Teleconnection between the reproductive parameters of the bearded vulture and macroclimatic oscillations. Implications for conservation.

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Abstract

The bearded vulture (Gypaetus barbatus) is a bird of prey belonging to the group of vultures. Although in the past it occupied mountain systems in Asia, Europe and Africa, and its distribution in the Iberian Peninsula was widely distributed, its current distribution in Spain is limited to very specific mountain ranges, including the Aragonese Pyrenees. The decline of the Iberian population is supposed to be linked to factors acting at a microscale level as the use of poisons, illegal hunting, human activity and the decrease in intensive livestock farming. There are, however, other factors acting on a biogeographical scale that may also be affecting the viability of populations that are not currently being considered. The aim of this study is to determine on a large scale the effect that environmental conditions may have on the temporal oscillations of the reproductive parameters of the bearded vulture. For this purpose, the breeding population in the Aragones Pyrenees has been used as the study population. We tested the degree to which each of 26 macroclimatic oscillation indices were teleconnected with three reproductive parameters (hatching rate, fledge rate and productivity). Two indices (the Tropical Northern Atlantic Index, and the East Atlantic/West Russia Pattern) were temporally correlated with the reproductive parameters of the bearbed vulture. The results are expected to provide novel information in the field of bearded vulture conservation, as there are no previous studies that address this issue from a biogeographical perspective. The results could have important implications for the management and conservation of the species and its successful reintroduction in other territories.

1. INTRODUCTION

The bearded vulture is a necrophagous bird specialising in an osteophagous diet (Margalida & Martínez 2020). It is found in mountain ranges with steep topography and rocky nesting sites, visiting surrounding plains and plateaus, where it requires large open areas with little or low vegetation to find food (Ferguson-Lees & Christie 2001; Orta et al. 2020). Bearded vultures are distributed throughout mountainous regions of Eurasia and Africa (Gil et al. 2019). In the last century, the distribution of the bearded vulture was increasingly restricted due to both direct and indirect persecution (Margalida & Martínez, 2020). This led to a crisis in the species, which reduced its area of distribution to the point of restricting it to a few massifs in the Pyrenees, Corsica, Greece and the Balkans (Margalida & Martínez, 2020). The different conservation and reintroduction projects have meant that the species is beginning to return to territories it occupied in past centuries and, therefore, improving the status of the species (Margalida & Martínez, 2020).

At the local level, the distribution of the species and the dynamics of the populations are conditioned by factors acting locally such as illegal hunting, poisoning, collision and electrocution with power lines, human disturbance in breeding areas, abandonment of extensive livestock farming and the consequent decrease in trophic resources and interspecific competition with griffon vultures for nesting sites (Margalida, 2016; Gil, 2020). On a wider geographical scale, the species distribution is linked to specific environmental conditions and changes in these entail modifications in the original distributions (Varderwal et al. 2013). Similarly, population dynamics are also related to the meteorological conditions existing at certain moments of the biological cycle (Kostin & Mooij 1995; Ramos et al. 2002; McDonald et al. 2004). At the same time, local weather conditions are controlled by remote macroclimatic atmospheric and oceanic circulatory patterns (Formenty et al. 2003), which are quantified by macroclimatic indices that allow us to compare between time series so that estimates of means can be made and extreme values and trends can be identified (Jiménez 2014). Therefore, temporal weather patterns can be described using monitored macroclimatic indices (Gordo et al. 2011), which ultimately trigger ecological processes that affect the population dynamics of species. Such links between ecosystem properties and distant climatic oscillation patterns, termed teleconnections (Heffernan 2014), have been reported for other species (Báez et al. 2021, 2022). Between macroclimatic oscillations and the ecological processes they activate, there is normally a time lag. This allows forecasting the weather conditions before they occur, which could provide advantages when planning management and conservation actions for the species.

