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Summer climate mediates UK wheat quality response to winter North Atlantic Oscillation

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Abstract

Previous studies have shown that a high North Atlantic Oscillation (NAO) index in winter is associated with better postharvest quality of the UK wheat crop. This prompted investigation of the possible mechanisms and two main hypotheses were proposed. The first hypothesis tested was that a high winter NAO index could, through higher winter temperatures, advance crop development to bring grain growth and ripening into a period of more favourable weather. This was examined by simulating wheat development in the UK from 1974 to 1999, using the AFRC wheat model and regressing wheat quality on development stage dates. No consistent relationship was found between the dates of development stages and the wheat quality variable specific weight, therefore this hypothesis was rejected. The second hypothesis tested was that a high winter NAO index could lead to sunnier and drier weather during grain growth and ripening, giving better grain quality. Two summer climate variables, cumulative sunshine between anthesis (pollen release) and the end of grain-filling, and unconditional probability of a wet day between the end of grain filling and harvest, were found to be important in determining specific weight. Prediction of these summer climate variables from the January NAO accounted for 70% of the variance of the relationship between the January NAO and specific weight. These results show that the memory of the January NAO-specific weight relationship is in the climate, and not in the crop.

Keywords: *Triticum aestivum*; Bread wheat; NAO; North Atlantic Oscillation; Specific weight; Test weight; Climate memory

1. Introduction

Kettlewell et al. (1999) previously demonstrated a statistically significant association between the winter North Atlantic Oscillation (NAO) and the quality of UK wheat harvested in the following summer. The relationship with one quality measure, specific weight, is illustrated in Fig. 1. The mechanisms involved in the relationship between winter NAO and specific weight are unknown, and the aim of this study was to understand the basis of the relationship.

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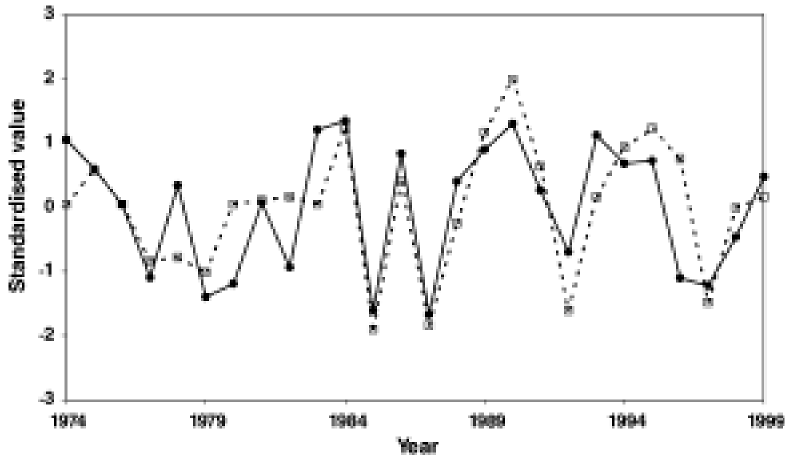

Fig. 1. January North Atlantic Oscillation index (filled circles, continuous line) and specific weight (open squares, dashed line), standardised over the period 1974–1999.

The NAO is a large-scale distribution of pressure across the Atlantic Ocean (see Wanner et al., 2001 and Hurrell et al., 2003 for reviews). The NAO has profound effects on the climate of Europe (Hurrell and Van Loon, 1997) including the UK (Wilby et al., 1997), especially on winter temperature. There are many documented examples of direct and indirect effects of the NAO on marine, freshwater and terrestrial ecosystems (Ottersen et al., 2001; Blenckner and Hillebrand, 2002).

The suitability of wheat grown in the UK for various end users depends in large part on certain quality criteria. For this reason, the ability to forecast quality has potential economic benefits for the end-user. This study considers the quality measure specific weight; this is the bulk density of the grain normally recorded in units of kilogrammes per hectolitre. Specific weight determines the yield of extracted flour (Marshall et al., 1986) and has a strong impact on transport and storage costs (Brooker and Bakke, 1992). Specific weight is one of the primary criteria used in the UK wheat market.

