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ORIGINAL ARTICLE

Distance to landfill and habitat cover predict colony size in a Western Mediterranean white stork population

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Abstract
Artificial food subsidies like landfills generate very strong impacts on animal ecology and spatial behavior. Landfills indeed have been considered to be one of the most influential factors explaining the very fast recovery of many colonial waterbird populations worldwide, as documented for the white stork *Ciconia ciconia*. More recently, the increase of rice fields in some regions have also been argued to be part of an influencial process underlying the spatio-temporal distribution patterns of this species over many areas in southern Europe. It remains unknown whether these two habitat factors play an important role at explaining the spatial distribution pattern of the white stork and, more particularly, whether colony funding or colony size is dependent on them. Using data from a census conducted in 2018, we aimed to assess the effect of distance to a landfill or to rice fields, among other habitat factors, on the breeding colony size of a white stork population in northern Spain. Larger colonies were more likely to appear in trees or cliff, but less likely in buildings or other artificial substrates. They were also significantly more likely with decreasing distance to landfill, and when the habitat was dominated by dry cropland and meadows close to water bodies. Rice fields did not seem to have any significant effect. Our findings fit with those from other regions in Europe, and highlight the effect landfills have on population dynamics and spatial ecology for those species which are able to feed on this type of food subsidy. Our results also show that the main habitat cover over large geographic scales still plays a role independently of landfills. The European agricultural policies associated with the type and management of crops, and the Common Agricultural Policy in particular, will still have a decisive role for the species.

Keywords Biogeography · Landscape management · Mediterranean agricultural mosaic · Waterbirds

Introduction

Artificial food subsidies like landfills generate very strong impacts on animal ecology and spatial behavior (Oro et al. 2013; Coulson 2015; Gilbert et al. 2016; Seif et al. 2018; Zorrozua et al. 2020). From a population perspective, landfills provide great amounts of spatio-temporal predictable food, which could enhance breeding success (Weiser and Powell 2010; Djerdali et al. 2016) and favor the concentration of birds in small areas, both in the breeding and non-breeding period, with the consequent positive and negative effects (Plaza and Lambertucci 2017; Arizaga et al. 2018). Artificial food supplies can also increase the carrying capacity of the ecosystems and, therefore, the lower limit at which density-dependent effects occur, hence allowing higher population densities (Gaston 2004; Carrete et al. 2006; Newton 2013).

Even though in many cases this anthropogenic food supply promotes positive population growth rates, negative consequences linked to such processes can also arise, since populations might become more vulnerable as they increasingly depend on a single feeding source (Carrete et al. 2006). Moreover, foraging individuals are exposed to sanitary threats (e.g., by ingestion of solid waste like plastic, glass, or metal, as well as pathogens and toxins) (Peris 2003; Ramos et al. 2010; Roscales et al. 2016; Seif et al. 2018). In such scenarios, recent research is aiming to better assess the influence of these sites offering food subsidies on the breeding and foraging behavior of species frequently using them (Ramos et al. 2009; Egunez et al. 2017; Zorrozua et al. 2020; Bialas et al. 2021).

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The white stork (*Ciconia ciconia*) is an opportunistic bird, very well adapted to breed in anthropogenic habitats and to forage on artificial food subsidies, including landfills (Tortosa et al. 2002; Kruszyk and Ciach 2010; Gilbert et al. 2016). Spain hosts one of the largest white stork populations in Europe, with more than 33,000 adult breeding pairs (Molina and Del Moral 2005). Landfills have been considered to be one of the most influential factors explaining the very fast recovery of this population at the end of the twentieth century and into the present one (Blanco 1996). More recently, the increase of rice fields in some regions has been also argued to be part of an influential process underlying the spatio-temporal distribution patterns of this species over many areas in southern Europe (Fasola and Ruiz 1996; Tourenq et al. 2001; Rendón et al. 2008; Toral and Figuerola 2010). Currently, there is still debate about the real impact of landfills or rice fields on the growth, but also the spatial distribution pattern of white stork populations in Spain.

