PROJECT REPORT 308

FORECASTING WHEAT QUALITY AND THE BREADMAKING PREMIUM FROM THE NORTH ATLANTIC OSCILLATION

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by

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PART A: ABSTRACT

Those wheat varieties classified by NABIM as group 2 are dual-purpose varieties and can be managed for a feed or bread-making market. Growers currently use a wide range of intelligence in making management decisions aimed at feed or bread markets and the results of this project offer quality and premium forecasts to inform this process.

The pressure difference across the North Atlantic Ocean (The North Atlantic Oscillation or NAO) in the winter, influences the average specific weight and Hagberg falling number of the subsequent UK harvest. This report addresses the feasibility of forecasting specific weight, Hagberg falling number and breadmaking premium from the winter NAO, and presents forecasts for 3 years, 2001, 2002 and 2003.

In the development of the forecasting procedure, several published NAO indices and other climatic indices were compared. The NAO indices in the different winter months and other months of the year were also compared for their ability to forecast. It was found that the November and January NAO indices were the most useful for forecasting specific weight, and that the January and February indices were best for forecasting Hagberg. Specific weight forecasts are more reliable than those for Hagberg. The necessity for obtaining February indices early in March led to the development of a custom index from freely available gridded pressure data. The potential of forecasting with climatic indices from the preceding summer was examined but found to be of no value.

Forecasts were attempted for specific weight and Hagberg for individual regions and NABIM groups. These were of limited success and were discontinued. The effect on the forecasts of varietal mixture differences between years was tested and found unimportant.

Studies of the mechanism of the relationship have fallen into two parts. (a) The role of winter climate related to the winter NAO in determining the rate of development of the crop. (b) The direct effect of the winter NAO on summer weather, and the effect of this on the development of the crop. Only the second is of importance both for specific weight and Hagberg. The influence of the winter NAO on the climate of the following summer remains poorly understood but is being increasingly recognised.

Models for bread-making premium show that the major determinant of premium is grain quality, specific weight and Hagberg together accounting for 72% of the year-to-year differences in the premium expressed as a percentage of the feed price. Proportion of bread-making varieties grown, import price of wheat and wheat stocks are smaller additional contributors. Forecasts of premium can be made from the NAO alone, since it is a predictor of quality, and quality is the main determinant of the premium.

PART B: SUMMARY REPORT

1. Introduction

The suitability of wheat for breadmaking depends in large part on the levels of the quality criteria specific weight and Hagberg falling number. These are substantially influenced by the weather during grain development. This project was initiated to substantiate an observation that specific weight and Hagberg falling number were closely related to the preceding winter North Atlantic Oscillation (Fig. 1), and to develop a forecasting procedure. Both growers and millers could benefit from any forward intelligence which could be provided by such a forecasting method.

The ability to forecast breadmaking premium (the difference between the prices per tonne of breadmaking and feed wheat) is also considered, since this information would be of primary interest to growers in planning crop management.

This report addresses the climatic and physiological basis of the mechanism of this long-lead relationship using a combination of crop modelling and regression analysis of quality and climatic data.

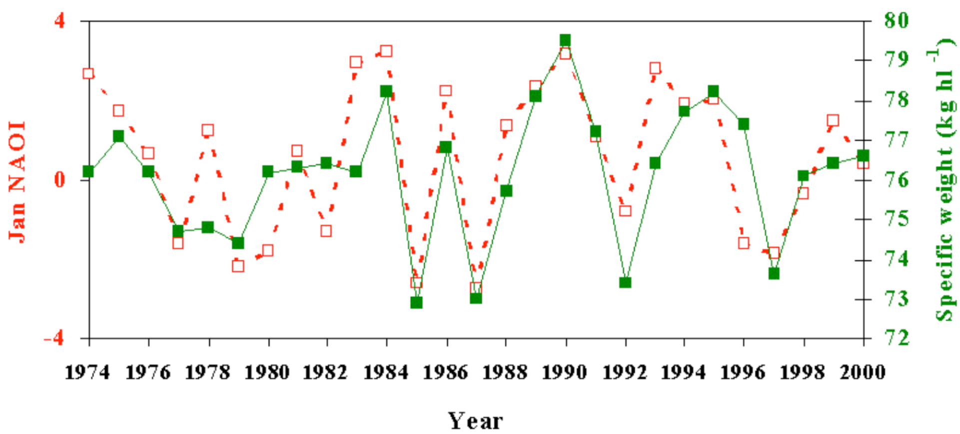

Figure 1. Time series of the winter North Atlantic Oscillation and UK specific weight.

2. Forecasting national quality

Forecasts of UK average specific weight and Hagberg falling number were developed using regression models with the NAO index as the explanatory variable.

