between variety´s performance and thus, dissect the basis, physical, genetical and environmental, of those differences ;(Becker & Leon 1988).

The variability between years and genotypes found may also be due to management conditions (fertilizer levels, pest control intensities, water availability) and differences in and within the field, i.e landscape (Roel et al. 2007).

Future challenges include the determination of how much of the observed quality traits' variability was caused by natural variation in yields and how much by differences in management practices, by analysing more data collected along more harvest seasons and across major areas of crop production. Therefore, it will be necessary to determine the best cost-effective management practices are most appropriate for what conditions, both edaphic and climatic, in the region to get the most of each variety. Also, it will be necessary to define the range of context within a variety is adapted, through collecting evidence for extrapolating results beyond the chosen sites, and trying to choose between harvest seasons the same sites to determine interactions and effects of the environment. An understanding of the mechanisms of these interactions, the size of them and their consequences would allow the development of a niche-matching list of varieties across the country.

6. Appendix

Tables 4.21.b *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations.*

	Balado *Oil*	**Gerald** *Oil*	**Mascani** *Oil*	**Tardis** *Oil*	**Balado** *Protein*	**Gerald** *Protein*	**Mascani** *Protein*	**Tardis** *Protein*	**Balado** *β-Glucan*	**Gerald** *β-Glucan*	**Mascani** *β-Glucan*	**Tardis** *β-Glucan*
Oil	1.00	1.00	1.00	1.00								
Protein	-0.53	-0.21	-0.44	-0.31	1.00	1.00	1.00	1.00				
B-Glucan	-0.35	-0.20	-0.75	-0.83	0.33	0.07	0.64	0.42	1.00	1.00	1.00	1.00
Kernel content	-0.73	-0.48	-0.20	-0.58	0.23	0.22	0.17	-0.28	0.15	-0.06	0.18	0.35
Hullability	-0.73	-0.14	-0.26	0.00	0.58	-0.04	-0.43	-0.10	0.02	0.14	-0.02	0.08
Specific weight	-0.37	-0.19	0.39	-0.09	-0.29	-0.08	-0.16	-0.15	0.00	-0.23	-0.31	-0.13
Yield	0.70	0.38	0.59	0.39	-0.55	-0.33	-0.49	-0.26	-0.26	-0.35	-0.58	-0.41
TGW	-0.62	-0.51	0.22	0.10	-0.10	-0.19	-0.50	-0.45	-0.04	0.02	-0.43	-0.28
Grain nº/m^2	0.81	0.58	0.56	0.32	-0.34	-0.17	-0.33	0.02	-0.20	-0.30	-0.46	-0.25
Area	-0.66	-0.79	-0.78	-0.59	0.19	0.25	0.28	-0.05	0.47	0.18	0.54	0.32
Width	-0.51	-0.39	0.37	0.23	-0.22	-0.30	-0.68	-0.52	-0.10	-0.05	-0.58	-0.40
Length	-0.37	-0.66	-0.80	-0.71	0.34	0.39	0.45	0.20	0.67	0.23	0.67	0.53
Area Groat	-0.88	0.42	0.77	0.64	0.30	-0.47	-0.57	-0.35	0.18	-0.23	-0.73	-0.58
width Groat	-0.59	-0.63	-0.21	-0.27	-0.17	0.08	0.14	-0.07	-0.10	-0.03	0.03	0.06
Length Groat	-0.92	-0.37	0.58	0.11	0.61	-0.36	-0.54	-0.38	0.37	-0.02	-0.68	-0.27
Groat Ratio	0.24	-0.68	-0.68	-0.59	-0.83	0.36	0.65	0.31	-0.48	-0.03	0.60	0.39
Grain Density	-0.13	0.37	0.77	0.57	-0.26	-0.69	-0.74	-0.67	-0.58	0.00	-0.79	-0.60
Circularity	0.13	0.23	0.76	0.49	-0.37	-0.43	-0.50	-0.35	-0.67	-0.13	-0.69	-0.45
Compactness	-0.14	0.50	0.76	0.66	0.37	-0.43	-0.50	-0.27	0.66	-0.23	-0.69	-0.55
Grain Ratio	0.03	-0.51	-0.77	-0.67	-0.40	0.44	0.50	0.28	-0.62	0.23	0.69	0.55

