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NOTES AND COMMENTS

Effects of the North Atlantic Oscillation (NAO) and meteorological variables on the annual Alcarria honey production in Spain

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La Alcarria is one of the most significant regions for honey production in Spain. Times series data of the annual Alcarria honey production from 2000 to 2013 revealed that the total production was highly variable ranging from ca. 60,000 kg in 2000 to almost three times as much in 2011, but without a remarkable trend through time. We hypothesized that these local fluctuations in honey production may be explained by broad-scale climatic patterns. Based on the multiple linear models, we found a significant positive relationship between honey production as a function of the overall means of the North Atlantic Oscillation (NAO) index and precipitation in January, which accounts for 80% of the variability in the Alcarria honey production. We propose that the effect of a negative phase of the NAO and precipitation in January could predict the Alcarria honey production a few months in advance.

Keywords: Alcarria honey; North Atlantic Oscillation; precipitation

Honey production reflects the relative success of the reproductive phenology of vegetation and the foraging of honey bees as pollinators; both are under the influence of climate (Gordo & Sanz, 2010; Potts et al., 2010). For this reason, honey production could reflect inter-annual climate variability, with emphasis on both extreme conditions and changes in the historical patterns of regional climate, as has been described for crops (Hoogenboom, 2000). Although several studies have focused on the effect of climate on honey production, the usual approach correlated a single meteorological factor, such as temperature (Langowska et al., 2017). However, climate variability is best described by integrative climatic indexes and, indeed, it has been found that the North Atlantic Oscillation (NAO) index is responsible for most of the climate variability in southern Europe (Corte-Real, Wang, & Zhang, 1995; Hurrel, 1995; Hurrel & van Loon, 1997; Hurrell, Kushnir, Ottersen, & Visbeck, 2003). In fact, it has been suggested that the NAO index can explain the inter-annual variability of both agroecosystems (Gimeno et al., 2002; Real & Báez, 2013; Rodríguez-Puebla, Ayuso, Frías, & García-Casado, 2007) and natural ecosystems (Báez, Gimeno, Gómez-Gesteira, Ferri-Yáñez, & Real, 2013; Báez et al., 2014; Melero-Jiménez et al. 2017) in the Iberian Peninsula and neighboring areas.

In Spain, La Alcarria is one of the most significant regions for honey production located in the provinces of Guadalajara and Cuenca in Castilla-La Mancha. The Alcarria region is characterized by a rich honey flora (mainly Lamiaceae) of the shrubs *Rosmarinus officinalis* L. and *Lavandula latifolia* Medik, and in a lower proportion, *Thymus*, *Genista*, *Satureja*, and cultivated sunflower (Ortíz Valbuena, 1992). Alcarria honey is a high-value, high-quality honey with "Denomination of Origin" recognized by the regulations of the Spanish Government and European Union in 1992 and 1996, respectively. The production of Alcarria honey has suffered strong oscillations in recent years, and we speculated that the production could be correlated to climate variability, in particular, to the inter-annual variability of the NAO index.

The aim of this study was to test the possible correlation between the NAO and meteorological variables with the Alcarria honey production. We found a significant multiple linear model linking the annual honey production from 2000 to 2013 with the NAO index and precipitation in January. We propose that this multiple linear model could be used to predict honey production.

We obtained official data on annual Alcarria honey production (2000–2013) from the Regulatory Council of the "Domination of Origin" of the Alcarria honey

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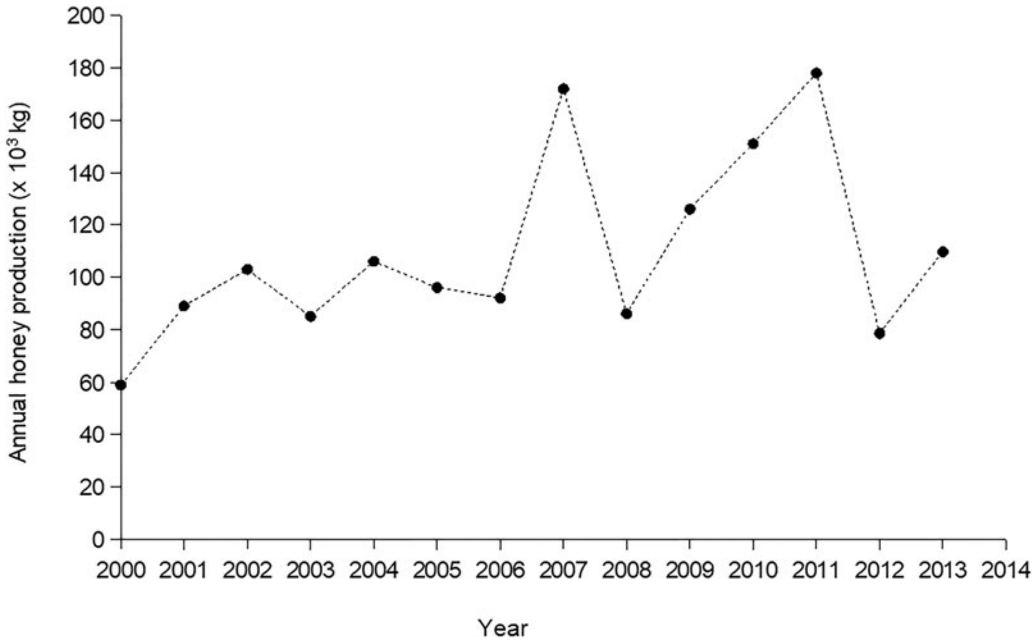

