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Dissecting the yield components of oats (*Avena sativa*)

by

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ABSTRACT

Yield is a complex trait and many procedures have been developed to monitor yield formation. This study comprised of a genetic diversity study and three sets of field experiments to help elucidate yield and its components.

- Both the marker data and the kinship analysis indentified five main ancestral cultivars within this study.
- The ancestral lines Solva and Bulwark tended to cluster closely with their progeny.
- Dry matter accumulation was positively correlated with yield.
- There was a negative relationship between height and panicle emergence.
- Grain size distribution was shown to be bimodal. When measured separately, primary KC and TGW had a highest correlation to the mixed grain sample.
- Grain shape altered with year of release with grain becoming more elongated.
- Yield increased with increased nitrogen application.
- For individual cultivars the amount of the nitrogen needed to produce optimal yield varies.
- Balado, Fusion, Hendon and Tardis had the highest yield at the RB209+70 nitrogen treatment. The remaining cultivars, 00-61Cn1, Brochan, Gerald and Racoon had the highest yield at the RB209+50 treatment.
- Total nitrogen content of the crop and the grain and total biomass increase with increasing nitrogen application.
- NUE and its components NUpE, crop NUtE and grain NUtE displayed a negative relationship with nitrogen applied to the crop.
- Fertile shoot number, grain number and height all increased with increasing nitrogen treatment.
- TGW was not greatly affected by nitrogen application but grain number per metre^2 increased with increasing nitrogen suggesting that this is a major determinant of grain yield.
- Dwarf cultivars had a later emergence date for both flag leaf and panicle than the conventional height cultivars.
- Little difference was seen in maturity dates of conventional height and dwarf lines.
- In a mapping population developed from a cross between a dwarf and tall population, the segregating population mean was closer to the conventional height mean than the dwarf mean for the majority of traits.
- Dwarf lines had a poorer panicle extrusion, grain quality and yield than tall cultivars. They also had a short period between panicle extrusion and maturity.

INTRODUCTION

In agriculture, yield is the term used to quantify the productivity of a crop. In general terms this means the amount of product per unit area of land. In more specific terms for cereal crops, it is the number of tonnes of grain produced for every hectare grown (Evans, 1999). Yield is a complex trait and many procedures have been developed to monitor yield formation. Adams and Grafius (1971) split yield up into three components; the number of panicles per unit area, the grain number per panicle and grain weight. Other traits which are influential in the yield forming process are harvest index (HI, Peltonen-Sainio *et al,* 2008), growth rate (Takeda and Frey, 1976, Helsel and Frey, 1983) and canopy longevity (Gregerson *et al*, 2008, Zhao *et al*, 2009).

The first major yield component to be determined in the field season is the number of shoots. Rasmusson and Cannell (1970) found a positive response between yield and the number of heads in barley. Cereals tend to over produce tillers. The plant cannot always support all of these tillers to produce fertile heads therefore there is some tiller death in the early part of the growth cycle. This has normally ceased by flag leaf emergence (Lauer and Simmons, 1998). Emerging tillers act as a strong sink for photoassimilates and any tillers not surviving can re-translocate these assimilates into the main stem (Lauer and Simmons, 1988).

There is some debate about how grain numbers are determined. Fischer (2008) suggested that there is an overlap between grain number determination and grain weight and that kernel weights can be influenced by events up to one week before anthesis. Alternatively, Sinclair and Jamieson (2008) suggest that plants adjust grain numbers to match the accumulated resources within a limited range of grain size. In oats the husk is fully formed prior to grain filling (Browne *et al*, 2006) giving a limit to grain size before grain filling. Peltonen-Sainio (2007) found grain number to be a more flexible trait than grain size. Consistency of kernel content and grain weight are achieved through abortion of kernels and the production of tertiary grains (Browne *et al*, 2006).

Grain filling in wheat depends on current photosynthesis and mobilisation of stored water soluble carbohydrates (Ehdaie *et al*, 2008). Moot *et al* (1998) found that grain weight distributions could not be manipulated by agronomic practices. In Finland the breeding program of oats has shortened the grain filling period in newly released cultivars (Peltonen-Sainio *et al*, 2007) by three to four days resulting in an increase in yield. The reduction in growing time and grain filling ultimately caused an increase in the rate of grain filling. In a summary of results from genetic mapping experiments, Snape *et al* (2007) found that grain size was the trait most correlated with grain yield in wheat.

In wheat the introduction of the dwarfing genes resulted in the improvement of yield through an increase in both harvest index (HI) and spikelet fertility. This sparked the hunt for dwarfing genes in oats. The *Dw6* gene is one of the most successful oat dwarfing genes. This gene however causes a reduction in extrusion and sterility of enclosed florets (Farnham *et al,* 1990). This phenomenon is also seen in rice which has a similar panicle to oats (Cho *et al*, 1994). The shorter stature is thought to favour tiller survival by increasing light availability in the lower canopy of the crop (Meyers *et al*, 1985).

The ability of the crop to use nitrogen efficiently is an important factor when considering yield potential. Nitrogen is one of the major essential elements for crop growth and development and it is heavily used in modern agriculture to maximize yields. Crops that are inefficient at using nitrogen supplied to them contribute to both pollution and global warming (Sylvester-Bradley *et al*, 2009). Nitrogen use efficiency (NUE) is the product of two components; these are Nitrogen Uptake Efficiency (NUpE) and Nitrogen Utilisation Efficiency (NUtE, Moll *et al*, 1982, Muurinen *et al*, 2006). NUpE for wheat and barley are 55% and 50% respectively (DEFRA, 2005). Oats are generally regarded to be more efficient at nitrogen use than other cereals (Sylvester-Bradley *et al*, 2009).

This report describes field experiments conducted on a range of commercial winter oat cultivars, some containing the *Dw6* dwarfing gene and others of conventional height. Measurements reported include yield component traits, growth analyses, height components and grain quality. Thousand grain weight (TGW), kernel content (KC), hullability and kernel/groat dimensions are traits that describe the quality of the grain (Doehlert *et al*, 2001). They also form important yield components for the oat crop. Results from yield trials conducted when each of the cultivars used were first added to the recommended list indicate that considerable increases in yield have been obtained in the past 20 years (fig 1). This study aims to provide understanding of the traits underlying this yield increase.

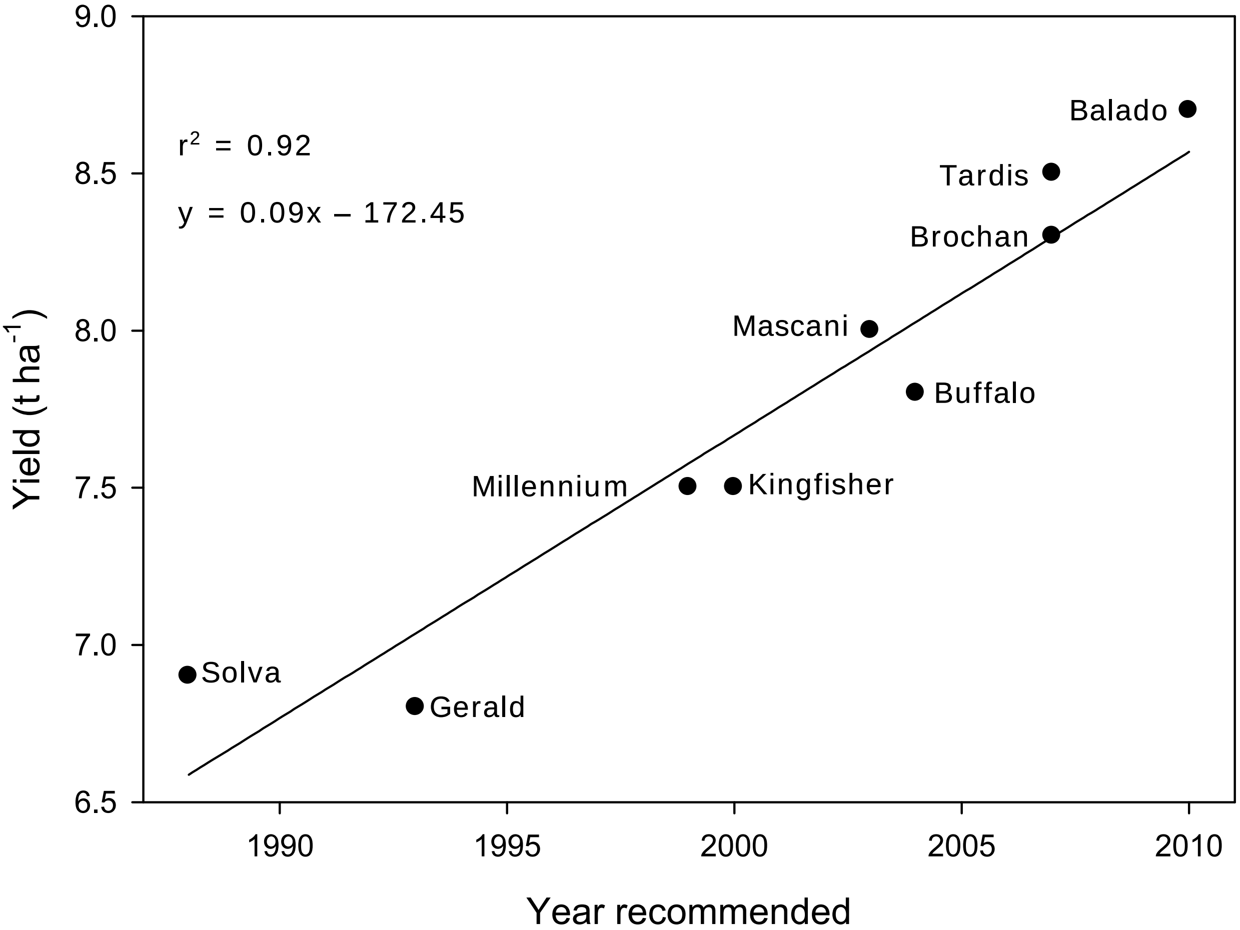

Figure 1 Relationship between year of recommendation and yield for nine cultivars used in this study. Based on yield results from the HGCA recommended list when the cultivars were first included on the list.

MATERIALS AND METHODS

Plant material

All seed material was supplied by Aberystwyth University. The cultivars used were all of commercial importance with the majority either currently on the HGCA recommended list or had been previously (Table 1). They were chosen to represent a range in year of release. Seven of the cultivars contained the *Dw6* dwarfing gene. Four cultivars had a naked grain type rather than a husked grain type (table 2).

Table 1 List of the cultivars indicating the year of the cross and the two parents. NB A sister of Millennium was used as one of the parents in the production of Tardis and Brochan. A sister of Solva was used as one of the parents in the production of Gerald.

Cultivar name	Year of cross	Year of recommendation	IBERS code	Male Parent	Female parent
B443			-	-	-
Grey Winter	Landrace		-	-	-
S147	1925	1938*		Marvelous	Grey Winter
S172	1928	1939*		(Kyko x Grey Winter)	(Bountiful x Grey
Bulwark	1970	1984	06684CnII/19	06535CII	Peniarth
Solva	1976	1988	76-17Cn22/2	07270Cn	Oyster
Gerald	1981	1993	81-26Cn11/1	Bulwark	76-17Cn26
84-139	1984		84-139	B443	Solva
Millennium	1987	2000	87-42Cn1/2/2/1	78-1Cn3/2/1/2	81-206Cn6
Kingfisher	1989	1999	89-26CnA6/1	Gerald	Chamois
Buffalo	1993	2003	93-76Cn1/1	85-47Cn1/1/2	90-153ACn2
Hendon	1993	2003	93-85ACn5/2/2	Lexicon	92-87Cn
Penderi	1994	2003*	94-116Cn4/1	89-158ACn5	89-26ACn4/1
Mascani	1995	2004	95-56ACn3	Jalna	Millennium
Racoon	1995	2005*	95-240Cn5/1/1	Krypton	91-221Cn4
Brochan	1996	2007	96-21Cn7	87-42Cn1/2/2/1/2	91-33Cn4/2
Tardis	1996	2007	96-41Cn3	87-42Cn1/2/2/1/1	95-69RCn
Balado	1998	2010	98-82Cn3	97-48Cn	Kingfisher
Fusion	1998	2010	98-82Cn	Icon	Dunkeld
00-61Cn3	2000		00-61Cn3	99-143Cn	93-98RCn1/2
01-148Cn4	2001		01-148Cn4	Mascani	92-92Cn2/1
01-150Cn1	2001		01-150Cn1	Mascani	Penderi

**Penderi and Racoon only on National List, S147, S172 year when first marketed*

Diversity study

A two-part diversity study was conducted on all cultivars. The first part consisted of a genetic diversity study based on molecular markers. A selection of 68 microsatellite markers were selected for use from those published by Saghai Maroof *et al* (1994), Li *et al* (1996), Roder *et al* (1998), Pillen *et al* (2000), Ramsay *et al* (2000), Pal *et al* (2002), Zhu *et al* (2003), Song *et al* (2005), Jannick *et al* (2005), King *et al* (2008) and others developed at IBERS (and through research agreement with Vialactia). The presence or absence of marker bands was recorded for each marker to form a binary matrix. In addition to the microsatellites, 1295 DArT markers were used (Tinker *et al*, 2009). The presence or absence of markers was recorded and added to the binary matrix. Genetic similarities were estimated from the binary matrix using the Dice similarity index (Dice, 1945) as described by Nei and Li (1979). The cluster analysis was performed using the statistical software package, NTSYS-pc 2.11a (Rohlf, 2000) with the unweighted pair-group method of arithmetic means (UPGMA).

The second half of the study used the pedigree of the oat cultivars to assess their relatedness. The computer program KIN (Tinker and Mather, 1993) was used to calculate a kinship coefficient (r) between cultivars. This used pedigree information downloaded from the website of pedigrees of oat lines (POOL, Tinker and Deyl, 2005). The relationship with a cultivar with itself is r = 100. Cultivars without a common parentage are assumed to be unrelated therefore r = 0. A list of cultivars of interest was used to construct a matrix of kinship coefficients. A dendrogram was produced from this matrix as described above.

Field trials

Two physiology field experiments were set up. The first was grown on the Gogerddan campus of Aberystwyth University. This trial used a range of cultivars, ten in the 2006/07 season and twelve in the following two field seasons (Table 2). The second trial was grown at ADAS Rosemaund, Herefordshire in two field seasons, 2006/07 and 2007/08. This trial consisted of eight cultivars, four of which contained the dwarfing gene the other four were of conventional height (Table 2). Similarly four were of the naked grain type with four having husked grain. This trial had four nitrogen treatments, nil, RB209, the standard nitrogen rate as set out by DEFRA guidelines, RB209+50 and RB209+70. Traits measured at each field site were similar (Tables 3 and 4). Some of the traits measured were direct yield traits such as thousand grain weight. Others have been shown to increase yield in other cereals for example biomass accumulation (Helsel and Frey, 1983). A more detailed study of panicle architecture was conducted in the Aberystwyth trials and the 2007/08 field season at Rosemaund (Table 3).

A third field experiment was grown on the Gogerddan campus at Aberystwyth University. 188 progeny from the cross between the tall cultivar Tardis and the dwarf cultivar Buffalo along with the parents were sown in two field seasons. Measurements made on this trial included height components and the three major yield components, panicles per unit area, grain number and TGW along with yield itself.

Weather data was collected from onsite met stations. Data included daily rainfall, daily average air temperature and daily solar radiation.

Table 2 Cultivars used in the trials, indicating at which site and field season. Height refers to presence or absence of the Dw6 dwarfing gene. Differences in grain type also indicated. Note: Only the Aberystwyth trial was grown in the 2008/09 field season.

Cultivar	Site		Years			Height	Grain type
	Aberystwyth	Rosemaund	2006/7	2007/8	2008/9		
Brochan	√	√	√	√		Tall	Husked
Gerald	√	√	√	√	√	Tall	Husked
Kingfisher	√		√	√	√	Tall	Husked
Mascani	√		√	√	√	Tall	Husked
Millennium	√		√	√	√	Tall	Husked
Racoon		√	√	√		Tall	Naked
Solva	√		√	√	√	Tall	Husked
Tardis	√	√	√	√	√	Tall	Husked
00-61Cn3		√	√	√		Dwarf	Naked
01-148Cn3	√			√	√	Dwarf	Husked
01-150Cn1	√			√	√	Dwarf	Husked
Balado	√	√	√	√	√	Dwarf	Husked
Buffalo	√		√	√	√	Dwarf	Husked
Fusion		√	√	√		Dwarf	Naked
Hendon		√	√	√		Dwarf	Naked
Penderi	√		√	√	√	Dwarf	Husked

Table 3 Panicle architecture traits measured.

Trait
Average grains/spikelet
Panicle length and weight
Total number of primary, secondary and tertiary grains per whorl and per panicle
Total weight of primary, secondary and tertiary grains per whorl and per panicle
Total number single, double and triple spikelets per whorl and per panicle
TGW for primary and secondary kernel per whorl
Whorl number

Table 4 Traits measured in all field seasons along with date taken.

Trait measured	RM 2006/07	RM 2007/08	AB 2006/07	AB 2007/08	AB 2008/09
Plant counts			√	√	
Habit			√	√	
Winter hardiness			√	√	
Height – weekly				√	√
Leaf counts (until GS39)			√	√	
Tiller counts			√	√	
GS31 fertile shoot number	√	√	√	√	
GS31 dry matter	√	√	√	√	
GS31 nitrogen content	√	√	√	√	
GS31 height		√	√	√	
Light interception			√	√	
GS39 fertile shoot number	√	√	√	√	
GS39 dry matter	√	√	√	√	
GS39 nitrogen content	√	√	√	√	
GS39 height		√	√	√	
GS59 fertile shoot number	√	√	√	√	
GS59 total crop dry matter	√	√	√	√	
GS59 straw dry matter	√	√	√	√	
GS59 panicle dry matter	√	√	√	√	
GS59 straw nitrogen content	√	√	√	√	
GS59 panicle nitrogen content	√	√	√	√	
GS59 height		√	√	√	
No. green leaves – weekly				√	√
Panicle extrusion – weekly				√	√
Grain filling			√	√	
Harvest index	√	√	√	√	
Pre-harvest straw nitrogen content	√	√	√	√	
Groat nitrogen content	√	√	√	√	
Pre-harvest height	√	√	√	√	
No. green leaves		√		√	√
Internode length		√	√	√	√
Panicle analysis		√	√	√	√
TGW	√	√	√	√	√
Adjusted TGW	√	√	√	√	√
Specific weight*	√	√			
Kernel content (husked only)	√	√	√	√	√
Hullability (husked only)	√	√	√	√	√
Grain shape		√		√	√
Yield	√	√	√	√	√
Adjusted yield	√	√	√	√	√

RM= Rosemaund, AB= Aberystwyth * measured by ADAS Rosemaund staff.

Data analysis

Analysis of variance (ANOVA) was used to identify differences between cultivars. For experiments conducted at Aberystwyth a one-way ANOVA was used for cultivars within field seasons whereas a two way ANOVA was used to find differences between field seasons. At Rosemaund due to the design of the trial a split plot ANOVA was used to find differences between nitrogen treatments and cultivars between years. Nitrogen was used as the main plot and cultivar as the split plot. For differences between field seasons a split split plot was used. This had year as the main plot, nitrogen as the split plot and cultivar as the split split plot. All ANOVAs were conducted using Genstat 11th edition.

Trait means were used for correlation analysis to identify relationships between traits especially yield. These were conducted within field seasons only using the data analysis tool of excel (2007).

RESULTS

Genetic diversity study

The dendrogram produced using the Dice (1945) similarity coefficient split the cultivars up into two main clusters (Fig. 2). The first of these contained the oldest cultivars examined, Grey Winter, S147 and S172 along with Gerald, Bulwark and Millennium. Bulwark is a direct parent of Gerald and a grand parent of Millennium. Clustering closely to Millennium were a group of varieties that have Millennium or a sibling of Millennium as a parent. The second main cluster contained Solva and five cultivars all of which have Solva in their pedigree along with the most recently recommended cultivar, Balado and its parent Kingfisher. 00-61Cn3 contained a number of novel alleles and was dissimilar to the other commercial cultivars. This could be due to the presence of both some wild germplasm and Australian breeding material in its pedigree. B443 is a large grained accession of Avena sterilis, a wild relative of oats and was shown to be very dissimilar to the other commercial cultivars. The range of genetic diversity detected between the oat cultivars in this study was relatively low. Novel alleles linked to valuable traits from lines such as B443 could be useful in expanding the genetic diversity of oats.

The schematic diagram (Fig. 3) shows the relationship between the commercial cultivars used in this study. This gives an idea of how interrelated the cultivars are in the IBERS winter oat breeding program. Although this figure gives a good visual representation of the interrelatedness of these cultivars it is important to note that this does not display the other important and often novel DNA that is present in the pedigrees of these cultivars as indicated in Table 1. There are five main ancestral lines. These are Grey Winter which can be found in the pedigree of all of the lines used in this study. S147 and S172 are found in the pedigree of thirteen of these cultivars. The more modern cultivars Bulwark and Solva are found in the pedigrees of eleven and nine cultivars respectively.

The dendrogram based on pedigree data, grouped the cultivars into four main clusters (not shown). The first cluster contained the three main ancestral lines S147, Greywinter and S172. The second cluster contained lines related to Millennium. The third cluster contained Bulwark along with Gerald, Kingfisher and Balado. The fourth and final cluster comprised the ancestral line Solva along with cultivars derived from it namely Hendon, Buffalo, 00-61Cn3, Fusion and Penderi. Racoon had a low kinship with the other cultivars included in this study and was therefore not found in any of these clusters. Racoon includes novel high oil germplasm from Iowa which could explain its low kinship with the other varieties.