In northern Spain, the southern half of Navarre province has historically comprised a Mediterranean mosaic of vineyards, cereal, and forest patches of mostly Aleppo pine (*Pinus halepensis*) or holm oak (*Quercus ilex*). In the last decades, the white stork population in this region showed a very fast growth, changing from ca. 80 adult breeding pairs in 1960 (the lowest known historical value) to ca. 740 pairs in 2018 (Barbarin et al. 2021). Both irrigated lands (including rice fields) and landfills are a relatively new element of the landscape and they both have been argued to play an important role at explaining the remarkable white stork population growth in Navarre (Barbarin et al. 2021). The main landfill site within the region, indeed, can host up to 4000 storks during migration period, which could comprise > 10% of the western European white stork adult population (Arizaga et al. 2018). It remains unknown, however, whether these two habitat factors play an important role at explaining the spatial distribution pattern of the white stork and, more particularly, whether colony funding or colony size is dependent on them (Bialas et al. 2021). Using data from a census conducted in 2018, this work aimed to assess the effect of distance to a landfill or to rice fields, among other habitat factors, on the breeding colony size of a white stork population in northern Spain. Assuming that these food resources play an important role, we hypothesized that the species would have higher breeding colony size when distance to these food supplies is smaller.

Material and methods

Study site and data collection

This study was conducted in the province of Navarre, in northern Spain. Located between the western Pyrenees in the north and the Ebro Valley in the south, Navarre is divided into three biogeographical areas: the Alpine, the Atlantic, and the Mediterranean (Lorda et al. 2011), with large differences among them (climatic, landscape, flora, and fauna). White storks only breed in the Mediterranean area that occupies the southern half of Navarre (Fig. 1).

In 2018, we monitored the whole white stork breeding population in Navarre in order to estimate the current breeding population size (Barbarin et al. 2021). The census was carried out in April, which is known to be the best time to estimate the number of white stork breeding pairs in this region (Vergara et al. 2010). Definition of breeding population size was based on the number of nests which had signs of being occupied (presence of adults), discarding unoccupied nests. Breeding sites were either a single nest or a colony (two or more nests, all of them noted). For each single nest or colony, we recorded its position (centroid, if a colony) and annotated the substrate (tree, cliff, building, or artificial—incl. power line posts) (Barbarin et al. 2021).

Geospatial analyses

For each breeding site (single nest or a colony), we measured the following habitat-related variables: *dcol*, distance to closest nest/colony; *dlan*, distance to closest landfill; *driv1*, distance to a main water flow; *driv2*, distance to a tributary of a main water flow; and habitat cover (percentage of habitat) using the layers provided by SITNA and Corine Land Cover from 2018 respectively. To simplify the analyses, habitats were combined into 14 categories (see Table 1 for details). All geospatial analyses were done in QGIS free software (QGIS.org 2021).

Habitat cover variables were highly autocorrelated among each other. Thus, to remove autocorrelations, we ran a Principal Component Analysis (PCA) for each set of habitat-related variables, i.e., those obtained at the 1-, 10-, and 20-km buffer around each breeding site. Then, the 14 habitat cover variables were transformed into three PCA components (see Table 1 for their interpretation).

Data analyses

Our data set had the typical pattern of a positive-skew distribution (Annex 1), with 101 isolated nests compared to 69 colonies. Our object variable (colony size) ranged from 2 to 97 nests. Thus, before starting to select alternative models, we tested for the function of distribution errors allowing an acceptable (~ 1) overdispersion. Otherwise, models with a high overdispersion tend to generate an over-estimation of significant coefficients. With that goal, we conducted a basic model with the number of nests per place (hereafter, *N*) as object variable, and the following independent variables (included additively, with no interactions): *subs*, substrate