2.1 Screening of NAO and other indices

The NAO is the most important large scale pressure pattern in the North Atlantic region and is particularly prevalent in the winter. Essentially it reflects the relative depth of the Iceland low and the Azores high pressure areas. A number of NAO indices are available from researchers, which measure the phenomenon in slightly different ways. Some of these are based on two stations (eg Jones' index is based on the pressure difference between Stykkisholmur (Iceland) and Gibraltar; Hurrell's index uses the pressure difference between Stykkisholmur and Lisbon). Rogers' index uses pressure data from Akureyri (Iceland) and Ponta Delgada (Azores). The National Oceanic and Atmospheric Administration – Climate Prediction Center (NOAA-CPC) index is based on a multivariate analysis of gridded pressure patterns across the North Atlantic.

A wide range of these NAO indices was screened for their value as predictors of wheat quality. Other climate indices were also screened, including the Arctic Oscillation Index, Southern Oscillation indices, other northern hemisphere indices, snow cover and sea-surface temperature indices. Various lag periods and monthly and seasonal indices were also compared.

The most effective predictors were Rogers' NAO index for the preceding November and the current January for forecasting specific weight; and the current January and February for Hagberg falling number.

2.2 Method for forecasting wheat quality

A number of the NAO indices were effective for forecasting (particularly Rogers' index) but these are not maintained up to date by their originators. For forecasting purposes we need to have the January index early in February and the February index early in March. Pressure data were taken from the NOAA-NCEP-NCAR dataset. These data are very rapidly updated and are suitable for forecasting purposes.

Mean sea-level pressures over a large rectangle near Iceland were averaged (30°W to 0°W, 60°N to 70°N) as were those over a rectangle near the Azores (50°W to 5°W, 30°N to 40°N). January MSL pressures were standardised over the period 1948-2000 and the northern pressure value subtracted from the southern for each year. This forecasting procedure is considered in greater detail in Technical papers 1 and 2.

2.3 The forecasts

National forecasts were carried out for the harvests of 2001, 2002 and 2003 for specific weight (Table 1) and Hagberg falling number (Table 2). It is clear that for the years 2001 and 2002, the forecasts for specific weight were very close to the measured values (Table 1). It is also evident that the forecast values for the three years are very similar and very close to 76 kg hl^{-1}, reflecting the similarity of the January NAO index for the three years.

Table 1. Comparison of forecast and measured values of specific weight (kg hl^{-1}). 75% confidence intervals are given for the forecast.

	Forecast	Measured
2001	76.0 ± 1.0	75.8
2002	76.3 ± 0.9	76.2
2003	76.0 ± 0.7	

On the other hand, the forecasts of Hagberg falling number have been less reliable. In 2002, the measured value for Hagberg was outside the lower forecast limit. Moreover, the forecast values for the three years are less similar than those for specific weight, because February NAO index has changed more than the January index over the three years.

Table 2. Comparison of forecast and measured values of Hagberg falling number (s). 75% confidence intervals are given for the forecast.

	Forecast	Measured
2001	239 ± 32	251
2002	281 ± 32	248
2003	255 ± 31	

These forecasts were posted on the project website at http://www.harper-adams.ac.uk/wheatqualityforecasts/.

3. Forecasts of regional quality

In 2002, specific weight and Hagberg were predicted on a regional as well as a national basis. For specific weight, the most accurate forecasts were for the HGCA regions Northern, Scotland and South Western. Those for the regions East, South Eastern and Midlands and West were less accurate. In all cases, the observed value was between the upper and lower 75% prediction limits.

For Hagberg falling number, the observed value was outside the 75% prediction limits for the East, Northern and Midlands and West regions, and within the limits in Scotland, South-eastern and South-western.

Due to the wide range of success in different regions and following consultation with HGCA and the industry sponsors, it was decided not to continue these in 2003. Also in 2002, forecasts were made of quality according to NABIM groups. These also were of variable value and were discontinued, again taking account of advice from the sponsors.

4. Varietal effects on forecasts

As well as having a climatic component, specific weight also has a genetic component; some varieties of wheat have an inherently higher specific weight than others if grown under the same conditions. Residual maximum likelihood (REML) analysis was used to separate the varietal effect on specific weight from the climatic effect. Thus a "correction factor" could be applied to the specific weight value for each year, simulating the effect of a constant variety mix for all years. The effect of varieties on the forecasts was not great, so it was not considered further.

5. Studies of the climatic mechanism

Studies of the mechanism of the relationship between winter NAO and harvest quality fall into two parts. Firstly, the part played by the winter NAO in its influence on winter weather. A high winter NAO gives a warm winter, and this may speed the development rate of the wheat crop allowing it to mature faster. Secondly, the effect of the winter NAO on the weather of the following summer, and the role this has in determining the quality of the crop.

