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The agronomic performance and nutritional content of oat and barley varieties grown in a northern maritime environment depends on variety and growing conditions

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ABSTRACT

Warmer temperatures and increasing interest in high provenance food and drink products are creating new opportunities for cereal growing in northern Europe. Nevertheless, cultivation of oats and barley in these areas for malting and milling remains a challenge, primarily because of the weather, and there are few reports of their nutritional content from this region. In this study, trials in Orkney compared agronomic characteristics and nutritional content of recommended UK oat and barley varieties with Scandinavian varieties over three years. For a subset of varieties, nutritional content was compared with samples cultivated in more southerly sites. For Orkney, barley was considered a more suitable crop than oats because varieties matured earlier. In both crops, Scandinavian varieties matured earlier than UK varieties and some produced comparable yields. The range of values for macronutrients and minerals in oats and barley in Orkney were similar to those reported previously for other locations, but there were some significant differences attributable to variety and year. Compared with grain samples from more southerly locations, oats in Orkney had a significantly lower β-glucan and higher sodium content. The lower β-glucan may have resulted from higher rainfall and lower temperatures during the months of grain filling and maturation.

1. Introduction

Diets high in whole grain cereals are thought to be beneficial for health and several large scale epidemiological trials have shown their consumption to be associated with a reduction in the risk of type 2 diabetes, obesity, cardiovascular disease (CVD) and colorectal cancer (Murphy et al., 2012; Cho et al., 2013). The fibre component of cereals is thought to be largely responsible for these actions through a variety of mechanisms, including: reducing low density lipoprotein (LDL) cholesterol and blood pressure; influencing glucose homeostasis; increasing satiation from a meal; increasing faecal transit time and lowering the exposure of colonocytes to faecal mutagens and carcinogens; and providing the colonic microbiota with growth substrates to produce beneficial short chain fatty acid metabolites (Beck et al., 2009; Othman et al., 2011; Louis et al., 2014).

Both oats and barley are high in the soluble fibre (1-3)(1-4) β-D-glucan. Mixed link β-glucan has been shown to reduce LDL cholesterol and reduce the risk of CVD in clinical trials and currently has several endorsed health claims worldwide including the European Food Standards Agency (EFSA, 2006).

Barley and oats are both important crops in northern areas and their production in this region is likely to expand with the warmer growing seasons projected to occur as a result of climate change

Abbreviations: NDF, Neutral detergent fibre; TKW, housand kernel weight; β-glucan, (1-3)(1-4) β-D-glucan Mixed Link β-glucan; AHDB, Agriculture and Horticulture Development Board; EFSA, European Food Standards Agency; DEFRA, Department for Environment and Rural Affairs; ANOVA, Analysis of variance.

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(Bindi and Olesen, 2011). Northern maritime areas, like Iceland, coastal Norway and parts of Scotland, are also likely to benefit from these effects, and recent years have seen considerable expansion of barley cultivation in Iceland (Martin, 2016). Nevertheless, growing barley and oats in such areas remains very challenging as gales and high winter rainfall often prevent the use of autumn-sown varieties, while high soil moisture or frozen ground delays cultivation and the planting of spring crops. With cool growing seasons and the risk of high rainfall at harvest, these areas have a particular requirement for early maturing varieties, especially if fully mature, dry grain is required for milling or malting.

Located about 10 km off the north coast of Scotland, the Orkney archipelago has a hyper-oceanic climate (Crawford, 2000) and currently grows about 4500 ha of cereals. Most of this is feed barley for the local livestock industry, but the expanding market for high provenance food and drink products (Martin, 2016) has increased interest in local cereals for this purpose. Spring oat and barley varieties in the United Kingdom's (UK) lists of recommended varieties produced by the Agriculture and Horticulture Development Board (AHDB, 2016) show only a small variation in days to maturity. Consequently earlier maturing varieties sourced from Scandinavia are being tested in Orkney by the Agronomy Institute of the University of the Highlands and Islands (UHI).

The environment in which cereals are grown is known to affect their nutritional composition, and studies have found differences in the protein, fat and β-glucan content of oats and barley grown in different environments (Zhou et al., 1999; Redaelli et al., 2013). There are no detailed reports on the composition of oats and barley grown in hyper-oceanic climates like Orkney's. The present study reports the chemical composition and agronomic performance of early and later maturing varieties of oats and barley grown in Orkney between 2012 and 2014. For a subset of varieties, nutritional composition in Orkney was compared with that of the same varieties grown in more southerly parts of the UK.

2. Materials and methods

2.1. Orkney field trials

Six oat and six barley varieties were grown in separate trials over three consecutive growing seasons from 2012 to 2014. The trials were located at Orkney College UHI (58° 59′ N and 2° 57’ W) on sandy loam soil. Trials used a randomised block design with five replicates. Barley varieties included Bere (an early maturing Scottish landrace), three Scandinavian varieties obtained from Lantmännen SW Seed AB (Vilde, Kannas and Vilgott), and two recommended (AHDB, 2016) UK varieties (Waggon for feed and Concerto for malting). Oat varieties included three Scandinavian varieties from Lantmännen SW Seed AB (Haga, Belinda, and Betania) and two recommended (AHDB, 2016) UK varieties (Firth and Canyon) and Lennon, a naked oat. Varieties were planted in plots 20 m long and 3 m wide with a plant population of 350 plants m^{-2} for barley and 400 plants m^{-2} for oats. Fertilizer was applied to both cereals at planting each year; oats received 50–60 kg ha^{-1} yr^{-1} of nitrogen and phosphorus (as P_2O_5) and 67–91 kg ha^{-1} yr^{-1} of potassium (as K_2O); barley received 65 kg ha^{-1} yr^{-1} of nitrogen and phosphorus (as P_2O_5) and 87–105 kg ha^{-1} yr^{-1} of potassium (as K_2O). The planting dates and inputs used are specified in Supplementary Table S1. Varieties were harvested when they reached senescence and usually when grain moisture content was below 25%. Plots were harvested with a Sampo combine with 2.3 m cutter bar and the weight of grain per plot measured. An 800 g sample of grain was collected from each plot and a 200 g subsample from this was used for determining grain moisture and thousand kernel weight (TKW) which was determined with a seed counter (Contador). TKW is often used as an indicator of grain quality in both barley and oats; in barley, it is correlated with grain plumpness and is a good indicator of starch in the kernel (Newman and Newman, 2008). The remaining 600 g sample was dried in an oven for 48 h at 35 °C and retained for the nutritional analyses. Grain yield (t ha^{-1}) per plot was calculated at 15% moisture content from the fresh weight of grain harvested and the laboratory determinations of grain moisture. Poor weather resulted in lodging of oats in the 2012 harvest and only Haga could be machine-harvested; all other varieties were hand-harvested to obtain samples for analysis.

One composite soil sample was collected from each of the oat and barley trials in February 2012, 2013 and 2014 and consisted of the mixed soil from 8 cores (0–30 cm depth). Samples were analysed by NRM laboratories (Bracknell, England) and results are summarised in Supplementary Table S2. Data for precipitation and temperature during each growing season were obtained for Kirkwall airport, about 6 km from the trial site from http://en.tutiempo.net/climate/europe.html and are summarised in Supplementary Table S3.

2.2. Other field trials

In additional trials in the same growing seasons, two recommended UK (AHDB, 2016) barley varieties (Waggon and Concerto) were grown by the James Hutton Institute at Balruddery near Dundee in Scotland (56° 28′N and 3° 4′W), and three recommended UK (AHDB, 2016) oat varieties (Lennon, Firth and Canyon) were grown by Aberystwyth University in Wales at Morfa (52° 54′N and 4° 32′W) and in the north of England at Berwick-upon-Tweed (55° 45′N and -2° 0′W). Weather data for Dundee were obtained from an automatic weather station at the trial site and for the other sites from the closest stations listed in the TuTiempo.net database (http://en.tutiempo.net/climate/europe.html). These sites were Gogarbank for Berwick-upon-Tweed and Aberporth for Morfa. For each site, total rainfall and degree days were calculated from the date of planting to that of harvesting. Degree days were calculated from each day's average temperature using a base temperature of 0 °C. From each site, a 100 g grain sample was obtained from each variety and used for the nutritional analyses.

