Drastic reduction of the population distribution of White Storks predicted in absence of landfills

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ABSTRACT
Organic waste production has greatly increased following human sprawl and led to the development of landfills in recent decades. This abundant and reliable anthropogenic food source has favored several species, some of which consequently became overabundant. Landfills present hazards to wildlife, which may suffocate on plastic materials, tangle on cords, and get exposed to pollutants and pathogens. In response to environmental and public health concerns over the maintenance of landfills, the European Commission proposed to close the landfills. Our objective was to determine the impact of Landfill European Directive on the White Stork (*Ciconia ciconia*) whose population recovery and growth was linked to landfill exploitation. We implemented species distribution models to project future distribution in the absence of landfills in the Community of Madrid (Spain). Habitat suitability was estimated based on nest occurrence and we included data from land cover types, human population density, and two different climate change scenarios (i.e., emissions in low and high shared socioeconomic pathways). Given that protection measures, particularly implemented in protected areas, were associated with population recovery, we also evaluated the overlapping degree between protected areas and projected distribution. Our models predicted a sharp decline in breeding population distribution with landfill closure, reaching values similar to the 1984 breeding census when the species was categorized as threatened. Our results also suggest a decrease in maximum habitat suitability. Climate change also contributed to a reduction in breeding population distribution given model predictions for the extreme emission pathway (ssp5). Measures such as gradual change in landfill management, continuous monitoring of breeding populations, and evaluation of the White Stork use of natural feeding areas before and after landfill closure, should be considered.

Keywords: anthropogenic food sources, *Ciconia ciconia*, climate change, landfill closure, management, species distribution model

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LAY SUMMARY

- Several animal species have thrived around landfills, which was particularly important for threatened species.
- However, the Landfill European Directive (1999/31/CE) promote the landfill closure in the next decade. Knowing the impact of this Directive prior to its implementation should be a priority for the responsible authorities.
- We projected habitat suitability and the future White Stork breeding population distribution in absence of landfill in the Community of Madrid (Spain) in two scenarios of climate change and growing urbanization.
- Our models signalled landfill closure, climate change and urbanization growing, as the main threats to the White Stork breeding population.
- We proposed gradual change in landfill management, continuous monitoring of breeding populations, and evaluation of the White Stork use of natural feeding areas, to determine the actual relevance of landfill closure in breeding populations.

Drástica reducción de la distribución de la población de Cigüeña blanca predicha en ausencia de vertederos

RESUMEN
La producción de residuos orgánicos se ha incrementado tras la expansión del ser humano y ha dado lugar al desarrollo de los vertederos en las últimas décadas. Esta fuente de alimentación antrópica predecible y abundante ha favorecido a varias especies, algunas de las cuáles se han convertido en super-abundantes. Los vertederos presentan ciertos riesgos para la fauna, tales como ahogamiento por plásticos, nudos y cuerdas, y la exposición a contaminantes y patógenos. En respuesta a la inquietud por la salud pública y el medio ambiente debido al mantenimiento de los vertederos, la Comisión Europea propuso el cierre de los vertederos. Nuestro objetivo era determinar el impacto de la Directiva Europea de Vertederos en la Cigüeña blanca, *Ciconia ciconia*, cuyo crecimiento poblacional estuvo asociado a la alimentación en vertederos.
Hemos implementado modelos de distribución de especies para proyectar la distribución futura de la población en ausencia de vertederos en la Comunidad de Madrid (España). La idoneidad del hábitat fue estimada basándonos en la presencia de nidos e incluimos información del tipo de cobertura del suelo, densidad de la población humana y dos escenarios climáticos distintos (*i.e.*, trayectorias socioeconómicas compartidas de bajas y de altas emisiones). Dado que las medidas de conservación, implementadas especialmente en las áreas protegidas, estuvieron asociadas con la recuperación de la población; también evaluamos el grado de solapamiento entre las áreas protegidas y la distribución proyectada. Nuestros modelos predicen un declive agudo en la distribución de la población reproductora tras la clausura de los vertederos, alcanzando valores similares a los del censo reproductor de 1984 cuando la especie estaba catalogada como amenazada. Nuestros resultados también sugieren una disminución de la idoneidad del hábitat en el futuro. El cambio climático también contribuyó en la reducción de la distribución de la población reproductora según las predicciones de nuestros modelos en la trayectoria de emisiones extremas (ssp5). Deberían ser consideradas medidas tales como el cambio gradual en la gestión de los vertederos, seguimiento continuo de las poblaciones reproductoras, y la evaluación del uso de las cigüeñas de fuentes de alimentación naturales antes y después del cierre de los vertederos.
Palabras clave: Fuente de alimentación antrópica, *Ciconia ciconia*, cambio climático, landfill closure, species distribution model, management

