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Soil moisture mediates association between the winter North Atlantic Oscillation and summer growth in the Park Grass Experiment

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Several aspects of terrestrial ecosystems are known to be associated with the North Atlantic Oscillation (NAO) through effects of the NAO on winter climate, but recently the winter NAO has also been shown to be correlated with the following summer climate, including drought. Since drought is a major factor determining grassland primary productivity, the hypothesis was tested that the winter NAO is associated with summer herbage growth through soil moisture availability, using data from the Park Grass Experiment at Rothamsted, UK between 1960 and 1999. The herbage growth rate, mean daily rainfall, mean daily potential evapotranspiration (PE) and the mean and maximum potential soil moisture deficit (PSMD) were calculated between the two annual cuts in early summer and autumn for the unlimed, unfertilized plots. Mean and maximum PSMD were more highly correlated than rainfall or PE with herbage growth rate. Regression analysis showed that the natural logarithm of the herbage growth rate approximately halved for a 250 mm increase in maximum PSMD over the range 50–485 mm. The maximum PSMD was moderately correlated with the preceding winter NAO, with a positive winter NAO index associated with greater maximum PSMD. A positive winter NAO index was also associated with low herbage growth rate, accounting for 22% of the interannual variation in the growth rate. It was concluded that the association between the winter NAO and summer herbage growth rate is mediated by the PSMD in summer.

Keywords: North Atlantic Oscillation; drought; potential soil moisture deficit; grassland; herbage growth rate

1. INTRODUCTION

The North Atlantic Oscillation (NAO) is a large-scale atmospheric circulation pattern with marked effects on Northern Hemisphere climate. The NAO is characterized by alternating pressure over the northern and southern regions of the North Atlantic Ocean and is quantified by indices calculated from atmospheric pressure measured in these regions. The physical aspects of the NAO have been reviewed by Wanner *et al.* (2001). The NAO is most strongly developed in winter and influences European and Scandinavian climate by alteration of the position of the winter storm tracks across the North Atlantic Ocean. A positive NAO index leads to more northerly winter storm tracks and vice versa. The main consequence for climate is that a positive NAO is associated with higher winter temperature and vice versa over a large part of northwest and central Europe.

Numerous associations between the NAO and terrestrial ecosystems mediated through this winter temperature influence have been reported (Ottersen *et al.* 2001). For example, the winter NAO is related to spring phenology of many plant species (Post & Stenseth 1999). The winter NAO is also correlated with herbage utilization by large mammals. Mysterud *et al.* (2001) have shown an association between the winter NAO and body weight of wild red deer and domestic sheep in Norway. They attribute this to the correlation between the winter NAO and winter snow depth leading to changes in subsequent summer foraging conditions.

In addition to the well-known relationships between the winter NAO and winter climate, the winter NAO has recently been shown to be related to the following summer climate in the UK in several studies using data from the last few decades. Significant correlations have been found between the winter NAO and summer temperature. Hollins *et al.* (2004) used the three month mean central England temperature (CET) for June, July and August for 1970–1998, and Westgarth-Smith *et al.* (2005) used separate monthly means for 1977–2001. CET is a single time-series based on records from a small number of meteorological stations representative of much of England. Both studies found that the winter NAO was significantly positively correlated with summer CET. Ogi *et al.* (2003) used gridded surface air temperature data for the Northern Hemisphere from 1958 to 2000 to relate to the winter NAO, and defined summer as May, June and July. They showed that the winter NAO was associated with summer temperature over northwestern Europe, central Siberia and northeastern Siberia. Qian & Saunders (2003) also studied the relationships between the winter NAO and summer CET and gridded temperature data for Europe, but in addition examined summer temperature

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data for seven UK cities from 1950 to 2001. They showed significant positive correlations between the January and February NAO index and temperature for all three datasets.