2.3. Processing of oat and barley samples

Oat and barley grains of all varieties were processed in the same way and were first heat-treated to deactivate endogenous lipase and β-glucanase enzymes. Samples were placed in uncovered containers and steamed in an autoclave for 10 min and then incubated at room temperature for 48 h to allow moisture to equilibrate. They were then dehulled for 30 s using a laboratory thresher (Streckel and Schrader, Hamburg, Germany) and barley underwent a second dehulling to replicate pearling. After a 15 min cooling period, samples were milled into a fine flour using a freeze mill (Spex, Certi Prep 6800 Freeze Mill). Milling consisted of 2 min of milling followed by a 2 min cooling period and a final 2 min milling period. Flours were then stored refrigerated between 2 and 8 °C and analyses were completed within 6 months.

2.4. Nutritional analyses

2.4.1. Macronutrient analysis by near-infrared reflectance spectroscopy (NIRS)

Compositional analysis (Ash, Lipid, Protein, Starch, Sugar and fibre as Neutral Detergent Fibre (NDF)) was carried out at the Royal Zoological Society of Scotland (Edinburgh) using near-infrared spectroscopy (NIRS). Each flour sample was analysed in triplicate and the mean value was used in the statistical analysis. Since differences in macronutrient content between plots of the same variety were negligible (Supplementary Table S4), grain samples from plots of the same variety in each separate year were pooled prior to further analysis. The mean nutrient composition of varieties presented in Tables 2–5 were calculated from combined data across the three growing seasons. The β-glucan content of grains were analysed in triplicate, enzymatically, according to the method of McCleary and Codd (1991), using a commercially available kit (Megazyme International Ireland, Bray, Ireland), following the manufacturer's instructions.

2.4.2. Mineral analysis by inductively coupled plasma-mass spectrometry (ICP-MS)

Mineral composition was quantified using inductively coupled plasma - mass spectrometry (ICP - MS) at the Rowett Institute. All samples were analysed in duplicate and the mean was used for the statistical analysis. The following minerals were quantified: Magnesium (Mg), Phosphorus (P), Potassium (K), Calcium (Ca), Sodium (Na), Manganese (Mn), Iron (Fe), Copper (Cu), Zinc (Zn), Chromium (Cr), Cobalt (Co), Nickel (Ni), Selenium (Se), Molybdenum (Mo), Cadmium (Cd) and Palladium (Pd). Mean mineral composition of a cultivar was determined by combining data across the three growing seasons. This data is summarised in Supplementary Tables S5 and S6.

2.5. Statistical analysis

Data were analysed with Genstat 13th Edition, release 17.1 (VSN International Ltd, Hemel Hempstead, Herts., UK). Grain yield and TKW from the Orkney trial used generalised analysis of variance with blocks as replicates, and with plot, year and their interaction nested within replicates. Treatment terms were variety, year and their interaction. Three years of data were analysed for the barley trial, but only two years (2013 and 2014) for the oat trial. Nutritional composition analysis including NIRS analysis, β-glucan content, mineral composition and comparison between locations were analysed by two-way ANOVA with variety and year as treatment factors. For all ANOVA analyses, significant differences between factors were determined by the F - test at $p < 0.05$. When significant, this was followed by an unprotected Fisher's exact test at $p < 0.05$ to identify significantly different treatment means. Correlation coefficient analysis was performed to determine the correlation between rainfall and degree days over the growing season and nutritional composition of varieties and between the agronomic traits TKW and yield, and nutritional composition. Correlations were considered significant when the correlation coefficient achieved a significance level of $p < 0.05$.

3. Results and discussion

3.1. Orkney agronomy trials

Harvest data for the oat and barley trials in Orkney are summarised for 2012 to 2014 in Table 1. In all years, barley required fewer days and degree days from planting to harvest than oats and the averages over varieties and years for barley and oats, respectively, were 143 and 160 days and 1659 and 1858° days. The earliest maturing barley varieties were Bere, Vilde and Kannas which required averages of 1562–1595° days to harvest compared with 1821 and 1836° days for the earliest oat varieties, Haga and Canyon. The advantage of early varieties under Orkney conditions was demonstrated in 2012, when Haga was the only oat variety that ripened sufficiently early to be harvested in good weather; varieties ripening later were either too wet or too badly lodged to harvest. The number of days and degree days to harvest decreased by year from 2012 to 2014 (Table 1), reflecting an increase in the average temperature of the growing season (1 April to 30 September) - 10.4, 11.3 and 12.1 °C for 2012, 2013 and 2014, respectively.

Average yields for oats were significantly higher in 2014 (5.27 t ha^{-1}) compared to 2013 (4.66 t ha^{-1}) ($p = 0.001$), and significant differences in grain yields occurred between varieties of both oats and barley ($p < 0.05$). The highest thousand kernel weight (TKW) for both oats and barley (41.8 and 44.9 g respectively) occurred in 2013. The 2012 growing season was particularly poor and had the lowest yields and TKW for barley and also for Haga, the only oat variety which was harvested in all years. Amongst oats, Lennon had significantly lower yields and TKW than the other varieties which can be attributed to it being a naked variety. The highest yielding oat varieties were Canyon in 2014 and Haga in 2013. Canyon had the highest TKW in both 2013 and 2014. Amongst barley varieties, Bere had the lowest yields in all years, reflecting its status as a landrace which has not been improved by plant breeding (Martin et al., 2009). Bere and Vilde are both 6-row barleys and their TKWs were always lower than those of the 2-row varieties. The highest yielding variety differed from year to year and was Vilgott, Kannas and Waggon in 2012, 2013 and 2014, respectively. In contrast, Kannas and Waggon were always the varieties with the highest TKW. The average annual grain yields of the Scandinavian varieties of both oats and barley are lower than those reported for other similar Scandinavian varieties grown near Helsinki in Finland (Peltonen-Sainio et al., 2008), but the latter were grown with higher levels of nitrogen fertilizer and the growing season is also normally warmer in Helsinki. However, the average TKWs of the Scandinavian varieties grown in Orkney were higher than the averages of those in Finland, especially for oats.

For TKW and yield, there were significant interactions ($p < 0.001$) between variety and year for both oats and barley showing that some varieties performed better in some years than others. For example, Kannas was relatively low yielding in 2012 and 2014, but had the highest yield in 2013. In Scotland, barley and oat national yields from 1963 to 2005 were both correlated negatively with rainfall in July and positively with total sunshine over the season (Brown, 2013). Variations in yield between varieties may result from varietal differences in ability to adapt to seasonal variations in these and other weather variables. Average Scottish yields for spring barley were 5.6 t ha^{-1} from 2012 to 2014 and 6.0 t ha^{-1} for spring oats from 2013 to 2014 (DEFRA, 2016). In comparison, the average yields in Orkney for the recommended UK oat (Canyon and Firth) and barley (Waggon and Concerto) varieties were about 5–12% less over these years, probably reflecting Orkney's more challenging growing conditions. Compared with these recommended varieties, the Scandinavian varieties Vilde, Kannas and Haga had similar yields and had the advantage of maturing earlier. Vilde and Haga had lower TKW, however, which might limit their acceptability for off-farm commercial use in Scotland. Nevertheless, because of their earliness, both varieties could be useful in the northern part of the country for particular, on-farm purposes like undersowing with grass or for making early whole-crop silage.

3.2. Macronutrient composition of oats and barley grown in Orkney

The macronutrient composition of oat and barley grains produced in Orkney between 2012 and 2014 are summarised in Table 2 and are similar to previously reported values (Peterson et al., 1975; Saastamoinen et al., 1992; Zhou et al., 1999; Andersson et al., 2008; Doehlert et al., 2013). There were significant differences between barley varieties for all macronutrients tested ($p < 0.05$). In oats there was a significant difference between varieties for β-glucan ($p = 0.001$) and near-significant differences between varieties for

Table 1
Days and degree days from planting to harvesting, thousand kernel weight (TKW) and yield of oat and barley varieties grown in Orkney, from 2012 to 2014. TKW and grain yield are presented at 15% grain moisture.