5.1 Influence of the winter climate

The winter NAO is well known to influence the winter weather. High NAO winters are associated with warm winters. To determine whether this had any effect on the rate of the development of the wheat crop, it was necessary to know the dates of various development stages in different years. This information was not available, so a wheat development model (AFRCWHEAT) was used to estimate development stage dates from daily temperature data. No significant relationships were found between the January NAO index and the dates of development stages. Nor were there any significant relationships between specific weight and the dates of development stages. The conclusion was therefore drawn that the January NAO does not affect specific weight through its influence on winter temperature. This is discussed further in Technical Paper 4.

The situation in regard to Hagberg falling number is similar in that dates of development stages are not related to Hagberg, so again, the conclusion is drawn that the January and February NAO do not affect Hagberg weight through their influence on winter temperature.

5.2 Summer climatic effects

Summer weather (particularly rainfall and sunshine) is well known to affect specific weight. The analysis presented here focuses on two stages of grain development; grain filling which takes place in early summer, and grain ripening, in late summer. These periods are defined in terms of the development stages; anthesis and end of grain fill, which can be defined from the AFRCWHEAT model. A study of the literature revealed that in the grain filling period (between anthesis and the end of grain fill) the amount of photosynthetic radiation strongly influences the weight of grains. There is a relationship between grain weight and specific weight. Therefore, increased photosynthetic radiation should be associated with higher specific weight. Hours of sunshine can be used as a substitute for radiation.

The grain ripening period, which starts with the end of grain filling and continues for about 19 days on average, is a period in which high specific weight is associated with drying of the grain. Any wetting in this period has the potential to reduce specific weight. The number of times a dry day followed a dry day was used to measure this factor.

Multiple regression was used to examine the relationships between the January NAO, sunshine during the grain filling period, dry days followed by dry days during grain ripening, and UK average specific weight. The results were expressed as a path diagram (see Fig. 2 for a simplified version). This shows that a majority (52%) of the variance of the relationship between the January NAO index and specific weight is explained by the relationship between the January NAO and the sunshine during grainfill and the incidence of rain during grain development. In other words, a relationship between winter NAO and summer weather is of overriding importance in explaining the effect of the NAO on specific weight.

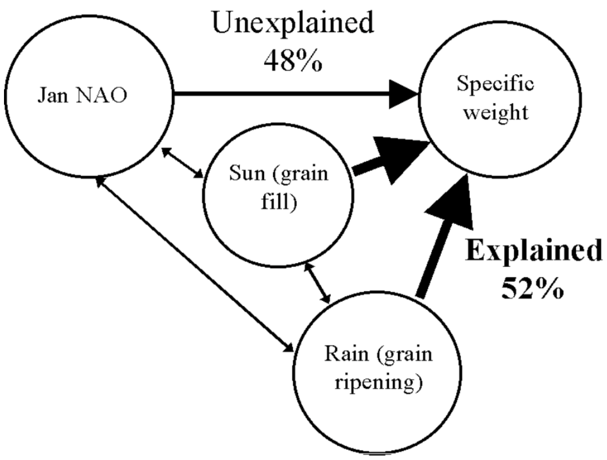

Figure 2. Simplified path diagram showing the relationship between the January NAO, specific weight and two summer weather variables

This work is presented in more detail in Technical Paper 4. The long-lead relationship between the winter NAO and summer precipitation is discussed in Technical Paper 3.

High values of Hagberg are positively associated with high values of summer temperature and sunshine and negatively associated with summer precipitation. As with specific weight, it is the relationship between winter NAO and summer weather which is the major factor in explaining this relationship.

6. Premium

Breadmaking premium is the difference between the price of breadmaking wheat and the price of feed wheat. The possibility of forecasting breadmaking premium from the winter NAO is due to the fact that wheat quality is an important factor in determining premium. Many other economic variables and processes come into play in affecting the level of premium (Fig. 3).