The main difference between the dendrograms produced by marker data and by pedigree analysis is the position of Bulwark and Gerald. Although these are, by pedigree analysis, closely related to Kingfisher and Balado this was not found by analysis using DNA based markers. Pedigree analysis only examines the parentage of cultivars. The difference between the dendrograms indicates the considerable selection that occurs following the initial cross.

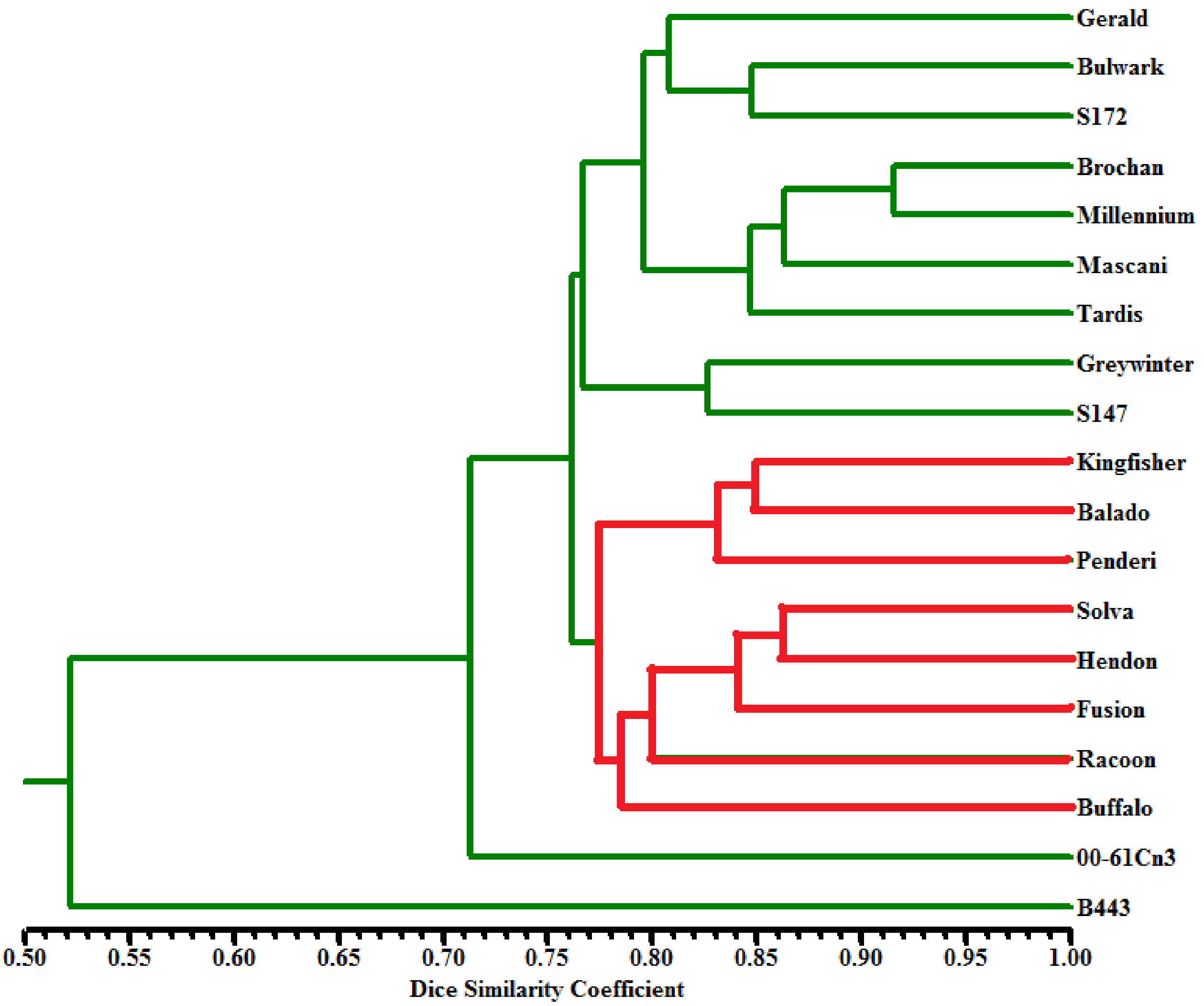

Figure 2 UPGMA dendrogram combining both the SSR and DArT marker information. Similarity between cultivars calculated using the Dice similarity coefficient (1945).

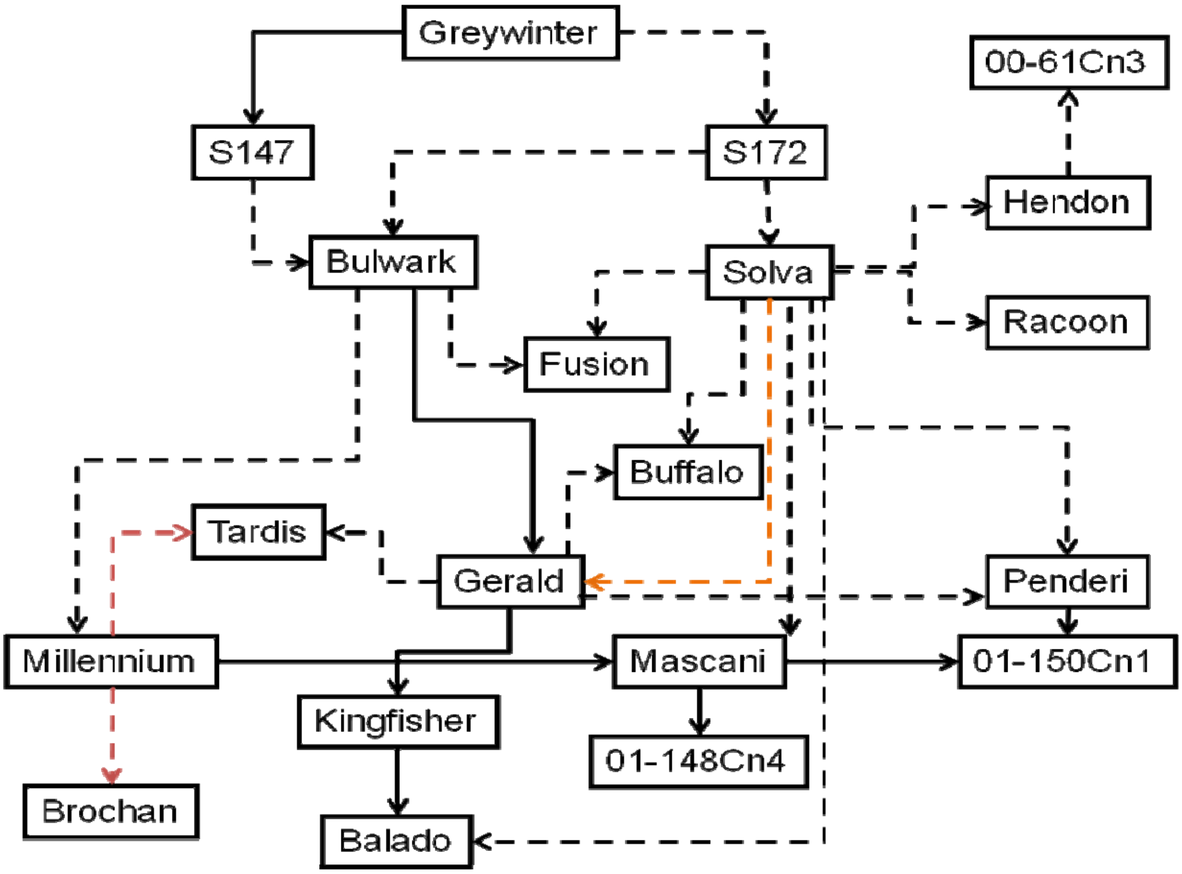

Figure 3 A diagram representing the pedigree relationship between the commercial cultivars used in this study. Solid black arrows indicate cultivars that are direct parents. The dotted black arrows indicate the presence of that cultivar in the pedigree. The red dotted arrows represent sister lines to Millennium that were used in the cross to form Brochan and Tardis. The orange dotted line represents a sister line that was used as a parent in the cross to produce Gerald. This web only includes the cultivars used in this study and it should be noted that other germplasm was used in the creation of these cultivars.

- Both the marker data and the kinship analysis indentified five main ancestral cultivars within this study.
- The ancestral lines Solva and Bulwark tended to cluster closely with their progeny.
- The introgression of wild germplasm had a large effect on the distinctness of the cultivar 00-61Cn3 due to a higher level of novel alleles present in its genome.

Aberystwyth physiology study

Fertile shoot numbers were recorded at five main developmental points throughout the life cycle. These were early stem extension (GS31), flag leaf emergence (GS39), panicle emergence (GS59), complete crop senescence (CCS) and pre-harvest (PH). Samples were taken on growth stage rather than calendar date. As the different cultivars developed at different rates, cultivars were harvested on different days. Shoot numbers were highest at GS31 and then declined throughout the season until PH (Fig. 4). Shoot numbers were lower in the 2006/07 field season when, on average, cultivars lost 300 shoots per m^{-2} between GS31 and pre-harvest. A third of the shoots were lost between GS31 and GS39. In the 2007/08 field season there was a significant interaction between cultivar and growth stage meaning that the decline of shoot numbers was different for different cultivars. On average cultivars lost only 200 shoots per m^{-2} with the largest loss again occurring between GS31 and GS39.

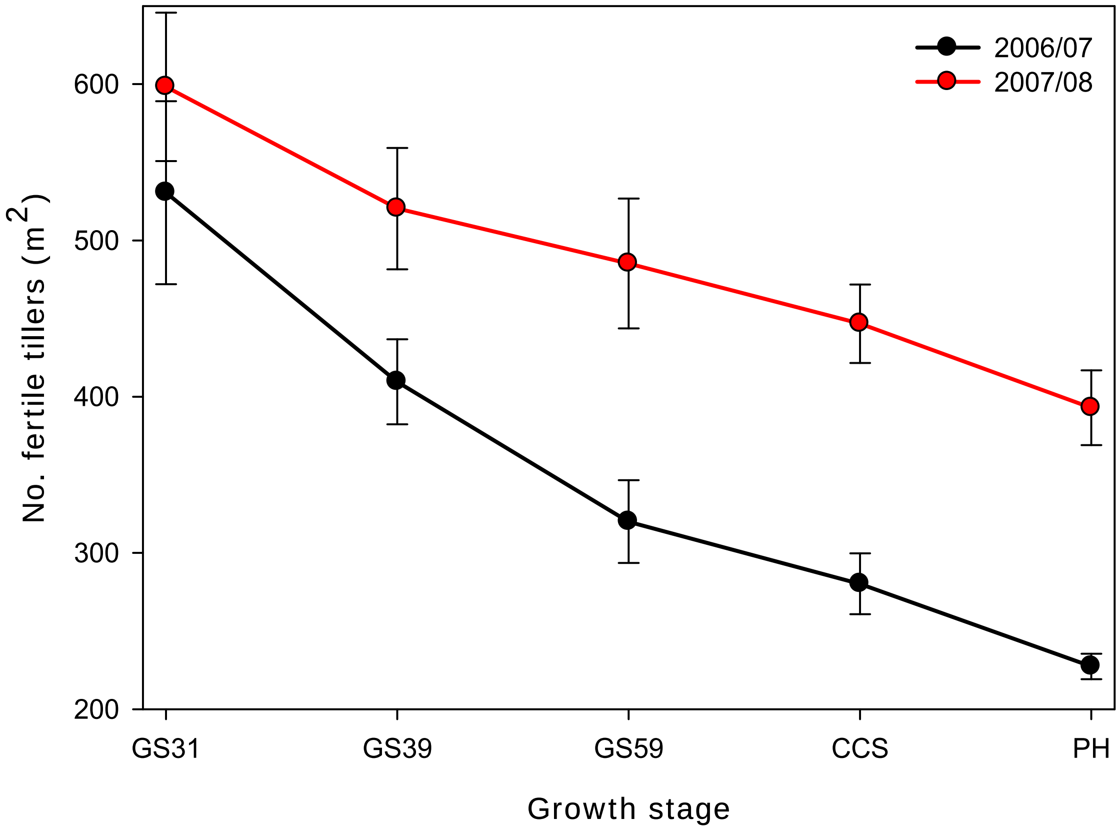

Figure 4 Decline in shoot numbers at Aberystwyth in field season 2006/07 (eight cultivars) and 2007/08 (12 cultivars). Each line represents the mean of all cultivars tested. Bars represent one standard error of the mean.

Dry matter accumulation and nitrogen content were also recorded at the same main five developmental points. Significant differences were seen between cultivars with Millennium and Mascani having high dry matter and nitrogen content in both field seasons. Accumulated biomass was higher in the 2007/08 field season (Fig. 5). In both field seasons biomass increased from GS31 up until CCS. The largest increase was seen between GS39 and GS59 (5 t ha^{-1} in 2007/08 compared to 4.5 t ha^{-1} in 2006/07). 3 t ha^{-1} biomass was lost between CCS and PH in both field seasons (Fig. 5).

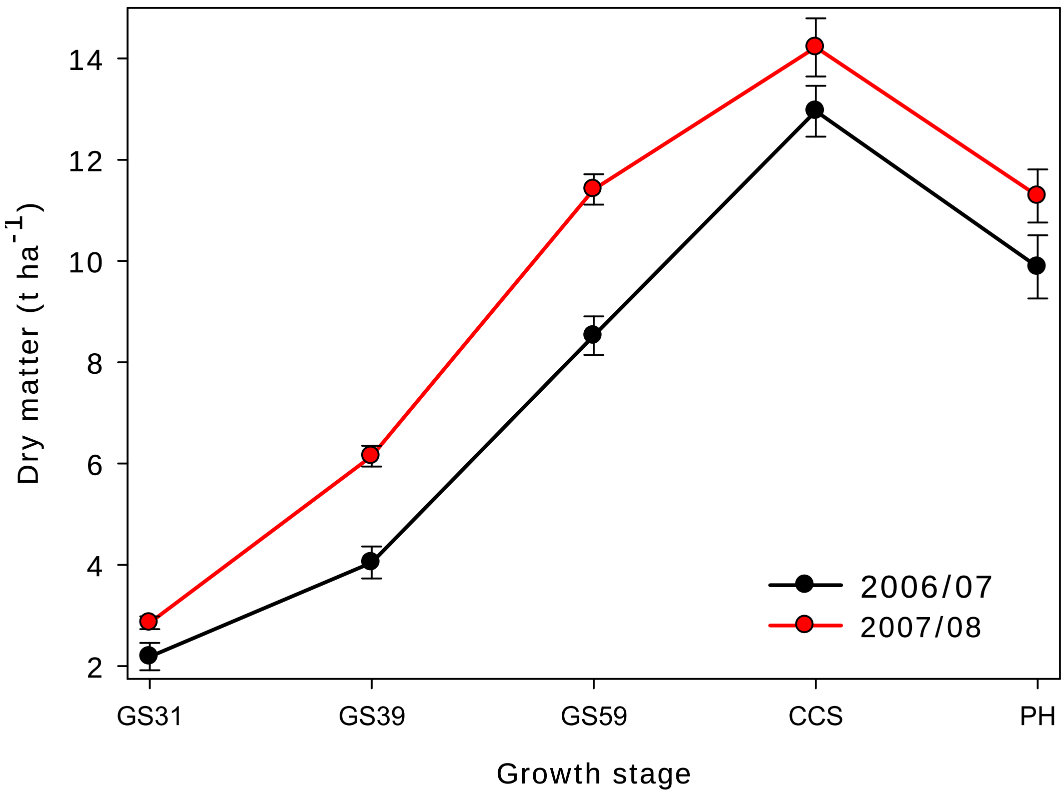

Figure 5 Summary of dry matter accumulation at Aberystwyth in field season 2006/07(eight cultivars) and 2007/08 (12 cultivars). Each line represents an average across cultivars. Bars represent one standard error of the mean.

The largest increase in nitrogen accumulation was found between GS31 and GS39 in both field seasons although in 2006/07 there was a more constant rate of increase in nitrogen until CCS (Fig. 6). Nitrogen uptake of the groat was measured at the PH sampling time in both field seasons. A massive redistribution of nitrogen had occurred by this time. Mean groat nitrogen values of 100 kg ha^{-1} and 94kg ha^{-1} were obtained as compared to mean straw nitrogen of 20 kg ha^{-1} and 15 kg ha^{-1} in the 2006/07 and 2007/08 field seasons respectively. In both years there was a significant difference between the cultivars both in groat nitrogen accumulation per ha^{-1} and in grain nitrogen utilisation efficiency, that is the grain yield produced per unit of nitrogen taken up by the crop. This will be discussed further in the section describing results from trials at Rosemaund.

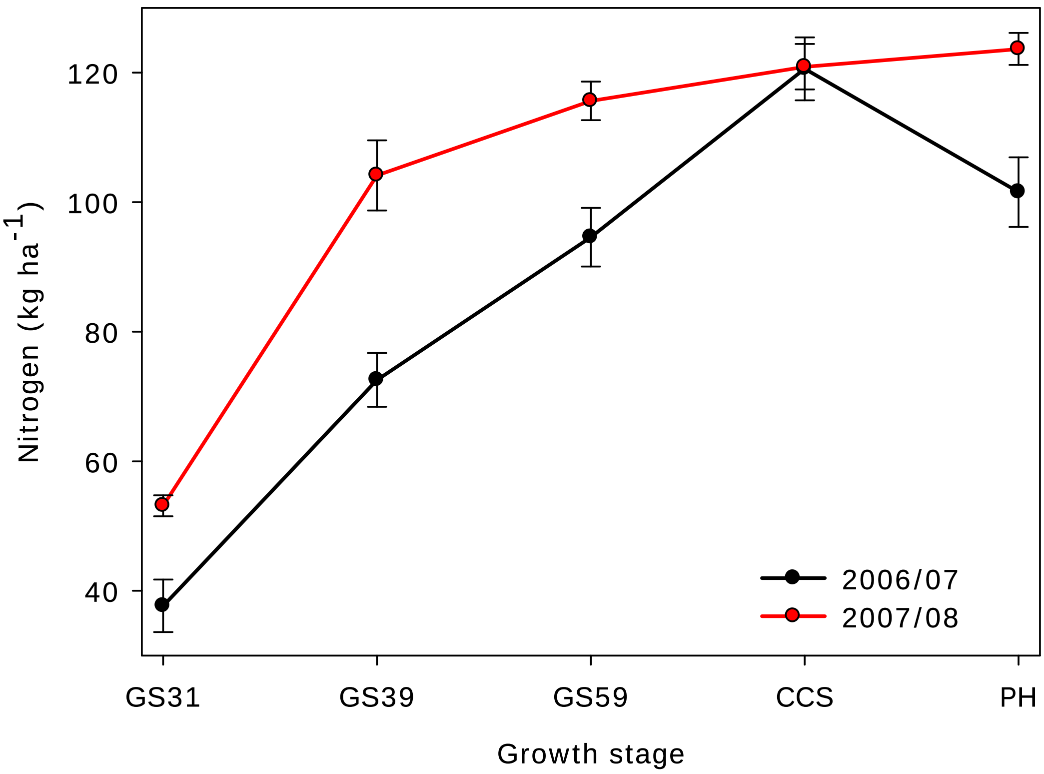

Figure 6 Summary of nitrogen accumulation at Aberystwyth in field season 2006/07 (eight cultivars) and 2007/08 (12 cultivars). Each line represents an average across cultivars. Bars represent one standard error of the mean.

Consecutive height measurements were taken in both the 2007/08 and 2008/09 field seasons (Fig. 7). Measurements were taken on a monthly basis at the start of the field seasons moving to weekly as the season progressed. In the 2007/08 field seasons the difference in height between the tall and the dwarf cultivars was first noticeable from the 29th May. Differences between tall and dwarf cultivars in the 2008/09 field were less obvious. Penderi was significantly taller than the other dwarf cultivars and not significantly shorter than Brochan or Tardis. In both field seasons Kingfisher was the tallest cultivar with Balado being the shortest. Brochan was the shortest tall cultivar in every field seasons. Penderi and 01-150Cn1 were the tallest dwarf cultivars. When individual internode lengths were measured Penderi had the longest lower internodes (Fig. 8). Tall cultivars had longer upper internodes especially internodes one and two. The length of the panicle exhibited a positive relationship with total height. Taller cultivars tended to have longer panicles.