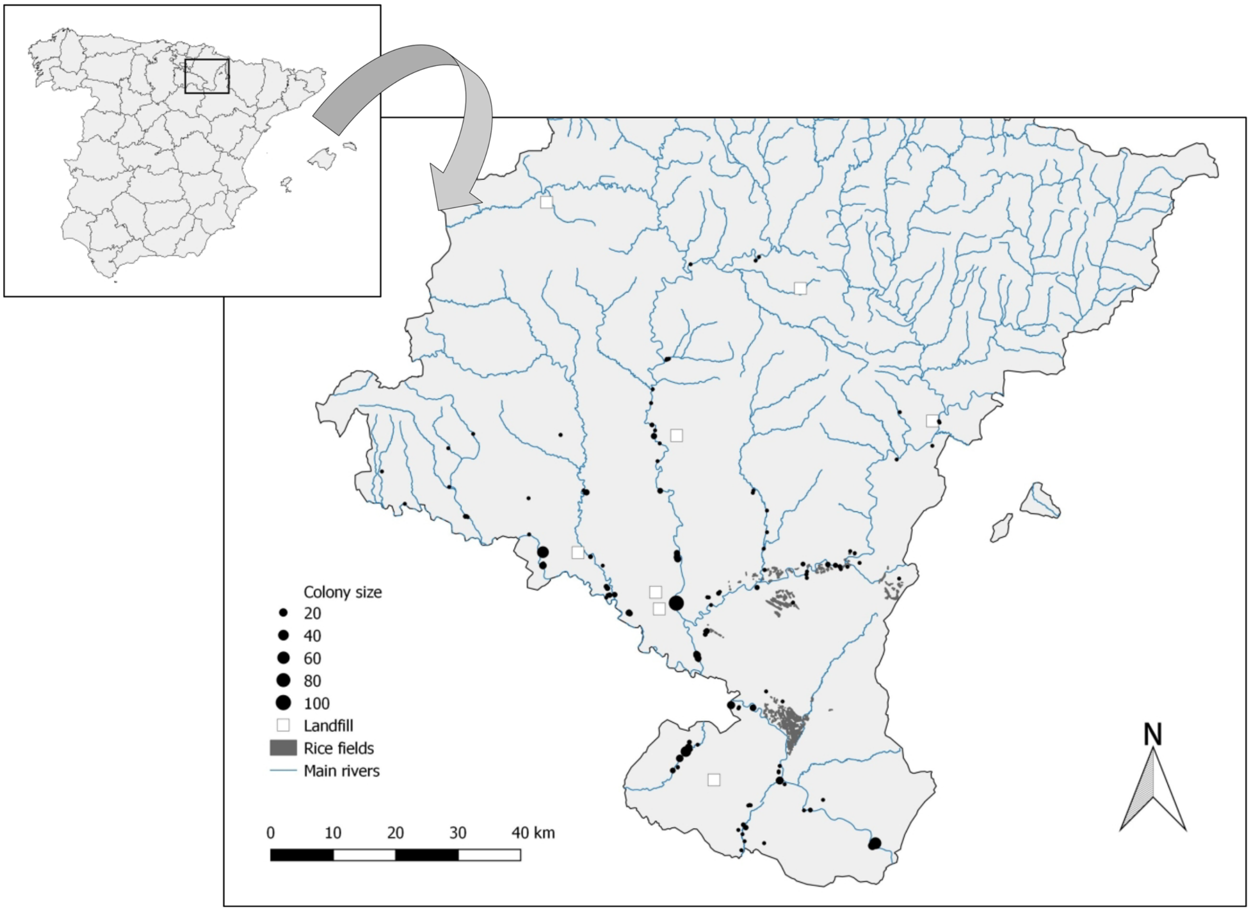


Fig. 1 Geographical distribution of white stork nests (size weighed by colony size), landfills, rice fields, and rivers in Navarre (Spain)

(as factor, with 4 levels); *dcol*, *dlan*, *driv1*, *driv2*, and the *PC1* to *PC3* (here, for the 1-km buffer). Due to the nature of *N*, we tested for the overdispersion of this model using the Poisson errors distribution, which was found to be 12.25 (i.e., very high overdispersion). The same value was found when using a quasi-Poisson distribution. Alternatively, we used a negative binomial distribution, and the overdispersion in this case lowered down to 1.65.

We then conducted alternative models considering the *PC1* to *PC3* for the 1-, 10-, and 20-km buffers. Models were compared using their Akaike value (AIC) (Burnham and Anderson 1998). Lower AIC values indicate a better fit to the data, and models differing in less than 2 AIC units would fit to the data equally well (Burnham and Anderson 1998). The (saturated) model which took into account the habitat variables within a buffer of 10 and 20 km around each nesting site fitted to the data equally well (AIC = 814.0 and 814.8, respectively). Even though the difference between the 10- and 20-km models was not high, we decided to work hereafter with the data set of a 10-km buffer since this model had a slightly lower AIC value. For this buffer, we detail our interpretation of the PCA loadings (Table 1) in Annex 2.