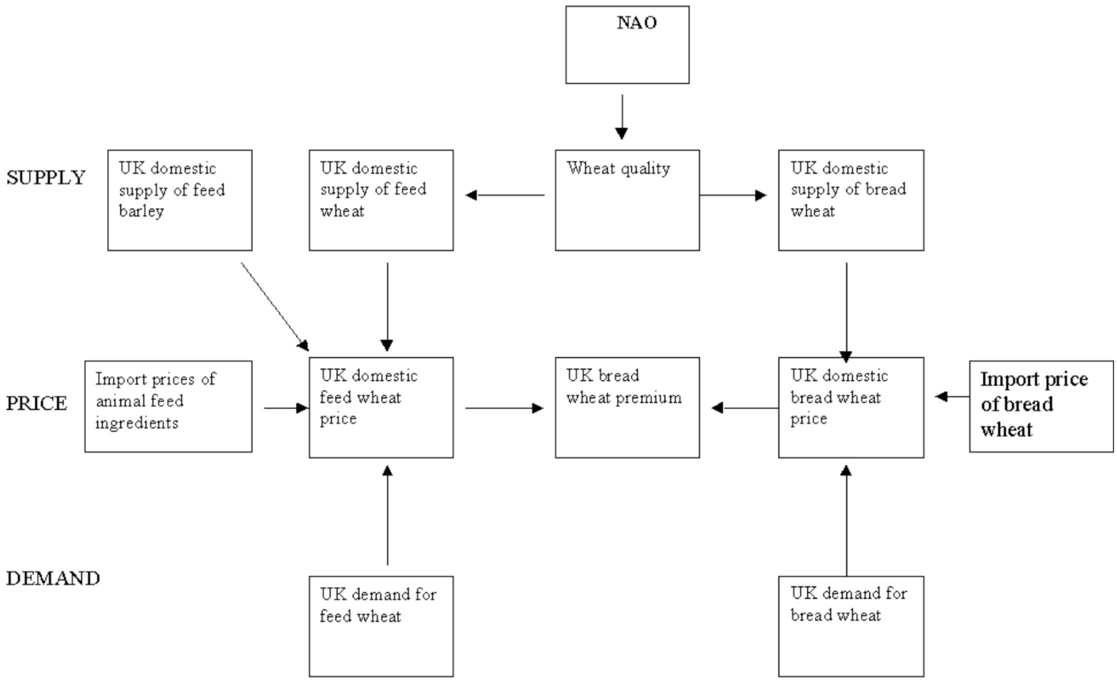

Figure 3. Theoretical model of variables likely to be involved in determining breadmaking premium.

6.1 Explanatory model

Before considering the possibility of forecasting premium, it is necessary to consider the variables which influence premium in the current year. Multiple regression was used to determine which of the many likely variables (shown in Fig. 3) were important. The result of this was to show that the most important factor in determining premium was wheat quality. Moreover, specific weight was of much greater importance than Hagberg falling number (Fig. 4). Other factors, which were of similar importance to Hagberg, were the proportion of breadmaking varieties (NABIM group 1 and 2 varieties) in the total mixture of varieties grown, and wheat stocks. Import price played a less important part. Interestingly, the third important breadmaking quality criterion, protein content, was not involved in the determination of premium.

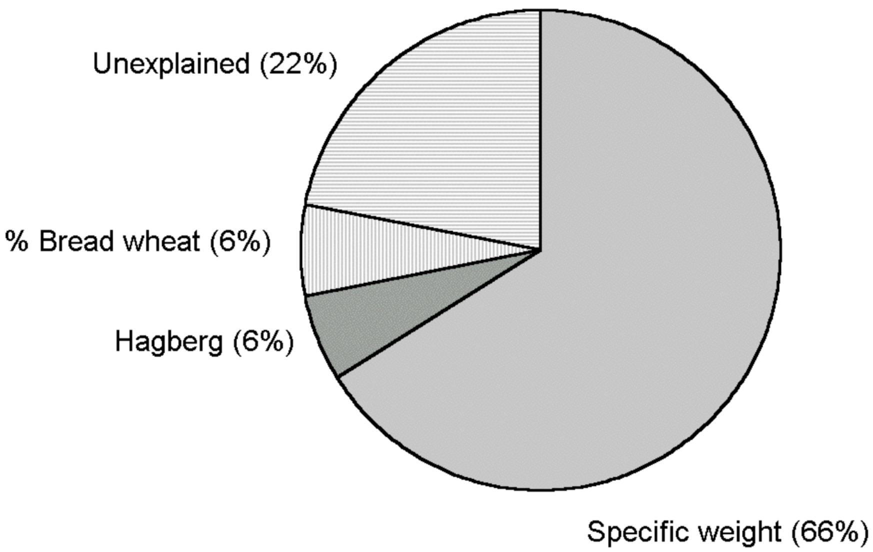

Figure 4. Chart showing the factors contributing to year-to-year variation in breadmaking premium.

6.2 Predictive model

The fact that quality is such an important determinant of breadmaking premium bodes well for the possibility of forecasting it. This is because the quality (specific weight and Hagberg falling number) is forecastable from the winter NAO. For forecasting of premium, the most effective model was judged to be one containing the three variables: November NAO index, January NAO index and the proportion of breadmaking varieties. Because of the difficulty of forecasting the proportion of breadmaking varieties and because its year-to-year change is small, it is set at the previous year's value.