In this study, we focus on understanding the relationship between the rates of macroclimatic oscillations and the rates of the reproductive parameters of the main bearded vulture population in Europe. First, we identified the relevant oscillation indices related to the reproduction of the species and, finally, the time lag between them and the different reproductive parameters studies. Based on our results we may predict the degree to which the meteorological conditions may influence the reproduction of the species and, consequently, improve management and conservation actions that could be applied to better conserve the species.

2. METHODS

Study area

The geographical context of this study was the Aragonese Pyrenees (northern Spain), where the main population of the species in Europe is located (Margalida & Martínez 2020) (Fig. 1). The study area is delimited by the recovery plan for the species, covering 9537km^2 that fully includes the Ordesa y Monte Perdido National Park, declared a World Heritage Site by UNESCO.

Study period

The database used covers reproductive parameters for a period of 32 years (1990-2021). Observations begin in December when the earliest clutches are laid. The latest clutches are usually in February (Heredia 1991; Margalida et al. 2003).

Target variables

Since 1990, the reproduction of the species in this region has been monitored by the Government of Aragon and the Fundación para la Conservación del Quebrantahuesos (FCQ).

We created a database containing information about laying, hatching and flight for all the Reproductive Units (RU) present in the study area and for each year of the study period. From the treatment of this information we defined the following reproductive parameters that we used as target variables:

- Hatching rate: percentage of eggs that hatch.

- Fledge rate: number of chicks fledged / number of pairs with hatched chicks.

- Productivity: number of chicks fledging / total number of pairs.

Annually, we calculated the average value of each reproductive parameter rate. To differentiate between high and low values we followed Vargas et al. (2006) and Farfán et al. (2012). For each target variable, we

established six intervals using a logarithmic scale among the extreme values obtained for each reproductive parameter rate. We considered the three highest classes, equal to or higher than 0.7, as representative of high rates and the three lowest, lower than 0.7, as low rates.

Macroclimatic oscillation indices

We compiled information for 26 different climate indices (Table 1) for which data were available from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (https://www.ncdc.noaa.gov; https://oceanview.pfeg.noaa.gov/erddap) and the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in) for the entire study period. These indices are calculated on a month-by-month basis from measurements of different climate characteristics over time (Xiao 2020).

Given that the oscillations in circulatory patterns could have a delayed teleconnection effect on bearded vulture reproductive parameters in the study area, we considered different features of the oscillation indices to represent different temporal lags in our predictors (Stenseth et al. 2002; Báez et al. 2013). Specifically, as a predictor for the high-low reproductive parameter rates (target variables) we tested the average value of the oscillation indices for the quarter previous to the start of the reproductive period (November-January), which is the appropriate period to decide the management measures to be carried out.

Predictive models

We trained predictive models for target variables for the period 1990-2021. We developed models of climatic favourable years for target variables using the Favourability Function, as described by Real et al. (2006):

$$F = \frac{\frac{P}{(1-P)}}{\left(\frac{n_1}{n_0}\right) + \left(\frac{P}{(1-P)}\right)}$$

where F is the meteorological favourability (ranging from 0 to 1), P is the probability of occurrence of a high reproductive parameter rate and n_1 and n_0 are the number of years during 1990-2021 with occurrence and absence of a high reproductive parameter rate, respectively. We used for each target variable the threshold value 0.7. Thus, all years with values equal to or higher than 0.7 were considered as 1 in the logistic regression and all years with values lower than 0.7 were considered as 0. Models based on the Favourability Function distinguish those years with weather conditions that favour high reproductive parameter rates from those with weather conditions detrimental to the occurrence of high reproductive parameter rates, irrespective of the prevalence (Acevedo and Real, 2012).