INTRODUCTION

Human-induced changes have deeply transformed ecosystems and wildlife communities (Vitousek et al. 1997). In addition to direct actions, such as landscape transformation or species translocation, anthropogenic food sources are important factors impacting animal biodiversity and distribution (Oro et al. 2013, Newsome et al. 2015). In developed countries, millions of tons of food generated by humans end up in landfills annually (Stenmarck et al. 2016). Many animal species, particularly birds, have developed strategies to take advantage of this abundant and predictable food source (Plaza and Lambertucci 2017). Anthropogenic food provides numerous benefits to wildlife, including reduced energetic costs (Gilbert et al. 2016, Soriano-Redondo et al. 2021) and increased body size, higher reproductive output, and greater offspring survival (Tortosa et al. 2002, Steigerwald et al. 2015, López-García et al. 2021), potentially resulting in rapid population growth.

The competition process between and within species can decrease with increasing abundance and reliability of resources (Restani et al. 2001, Corman et al. 2016). In addition to increased reproduction, wildlife is attracted to landfills and adjacent areas for both breeding and foraging, explaining resource selection and alterations in distribution of some populations (Duhem et al. 2008). The continuous abundance of anthropogenic resources has also been correlated with alterations in migration patterns and seasonality. For instance, some migratory birds use anthropogenic sites, such as landfills, as important stop-overs, while others may shorten or suppress migratory behavior (Flack et al. 2016, Rotics et al. 2017, Arizaga et al. 2018). The increase in density of a particular species at these sites can promote competitive displacement of species, resulting in an ecological impact on trophic webs and homogenization of local community composition (Malekian et al. 2021).

All of these changes in avian behavior and distribution can translate to the aggregation of birds and abnormally high densities that usually produce conflicts with humans such as nuisance activity, damage to buildings, or even health issues (Hatch 1996, Belant 1997, Vergara et al. 2007a). Additionally, the risk of bird collision with power-lines and airplanes increases with proximity to landfills (Garrido and Fernandéz-Cruz 2003, Moreira et al. 2018, Pfeiffer et al. 2020, Marcelino et al. 2021). The conflicts of human and wildlife generally change the human perception of animals to so-called pest species (Belant 1997, Payo-Payo et al. 2015).

Landfills are generally associated with several environmental risks, including soil contamination, greenhouse gases, hazardous emissions, and water pollution from runoffs (Butt et al. 2008, Vaverková 2019). Landfills also pose important challenges to wildlife. For instance, decomposing organic waste provides the optimal environment for a number of pathogens to proliferate (Plaza and Lambertucci 2018, Tauler-Ametlller et al. 2019, Martín-Maldonado et al. 2020). Additionally, ingestion of plastics poses choking and injury hazard, while heavy metals and other pollutants may intoxicate birds (Peris 2003, Henry et al. 2011, Muñoz-Arnanz et al. 2011).

As a consequence, the European Union passed environmental policies to reduce the production of human refuse, diminish the percentage of biodegradable waste at landfills, and transform the organic waste in compost or biofuel by 2030 (Landfill Waste Council European Directive 1999/31/CE and Directive 2018/850/CE). The new waste facilities will prevent wildlife access to refuse while the "old" open air landfills will be closed or substantially modified (Directive 2008/98/CE and Directive 2018/850/CE).