The premium forecast for 2003 is 25.9 ± 6.7%

7. Introduction to Section C: Technical Papers

The development of a forecasting method was the principal aim of this project. The forecasting of specific weight is presented in Technical Paper 2. A protocol for data extraction and manipulation for the construction of NAO indices and regression equations for both specific weight and Hagberg falling number are given in Technical Paper 1.

Studies of the mechanism by which the winter NAO reflects grain quality at harvest are an important part of this work, as they help to underpin the forecasting method. A detailed examination of two possible mechanisms for the determination of specific weight is presented in Technical Paper 4. One of these mechanisms involves a long-lead relationship between the winter NAO and summer precipitation across England and Wales which is considered in Technical Paper 3.

PART C: TECHNICAL PAPERS

TECHNICAL PAPER 1

MD Atkinson, PS Kettlewell, PD Hollins (unpublished)

Protocols for forecasting wheat quality and premium

Two methods are presented here for forecasting wheat quality. Firstly (in section A), the procedure used to produce the published forecasts of specific weight and Hagberg. This method involves construction of an NAO index from sea-level pressure data, followed by regression analysis of these data and HGCA Quality data. A second, simplified method (in section B) involves using a published NAO index and a fixed regression equation. Thirdly (in section C), a method is presented for forecasting breadmaking premium which uses the NAO indices derived in section A.

It is emphasised that the second method for forecasting quality is presented because of its greater simplicity but is less accurate than the full method. The R^2 for the regression (proportion of the variance accounted for by the regression) of specific weight on the custom index was 67%. The R^2 for the simplified method was 36%. Forecasts for 2003 for the two methods are shown in Table 1.

Table 1. Forecasts for specific weight and Hagberg by two methods.

	Method 1 (full)	Method 2 (simplified)
Specific weight	76.0 ± 0.7	76.2 ± 1.0
Hagberg	255 ± 31	235 ± 33

(A) Procedure for published forecasts of quality

The method of forecasting UK specific weight and Hagberg falling number is based on weighted linear regression. To forecast specific weight for 2003, the variables included in the multiple regression are; specific weight (1974-2002) (dependent variable), number of samples (1974-2002) (weights), November NAO index (1973-2001) and January NAO index (1974-2002) as the independent variables.

To forecast Hagberg falling number for 2003, the variables included in the simple regression are; Hagberg falling number (1974-2002) (dependent variable), number of samples (1974-2002) (weights), sum of the January and February NAO indices (1974-2002) as the independent variable.

Collecting pressure data

Monthly sea-level pressure data are used. These data are from the NCEP-NCAR reanalysis which are on a 2.5° grid. Data are required for November, January and February, and should be available around the 6th of the following month. The data repository used is that of the Lamont-Doherty Earth Observatory, Columbia University, New York (http://ingrid.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/).

Data are needed for 2 areas of the north Atlantic; the northern area bounded by 0° W, 30° W, 60° N and 70° N, and the southern area, bounded by 5° W, 50° W, 30° N and 40° N.

Click on the 'Data Selection' link, and a long list of available data will be displayed. The particular data required are called 'CDAS-1 MONTHLY Intrinsic MSL pressure'. Fill in the "Setting Ranges" Table. In the row " X Longitude", put 0W to 30W, in the central row "Y Latitude", put 60N to 70N, and in the bottom row "T Time", put Jan 2003". Click on the button "Restrict Ranges". Then a box appears with a button "Stop Selecting". Click on this.

Use the 'Data files' link and choose the 'Columnar table' option. Copy the column of pressure data, transpose it into a row and copy it into the appropriate place in the Excel spreadsheet NAOIndexCalculation. This spreadsheet contains pressure data for the northern and southern areas, for the months January, February and November for the years 1949-2003. This spreadsheet is organised in blocks by month. The first block is for January, in rows 1 to 58. The second block is for February, rows 74 to 131. In each block, the first part (columns B to BN) are for the northern area, the second part (columns BU to FK) are for the southern area.

This must be repeated to extract the data for the southern area. In the "X Longitude" put 5W to 50W; in "Y Latitude" put 30N to 40N. The whole process above must be repeated for each monthly index required.

Calculating the NAO index

When a new row of data has been copied to the end of the appropriate monthly block in the Excel spreadsheet NAOIndexCalculation, calculate the average pressure for the northern area by copying a cell from column BP onto the new row, and the standardised pressure by copying a cell from column BQ. The same procedure should be followed for the southern area by copying a cell from column FM onto the new row, and the standardised pressure by copying a cell from column FN. Copy a cell from a preceding row into the new row of column FP. This is the NAO index for the month. Row FQ is simply the value in FP saved as a value (Copy, Paste Special, Values), which is recommended when transferring data to other spreadsheets).

Collating quality data

Average UK Hagberg falling number and specific weight are taken from the final results of the HGCA Cereal Quality Survey. The sample numbers for these variables are also used to calculate regression weights.