Figure 1. Annual Alcarria honey production (2000–2013).

(https://mieldelaalcarria.org) From 2000 to 2013, the annual Alcarria honey production ranged from ca. 60, 000 kg in 2000 to 178,000 kg in 2011, although a clear trend cannot be established (Figure 1).

Monthly values of the NAO index were collected from the U.S. National Oceanic and Atmospheric Administration (www.cpc.noaa.gov). The NAO index can be determined from monitoring station data (Hurrell, 1995) or identified by means of Empirical Orthogonal Function analysis. It is currently computed by using teleconnection monthly standardized 500 mb height anomalies, from the region 20°N to 90°N.

The NAO exhibits strong inter-annual and intra-annual variability (Hurrell, 1995) and has been found to have a delayed effect on ecosystem processes (Báez et al., 2013, 2014; Melero-Jiménez et al., 2017). There is strong evidence that winter NAO values affect the vegetation activity in the following spring and summer seasons (Atkinson, Kettlewell, Hollins, Stephenson, & Hardwick, 2005; Gouveia, Trigo, DaCamara, Libonati, & Pereira, 2008). Taking into account that the main flowering season in La Alcarria starts in spring, we selected as variables the overall monthly mean NAO indexes from November to April.

We further included additional meteorological variables relevant to the study area from the Spanish Meteorological Agency (www.aemet.es). The meteorological data analyzed were monthly recorded maximum, minimum and average temperatures, total precipitation, number of days with rain, and number of days with snow recorded at the station Salto del Bolarque, Guadalajara, within La Alcarria region. The time series data of the NAO index and the meteorological variables extended from 1950 to 2014, with the exception of the years 2000–2002 and 2004, when no meteorological data were recorded.

We tested the relationship between Alcarria honey production, and NAO indexes and monthly meteorological data (maximum, minimum and average temperature, total precipitation, number of days with rain, and number of days with snow) recorded from 2000 to 2013, by using multiple stepwise conditional linear regression. In addition, in order to disentangle the possible relationships between NAO and meteorological variables, we correlated the monthly NAO index and meteorological data recorded from 1950 to 2014. All the analyses were performed with the software IBM SPSS (Version 19, Release 2010), IBM Corp., Armonk, NY.

To analyze the effect of the NAO and of the winter meteorological variables from the winter months on the Alcarria honey production, we performed multiple linear models. The best fit accounted for 80% of the variability in honey production (2002–2003, and 2005–2013, $n = 11$) as a function of the overall means of the NAO index and the precipitation in January (Figure 2). Moreover, the *d*-Durbin–Watson test indicated that the residual error does not represent autocorrelation (Table 1). No other result derived from the multiple regression analyses could explain more than 80% of the variability.

In order to disentangle the possible roles of the meteorological variables and the NAO index, we performed correlations with the values in January from the time series 1950 to 2014 (supporting information Table S1). NAO in January (overall mean 0.06 ± 0.98; median 0.25; range = 2.12–1.66) significantly correlated ($r = -0.647$, $p = 0.0001$, $n = 61$) with the monthly average of the daily minimum temperatures (overall mean