The recent landfill legislation may come at cost to some wildlife. Landfills have been associated with recovery of multiple populations of threatened and endangered species (Tortosa et al. 2002, Rumbold et al. 2009, Tauler-Ametller et al. 2017, Arnold et al. 2021). For example, the Western European population of White Storks (*Ciconia ciconia*) was suffering a generalized sharp decline between the 1950s and 1980s (Barlein 1991). This decline was mainly associated with habitat loss and changes in agricultural practices (Barlein 1991, Senra and Ales 1992, Schulz 1999). A total of only 6,753 White Stork breeding pairs was reported by the National Census of 1984 in Spain, the lowest number of nesting pairs ever recorded (Lázaro et al. 1986). The conservation campaign in the following years and the White Stork's exploitation of landfills resulted in the rapid recovery of their breeding population in Western Europe (Schulz 1999, Tortosa et al. 2002, Massemin-Challet et al. 2006). Although many studies discuss the potential effects of change in waste management on species that rely on landfills (see references in Plaza and Lambertucci 2017), only a few have explored the effects of landfill closure, for example, on Yellow-legged Gull (*Larus michahellis*) (Payo-Payo et al. 2015, Delgado et al. 2021, Pinto et al. 2021). In this species, the absence of landfills forced them to shift diet preferences but the scarcity in alternative feeding sources negatively impacted their population dynamics (Steigerwald et al. 2015, Zorrozua et al. 2020). Similar to gulls, White Storks may return to feeding sources used before landfill development and exploitation.

In addition to facing the shifts in landfill management, White Storks need to cope with climate change. In the Iberian Peninsula, White Storks naturally have a diet mostly based on earthworms, insects, amphibians and freshwater fishes (Lázaro 1982, Carrascal et al. 1990). However, these groups of prey are sensitive to extremely warm or cold temperatures and/or variation in precipitation and hydrological systems, such as increasing drought periods in our region (Corn 2005, Bosch et al. 2007, Fourcade and Vercauteren 2022, Harvey et al. 2022). Therefore, climate change may affect the abundance and distribution of potential prey, modifying population dynamics of White Storks (Dallinga and Schoenmakers 1987, Zheng et al. 2016). In addition, this variation in prey availability may interfere with the phenology of White Storks. Warmer weather advances the dates they reach the breeding grounds, resulting in lower breeding success (Gordo et al. 2007, Martín et al. 2021).

We focused on the breeding population of White Storks of Community of Madrid, Spain where the number and location of main landfills were nearly constant over the last 35 years. Our main objective was to evaluate the potential future impact of landfill closure on breeding population distribution and habitat suitability (Hirzel and Le Lay 2008), in a species that heavily relies on these landfills, under different climate change scenarios (i.e., climatic variables in the lowest and the highest shared socioeconomic pathways (Riahi et al. 2017)). We categorized both areas of high stork suitability for White Storks and areas with potential habitat loss or gain in 30-yr (2050) and 50-yr (2070) projections. We also evaluated the relevance of the landfills and other anthropo-ecological variables (e.g., land cover class, distance to water bodies, human density, etc.) in our models and we determine the effect of landfills, controlling by other anthropo-ecological variables, in the nest site selection in 2021. The combined use of both climate and habitat variables improves the predictive accuracy of species distribution models (SDMs) (Barbet-Massin et al. 2012). Finally, we predicted the effectiveness of protected areas to serve as breeding habitat.

MATERIALS AND METHODS

Study Area and Data Collection

All the municipalities of the Autonomous Community of Madrid (central Spain) were surveyed between the first week of March to the end of June in 2021 (Figure 1). Nests were monitored based on methodology from previous National and European censuses (Schulz 1999, Molina and Del Moral 2005). During the complete census of the region, we recorded nest location and occupancy during each visit. Most nests were visited 3 to 5 occasions, but only 1 visit was possible in some locations. For the latter, we conducted these single visits during the peak of the breeding season (i.e., end of April to middle of May) and considered nests to be occupied if breeding adults or nestlings were sighted. This method allows us to detect ~90% of breeding pairs within the nesting season (Aguirre and Vergara 2009). We assumed that our sampling effort is representative of the total White Stork breeding population in central Spain.

Landfill locations were obtained from PRTR-España, the Spanish Registry of Emissions and Pollutant Sources (https://en.prtr-es.es/Informes/InventarioInstalacionesIPPC.aspx). During the breeding season of 2021, there were 4 active landfills in the study area (Alcalá de Henares, Colmenar Viejo, Pinto y Las Dehesas) (Figure 1). White Storks were frequently observed feeding in all of them. The first landfill was opened in 1978 within our study area, but White Storks were not observed to forage at that location until the mid-1980s (Chozas 1983, Blanco 1996).

In response to our recent finding that landfill exploitation altered habitat use in White Storks (López-García et al. 2022 in review), we gathered locations of breeding populations from the national census of 1984 (Lázaro et al. 1986) to project the future distribution of White Storks in the future absence of landfills. Overall, 215 occupied nests were recorded in 1984. We recorded 2327 occupied nests in 2021.

