

The Impacts of the NAO on the Vegetation Activity in Iberia

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Abstract The present study analyses the relation between North Atlantic Oscillation (NAO) and satellite-based measures of vegetation dynamics (as obtained using Normalized Difference Vegetation Index, NDVI), carbon absorption by living plants (obtained by Net Primary Production, NPP estimates) over Iberian Peninsula and wheat yield in Portugal. There is a strong evidence that positive (negative) values of winter NAO induce low (high) vegetation activity in the following spring and summer seasons. Consequently, significant correlations patterns between NAO and NPP were also obtained, identifying a negative impact in spring and summer over southern Iberia. These features are mainly associated with the impact of NAO on winter precipitation, together with the strong dependence of the spring and summer vegetation activity on water availability during the previous winter. The different role played by NAO along the vegetative cycle of wheat yield in Portugal is also assessed and results obtained suggest using spring NDVI together with NAO in April and June to build up a simple model of wheat yield in Portugal. Results reveal to be satisfactory and are expect to be useful to estimate crop production and to perform agricultural monitoring.

Keywords NAO · Vegetation activity · NDVI · NPP · Wheat yield

1 Introduction

Recent global changes in vegetation dynamics have been continuously monitored from space and, additionally, significant connections with changes of surface climatic variables, such as temperature and precipitation, have been established (Myneni et al., 1997; Zhou et al., 2001; Nemani et al., 2003). In particular, the observed increment in temperature during spring and autumn over high latitude regions of the Northern Hemisphere leads to higher photosynthetic activity and larger growing seasons (Groisman et al., 1994; Boagert et al., 2002; Shabanov

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et al., 2002). However, whereas in spring photosynthesis dominates respiration, the opposite takes place in autumn and therefore it is in spring that an increase in CO₂ sequestration is expected to occur (Piao et al., 2008). Accordingly, in a future warmer world, carbon sequestration capacity by northern hemisphere ecosystems may decrease faster than previously suggested due to a faster warming in autumn than in spring (Sitch et al., 2008). Nevertheless, changes in the seasonality of temperature and precipitation may have distinct impacts, depending on local characteristics. The strong dependence of vegetation dynamics on water availability in the Mediterranean regions has been now widely recognized (e.g. Gouveia et al., 2009; Vicente-Serrano, 2007; Lindner et al., 2010). It has been showed that the lack of precipitation over a certain period, combined with other climatic anomalies, such as high temperature, strong wind and low relative humidity over a particular area, may result in reduced green vegetation cover.

The above mentioned changes in the vegetation annual cycle can be detected, using satellite information, namely from observed changes in the most widely used vegetation-related satellite variable, the Normalised Difference Vegetation Index (NDVI) (Stöckli and Vidale, 2004; Vicente-Serrano and Heredia-Laclaustra, 2004). However, there is a strong need of long term studies of the impact of atmospheric circulation variability on vegetation greenness. In this context, special attention has been devoted to study the links between vegetation dynamics and the North Atlantic Oscillation (NAO). D'Odorico et al. (2002) showed that spring phenology and timing of pollen season in British Isles, Poland, Norway and Sardinia are influenced by NAO, with leaf unfolding occurring later (earlier) for negative (positive) phases of NAO. Stöckli and Vidale (2004) found that spring phenology over Europe, as obtained using AVHRR Pathfinder NDVI data, correlates well with anomalies in winter NAO index, as well as in winter temperature. More recently, Maignan et al. (2008) showed the strong impact of NAO on the vegetation onset over a large fraction of Northern Europe. The pattern of the NAO control on the vegetation dynamics is clearly apparent over a large extension of Europe revealing in general an evident North–South gradient.

On a more regional context, Vicente-Serrano and Heredia-Laclaustra (2004) analysed the NAO control on Iberian vegetation productivity trends, as represented by the annual integral of monthly AVHRR Pathfinder NDVI values. The NAO impact revealed to be stronger in southern Iberia that corresponds to areas of stable or decreasing vegetation productivity. On the other hand the NAO impact on vegetation greenness is weaker in the north of the peninsula, over areas where significant positive productivity trends occur. Gouveia et al. (2008) expanded the analysis on the relationship between vegetation greenness and NAO to the entire Europe. The authors relate the different vegetation behaviours particularly over Iberian Peninsula and Northeastern Europe, with a strong dependence of vegetation dynamics from water availability in Iberia and from winter temperature in Northeastern Europe.

Terrestrial Net Primary Production (NPP) is a measure of the amount of carbon fixed by the living plants and converted into plant biomass. Nemani et al. (2003) showed that changes in climate, related to increasing temperature and solar radiation, have eased several critical constrains to plant growth, leading to an upward

trend in global NPP from 1982 to 1999. However, they have also shown that NPP respond differentially with respect to latitude to major climate events, such as volcanic eruptions and El Niño episodes. Globally, NPP decreases during the three major El Niño events (particularly over tropical regions), while the decrease after Mount Pinatubo eruption was mostly restricted to northern hemisphere high latitudes. Recently, Zhao and Running (2010) showed that large-scale droughts have reduced NPP during the last decade, imposing a drying trend for the entire southern hemisphere, whereas an increased NPP can be found over the majority of the northern hemisphere.