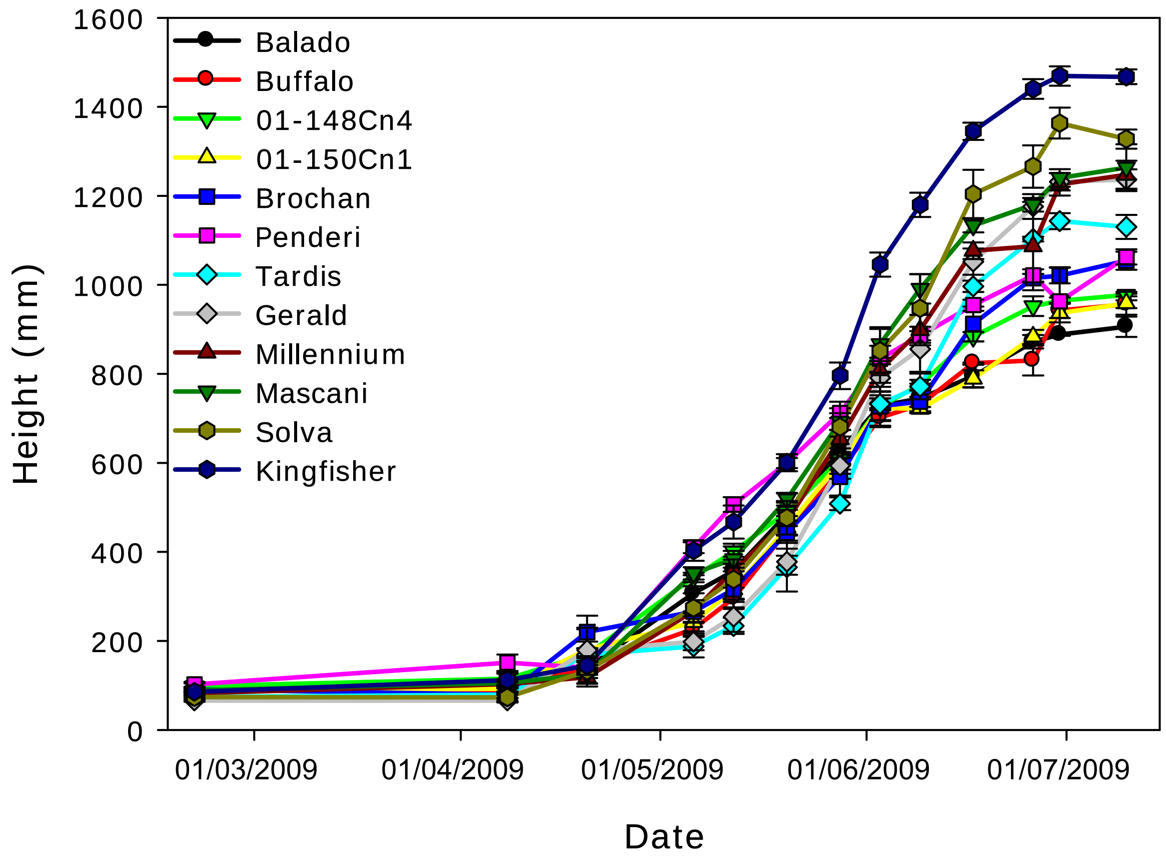

Figure 7 Height measurements of the twelve cultivars in the 2007/08 field season. Measurements were taken monthly at the beginning of the life cycle and then weekly as the season progressed.

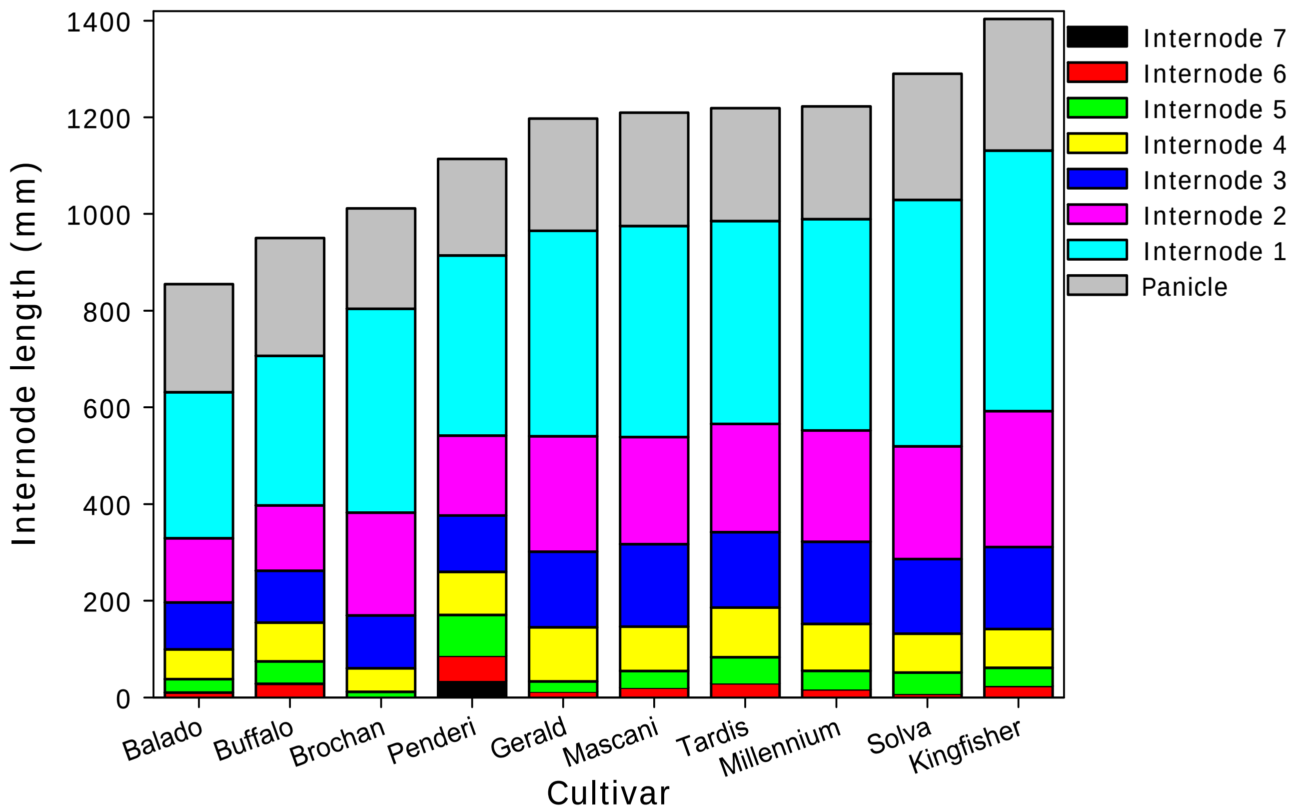

Figure 8 Internode lengths in the 2006/07 field season. Cultivars arranged in height order.

Panicle extrusion was measured weekly in the 2007/08 and 2008/09 field seasons beginning when the first panicles were emerging and continuing until height was constant. The distance measured was from the ligule of the flag leaf to the base of the panicle. If the panicle was enclosed within the flag leaf sheath this figure was negative. There was a clear difference in panicle extrusion date between the tall and the dwarf cultivars (Fig. 9). The panicles of the tall cultivars extrude from the flag leaf sheath between five and fifteen days earlier than the dwarf cultivars. Balado was the last cultivar to be fully emerged from the flag leaf sheath. The dwarf cultivars exhibited a poorer panicle extrusion in the 2008/09 field season. The panicles of Balado and Buffalo did not fully extrude from within the flag leaf sheath at any point during the life cycle. Kingfisher had the highest extrusion in both field seasons.

There was a strong negative relationship between height and the number of days from sowing until panicle emergence. Shorter cultivars tended to have a longer period between sowing and panicle emergence than taller cultivars.

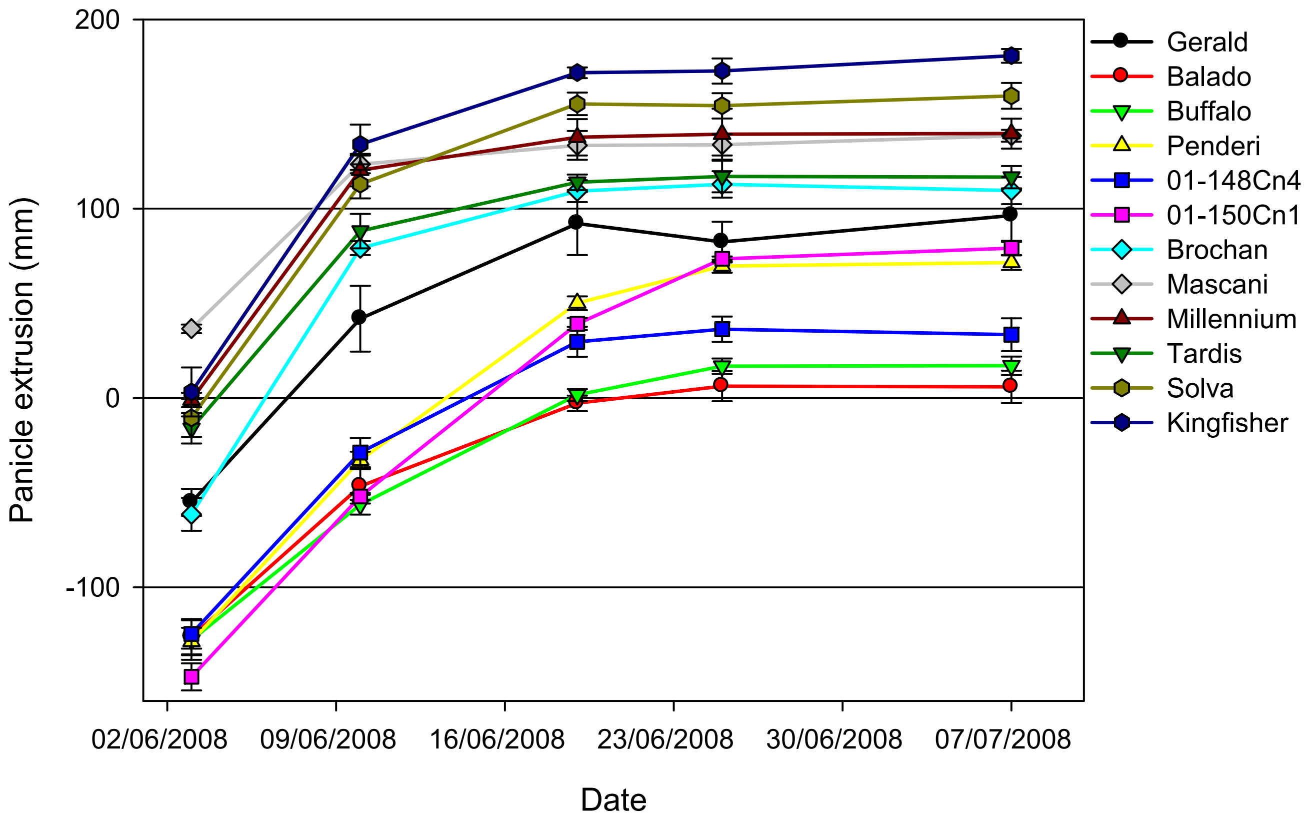

Figure 9 Panicle extrusion measurements taken in the 2007/08 field season weekly.

An in depth dissection of panicle traits was conducted in every field season. The spikelet of the husked oat can contain between one and three kernels. These are known as primary, secondary and tertiary kernels. The primary kernel is normally the largest with the tertiary kernel the smallest (Browne *et al*, 2008). Thus, harvested oats comprise three very distinct sub-populations of primary, secondary and tertiary grain.

Cultivars vary not only in the proportion of primary, secondary and tertiary grain but in the sizes of those grains. These are important quality characteristics of the grain lot particularly for the milling industry. Three calculations were performed to quantify this. The first, primary kernel ratio by number was calculated by dividing the number of primary kernels by the total kernel number. The majority of cultivars had a ratio of over 0.5 indicating that the proportion of primary kernel within the grain lot of the panicle was higher than secondary and tertiary kernels (Fig. 10). Significant differences between cultivars were obtained. Tardis was the only cultivar to have a ratio of less then 0.5 indicating that this cultivar had a higher proportion of secondary and tertiary kernels. Balado and Kingfisher had the highest values indicating that these cultivars have a high proportion of primary grain.

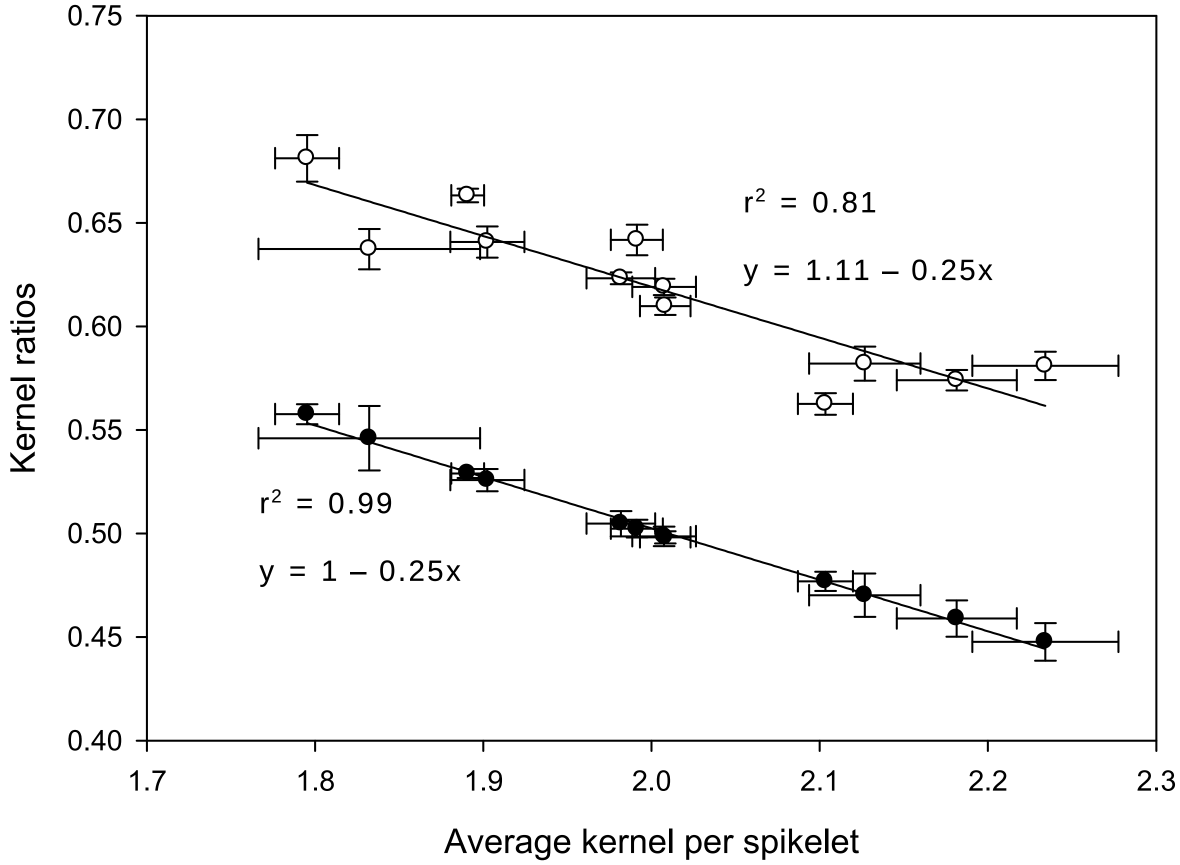

***Fig 10**: The relationship between average kernel number per spikelet and primary kernel ratios by weight and by number in the 2008/09 field season.*

The second ratio, primary kernel ratio by weight was calculated by dividing the weight of the primary kernels by the total kernel weight. This provides an indication of importance of primary grain weight in the total grain sample. These ratios were higher than the primary kernel by number ratio with yearly averages of 0.66, 0.63 and 0.63 for the 2006/07, 2007/08 and 2008/09 field season respectively (Fig. 10). This demonstrates that the weight of the primary kernels has a higher influence on the grain lot than the number. Again significant differences between cultivars were obtained with Kingfisher and Solva having the highest values. A final calculation was made by dividing the total number of kernels by the total number of spikelets giving a figure for the average number of grains per spikelet. The yearly means were 1.76, 1.98 and 1.99 for 2006/07, 2007/08 and 2008/09 respectively (Fig. 10) with significant differences between cultivars. Balado and Kingfisher had the lowest average number of grains per spikelet whereas Tardis, Penderi and 01-148 had the highest values with averages of over 2. This means that they had a percentage of spikelets containing three kernels. In the two latter field seasons Tardis had the highest ratio of 2.32 and 2.27 respectively.

Kernel content (KC) is a grain quality trait. It is calculated by recording the fresh weight of a kernel sample and then the weight of the groat after the husk has been removed. The KC is the proportion of the sample which is groat and is normally expressed as a percentage. KC was calculated in every field season on a mixed grain lot. KC was a stable trait showing good correlation between field seasons. Buffalo had the lowest KC in all three field seasons never having a KC of above 70%. Millennium, Mascani and 01-148Cn4 had a high KC in all field seasons with a KC at least 75%.
In addition, in the 2007/08 and 2008/09 field seasons, a KC was conducted on a separated sample of primary and secondary kernels. In general the KC of the secondary grain was higher than that of the primary grains (Fig. 11). For the primary KC the three dwarf cultivars Balado, Buffalo and Penderi had the lowest KC. 01-180Cn4, Brochan, Mascani and Millennium had the highest KC in both field seasons. For secondary KC there was a divide between the twelve cultivars in both field seasons (Fig. 11). 01-148Cn4, Brochan, Kingfisher, Mascani, Millennium and Solva all had a higher secondary KC than the other six cultivars. Buffalo and Tardis had the lowest secondary kernel content overall.

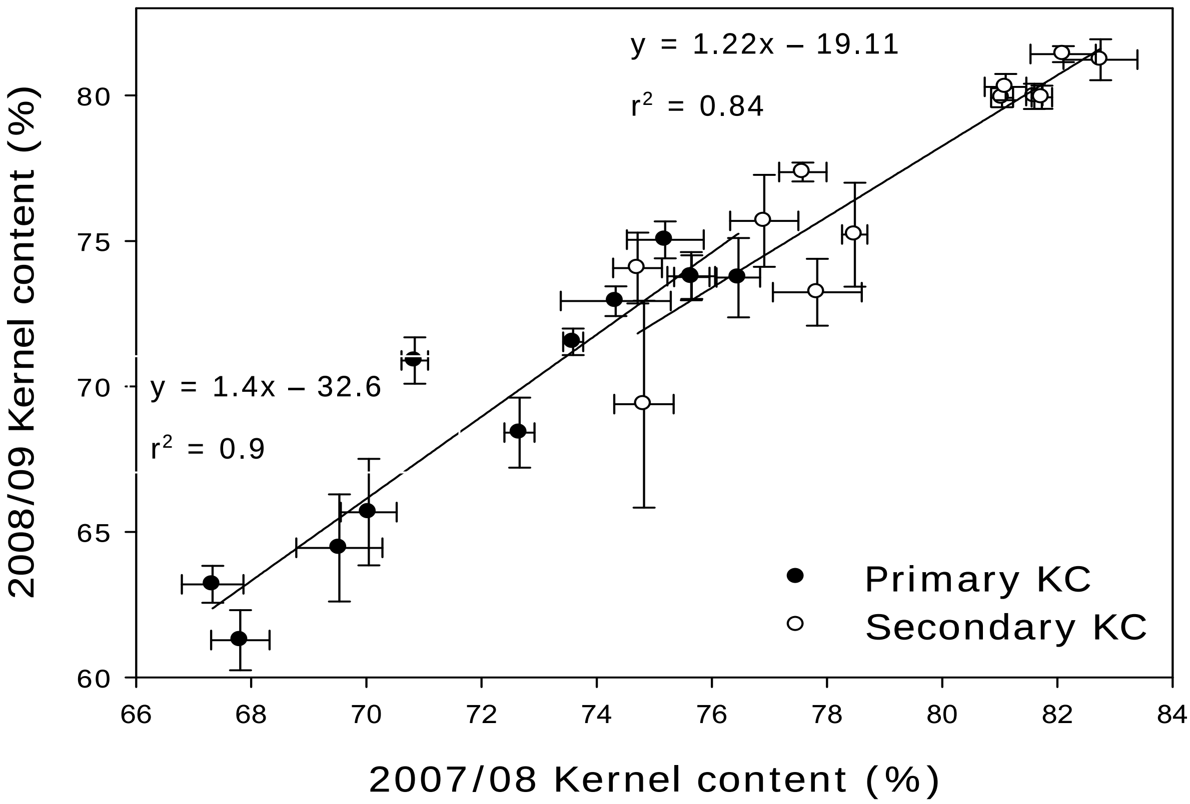

Figure 11 Relationship between KC in the 2007/08 and 2008/09 field seasons. KC was measured separately for primary and secondary kernels.

When comparing the relationship between the mixed KC and the separated KC it was found that the primary KC had a stronger correlation with the mixed KC. The primary kernels make up a higher proportion of the grain lot and therefore have a larger influence on the mixed grain KC.

Thousand grain weight (TGW) was calculated in every field season on a mixed grain sample. This was conducted by mixing the sample well then counting out 100 grains three times and recording the weight. An average weight was calculated and divided by 100 and multiplied by 1000 to get the TGW. Mascani and Millennium had the highest TGW in every field season with a mean of 47.25g. Buffalo, Gerald and Penderi had the lowest TGW with a mean of 35.48g between field seasons. TGW was a stable trait with strong correlations between field seasons (Fig 12).