Cereal/Variety	Days to harvest				Degree days to harvest				TKW (g)				Grain yield (t ha^{-1})			
	2012	2013	2014	Mean 2012 to 2014	2012	2013	2014	Mean 2012 to 2014	2012	2013	2014	Mean 2012 to 2014	2012	2013	2014	Mean 2012 to 2014
Oats																
Haga	164	163	142	156	1822	1852	1788	1821	36.9	41.4^c	38.9^c	40.2^c	5.18	5.32^c	5.62^c	5.47^{cd}
Belinda	169	163	147	160	1861	1852	1854	1856	–	43.6^d	42.5^d	43.0^d	–	5.01^d	5.51^c	5.26^c
Betania	197	163	147	169	2058	1852	1854	1921	–	46.2^e	42.6^d	44.4^e	–	4.67^e	4.62^b	4.65^b
Canyon	170	163	142	158	1869	1852	1788	1836	–	47.2^e	43.8^d	45.5^e	–	4.82^e	6.18^e	5.50^d
Firth	169	163	147	160	1861	1852	1854	1856	–	38.7^b	35.9^b	37.3^b	–	4.68^b	5.88^d	5.28^c
Lennon	170	163	147	160	1869	1852	1854	1858	–	33.8^a	28.3^a	31.1^a	–	3.49^a	3.83^a	3.66^a
Mean	173	163	145		1890	1852	1832		–	41.8^x	38.7^y		–	4.66^x	5.27^y	
									p variety			**<0.001**	p variety			**<0.001**
									p year			**<0.001**	p year			**<0.001**
									p variety x year			**0.018**	p variety x year			**<0.001**
Barley																
Vilde	145	146	121	137	1638	1632	1515	1595	37.7^c	39.3^b	38.4^a	38.5^b	5.02^{bc}	5.00^{bc}	5.69^c	5.24^b
Kannas	145	146	121	137	1638	1632	1515	1595	39.3^c	48.9^d	48.3^c	45.5^e	4.81^b	5.50^d	4.83^b	5.05^b
Vilgott	154	154	127	145	1733	1743	1583	1686	35.3^b	46.0^c	42.4^b	41.2^c	5.51^c	5.12^{bcd}	5.09^b	5.24^b
Bere	146	146	116	136	1600	1632	1453	1562	30.2^a	37.1^a	35.9^a	34.3^a	3.59^a	4.38^a	4.09^a	4.05^a
Concerto	164	154	136	151	1822	1743	1711	1758	34.5^b	48.0^d	44.9^b	42.5^d	4.99^{bc}	5.33^{cd}	5.52^c	5.28^b
Waggon	164	154	136	151	1822	1743	1711	1758	38.4^c	50.2^e	48.2^c	45.6^e	4.96^{bc}	4.83^{ab}	5.74^c	5.18^b
Mean	153	150	126		1709	1688	1581		35.9^x	44.9^z	43.0^y		4.83^x	5.03^y	5.16^y	
									p variety			**<0.001**	p variety			**<0.001**
									p year			**<0.001**	p year			**0.003**
									p variety × year			**<0.001**	p variety × year			**<0.001**

Different letters indicate significant differences at $p < 0.05$ between varieties within a year or between annual means across all varieties or between varieties across all years.
- Indicates no data available.
p variety, p year and p variety × year are the p-values for the treatment terms and interactions in the table.
Analysed by ANOVA with blocking for replicate (i.e. strip of land), and with plot, year and their interaction nested within replicate. Treatment terms were variety, year and their interaction. When one of the main effects was significant ($p < 0.05$) post hoc *t*-test was conducted to compare treatment means. Significant differences are highlighted in bold.

ash ($p = 0.056$), sugar ($p = 0.088$) and fat ($p = 0.051$). The most abundant nutritional component of oat and barley grains was starch, followed by either NDF or protein and then fats. Waggon and Concerto barley contained a high starch and low protein content

Table 2
Macronutrient composition (g/100 g) of oat and barley flour of varieties grown in Orkney, between 2012 and 2014.

Crop/Variety	Ash	Protein	Starch	Sugar	NDF	β-glucan	Fat
Oats							
Variety means							
Haga	1.55 (0.20)	9.29 (1.25)	57.64 (4.41)	2.13 (0.13)	9.16 (5.63)	2.59 (0.10)^a	5.45 (0.60)
Belinda	2.39 (0.43)	9.51 (0.87)	49.32 (1.87)	5.63 (0.57)	12.82 (3.36)	3.44 (0.12)^c	6.91 (0.23)
Betania	1.96 (0.13)	10.27 (0.87)	53.28 (1.65)	3.25 (0.39)	9.33 (3.12)	3.76 (0.35)^d	7.33 (0.71)
Canyon	1.82 (0.15)	8.97 (0.59)	53.74 (2.72)	3.06 (0.73)	10.16 (3.34)	3.23 (0.01)^{bc}	6.47 (0.29)
Firth	1.56 (0.13)	7.87 (0.63)	54.17 (4.34)	4.43 (0.54)	19.01 (5.38)	2.86 (0.07)^{ab}	6.27 (0.24)
Lennon	1.68 (0.16)	9.19 (0.93)	53.06 (3.95)	5.11 (1.08)	11.40 (4.54)	3.33 (0.11)^{bc}	6.80 (0.77)
Means	1.83 (0.13)	9.18 (0.32)	53.53 (1.09)	3.93 (0.55)	11.98 (1.52)	3.20 (0.17)	6.54 (0.26)
p variety	0.056	0.191	0.114	0.088	0.325	**0.001**	0.051
p year	**0.009**	**0.001**	**0.002**	0.572	**0.001**	0.696	**0.003**
Barley							
Variety means							
Vilde	1.42 (0.05)^{bc}	9.82 (0.70)^{bc}	56.03 (1.10)^{bc}	2.79 (0.54)^{bc}	12.99 (2.29)^{cde}	3.11 (0.14)^{bc}	2.84 (0.15)^{bc}
Kannas	1.45 (0.02)^c	10.38 (0.88)^c	53.88 (0.18)^{ab}	2.24 (0.65)^{abc}	14.00 (1.65)^{de}	3.60 (0.10)^d	2.74 (0.10)^{abc}
Vilgott	1.47 (0.06)^c	9.85 (0.89)^{bc}	53.41 (0.78)^a	1.59 (0.60)^{ab}	16.66 (2.37)^e	3.45 (0.15)^{cd}	2.84 (0.05)^{bc}
Bere	2.19 (0.39)^e	11.05 (0.18)^c	54.63 (1.17)^a	3.44 (0.20)^c	13.76 (1.79)^{de}	2.27 (0.07)^a	3.13 (0.17)^c
Concerto	1.00 (0.08)^a	8.41 (0.58)^a	59.24 (0.72)^d	0.98 (0.72)^a	8.48 (1.14)^{abc}	2.95 (0.08)^b	2.17 (0.20)^a
Waggon	1.31 (0.12)^{abc}	8.22 (0.68)^a	58.56 (1.50)^{cd}	1.33 (0.20)^a	9.99 (1.87)^{bcd}	3.07 (0.10)^b	2.47 (0.15)^{ab}
Means	1.47 (0.16)	9.62 (0.45)	55.96 (1.00)	2.06 (0.38)	12.65 (1.21)	3.08 (0.19)	2.70 (0.14)
p variety	**0.006**	**0.001**	**0.002**	**0.024**	**0.008**	**0.001**	**0.004**
p year	0.730	**0.001**	0.570	0.073	**0.010**	**0.013**	0.770

For variety means of each type of cereal, different letters down the column indicate significant differences between varieties at $p < 0.05$. Variety means were calculated across the 3 growing seasons. Values in brackets are standard errors.
p variety and p year are the level of significance of these factors in the ANOVA table.
Analysed by two-way ANOVA with variety and year as treatment factors. When the effect of variety was significant post-hoc *t*-test was conducted to compare treatment means. Significant differences are highlighted in bold.

Table 3
Abundant mineral composition (mg/100 g) of oat and barley flour of varieties grown in Orkney, between 2012 and 2014.