P was calculated using logistic regression, a commonly used supervised machine learning algorithm (Schein & Ungar 2007; Rymarczyk 2019). We performed a regression of each target variable on each macroclimatic oscillation index, following Hosmer and Lemeshow (2000) for logistic regression model-building. The values of the parameters of the logistic regression were established by maximum likelihood estimation using a gradient ascent machine learning algorithm. To minimize multicollinearity between predictors, we grouped predictor variables that showed significant correlation values (using Spearman correlation coefficient) between them. We maintained only the variable within the group with the most significant relationship with the spatio-temporal distribution of the target variables. We generated ensemble forecasting models based on the assumption that the effects of the different predictors could compensate for each other (Romero et al. 2016)

by performing a multivariate logistic regression of each target variable on the subset of significant predictors, using a forward-backwards stepwise approach. This stepwise process identifies the most significant model with only one predictor, for which we used Rao's score test. Next add new variables, one at a time, only if the variable contributes significantly to improving the model of the previous step according to the Omnibus test (Hosmer & Lemeshow 2000). The relative weight of each predictor was assessed using the Wald test (Freund 1993).

To evaluate the models obtained we used their classification and discrimination capacity. To assess the classification capacity of the models we classified each year as favourable or unfavourable for the occurrence of high reproductive parameter rates using as a threshold the favourability value of F= 0.5 according to each model. We evaluated the classification capacity using four indices: sensitivity (proportion of years with high reproductive parameter rate classified as favourable), specificity (proportion of years with low reproductive parameter rate classified as unfavourable), correct classification rate (CCR: proportion of years that either were classified as favourable and high reproductive parameter rate occurred or were classified as unfavourable and no high reproductive parameter rate occurred) and Cohen's Kappa coefficient (proportion of specific agreement between the occurrence of high reproductive parameter rates and favourability classification) (Fielding and Bell 1997).

To assess the discrimination capacity of the models we used the area under the receiver operating characteristic curve (AUC), a measure independent of favourability thresholds (Lobo et al. 2008).

3. RESULTS

We obtained significant climatic favourability models for all target variables (Table 2). The classification and discrimination capacity of every model is shown in Table 3.

The Tropical Northern Atlantic Index (TNA) was the most important indicator of climatic favourable quarters for high reproductive paratemet rates, as it was a significant predictor for all target variables (Table 2). We found that the TNA was significantly and negatively associated with the likelihood of high reproductive parameter rates.

The variation of the TNA during the period 1990-2021 is shown in Fig. 2A. The average TNA in the quarter previous to the start of the reproductive period (November-January) was positive on 23 occasions (71.9%) and negative on 9 occasions (28.1%). However, high hatching, fledge and productivity rates occurred in 7 (63.6%), 8 (47.1%) and 7 (87.5%) occasions, respectively, after quarters with negative TNA values. Fig. 2B, 2C y 2D show how the occurrence of high reproductive parameter rates were favoured (F >0.5) by values of TNA equal or lower than 0.2 in the quarter previous to the start of the reproductive period, whereas they were unfavoured (F <0.5) when TNA in the quarter previous to the start of the reproductive period was upper than 0.2.

The other significant indicator oscillation index was the East Atlantic/West Russia Pattern (EA/WR). The averaged values during the quarter previous to the start of the reproductive period were significantly and positively associated with the likelihood of high productivity rates.

The variation of the EA/WR during the study period (1990-2021) is shown in Fig. 3A. The EA/WR in the quarter previous to the start of the reproductive period (November-January) was positive on 13 occasions (40.6%) and negative in 19 occasions (59.4%). However, on 3 occasions (37.5%), high productivity rates occurred after quarters with positive EA/WR values. Fig. 3B shows how the occurrence of high productivity rates was favoured (F >0.5) by positive values of EA/WR in the quarter previous to the start of the reproductive period, whereas they were unfavoured (F <0.5) when EA/WR in the quarter previous to the start of the reproductive period was negative.