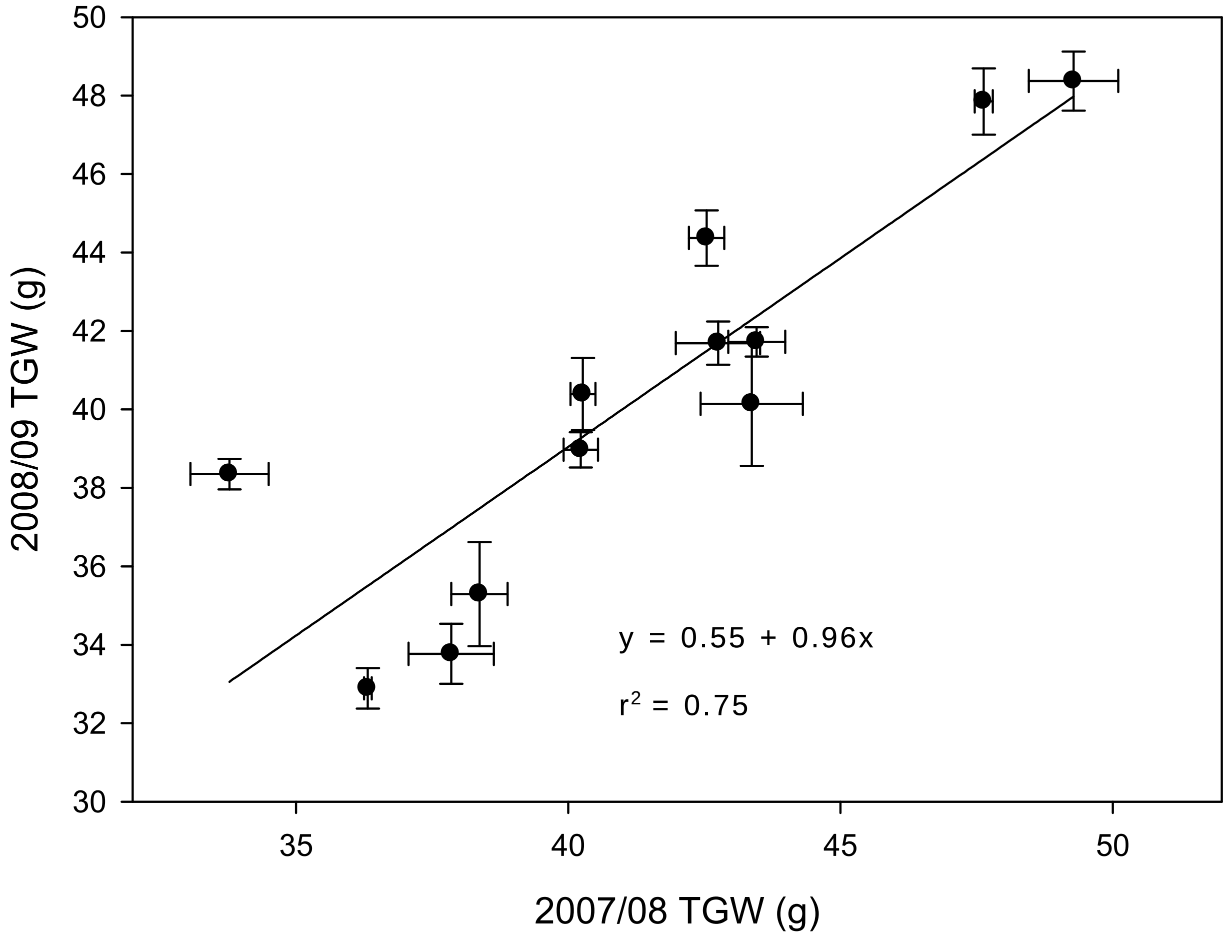

Figure 12 The relationship between TGW in the 2007/08 and 2008/09 field seasons.

A TGW was also calculated on separated primary and secondary kernels in every field season. The TGW of the primary kernel was larger than the secondary kernels by on average 19g across field seasons. The primary kernels make up a large proportion of the grain lot and therefore the TGW of the primary kernels had a stronger correlation with the mixed TGW. Penderi and Buffalo had the lowest primary TGW whereas Solva and Buffalo had the lowest secondary TGW. Mascani and Millennium had the highest TGW for both primary and secondary kernels.

In the 2007/08 and 2008/09 field seasons the grain size of separated primary and secondary grains was determined using image analysis. The grains were spread onto a piece of acetate so that no grains were touching and then scanned with a known standard, in this case a two pence piece (Fig. 13A). The files were then analysed using MATLAB which first converted the picture to black and white so the grains showed up in white (Fig. 13B). An ellipse was then fitted to the outside of the grain. The length and the width of the ellipse were then measured in relation to the size of the standard as an estimate of the length and width of the grains (Fig. 13C). Any touching grains were removed from the sample. An excel spreadsheet was generated providing the size dimensions of each object. This was conducted on primary and secondary grains of both whole kernels and de-hulled groats for. A ratio for roundness of grain was calculated by dividing the width by the length of the grain.

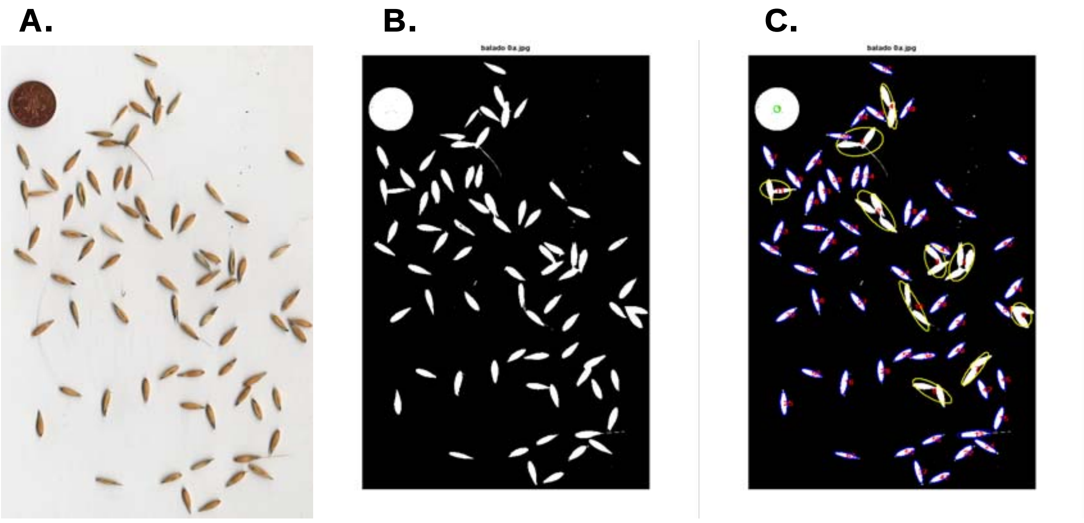

Figure 13 A: A scanned picture of oats grains spread on a piece of acetate so that no grains are touching. A two pence piece is used as a standard of a known size, 2.5cm in diameter. B: the scanned picture is transferred to a black and white picture in MATLAB. C: an ellipse is fitted to each grain the length and width can then be calculated from the size of the standard. Any grains that appear to be touching can be removed. The small green circle represents the standard. Any grains circled in yellow have been removed from the calculations. Grains circled in blue have been measured.

The ratios of secondary kernels were higher than primary kernels indicating that secondary kernels have a more rounded shape. Solva and Gerald had the highest primary kernel ratios in both field seasons. Kingfisher and 01-150Cn1 had the lowest. Gerald and Solva had the highest secondary kernel ratio with Tardis having the lowest. Strong correlations were seen between the field seasons with the r^2 value for primary kernel ratios being 0.95 and 0.73 for secondary kernel ratios (Fig. 14). Groat ratios were higher than kernel ratios demonstrating that the groats were more rounded than the kernels. Balado had a low groat ratio for both primary and secondary groats in both field seasons. Gerald, Penderi and Solva had high primary and secondary groat ratios in both field seasons. Strong correlations between field seasons were seen for both primary and secondary groat ratios with the r^2 value being 0.74 and 0.76 respectively (Fig. 15). The range of the primary groat ratios was smaller than those of the secondary groat ratios demonstrating than the size of the secondary groats was more variable than that of the primary groats.

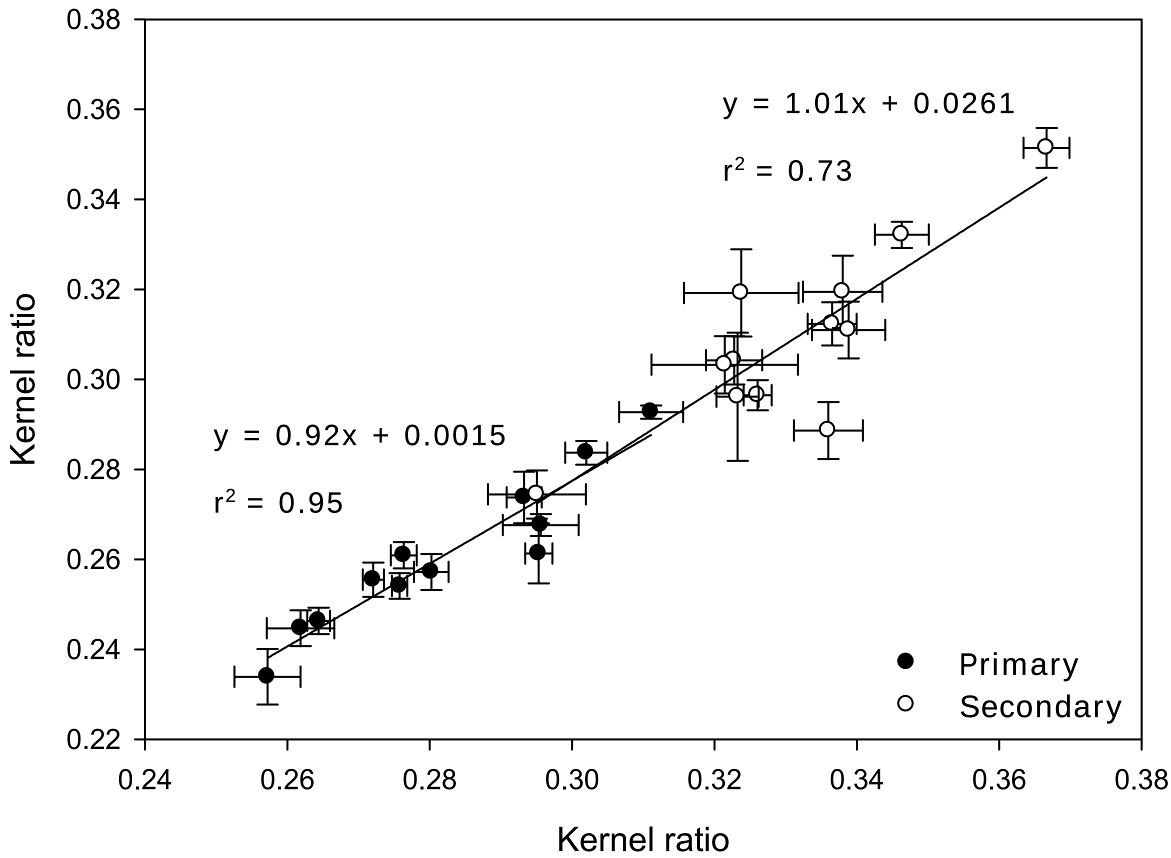

Figure 14 Relationship between kernel ratios (measured separately for primary and secondary kernels) in the 2007/08 and 2008/09 field seasons.

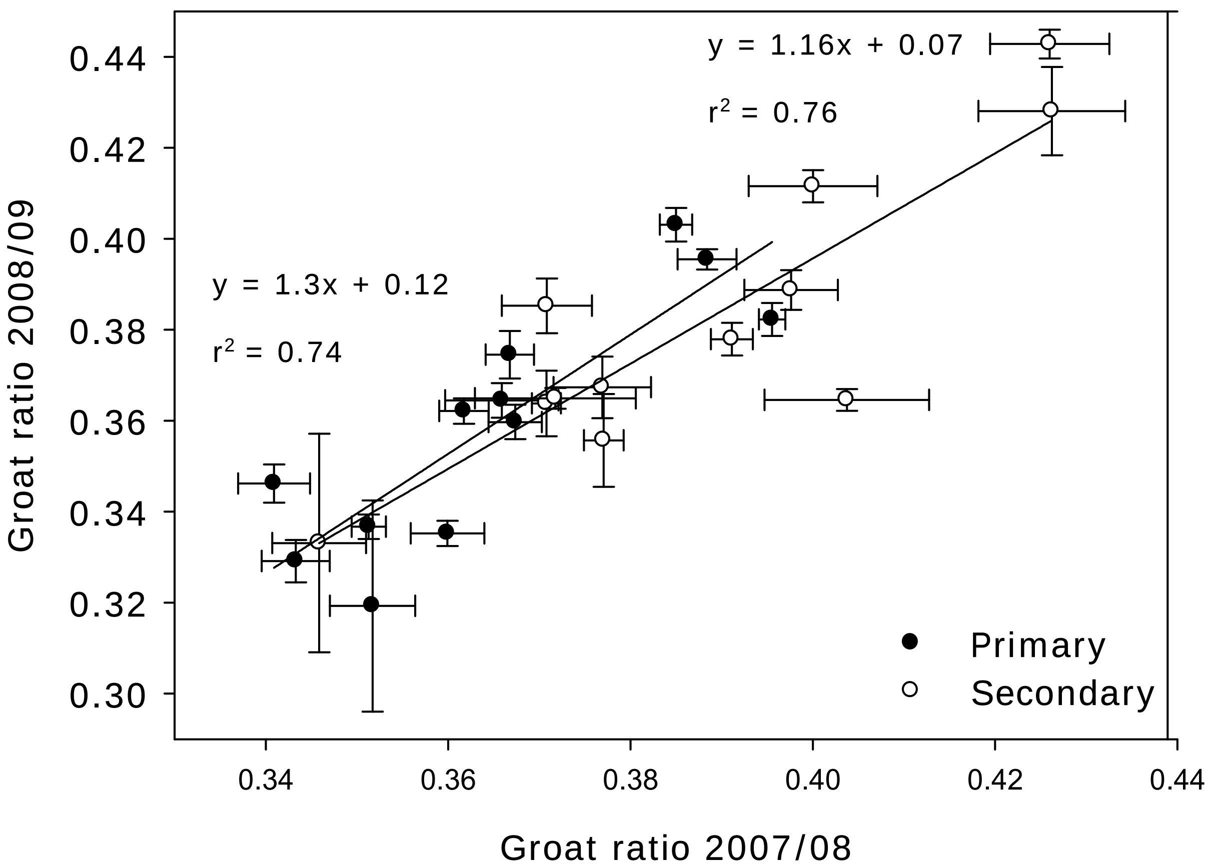

Figure 15 Relationship between groat ratios (measured separately for primary and secondary kernels) in the 2007/08 and 2008/09 field seasons.

A study of the distribution of individual grain dimensions was also conducted which indicated the wide range of grain sizes within a grain lot. Cultivars which had both primary and secondary kernels within the grain lot had bimodal distributions of kernel length and width. Cultivars with a high proportion of tertiary kernels, for example Tardis, exhibited a trimodal distribution. Within these bi- and trimodal distributions the dimensions of primary, secondary and tertiary grain followed a normal distribution. Similar distributions were seen for the groat dimensions.

Millennium and Solva had the highest and lowest kernel length from the 2007/08 field season (Fig. 16). It was seen that the secondary kernels from Millennium were of a similar length to the primary kernels of Solva. The primary kernels of Millennium were longer and the secondary kernels of Solva were shorter.

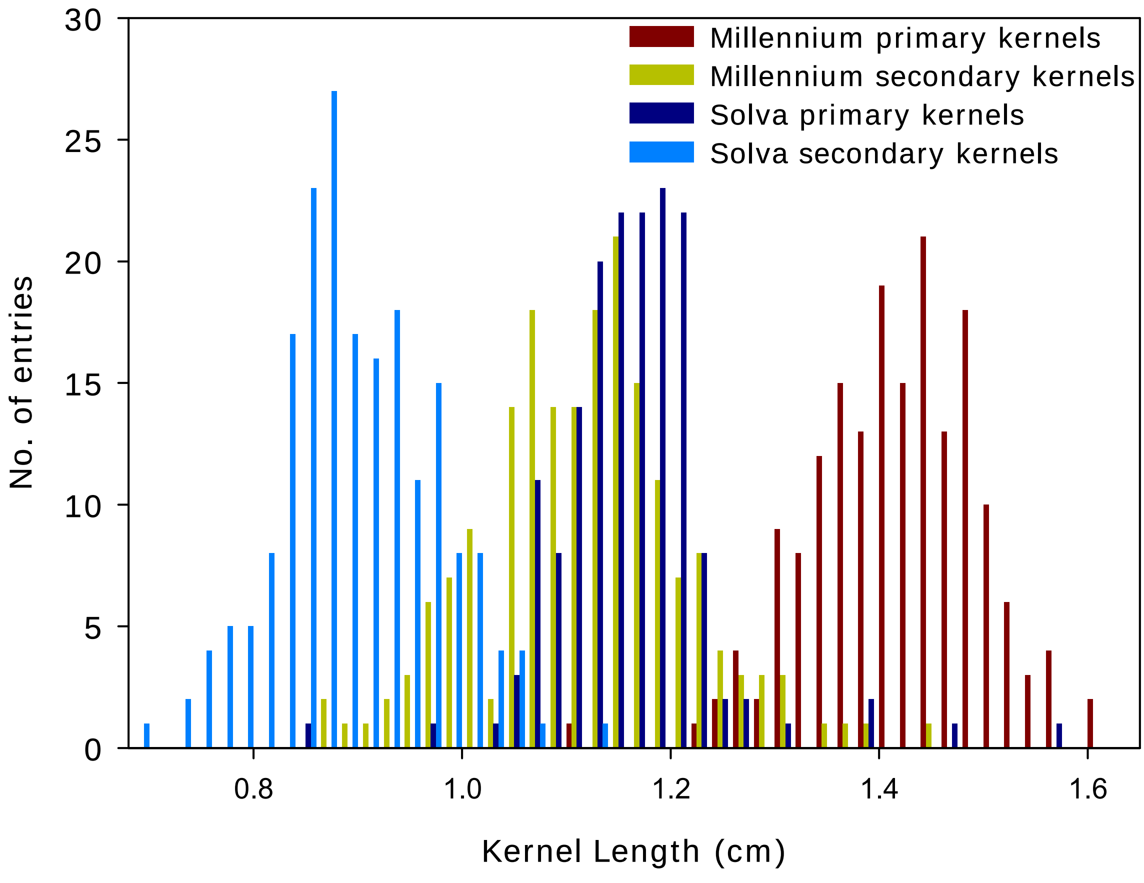

Figure 16 Distribution of individual kernel lengths in the 2007/08 field season for Millennium and Solva.

Yield (adjusted to 85% dry weight) was recorded in all three field seasons using a small plot combine (Sampo 2020) (Fig. 17). In the 2006/07 field seasons Solva and Brochan had poor establishment and therefore had a significantly lower yield than the other cultivars. Mascani, Millenium and Penderi had the highest yield in this field season.

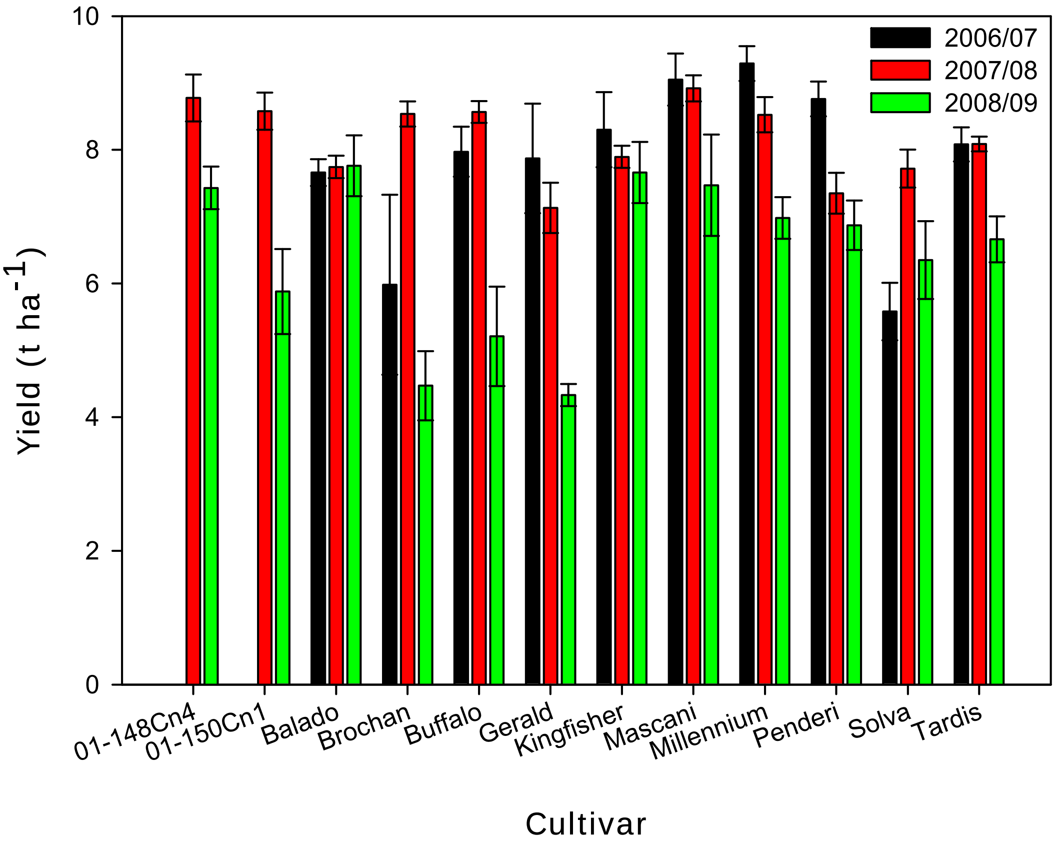

Figure 17 Yield results from all three field seasons.

Gerald had the lowest yield in the 2007/08 field season. In this season it was infected with oat mosaic virus which causes stunted growth and yellowing of tissues and a negative effect on yield. Mascani had the highest overall yield of 8.9 t ha^{-1}, but not significantly different from Millennium, Brochan, Buffalo, 01-150Cn1 or 01-148Cn4.

The 2008/09 field season was greatly affected by winter damage with a consequent effect on plant numbers and subsequent yield. Gerald, Brochan and Buffalo had the lowest yield in the 2008/09 field season. Balado had the highest overall yield but not significantly different from Kingfisher, Mascani and Millennium.

The relationships between the field seasons were not strong with the ranking of the cultivars changing between years. For example Balado was one of the lowest yielding cultivars in the 2006/07 and 2007/08 seasons but the highest yielder in the 2008/09 field season.