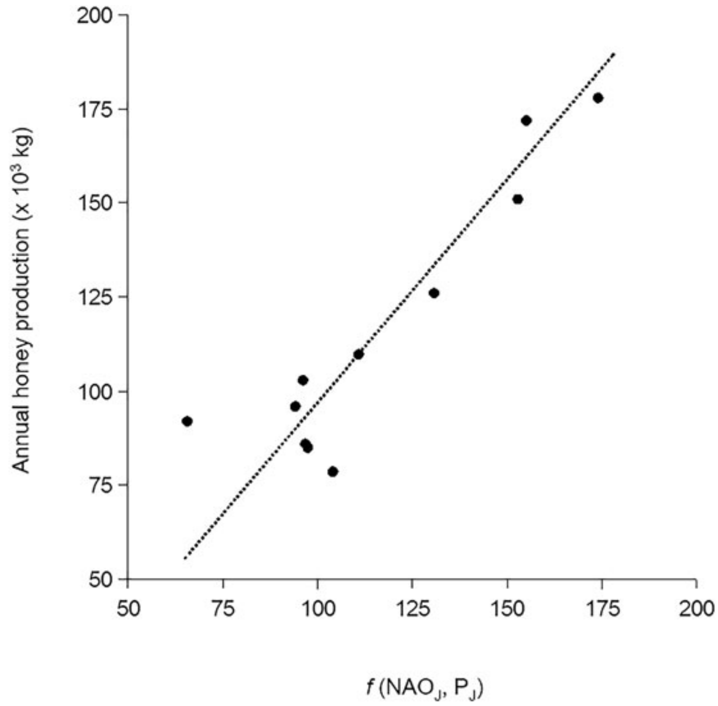

Figure 2. Alcarria honey production (2003–2013) as a function (f) of NAO and precipitation in January (NAO_J and P_J, respectively; see Table 1). Meteorological data from 2000 to 2001, and 2004, were not recorded.

Table 1. Coefficients of the significant variables and standardized coefficients (β) derived from the multiple stepwise conditional linear regression between Alcarria honey production (2002-2003, 2005-2013, $n = 11$) and the NAO index and meteorological variables in January (see Materials and methods for details).

	Coefficient	β	t	p
Constant	180.34		12.036	<0.001
NAO	−56.46	−1.324	−6.406	<0.001
Precipitation	−0.14	−0.772	−3.736	0.006

R^2-adjusted = 0.8045.
$F = 21.575$.
$p = 0.001$.
d-Durbin–Watson = 1.790 (d_{lower} = 0.658, d_{upper} = 1.641).

0.4 ± 2.1 °C; median 0.2 °C; range = 3.9 °C–5.1 °C). The other meteorological variables did not correlate with NAO ($p > 0.5$) (data not shown). That it is to say, positive phases of NAO and extremely low temperatures in January are linked in the Alcarria region.

Honey production is strongly dependent on the flowering success of honey shrubs and reproductive phenology of plants, and in turn is linked to the climate (Pearson & Braiden, 1990; Wubie, Bezabeh, & Kebede, 2014). In this framework, our results support the hypothesis that the NAO index (which is significantly inversely correlated with temperature) and the precipitation in January can explain ~80% of the variability in the Alcarria honey production in the period 2000–2013.

In the Iberian Peninsula, the positive phases of NAO in wintertime induce inhibition of the circulation of low pressure systems, leading to atmospheric stagnation that is frequently responsible for extremely low temperatures (Prieto, García, Díaz, Hernández, & del Teso, 2002). Indeed, we found that in the long time-series 1950–2014, positive phases of NAO in January and extremely low temperatures are correlated in the study region. The lower temperatures during the month of January could have damaged the floral buds of the honey plants, causing a reduction of flowering (especially in *R. officinalis*, which produces flowers all through the year except in the coolest months) and, furthermore it could have caused lower nectar and pollen production (Khodorova & Boitel-Conti, 2013). Moreover, winter is the critical period in the honey bee life cycle because extreme cold periods jeopardize their survival; energy demands are increased yet foraging is almost nil (Switanek, Crailsheim, Truhetz, & Brodschneider, 2017). In a similar way, heavy rains could damage plants and inhibit the foraging of the honey bees. Consequently, the Alcarria honey production could be similarly affected in those years with a positive NAO winter phase. Therefore, the quantitative model found in this study could be used as a predictive tool for honey production several months in advance.

In a long-time series extending two centuries, a strong relationship between tupelo (*Nyssa ogeche* Bartram ex Marsh.) honey from Florida and the Atlantic Multidecadal Oscillation has been demonstrated (Maxwell, Knapp, & Ortegren, 2013). Our study shows that the Alcarria honey production is also modulated by low-frequency atmospheric oscillations such as NAO.

In conclusion, the variability in the annual Alcarria honey production seems to be modulated by NAO variability, which, in turn, is correlated with temperature, and the precipitation in January. In particular, positive phases of NAO (resulting in extreme low temperatures) and scant rainfall in January are linked to the lower annual honey production values, whereas the contrary occurred under negative NAO indexes and higher precipitation. The analysis of future time series may allow us to validate the proposed relationship.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplementary material

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