Scaling the sample numbers

In order to calculate 75% prediction limits for the quality variables, it is necessary to calculate weights such that the sum of weights is equal to the number of observations. The weights are created by dividing the sample number for each year by the average of the sample numbers for all years.

Doing the regression analysis and calculating quality values and limits

The software used for the regression analysis is R 1.1.1 (The R Development Core Team, www.r-project.org). This can be downloaded from this address and installed on a PC.

An example of the “R” commands needed to perform the regression analysis and predict the current year’s specific weight (2003) is given below. These commands operate on two data files; prednat 2003.txt (Appendix 1), which contains the historical data needed to derive the regression equation, and datanat2003.txt which contains NAO values for the current year in order to do the prediction.

```
prednat2003<-read.table("g:/predictions/prednat2003.txt",header=TRUE)
attach(prednat2003)
fm<-lm(spwt~novNAO, janNAO, weight=spwtno)
prednew<-read.table("g:/predictions/datanat2003.txt",header=TRUE)
attach (prednew)
predict.lm(fm,prednew,interval=c("prediction"), level=0.75)
```

for Hagberg

```
prednat2003<-read.table("g:/predictions/prednat2003.txt",header=TRUE)
attach(prednat2003)
fm<-lm(hfnt~jpfNAO, weight=hfnno)
prednew<-read.table("g:/predictions/datanat2003.txt",header=TRUE)
attach (prednew)
predict.lm(fm,prednew,interval=c("prediction"), level=0.75)
```

(B) Simplified procedure for forecasting quality

This method uses a published NAO index which is available on the internet and published very soon after the end of the month. The values can be obtained from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/bulletin/TABT3.html.

For specific weight, the January index value is needed (the November index is not related to specific weight) and for Hagberg, both January and February values are required. For specific weight, the January index value can be read on the horizontal axis of Fig. 1, and a vertical pencil line drawn on the figure. The forecast specific weight can be read on the y axis at the intersection of the vertical line with the fitted line (the middle straight line on the figure). The intersection of the vertical line with the lower curved line gives the lower 75% prediction limit. The intersection with the upper curved line gives the upper 75% prediction limit. The observed value has a 75% chance of falling between these limits. This graph is based on a weighted linear regression with data from 1974-2002. With Hagberg, follow a similar procedure by reading the value of January NAO + February NAO on the horizontal axis of Fig. 2.

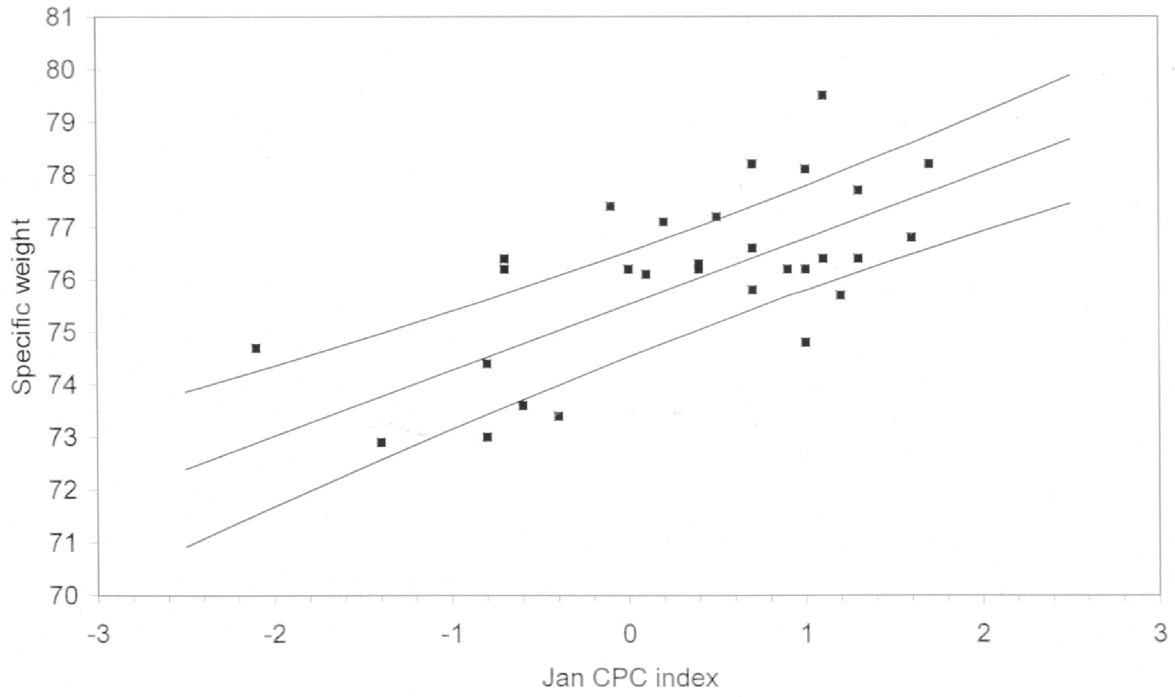

Figure 1. Plot of UK specific weight against January NOAA-CPC index, for estimating specific weight. The central line is the best fit line. The upper and lower lines are the 75% prediction limits.