Correlations between traits measured and yield were calculated using the data analysis tool of excel (2007). Few traits showed a positive relationship to yield in all three field seasons due to the variability in the yield results between seasons. One trait that showed a positive relationship in both the 2006/07 and 2007/08 field seasons was total dry matter accumulation. This trait was not measured in 2008/09. In the 2006/07 season dry matter at GS59, CCS and PH all exhibited a positive relationship with yield (Fig. 18). As the season progressed the relationship between these two traits became stronger with r^2 values of 0.23, 0.38 and 0.71 for GS59, CCS and PH respectively. In the 2007/08 field season dry matter at GS59 and PH had the strongest correlation with yield with r^2 values of 0.51 and 0.6 respectively.

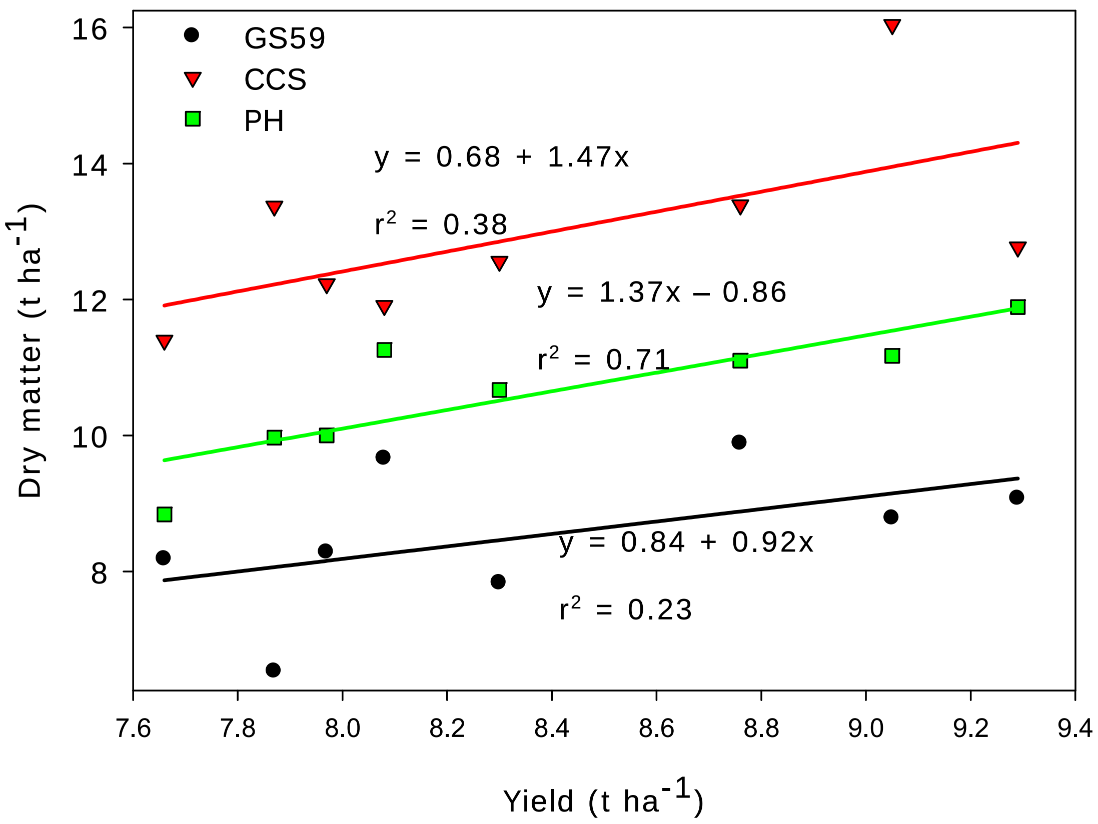

Figure 18 Relationship between total dry matter at the final three sampling times in the 2006/07 field season and grain yield.

The two most consistent correlations between panicle components and yield were primary kernel ratio by weight (Fig. 19) and total secondary grain weight. Primary kernel weight ratio had a negative relationship with yield meaning that the higher proportion of primary kernels the lower the expected yield (Fig. 19). The relationship between yield and secondary grain weight had a positive relationship so the higher the weight the higher the expected yield.

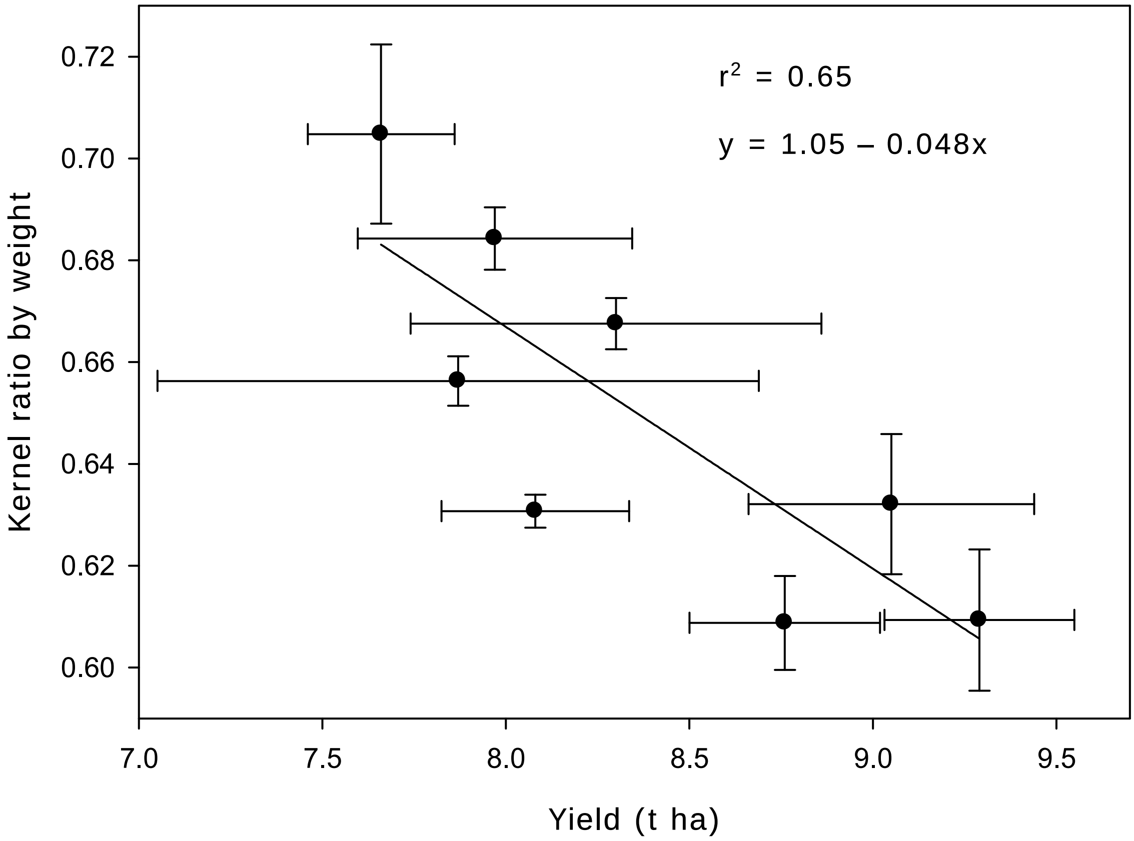

Figure 19 the relationship between yield and primary kernel ratio by weight in the 2006/07 field season.

Correlations between year of release and yield were calculated for every field season. The most consistent trait between field seasons was grain shape especially grain ratios. A negative relationship was seen between year of release and kernel ratio demonstrating that more recent cultivars have a more elongated kernel (fig 20) or groat shape. The correlations for both kernel and groat ratios were stronger in the 2008/09 field season.

- There was a negative relationship between height and panicle emergence
- Dry matter accumulation was positively correlated with yield
- Grain size distribution was shown to be bimodal. When measured separately, primary KC and TGW had the highest correlation to the mixed grain sample
- Grain shape altered with year of release with grain becoming more elongated

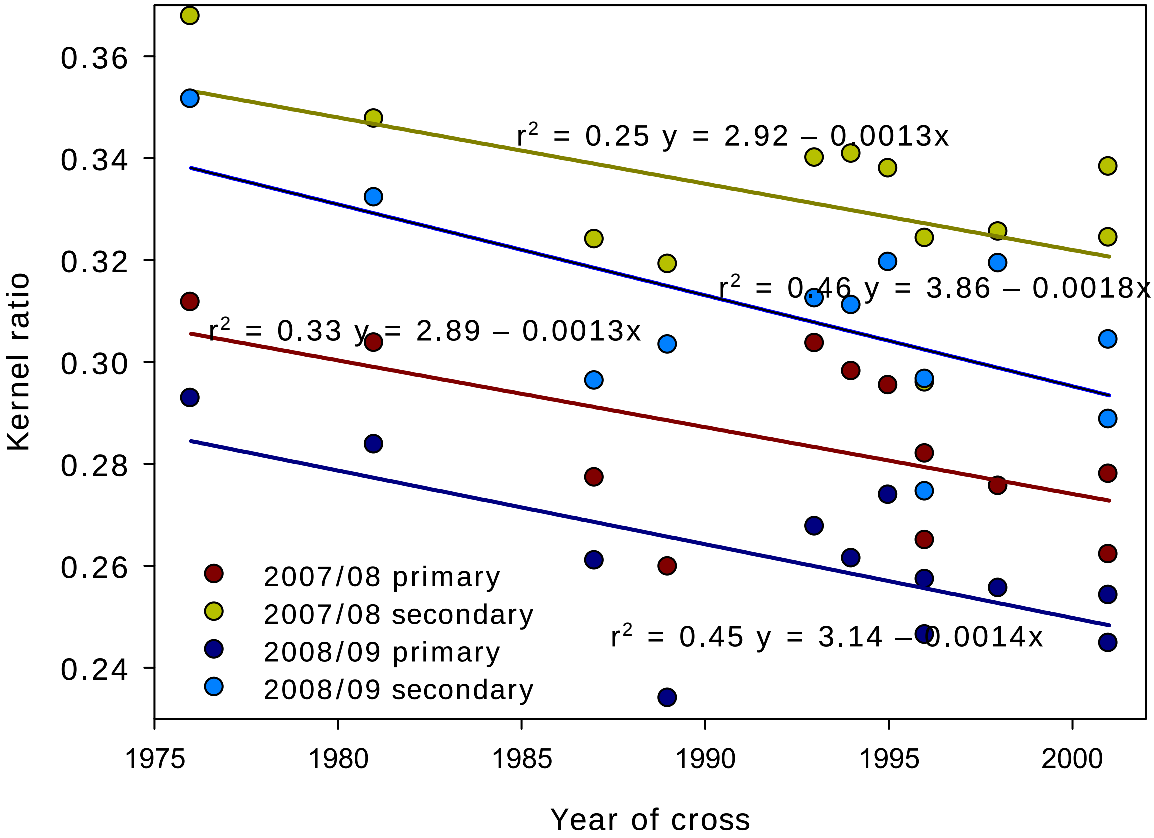

Figure 20 Relationship between year of release and kernel ratios in both the 2007/08 and 2008/09 field seasons.

Rosemaund nitrogen trial

The Rosemaund trial was designed to identify the effect of nitrogen on yield and its formation. Similar traits were measured in this trial as in the Aberystwyth trial (Table 4). Four husked and 4 naked winter oats were grown (Table 2), however, in this report only the response to increasing nitrogen on the mean values of all cultivars for selected traits are described. Detailed results for individual cultivars are available and a summary of these is presented in Table 5. Four levels of applied nitrogen were present in this study; nil, RB209, RB209+50 and RB209+70. In each year the amount of nitrogen in the soil was determined. The RB209 fertiliser guidelines were then used to determine how much nitrogen to apply. In the 2006/07 field season these values were 40, 90 and 110 kg ha^{-1} for the RB209, RB209+50 and RB209+70 rates respectively. In the 2007/08 field season soil nitrogen values were lower and therefore applied nitrogen amounts were 70, 120 and 140 kg ha^{-1}.

In both field seasons grain yield increased with the application of nitrogen up until the RB209+50 treatment. A difference between the nil and RB209+50 of 2.8 and 2.3 t ha^{-1} was seen in the 2006/07 and 2007/08 seasons respectively (Fig. 21). A 0.2 t ha^{-1} reduction in grain yield was seen between the RB209+50 and RB209+70 applications in both field seasons.

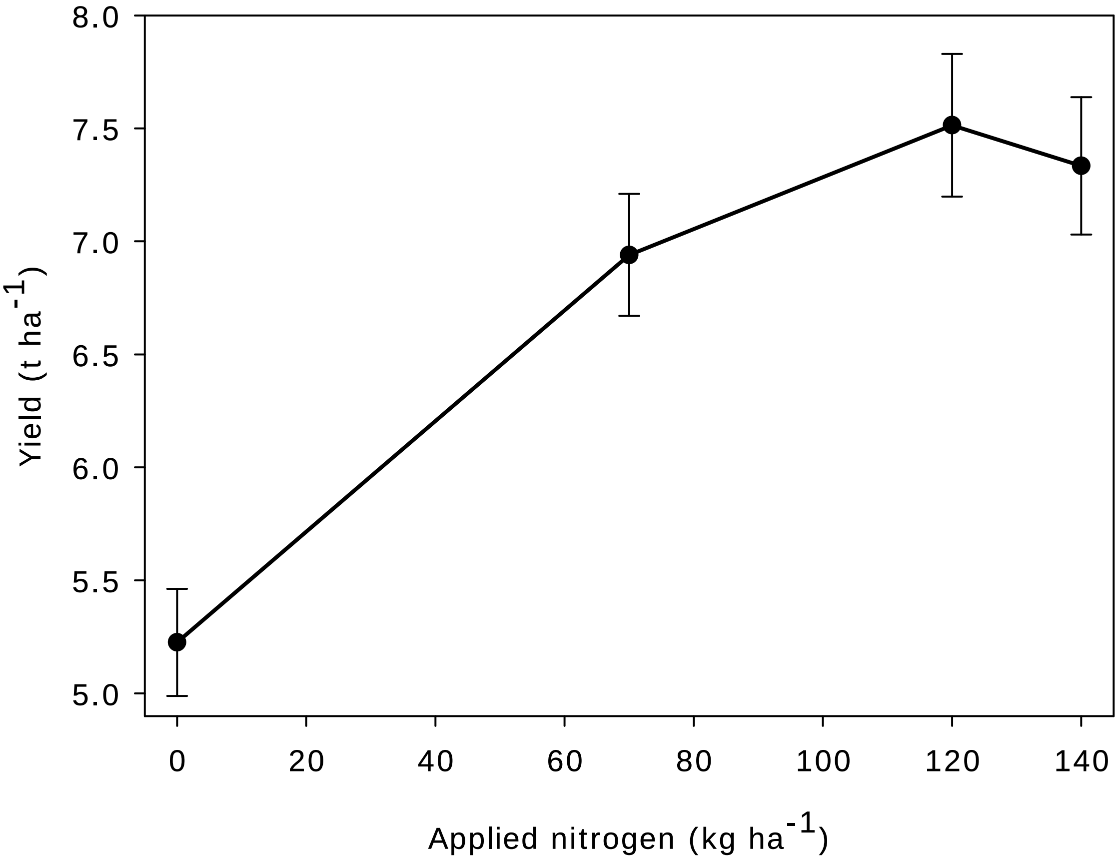

Figure 21 Effect of applied nitrogen on mean yield results for the 2007/08 field season.

In the 2006/07 field season total crop biomass increased with applied nitrogen from 11 t ha^{-1} at the nil rate to 14.2 t ha^{-1} at the RB209+50 treatment and decreased by 1.2 t ha^{-1} above this rate. In 2007/08 biomass increased by 3.4 t ha^{-1} between the nil and RB209 treatments and then fluctuated around 13 t ha^{-1} (Fig. 22). Correlation between dry matter at PH and yield were high with r^2 values of 0.89 and 0.77 in the 2006/07 and 2007/08 field seasons respectively.

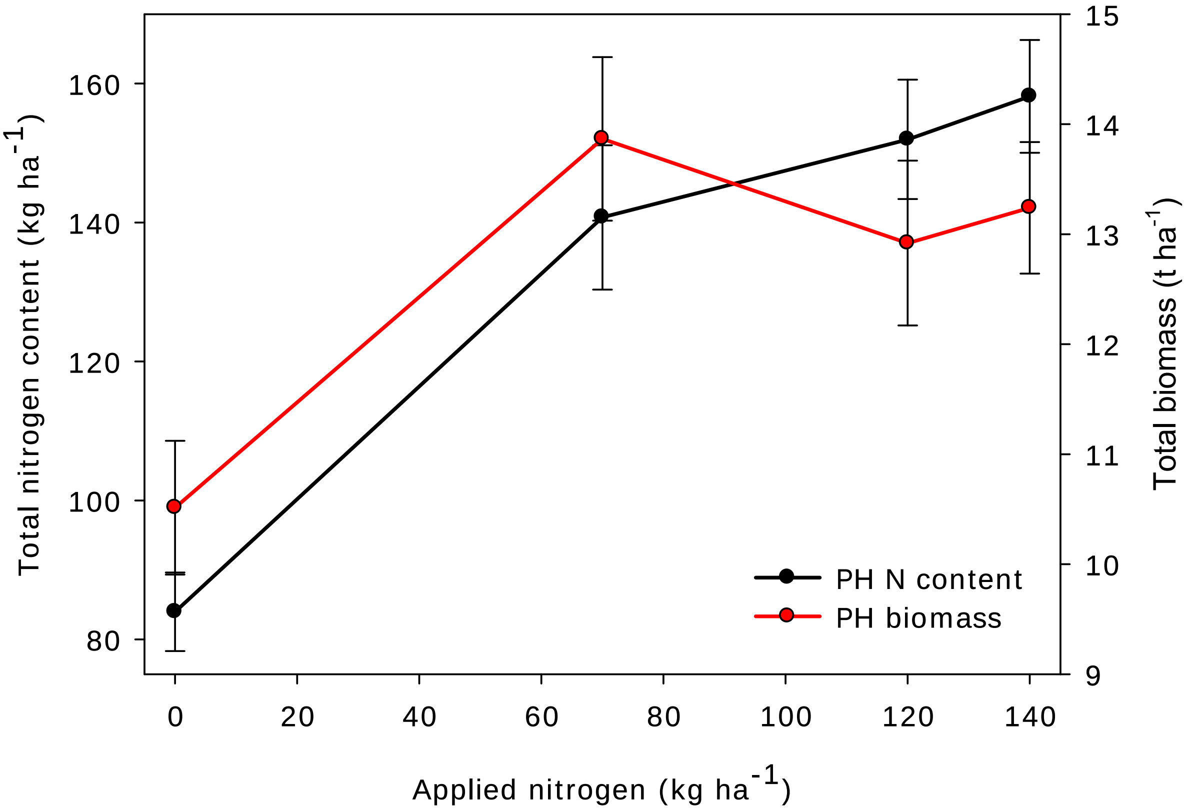

Figure 22 The relationship between total crop biomass and nitrogen content to applied nitrogen in the 2007/08 field season.

Total crop nitrogen content in the 2006/07 field season exhibited the same pattern of increase and decrease as the total biomass. Nitrogen content increased from the nil treatment to the RB209+50 by 45.1 kg ha^{-1} and then declined by 9.6 kg ha^{-1}. In the 2007/08 field season nitrogen content increased throughout the season from 84 kg ha^{-1} at the nil treatment to 158 kg ha^{-1} at the RB209+70 treatment (Fig. 22). Yield and crop nitrogen had a strong positive relationship with r^2 values of 0.96 and 0.98. These were higher than those found for dry matter. Nitrogen content could have a higher importance in yield formation than dry matter accumulation.

The nitrogen content of the groat was determined and expressed as a percentage of the whole groat in both field seasons. In 2006/07 the groat nitrogen percentage for the nil treatment was 1.88%. As the amount of nitrogen applied to the crop increased so did the groat nitrogen percentage increasing to 2.12% by the RB209+70 treatment. In the 2007/08 field season the groat percentage of the nil treatment was 1.64% with a maximum of 2.27% for the RB209+50 treatment (Fig. 23). A slight decrease to 2.23% for the RB209+70 treatment was observed.