Use has been made of large-scale climatic variables in forecasting agricultural yields in several regions of the world. Hsieh et al. (1999) noted a relationship with a lead time of several months between Canadian wheat yield and a Pacific sea-surface temperature index. An association between the El Nino/Southern Oscillation and global wheat grain yield data was linked to Indian monsoon droughts (Garnett and Khandekar, 1992). The relationship presented in this paper is being used as an experimental forecasting system (Atkinson et al., 2002; http://www.harperadams.ac.uk/wheatquality-forecasts/monthlyNAO.htm). The possible mechanisms underlying the relationship are described below, following a brief description of wheat development.

The majority of wheat in the UK is sown in September and October, and harvested in August and September in the following year. The development stages used in this study are described in detail by McMaster (1997). In the analyses described below, two developmental periods are referred to: grain filling and grain ripening. Grain filling is the period between the development stages: anthesis and end of grain fill (maximum grain weight). The start of the grain-ripening period was defined as the day after the end of grain fill and the end as 19 days after the end of grain fill (Kettlewell, 1998).

The weather conditions during both grain growth and grain ripening will have an important effect on specific weight. Solar radiation is necessary as the energy source for synthesis of the carbohydrate needed to fill the grain. Well-filled grain often relates closely to specific weight (Bayles, 1977) and thus a priori solar radiation would be expected to influence specific weight. The importance of irradiance in the grain-filling period was emphasised by Brocklehurst et al. (1978) in a series of field and pot experiments on two varieties of wheat. The reduction of irradiance by shading decreased the rate of accumulation of dry matter in the grain and thereby reduced the grain weight at maturity. There appears to be no published work on the effects of irradiance on specific weight, but correlations between grain weight and specific weight are significant in some varieties, under some growing conditions, although not under others (Bayles, 1977; Bayles et al., 1978). In addition, a weighted regression of UK national specific weight (1974, 1976–1994) with UK national grain weight (Home Grown Cereals Authority, 1974–1999a, 1999b), showed a weak, but significant positive relationship ($R^2 = 0.23$, $P = 0.019$). In spite of variation between sites and varieties, this indicates at the national level that if low irradiance reduces grain weight this may lead to low specific weight.

Bracken and Bailey (1928) showed that wetting during grain ripening after the end of grain filling could reduce specific weight. Wetting and drying causes weathering of the surface of the grain and cracking of the kernel, leading to an increase in the volume of the grain, but no loss in weight, thus leading to a decrease in specific weight. The importance of wet conditions immediately prior to harvest is illustrated by specific weights of samples collected from farmers and millers by Swanson (1943) during the wet harvest of 1941 in Kansas. Samples which ripened and were harvested in dry conditions had a mean specific weight of 78.0 kg hl^{-1} (44 samples) and those which had been weathered by wetting before harvest had a mean specific weight of 73.1 kg hl^{-1} (38 samples). This difference was statistically highly significant ($P < 0.001$, t-test).

Two alternative hypotheses are presented to explain the relationship between the January NAO index and the specific weight at the following harvest. In the first hypothesis (winter temperature hypothesis), a high winter NAO index is associated with a warmer winter in the UK due to more temperate conditions caused by stronger westerly flow. Since temperature is the dominant factor influencing rate of wheat development (Porter and Gawith, 1999), this may accelerate the development of the wheat crop, such that the grain filling period occurs when radiation received is greater, leading to greater grain weight and therefore, higher specific weight. The confirmation of this hypothesis would indicate that the memory of this system (with a 6-month lead time) is in the crop.

The alternative hypothesis (summer weather hypothesis) is that it is primarily summer weather which is the major determinant of specific weight. There is now known to be a lag-effect of the winter NAO on the summer climate. Four recent studies have observed long-lead links between the winter NAO and summer hydrology (Wedgbrow et al., 2002), precipitation (Kettlewell et al., 2003) and temperature (Qian and Saunders, 2003; Hollins et al., 2003) in the UK. A high winter NAO tends to be followed by a warmer and drier summer. Although it has not been explicitly shown that summer solar radiation relates to the preceding winter NAO, solar radiation and rainfall are negatively associated in summer due to cloudiness. Thus, a high NAO is likely to give more solar radiation for grain-filling and drier weather during ripening thereby reducing weathering. Both these effects should lead to greater specific weight. The confirmation of this hypothesis would demonstrate that the memory inherent in the relationship was in the climate system.