Anthropo-Ecological Variables

Based on the previously acquired knowledge of this species' habitat use during the breeding season (Carrascal et al. 1993, Radović et al. 2015, Orłowski et al. 2019, Hmamouchi et al. 2020, Bialas et al. 2021), we selected a set of environmental variables to estimate the potential distribution of breeding pairs (Supplementary Material Figure S1). Corine Land Cover layers were reclassified into 7 land cover classes (López-García and Aguirre 2023): urban areas (CLC class 1); arable fields (CLC class 21); other agricultural land (CLC class 22 and 24, except 244); pastures, meadows & agro-forestry areas (CLC class 231, 321 and 244); forests (CLC class 31 and 32, except 321); non-suitable habitat (CLC class 33); and inland waters (CLC class 41 and 51). We discarded forests, inland waters, and non-suitable areas from our dataset. Urban areas were defined based on a human population density layer (i.e., urban extents [UE] have a population density of ≥1,000 persons km^{-2}; Supplementary Material Table S1). Distances between landfills, water bodies or urban areas, and nests were measured with a *Distance* matrix tool. Furthermore, we incorporated information on the current climate from WorldClim database version 2.1 (Supplementary Material Table S1). We used a resolution of 30 arc-sec (grid cell of 1 × 1 km size) for all the ecological and land cover variables.

To ensure the independence of variables, we performed a hierarchical cluster analysis showing the similarity among all variables in a dendrogram, following the methodology presented by Polidori et al. (2021) (Dormann et al. 2013). We used one of the most commonly suggested methods based on the correlation matrix, the Ward-clustering (Harrell 2001) (Figure 2A). The distance-threshold to form the clusters was established at 0.3 (i.e., <70% correlation). Among the 15 variables that passed this threshold, we chose the most derived variable in each cluster. Finally, we calculated a variance inflation factor (VIF) (Lin et al. 2011) and eliminated redundant variables that overestimated the variance (VIF > 5) (Stine 1995) (Supplementary Material Figure S1). The final set of selected variables included 12 variables (Supplementary Material Table S1).

We used QGIS 3.16.11 *Hannover* open-source software (QGIS Development Team 2022).

Future Climate Variables

We gathered bioclimatic variables from WorldClim (CanESM5; https://www.worldclim.org/data/cmip6/cmip6climate.html) with 30 arc-sec resolution to explore changes in population dynamics in response to different climate change predictions. We selected a conservative and an extreme emission pathway (Shared Socioeconomic Pathways SSP1-2.6 and SSP5-8.5, respectively) for each scenario. Projections were calculated for 2 periods, 2041–2060 (2050) and 2061–2080 (2070). Predictions are referred herein as 2050–ssp1, 2050–ssp5, 2070–ssp1 and 2070–ssp5 for simplicity. We also obtained human population density and measured distance to urban areas from Global 1-km Downscaled Population Base Year and Projection Grids Based on the SSPs, v1.01 (https://sedac.ciesin.columbia.edu/data/set/popdynamics-1-km-downscaled-pop-base-year-projection-ssp-2000-2100-rev01). We used Corine Land Cover 2018 to assess potential distribution of breeding pairs in our projections.

Species Distribution Model

We estimated the habitat suitability of White Storks through a set of SDMs using the occurrence data of nests surveyed in 2021 (n = 2,327), where Storks are known to use landfills. Habitat suitability is a type of potential distribution measure that relates environmental variables to the likelihood of occurrence of a species. In our case, habitat suitability relates the 12 selected anthropo-ecological variables to the occurrences of White Stork nests in the study area (Hirzel and Le Lay 2008). This parameter represents by values between 0 and 1, the low or high suitability (correspondingly) of the habitat at a scale of 1 × 1 km for the species.