Tables 4.21.c *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations.*

	Balado *Kernel content*	**Gerald** *Kernel content*	**Mascani** *Kernel content*	**Tardis** *Kernel content*	**Balado** *Hullability*	**Gerald** *Hullability*	**Mascani** *Hullability*	**Tardis** *Hullability*
Kernel content	1.00	1.00	1.00	1.00				
Hullability	0.47	0.54	0.37	0.29	1.00	1.00	1.00	1.00
Specific weight	0.68	0.49	-0.32	0.24	0.09	0.00	-0.03	0.03
Yield	-0.45	-0.52	-0.75	-0.35	-0.75	-0.57	-0.34	-0.26
TGW	0.82	0.66	0.12	0.28	0.39	0.18	0.43	0.20
Grain nº/m^2	-0.73	-0.74	-0.78	-0.46	-0.70	-0.54	-0.47	-0.31
Area	0.74	0.33	-0.03	0.42	0.16	-0.21	0.11	-0.36
Width	0.71	0.58	0.12	0.18	0.33	0.15	0.50	0.14
Length	0.38	0.01	-0.11	0.32	-0.14	-0.39	-0.11	-0.50
Area Groat	0.86	0.27	0.14	-0.18	0.59	0.42	0.24	0.45
width Groat	0.74	0.65	0.06	0.37	0.36	0.23	0.12	0.16
Length Groat	0.80	0.47	-0.05	0.17	0.65	0.11	0.19	0.04
Groat Ratio	0.04	0.60	0.16	0.45	-0.24	0.20	-0.03	0.16
Grain Density	0.31	-0.20	-0.12	-0.15	0.37	-0.10	0.14	-0.07
Circularity	-0.06	0.41	0.11	-0.01	0.29	0.45	0.16	0.50
Compactness	0.10	0.21	0.16	-0.24	-0.27	0.46	0.21	0.49
Grain Ratio	0.09	-0.17	-0.14	0.26	0.30	-0.46	-0.18	-0.49

Tables 4.21.d *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations.*

	Balado *Sp Wt*	**Gerald** *Sp Wt*	**Mascani** *Sp Wt*	**Tardis** *Sp Wt*	**Balado** *Yield*	**Gerald** *Yield*	**Mascani** *Yield*	**Tardis** *Yield*
Specific weight	1.00	1.00	1.00	1.00				
Yield	-0.13	0.25	0.42	0.36	1.00	1.00	1.00	1.00
TGW	0.85	0.67	0.25	0.45	-0.34	-0.09	0.13	-0.02
Grain nº/m^2	-0.50	-0.09	0.35	0.10	0.89	0.89	0.96	0.89
Area	0.68	0.22	-0.19	0.06	-0.42	-0.19	0.26	-0.12
Width	0.82	0.73	0.30	0.41	-0.25	0.04	0.22	0.07
Length	0.23	-0.12	-0.25	-0.10	-0.24	-0.19	-0.25	-0.10
Area Groat	0.67	0.44	0.29	0.24	-0.56	0.17	0.26	0.11
width Groat	0.79	0.57	0.05	0.46	-0.26	-0.12	-0.08	-0.23
Length Groat	0.47	0.74	0.40	0.47	-0.68	0.18	0.38	0.08
Groat Ratio	0.45	0.35	-0.24	0.43	0.39	-0.28	-0.47	-0.47
Grain Density	0.33	0.28	0.40	0.19	0.00	0.43	0.52	0.45
Circularity	0.10	0.43	0.29	0.38	0.08	0.01	0.27	0.03
Compactness	-0.07	0.34	0.26	0.15	-0.09	0.15	0.22	0.09
Grain Ratio	0.26	-0.30	-0.25	-0.12	0.06	-0.16	-0.23	-0.07