Summer rainfall has also been found to be associated with the winter NAO. Westgarth-Smith *et al.* (2005) found that August England and Wales precipitation (EWP) was significantly negatively correlated with the previous January NAO. Kettlewell *et al.* (2003) also examined EWP as well as regional precipitation data for the UK and gridded precipitation for the Northern Hemisphere. They discovered significant negative correlations of summer precipitation with the winter NAO for all three data sources. The only regions of the UK where summer precipitation was not correlated significantly with the winter NAO were northern Scotland and northwest England.

The correlations of winter NAO with both summer temperature and summer precipitation would be expected to change soil water availability. The usual measure of soil water availability used in plant growth studies in the field is soil moisture deficit (SMD), which, in essence, is the difference between cumulative evapotranspiration and cumulative rainfall (French & Legg 1979). Higher summer temperature following a positive NAO index winter will result in greater soil water loss through more evapotranspiration. This will combine with lower rainfall following a positive NAO index winter to increase summer SMD. There appear to be no published reports of the correlation between winter NAO and summer SMD, but Wedgbrow *et al.* (2002) showed that another measure of soil moisture in summer, the Palmer drought index, was correlated with the winter NAO over much of central England. Furthermore, evidence for the importance of the winter NAO to the hydrological cycle has accrued from two studies showing that summer river flows in the UK are negatively correlated with the winter NAO (Wedgbrow *et al.* 2002; Svensson & Prudhomme 2005). This was not simply a result of persistence into the summer of a relationship between the winter NAO and winter river flow, since it occurred for individual rivers (Wedgbrow *et al.* 2002) and regional clusters of rivers (Svensson & Prudhomme 2005), where no correlation existed between winter and summer river flows. The winter NAO–summer river flow correlations are inferred by the authors to reflect winter NAO–summer precipitation relationships.

Some biological and ecological processes in terrestrial ecosystems are likely to be correlated with the winter NAO through summer climate, in addition to the well-known associations mediated by winter climate. Specific associations have already been shown with wheat grain quality (Kettlewell *et al.* 1999; Atkinson *et al.* 2005), concentration of airborne fungal spores (Hollins *et al.* 2004) and butterfly abundance (Westgarth-Smith *et al.* 2005). These associations have been deduced to be mediated by one or more of summer temperature, rainfall and sunshine. A more general association with plant growth should, however, be detectable since soil water availability is a major limitation on plant growth during the summer in the UK. In order to detect plant growth associations with the winter NAO a reasonably long time-series of data is needed. The Park Grass Experiment at Rothamsted, UK is a source of long-term growth data for semi-natural grassland. This paper reports the results of an investigation of the relationships between the winter NAO and herbage growth in the Park Grass Experiment. The hypothesis was tested that the winter NAO is associated with summer herbage growth through soil water availability.

2. THE PARK GRASS EXPERIMENT

The Park Grass Experiment was started in 1856 at Rothamsted in Hertfordshire to compare herbage yield of unfertilized plots with that from plots given various combinations of fertilizers. The site had been under grass for at least a century before this. The unfertilized plots, therefore, represent semi-natural grassland with cutting and herbage removal twice a year being the only human intervention. The yield of dry matter has been recorded from one cut in June and a second cut between September and December since 1856 (1876 for the second cut). A major change to cutting procedure for the first cut occurred in 1960 (Thurston *et al.* 1976). Before this year, yield of the first cut was recorded each year after haymaking, but from 1960 yield of fresh herbage was recorded (and corrected to dry matter) from strips within each plot using a flail type forage harvester. The rest of the plot was mown and made into hay as before. As a result, dry matter production at the first cut was apparently greater from 1960 due to avoidance of dry matter losses during haymaking. The forage harvester was used for the second cut from 1959. It is possible that this resulted in larger yields than before when the plots were cut with a mower and raked up. Since 1959 the second cut (when taken) was carted green. Previously the second cut was occasionally made into hay.

The unfertilized plots are botanically diverse with approximately equal contributions to the dry weight of herbage from grass species and from dicotyledonous species (Thurston *et al.* 1976). Although some changes in botanical composition have occurred, Thurston *et al.* (1976) stated that the unfertilized plots remain 'the closest approximation to the state of the whole field in 1856'.