4. DISCUSSION

Our results show that the temporal variation of reproductive parameter rates of the bearded vulture in the study area was non-random and also that they decreased during the study period. The most significant

finding was that reproductive parameter rates are teleconnected with two macroclimatic oscillation indices. From the perspective of environmental sciences, teleconnection refers to any phenomenon that creates links between distant and otherwise disconnected regions (Heffernan et al. 2014) including the link between ecosystem features and distant global circulation patterns. This implies the existence of macroclimatic patterns of meteorological effects that could trigger ecosystem changes favouring or unfavouring the reproductive parameter of the bearded vulture.

It is well known that the Pyrenean bearded vulture population is strongly affected by a phenomenon of negative density-dependence (Margalida & Martínez 2020) along with other factors that also act on a local scale, such as human disturbance, poisoning or illegal hunting (Margalida, 2016; Gil, 2020). It is essential, however, to know in detail those other factors that, acting on a larger spatial scale, on a biogeographical scale, may also be conditioning the reproductive parameters and, ultimately, the viability of the population. As our results show, the TNA seems to be the most important macroclimate driver of reproductive parameter rates of the bearded vulture in the study area. The TNA index is an indicator of the ocean surface temperatures in the eastern tropical North Atlantic Ocean, mainly associated with the thermodynamic air-sea interactions (Huang et al. 2004). Several authors have shown that the TNA index has a clear influence on weather conditions in many regions. For instance, variations in precipitation in the Caribbean and in northeastern Brazil are closely related to changes in the TNA index (Uvo et al. 1998; Enfield & Alfaro 1999), or precipitation in southeastern Europe and East Asia is strongly conditioned by the TNA (Hatzaki & Wu 2015; Chen et al. 2018; Li et al. 2018). In our study area positive TNA values cause frequent and severe droughts, whereas opposite trends are associated with negative TNA values (ICTP 2011; Souza & Reboita 2021). Consequently, our results, which show that negative TNA values favour the occurrence of high reproductive parameter rates, are strongly consistent with the existing literature on bearded vultures, which states that reproduction is adversely affected by prolonged periods of drought and favoured by moderate rainfall and temperatures (Margalida, 2010). TNA values from November to January are a good predictor of these conditions in the critical period for the success of bearded vulture reproduction in the area.

The East Atlantic/West Russia Pattern (EA/WR) is the other macroclimatic oscillation index linked with the reproductivity rate of the bearded vulture in our study area. The EA/WR index is driven by both stationary eddy advection and transient eddy vorticity fluxes and has whether impact from eastern North America to Eurasia (Franzke & Feldstein 2005; Lim 2015). In the Mediterranean region, for instance, Krichak et al. (2013) showed how the frequency of extreme precipitation is closely conditioned by EA/WR pattern, whereas in East Asia it has a role in modulating the winter monsoon variability (Kim et al. 2013). In our study area, the positive values of the EA/WR index are related to moderate rainfall and temperatures, whereas very low temperatures and excess precipitation are associated with negative EA/WR values (World Climate Service 2021). Again, our results regarding productivity being favoured by positive values of the EA/WR and negatively affected by negative values of this index fully coincide with the specialized literature on the meteorological conditions that favour the reproductive biology of bearded vultures (Margalida 2010).

The conservation measures currently being carried out include reducing damage due to accidents, maintaining extensive livestock farming, creating and maintaining supplementary feeding points, as well as marking and monitoring individuals, which has made it possible to prevent the species from becoming extinct (López-Sañudo et al. 2001; Margalida & Martínez 2018). One of the measures currently being carried out includes the extraction of clutches from nests with a high risk of failure, their breeding in captivity and their reintroduction in territories where the bearded vulture had become extinct, such as Picos de Europa and Maestrazgo, with the aim of achieving a stable population (Margalida & Martínez 2018). Having information about the weather conditions during the reproductive period can be a very useful tool for making decisions about which nests to act on. This approach can be reached from the biogeographical perspective addressed in this study. The models based on teleconnections with macroclimatic oscillations indices can be the basis from which to make specific management decisions aimed to improve the viability of populations. Undoubtedly, the conservation objectives of threatened species will be favoured if we can forecast in advance what the weather conditions will be at specific times such as the reproduction period, or if we can anticipate extreme weather events which are becoming more important in the context of the global change that is being experienced.