	Mg	P	K	Ca	Na	Mn	Fe	Cu	Zn
Oats									
Variety									
Haga	127.4 (5.9)[cd]	423.3 (17.1)[b]	447.5 (9.3)	71.7 (1.5)[c]	12.6 (2.7)	4.96 (0.08)	4.38 (0.34)	3.82 (0.37)[bc]	3.07 (0.15)[ab]
Belinda	107.3 (5.2)[ab]	361.1 (17.0)[ab]	416.0 (22.0)	49.7 (1.3)[a]	14.3 (3.1)	3.70 (0.40)	3.95 (0.08)	3.67 (0.96)[c]	2.80 (0.25)[ab]
Betania	108.5 (3.8)[ab]	372.9 (10.8)[ab]	387.6 (35.0)	55.6 (3.96)[abc]	12.7 (2.7)	4.14 (0.10)	4.28 (0.62)	4.56 (0.37)[c]	3.35 (0.17)[bc]
Canyon	108.9 (3.5)[abc]	373.3 (5.6)[ab]	443.1 (32.3)	50.9 (4.2)[a]	11.7 (1.5)	3.53 (0.01)	4.02 (0.29)	4.47 (0.38)[c]	2.59 (0.12)[ab]
Firth	97.5 (8.1)[a]	344.1 (31.7)[a]	402.2 (31.0)	42.8 (1.2)[a]	14.6 (0.9)	3.17 (0.17)	3.76 (0.39)	2.74 (0.24)[ab]	2.36 (0.23)[a]
Lennon	105.9 (5.2)[ab]	355.5 (9.6)[ab]	352.5 (11.1)	59.2 (5.1)[bc]	9.7 (1.8)	4.91 (0.17)	3.95 (0.20)	1.42 (0.27)[a]	2.21 (0.21)[a]
Means	109.3 (4.5)	371.7 (151.7)	408.2 (166.6)	54.9 (22.4)	12.6 (5.1)	4.06 (0.03)	3.95 (0.16)	3.45 (0.49)	2.73 (0.17)
p variety	**0.009**	**<0.001**	0.054	**0.020**	0.185	0.066	0.469	**<0.001**	**0.013**
Annual means									
2012	109.2 (4.1)[ab]	379.6 (12.8)[ab]	379.3 (19.9)[a]	49.1 (4.2)[a]	14.5 (1.4)	4.26 (0.32)	3.91 (0.37)	3.74 (0.75)	3.15 (0.21)
2013	101.1 (5.4)[a]	342.7 (16.5)[a]	396.8 (16.7)[a]	56.5 (5.0)[a]	9.8 (1.6)	3.98 (0.48)	4.12 (0.44)	3.01 (0.52)	2.42 (0.2)
2014	118.4 (4.8)[b]	395.1 (12.9)[b]	456.2 (20.4)[b]	59.1 (3.7)[a]	14.4 (4.7)	4.09 (1.71)	3.80 (1.53)	3.95 (1.44)	2.64 (0.99)
p year	**0.005**	**0.006**	**<0.001**	0.195	0.340	0.190	0.603	0.094	0.153
Barley									
Variety means									
Vilde	111.4 (5.5)	371.0 (18.0)[ab]	479.7 (27.4)	32.4 (2.4)	15.5 (1.7)[bc]	1.49 (0.14)[bc]	3.59 (0.32)	1.35 (0.32)[ab]	2.43 (0.43)[abc]
Kannas	123.7 (9.4)	416.0 (38.0)[ab]	559.4 (54.8)	41.7 (3.4)	17.4 (1.7)[bc]	1.84 (0.16)[c]	5.48 (0.35)	2.38 (0.39)[b]	3.17 (0.21)[bc]
Vilgott	107.2 (9.8)	352.0 (28.1)[a]	474.6 (39.8)	28.8 (3.1)	12.8 (3.3)[abc]	1.53 (0.18)[abc]	4.67 (0.97)	1.66 (0.38)[ab]	2.44 (0.35)[ab]
Bere	131.2 (14.5)	472.1 (52.8)[b]	498.3 (53.3)	43.2 (5.9)	16.8 (2.6)[bc]	1.92 (0.18)[bc]	6.48 (0.12)	3.88 (0.53)[b]	3.72 (0.21)[c]
Concerto	122.3 (11.6)	354.7 (18.7)[a]	477.8 (31.4)	36.3 (1.1)	8.5 (3.5)[a]	1.29 (0.09)[a]	4.84 (0.43)	1.88 (0.36)[ab]	2.10 (0.47)[a]
Waggon	104.0 (10.4)	355.2 (18.6)[a]	479.6 (24.9)	40.6 (6.3)	7.6 (2.3)[a]	1.53 (0.18)[ab]	4.61 (0.59)	1.88 (0.34)[ab]	2.41 (0.34)[ab]
Means	116.6 (47.6)	386.8 (157.9)	494.9 (202.0)	37.2 (15.2)	13.1 (5.3)	1.60 (0.09)	4.95 (0.39)	2.17 (0.37)	2.71 (0.25)
p variety	0.128	**0.045**	0.289	0.292	**0.018**	**0.013**	0.367	**0.004**	**<0.001**
Annual means									
2012	115.9 (3.7)[a]	384.5 (12.4)[a]	477.9 (8.7)[a]	36.8 (1.6)[ab]	14.3 (1.0)	1.77 (0.16)[b]	5.96 (0.47)	2.79 (0.38)	3.29 (0.13)[b]
2013	98.6 (4.7)[a]	337.3 (16.2)[a]	444.6 (16.6)[a]	31.1 (1.6)[a]	10.2 (4.2)	1.29 (0.52)[a]	4.49 (1.82)	1.33 (0.50)	2.04 (0.84)[a]
2014	144.3 (8.3)[b]	474.1 (40.9)[b]	605.6 (28.7)[b]	44.9 (4.5)[b]	14.4 (5.8)	1.66 (0.70)[b]	4.97 (2.04)	2.35 (1.00)	2.95 (1.27)[b]
p year	**<0.001**	**0.007**	**<0.001**	**0.016**	0.312	**0.032**	0.160	0.056	**0.015**

For variety and annual means of each type of cereal, different letters down the column indicate significant differences at $p < 0.05$. Variety means were calculated across the 3 growing seasons, while annual means were calculated for the 6 varieties grown each year. Values in brackets are standard errors.
p variety and p year are the level of significance of these factors in the table. Significant differences are highlighted in bold.
Analysed by two-way ANOVA with variety and year as treatment factors. When the effect of variety was significant post-hoc *t*-test was conducted to compare treatment means.

which is particularly desirable in a malting barley variety like Concerto.

The levels of NDF and β-glucan within oats and barley (NDF, 5–24 g per 100 g; β-glucan, 2–5 g per 100 g) corresponded to the ranges previously reported (Andersson et al., 2008; Ward et al., 2008; Doehlert et al., 2013) and the ranges of β-glucan in the two cereals were similar. Bere barley and Haga oats both had particularly low β-glucan content (Bere, 2.27 g per 100 g; Haga, 2.59 g per 100 g) and were both early maturing varieties. The Scandinavian variety Kannas had the highest β-glucan content of all the barley varieties (3.60%), was early maturing and gave reasonable yields. Modern Scandinavian varieties could therefore be valuable crops both nutritionally and agronomically for northern maritime areas. Oat β-glucan content did not vary significantly between years, and other studies have indicated that environment may be more important in determining the molecular weight of β-glucan rather than the total content (Andersson and Börjesdotter, 2011).

Previous studies in oats and barley (MacArthur and D'Appolonia, 1979; Chatterton et al., 2006) reported free sugar to be less than 2.3 g per 100 g, while we found values as high as 5.63 g per 100 g in oats and 3.44 g per 100 g in barley. However, free sugars are often either unreported or are contained within the total carbohydrate value which includes starch and free sugars. The mean total of all the macronutrients was between 92 and 106%. Analysis of the macronutrient content of varieties averaged over years showed significant differences (see *p* year in Table 2; mean values for each year are given in Table 6) for ash, protein, starch, NDF and fat in oats and for protein, NDF, and β-glucan in barley ($p < 0.05$). The difference in sugar between years in barley was nearly significant ($p = 0.073$). It is likely that some of these differences were due to annual variations in the weather which are considered later. The ash component is thought to contain many of the micronutrients and the ranges encountered were 1.6–2.5 g per 100 g in oats and 1.0–2.2 g per 100 g in barley.

In common with results from other research on barley in northern areas (Peltonen-Sainio et al., 2012), there was a significant negative correlation between protein and both yield ($p < 0.05$; correlation coefficient, −0.492) and TKW ($p < 0.01$; correlation coefficient, −0.742) for barley. Particularly high grain protein content and low yields and low TKW occurred in 2012 which may have been caused by the low growing season temperature and low sunshine hours in July and August limiting photosynthesis and starch accumulation more than nitrogen uptake. This contrasts with drier regions, where high grain protein is associated with water stress pre-anthesis, or during grain filling (Bertholdsson, 1999). The negative correlation between yield and protein was linked to the finding that the highest yielding varieties were those with a high starch and low protein content (Waggon and Concerto) while the lowest yielding varieties tended to be those with low starch and high protein content (Bere and Kannas). Previous studies have shown TKW to be both positively and negatively associated with β-glucan (Zhou et al., 1999; Andersson and Börjesdotter, 2011), but no significant correlation was found in the Orkney trial for either oats or barley. Although the design of the trials did not allow

Table 4
Macronutrient composition (g/100 g) of oat and barley flour of varieties grown at different locations between 2012 and 2014.