Trends in dry matter production for some of the plots, including the unfertilized plots, were reported by Jenkinson *et al.* (1994). They found no evidence for trends in total annual dry matter production on the unfertilized plots. A trend up to 1959 for increasing dry matter production was found for the first cut, with a suggestion of decreasing dry matter production at the second cut. No trends were, however, detected in the yield of either cut in the period 1960 to 1992. In addition, no autocorrelation was found in the yield of unfertilized plots.

3. DATA ANALYSIS

The NAO index of Hurrell for the conventional winter months of December, January and February was obtained from http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#naostatseas. Dry matter yield data and dates of the cuts were retrieved from the electronic Rothamsted archive (ERA) at http://www.era.iacr.ac.uk. Data were obtained for unlimed areas of plots 2, 3 and 12 and, after subdivision for further treatments in 1965, for the unlimed sub-plots (2d, 3d and 12d). Plots 3d and 12d have never received any fertilizer or manure since 1856, and although plot 2d received manure from 1856 to 1863, it has received nothing since and is regarded as a replicate of 3d and 12d. Data analysis focused on the period between 1960 and 1999, i.e. after changes in the cutting regime. An earlier period, 1902–1926 was also used to explore whether any relationships existed in the early part of the twentieth century. Some data were not readily available for five of the years between 1902 and 1926. Dry matter yield and dates of cut were available for all years from 1960 to 1999. However, in 1964 the yield from the second cut was recorded as zero for all three unlimed and unfertilized plots. This may indicate that a subjective judgement was made that insufficient herbage was present for the forage harvester to collect and, therefore, plots were not cut. The machine used appears to be able to collect a minimum equivalent to about 0.1 t ha^{-1}, so that a zero yield indicates that the yield could be anywhere between zero and 0.1 t ha^{-1}. Because of this uncertainty, and also because inclusion of a zero value leads to an extreme outlier in subsequent analysis, it was decided to omit 1964, giving 39 years of data for analysis between 1960 and 1999. The mean of the dry matter yield from the three plots was calculated for subsequent analysis.

Data analysis focused on the period between the two cuts since this largely encompassed the conventional meteorological summer of June, July and August relevant to the hypothesis under test. The date of the first cut in the retrieved data varied from 4th June to 9th July and for the second cut from 3rd September to 11th December. The period of growth between the two cuts varied from 83 to 174 days. To make comparison between years more meaningful, the growth rate per day over the growth period was calculated by dividing the dry matter yield at the second cut by the number of days since the first cut. The natural logarithm of the growth rate data was analysed since greater variation was evident at high than at low growth rates.

Moisture supply to the soil is entirely through rainfall in the unirrigated Park Grass Experiment. Daily rainfall was obtained from ERA and mean rainfall per day was calculated for each year by dividing cumulative rainfall between the first and the second cuts by the number of days between the cuts. Atmospheric demand for water was calculated as potential evapotranspiration (PE) and the available soil moisture for growth was calculated as the cumulative difference between supply and demand: potential soil moisture deficit (PSMD). Daily PE over grass and daily PSMD were calculated using the ERA PSMD calculator at http://www.era.iacr.ac.uk/metcalc.html. The ERA PSMD calculator uses the Penman formula to calculate PE and computes cumulative PSMD in a daily balance sheet by subtracting rainfall and adding PE to the total for the previous day. The calculation of the PSMD was started at zero on 1st January 1960 and run continuously until the end of the data in 1997, except that the calculations had to be restarted from zero on 1st January 1973 and again on 1st January 1977 following substantial periods of missing data. The necessary meteorological data were not readily available on ERA for the entire period 1902–1926, and for four of the years from 1960 to 1999, giving 36 years of PSMD data for the latter period. For each year of available data the mean PE and mean PSMD between the two cuts was calculated. In addition, the maximum PSMD in this period was identified and used as a variable in subsequent data analysis. Maximum PSMD is a measure of the total drought stress experienced by a crop (French & Legg 1979) and has previously been shown to relate closely to grass growth (Garwood 1988).