Tables 4.21.e *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations).*

	Balado *TGW*	**Gerald** *TGW*	**Mascani** *TGW*	**Tardis** *TGW*	**Balado** *grain nº/m²*	**Gerald** *grain nº/m²*	**Mascani** *grain nº/m²*	**Tardis** *grain nº/m²*
TGW	1.00	1.00	1.00	1.00				
Grain nº/m²	-0.72	-0.53	-0.15	-0.47	1.00	1.00	1.00	1.00
Area	0.70	0.56	0.11	0.33	-0.67	-0.45	-0.31	-0.28
Width	0.96	0.96	0.93	0.97	-0.63	-0.40	-0.03	-0.38
Length	0.14	0.12	-0.27	-0.32	-0.29	-0.25	-0.19	0.04
Area Groat	0.89	0.33	0.50	0.64	-0.84	0.03	0.13	-0.18
width Groat	0.97	0.85	0.56	0.81	-0.64	-0.49	-0.23	-0.57
Length Groat	0.67	0.91	0.86	0.91	-0.82	-0.26	0.15	-0.34
Groat Ratio	0.44	0.61	-0.09	0.43	0.08	-0.52	-0.44	-0.60
Grain Density	0.52	0.17	0.60	0.68	-0.22	0.29	0.36	0.08
Circularity	0.25	0.48	0.60	0.66	-0.01	-0.18	0.12	-0.27
Compactness	-0.21	0.20	0.44	0.54	-0.01	0.07	0.11	-0.15
Grain Ratio	0.42	-0.15	-0.41	-0.51	-0.11	-0.10	-0.13	0.15

Tables 4.21.f *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations.*

	Balado *Area*	**Gerald** *Area*	**Mascani** *Area*	**Tardis** *Area*	**Balado** *Width*	**Gerald** *Width*	**Mascani** *Width*	**Tardis** *Width*	**Balado** *Length*	**Gerald** *Length*	**Mascani** *Length*	**Tardis** *Length*
Area	1.00	1.00	1.00	1.00								
Width	0.61	0.46	-0.08	0.27	1.00	1.00	1.00	1.00				
Length	0.79	0.87	0.91	0.75	0.02	-0.01	-0.44	-0.38	1.00	1.00	1.00	1.00
Area Groat	0.78	-0.56	-0.77	-0.47	0.80	0.47	0.67	0.69	0.33	-0.89	-0.96	-0.93
width Groat	0.61	0.65	0.50	0.38	0.97	0.80	0.35	0.75	0.03	0.28	0.30	-0.12
Length Groat	0.77	0.37	-0.26	0.26	0.53	0.93	0.86	0.92	0.51	-0.07	-0.56	-0.32
Groat Ratio	-0.07	0.71	0.71	0.36	0.59	0.52	-0.32	0.33	-0.48	0.48	0.73	0.15
Grain Density	-0.20	-0.39	-0.59	0.02	0.49	0.29	0.74	0.78	-0.67	-0.55	-0.80	-0.47
Circularity	-0.49	-0.44	-0.71	-0.47	0.36	0.50	0.66	0.64	-0.92	-0.76	-0.90	-0.86
Compactness	0.53	-0.66	-0.80	-0.55	-0.30	0.33	0.60	0.59	0.94	-0.94	-0.98	-0.96
Grain Ratio	-0.32	0.70	0.83	0.59	0.55	-0.29	-0.57	-0.56	-0.82	0.96	0.98	0.97

Tables 4.21.g *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlation*

	Balado *Area Groat*	**Gerald** *Area Groat*	**Mascani** *Area Groat*	**Tardis** *Area Groat*	**Balado** *width Groat*	**Gerald** *width Groat*	**Mascani** *width Groat*	***Tardis*** *width Groat*	**Balado** *Length Groat*	**Gerald** *Length Groat*	**Mascani** *Length Groat*	**Tardis** *Length Groat*
Area Groat												
width Groat	1.00	1.00	1.00	1.00								
Length Groat	0.86	0.77	0.47	0.88	1.00	1.00	1.00	*1.00*				
Groat Ratio	0.92	0.90	0.70	0.83	0.59	0.44	-0.28	*0.49*	1.00	1.00	1.00	1.00
Grain Density	0.06	-0.24	-0.15	0.34	0.56	0.43	0.79	*0.74*	-0.33	-0.62	-0.80	-0.23
Circularity	0.32	0.22	0.03	0.46	0.54	0.55	0.81	*0.60*	0.09	-0.07	-0.57	0.16
Compactness	0.02	0.01	-0.18	0.30	0.34	0.35	0.67	*0.50*	-0.24	-0.26	-0.70	-0.05
Grain Ratio	0.01	0.03	0.21	-0.28	-0.30	-0.32	-0.65	*-0.48*	0.26	0.30	0.70	0.07