Cereal/Variety	Location	Ash	Protein	Starch	Sugar	NDF	β-glucan	Fat
Oats								
Canyon	Orkney	1.82 (0.15)	8.97 (0.59)	53.74 (2.72)	3.06 (0.73)	10.16 (3.34)	3.23 (0.01)	6.47 (0.29)
	Berwick	1.47 (0.40)	9.10 (0.49)	50.91 (2.23)	3.77 (0.63)	13.20 (2.44)	3.53 (0.11)	4.62 (1.30)
	Morfa	1.82 (0.19)	9.41 (1.28)	49.90 (5.15)	3.91 (0.84)	13.94 (6.27)	3.43 (0.20)	6.20 (0.25)
Firth	Orkney	1.56 (0.13)	7.87 (0.63)	54.17 (4.34)	4.43 (0.54)	14.39 (5.38)	2.86 (0.07)	6.27 (0.24)
	Berwick	1.77 (0.04)	8.83 (1.15)	53.26 (5.44)	5.08 (1.40)	14.40 (7.37)	3.17 (0.11)	5.44 (0.18)
	Morfa	1.44 (0.14)	10.38 (0.80)	57.64 (2.21)	4.07 (0.80)	6.53 (2.87)	3.28 (0.12)	6.06 (0.05)
Lennon	Orkney	1.68 (0.16)	9.19 (0.93)	53.06 (3.95)	5.11 (1.08)	11.40 (4.54)	3.33 (0.11)	6.80 (0.77)
	Berwick	1.66 (0.08)	10.61 (0.37)	61.11 (0.39)	4.85 (0.83)	3.86 (0.80)	3.82 (0.25)	8.26 (0.33)
	Morfa	1.60 (0.06)	10.29 (0.56)	60.42 (1.25)	5.61 (0.89)	3.49 (0.79)	3.52 (0.20)	8.25 (0.14)
Variety means								
Canyon		1.70 (0.12)	9.16 (0.13)	51.52 (1.15)[a]	3.58 (0.26)[a]	12.43 (1.16)	3.40 (0.11)[b]	5.76 (0.58)[a]
Firth		1.59 (0.09)	9.03 (0.73)	55.02 (1.33)[ab]	4.53 (0.29)[ab]	11.77 (2.62)	3.10 (0.10)[a]	5.92 (0.25)[a]
Lennon		1.65 (0.02)	10.03 (0.45)	58.20 (2.58)[b]	5.19 (0.22)[b]	6.25 (2.58)	3.54 (0.19)[b]	7.77 (0.48)[b]
Location means								
Orkney		1.69 (0.08)	8.68 (0.41)	53.65 (0.32)	4.20 (0.60)	11.98 (1.43)	3.14 (0.14)[a]	6.51 (0.38)
Berwick		1.63 (0.09)	9.51 (0.55)	55.10 (3.08)	4.57 (0.40)	10.49 (3.33)	3.51 (0.19)[b]	6.11 (1.10)
Morfa		1.62 (0.11)	10.03 (0.31)	55.98 (3.15)	4.53 (0.54)	7.99 (4.18)	3.41 (0.07)[b]	6.84 (0.69)
Year means								
2012		1.39 (0.12)[a]	10.72 (0.26)[b]	60.55 (0.91)[b]	3.85 (0.44)	3.16 (0.82)[a]	3.26 (0.08)[a]	6.08 (0.63)
2013		1.79 (0.06)[b]	9.06 (0.38)[a]	51.21 (2.02)[a]	4.84 (0.32)	14.80 (2.33)[b]	3.49 (0.14)[b]	6.57 (0.34)
2014		1.78 (0.08)[b]	8.32 (0.43)[a]	53.47 (1.78)[b]	4.21 (0.76)	12.06 (2.27)[b]	3.34 (0.08)[ab]	6.80 (0.34)
p Variety		0.529	0.086	**0.014**	**0.039**	0.051	**0.004**	**0.001**
p Location		0.984	0.123	0.998	0.716	0.860	**0.011**	0.339
p Year		**0.029**	**0.001**	**0.003**	0.155	**0.004**	**0.035**	0.124
Barley								
Concerto	Orkney	1.00 (0.08)	8.41 (0.58)	59.24 (0.72)	0.98 (0.72)	8.48 (1.14)	2.95 (0.08)	2.17 (0.20)
	Dundee	0.91 (0.12)	7.97 (0.36)	61.77 (1.83)	1.94 (0.55)	6.58 (1.36)	2.80 (0.13)	2.49 (0.16)
Waggon	Orkney	1.31 (0.12)	8.22 (0.66)	58.56 (1.50)	1.33 (0.20)	9.99 (1.87)	3.07 (0.10)	2.47 (0.15)
	Dundee	1.02 (0.17)	7.82 (0.45)	60.65 (3.10)	2.25 (0.51)	7.64 (3.41)	3.11 (0.20)	2.47 (0.14)
Variety means								
Concerto		0.96 (0.07)	8.19 (0.32)	60.51 (1.04)	1.46 (0.46)	7.53 (0.90)	2.88 (0.08)	2.33 (0.13)
Waggon		1.11 (0.08)	8.13 (0.47)	58.87 (1.61)	1.71 (0.34)	9.63 (1.86)	3.09 (0.02)	2.54 (0.08)
Location means								
Orkney		1.09 (0.06)	8.42 (0.47)	58.16 (0.60)	1.07 (0.33)	10.05 (1.04)	2.99 (0.08)	2.39 (0.14)
Dundee		0.97 (0.10)	7.89 (0.26)	61.21 (1.63)	2.10 (0.34)	7.11 (1.66)	2.95 (0.13)	2.48 (0.09)
Year means								
2012		0.85 (0.12)[a]	9.15 (0.44)[b]	61.75 (2.14)	1.95 (0.67)	5.53 (1.66)[a]	2.92 (0.12)	2.38 (0.24)
2013		1.00 (0.04)[b]	7.89 (0.15)[ab]	57.27 (0.87)	1.74 (0.28)	8.97 (1.15)[ab]	3.14 (0.11)	2.49 (0.05)
2014		1.07 (0.05)[ab]	7.43 (0.24)[a]	60.04 (1.06)	1.07 (0.40)	11.24 (1.48)[b]	2.87 (0.15)	2.44 (0.09)
p Variety		0.073	0.854	0.318	0.653	0.170	0.252	0.252
p Location		0.117	0.199	0.089	0.098	0.072	0.784	0.616
p Year		**0.024**	**0.021**	0.125	0.415	**0.036**	0.383	0.873

For each type of cereal, year means in the same column followed by the same letter were not significantly different at $p < 0.05$.
Data for each cereal variety in each location are means based on three growing seasons, with standard errors given in brackets. Where standard errors were less than 0.05, these have not been given.
p variety, p Location and p year are the level of significance of these factors in the table.
Data were analysed by three way ANOVA with variety, year and location as treatment factors. When one of the main effects was significant ($p < 0.05$) post hoc *t*-test was conducted to compare treatment means. Significant differences are highlighted in bold; Abbreviations: NDF Neutral Detergent Fibre; Berwick, Berwick-upon-Tweed.

a statistical comparison of oats and barley, averaged over varieties and years the concentrations of fats and sugar were higher in oats, while NDF and starch were higher in barley.

3.3. Mineral composition of oats and barley grown in Orkney

The content of abundant minerals in grains of oat and barley varieties grown in Orkney is summarised in Table 3 and that of several trace elements in Supplementary Table S5. The most abundant minerals detected were potassium, phosphorus, magnesium, calcium and sodium while manganese, iron, copper and zinc were all present in low, relatively similar amounts (<6 mg per 100 g for both oats and barley). Other studies (Peterson et al., 1975; Doehlert et al., 2013) have also reported magnesium, phosphorus, potassium and calcium as the most abundant minerals in oats and barley. The high levels of phosphorus and potassium probably reflect their application in fertilisers. The trace elements chromium, cobalt, nickel, and molybdenum were all present at less than 2 μg per 100 g of cereal, while negligible amounts of selenium, cadmium and lead were detected. There were significant differences between varieties of oats for magnesium, phosphorus, calcium, copper, zinc, and molybdenum ($p < 0.05$) and varieties of barley for phosphorus, sodium, manganese, copper, and zinc ($p < 0.05$). However, differences in the minerals manganese, copper, zinc, nickel, and molybdenum were small and were based upon measurements of very low levels (less than 4 mg per 100 g in most cases). In both oats and barley, some varieties seemed better at accumulating minerals than others, with the highest concentrations often occurring in Haga, Bere and Kannas and the lowest in Vilgott and Firth.