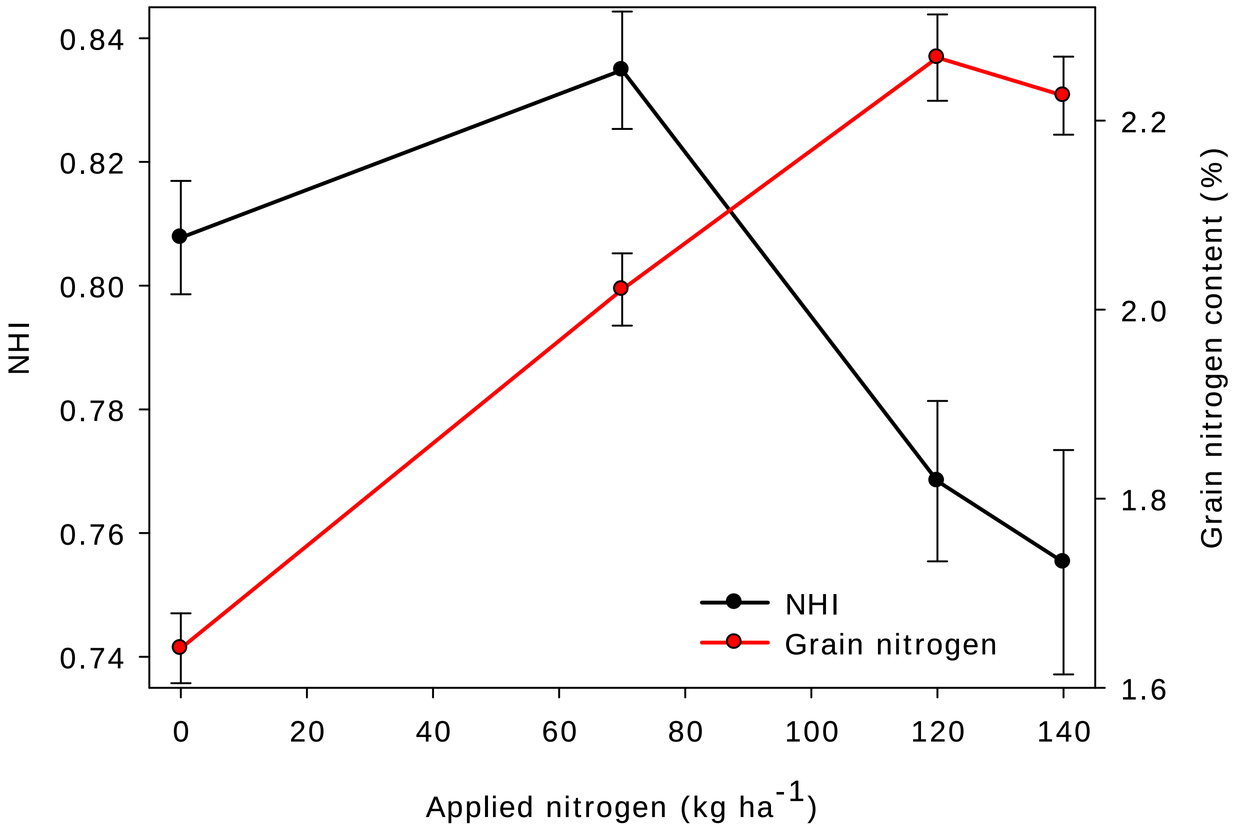

Figure 23 Effect of applied nitrogen on NHI and grain nitrogen percentage in the 2007/08 field season.

The proportion of the total plant nitrogen that is found in the grain at maturity is called the nitrogen harvest index (NHI). NHI index represents the ability of a cultivar to mobilize and translocate nitrogenous compounds from the leaves, stem, and chaff into the grain. In the 2006/07 field season NHI was 0.79 for the nil treatment increasing to 0.81 for the RB209+70 treatment. In the 2007/08 season the NHI was highest for the RB209 treatment with a value of 0.83 and decreased to 0.76 for the RB209+70 treatment (Fig. 23). This indicated that the total nitrogen content of the crop had increased more than the grain nitrogen content therefore causing a decrease in NHI.

From the dry matter and nitrogen values determined it is possible to calculate the Nitrogen Use Efficiency (NUE). NUE is defined as the yield of biomass or grain per unit of nitrogen available to the crop from both the soil and applied fertiliser. NUE is the product of 2 components, Nitrogen Uptake Efficiency (NUpE) which is the proportion of N taken up by the crop that is available to it and the Nitrogen Utilization efficiency (NUtE) which is the amount of dry matter produced per unit of N taken up by the crop. NUtE (and consequently NUE) can be determined both for total biomass production and also for grain yield.

The NUpE of the nil treatment in 2006/07 was high with a value of 0.76 kg kg^{-1}. However as the nitrogen application increased the NUpE of the crop declined. The NUpE of the crop at the RB209+70 treatment was 0.57 kg kg^{-1}, a reduction in NUpE of 19%. A small difference was seen between the nil and RB209 NUpE in the 2007/08 of 0.03 kg kg^{-1} (Fig. 24) with the RB209 treatment being higher at 0.76 kg kg^{-1}. From the RB209 application to the RB209+70 treatment a 14% reduction in NUpE was observed (Fig. 24).

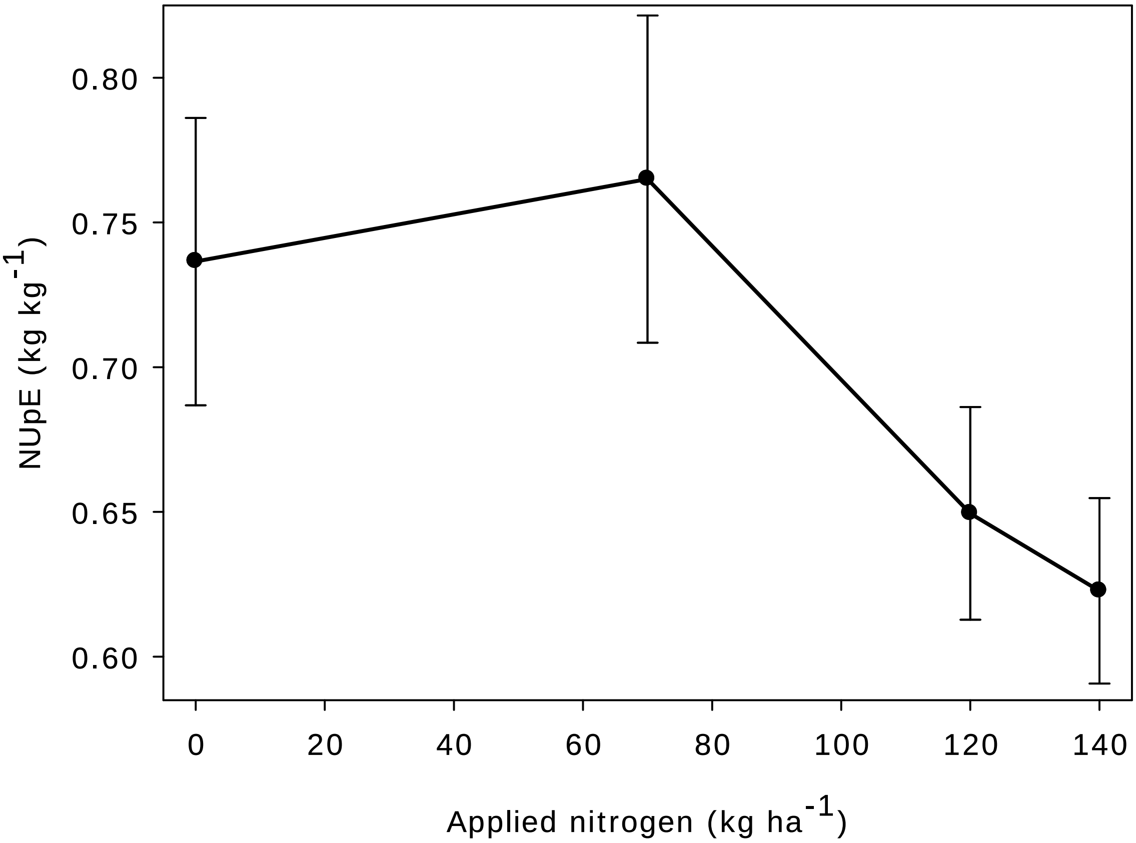

Figure 24 Effect of applied nitrogen on NUpE at PH in 2007/08.

NUtE was calculated separately for total crop biomass and grain yield. Crop NUtE was defined as the amount of total biomass produced for each kg of nitrogen within the crop. In both field seasons, NUtE decreased with increasing nitrogen rate (Fig. 25). Crop NUtE was 103.01 kg kg^{-1} and 128.64 kg kg^{-1} at the nil nitrogen rate in 2006/07 and 2007/08 respectively. The crop NUtE decreased to 92.19 kg kg^{-1} and 84.90 kg kg^{-1} at the RB209+70 rate in 2006/07 and 2008/09 respectively.

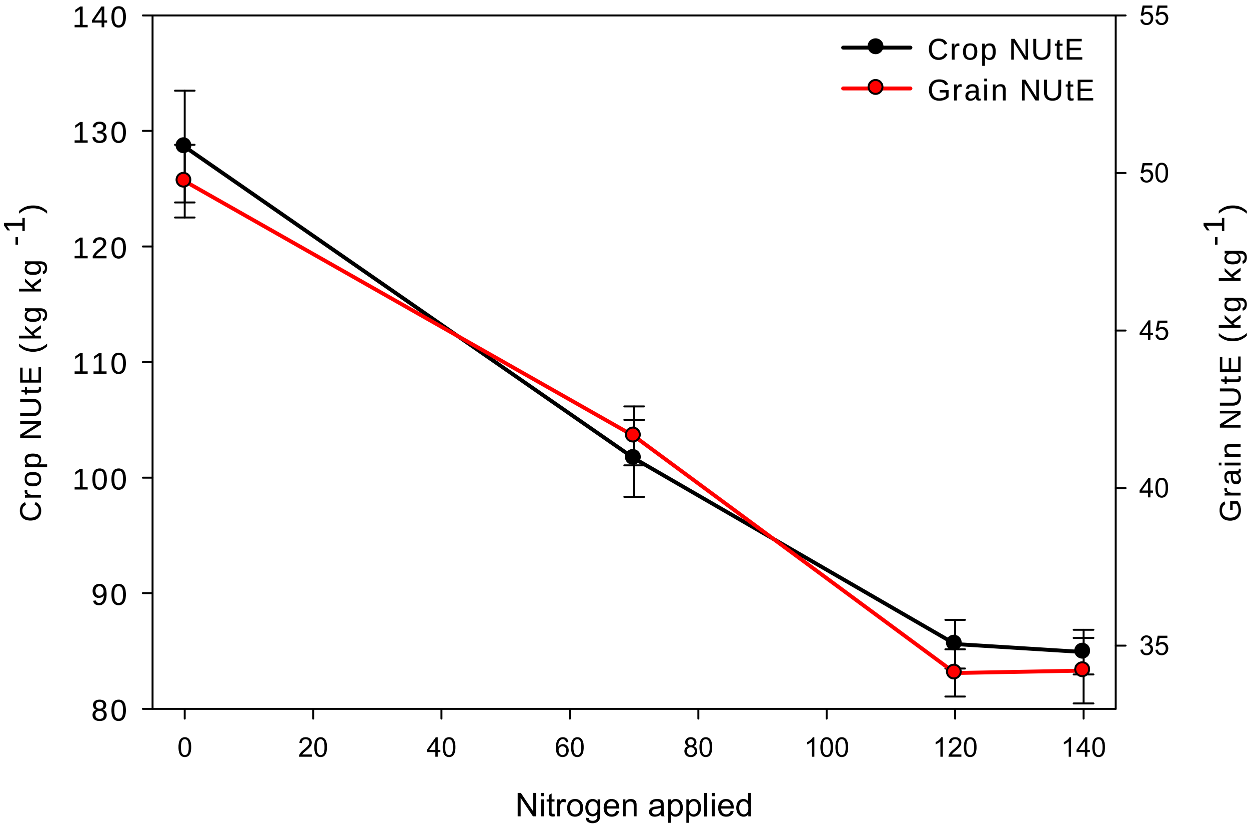

Figure 25 The effect of applied nitrogen on crop and grain NUtE in 2007/08.

Grain NUtE is defined as the amount of grain yield produced per kg of nitrogen taken up by the crop. Both field seasons exhibited a similar trend for this trait. NUtE was highest for the nil rate with a value of 42.12 kg kg^{-1} in the 2006/07 and 49.74 kg kg^{-1} in the 2007/08 field season (Fig. 25). NUtE then decreased as more nitrogen was applied. The was a largest decrease in grain NUtE in the 2007/08 field season of 15.60 kg kg^{-1} compared to 4.03 kg kg^{-1} in the 2006/07 field season. Little difference was observed between the RB209+50 and RB209+70 treatments.

In the 2006/07 field season the relationship between crop and grain NUtE with nitrogen was similar with the NutE and crop NUtE decreasing with added nitrogen. In 2007/08 the relationship between these two traits was stronger (Fig. 25) with a larger decrease between the nil and RB209+50 treatments for both traits. In both seasons, there was little difference in crop and grain NUtE between the RB209+50 and RB209+70 treatments. A comparison between the two field seasons shows that both crop and grain NUtE were higher in the 2007/08 field season.

NUE was also calculated separately for crop and grain biomass. In both field seasons the nil treatment had the highest NUE of 77.21 and 92.22 in the 2006/07 and 2007/08 field seasons respectively (Fig. 26). As the nitrogen applied increased the NUE of the crop decreased. The RB209+70 treatment had the lowest NUE of 51.47 and 52.12 in the two field seasons.

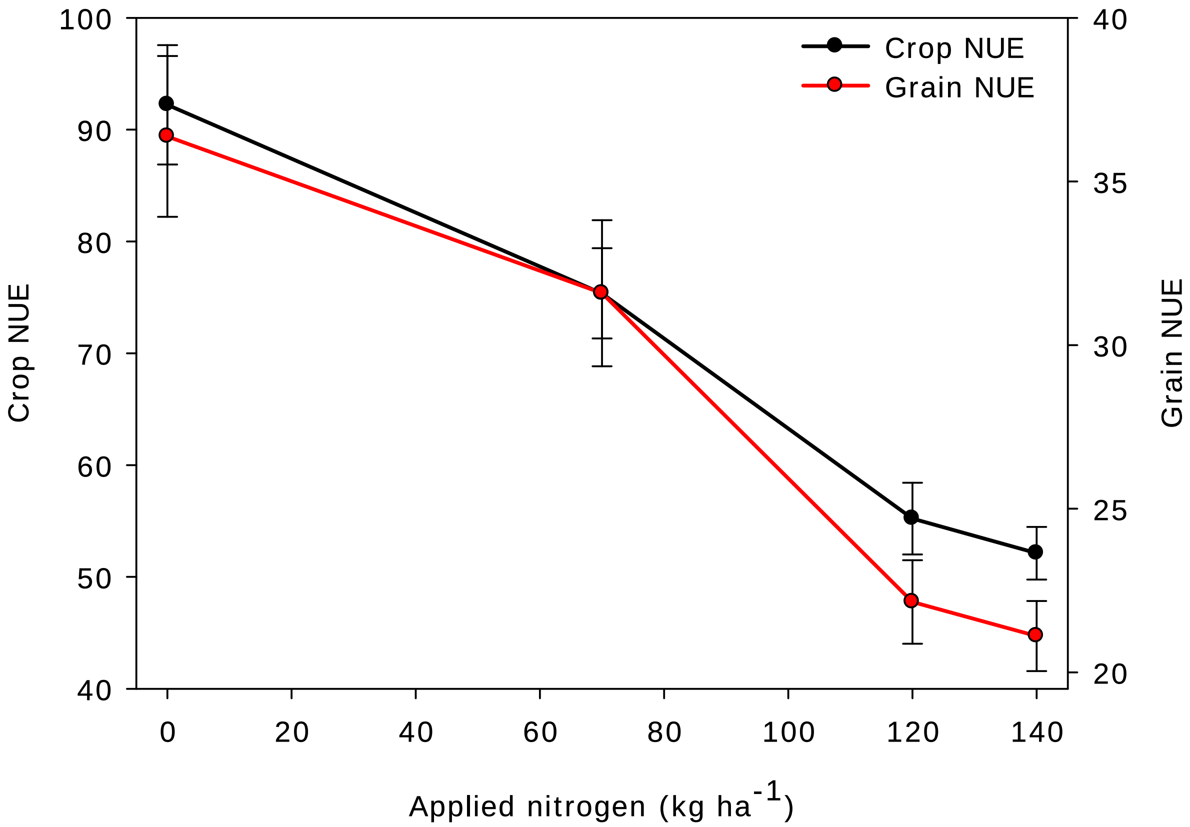

Figure 26 The effect of applied nitrogen in the NUE of the crop and the grain in the 2007/08 field season.

Grain NUE was highest for the nil treatment and lowest for the RB209+70 in both field seasons. Nil treatment grain NUE were 32.01 and 36.38 in 2006/07 and 2007/08 respectively (Fig. 26). These decreased to 21.61 and 21.11 by the RB209+70 treatment.

Significant cultivar differences were observed for yield and NUE in response to applied nitrogen (Table 5). Balado, Fusion, Hendon and Tardis had the highest yield at the RB209+70 treatment. The remaining cultivars, 00-61Cn1, Brochan, Gerald and Racoon had the highest yield at the RB209+50 treatment. On average the naked cultivars yielded 2.20 t ha^{-1} less than the husked cultivars. There was no significant difference in groat yield once the husk had been accounted for.

Balado and Tardis had the highest NUpE at the nil nitrogen treatment. Balado had the highest at the RB209 treatment and Tardis had the highest at the RB209+70 treatment. The naked cultivars had a significantly lower mean NUpE of 0.60 compared to 0.77 for the husked cultivars.

Table 5 Cultivar means for yield and grain nitrogen use efficiencies. Values are means across field seasons.

Trait	Nitrogen treatment	Balado	Brochan	Gerald	Tardis	00-61Cn3	Fusion	Hendon	Racoon
Yield (t ha^{-1})	Nil	6.08	5.83	5.80	6.28	4.15	4.52	4.31	3.39
	RB209	7.89	7.10	6.87	8.02	5.58	6.06	5.37	4.52
	RB209+50	9.06	8.52	8.94	8.92	6.80	6.41	6.08	5.98
	RB209+70	9.16	7.98	7.76	9.27	6.69	6.66	6.50	5.28
Groat N (%)	Nil	1.75	1.76	1.90	1.91	1.71	1.53	1.60	1.92
	RB209	2.07	1.92	2.00	2.22	1.92	1.81	1.81	2.09
	RB209+50	2.17	2.22	2.03	2.42	2.06	2.05	2.13	2.39
	RB209+70	2.19	2.12	2.05	2.45	2.03	2.04	2.15	2.38
NHI	Nil	0.81	0.80	0.81	0.82	0.77	0.76	0.83	0.77
	RB209	0.82	0.82	0.83	0.86	0.81	0.78	0.81	0.80
	RB209+50	0.80	0.76	0.80	0.83	0.73	0.74	0.80	0.80
	RB209+70	0.83	0.78	0.82	0.78	0.76	0.73	0.80	0.78
NUpE (kg kg^{-1})	Nil	0.96	0.88	0.80	0.91	0.63	0.57	0.63	0.61
	RB209	1.07	0.65	0.84	0.78	0.77	0.52	0.68	0.60
	RB209+50	0.73	0.78	0.59	0.70	0.66	0.62	0.59	0.55
	RB209+70	0.64	0.61	0.62	0.78	0.45	0.56	0.62	0.50
Grain NUtE (kg kg^{-1})	Nil	46.65	46.12	43.19	43.27	46.10	49.83	51.82	40.44
	RB209	39.72	42.50	41.84	38.84	42.63	43.48	45.19	38.32
	RB209+50	37.18	34.21	39.62	34.36	35.68	36.24	37.60	33.97
	RB209+70	38.08	36.88	39.95	31.92	37.75	35.84	37.43	33.06
Grain NUE	Nil	44.18	41.19	34.54	38.98	29.14	28.20	32.57	24.74
	RB209	42.50	27.42	34.61	29.86	32.42	22.50	30.89	22.65
	RB209+50	27.33	26.62	23.65	24.28	23.67	22.01	22.30	18.26
	RB209+70	24.01	22.49	24.52	24.26	16.77	19.82	22.44	16.58

Both grain NUtE and grain NUE calculations are influenced by the lower grain yield of the naked cultivars. The two naked cultivars Fusion and Hendon had the highest NUtE for the nil and RB209 treatments (Table 5). Balado had the highest NUtE for the husked cultivars. The husked cultivars had a higher NUE than the naked cultivars. Balado had the highest grain NUE for the nil, RB209 and RB209+50 treatments. Hendon and 00-61Cn3 had the highest grain NUE for the naked cultivars. The average reduction in grain NUE for the husked cultivars with increasing applied nitrogen was higher than the naked cultivars. This means that the husked cultivars were less efficient at high nitrogen than the naked cultivars. Additional nitrogen causes the oat plants to grow taller. Tall cultivars increased in height proportionally more than dwarf cultivars (Fig. 27). Both the increase in height and heavier panicles as a result of nitrogen fertiliser increase the risk of lodging towards the latter end of the growing season. Lodging is caused by either lower stem weakness or poor anchorage of the plants in the soil (Berry *et al*, 2004). There is a balance required for the most efficient use of nitrogen and optimal yields. Lower nitrogen rates lead to poorer yields but highly efficient use of supplied nitrogen. Higher nitrogen application rates lead to higher yields, poorer nitrogen efficiencies and a higher risk of lodging. Using these data, curve fitting can be used to estimate the nitrogen level which produces the optimum yield and acceptable nitrogen efficiencies.