We performed six different algorithms using the *biomod2* library (Thuiller et al. 2019): generalized linear model (GLM), generalized additive model (GAM), artificial neural network (ANN), Classification Tree Analysis (CTA), maximum entropy (MaxEnt) and Random Forest (RF). GLM represents an extension (i.e., a generalization) of the classical linear regression method (McCullagh and Nelder 1989). GAM does not use parametric shapes but rather let the data find the best solution, applying a selection of local smoothing functions along the predictors (Hastie and Tibshirani 1990). ANN find complex relations among the predictors, with a high tolerance to data uncertainty, and provides predicted variable patterns instantaneously (Ripley 1996). CTA uses an iterative optimization algorithm that searches to optimize a dichotomous decision key for explaining a dependent variable from a set of independent predictors (Breiman et al. 1984). MaxEnt is a correlative machine learning method that estimates a species' potential distribution by finding the probability distribution using the highest uniformity (i.e., maximum entropy; Elith et al. 2006). RF is another machine learning method that developed out of Classification and Regression Trees and uses a collection of tree-structured weak learners comprised of identically distributed random vectors where each tree contributes to a prediction for the predictors (Breiman 2001).

The average ensemble model based on 34 iterations of these 6 algorithms (204 individual models) was used to predict the potential distribution of White Storks. The construction of background and pseudoabsences were based on a 1-km buffer from each nest based on the previous acquired knowledge of the species (Olsson and Bolin 2014, Zurell et al. 2018, Orłowski et al. 2019). In the areas within the buffers, we generated 10,000 random points to generate the background points, and outside these areas, we generated the same number of nest occurrences as random points to construct the pseudoabsences.

Presence and pseudoabsence data of nest sites were split in 75/25% to generate an external Area Under the receiver operating characteristic Curve (AUC) evaluation for the final models, independently of the internal AUC evaluation of each individual model generated by *biomod2*. The 204 individual models were tested and only models with AUC >

0.7 were chosen (i.e., good to excellent performance of the model following the scale of Thuiller 2003). A final ensemble average model was then obtained. Finally, the final average model was evaluated though the external AUC test with 25% of the data. AUC value of the final model was 0.98, indicating an excellent discrimination capability. A cut-off value of the final model based on the lowest suitability values among all occurrences was also calculated with the *bm_FindOptimStat* function (0.532) to establish the areas of presence (>0.532) and absence (<0.532) of White Storks nests.

We projected habitat suitability considering scenarios in which there were no landfills as a source of food under EU regulations. As the 2021 occurrences were strongly influenced by landfills (see Results), we cannot use them without biasing resource selection. To emulate the conditions that Storks would be subject to in the absence of landfills, we used nest survey data from 1984 (n = 215), when these birds did not yet forage at landfills. We performed another ensemble SDM with these occurrences and with the same methodology described above to obtain habitat suitability in future scenarios. Finally, we projected this model into 4 future scenarios with the variables concerning 2050 and 2070 (2050–ssp1, 2050–ssp5, 2070–ssp1 and 2070–ssp5) (see the future variables section below). AUC of this model was 0.98 and cut-off value was 0.547.

Statistical Analysis

We use the function *BIOMOD_RangeSize* to evaluate change between 2021 and future White Stork breeding distribution in our study area. This function determines percent potential changes breeding distribution. Breeding population distribution in future scenarios was based on presences or absences of nests obtained from the cut-off value of the habitat suitability of each scenario We also considered the overlap between present and future distributions and the protected areas in Madrid. We considered the Peñalara National Park and Natura 2000 areas as protected areas (Figure 1).

We performed a GLM with binomial distribution and logit error structure to determine differences in nest site selection (presence vs absence) in relation to environmental variables in the predicted model of 2021. Nest site selection is defined as the occupation of a particular nest site from all possible sites based on the characteristics of the environment.

We performed a logistic regression to evaluate habitat suitability variation, measured as changes in habitat suitability in each future scenarios, as a response to environmental variables.

All statistical and spatial analysis were performed on R, v 4.2.2 program (R Development Core Team, 2015) using RStudio Software, v 1.1.453 (RStudio Team, 2015).

RESULTS

Breeding Population Distribution and Habitat Suitability

Our methodology included all nests observed in each grid cell, allowing us to establish a relationship between habitat suitability and nest density in our projections. Therefore, higher nest density implies higher habitat suitability and vice versa. Suitability decreased in areas far from water bodies and far from urban areas with high human population density in all our projections (Table 1). Areas with high presence of power lines, higher percentage of agriculture fields and arable lands, higher forest coverage, lower percentage of pastures & agro-forestry, lower isothermality, and higher precipitation were also associated with reduced suitability (Table 1). In addition, average temperature of the warmest annual quarter had a significant negative impact on suitability in the extreme emission pathway, ssp5 (Table 1). As a result, projected higher suitability areas were located in floodplains of main rivers (Jarama, Henares, Manzanares and Tajo) and valleys of the Northern region and the West municipalities of Madrid, which are associated with livestock (Figure 2).