Table 1. Correlations of herbage growth rate with summer meteorological variables and the winter NAO between 1960 and 1999. (Herbage growth rate transformed to natural logarithm before analysis. All summer meteorological variables, except maximum PSMD, calculated as daily mean for the period between the first and second cuts. *$p<0.05$; **$p<0.01$; ***$p<0.001$.)

variable	raw	differenced
mean rainfall	0.388*	0.233
mean PE	−0.404*	−0.331*
mean PSMD	−0.778***	−0.726***
maximum PSMD	−0.788***	−0.760***
winter NAO	−0.472**	−0.430**

Although Jenkinson *et al.* (1994) found no autocorrelation in the yield of the unfertilized plots from 1960 to 1992, a further 7 years of data have been included in the present study. Therefore, the herbage growth rate autocorrelation coefficients for lags of several years were calculated to test for trend. The NAO has shown a trend to increase in recent decades (Wanner *et al.* 2001), and when one or both time-series variables used in correlation or regression analysis include trend the conclusions can be distorted (Stephenson *et al.* 2000). In order to discover whether there was a risk of distortion of conclusions from statistical analyses by coincident trends, the first order differences of all variables were also calculated and used in correlation analysis. This is a useful method of removing trends (Stephenson *et al.* 2000). Firm conclusions on significance of relationships were only drawn if differencing did not substantially change the outcome of analysis.

4. RESULTS AND DISCUSSION

Significant autocorrelation was found in the herbage growth rate time-series for lag 1 ($r=0.36$; $p<0.05$) and lag 3 ($r=-0.42$; $p<0.05$), indicating significant serial correlation over time. Together with the known trend in the NAO (Wanner *et al.* 2001), this gives rise to the possibility that correlation and regression analyses of raw data may give spurious results. Correlation analysis, however, gave similar results with both raw and differenced variables except for rainfall (table 1). This gives confidence that, except for the rainfall correlation, any coincident trends were too small to give rise to spurious significance and that conclusions based on raw data were valid.

Herbage growth rate was positively correlated with water supply to the soil (rainfall) and negatively correlated with atmospheric demand (PE; table 1). These results are consistent with the analysis by Sparks & Potts (1999) of data from the Park Grass Experiment since 1965. They found that yield at the second cut was positively related to summer rainfall. The associations of summer growth rate or second cut yield with rainfall would be expected in grassland dependent only on natural rainfall for water supply. The positive correlation of rainfall with growth rate in our study may, however, be partly due to coincident trends in the two variables since the correlation coefficient is reduced below the significance level when first order

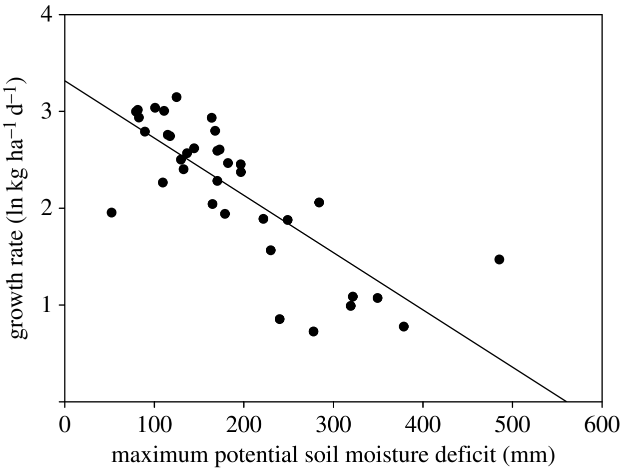

Figure 1. The relationship between herbage growth rate and the maximum potential soil moisture deficit from early summer to autumn 1960–1997.