In addition, the information provided by these models based on teleconnections with macroclimatic oscillation indices can be complemented with that obtained from species distribution models, which allow relating the geographical distribution of a species with multiple factors (historical, topographical, environmental o anthropic) (Muñoz & Real 2006; Acevedo et al. 2011; Olivero et al. 2017). The joint use of these biogeographic tools would allow, first, to adopt specific management measures such as the removal of eggs for *ex-situ*incubation based on forecasts of weather conditions that are unfavourable to the species. Secondly, our results could complement those obtained through distribution models that identify the most favourable areas for the species and the carrying capacity (Muñoz et al. 2005, 2015) for the selection of the locations to reintroduce the specimens extracted from the source population. These actions, in conjunction, would help in egg extraction decisions, as well as in the identification of release areas, with the aim of conservation of species that are subject to reintroduction programs.

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Figure 1. Study area. 1: Iberian Peninsula Context; 2: Pyrenean Context.

Table 1. Macroclimatic oscillation indices used to assess possible links with reproductive parameters of bearbed vulture.

INDEX		*INDEX*	
AAO	Atlantic Oscillation Index	AMM	Atlantic Meridional Mode
AMO	Atlantic Multidecadal Oscillation	AO	Artic Oscillation Index
EA	East Atlantic Pattern	DMI	Dipole Mode Index
EP/NP	East Pacific/North Pacific Pattern	EA/WR	East Atlantic/West Russia Pattern
NAO	North Atlantic Oscillation	MEI	Multivariate ENSO Index
NIÑO 34	East Central Tropical Pacific SST	NIÑO 1+2	Extreme Eastern Tropical Pacific SST
NP	Nort Pacific Pattern	NIÑO 4	Central Tropical Pacific SST
ONI	Oceanic Nino Index	NTA	North Tropical Atlantic SST Index
POL	Polar/Eurasia Pattern	PNA	Pacific/North American Pattern
SCA	Scandinavian Pattern	QBO	Quasi-Biennial Oscillation
TNA	Tropical Northern Atlantic Index	SOI	Southern Oscillation Index
TSA	Tropical Southern Atlantic Index	TNH	Tropical/Northern Hemisphere Pattern
WP	West Pacific Pattern	WHWP	Western Hemisphere Warm Pool

Table 2. Logits of the significant models for target variables according to the features of the macroclimatic oscillation indices. Logits represent either univariate models or multivariate combinations under the assumption that the individual effects of predictors could compensate each other. Predictor abbreviations as Table 1. B: coefficient of predictors. Wald: Value of Wald test statistic quantifying predictor weight in the model. p: statistical significance.

Model	Predictors	p	B	Wald	Constant
Hatching rate	TNA	0,053	-2,886	3,732	-0,069
Fledge rate	TNA	0,020	-3,664	5,394	1,024
Productivity	TNA	0,010	-6,341	6,677	1,011
	EA/WR	0,048	1,650	3,925	

Table 3. Classification and discrimination measures of the significant climatic favourability models. AUC: Area Under the receiver-operating-characteristic Curve. Kappa: Cohen's Kappa coefficient. CCR: Correct classification rate. H-L: Hosmer-Lemeshow calibration index.