This paper examines the part played by these two mechanisms in the relationship between the winter NAO and specific weight by quantifying the relationships between the NAO, winter climate, summer climate during grain development and specific weight between 1974 and 1999 using multiple regression and path analysis.

The national wheat quality data is obtained by a survey of up to 20,000 grain samples per annum, but the details of the crops from which the grain samples originate are unknown. In order to calculate weather variables over the appropriate phases of development, a simulation model of wheat development was run for each year of the survey to determine the mean dates of grain development in each year.

2. Methods and data

2.1. Data

Since the NAO is a large-scale climate phenomenon, and since wheat is grown over a large part of the UK, data analysis was based on a national scale and climatic data was acquired for an area approximating to the major area where wheat is grown.

Consideration was given early in the course of this work to the importance of obtaining timely estimates of NAO indices for forecasting purposes. Because the classical NAO indices are not always updated rapidly, a more operational NAO index was constructed. January NAO indices were calculated from NCEP-NCAR gridded reanalysis data (Kistler et al., 2001). These data are freely available, with only a few days delay, from the Climate Data Library of the Lamont Doherty Earth Observatory, Columbia University, New York (http://iridl.ldeo.columbia.edu/SOURCES/NOAA/NCEP-NCAR). 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 index is highly correlated with the January NAO index of Hurrell (1995) over the period 1974–1998 ($r = 0.995$, $P < 0.001$) and is available at http:www.harper-adams.ac.uk/wheatqualityforecasts/monthly-NAO.htm.

The principal wheat growing area is in the south and east of England (Fig. 2). Since less than 2% of wheat is grown outside this region, it was considered justified to focus on the English wheat growing area. The wheat development model used requires temperature data, and to calculate the dates of wheat development stages, daily maximum and minimum Central England Temperatures (CET) (Parker et al., 1992) were obtained from the Hadley Centre for Climate Research for the period 1974–1999. Over this period, CET was derived from four stations; Squires Gate, Malvern, Manchester Ringway and Rothamsted (Fig. 2), adequately representing the principal wheat growing area.

Solar radiation data was very sparsely available nationally and sunshine hours was used as a surrogate. Time series of daily precipitation totals and sunshine hours for 1974–1999 were obtained from the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/surface/) for a series of weather stations chosen to represent the main wheat growing area of England. The stations selected were: Brize-Norton, Brooms Barn, Bugbrooke Mill, Cambridge NIAB, Colchester Severalls Lane, Cromer, Kirton, Leeming, Lowestoft, Lyneham, Manston, Monks Wood, Moulton Park, Newtown Linford, Sheffield, Skegness, Stanford le Hope, Terrington St. Clement, Waddington and Writtle.

A source of development stage data was sought to further validate on a national scale the wheat development model used. The National Disease Survey carried out by the Central Science Laboratory records sowing date and the development stage during grain growth when the disease assessment is carried out. For each year, there were between 279 and 438 crops (mean 364), and a mean sowing date was calculated. Data were available from this survey for the dates of development stages on the Zadoks scale (Tottman, 1987) which fall during the grain filling period, viz.70–89. For each year from 1974 to 2001, the mean date of all these growth stages was calculated. Neither sowing dates nor development stage data were available for 1983 and 1984.

Annual values for UK mean wheat specific weight were obtained from the annual HGCA (Home-grown Cereals Authority; Home-grown Cereals Authority, 1998) Cereal Quality Surveys, 1974–1999 (Home-grown Cereals Authority 1974–1999a, b). Data for 2000 and 2001 were obtained from http://www.hgca.com. These surveys also provided the numbers of samples used to calculate means, which were used as weights in regression analyses.