Finally, climate is a key factor for the majority of agricultural systems, due to their dependence on interannual climate variability and in particular, their vulnerability to extreme events such as; droughts, floods and frost or hail occurrences. Important relations between regional distributions of temperature and precipitation and wheat yield for the European countries have been found (Cantelaube et al., 2004). In particular the winter NAO index has been associated with UK wheat crop and with better wheat, rye, oat and citrus yields in the Iberian Peninsula (Atkinson et al., 2005; Gimeno et al., 2002). Although not directly related to NAO, some authors have analysed in detail the links to climate variables that are ultimately related to this mode of variability. Iglesias and Quiroga (2007) evaluated over five sites in Spain the effects of climate variability on the final crop. Similarly drought indices and remote-sensed data were used to predict wheat and barley yields in the Ebro valley (Vicente-Serrano et al., 2006). Rodríguez-Puebla et al. (2007) have derived a model that integrates the effects of abundant precipitation together with dynamic aspects of the air masses during the maturation in order evaluate their effects on winter cereals productivity in Spain.

1.1 Objectives

Here we intend to provide a comprehensive assessment on the impact of NAO on various vegetation related variables, namely NDVI, NPP and crop yields. While some of these analyses were initially performed for other regions in northern Europe we opted here to focus only on the western Mediterranean sector.

1.2 Data

A number of restrictions on access to different types of dataset implied slightly distinct periods of analysis. The NPP monthly estimates were obtained in the frame of a Portuguese funded project entitled CARBERIAN, using the Carnegie Ames Stanford Approach (CASA) terrestrial biogeochemical model (Potter et al., 1993; Friedlingstein et al., 1999) for the period 1982–1999. The CASA simulates plant and soil processes allowing the estimation of both NPP and NEP (Net Ecosystem Productivity). Besides climate variables (precipitation, temperature and radiation)

the model incorporates information from vegetation and land cover types using satellite data, as well as soil texture and soil depth (Seixas et al., 2009).

The NDVI monthly anomalies, with 8 km of spatial resolution, were obtained from the Global Inventory Modeling and Mapping Studies (GIMMS) dataset. This dataset holds 24 values per year (i.e. twice a month) and corresponds to the most complete and longest remote sensing dataset covering the entire Mediterranean region. In the case of the assessment of the NAO impact on vegetation dynamics we have performed the analysis for the period 1982–2002. Finally, the evaluation of the NAO impact on Portuguese crop yields covers the period spanning between 1982 and 2005.

The NAO index used in this study is based on the one developed by the Climatic Research Unit (CRU), which was originally defined, on a monthly basis, as the difference between the normalized surface pressure at Gibraltar, in the southern tip of the Iberian Peninsula and Stykkisholmur, in Iceland (Jones et al., 1997). For each year covering the above mentioned periods, we have derived a late winter NAO index (hereafter referred only as NAO), defined as the average of the monthly values for January, February and March of the corresponding year.

2 Results

2.1 NAO and Vegetation Dynamics

Figure 1 displays the spatial patterns over Iberia of point correlation values of winter NAO and NDVI for spring ($NDVI_{MAM}$), summer ($NDVI_{JJA}$) and autumn ($NDVI_{SON}$) for the period between 1982 and 2002. Results show a negative correlation over the Iberian Peninsula in spring and summer, with some values reaching as low as -0.8 . Positive correlations are found in northern and eastern Iberia, as well as in Murcia region in spring (values around 0.7). However in summer the positive

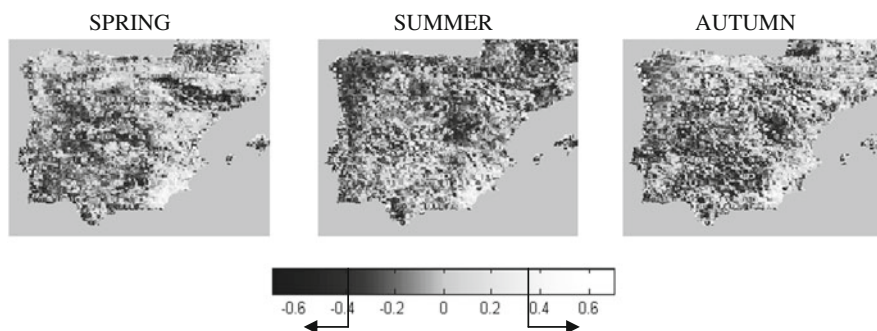


Fig. 1 Point correlation fields of NAO vs. $NDVI_{MAM}$ (left panel) and NAO vs. $NDVI_{JJA}$ (middle panel) and NAO vs. $NDVI_{SON}$ (right panel) for the period from 1982 to 2002. The colorbar identifies values of correlation and the two arrows indicate the ranges that are significant at 5% level