Tables 4.21.h *Pearson´s correlation coefficients between quality traits and grain and groat size of each of the four winter oat varieties. Green numbers show negative correlations whilst red numbers show positive correlations.*

	Balado *Groat Ratio*	Gerald *Groat Ratio*	Mascani *Groat Ratio*	Tardis *Groat Ratio*	Balado *Grain Density*	Gerald *Grain Density*	Mascani *Grain Density*	Tardis *Grain Density*
Groat Ratio	1.00	1.00	1.00	1.00	1.00			
Grain Density	0.53	0.54	0.86	0.86	0.82	1.00	1.00	1.00
Circularity	0.64	0.57	0.85	0.85	-0.82	0.86	0.93	0.93
Compactness	-0.62	-0.58	-0.84	-0.84	0.83	-0.86	-0.93	-0.93

7. References

Achleitner, A. Tinker, N., Zechner, E. & Buerstmayr, H. 2008. Genetic diversity among oat varieties of worldwide origin and associations of AFLP markers with quantitative traits. *Theoretical and Applied Genetics*, 117(7), pp.1041–1053..

Adams, M.W. & Grafius, J.E., 1971. Yield component compensation - Alternative interpretations. *Crop Science*, 11(1), pp.33–35.

AHDB, 2012. AHDB Cereals & Oilseeds : RL Archive 2011-12.

Andersson, A.A.M. & Börjesdotter, D., 2011. Effects of environment and variety on content and molecular weight of β-glucan in oats. *Journal of Cereal Science*, 54(1), pp.122–128.

Anon, 2015. Met Office. *2014*. Available at: https://www.metoffice.gov.uk /climate/uk/summaries.

Ashraf, M., Qureshi, A.S., Ghafoor, A. & Niaz, K., 2001. Genotype-Environment Interaction in Wheat. *Journal of Biological Sciences*, 1(5), pp.356–357.

Asif, M. Mustafa, S.Z. & Asim, M., 2003. Stability of Wheat Genotypes for Grain Yield under Diverse Rainfed Ecologies of Pakistan.*Asian Journal of Plant Sciences 2*, pp.400–402.

Becker, H.C. & Leon, J., 1988. Stability Analysis in Plant Breeding. *Plant Breeding*, 101(1), pp.1–23.

Browne, R., White, E. & Burke, J., 2002. Hullability of oat varieties and its determination using a laboratory dehuller. *Journal of Agricultural Science*, (2002), pp.185–191.

Brunner, B.R. & Freed, R.D., 1994. Oat Grain β-Glucan Content as Affected by Nitrogen Level, Location, and Year. *Crop Science*, 34(2), p.473.

Burke, J.I., Browne, R.A. & White, E.M., 2001. *Factors Affecting Yield and Quality of Oats*, End of Project Reports, Teagsc, 2001.

Clarke, M.P., Gooding, M.J. & Jones, S.A., 2004. The effects of irrigation, nitrogen fertilizer and grain size on Hagberg falling number, specific weight and blackpoint of winter wheat. *Journal of the Science of Food and Agriculture*, 84(3), pp.227–236.

Cooper, L., 1937. Oats and Other Grains. *PMLA*, 52(3), p.785.

Doehlert, D.C. Mcmullen, M. S.Jannink, J. L.Panigrahi, S.Gu, H.& Riveland, N. R.., 2005. A bimodal model for oat kernel size distributions. *Canadian Journal of Plant Science*, 85(2), pp.317–326.