MODEL	Hatching rate	Fledge rate	Productivity
AUC	0.701	0.859	0.870
Kappa	0.188	0.502	0.680
Sensivity	0.636	0.706	0.846
Specificity	0.571	0.800	0.842
CCR	0.594	0.750	0.844
Over-prediction	0.563	0.200	0.214
Under-prediction	0.250	0.294	0.111
H-L	χ^2= 4.317, P > 0.05	χ^2= 14.166, P > 0.05	χ^2= 5.324, P > 0.05

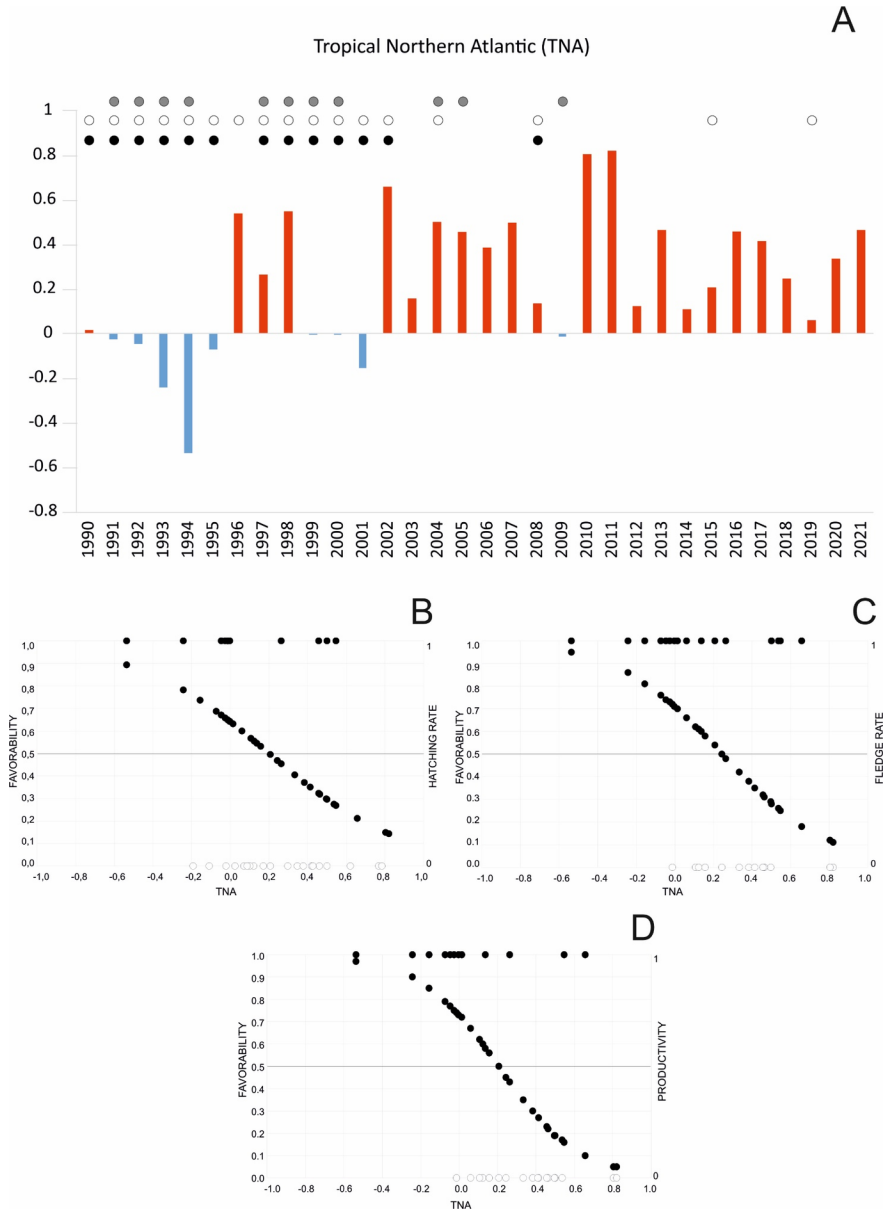

Figure 2. A. Variation of the Tropical Northern Atlantic Index (TNA) on the quarter November-January during the years covered by this study and occurrence of high reproductive parameter rates (circles). Grey circle: High hatching rate; White circle: High fledge rate; Black circle: High productivity. B, C and D. Relationship between climatic favourability for the occurrence of high hatching rate, fledge rate and productivity and the TNA values of the previous quarter to the start of the reproductive period (November-January).