correlations are restricted to the Murcia region. A weaker pattern of correlations is found during autumn, presenting lower but still significant positive correlation (values around 0.4) spreading over eastern and Northern Iberia and presenting a negative pattern in Southern Iberia. These patterns are in good agreement with those obtained previously in the works of Buermann et al. (2003) and Vicente-Serrano and Heredia-Laclaustra (2004). This behaviour reflects the response of the annual variability of meteorological variables to large-scale atmospheric variability associated to the NAO mode, as well as the different response of vegetation to atmospheric variability, namely the changes induced by temperature and precipitation in the annual cycle of heat and moisture.

It should be stressed that other factors linked to the human influence can disturb the relationship between atmospheric parameters and vegetation, such as the nature and quality of the plant substrate, the over-use of agriculture land and the employment of irrigation (Gouveia et al., 2008). In order to isolate the NAO effect on vegetation dynamics, as obtained by NDVI, from factors related to the human influence, we have compared the NDVI anomalies for two subsets of years associated to extreme NAO indices: (i) higher than usual values of seasonal NAO index (whenever the NAO index is higher than the percentile 75 of its distribution) and (ii) lower than usual (whenever the NAO index is lower than the percentile 75 of its distribution). Figure 2 shows a comparison of seasonal NDVI anomalies for the two subsets of years associated with NAO- (upper panel) and NAO+ (lower panel). In the case of spring NDVI anomalies present well defined pattern over central and western Iberia. The southern anomaly center is particularly intense, positive (negative) anomalies being observed in spring NAO- (NAO+). The pattern is remaining in

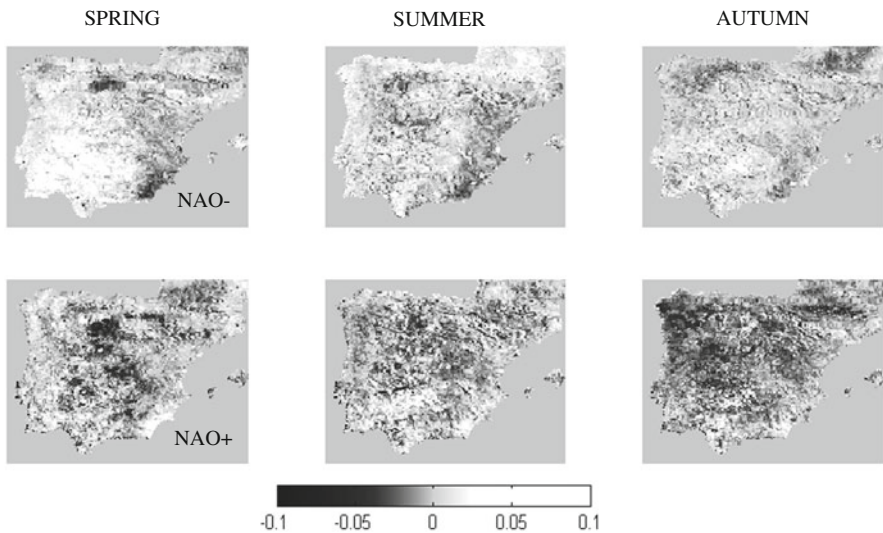


Fig. 2 Seasonal anomalies of NDVI for years of NAO- (top panel) and NAO+ (bottom panel) for spring (left), summer (middle) and autumn (right)

the following seasons, albeit with lower correlation values. Therefore, it means that for years characterised with positive winter NAO values, the vegetation is in vegetative stress, with lower than usual NDVI values, a feature that is common during drought years, like the recent 2004/2005 drought event (Gouveia et al., 2009).

In fact, Gouveia et al. (2008) have found significant correlations between winter NAO and contemporaneous late winter means of surface temperature and precipitation. For precipitation a well-developed meridional dipolar structure over Europe, delimiting two well-defined zonal bands of positive and negative correlation values along Northern Europe and Mediterranean region respectively. However it is also known that the connection between NAO and temperature over Iberia is not as clear-cut as for precipitation (Castro-Díez et al., 2002; Trigo et al., 2002). Although it is known that the impact of NAO on temperature and precipitation described above is especially prominent in winter (e.g. Vicente-Serrano and Heredia-Laclaustra, 2004; Trigo et al., 2004), such behaviour contrasts with that obtained for vegetation activity (Fig. 1), where the impact of NAO is clearly significant in spring, summer and autumn. Consequently the relationship between late winter temperature and precipitation with vegetation greenness in the following seasons are very important.

Additionally the work of Gouveia et al. (2008) showed that almost two thirds (64%) of the pixels that exhibit the highest (lowest) values of positive (negative) correlations of NDVI_{MAM} and NDVI_{JJA} with NAO correspond to areas of spring crops and about one sixth (17%) to forests and shrublands. The relative proportion of the two types undergoes a significant change in summer with only 29% relative to forest and shrubland, and an increase to 47% associated to cultivated areas. These results reflect the distinct responses of the various land cover types to moisture and heat conditions prevailing during the previous winter.