Areas with higher habitat suitability in 2021 were estimated to show the highest declines in nest density based on our projections: 2050-ssp1 (Est = –0.013 ± 0.0004, t = –31.82, $p < 0.0001$), 2050 – ssp5 (Est = –0.013 ± 0.0004, t = –34.05, $p < 0.0001$), 2070-ssp1 (Est = –0.013 ± 0.0004, t = –32.23, $p < 0.0001$), 2070-ssp5 (Est = –0.013 ± 0.0004, t = –34.27, $p < 0.0001$). Therefore, our projection points out that nest density also declines in future scenarios (Figure 2).

Nest Site Selection in 2021

The ensemble model for 2021 distribution clearly revealed that the most important variable is distance to landfill (Figure 3). Other relevant variables influencing the suitability are distance to urban areas, distance to water bodies, percentage of forest cover, and climatic variables (isothermality, average temperature of the warmest annual quarter, and higher precipitation) (Figure 3).

However, the most relevant variables in 1984 were human population density (39.84%), isothermality (22.35%), forest (18.27%), arable lands (17.78%), distance to water bodies (17.04%) and pastures & agro-forestry (12.73%).

White Storks significantly prefer areas near landfills (Est = –0.002 ± 0.0001, Wald = –4.877, p < 0.0001), near water bodies (Est = –0.001 ± 0.0001, Wald = –3.958, $p < 0.0001$), with high percentage of pastures & agro-forestry (Est = 0.014 ± 0.004, Wald = 3.223, $p < 0.0001$), lower percentage of arable lands (Est = –0.029 ± 0.005, Wald = –5.52, $p < 0.0001$), higher isothermality (i.e., day-to-night temperatures oscillations relative to the summer-to-winter annual oscillations; , Est = 1.178 ± 0.244, Wald = 7.026, $p < 0.0001$), lower maximum temperature (Est = –0.227 ± 0.101, Wald = –2.257, $p = 0.024$) and lower precipitation in the coldest quarter (Est = –0.046 ± 0.017, Wald = –2.655, $p < 0.0001$) (Figure 4). Moreover, our ensemble model seems to show that White Storks avoided urban areas (Est = 0.0001 ± 0.001, Wald = 3.88, $p = 0.008$) in 2021 (Figure 4). None of the other environmental variables were significant ($p > 0.05$).

Range Distribution Loss

The actual breeding population distribution of White Storks in 2021 is 321 grid cells (321 km^2) and the model prediction estimation is 289 grid cells (289 km^2) in 2021. Our models predicted a large reduction in the breeding population in all future scenarios. For instance, the distribution range of the breeding population diminished by 56.40% in 2050-ssp1 and 70.16% in 2070-ssp1 (Figure 5), compared to 2021. Pronounced breeding population declines were predicted in the extreme emission pathway scenario, declining by 77.16% in 2050-ssp5 and 92.73% in 2070-ssp5 when compared to distribution ranges from 2021 (Figure 5). Both 2050-ssp5 and 2070-ssp5 highlight the high impact of climate change on White Stork breeding populations; the distribution ranges are even lower than the smallest distribution range recorded for this species (in 1984), when breeding area was 73.36% smaller than in 2021.

The model projections also showed an interesting spatial pattern. Loss of potential distribution range mainly occurred in the nearby area of 3 out of the 4 major landfills of Community of Madrid (Colmenar Viejo, Pinto and Las Dehesas). In fact, the potential distribution range in the nearby area of Alcala de Henares (East landfill) increased in 2050-ssp1, 2050-ssp5 and 2070-ssp1 when compared to Henares River (Figure 5).

Protected Areas

In 2021, more than a half of the predicted breeding areas overlapped with protected areas (62.28%). While the potential breeding population distribution area decreased in our projections (see above), the percentage of potential distribution of breeding areas overlapping with protected areas in 2050-ssp1 (69.05%), 2050-ssp5 (65.15%) and 2070-ssp1 (63.95%)

remained similar to population distribution in 2021. However, the percentage of overlap with protected areas decreased to 42.86% in the extreme emission pathway scenario in 2070 (i.e., 2070-ssp5).