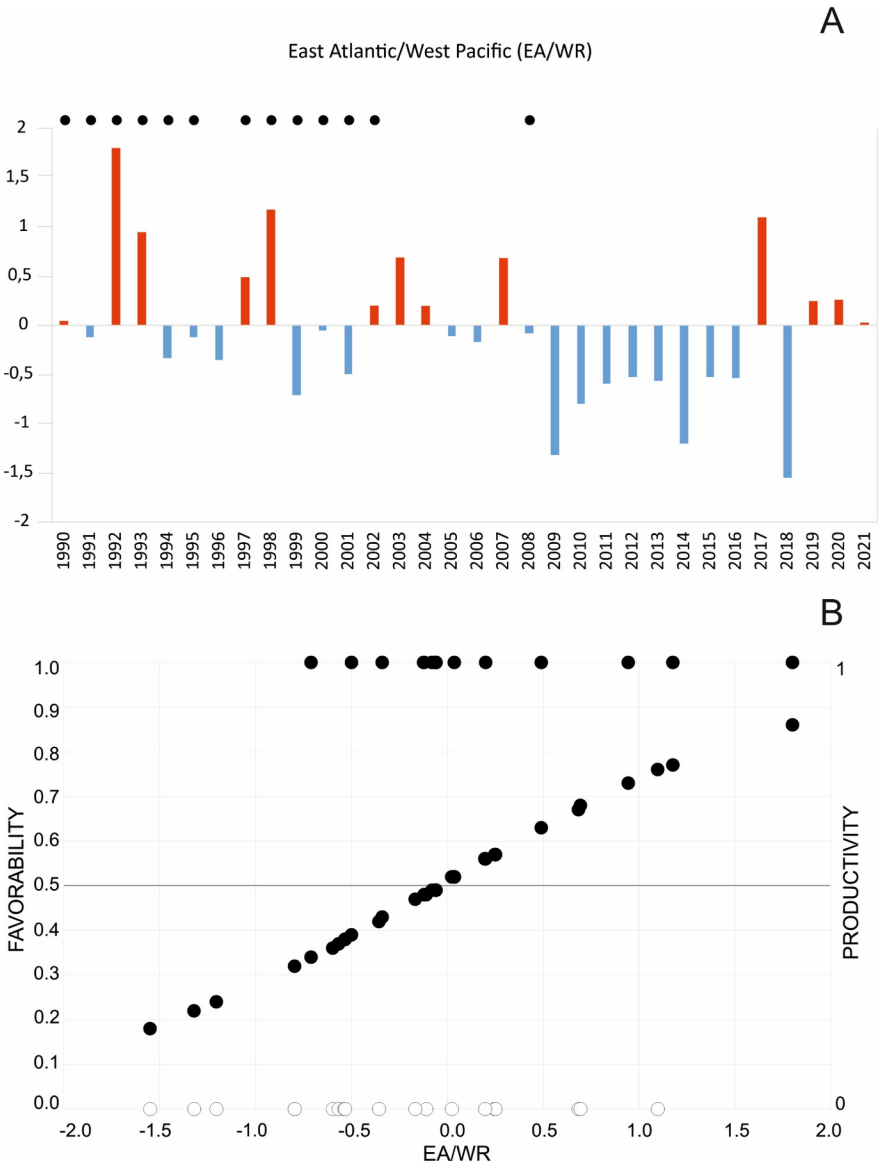

Figure 3. A. Variation of East Atlantic/West Russia Pattern (EA/WR) on the quarter November-January during the years covered by this study and occurrence of high productivity (black circles). B. Relationship between climatic favourability for the occurrence of high productivity and the (EA/WR) values of the previous quarter to the start of the reproductive period (November-January).