The Iberian Peninsula presents the same response of vegetation to precipitation in spring and summer, i.e. an increase (decrease) of vegetation greenness for NAO– (NAO+) years. A small dependence of vegetation greenness on temperature is also apparent in the case of spring (Gouveia et al., 2008). Additionally, Gouveia et al. (2008) have emphasized that the impact on precipitation is three times larger over Iberian Peninsula than the corresponding impact over Northern Europe. This feature is consistent with the specific dependence of NDVI on precipitation over Iberia, since vegetation growth is much more water-limited in Iberia than in Northern Europe, where temperature and snow cover play a major role (Trigo et al., 2002; Gouveia et al., 2008).

The remarkable differences in the response of vegetation to moisture and heat conditions, lead us to analyse the NDVI annual cycle for the highest (lowest) values of positive (negative) correlations of NDVI_{MAM} and NDVI_{JJA} with NAO over Iberia. Figure 3 shows the annual cycles of NDVI monthly values for the highest (lowest) values of positive (negative) correlations of NDVI_{MAM} and NDVI_{JJA} with winter NAO, for spring (left panel) and summer (right panel). The annual cycles of averages for the NAO+ (NAO–) subsets are identified by the thin solid (dashed) curves, while the annual cycles of mean NDVI for the entire period (1982–2002) are represented by thick solid lines.

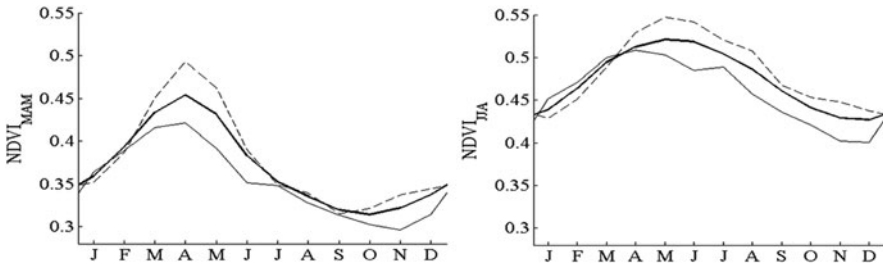


Fig. 3 Annual cycles of monthly values of NDVI for the highest (lowest) values of positive (negative) correlations of $NDVI_{MAM}$ and $NDVI_{JJA}$ with winter NAO, for spring (left panel) and summer (right panel), over Iberia. The annual cycles of averages for the NAO+ (NAO-) subsets are identified by the thin solid (dashed) curves and the annual cycles of mean NDVI for the entire period (1982–2002) are represented by thick solid lines

The highest impact of NAO is observed to occur during the periods of the year characterised by more intense vegetation activity (Ji and Peters, 2003), i.e. around April (June) in the case of highest correlated pixels for spring (summer). In the case of spring vegetation, two thirds of the pixels correspond to cultivated areas that are mostly associated to non irrigated crops, adapted to the relatively dry Iberian conditions. Vegetation has a short growth cycle, due to the generally observed high temperatures, starting as soon as water is available. This is a typical situation that can be favoured by NAO-. In the case of summer, the growing period of the most impacted vegetation starts later and therefore the response to precipitation tends to extend late in the year (Gouveia et al., 2008).

2.2 NAO and NPP Estimates

Figure 4 displays the spatial patterns over Iberia of point correlation values of winter NAO (NAO_{JFM}) and NPP for spring (NPP_{MAM}), summer (NPP_{JJA}) and autumn (NPP_{SON}) for the period between 1982 and 1999. This slightly shorter period results from the limited period of available data obtained with the CASA model by our colleagues within the CARBERIAN project that started in the early 2000s. Results show a negative correlation between NAO and NPP over the Iberian Peninsula in spring and summer, with values as low as -0.7 (Fig. 4, top panel). Positive correlations are found in northern and eastern Iberia and Northwestern Portugal. The highest positive correlations (values around 0.6) are found in Pyrenees and in coastal Mediterranean region of Murcia in spring. However in summer the positive correlations are mostly restricted to the Murcia region. A weaker pattern of correlations is found during autumn, presenting lower but still significant positive correlation (values around 0.4) spreading over eastern and Northern Iberia, Murcia region and southern Portugal. Interesting to notice the strong pattern of negative correlations located in the Southern interior of Iberia.