In several cases, the mineral content of oat and barley varieties was significantly affected by the year. There were significant differences in the annual means for magnesium, phosphorus, potassium and calcium for oats ($p < 0.05$), and for all minerals except iron, nickel and chromium for barley ($p < 0.05$). Since soil analyses showed only small differences in soil mineral content between years (Supplementary Table S2), this may reflect differences in the

Table 5
Mineral composition (mg/100 g) of oat and barley flour of varieties grown at different locations between 2012 and 2014.

Cereal/Variety	Location	Mg	P	K	Ca	Na	Mn	Fe	Cu	Zn
Oats										
Canyon	Orkney	109.9 (3.5)	373.3 (6.4)	443.1 (37.3)	50.8 (4.9)	11.72 (1.70)	3.53 (0.02)	4.02 (0.34)	4.48 (0.44)	2.12 (0.55)
	Berwick	96.0 (8.5)	333.6 (16.3)	410.7 (31.5)	55.2 (7.0)	4.08 (1.61)	4.11 (0.69)	3.44 (0.53)	4.06 (1.90)	2.05 (0.55)
	Morfa	102.1 (10.3)	332.1 (39.6)	366.5 (31.9)	56.4 (6.9)	7.04 (2.14)	3.54 (0.35)	3.45 (0.60)	4.63 (1.28)	2.05 (0.55)
Firth	Orkney	97.5 (8.1)	344.3 (36.6)	402.4 (35.7)	42.7 (1.4)	14.59 (1.06)	3.17 (0.19)	3.76 (0.34)	2.74 (0.28)	2.36 (0.27)
	Berwick	108.9 (11.0)	389.5 (27.2)	442.1 (46.4)	62.9 (10.2)	2.48 (0.55)	4.73 (0.60)	4.20 (0.53)	1.48 (0.59)	1.89 (0.41)
	Morfa	102.2 (12.4)	365.2 (49.7)	382.6 (44.5)	48.8 (5.2)	6.93 (1.51)	3.25 (0.22)	3.78 (0.60)	2.88 (0.84)	2.18 (0.12)
Lennon	Orkney	105.9 (5.2)	355.5 (11.0)	352.5 (12.9)	59.1 (5.9)	9.72 (2.08)	4.91 (0.19)	3.95 (0.23)	1.42 (0.31)	1.82 (0.38)
	Berwick	89.0 (1.5)	330.1 (5.4)	352.3 (11.7)	56.4 (7.3)	1.77 (0.65)	4.60 (0.75)	3.85 (0.25)	0.60 (0.03)	2.57 (0.24)
	Morfa	103.0 (9.4)	332.7 (16.7)	309.4 (13.8)	63.5 (3.9)	5.60 (2.33)	4.57 (0.24)	3.55 (0.50)	1.30 (0.34)	1.67 (0.49)
Variety means										
Canyon		102.5 (2.9)	346.4 (13.1)	406.7 (22.2)^{b}	54.1 (1.6)^{a}	7.61 (2.22)	3.71 (0.51)^{a}	3.63 (0.19)	4.39 (0.17)^{b}	2.14 (0.02)
Firth		103.3 (3.7)	366.3 (13.5)	409.0 (17.4)^{b}	51.4 (5.9)^{a}	8.00 (3.54)	3.73 (0.19)^{a}	3.91 (0.14)	2.37 (0.44)^{a}	2.14 (0.14)
Lennon		99.3 (5.2)	340.4 (8.1)	338.0 (14.3)^{a}	59.6 (2.1)^{b}	5.69 (2.95)	4.69 (0.11)^{b}	3.78 (0.12)	1.11 (0.26)^{a}	2.02 (0.28)
Location means										
Orkney		104.2 (3.4)	357.6 (8.5)	399.3 (26.2)^{b}	50.9 (4.7)	12.01 (1.41)^{b}	3.87 (0.53)	3.91 (0.08)	2.88 (0.89)	2.09 (0.15)^{a}
Berwick		97.6 (5.5)	351.1 (19.2)	401.7 (26.3)^{b}	58.2 (2.4)	2.78 (0.68)^{a}	4.48 (0.19)	3.82 (0.22)	2.05 (1.04)	2.17 (0.20)^{b}
Morfa		102.4 (0.3)	343.3 (10.9)	353.8 (22.2)^{a}	56.2 (4.2)	6.52 (0.46)^{a}	3.78 (0.39)	3.59 (0.09)	2.94 (0.96)	1.97 (0.15)^{a}
Year means										
2012		90.4 (9.2)^{a}	336.9 (23.5)^{a}	352.8 (15.7)	44.5 (2.5)^{a}	6.87 (1.42)	3.98 (0.25)^{ab}	3.22 (0.23)^{a}	1.91 (0.42)^{a}	2.39 (0.11)^{b}
2013		99.2 (1.6)^{a}	332.1 (15.9)^{a}	370.9 (22.6)	60.0 (1.1)^{b}	5.66 (1.58)	3.69 (0.29)^{a}	3.91 (0.19)^{a}	2.21 (0.55)^{a}	1.41 (0.17)^{a}
2014		121.5 (2.0)^{b}	403.6 (4.1)^{b}	453.3 (28.6)	64.8 (4.1)^{b}	9.66 (1.56)	4.43 (0.30)^{b}	4.24 (0.17)^{b}	4.13 (0.72)^{b}	2.43 (0.11)^{b}
p Variety		0.739	0.590	0.027	0.003	0.132	<**0.001**	0.306	<**0.001**	0.299
p Location		0.293	0.314	**0.006**	0.177	**0.001**	0.062	0.246	0.886	**0.006**
p Year		<**0.001**	<**0.004**	0.448	<**0.001**	0.526	**0.005**	**0.003**	**0.004**	<**0.001**
Barley										
Concerto	Orkney	113.7 (5.6)	341.3 (10.5)	455.8 (18.5)	35.7 (1.0)	8.51 (4.05)	1.29 (0.11)	4.84 (0.50)	1.89 (0.42)	1.74 (0.26)
	Dundee	106.2 (6.8)	331.3 (33.8)	445.0 (34.9)	32.1 (1.6)	7.70 (3.51)	1.19 (0.21)	3.64 (0.36)	1.94 (0.35)	2.04 (0.35)
Waggon	Orkney	96.7 (4.3)	341.3 (6.1)	463.4 (13.6)	36.2 (2.8)	7.63 (2.27)	1.53 (0.18)	4.61 (0.59)	1.88 (0.34)	2.41 (0.34)
	Dundee	99.8 (6.1)	323.9 (17.9)	465.8 (27.3)	28.7 (2.2)	10.71 (7.39)	1.22 (0.24)	3.55 (0.72)	1.35 (0.21)	2.23 (0.39)
Variety means										
Concerto		109.9 (3.7)	336.3 (4.9)	450.4 (5.4)	33.9 (1.8)	8.11 (0.27)	1.24 (0.05)	4.24 (0.07)	1.92 (0.06)	1.89 (0.03)
Waggon		98.3 (1.6)	332.8 (8.8)	464.5 (1.2)	32.5 (3.7)	9.17 (2.56)	1.38 (0.03)	4.08 (0.06)	1.62 (0.03)	2.32 (0.05)
Location means										
Orkney		105.2 (8.5)	341.5 (0.2)	459.6 (3.8)	35.9 (0.2)	8.07 (0.43)	1.41 (0.12)	4.72 (0.12)^{a}	1.88 (0.03)	2.08 (0.33)
Dundee		103.0 (3.2)	327.6 (3.7)	455.4 (10.3)	30.4 (1.7)	9.21 (1.50)	1.21 (0.02)	3.59 (0.04)^{b}	1.65 (0.29)	2.13 (0.09)
Year means										
2012		104.5 (6.1)^{a}	339.9 (17.4)^{a}	461.8 (17.3)^{a}	31.8 (2.3)	9.64 (3.39)	1.37 (0.17)	4.62 (0.85)	2.27 (0.23)^{b}	2.62 (0.34)^{b}
2013		139.2 (4.3)^{b}	309.2 (14.8)^{a}	436.0 (24.6)^{a}	30.9 (1.0)	5.03 (1.24)	1.04 (0.87)	3.72 (0.26)	1.09 (0.92)^{a}	1.42 (0.16)^{a}
2014		95.3 (3.8)^{a}	416.9 (0.4)^{b}	568.9 (5.5)^{b}	43.7 (1.9)	10.93 (5.38)	1.43 (0.87)	4.47 (0.34)	1.89 (0.18)^{b}	2.52 (0.77)^{b}
p Variety		0.118	0.516	0.420	0.863	0.768	0.692	0.908	0.111	0.834
p Location		0.653	0.870	0.933	0.242	0.642	0.430	**0.030**	0.268	0.608
p Year		**0.002**	**0.016**	**0.014**	0.095	0.271	0.197	0.302	**0.006**	**0.027**