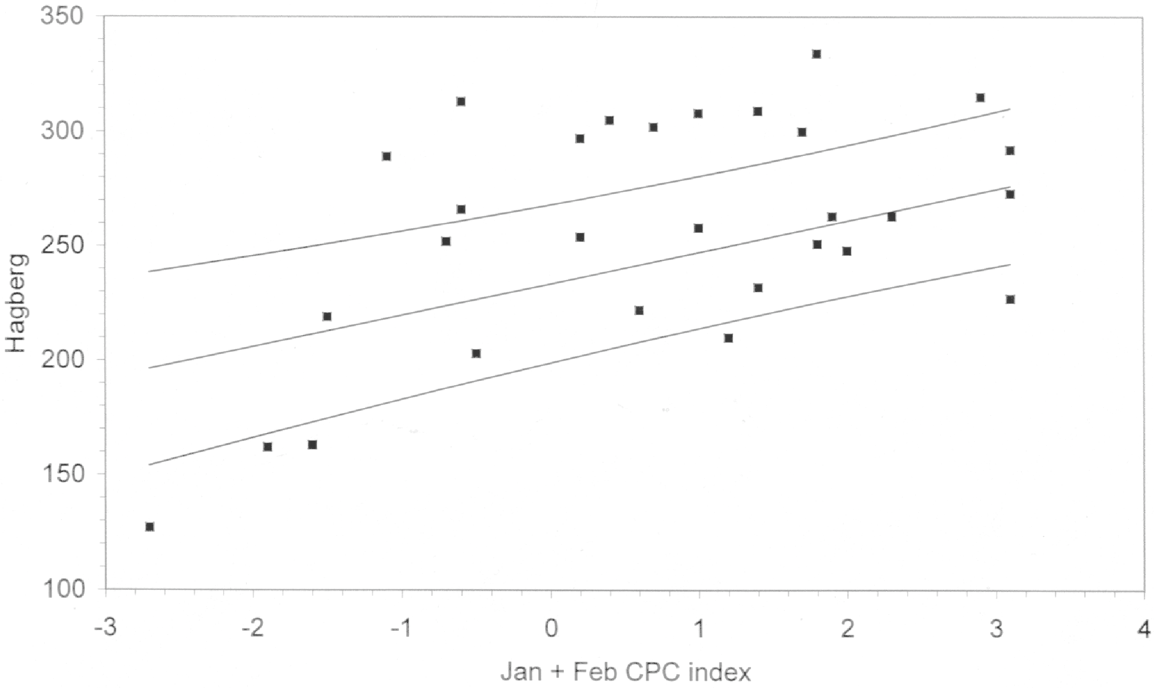

Figure 2. Plot of UK Hagberg against January and February NOAA-CPC indices, for estimating Hagberg weight. The central line is the best fit line. The upper and lower lines are the 75% prediction limits.

(C) Procedure for forecasting premium

The model used for forecasting breadmaking premium includes three variables; preceding November NAO index, current January NAO index and the proportion of breadmaking varieties grown. The model uses differences between the current year and the previous year for all variables, because trends in the data were causing some distortion. In practice, having developed a regression equation from the historical data, the NAO index differences are substituted in the regression equation, and a difference of zero is entered for the proportion of breadmaking varieties. This is because it is not easy to forecast this variable and differences from preceding years tend to be small. The NOAA-CPC index is not related to premium so a simplified method cannot be presented.

Three sets of data are required for this prediction. November and January NAO indices as detailed above in section A, and the proportion of varieties grown in a year which are for breadmaking. The latter data are taken from the HGCA Quality Surveys and are calculated as the number of samples of NABIM group 1 and 2 varieties as a proportion of the total number of samples. Historical premium data were taken from HGCA statistics. Annual premia are calculated. For 2002, the latest premium values are used. For the prediction of premium for 2003, values of January NAO, November NAO indices and proportion of breadmaking varieties from 1983 to 2002 were used. Differences between the current year's and the previous year's values were used in a multiple regression analysis. To predict the premium for 2003, the difference between the values of January NAO, November NAO and proportion of breadmaking varieties for 2001 were subtracted from those of 2002, and these values were entered into the regression equation. 75% confidence limits were calculated.