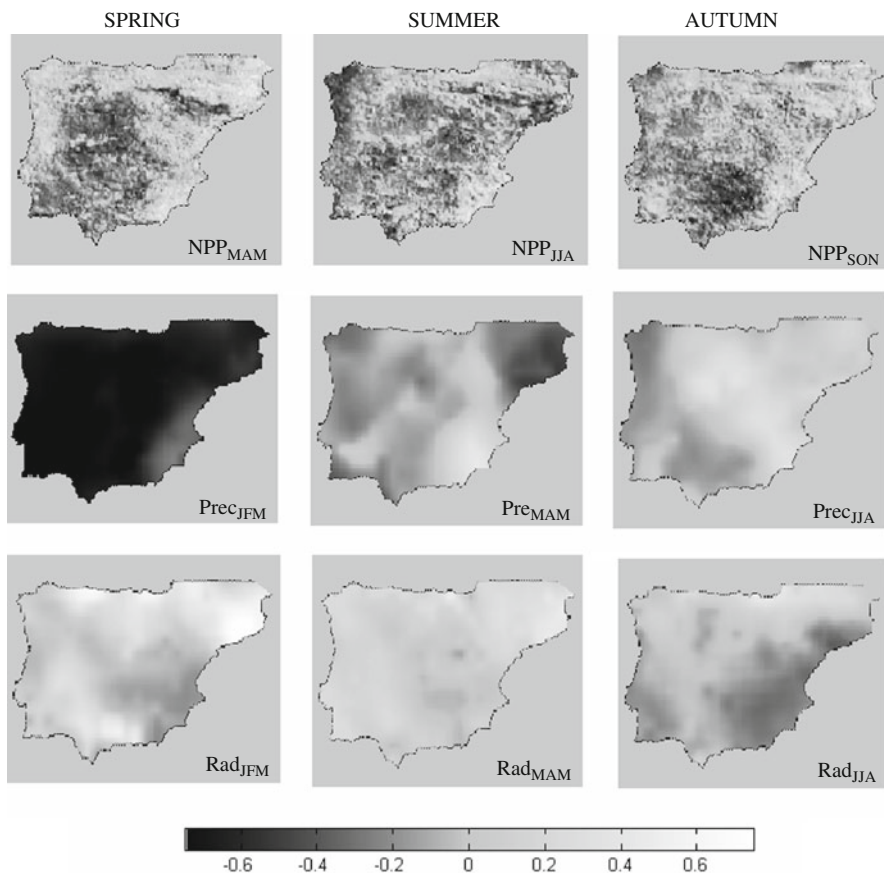


Fig. 4 Correlation fields of NAO vs. NPP, for spring (*left panel*), summer (*middle panel*) and autumn (*right panel*) over the period from 1982 to 1999 (*top panel*) and NAO vs. Precipitation (*middle panel*) and NAO vs. short wave radiation (*bottom panel*), for winter (*left panel*), spring (*middle panel*) and summer (*right panel*) over the period from 1982 to 1999

The impact of NAO in the previous winter, as well as in spring and summer in precipitation and short wave radiation is also provided in Fig. 4 (middle and bottom panels, respectively). As expected the negative pattern of correlations between NAO and NPP in spring is highly related to the corresponding impact of NAO on winter precipitation and short wave radiation. Thus, during the years characterised with a positive NAO mode in winter, lower precipitation and higher short-wave radiation (and fewer clouds) can be observed in the central Iberia, corresponding to lower NPP estimates. These results are in good agreement with the works of Nemani et al. (2003) and Zhao and Running (2010). This behaviour reflects the response of short-rooted grassland and croplands characteristic of the northern mid-latitudes, where water availability is a dominant control for plant growth. Accordingly to the analysis

undertaken by the above mentioned authors, NPP has a significant positive correlation with both total precipitation and Palmer Drought Severity Index (PDSI), which means that higher precipitation values and consequently lowers than usual NAO values, usually lead to higher NPP estimates. This result is compatible with the negative values of correlations between winter NAO and NPP that are prevailing during spring, summer and autumn. The exceptions for this behaviour are the forest areas typical over the Northwestern Iberia and higher altitude mountains in Pyrenees, that are more insensitive to precipitation and temperature and also the Murcia region where the NAO plays a negligible role.

The above mentioned differences in the response of vegetation to moisture and heat conditions prompted the analysis of the evolution (for NAO+ and NAO-) of NPP annual cycles for two sites over Iberia, used to calibrate and validate the CASA Model over Iberia (Seixas et al., 2009). Figure 5 (left panel) shows the annual cycles of monthly NPP for the above selected sites. The two selected sites correspond to two contrasting situations; one site being characterised mainly by negative correlation between NAO and NPP estimates located in the south of Iberia (site 1 in Fig. 5, top panel) while the other is characterised by positive correlations located in the North of Iberia (site 2 in Fig. 5, bottom panel). Moreover, while site 1 presents a maximum of NPP estimates during spring and site 2 corresponds to pixels with a maximum of NPP estimates during summer. Figure 5 (left panel) shows the annual cycles of NPP monthly anomalies for the above selected sites.