For each type of cereal, variety or location means in the same column followed by the same letter were not significantly different at $p < 0.05$.
Data for each cereal variety in each location are means based on three growing seasons with standard errors in brackets. Where standard errors were less than 0.05, these have not been given.
p variety and p location are the level of significance of these factors in the tables.
Data were analysed by three way ANOVA with variety, year and location as treatment factors. When one of the main effects was significant ($p < 0.05$) post hoc *t*-test was conducted to compare treatment means. Significant differences are highlighted in bold; Abbreviations: Berwick, Berwick-upon-Tweed.

availability of soil nutrients or the growth of roots between years.

3.4. Influence of location and weather on the nutrient composition of oats and barley

The nutritional content of some of the oat and barley varieties grown in Orkney was compared with that of the same varieties grown further south in the UK between 2012 and 2014. Tables 4 and 5, respectively, summarise the macronutrient and mineral composition of the oat varieties Canyon, Firth and Lennon grown in Orkney, Morfa and Berwick-upon-Tweed and the barley varieties Concerto and Waggon grown in Orkney and Dundee.

There were significant differences between oat varieties for β-glucan (lowest in Firth), starch (highest in Lennon), sugar (lowest in Canyon) and fat content (highest in Lennon) ($p < 0.05$) and near-significant differences for protein ($p = 0.086$), NDF ($p = 0.051$), starch ($p = 0.091$) and sugar ($p = 0.074$). The only macronutrient differing significantly between locations was β-glucan ($p = 0.011$), which was lowest for all varieties when grown in Orkney. These results suggest that the Orkney environment may not be optimal for growing oats for a high β-glucan market. Nevertheless, this disadvantage might be mitigated by careful variety selection – for example, the Scandinavian variety Betania had a significantly higher β-glucan content than any of the other varieties grown in Orkney (Table 2), with concentrations similar to the highest values for oats grown further south. However, the relationship between climate and β-glucan is complex (Redaelli et al., 2013) and studies over more seasons, more varieties and on other soils are required to investigate this further. The ash, protein, starch, NDF and β-glucan content of oats was also affected by the growing year ($p < 0.05$). Comparing the barley varieties grown in Orkney and Dundee, no significant differences were detected for either variety or location, although several differences were almost significant (Table 4). Year, however, influenced several macronutrients in barely including ash, protein, and NDF ($p < 0.05$). Previous studies have shown that nutritional content can be affected by differences between growing

Table 6
Annual averages for the macronutrient composition (g/100 g of flour) of oat and barley varieties grown at different trial locations and correlation coefficients for macronutrient content on rainfall and degree days at each location.

Cereal/Location/Year	Rainfall (mm)	Degree days	Ash	Protein	Starch	Sugar	NDF	β-glucan	Fat
Oats									
Orkney									
2012	479	1821	1.58 (0.18)	11.20 (0.28)	58.16 (1.42)	4.32 (0.64)	3.57 (0.97)	3.31 (0.17)	6.19 (0.65)
2013	438	1863	2.00 (0.10)	8.69 (0.98)	48.14 (2.31)	4.12 (0.68)	18.26 (1.42)	3.29 (0.23)	7.11 (0.89)
2014	392	1862	1.87 (0.21)	8.33 (0.83)	53.49 (2.02)	5.23 (1.21)	13.21 (1.74)	3.08 (0.13)	7.34 (0.29)
Correlation coefficient, rainfall ($n = 18$)			−0.341	0.826	0.646	−0.249	−0.740	0.009	−0.668
Correlation coefficient, degree days ($n = 18$)			0.474	−0.793	−0.740	0.181	0.830	−0.032	0.669
p-value, correlation coefficient rainfall			0.179	**<0.001**	**0.005**	0.334	**<0.001**	0.972	**0.003**
p-value, correlation coefficient degree days			0.054	**<0.001**	**<0.001**	0.486	**<0.001**	0.902	**0.003**
Berwick-upon-Tweed									
2012	637	2369	1.37 (0.35)	10.38 (0.39)	59.49 (2.25)	4.26 (1.17)	5.01 (1.82)	3.31 (0.15)	5.44 (1.91)
2013	230	2110	1.71 (0.09)	9.97 (0.44)	54.40 (4.15)	5.48 (0.48)	10.60 (4.18)	3.80 (0.27)	6.27 (0.69)
2014	327	1886	1.82 (0.02)	8.20 (0.97)	51.40 (4.92)	4.01 (1.17)	15.86 (6.63)	3.38 (0.19)	6.61 (0.98)
Correlation coefficient, rainfall ($n = 9$)			−0.482	0.324	0.422	−0.224	−0.414	−0.472	−0.232
Correlation coefficient, degree days ($n = 9$)			−0.493	0.698	0.494	0.117	−0.552	−0.028	−0.239
p-value, correlation coefficient rainfall			0.189	0.394	0.257	0.561	0.268	0.199	0.561
p-value, correlation coefficient degree days			0.177	**0.036**	0.176	0.763	0.123	0.942	0.534
Morfa									
2012	568	2039	1.38 (0.18)	11.52 (0.15)	60.64 (1.35)	3.88 (0.90)	2.93 (0.65)	3.35 (0.19)	7.00 (0.65)
2013	236	1795	1.84 (0.16)	8.65 (0.91)	51.42 (6.12)	5.21 (0.89)	14.14 (6.57)	3.38 (0.24)	6.72 (0.88)
2014	301	1770	1.61 (0.10)	9.47 (0.11)	54.96 (1.89)	3.95 (1.11)	8.43 (2.00)	3.49 (0.02)	6.82 (0.60)
Correlation coefficient, rainfall ($n = 9$)			−0.621	0.841	0.567	−0.279	−0.593	−0.760	0.111
Correlation coefficient, degree days ($n = 9$)			−0.540	0.790	0.515	−0.189	−0.513	−0.726	0.102
p-value, correlation coefficient rainfall			0.073	**0.044**	0.111	0.467	0.092	**0.017**	0.776
p-value, correlation coefficient degree days			0.137	**0.011**	0.156	0.624	0.157	**0.026**	0.793
Barley									
Orkney									
2012	479	1821	1.31 (0.11)	11.00 (0.39)	55.83 (1.01)	1.53 (0.37)	10.88 (1.44)	3.38 (0.17)	2.80 (0.22)
2013	438	1863	1.40 (0.18)	8.88 (0.35)	55.04 (2.49)	2.67 (0.12)	14.90 (3.02)	3.28 (0.21)	2.76 (0.12)
2014	392	1862	1.39 (0.11)	8.9 (0.47)	55.61 (0.99)	1.76 (0.45)	14.09 (1.15)	3.03 (0.15)	2.69 (0.15)
Correlation coefficient, rainfall ($n = 18$)			0.121	0.670	0.812	−0.171	−0.475	0.238	0.096
Correlation coefficient, degree days ($n = 18$)			−0.123	−0.701	−0.111	0.272	0.518	−0.185	−0.079
p-value, correlation coefficient rainfall			0.633	**0.002**	0.749	0.496	**0.045**	0.339	0.704
p-value, correlation coefficient degree days			0.628	**0.001**	0.658	0.274	**0.027**	0.461	0.753
Dundee									
2012	550	1857	0.69 (0.00)	8.43 (0.09)	65.44 (0.39)	3.11 (0.12)	2.83 (1.06)	2.72 (0.05)	2.50 (0.28)
2013	293	1837	1.17 (0.08)	8.15 (0.05)	56.91 (1.81)	1.57 (0.47)	10.92 (2.66)	3.21 (0.17)	2.50 (0.05)
2014	335	1967	1.05 (0.08)	7.10 (0.18)	61.29 (0.26)	1.63 (0.12)	7.59 (0.00)	2.94 (0.35)	2.45 (0.21)
Correlation coefficient, rainfall ($n = 6$)			−0.951	0.531	0.884	0.922	−0.862	−0.607	0.036
Correlation coefficient, degree days ($n = 6$)			0.123	−0.921	0.150	−0.314	−0.379	−0.125	−0.101
p-value, correlation coefficient rainfall			**0.003**	0.277	**0.019**	**0.008**	**0.027**	0.201	0.945
p-value, correlation coefficient degree days			0.816	**0.009**	0.776	0.543	0.943	0.813	0.849

Values are the average annual macronutrient content for each cereal at each site. Values in brackets are standard errors. Abbreviations: NDF Neutral Detergent Fibre.
n = number of data pairs.
Correlations with rainfall and degrees days with the macronutrient content for oat and barley varieties grown at different trial locations.
Significant differences are highlighted in bold where $p < 0.05$.

sites, variety and agronomic factors (Zhou et al., 1999; Doehlert et al., 2013; Redaelli et al., 2013; Sikora et al., 2013). It is possible that the environmental differences between the sites in this study may not have been diverse enough to result in larger differences in nutrient content.