DISCLAIMER

The material available in Technical Paper 1 is designed to provide general information only. Whilst every effort has been made to ensure that the information provided is accurate, it does not constitute legal or other professional advice.

Neither Harper Adams University College, The University of Reading, nor the sponsors of this research can accept any liability for any loss sustained after using the forecasting methods. Those using the forecasts do so entirely at their own risk.

Appendix 1

The files used for calculating the regression equations and predicting the current year's quality values

prednat 2003.txt

year	hfn	hfnno	spwt	spwtno	pnovNAO	cjanNAO	cfebNAO	cjfNAO
1974	210	0.169715485	76.2	0.15688832	-1.7321167	2.657841935	0.84061021	3.4984521
1975	289	0.223085134	77.1	0.22102505	0.63299803	1.754905005	-0.74340263	1.0115024
1976	297	0.211699609	76.2	0.21872271	1.0723053	0.655475	1.11955133	1.7750263
1977	127	0.19319813	74.7	0.19635708	1.27548093	-1.6026841	-0.48322407	-2.085908
1978	203	0.097844357	74.8	0.10294768	0.82690621	1.241743462	-3.16091244	-1.919169
1979	219	0.091084201	74.4	0.09472502	2.97941257	-2.20592065	-1.57472865	-3.780649
1980	252	0.08361245	76.2	0.09439612	1.34078241	-1.79098561	-0.05924178	-1.850227
1981	263	0.072226925	76.3	0.08387111	-3.096713	0.711677798	0.63255348	1.3442313
1982	313	0.085391439	76.4	0.07926643	-0.2160533	-1.28999049	1.38443992	0.0944494
1983	305	0.07756389	76.2	0.08123986	3.33164799	2.964228133	-1.78220012	1.182028
1984	273	0.085391439	78.2	0.09110705	-3.4091257	3.243640544	1.32769746	4.571338
1985	162	0.237672838	72.9	0.26246725	0.20531585	-2.61355379	-1.32368241	-3.937236
1986	222	0.400272369	76.8	0.42001338	-2.7182291	2.225777136	-3.10099296	-0.875216
1987	163	0.41841805	73	0.44369464	4.06325693	-2.74518641	-1.13885185	-3.884038
1988	263	0.407032525	75.7	0.4259337	-0.2686647	1.36855631	0.52283434	1.8913906
1989	315	0.498472524	78.1	0.52921029	-2.2477934	2.357496226	3.38096558	5.7384618
1990	334	0.54614941	79.5	0.6081478	-1.5022319	3.145774247	3.358864	6.5046382
1991	300	0.395647	77.2	0.46310011	-1.2228782	1.093629186	0.22849996	1.3221291
1992	254	0.335161397	73.4	0.37988681	2.17492633	-0.81889428	1.78524752	0.9663532
1993	232	0.408099918	76.4	0.42363135	3.50377404	2.796350481	0.11299959	2.9093501
1994	308	0.535475481	77.7	0.53151263	1.95356197	1.924351445	-0.33512629	1.5892252
1995	309	0.471076104	78.2	0.48184777	0.5360636	2.005903414	2.43691892	4.4428223
1996	302	0.350104899	77.4	0.35752118	-2.6334652	-1.61673286	0.5140758	-1.102657
1997	258	0.448660851	73.6	0.43876104	1.49424914	-1.85251978	3.78191322	1.9293934
1998	266	0.503453691	76.1	0.50585794	-0.684599	-0.35383261	0.26416958	-0.089663
1999	227	0.444391279	76.4	0.43744542	0.54716531	1.5037722	1.65924771	3.1630199
2000	292	3.219257242	76.6	3.0811945	0.89733927	0.395888929	2.97875364	3.3746426
2001	251	7.167188094	75.8	7.4306518	0.16705218	0.079967988	-0.52972907	-0.449761
2002	248	10.82265327	76.2	10.358576	0.672157	0.821417	1.796389	2.617806

datanat 2003.txt

year	pnovNAO	cjanNAO	cfebNAO	cjfNAO
2003	0.92568	0.527748	0.856	1.384

TECHNICAL PAPER 2

M D Atkinson, P S Kettlewell, P D Hollins and D B Stephenson (2002) Regression forecast of UK harvest wheat quality from the preceding winter North Atlantic Oscillation. Experimental Long-Lead Forecast Bulletin, 11(2) (published on the internet only at: http://grads.iges.org/ellfb/Jun02/atkinson/atkinson.htm)

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Kettlewell PS, Stephenson DB, Atkinson MD & Hollins PD (2003) Summer rainfall and wheat grain quality: relationships with the North Atlantic Oscillation. Weather, 58, 155-163

Can be seen at http://www.harper-adams.ac.uk/wheatqualityforecasts/Kettlewelletal2003.pdf

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