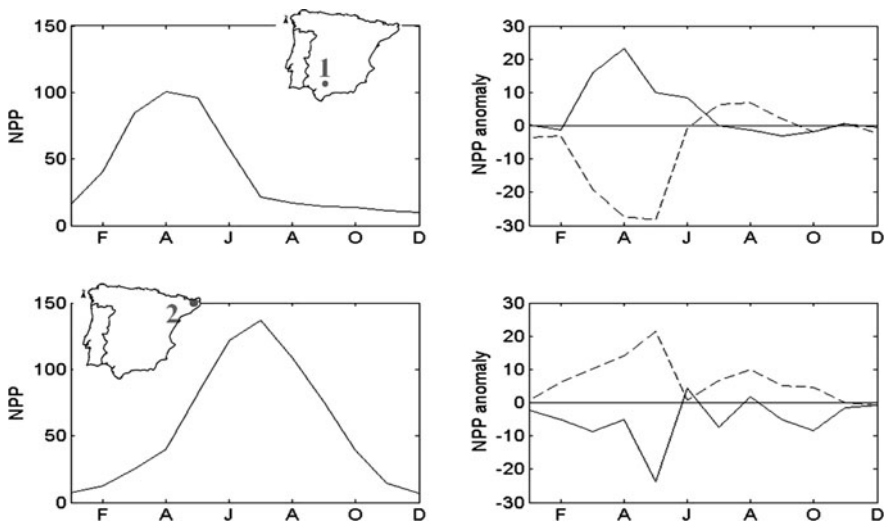


Fig. 5 *Left panel:* Annual cycles of monthly NPP estimates for site 1 located in the south of Iberia (*top panel*) and a site 2 located in the north of Iberia (*bottom panel*). *Right panel:* corresponding annual cycles of monthly anomalies of NPP estimates for the NAO- (*thin solid line*) and NAO+ (*thin dashed line*) subsets over site 1 (*top panel*) and site 2 (*bottom panel*)

The annual cycles of NPP anomalies for the NAO– (NAO+) subsets are identified by the thin solid (dashed) curves. The highest impact of NAO is observed to occur during spring and also in summer in the case of site 2. Differences in topography should be taken into account, as site 1 corresponds to low altitude areas while site 2 is located in a mountainous region. Moreover there are disparities in the main vegetation type characteristic of these sites; while site 1 are mainly grasses, cereal crops, site 2 is dominated by needleleaf forest. During years characterized by positive winter NAO, NPP estimates present low values during spring over site 1. This situation corresponds to years with considerably lower (higher) than usual precipitation (short wave radiation) that may inhibit the vegetation greenness and consequently low NPP estimates. This is the typical situation during drought events (García-Herrera et al., 2007). In the case of mountainous areas (site 2) where the vegetation activity is not dependent of the scarcity of water in part due to the lower temperature, the NPP estimates are relatively high during spring and even during summer although with relatively lower values than in spring. These features are in good agreement with the previously mentioned authors that related the climate variability and the carbon absorption from living plants (Nemani et al., 2003; Zhao and Running, 2010).

2.3 NAO and Wheat Yield

In order to quantify the climate impact on the wheat yield in Portugal it must be stressed that it is considerably smaller than the corresponding wheat yield obtained in the North-western European countries, with cold (but not too wet) winters and relatively wet summers (Gouveia and Trigo, 2008). During the grain filling until the complete grain ripening phase, the Mediterranean conditions may even get worse, due to the short period of time between frost episodes and relatively high temperatures at the end of spring (May/June). Another adverse situation, especially when compared with the same period for North-western European countries, consists in the low photoperiod (number of sun hours) and the high temperatures, which may occur at the end of the maturation phase. During this phase large values of potential evapotranspiration may lead to weak photosynthetic activity, since the plant mostly spends most of energy in the transpiration process in order to offset the warm season effects, thus reducing its capacity to produce dry matter. An excess of evapotranspiration may therefore lead to a decrease of wheat quality (Gouveia and Trigo, 2008).

In order to evaluate the seasonal evolution of the correlation between NAO and wheat yield we have performed a monthly evaluation (Table 1) reflecting the different role played by NAO along the vegetative cycle of wheat. In fact, the contrast between late winter/early spring and late spring/early summer is well apparent, with low correlations between NAO and yield in January to March being replaced by positive correlations for April and June (the last one significant at the 5% level). The role of NAO in June appears to be related to the need of warm temperatures during the wheat maturation phase, and simultaneously the absence of precipitation.