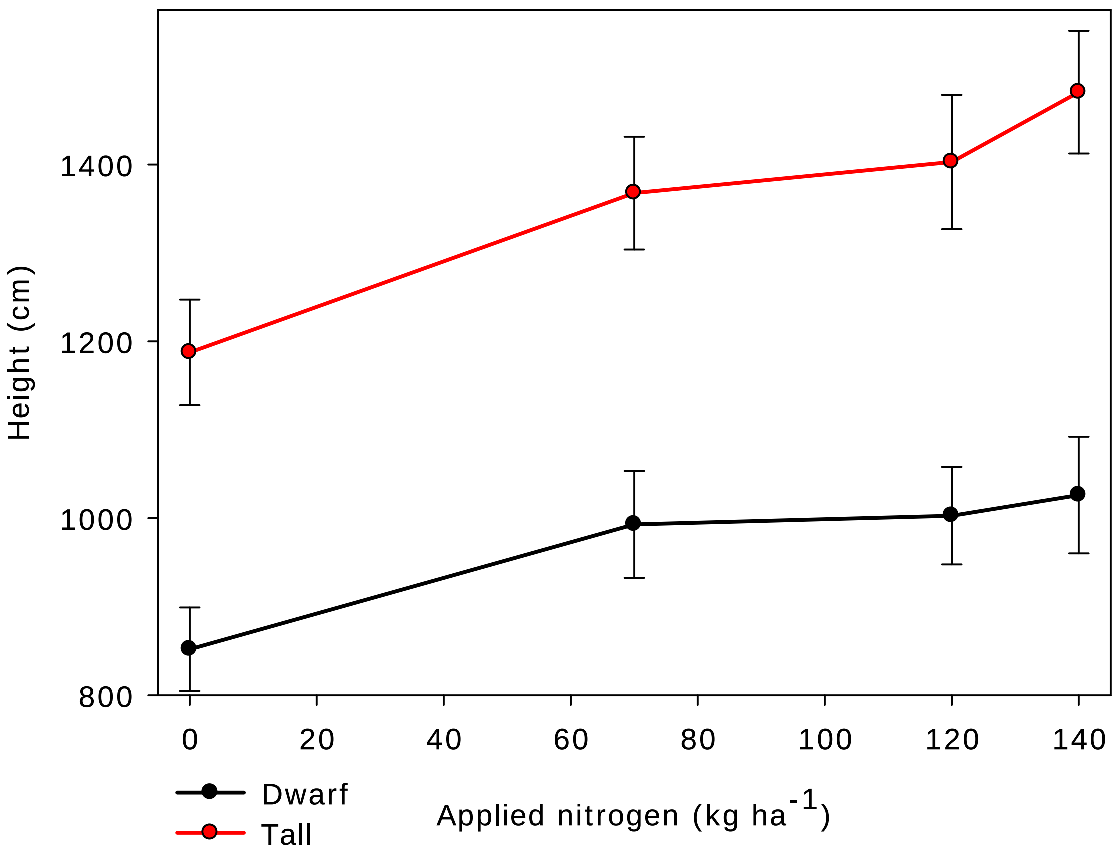

Figure 27 Average height of tall and dwarf cultivars within increasing nitrogen treatment in the 2007/08 field season.

Nitrogen had an effect on the three main yield components, fertile shoot number, total grain number and grain weight. In 2006/07 fertile shoot numbers at GS59 increased with increasing nitrogen treatment up to the RB209+50 treatment then showed a decline of 30 shoots per m^2. In the 2007/08 field season shoot numbers continued to increase from the nil treatment up to the RB209+70 treatment (Fig. 28). A positive relationship between fertile shoot numbers at GS39 and GS59 and yield was obtained. The relationship between GS39 shoot numbers and yield had r^2 values of 0.72 and 0.66 for the 2006/07 and 2007/08 field season respectively. For GS59 the relationship with yield was stronger with r^2 values of 0.95 and 0.91 respectively.

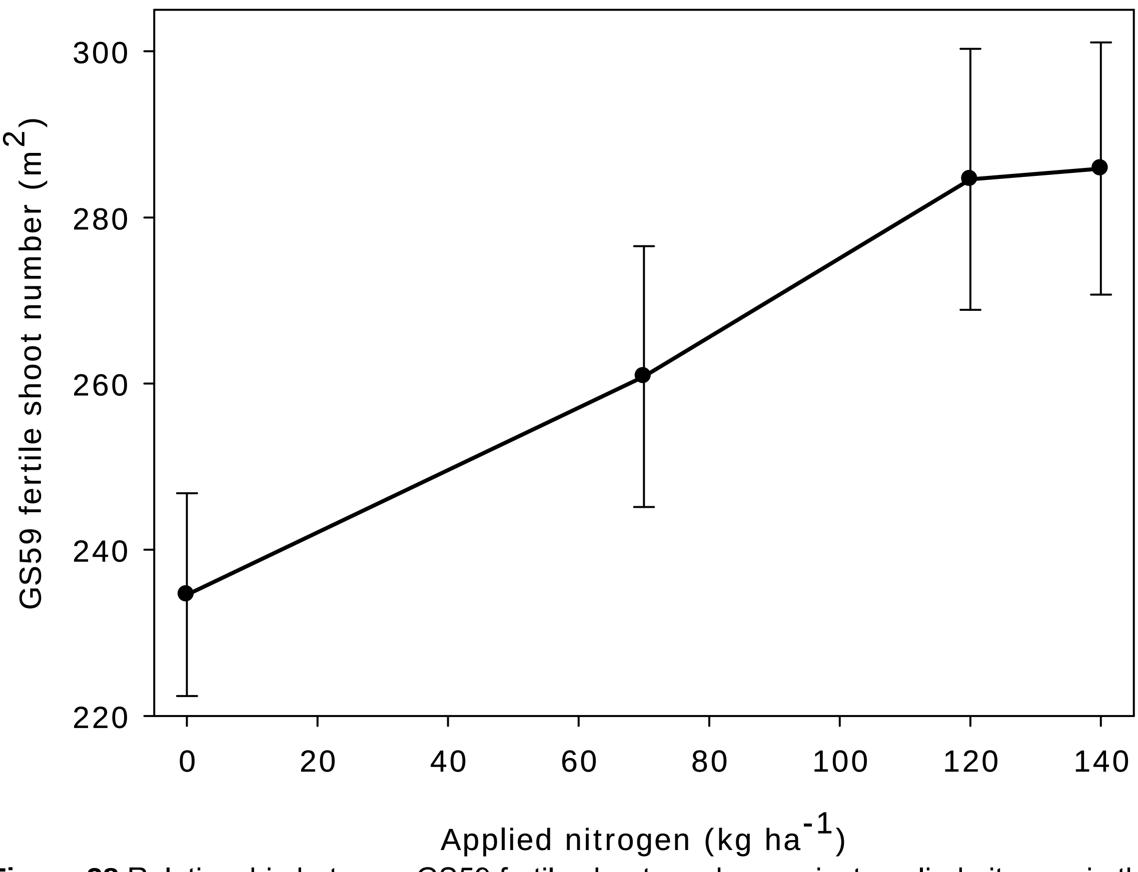

Figure 28 Relationship between GS59 fertile shoot number against applied nitrogen in the 2007/08.

Total grain number per panicle was recorded in the 2007/08 field season as part of the panicle analysis. Total grain numbers increased up to the RB209 + 50 treatment and then declined slightly (Fig. 29). A positive relationship was seen between total grain number and yield with an r^2 value of 0.85. TGW was recorded in both field seasons. In 2006/07 TGW decreased as applied nitrogen increased. The nil treatment had the highest TGW of 34g compared to the RB209+70 treatment which had a mean of 32.1 g but were not significant different. In the 2007/08 field season there was not a clear relationship between TGW and nitrogen treatment (Fig. 29). TGW showed an increase of 1.4 g between the nil and RB209 treatments and a decrease of 1.0 g was seen between the RB209+50 and RB209+70 treatments. The relationship between TGW and yield was variable being negative in the 2006/07 field season and positive in the 2007/08.

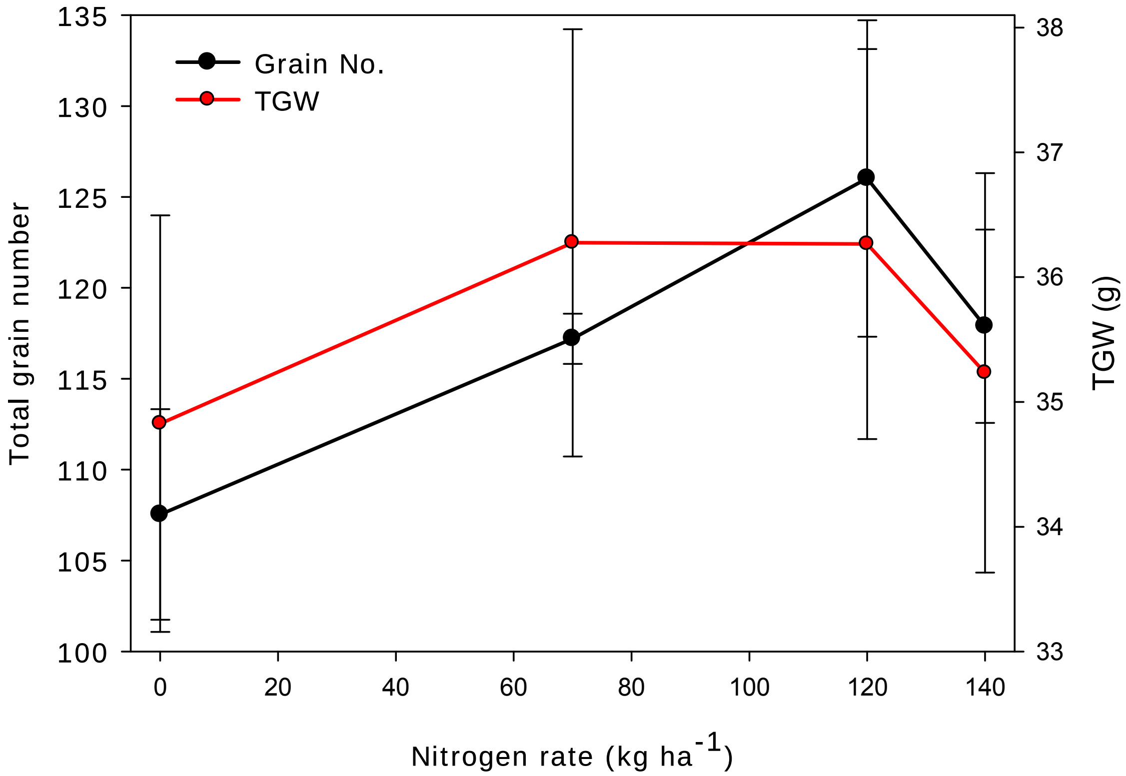

Figure 29 Effect of applied nitrogen on total grain number and TGW in the 2007/08 field season.

Grain number per square metre was calculated by dividing the grain yield per square metre by TGW. Grain numbers increase from the nil treatment to RB209+50 in both field seasons. In 2006/07 a small decrease was seen between RB209+50 and RB209+70 whereas in 2007/08 grain numbers continued to increase. In both field seasons very strong correlations were seen between grain number and yield with r^2 values of 0.99 and 0.97 in 2006/07 and 2007/08 respectively (Fig 30).

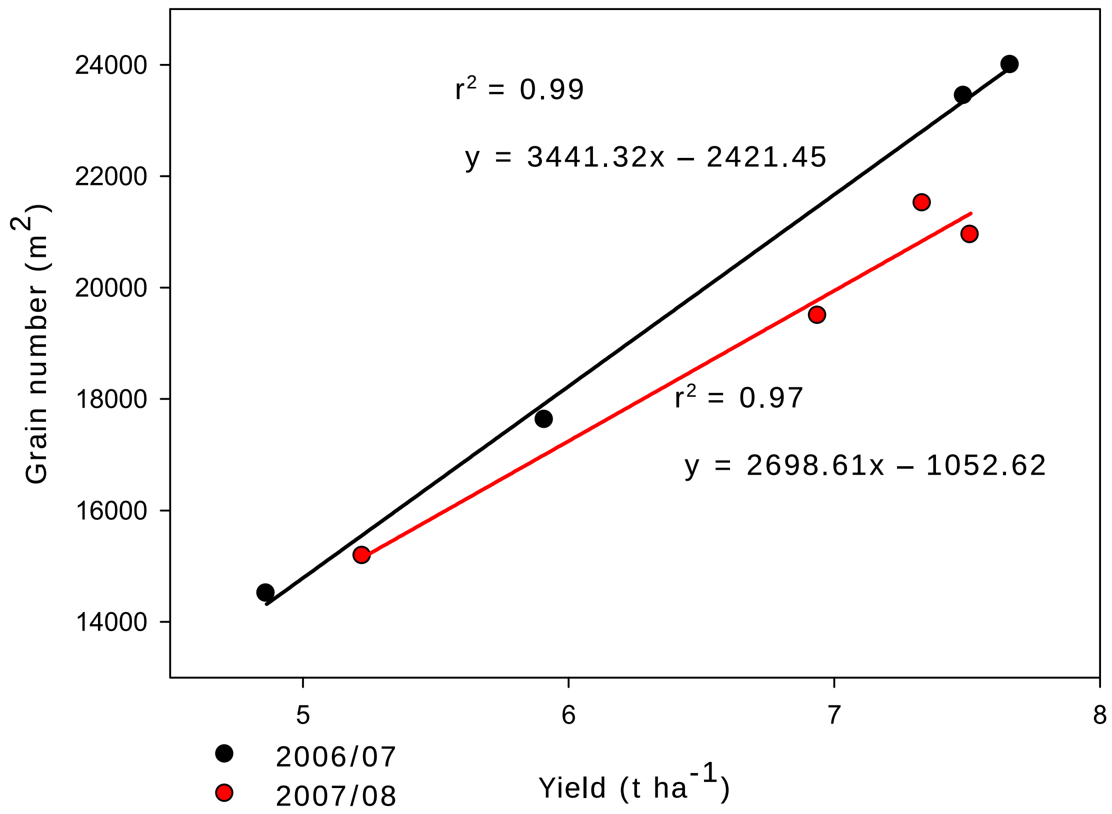

Figure 30 Relationship between yield and grain number m^2 in both field seasons.

TGW and grain number comprise two components of grain yield. Nitrogen means of individual cultivars show that TGW remained stable across nitrogen treatments (Fig. 31). Grain number was seen to be the higher determinant of grain yield with an r^2 of 0.87 for the husked cultivars in 2006/07. This suggests that grain number per $metre^2$ and consequently grain yield are constrained by the nitrogen available to the plant.

- Yield increased with increased nitrogen application
- For individual cultivars the amount of the nitrogen needed to produce optimal yield varies
- Total nitrogen content of the crop and the grain, and total biomass increased with increasing nitrogen application
- A high correlation was found between grain yield and the amount of both biomass and nitrogen accumulation.
- NUE and its components NUpE, crop and grain NUtE decreased with applied nitrogen
- Fertile shoot number, grain number and height all increased with increasing nitrogen treatment

- TGW was not greatly affected by nitrogen application but grain number per metre^2 increased with increasing nitrogen suggesting that this is a major determinant of grain yield.

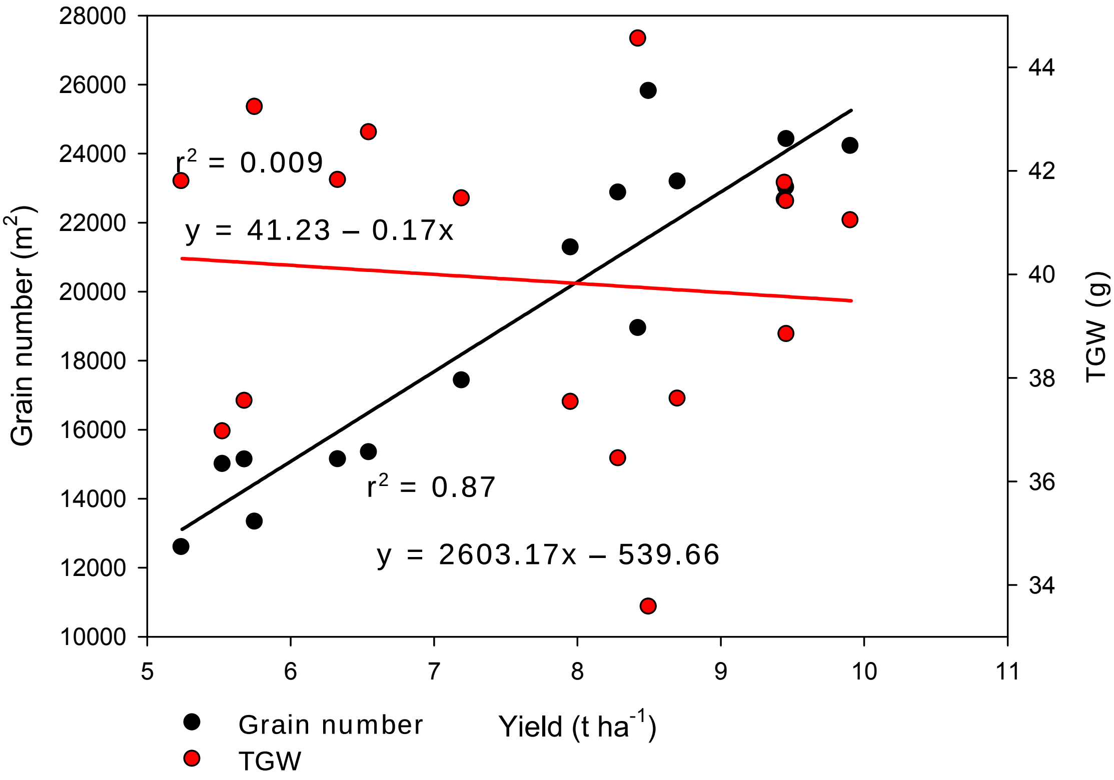

Figure 31 Relationship between grain yield and its components, TGW and grain number per metre^2 for the husked cultivars in the 2006/07 field season.

Aberystwyth mapping family

The first two sets of experiment described in this report indicate that genetic variation exists for most of the traits discussed. However, it is not straightforward to select for many of them due to their quantitative nature. So that molecular markers could be identified associated with regions of the genome influential in determining yield component traits, a third field experiment was grown on the Gogerddan campus at Aberystwyth University in association with the DEFRA sustainable link project, Oatlink. These markers could then be used to develop marker assisted breeding techniques in the future

This trial used a mapping family derived from 2 elite cultivars from the Aberystwyth breeding programme that were both characterised in experiment 1. These were the tall cultivar Tardis and the dwarf cultivar Buffalo. This population was designed to dissect components of yield particularly in relationship to the effect of the dwarfing gene *Dw6*. In this report, results from phenotyping this population are described. Work on genetic mapping and QTL analysis will be reported as part of the Oatlink project.

The mapping population of 188 lines along with the parents were grown out in a replicated field trial in two field seasons, 2006/07 and 2007/08. The dwarfing gene *Dw6* is a major dominant gene affecting height. Figure 32 shows how the gene segregates in the population. All the F_1 progeny of the initial cross were dwarf as they were heterozygous for the *Dw6* dwarfing gene. A single F_1 plant was selected for seed production. In the F_2 population, recombination occurs and some of the progeny would have inherited two height alleles from Tardis and therefore were of conventional height. Some of the population inherited two copies of the *Dw6* gene and were dwarf. The remaining population would have one *Dw6* allele and one conventional height allele and were dwarf. The ratio of dwarf to tall plants in the F_2 generation was 3:1 confirming the dominant nature of the *Dw6* gene. The F_2 plants were selfed and the progeny continued to display segregation for the height trait. The F_3s displayed a ratio of 1 dwarf: 2 heterozygous: 1 tall. The segregating nature of the Tardis by Buffalo population effectively splits the progeny into three distinct populations. These are the homozygous tall progeny, the homozygous dwarf progeny and the *Dw6* heterozygous progeny that segregate for height. In this study these three populations were analysed separately in relation to development through the season and yield.

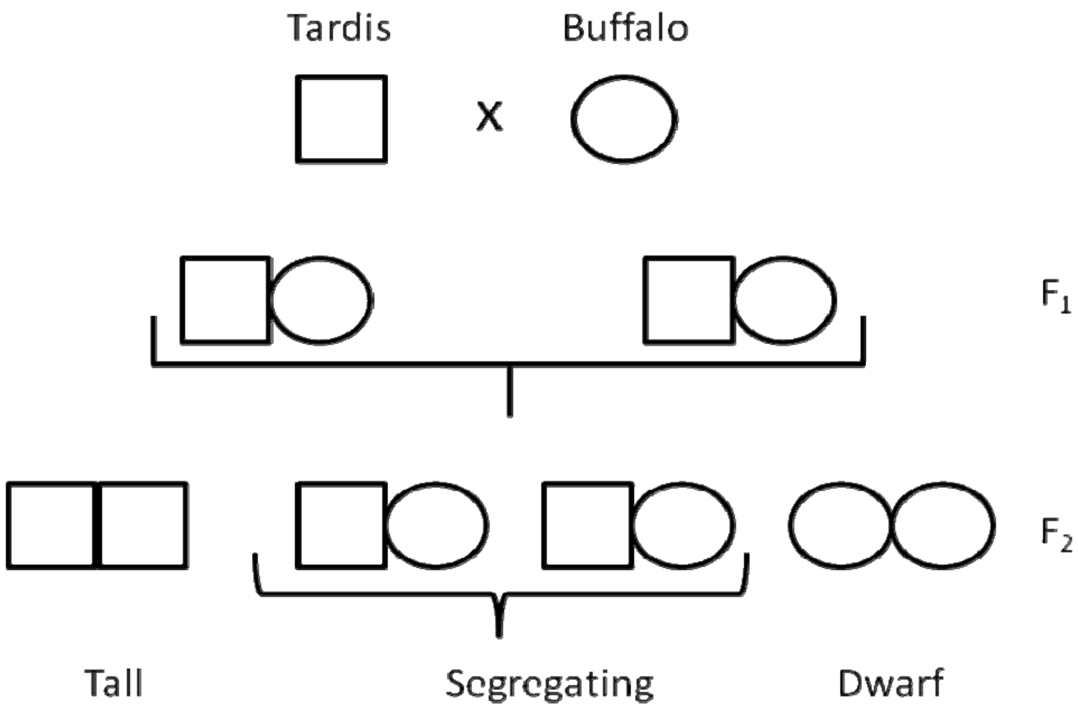

Figure 32 Diagram illustrating the segregating on the *Dw6* gene in the mapping population.