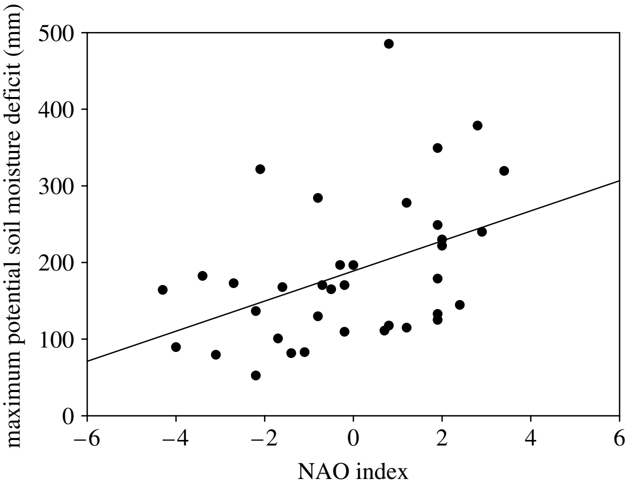

Figure 2. The relationship between maximum potential soil moisture deficit from early summer to autumn and the preceding winter NAO index 1960–1997.

differences are calculated. Sparks & Potts (1999) also found that second cut yield was strongly inversely related to mean maximum temperatures in July and August. This finding is compatible with our negative correlation between growth rate and PE, since temperature is an important component of PE.

Both PSMD variables were highly negatively correlated with herbage growth rate, demonstrating that summer herbage growth in the Park Grass Experiment is strongly dependent on the availability of soil moisture. The maximum PSMD was more highly correlated and this variable was chosen to illustrate the dependence of growth rate on soil moisture in a regression analysis (figure 1). This showed that the natural logarithm of growth rate declined by about half for a 250 mm increase in maximum PSMD over the range 50–485 mm.

The maximum PSMD between the two cuts was moderately correlated with the preceding winter NAO index (figure 2) with 18% of the interannual variation in maximum PSMD accounted for by the winter NAO. The maximum PSMD tended to be greater following high NAO index winters. This is consistent with the previously reported association of high NAO index winters with higher summer temperature (Ogi *et al.* 2003; Qian & Saunders 2003; Westgarth-Smith *et al.* 2005) and reduced precipitation (Kettlewell *et al.* 2003; Westgarth-Smith *et al.* 2005). The former would contribute to greater PE and thus atmospheric demand for water, thereby increasing PSMD, and the latter would contribute to reduced supply of water to the soil also, therefore, increasing PSMD. The relationship between maximum PSMD at Rothamsted and the winter NAO supports the finding of Wedgbrow *et al.* (2002) that the Palmer drought index in summer months calculated for 1° grid squares was correlated with the preceding winter NAO over most of southern and eastern England, including Rothamsted.

It is assumed that the winter NAO is associated with the maximum PSMD in summer through the lag effect on summer climate. It is possible in some years, however, that a deficit could accumulate during the winter months, through effects of the contemporaneous NAO on winter climate, and persist into the summer months. This is very unlikely in most years at Rothamsted since the maximum SMD in May, the month preceding the first cut in most years, was not significantly correlated with the preceding winter NAO ($r=0.24$; n.s.).

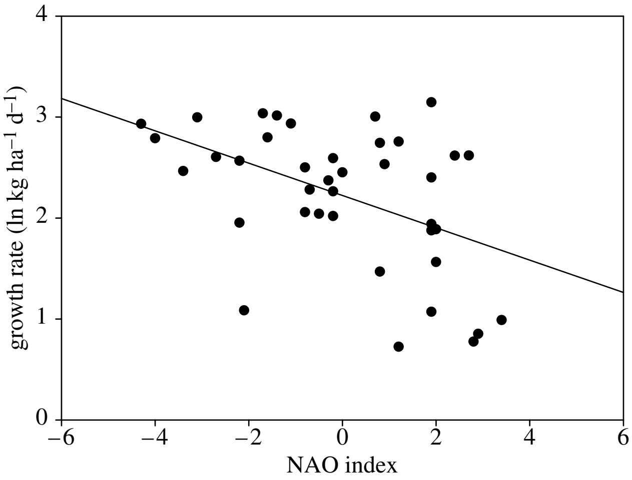

Figure 3. The relationship between herbage growth rate from early summer to autumn and the preceding winter NAO index 1960–1999.