Table 1 Correlation coefficient values between annual wheat yield and monthly NAO (from January to June) for the pixels coded as arable land not irrigated. Bold values highlighted when significant at the 5% level

	Jan	Feb	Mar	Apr	May	Jun
NAO	0.06	0.08	-0.04	0.27	-0.06	0.53

The first and simplest assessment on the NAO effective impact on wheat production is shown in Fig. 6 (top panel) that depicts the inter-annual evolution of the NAO during April and June (NAO_{AJ}) and detrended wheat yield, considering the 24 year period between 1982 and 2005, presenting a correlation value of 0.49. With the aim of isolating the effect NAO on annual wheat yield from human-related factors we adopted the methodology described in Section 2.1, comparing the detrended wheat yield for two subsets of years associated to extreme NAO indices: (i) higher than usual values of seasonal NAO index ($NAO >$ percentile 75) and (ii) lower than usual (NAO lower than percentile 25). Figure 6 (lower panel) shows a comparison of annual wheat yield for the three subsets of years associated with $NAO+$, $NAO-$ and intermediate class. Generally speaking, years presenting positive (negative) anomalies for wheat yield are usually characterized by positive (negative) NAO index values in late spring. Therefore, it is possible to confirm that late spring correspond to an important moment for the wheat vegetative cycle in Portugal and that the NAO index controls, at least partially, what is happening in this moment of the vegetative cycle.

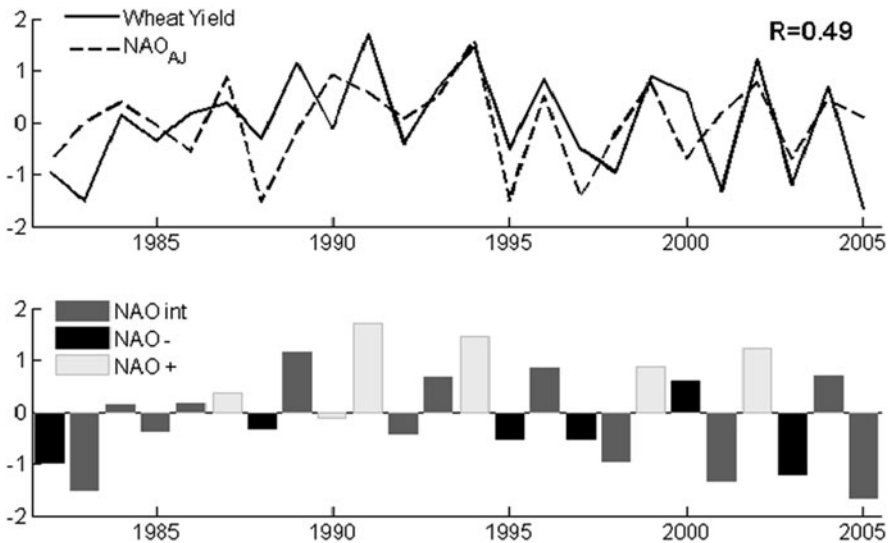


Fig. 6 Top panel: Inter-annual variability of spring NAO Index (dashed line) and wheat yield over the period 1982–2005. Bottom panel: Inter-annual evolution of annual wheat yield for years characterised by NAO_{AJ+} , NAO_{AJ-} and intermediate subsets

In summary, a good wheat yield usually corresponds to years characterized by positive NAO values in spring, particularly in April and June. This behaviour may be viewed as reflecting the integrated impact on radiation, temperature and precipitation fields of the large scale atmospheric circulation patterns associated to the different phases of NAO. The role of NAO in June could be especially related to the necessity of warm temperatures during the maturation phase of wheat.

Figure 7 (left panel) shows the grid point correlations between spring NDVI composites ($NDVI_{MAM}$) and detrended wheat yield, considering the 24 year period between 1982 and 2005. The highest positive and significant correlations (at the 1% level) are found over the southern region of Alentejo (Fig. 7, left panel). The analysis was restricted to the set of pixels that were coded, using Corine Land Cover Map (CLC2000) as non irrigated arable land. The average of spring NDVI for this subset of pixels holds a correlation value of 0.70 (significant at the 1% level). Results obtained above suggest using spring NDVI together with late spring NAO to build up a simple model of wheat yield for Portugal for the period 1982–2005. Spring NDVI is an indicator of the healthiness of wheat during the growing stage which in turn reflects the meteorological conditions in terms of radiation, temperature and