That we obtained a lower overdispersion value when we used negative binomial errors is attributed to the fact that, rather than responding to a continuous object variable, the system had a better fit when the original object variable is converted into a binary variable, given that a very high proportion of the sample was composed by isolated nests or small colonies. Therefore, we decided to convert our original object variable (*N*) into a binary variable (0/1) with the following two categories: isolated nests/small colonies *versus* large (> 5 nests) colonies. We used the "dredge" function from "MuMIn" package (Barton 2014) in R (R Core Team 2020). This was done to start a model selection procedure that ranked all the possible nested models from the saturated one (i.e., $n \sim subs + dcol + dlan + driv1 + driv2 + PC1 + PC2 + PC3$), according to their Akaike value. In this case, *n* is a binary object variable representing whether the nesting location was an isolated nest/small colony (0) or a large colony

Table 1 Factor loadings, percentage of explained variance, and eigenvalue of Principal Component Analyses on habitat cover variables (percentage of habitat) within 1-, 10-, and 20-km buffers around breeding sites (either a single nest or a colony) of white storks in Navarre. Abbreviations: *wat*, open continental waters (incl. reservoirs, lagoons, etc.); *mfo*, mixed forest patch; *cfo*, coniferous forest; *dfo*, deciduous/broad leaved forest; *shr*, shrublands; *poo*, poor vegetation, mostly bare soil; *mea*, meadow; *dry*, Mediterranean cropland; *ric*, rice fields; *irr*, irrigated croplands, incl. greenhousing; *mos*, Mediterranean mosaic with crops and natural habitat; *pas*, pastures; *gro*, groves; *urb*; urban areas

	1 km			10 km			20 km		
	PC1	*PC2*	*PC3*	*PC1*	*PC2*	*PC3*	*PC1*	*PC2*	*PC3*
WAT	+0.36	−0.43	+0.12	+0.03	+0.51	−0.06	+0.22	+0.13	+0.33
MFO	+0.07	+0.25	+0.22	−0.22	+0.21	+0.30	−0.30	+0.04	+0.45
CFO	+0.20	+0.22	+0.46	−0.32	+0.07	+0.22	−0.23	−0.28	+0.37
DFO	+0.00	−0.54	−0.13	+0.42	−0.19	+0.05	+0.27	−0.22	−0.20
SHR	+0.15	+0.18	−0.14	−0.03	+0.12	−0.43	+0.24	+0.30	+0.08
POO	+0.11	+0.19	+0.34	−0.21	+0.09	+0.52	−0.31	−0.37	+0.10
MEA	+0.02	−0.29	+0.34	−0.02	+0.42	−0.13	+0.34	+0.09	+0.24
DRY	−0.06	+0.00	+0.33	+0.12	+0.49	−0.19	+0.33	+0.27	+0.26
RIC	+0.31	+0.14	−0.40	−0.35	−0.30	−0.07	−0.34	+0.21	−0.37
IRR	+0.52	+0.11	−0.30	−0.32	−0.18	+0.06	−0.20	−0.04	+0.41
MOS	−0.45	−0.12	−0.25	+0.36	−0.22	+0.00	+0.31	−0.13	+0.10
PAS	+0.16	−0.46	+0.10	+0.14	+0.20	+0.38	+0.07	−0.29	+0.17
GRO	−0.31	+0.09	−0.13	+0.43	−0.05	+0.22	+0.21	−0.47	+0.01
URB	−0.31	−0.01	+0.12	+0.22	+0.10	+0.38	+0.25	−0.44	−0.18
Variance (%)	0.16	0.13	0.11	0.26	0.20	0.15	0.33	0.18	0.16
Eigenvalue	2.28	1.77	1.49	3.65	2.81	2.10	4.56	2.56	2.17

(1). In this case, we used a binomial in spite of a negative binomial distribution of errors.

Results

The white stork population in Navarre in 2018 reached 743 nests (in 172 locations); of them, 101 (13.6%) nests were found to be isolated, while the rest belonged to colonies of 2 (17 localities) to 97 (1 locality) nests (for details, see also Annex 1).