The growth rate between the two cuts declined significantly ($p=0.002$) as the winter NAO index increased (figure 3), and fitted values showed that the growth rate nearly halved from the lowest NAO index (−4.3) to the highest (3.4). The winter NAO accounted for 22% of the interannual variation in growth rate, similar to the proportion of the variation in maximum PSMD accounted for by the winter NAO. Together with the strong dependence of growth rate on maximum PSMD, this provides evidence that the association between the winter NAO and herbage growth rate in the Park Grass Experiment is mediated through PSMD.

Although this effect of the winter NAO on growth is only at a single site in southeast England, there is evidence that growth in a very different type of grassland experiment over a shorter period at North Wyke in southwest England (approximately 270 km from Rothamsted) is also correlated with the winter NAO (Kettlewell *et al.* 2005). Perennial ryegrass was newly sown each year in the experiment at North Wyke and fertilized intensively in contrast to the mixed species, unfertilized sward in the Park Grass Experiment. Weekly cuts were taken in the second year of growth and this enabled a much more accurate growth rate to be calculated specifically for June, July and August compared with the average over the long and varying period between the two cuts at Rothamsted. The summer growth rate at North Wyke showed a significant relationship with the winter NAO over the years 1982–1992 with the winter NAO index accounting for 74% of the interannual variation in growth rate.

The shorter and earlier of the two periods (1902–1926) was examined to discover whether the relationship between the NAO and growth rate also existed in the early part of the twentieth century. Examination of a scatter graph and correlation analysis of the summer herbage growth rate and the winter NAO index showed that no relationship existed between these two variables over this period ($r=0.068$; n.s.). This implies that the winter NAO may not have been correlated with summer climate at that time. Three published studies have investigated temporal stability in the relationships between the winter NAO and UK summer climatic variables. Kettlewell *et al.* (2003) showed that the correlation between the winter NAO and June, July, August EWP became much weaker when extended back in time from the 1974–2000 period to cover 1865–2000. Similarly, Wilby *et al.* (2004) found that the relationship between the August CET and the winter NAO index was temporally unstable. There was no apparent relationship from 1946 to 1970, but a significant correlation from 1971 to 1995. Qian & Saunders (2003) computed running 30 year correlations between the January–February NAO and summer (June, July, August) CET from 1824 to 2001. They found significant correlations only since the Mid-1960s. Therefore, it appears that the lack of correlation between summer herbage growth rate and the winter NAO early in the twentieth century compared with the later twentieth century may have resulted from temporal instability in the relationship between the winter NAO and UK summer climate. Support for these results from the Park Grass Experiment comes from analysis of the quality of wheat grain from the wheat experiment on Broadbalk Field at Rothamsted. This also shows that no relationship with the winter NAO existed in the early twentieth century in contrast to the later twentieth century (M. D. Atkinson 2005, personal communication).

The correlations between the winter NAO and summer climate and drought have been shown to occur over a large part of Britain, but not to extend very far into mainland Europe (Wedgbrow *et al.* 2002; Kettlewell *et al.* 2003; Qian & Saunders 2003). Thus, it can be inferred that summer primary productivity of grassland ecosystems in many parts of Britain may be associated with the preceding winter NAO. In contrast, primary productivity of grassland ecosystems in most of mainland Europe and Scandinavia is unlikely to be related to the winter NAO. Body weight of species further down the food web such as large mammals in Norway is, therefore, unlikely to be associated with summer climate, supporting the conclusion of Mysterud *et al.* (2001) that the correlation of the winter NAO with body weight of sheep and red deer is indirect, through association with winter climate. In contrast, growth of mammals grazing grassland ecosystems in the UK and neighbouring parts of mainland Europe may be associated with the winter NAO mediated through the summer climate and soil moisture supply.

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