2.2. Crop modelling

A computer model for wheat crop development (AFRCWHEAT) was used to provide the dates of grain development stages (Weir et al., 1984). This model has been extensively validated in the UK and other countries and is often used in simulating effects of climate change on wheat (e.g. Laurila, 1995). The part of this model concerned with predicting development stages requires only the latitude of the site, sowing date and daily maximum and minimum temperatures as input variables. The variety (Avalon), and sowing density ($320\,m^{-2}$) were kept constant. Mean sowing date from the National Disease Survey for each year, and the daily maximum and minimum Central England Temperature series (CET) were used. The latitude used was 52°48′N, which represents the centre of the area from which CET is derived (Parker et al., 1992). Input to the model for a single year, consisted of daily maximum and minimum tempera-

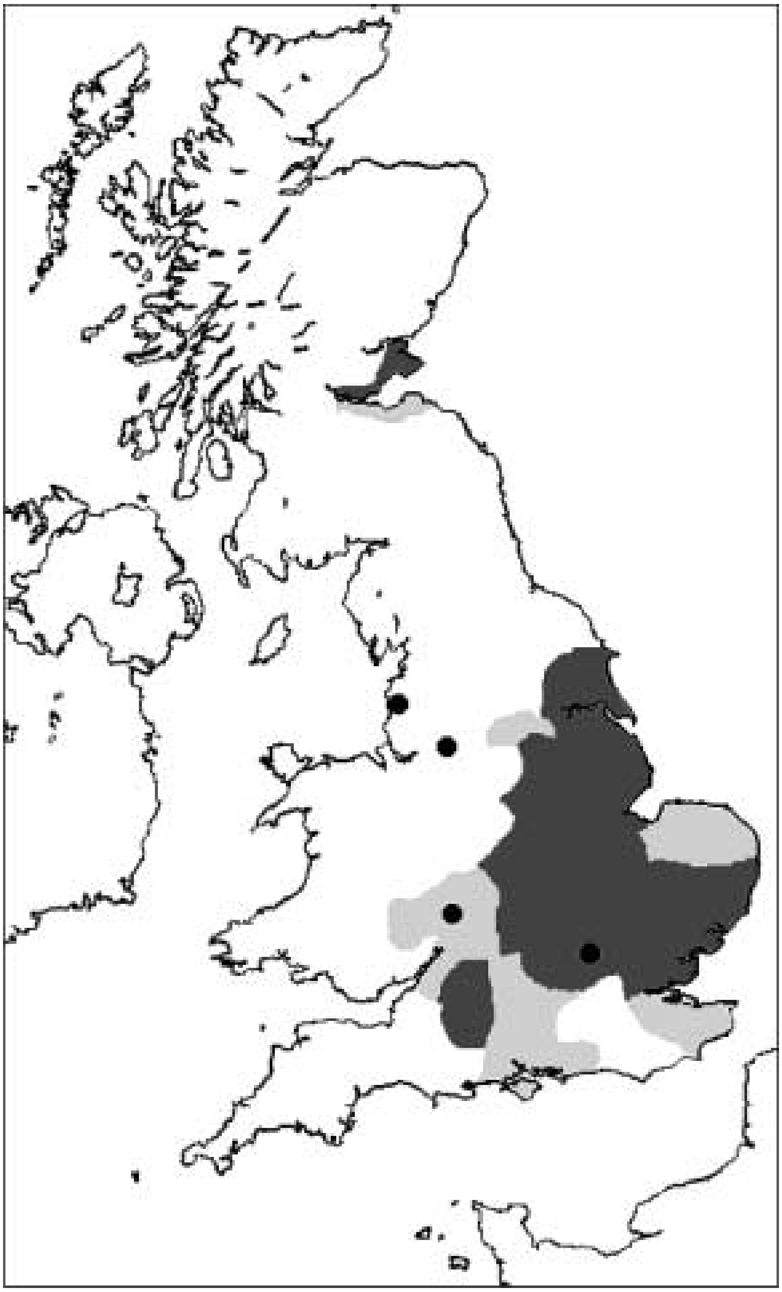

Fig. 2. Map showing the four meteorological stations from which daily maximum and minimum Central England Temperatures are derived. The principal wheat growing areas are also shown by shading. No shading indicates areas where wheat occupies less than 10% of the land area; light shading, 10–14%; dark shading, 15% and above. Wheat growing areas were taken from Ministry of Agriculture, Fisheries and Food and Scottish Office annual agricultural census figures.

ture for every day of the year. The model was run for the years 1974–1999, except 1983 and 1984. The grain development stage data from the National Disease Survey were used for comparison with the model output to test the validity of using the model for other development stages.