After applying a model selection procedure using the "dredge" function, the model which had a higher predicting capacity ($R^2 = 0.34$) of colony size showed some significant coefficients (Table 2). In this case, larger colonies were more likely in trees or cliff, but less likely in buildings or other artificial substrates (Fig. 2). Furthermore, larger colonies were also significantly more likely with decreasing distance to landfill (Fig. 3), and when the habitat was dominated by dry cropland and meadows close to water bodies (Fig. 4).

Discussion

The white stork population in Navarre breeds either in isolated nests or small to large (up to ca. 100 nests) colonies. Models revealed that larger colonies were not randomly distributed, but that they tended to be formed with decreasing distance to landfill, when the habitat was dominated by dry cropland and meadows close to water bodies as well as in natural substrates such as a cliff or trees. Note that these last substrates tend to be common near larger rivers that host relevant riparian forest along their banks, often interrupted by abrupt cliffs where meanders exert a greater erosive force.

Previous studies carried out in the region showed that landfills play a significant role at explaining the spatial ecology and stopover behavior of white stork in Navarre (Resano-Mayor et al. 2016; Arizaga et al. 2018). Now, we also demonstrate that landfills also shape the species nesting location and its colony size in Navarre. Such findings fit with those from other regions in Europe (Bialas et al. 2021), and highlight the effect that landfills have on population dynamics and spatial ecology for species that are able to feed on this type of food subsidy (Oro et al. 2013; López-García et al. 2021).

Table 2 Beta-parameter estimates from binomial model used to estimate whether breeding in isolated nests or small colonies compared to large colonies ($n > 5$ nests) varied in relation to substrate (*subs*), distance to landfill (*dlan*), distance to main rivers (*driv1*) or tributaries to main rivers (*driv2*), and the *PC1* to *PC3* (for details, see Annex 1). $R^2 = 0.34$

	Beta	SE (Beta)	*P*
Intercept	−1.97	0.44	<0.001
Subs = tree	+0.79	0.46	0.088
Subs = artificial	−2.92	0.83	<0.001
Subs = cliff	+2.80	0.73	<0.001
dlan (scaled)	−0.96	0.45	0.034
driv1 (scaled)	−0.45	0.40	0.266
driv2 (scaled)	−0.01	0.36	0.973
PC1 (scaled)	+0.69	0.40	0.087
PC2 (scaled)	+0.75	0.33	0.022
PC3 (scaled)	−0.78	0.53	0.138