In the 2007/08 field season the number of days for the crop to reach flag leaf emergence, panicle emergence and crop maturity were recorded from April 1st. For this measurement the

tall and dwarf progeny in the segregating plots were recorded separately (Fig. 33). The flag leaf of the tall cultivars emerged earliest with the flag leaves of the segregating population emerging at a similar time. The leaves of the dwarf cultivars emerged on average 5.60 days later than those of the other populations. The panicles of the dwarf population emerged on average 7.36 days later than the tall population. There was also a large spread of emergence dates for the dwarf cultivars. A difference was also seen between the tall and the dwarf plants in the segregating population with a difference of 5.35 days between the means. At maturity there was very little difference between the tall and the dwarf populations of just 0.76 days. The range in the segregating population was larger than the tall and dwarf populations indicating that there was more variation in this population for this trait. The length between panicle emergence and crop maturity for the tall cultivars was 51.55 days. For the dwarf cultivars it was 44.94 days a difference of 6.61 days.
Yield was recorded in both field seasons. Yields were higher in the 2006/07 field season (Fig. 34). The mean yield for the dwarf lines in the 2006/07 field season was double than in the 2007/08 field season. Differences between the segregating and tall populations were less extreme of 285g and 369g respectively.

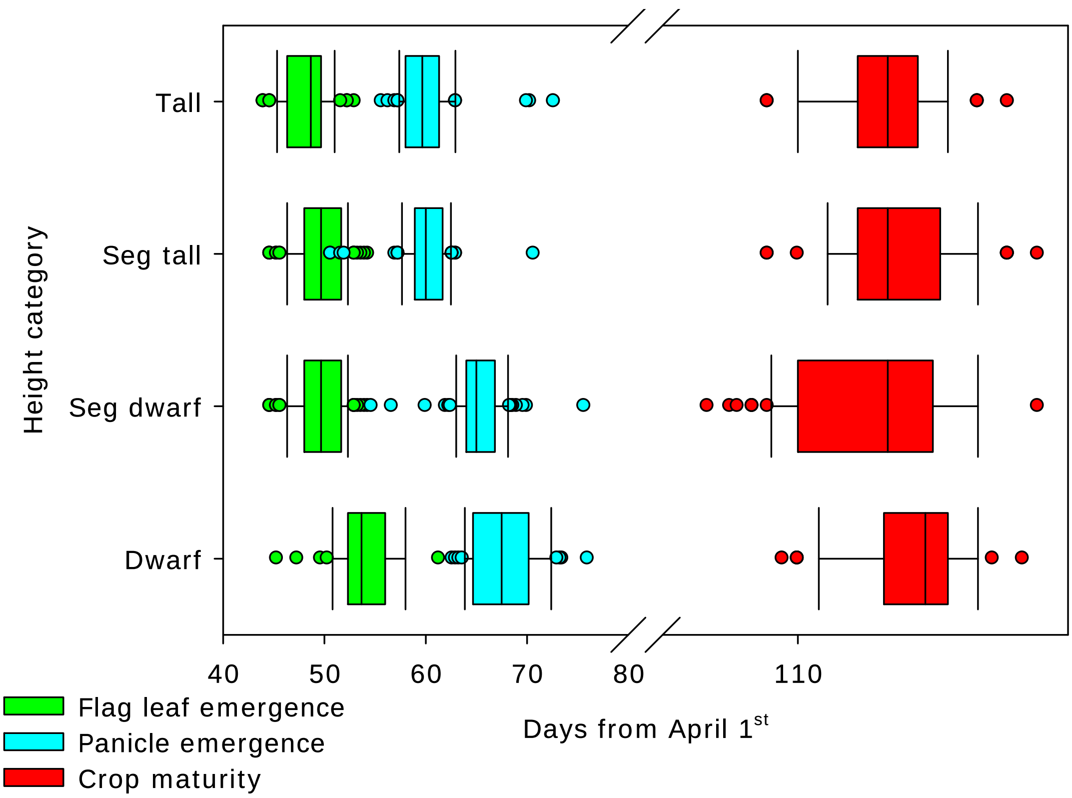

Figure 33 The development of tall, segregating and dwarf cultivars throughout the season.

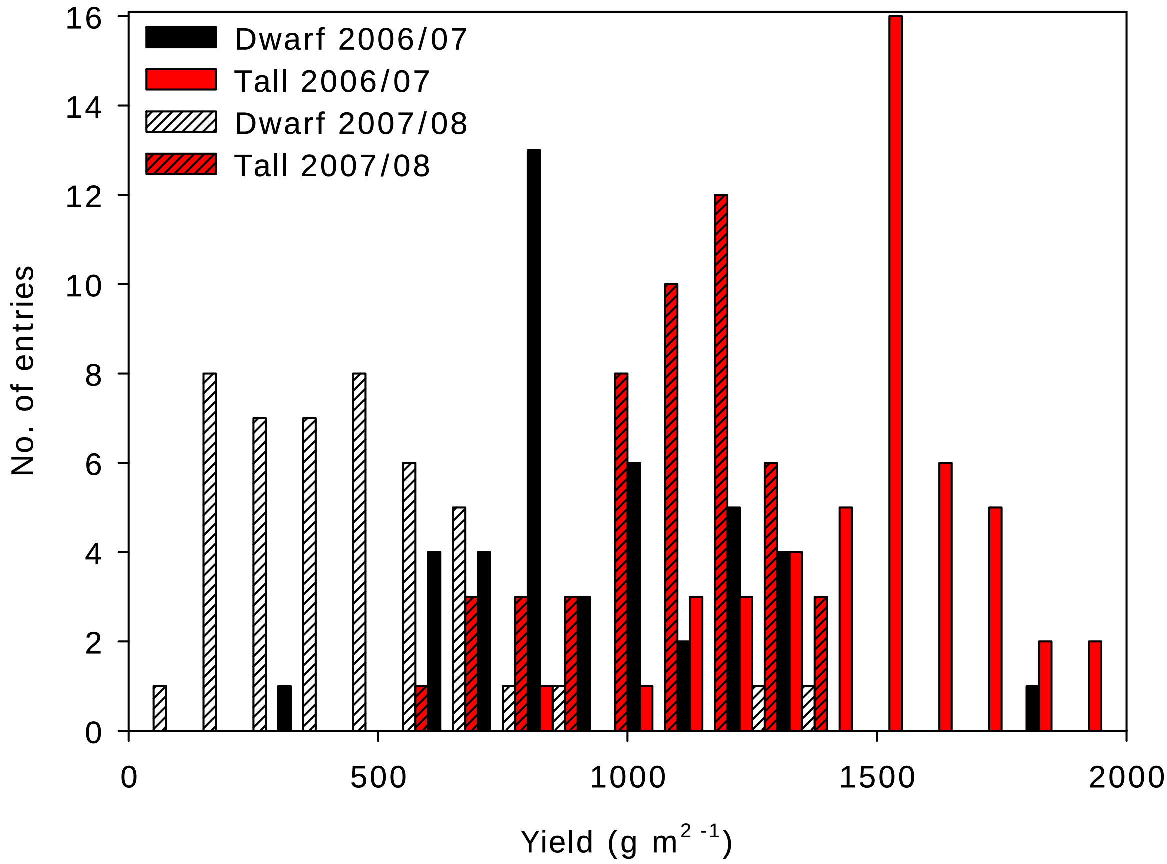

Figure 34 The distribution of yield for tall and dwarf cultivars in the two field seasons.

In the 2006/07 field season the tall population had a 290g and 546g higher yield than the segregating and dwarf populations respectively. In the 2007/08 field season the dwarf population had a very low mean yield of 430g per plot. The segregating population had a much higher mean yield of 877g per plot. The tall population had the highest mean yield of 1049g per plot. This was 619g higher than the dwarf yield.

The correlation between the height and yield was calculated for the 2007/08 field season. This indicates that the trend was for the taller the plant the higher the yield (Fig. 35). The majority of the dwarf progeny were below the regression line whereas the tall progeny were above the line. Dwarf progeny in the segregating population tended to be taller than those in the dwarf population. Conversely the tall progeny of the segregating population was slightly shorter than the tall population.

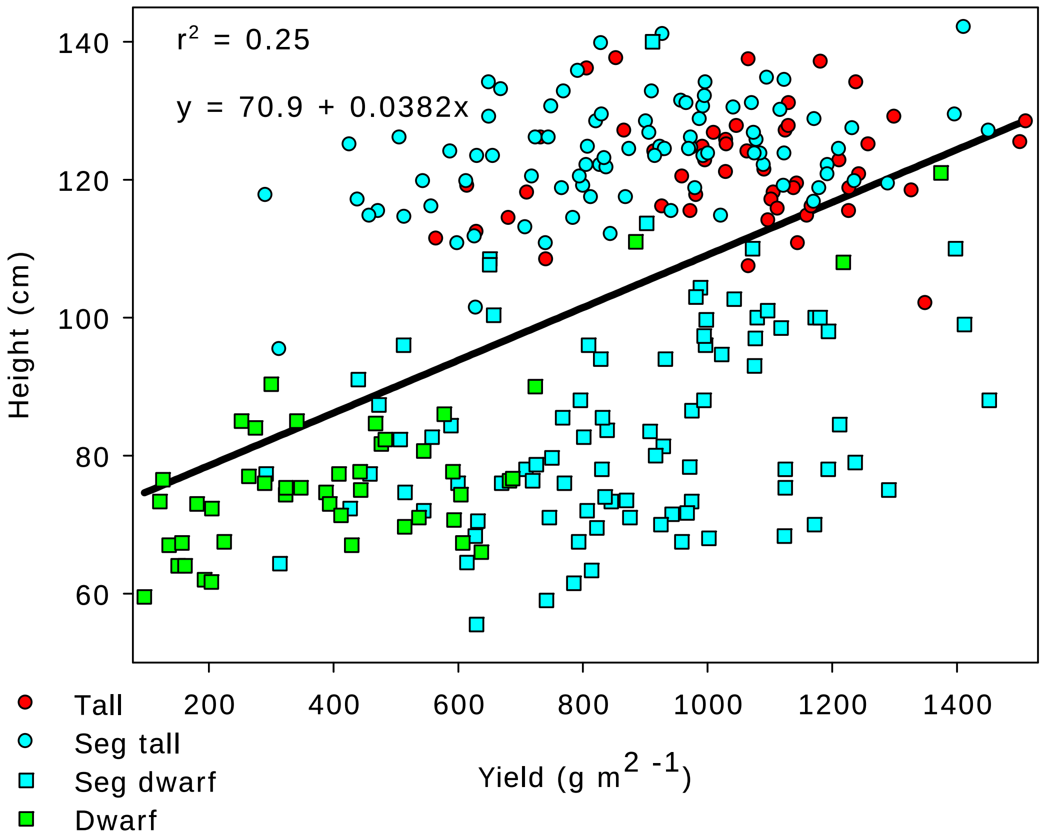

Figure 35 The relationship between yield and height in the 2007/08 field season.

Panicle emergence dates displayed a negative relationship to yield. The greater the number of days it took for the panicle to emerge the lower the yield (Fig. 36). The dwarf population had the lowest yield and also took the longest time for the panicle to emerge. As the height increased, yield and panicle emergence dates increased. The dwarf cultivars had the lowest yield, moving on to the dwarves in the segregating population then the tall segregating plants and finally the tall population (Fig. 36). The overlap between the tall plants from the segregating population was larger than the overlap between the dwarf populations.

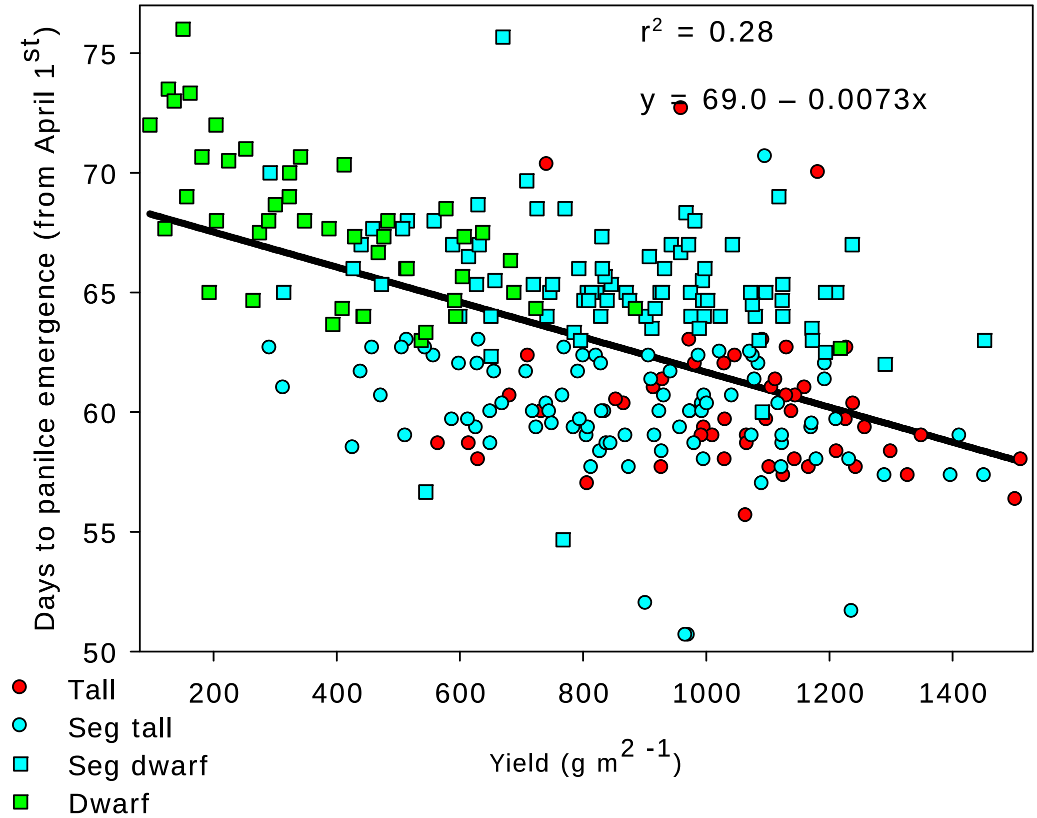

Figure 36 The relationship between panicle emergence and yield in the 2007/08 field season.

KC was conducted on a mixed grain sample in both field seasons. In both field seasons there was a positive relationship between KC and yield. The relationship was stronger in the 2007/08 field season (Fig. 37) with an r^2 of 0.43 compared to 0.4 in the 2006/07 field season. In general KC were higher in the 2007/08 field seasons with differences in the means being 7, 6 and 4% respectively for the dwarf, segregating and tall populations.

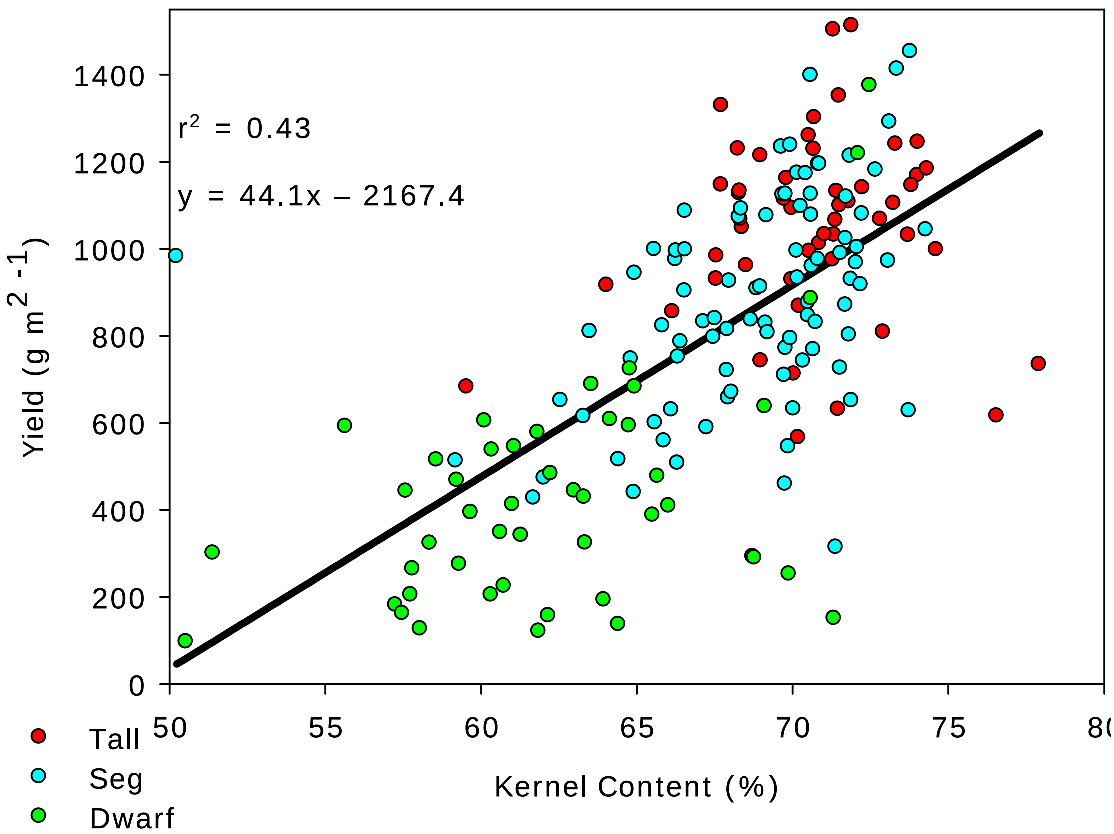

Figure 37 The relationship between kernel content and yield in the 2007/08 field season.

In the 2006/07 field season there was an 11% difference in the mean KC between the tall and the dwarf populations. The segregating population had a mean which was closer to the tall mean with a difference of 3.5% compared to a difference of 7.6% with the dwarf mean.

In the 2007/08 field season the difference between the tall and dwarf populations was less at just 8%. There was a difference of 1.9% between the tall and the segregating mean. A greater differences was seen between the dwarf and segregating mean of 6.5%.

- Dwarf cultivars had a later emergence date for both flag leaf and panicle than the conventional height cultivars
- Little difference was seen in maturity dates of conventional height and dwarf lines
- The segregating population mean was closer the conventional height mean than the dwarf mean for the majority of traits
- Dwarf lines had a poorer grain quality and yield than tall cultivars

Comparison of results obtained for oats with wheat and barley

Comparisons can be made between cereal species using the Benchmarks from the wheat and barley growth guides (HGCA, 2008, HGCA, 2006) with the data collected in this study. The benchmarks represent quantitative reference points against which a crop's performance can be compared. They were derived from the median values obtained from multi locational field trials of a single cultivar grown with ample nutrition (for feed quality grain), complete crop protection and lodging control to minimise potential crop losses. The oat data described in this report was obtained from two harvest years at two sites but with a wider range of cultivars including dwarf and conventional height winter oats. Only results from the RB209 nitrogen treatment at Rosemaund were included in the analysis and results from naked oats were excluded from this comparison. The barley and wheat growth guides illustrate that the two crops differ in many important aspects and need different management techniques. The results obtained here indicate that the oat crop is also distinct in many respects. At all growth stages measured, oats had lower shoot numbers per metre^2, biomass accumulation and green area index (GAI) out of the three species. When GAI was split into stems, leaves and panicles/ears oats had the highest percentage of GAI for panicles.

A major difference between the 3 cereals is in the number of grains per panicle (in the case of oats) or per ear (in the case of wheat and barley). The panicle of oats contains far more grains than the ear of either wheat or barley with a result that the number of grains per metre^2 in oats was similar to that found in barley and not greatly less than wheat. High yields in barley depend on high numbers of ears. Oats had on average 5 times the amount of grain per panicle than does the benchmark for grains per barley ear.

Mean thousand grain weight of oats was slightly less than either barley or wheat with the result that the mean yields obtained for oats was less than the benchmarks for wheat and barley. However, as reported in the HGCA growth guides almost all average farm yields are below the benchmark for both wheat and barley.

The results in table 6 are for oats grown at RB209 nitrogen levels. RB209 regulations revised for wheat and barley but no revision is in progress for oats crop as insufficient data was available. The results in this study have shown that the yield of oats was limited by the nitrogen available to the crop. Oats have the same length of grain filling period as wheat of 45 days. However the TGW, grain number per metre^2 and yield were lower. With proper revision of the RB209 nitrogen levels for oats and introduction of even more nitrogen efficient cultivars, oat yield could be substantially improved.

Table 6 Mean values from Aberystwyth and Rosemaund for husked oat varieties grown at RB209 (180kg available N /ha) as compared to the Benchmarks provided in the HGCA wheat (2008) and barley (2006) growth guides

Growth stage	**Oats**			**Wheat**	**Barley**
Trait	**mean**	**min**	**max**		
GS31					
shoots/m^2	593	309	997	902	1180
GAI	2.4	1.3	3.6	2	2.4
biomass t/ha	2.9	1.3	5.0	1.9	2.4
No.of tillers/plant	4.3	1.6	6.4	3.5	3.9
GS39					
shoots/m^2	446	240	636	655	*
GAI	4.5	2.6	6.2	6.2	5.1
biomass	5.7	3.0	7.5	6.9	5.2
No. of leaves	13	11	15	14	14
GS59					
shoots/m^2	379	207	589	495	855
GAI	4.8	3.7	7.0	6.3	5.8
biomass	9.1	6.5	12.3	11.4	9.6
GAI leaf	64%	58%	70%	74%	53%
GAI stem	20%	17%	22%	19%	36%
GAI panicle	15%	12%	23%	7%	11%
CCS					
shoots/m^2	364	201	533	460	775
biomass t/ha	13.6	11.4	18.1	19.6	15.7
PH					
grains/ear	125	81	163	48	24
TGW	42	35	49	50	46
Total biomass	12.2	8.8	19.3	18.4	14.8
grain/m^2	19056	15137	24555	22000	19130
Yield t/ha	8.1	5.7	9.5	11.0	8.8
Grain N %	1.90	1.38	2.10	1.96	1.76

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