Table 1
Definition of daily precipitation terms

Symbol	Description	Calculation
p_{00}	Conditional probability of a dry day following a dry day	dd/(dw+dd)
p_{01}	Conditional probability of a wet day following a dry day	dw/(dw+dd)
p_{11}	Conditional probability of a wet day following a wet day	ww/(wd+ww)
u_w	Unconditional wet day probability	(ww+wd)/(dw+wd+dd+ww)

The number of instances of: a dry day following a dry day is termed dd; dry day following a wet day, wd; wet day following a dry day, dw; wet day following a wet day, ww.

The model was used to address both the winter-temperature and summer weather hypotheses. For the winter temperature hypothesis, the dates of the following development stages were derived from the model for each year; double ridge, terminal spikelet, anthesis, beginning of grain fill and end of grain fill. These dates were then used in regression analyses (see Section 2.3).

For the summer weather hypothesis, dates of anthesis and end of grain fill were used to derive cumulative weather variables between these dates. To quantify total irradiance during the period of grain filling, daily sunshine hours were totalled for each station, and the mean across all the stations was taken. In order to quantify wetting and drying of the grain, analyses were made of the frequency of precipitation within the grain-ripening period.

Four measures of the precipitation frequency were used (Table 1). For a particular year, and for each threshold value, numbers of successive wet and dry days (i.e. ww, wd, dd, dw as detailed in Table 1), were counted separately for each station. The four measures (p_{00}, p_{01}, p_{11}, uw as detailed in Table 1), were calculated separately for each station and the mean of each of these measures across all the stations was taken. A range of thresholds (0, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 mm), i.e. the daily precipitation amount above which a day is considered wet, was used to determine which best represents differences in specific weight. A comparison was made between measures of balance between wet and dry days and also between thresholds, on the basis of weighted regression with specific weight.

2.3. Regression and path analysis

Regression analyses were carried out using Genstat for Windows, (fifth edition, VSN International Ltd., Hemel Hempstead, UK). Path analysis was used to determine the contribution of intermediate steps to the overall NAO-specific weight relationship. A weighted regression was carried out with standardised variables, and the resulting regression coefficients are equivalent to partial correlation coefficients, and are termed path coefficients (Shipley, 2000). Specific weight was treated as the response (dependent) variable (weighted with sample numbers), to be explained by the explanatory (independent) variables: cumulative sunshine hours during the grain-filling period, and one of the measures of precipitation frequency.

2.4. Data detrending and assessment of the effect of wheat varieties on specific weight estimates

Significant relationships between two time series can occur simply through the existence of coincident trends without any mechanistic relationship. To ensure that relationships between a climatic variable and specific weight did not simply reflect coincident trends in the two variables, first order difference detrending was carried out in all cases on both variables; the difference was taken between the value of the variable in two successive years (Stephenson et al., 2000). To be considered trustworthy, a regression coefficient representing the relationship between two variables had to be significant both for the raw and the difference detrended variables. In order to do weighted regressions with differenced data, the weights for the differences were calculated as the harmonic mean of the sample numbers.

As well as having a climatic component, specific weight also has a genetic component; some varieties of wheat have inherently higher specific weight than others if grown under the same conditions. Residual maximum likelihood (REML) analysis (Smith and Gooding, 1999) 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. A slight trend was seen in specific weight, in that values in early years were lower than those in later years. Difference detrending was therefore effective in removing this effect.

3. Results and discussion

3.1. Effects of winter temperatures on wheat development

A high January NAO index is associated with a high winter temperature. The correlation between the January NAO index used in this study and January CET is 0.79 ($P < 0.001$, 26 d.f.). Moreover, the correlation between the January CET and specific weight is 0.65 ($P < 0.001$, 26 d.f.). Both these factors strongly indicate that January temperature, may, through influencing the development of the plant, account for the relationship between the winter NAO and specific weight.