Reference category in *Subs* (i.e., *Beta* = 0): building

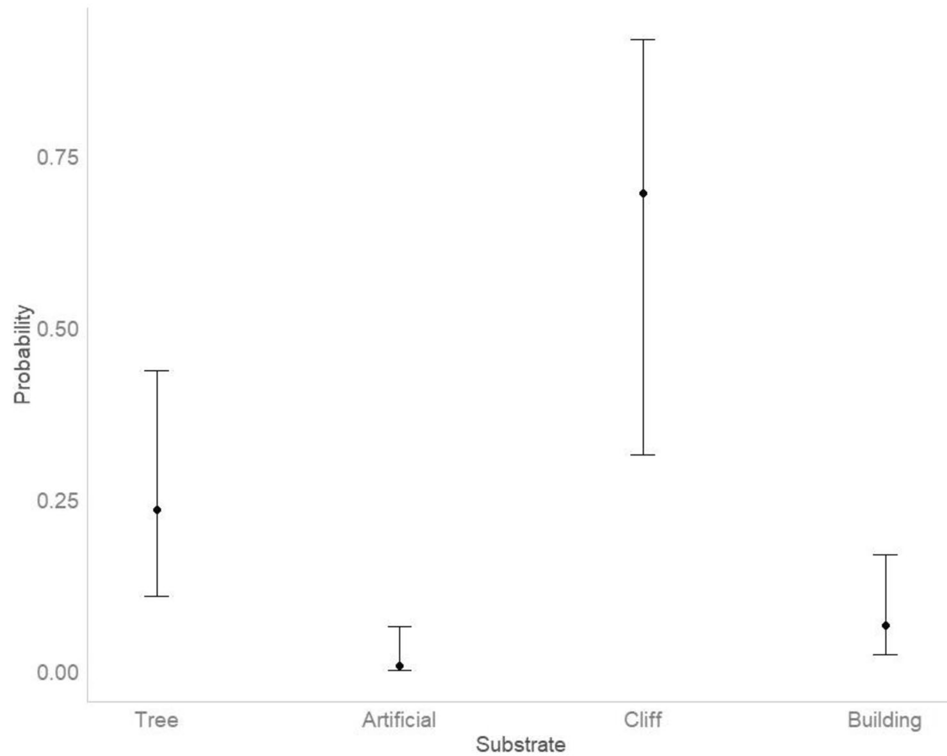


Fig. 2 Predicted probabilities of having a white stork colony larger than 5 nests in Navarre in relation to type of substrate

Interestingly, Bialas et al. (2021) also found that the presence of non-irrigated arable lands and the cover of meadows (to a high extent equivalent to our PC2) were good predictors of nest occupancy. This suggests that the main habitat cover over large geographic scales still plays a role independently of landfills. The European agricultural policies associated

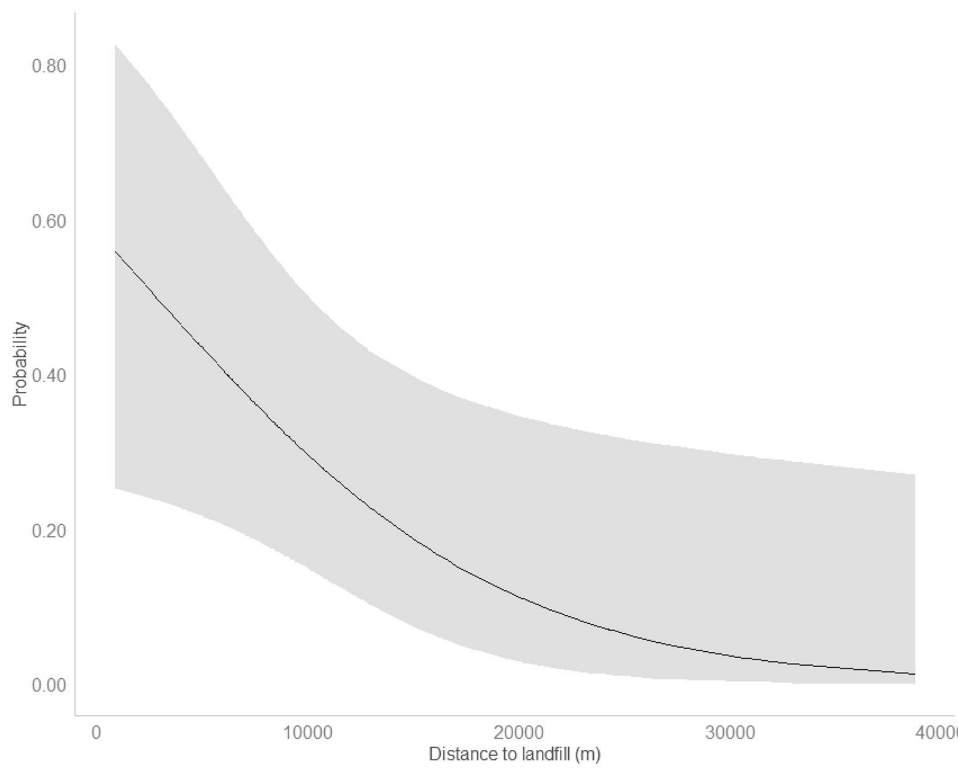


Fig. 3 Predicted probability of having a colony larger than 5 nests in relation to distance to a landfill site