For minerals, there were significant differences between oat varieties in potassium, calcium, manganese, and copper ($p < 0.05$) (Table 5). Potassium, sodium and zinc were significantly influenced by location ($p < 0.05$), with the potassium content being lowest at Morfa, the sodium content highest in Orkney and the zinc content highest at Berwick-upon-Tweed (Table 5). In the case of sodium, this probably resulted from the Orkney trial site being only about 1 km from the sea. The difference in zinc content between the sites was low (less than 0.2 mg) and should be interpreted with caution. The content of the following minerals also differed with harvesting year: magnesium, phosphorus, calcium, manganese, iron, copper and zinc. In most cases these were highest in 2014 and often lowest in 2012. In barley, the iron content was significantly higher ($p = 0.03$) in Orkney compared to Dundee and may reflect the high levels of iron which occurred in soils at this trial site (Supplementary Table S2). Analysis of trace mineral composition (Supplementary Table S6) identified few significant differences related to location or variety, with the exception of a higher content of molybdenum in Waggon than Concerto barley. The content of some minerals (phosphorus, potassium, magnesium, copper and zinc) in barley flour (Table 5) was also significantly affected by year, with the highest concentrations of phosphorus, potassium, calcium, sodium, and manganese found in 2014. It is likely that the high concentrations of some minerals which occurred in 2014 in both barley and oats is related to weather patterns but more years of data would be required to clarify this. Apart from a significantly lower β-glucan content in oats and minor differences in mineral content for both oats and barley, these analyses indicated that the nutritional content of oats and barley in Orkney was not very different from that of the same varieties grown at more southerly UK sites. Nevertheless, the few near-significant differences may justify further investigation.

The annual macronutrient content of oats and barley averaged over varieties at each site together with growing season rainfall and degree days is shown in Table 6. There were several significant correlations between rainfall and degrees days and nutrient content. Rainfall had a strong positive correlation with protein concentration for oats and barley in Orkney, and oats at Morfa. At these sites, protein concentrations were highest in the wettest year, 2012, and were lowest in the driest year (2014 in Orkney and 2013 at Morfa). Degree days, however, was negatively correlated with protein content for oats and barley in Orkney and barley at Dundee, but positively correlated with protein in oats grown in Berwick-upon-Tweed and Morfa. Weather factors were one of the principal drivers for a large environmental effect on grain protein concentration reported for oats and barley grown in Finland, and exceeded the effect of genotype (Peltonen-Sainio et al., 2012). In Orkney, the fat content of oats was correlated positively with degree days but negatively with rainfall. Starch and NDF content often showed the opposite relationships with rainfall and degree days. Rainfall showed a positive association with the starch content of oats grown in Orkney and barley grown in Dundee while, NDF was negatively correlated with rainfall for oats and barley grown in Orkney and barley in Dundee. In contrast, degree days was negatively correlated with starch but positively correlated with NDF for oats in Orkney. It can also be seen that the highest starch concentrations occurred in all trials in 2012 and were accompanied by particularly low levels of NDF. Conversely, the lowest starch contents mostly occurred in 2013 and were accompanied by the highest concentrations of NDF. Previously, Becker et al. (1995) and Tiwari and Cummins (2009) have suggested that non-starch polysaccharide synthesis competes for the same glucose molecules that are required for the biosynthesis of starch and therefore an increase in starch content may be at the expense of the fibre component (Thitisaksakul et al., 2012; Beckles and Thitisaksakul, 2013). It may therefore be that the opposite correlations which were found above between starch and NDF and weather variables, reflect this competition. The dynamic between starch and NDF may also go some way to explaining the relationship between rainfall, temperature and protein content. Carbohydrate makes up the largest proportion of the grain, and when weather conditions constrain starch and NDF synthesis, the proportion of protein within the grain increases. This would help to explain the negative correlations seen in Orkney between protein concentration and both yield and TKW.

Although significant correlations between β-glucan and rainfall and degree days were only found for oats grown at Morfa, significant differences between β-glucan attributable to location are reported in Table 4 for three varieties of oats. For these varieties, β-glucan was highest at Berwick-upon-Tweed (3.5 g/100 g) and lowest in Orkney (3.1 g/100 g). The main differences in growing season weather between these two locations were the higher rainfall and lower temperatures in Kirkwall. Differences were particularly marked during the months of grain filling and maturation (August to September) with much higher rainfall in Orkney (average, 203 mm for 2012 to 2014 compared with 141 mm at Berwick-upon-Tweed) and higher temperatures at Berwick-upon-Tweed (average, 14.5 °C compared with 13.0 °C in Orkney). Warmer, drier conditions were also found to favour β-glucan production by Andersson and Börjesdotter (2011), although the opposite has also been reported by Doehlert et al. (2013), while Redaelli et al. (2013) reported the highest β-glucan content under intermediate temperature and rainfall conditions. In barley, protein content is an important determinant of end-use with low protein and high starch especially desirable for malting. Data in Table 5 for Concerto and Waggon suggest that conditions in Orkney may favour a higher protein content than those in Dundee. Comparison of the weather data for the two sites from 2012 to 2014 showed a consistent pattern of lower rainfall in Orkney from May to July (average, 128 mm compared with 210 mm in Dundee), but higher rainfall from August to September (average, 203 mm compared with 109 mm in Dundee). Growing season average monthly temperatures were all higher in Dundee, but especially for the period May to July (average 11.7 °C in Orkney and 12.2 °C in Dundee).

4. Conclusions

Agronomy trials and detailed nutritional analyses were carried out for a diverse group of barley and oat varieties grown in Orkney and at other sites in the UK. There has been no previous report of the nutritional content of oats and barley grown in hyper-oceanic climates like Orkney's. These trials indicated that Scandinavian early maturing varieties of both oats and barley are suitable for growing in the north of Scotland and the nutritional analyses showed that some of these had significantly higher β-glucan content than the recommended UK varieties grown in the trial. Since Scandinavian varieties were not included in trials in more southerly locations where oat β-glucan contents were generally higher, it would be useful to test some of these varieties in these locations to assess the impact on β-glucan levels. Significant varietal differences were found in both oats and barley for most macronutrients and abundant minerals, demonstrating the importance of selecting varieties for specific end-uses. Weather conditions appeared to affect the nutrient content of the varieties, with the level of several nutrients varying from year to year. Future work should investigate the influence of weather factors before and after the grain filling period on nutritional content. It would also be valuable to screen a wider range of Scandinavian varieties for growing in the north of Scotland.

Compared with the other barley varieties, the Scottish landrace Bere, which has a tradition of use for milling into beremeal and also for brewing and distilling (Martin et al., 2009), had low β-glucan, but high fat, sugar and protein; it also contained the highest concentrations of several minerals. In spite of the weather-related challenges of growing oats and barley in Orkney, the nutritional analyses showed few statistically significant differences between the nutritional content of their grains from Orkney compared with those from trials in more southerly parts of the UK. The main exception was β-glucan, which was lower in Orkney oats. Although not significant, it was also noted in barley that protein tended to be higher in Orkney, which may make it harder to produce good quality malting barley. It is not clear to what extent the results from Orkney can be extrapolated to more northern maritime locations like Iceland, the Faroes and coastal Norway, but analyses of a small number of samples from the same varieties of barley grown in these areas in 2014 showed a higher sugar, but lower starch content in the samples from Orkney. It is therefore likely that differences will occur, and this is under investigation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jcs.2017.01.005.

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