The hypothesis to be tested here is that winter temperature influences the rate of development of the wheat crop bringing it into a more favourable climatic window for grain filling.

A test was first made of whether growth stage dates predicted by the AFRC model were comparable with growth stage dates recorded in the National Disease Survey. The relationship between the midpoint of the model-derived development stages; beginning of grain-fill and end of grain fill, and the mean of growth stages 70–89 from the National Disease Survey (Fig. 3) has $R^2 = 0.73$, showing a close relationship. The root mean square error of model-derived development stages is 7 days, a reasonably accurate prediction given a grain-filling period of 30–40 days. This indicates that the model-derived development stage dates can be used with confidence to reflect the development of the crop, in spite of the wide range of sowing dates represented by each annual mean. This is supported by the observation that crops sown at a single site in Scotland at a wide range of dates (between 9 September 1982 and 9 March 1983) flowered over a period of only 17 days (Hay, 1986).

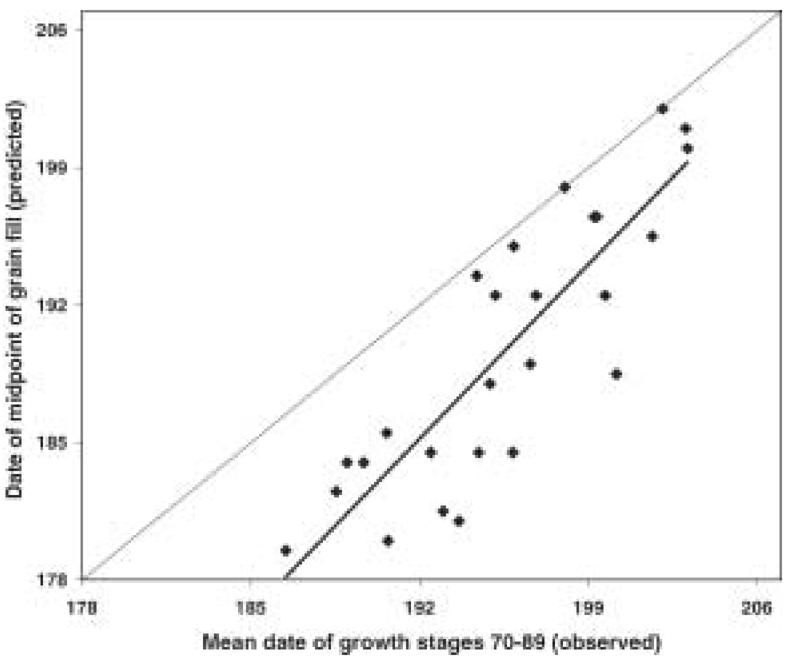

Fig. 3. Linear regression of the annual values of the midpoint between the dates beginning and end of grainfill (calculated by the simulation model) against mean dates of growth stages 70–89 (from the National Disease Survey). Both axes show dates. The faint line shows y = x, the bold line shows the best-fit line for the regression of y on x.

Table 2
Regression coefficients between dates of wheat development stages and climatic and quality variables

		Development stages					
		Double-ridge	Terminal spike	Anthesis	Start of grain filling	End of grain filling	Mature
Raw	Specific weight	−0.04 (*) 0.17	−0.05 (*) 0.13	−0.06 (NS) 0.03	−0.09 (NS) 0.01	−0.09 (NS) 0.08	−0.08 (NS) 0.09
	Jan NAOI	−3.58 (*) 0.12	−2.34 (NS) 0.09	−1.14 (NS) 0.06	−1.12 (NS) 0.05	−1.54 (NS) 0.10	−1.81 (NS) 0.11
Difference detrended	Specific weight	−0.02 (NS) 0.003	−0.02 (NS)–	−0.001 (NS)–	−0.01 (NS)–	−0.02 (NS)–	−0.01 (NS)–
	Jan NAOI	−2.09 (NS) 0.01	−1.12 (NS)–	−0.69 (NS)–	−0.85 (NS) 0.02	−0.45 (NS)–	−0.62 (NS)–

In weighted regressions with specific weight, the development stages are single independent variables. In regressions with January North Atlantic Oscillation index (NAOI), the development stages are dependent variables. The development stages are described in the text. Each table entry consists of the regression coefficient followed by significance in parentheses, followed by R^2 value in bold. Values marked (NS) are not significant at the 0.05 level, (*) significant at the 0.05 level, dash (–) indicates that the residual variance exceeds the variance of the response variate.