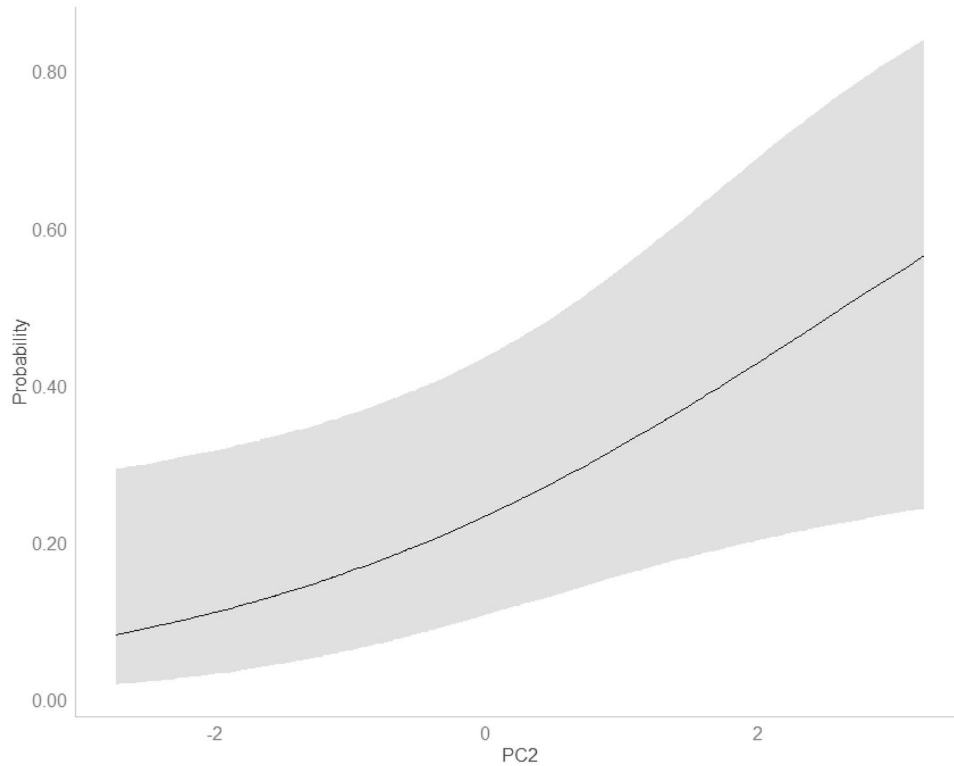


Fig. 4 Predicted probability of having a colony larger than 5 nests in relation to an increasing relative area of dry crops and meadows close to water bodies (represented by PC2 for 10-km buffer around breeding sites; for details, see Annex 2)

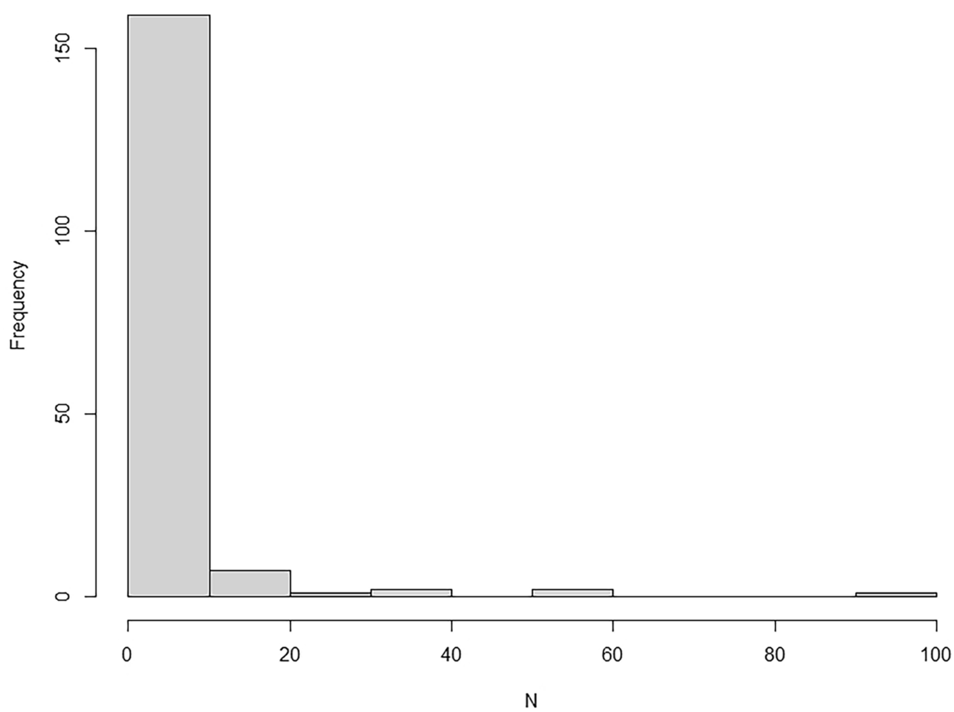
with the type and management of crops, and the Common Agricultural Policy in particular, will still have a decisive role for the species. Furthermore, the Directive 1993/31/EC and the Amending Directive 2018/850, on landfill of waste, aim, among several other objectives, to reduce landfilling to prevent detrimental impacts on human health and the environment and to ensure that economically valuable waste materials are gradually and effectively recovered through proper waste management. This will have a predictable strong impact on those animals which, currently, have a more or less high dependency in this predictable food subsidy. In particular, it can be stated that the big colonies found close to landfill sites might reduce their size or even disappear once the landfills are closed. As a consequence, the actual spatial distribution pattern of the species may change at a regional scale. Navarre is experiencing a very fast change in the type and distribution of crops, with an increasing amount of hectares dedicated to irrigated land. From 2000 to 2016, the surface covered by dry croplands has passed from 201,621 to 178,033 ha (−11.70%), while for the case of irrigated land this area passed from 68,370 ha to 85,389 (+24.90%) (source: Government of Navarre). Our results suggest that the white stork has a preference for the traditional Mediterranean mosaics, especially when this is linked or occurs together with open areas with meadows close to water bodies. In this scenario, the conversion of these agricultural zones into irrigated croplands could be a threat for the species, which seems to avoid (at least to reduce its nesting density and, therefore, its absolute population size) humid crops, including rice fields.