Doehlert, D.C., 2001. Genotypic and environmental effects on grain yield and quality of oat grown in North Dakota. *Crop Science*, 41(4), pp.1066–1072.

Doehlert, D.C., McMullen, M.S. & Baumann, R.R., 1999. Factors Affecting Groat Percentage in Oat. *Crop Science*, 39(6), p.1858.

Finlay, K. & Wilkinson, G., 1963. The analysis of adaptation in a plant-breeding programme. *Australian Journal of Agricultural Research*, 14(6), p.742.

Forsberg, R.A. & Reeves, D.L., 1995. Agronomy of oats. In *The Oat Crop*. Dordrecht: Springer Netherlands, pp. 223–251.

Gibson, R..Pearce, S., Morris, R.J., Symondson, W.O.C. & Memmott, N., 2007. Plant Diversity and land use under organic and conventional agriculture: a whole-farm approach. *Journal of Applied Ecology*, (44), pp.792–803.

Griffiths, I. 2008. Dissecting the Components of Yield in Oats (*A . sativa*). PhD thesis Aberystwth University.

Hongyu, K., Penña M.G., Araújo L.B. & Dias C.T.S., 2014. Statistical analysis of yield trials by AMMI analysis of genotype × environment interaction.*Biometrical letters* , 51(2), pp.89–102.

Huehn, M., 1990. Nonparametric measures of phenotypic stability. Part 1: Theory. *Euphytica*, 47(3), pp.189–194.

Humphreys, D.G., Smith, D.L. & Mather, D.E., 1994. Nitrogen Fertilizer and Seeding Date Induced Changes in Protein, Oil and β-Glucan Contents of Four Oat Cultivars. *Journal of Cereal Science*, 20(3), pp.283–290.

Hundal, R.K., Kang, J.S. & Singh, A., 2017. Variation in Growth, Yield and Quality of Happy Seeder Sown Wheat with Different Planting Patterns and Times of Nitrogen Application. *Int.J.Curr.Microbiol.App.Sci*, 6(8), pp.1420–1428.

Jackson GD, Berg RK, Kushnak GD, Blake TK & Yarrow GI, 1994. Nitrogen effects on yield, beta-glucan content, and other quality factors of oat and waxy hulless barley. *Communications in Soil Science and Plant Analysis*, 25(17–18), pp.3047–3055.

Lehmensiek, A., Sutherland, M.W. & McNamara, R.B., 2008. The use of high resolution melting (HRM) to map single nucleotide polymorphism markers linked to a covered smut resistance gene in barley. *Theoretical and Applied Genetics*, 117(5), pp.721–728.

Lin, C.S. & Binns, M.R., 1991a. Assessment of a method for cultivar selection based on regional trial data. *Theoretical and Applied Genetics*, 82(3), pp.379–388.

Lin, C.S. & Binns, M.R., 1991b. Genetic properties of four types of stability parameter. *Theoretical and Applied Genetics*, 82(4), pp.505–509.

Ma, B.L. Biswas, D. K.Zhou, Q. P. & Ren, C. Z., 2012. Comparisons among cultivars of wheat, hulled and hulless oats: Effects of N fertilization on growth and yield. *Canadian Journal of Plant Science*, 92(6), pp.1213–1222.

Manley, M. Engelbrecht, M.L.Williams, P.C.& Kidd, M., 2009. Assessment of variance in the measurement of hectolitre mass of wheat, using equipment from different grain producing and exporting countries. *Biosystems Engineering*, 103(2), pp.176–186.

Mannerstedt Fogelfors, B. & Peterson, D.M., 2004. Cultivation environment affects antioxidants, protein and oil content of oat genotypes differently. *Agrifood Research Reports*, 51, p.154.

MathWorks, 2013. Matlab. Available at: https://uk.mathworks.com/?s _tid=gn_logo.

Miller, P., Lanier, W. & Brandt, S., 1997. Using Growing Degree Days to Predict Plant Stages E-5. Available at: http://store.msuextension.org/ publications/agandnaturalresources/mt200103ag.pdf [Accessed January 31, 2018].