In weighted regressions with specific weight, dates of two development stages were found to be significant factors at the 5% level when used singly as explanatory variables (Table 2). In regressions with January NAOI, with dates of development stages as response variables, one was found to be statistically significant at the 5% level when raw data were used. None were found to be statistically significant at the 5% level when variables were difference detrended (Table 2). Therefore, it is assumed that the significant regressions found with the raw data were spurious and due to coincident trends. The winter temperature hypothesis is thus rejected, supporting the idea that the crop system does not hold the key to the long-term memory inherent in this relationship.

3.2. Mediation by summer climate

Weighted linear regressions were performed of specific weight on cumulative sunshine and each measure of wet-dry day frequency, at each threshold. These regressions were carried out using both raw and differenced data.

The threshold value and frequency measure chosen was that for which both the coefficients of variables in the regression (cumulative sunshine hours and the precipitation frequency variable) had the highest levels of significance, both using the raw and the differenced data. In this way, u_w was chosen, with a threshold of 2 mm.

A weighted multiple regression was done with specific weight as the dependent variable and unconditional wet-day probability (with a 2 mm threshold) and cumulative sunshine hours as the independent variables. The relationship between specific weight and cumulative sunshine hours (taking into account the effect of unconditional wet-day probability) is shown in Fig. 4. The relationship between specific weight and unconditional wet-day probability (taking into account the effect of cumulative sunshine hours) is shown in Fig. 5.

Bracken and Bailey (1928) investigated rainfall events throughout the summer and early autumn of 1925 and 1926 and measured the specific weight of grain harvested on particular days. The lowest rainfall total recorded during a period (10 days) in which a specific weight reduction was noted (1.9 kg hl^{-1}) was 2.2 mm. This is consistent with the present finding that a threshold of 2 mm best described the relationship between wet day frequency and specific weight.

A path diagram constructed with raw data (Fig. 6) shows that the two climatic factors (cumulative sunshine and unconditional wet-day probability) together account for 70% of the variance of the relationship between the January NAO index and specific weight. In the case of difference detrended data, these two climatic variables account for 52% of the variance. Thus a substantial proportion of the relationship between the January NAO index and specific weight can be accounted for by the effect of the NAO on the summer climate and both these climatic influences (sunshine in grain fill and wet day

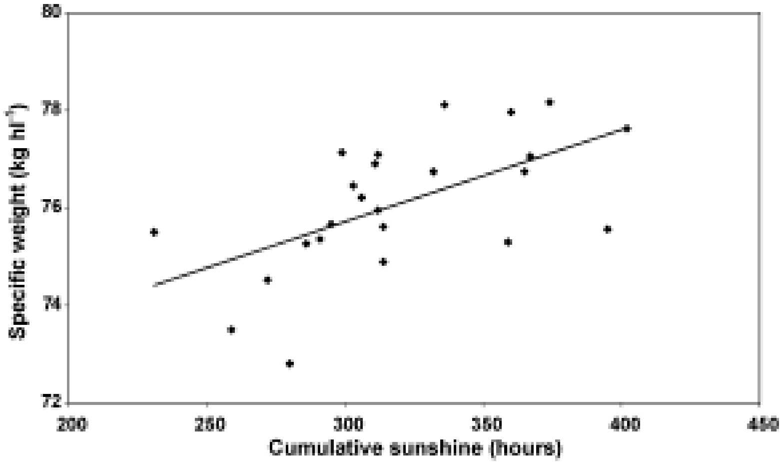

Fig. 4. Weighted linear regression of annual values of specific weight against cumulative hours of sunshine during the grain-filling period, taking into account the effect of the unconditional probability of a wet day, during the grain-ripening period.

probability during ripening) are of approximately equal importance.