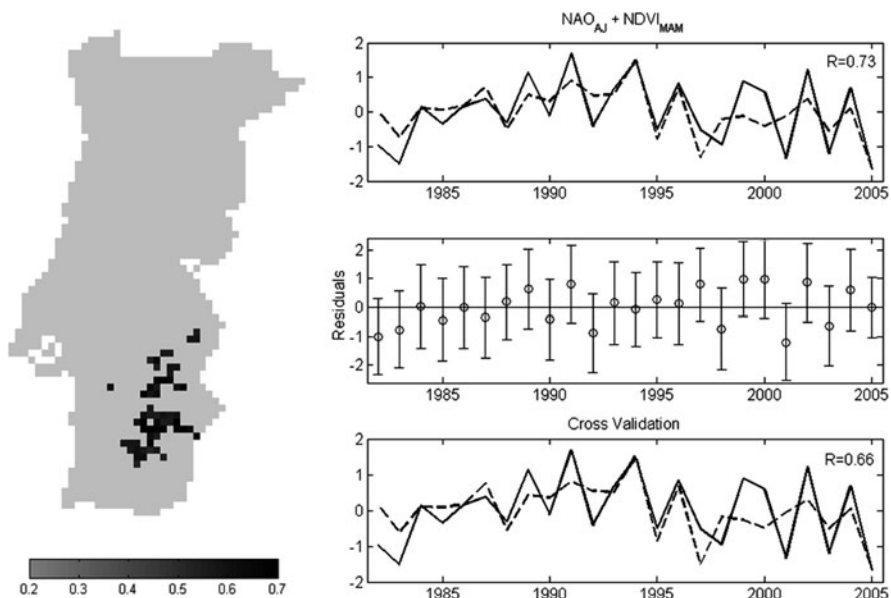


Fig. 7 *Left panel*: Patterns of simple correlation between spring NDVI composites and wheat yield in Portugal, for the period of 1982–2005, for pixels coded as arable land non-irrigated and significant at the 1% level. *Right panel*: Time series (1982–2005) of observed (*dark curve*) wheat yield in Portugal and of corresponding modelled values (*dashed curve*) when using a linear regression model based on spring NDVI and NAO in April and June (*upper panel*). Time series (1982–2005) of residuals and respective 95% level confidence intervals (*central panel*). Time series (1982–2005) of observed (*dark curve*) wheat yield in Portugal and of corresponding modelled values (*dashed curve*) as obtained from the leave-one-out cross-validation procedure

precipitation regimes. On the other hand late spring NAO is an indicator of the large-scale circulation affecting Portugal which in turn is related to regional conditions in terms of radiation, temperature and precipitation that have an important role in the wheat maturation process.

In fact a simple multi-linear regression model was calibrated and validated for the 24-year period of available data, using as predictors the spring NDVI_{MAM} together with NAO_{AJ}. Figure 7 (right-upper panel) presents the time series of observed and modeled wheat yield. The overall agreement is worth being noted, with the two time-series presenting a correlation of 0.73. Figure 7 (right-central panel) shows the time series of residuals, defined as departures of observed values from modeled ones. The 95% confidence intervals relative to these residuals are plotted as error bars and it may be noted that there is not presenting any outlier since its error bar does not cross the zero reference line. Simple calibration approaches, using the entire period of available data, can lead to misleading results, namely over-fitting (Wilks, 2006). Therefore it is advisable to use more robust validation approaches, such as the leave-one-out cross validation (Fig. 7, right-lower panel). The good agreement between the modelled time series by the regression model (upper panel) and the one obtained by the cross validation indicate that the developed model is relatively robust with only a slight decrease (from 0.73 to 0.66) on the correlation between original and modelled time series. In summary, these results are statistically robust but also physically sound, revealing a very satisfactory performance and are expect to be useful to estimate crop production as well as to perform agricultural monitoring.

3 Conclusions

The behaviour of vegetation reflects the different response of surface climate to large-scale atmospheric variability associated to the NAO mode. Over Iberia there is strong evidence that positive (negative) values of winter NAO induce low (high) vegetation activity in the following spring and summer seasons. This feature is mainly associated with the impact of NAO on winter precipitation, together with the strong dependence of spring and summer NDVI on contemporary water availability. It is also related with the strong impact of climate variability in semi-arid areas, namely regarding effects of drought conditions on vegetation activity (Vicente-Serrano and Heredia-Laclaustra, 2004), in particular during the intense spring vegetation growth period.

In Iberia the NAO impact is greater on non-forested vegetation which responds rapidly to spatio-temporal variations in precipitation and soil moisture. During summer, forests and other dense vegetation areas display the highest sensitivity to NAO dynamics, as this type of vegetation shows slower response to precipitation, and therefore the NAO impacts are delayed until late in the year. Consequently, the NAO impact negatively on NPP estimates in southern and central Iberia and positively over the Northern mountainous areas. In fact, in Iberia the NAO impacts negatively the short-rooted grassland and croplands which responds rapidly to spatio-temporal

variations in precipitation and soil moisture. This type of vegetation is very sensitive to drought events.

It should be stressed that our lagged relationships between winter NAO and NDVI values for spring, summer and autumn already represent an added value since they allow formulating, by the end of March, simple outlooks of vegetation greenness for certain land cover types over the Iberian Peninsula that may provide useful information for a wide range of applications, including long-lead wildfire risk assessment and crop forecasts. It is within this context that we have evaluated the impact of NAO on cereal production over a specific region of Iberia with sufficient data. Accordingly, a strong negative correlation (range from 0.6 to 0.8) between NDVI and wheat yield for the 24 year-long period 1982–2005, over the southern part of Portugal (Alentejo) was obtained. A good year for wheat yield is usually characterized by positive NAO values for late spring. To obtain a good wheat yield, the NAO index signal in late spring should be positive, inducing higher values of short wave radiation and lower values of precipitation in the Iberian Peninsula. The low precipitation wheat requirements in this period allow a slow maturation to origin well formed grains and avoid the pests development and potential decrease of the wheat quality as mentioned before.

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