Owens, B. Mccann, M E E. Park, R. & Mccracken, K. J., 2007. *Defining feed wheat quality for broilers*, Available at: https://cereals.ahdb.org.uk/ media/312226/pr423-final-project-report.pdf

Paroda, R.S. & Hayes, J.D., 1971. An investigation of genotype-environment interactions for rate of ear emergence in spring barley. *Heredity*, 26(2), pp.157–175.

Peterson, D.M., 1991. Genotype and Environment Effects on Oat Beta-Glucan Concentration. *Crop Science*, 31(6), p.1517.

Peterson, D.M. Wesenberg, D.M., Burrup, D.E. & Erickson, C.A., 2005. Relationships among Agronomic Traits and Grain Composition in Oat Genotypes Grown in Different Environments. *Crop Science*, 45(4), p.1249.

Peterson, D.M., Wesenberg, D.M. & Burrup, D.E., 1995. β-Glucan Content and Its Relationship to Agronomic Characteristics in Elite Oat Germplasm. *Crop Science*, 35(4), p.965.

Peterson, D.M. & Wood, D.F., 1997. Composition and Structure of High-Oil Oat. *Journal of Cereal Science*, 26(1), pp.121–128.

Pushman, F.M. & Bingham, A.J., 2017. Components of test weight of ten varieties of winter wheat grown with two rates of nitrogen fertilizer application. *J. agric. Sci.,* 85, pp.559–563.

Redaelli, R. Del Frate, V., Terracciano, S., Ciccoritti, G., Germeier, R. De Stefanis, E. C. Sgrulletta, E. & Daniela, S. 2013. Genetic and environmental variability in total and soluble B-glucan in European oat genotypes. *Journal of Cereal Science*, 57(2), pp.193–199.

Roel, A., Firpo, H. & Plant, R.E., 2007. Why do some farmers get higher yields? Multivariate analysis of a group of Uruguayan rice farmers. *Computers and Electronics in Agriculture*, 58(1), pp.78–92.

Sial, M.A., Arain, M.A. & Ahmad, M., 2000. Genotype x Environment interaction on bread wheat grown over multiple sites and years in Pakistan. *Pak.J.Bot*, 32(1), pp.85–91.

Subira, J., Álvaro, F., García del Moral, LF. & Royo C., 2015. Breeding effects on the cultivar × environment interaction of durum wheat yield. *European Journal of Agronomy*, 68, pp.78–88.

Symons, S.J. & Fulcher, R.G., 1988a. Relationship between oat kernel weight and milling yield. *Journal of Cereal Science*, 7(3), pp.215–217.

Symons, S.J. & Fulcher, R.G.G., 1988b. Determination of variation in oat kernel morphology by digital image analysis. *Journal of Cereal Science*, 7(3), pp.219–228. Available at:

Weisstein, E.W., 2018. Box-and-Whisker Plot. Available at: http://mathworld.wolfram.com/Box-and-WhiskerPlot.html [Accessed June 16, 2018].

Welch, R.W., 1995. *The oat crop : production and utilization*, Chapman & Hall.

White, E. & Watson, S., 2010. An investigation of the relationship between hullability and morphological features in grains of four oat varieties. *Annals of Applied Biology*, 156(2), pp.281–295.

White, E.M., McGarel, A.S.L. & Ruddle, O., 2003. The influence of variety, year, disease control and plant growth regulator application on crop damage, yield and quality of winter oats (Avena sativa). *Journal of Agricultural Science*, 140(1), pp.31–42.

Wilkinson, J. Miller, H. M. McCracken, K.J. Knox, A. & McNab, J. Rose, S.P., 2003. Effect of specific weight on the metabolizable energy content of four cultivars of wheat grain in ewes. *Animal Feed Science and Technology*, 105(1–4), pp.215–224.

Wychowaniec, J. Griffiths, I. Gay, A. Mughal, A. I., 2013. Compaction of cereal grain. *Philosophical Magazine*, 93, pp.31–33.

Youngs, V.L. & Forsberg, R.A., 1979. Protein-Oil Relationships in Oats1. *Crop Science*, 19, pp.798–802.