The only comparable study of the effects of climate on specific weight is that of Smith and Gooding (1999) in which the major climatic factor influencing specific weight was average maximum daily temperature between 22 July and 4 August. This corresponds closely to the grain ripening period recognised in the present study. The relationship is positive, as is the relationship between unconditional wet day probability and specific weight in the present work, a relationship between wet day probability and maximum temperature would be expected. Smith and Gooding (1999) also noted a relationship between January temperature (between 7 and 27 January) and specific weight. This would appear to support the relationship between the January NAO index and specific weight, because of the close relationship between the winter NAO and the winter temperature (40% of the variance in December–January–February (DJF) CET was accounted for by regression on the DJF NAO index of Hurrell (Wilby et al., 1997)). The regression of January CET on the January NAO index used in the

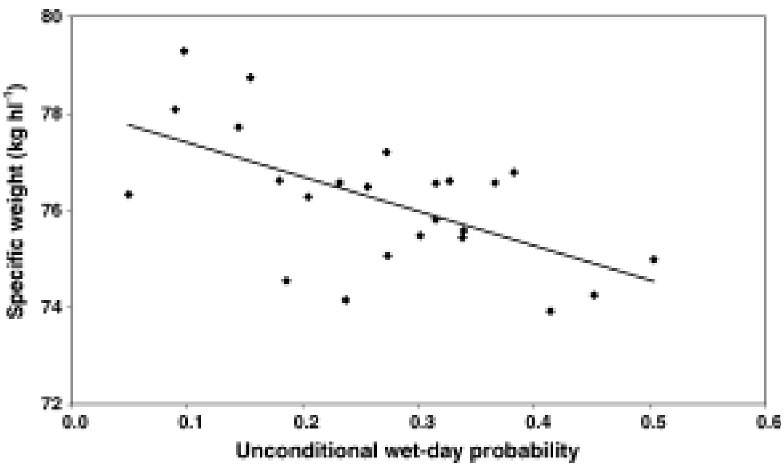

Fig. 5. Weighted linear regression of annual values of specific weight against the unconditional probability of a wet day, during the grain-ripening period, taking into account the cumulative hours of sunshine during the grain-filling period.

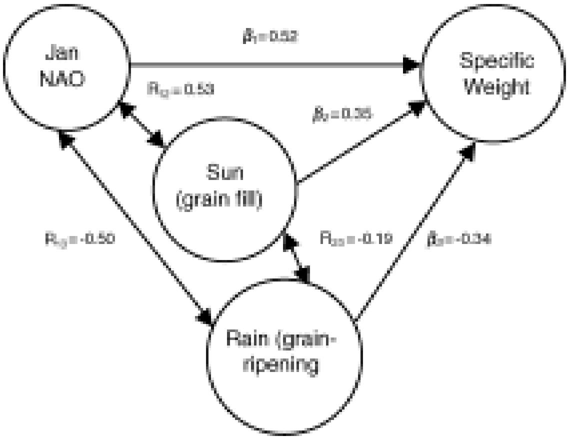

Fig. 6. Path diagram mapping the relationships between climatic variables and specific weight. β_1, β_2 and β_3 are path coefficients between January North Atlantic Oscillation (NAO) and specific weight. β_1 is for the direct path, β_2 is for the indirect path through cumulative sunshine and β_3 is for the indirect path through unconditional wet-day probability. Correlation coefficients between the dependent variables are denoted R_{12}, R_{23} and R_{13}.

present study accounted for 62% of the variance in the January CET.

4. Conclusion

The present work shows that sunshine during grain growth and late summer precipitation during grain ripening, are the most important climatic factors determining specific weight of harvested UK wheat. Climatic factors during the early life of the crop (from sowing to flowering) do not appear to have any substantial effect on specific weight through their modification of the timing of crop development. Thus it is concluded that the mechanism of the long-lead relationship appears to be largely climatic. That is, the long-term memory inherent in this relationship is not in the crop.

Mechanisms for this relationship remain elusive and require further investigation. Possible causes must involve memory in the climate system for which an obvious contender is the North Atlantic Ocean. However, the details are not clear about how the memory of winter atmospheric conditions can be fed back to the atmosphere in summer. Future studies with coupled ocean-atmosphere models may be able to shed some light on these processes.

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