Rice fields constitute in several regions in Iberia a novel habitat which provides huge amounts of food to waterbirds (Sánchez-Guzmán et al. 2007; Rendón et al. 2008; Lourenco et al. 2010; Masero et al. 2010). This phenomenon also happens in Navarre, with a surface of ca. 2200 ha of rice fields located, however, in a very specific area (Aragón main stream, Arguedas zone near the Ebro river). Our results suggest, however, that these crops would have no effect in white stork nesting density in Navarre. As compared to other areas in Iberia, it could be that either other factors would simply have a higher influence for the case of Navarre, and/or that the current surface of rice fields in Navarre is small. Indeed, rice fields in Navarre show a very local distribution range, so this habitat alone, probably, is insufficient to sustain large white stork populations. Part of this could also be caused by the fact that the rice fields are subjected to seasonality, and they only offer food along part of the annual cycle, from late spring (when the rice is sown) to ca. September/October (when the rice is harvested). From late autumn to spring, therefore, rice fields remain dry and, therefore, they lack interest for the waterbird community. Thus, rice fields remain dry for a significant part of white stork breeding cycle (especially when they look for breeding places).

In conclusion, larger colonies were more likely in trees or cliff, and less likely in artificial substrates. They were also significantly more likely with decreasing distance to landfill, and when the habitat was dominated by dry cropland and meadows close to water bodies. Rice fields did not seem to have any significant effect. Our findings fit with those from other regions in Europe and highlight the effect landfills have on population dynamics and spatial ecology for those species which are able to feed on this type of food subsidy. The main habitat cover over large geographic scales still plays a role independently of landfills. The European agricultural policies associated with the type and management of crops, and the Common Agricultural Policy in particular, will still have a decisive role for the species. The European policies forcing the closure of open-air landfills will also have an impact, possibly reducing the size of those colonies which, currently, strongly depend on this type of predictable anthropogenic food subsidies (Gilbert et al. 2016).

Annex 1

Frequency distribution of the number of white stork nests (*N*) per breeding location in 2018 in Navarre (northern Spain).



Annex 2

Interpretation of the PCA on habitat-related variables for a buffer of 10 km around breeding location (either if an isolated nest or a colony) of white stork in Navarre.

	Positive correlation with:	Negative correlation with:
PC1	GRO, DFO, MOS	RIC, IRR, CFO
Meaning:	More Mediterranean mosaic with dry crops and natural habitat; Less humid zones, incl. rice fields, as well as less coniferous forest	
PC2	WAT, DRY, MEA	RIC
Meaning:	More dry crops and meadows close to water bodies; Less rice fields	
PC3	POO, PAS, URB	SHR,
Meaning:	More bare soil, urban areas, and pastures; Less shrubland	

Declarations

Conflict of interest The authors declare no competing interests.

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