DISCUSSION

Our projections showed a significant reduction in population distribution and suggested a decline in the habitat suitability in the absence of landfills. Our model results agreed with predictions from previous studies in gulls and vultures (Duhem et al. 2008, Tauler-Ametller et al. 2017), supporting the importance of close proximity to landfill in nest-site selection above every other variable. This indicates the role of landfills as reliable and abundant food resources during breeding season (López-García et al 2021).

Several processes potentially underly the predicted reduction in Stork population distribution and suitability in the absence of landfills. As a consequence of landfill closure, breeding pairs may increase range size to cope with the decrease in food abundance (Zurell et al. 2018) while food uncertainty reduces feeding success rate (Cowie 1977, Olsson and Bolin 2014). Larger home ranges along with food uncertainty would produce an increase in energetic demands and less time devoted to parental investment (Schoener 1971). Lower feeding rates may have negative effects on body condition and nourishment of both adults and nestlings (Tauler-Ametlller et al. 2019, Pineda-Pampliega et al. 2021), impacting adult survival and breeding success (Steigerwald et al. 2015, Delgado et al. 2021). Unsuccessful breeding pairs would likely progressively replace original nesting areas with areas with higher availability of food resources (Vergara et al. 2006). Secondly, the absence of extra food-supply promotes intra-specific competition and territoriality (Hixon 1980), restricting breeding opportunities for young breeders and poor-quality individuals (Vergara et al. 2007b). In fact, we found the strongest declines of future suitability in areas near landfills with higher suitability in 2021. Third, this sudden change in anthropogenic food resources was described to directly lead to diet shifts in gulls (Zorrozua et al. 2020, Spelt et al. 2021). The increase in pressure on natural prey may produce temporary imbalances of the system with potential ecological consequences such as local extinctions of some prey species.

In addition to the effect of landfill closure, our projections show that climate change can have dramatic consequences on future breeding population distribution. Future climate predictions indicate extreme temperatures, lower precipitation, marked seasonality, and extreme climatic phenomena (e.g., droughts and frost events) which may relocate European birds to more temperate areas (Barbet-Massin et al. 2012). According to this, our study region, which is characterized by a Mediterranean climate, would likely see White Storks shift their distribution towards areas with higher isothermality (i.e., showing the thermal "stability" of a region relative to annual variations in temperature), such as floodplains or valleys as our results suggested. These geographic regions overlap with areas typically preferred by White Storks, and their protection should be considered to preserve this species (Carrascal et al. 1993, Nowakowski 2003, Radović et al. 2015). Higher maximum temperatures and short periods of extreme precipitation have previously been demonstrated to have a direct negative impact on body condition and survival of nestlings (Carrascal et al. 1993, Jovani and Tella 2004, Fasolă-Mătăsaru et al. 2018).

Climate change also indirectly impacts population dynamics through variation in abundance and distribution of food resources whereas land-use changes may decrease most suitable feeding areas. While our study population showed consistent preference for breeding areas with pasture and agro-forestry and near water bodies, similar to other European populations (Radović et al. 2015, Zurell et al. 2018, Bialas et al. 2020), several studies forecasted a decrease in pastures in the future mainly due to the scarcity of water and land-use changes (Riahi et al. 2017, Fitton et al. 2019). Furthermore, scarce precipitation may reduce several typical prey species of White Storks (e.g., amphibians, earthworms or insects) (Markovic et al. 2014, Wessely et al. 2017, Fourcade and Vercauteren 2022). Nonetheless, the ability of generalist species to exploit new food resources, like invasive species, may mitigate landfill closure and climate change effects in some areas of the breeding distribution (Negro et al. 2014).

Our models showed that increasing urbanization restricted the already limited White Stork population distribution in future scenarios. Even when White Storks show some tolerance to human presence, as demonstrated by their habit of constructing nests on buildings, this species is not typically found in densely populated urban areas (Hmamouchi et al. 2020). High human densities induce physiological stress in White Storks, and the high percentage of impervious cover in massive cities reduces their access to food resources (Garroway and Sheldon 2013, Lowry et al. 2013, Blas et al. 2018).

Effective conservation measures have been diluted as White Stork population have increased in the last decades (ALG personal observation). Deterrent devices as well as nest removal have been promoted or, at least, treated with permission by administration entities (Garrido and Fernandéz-Cruz 2003, Vergara et al. 2007a, Moreira et al. 2018). It is particularly noticeable that current protected areas overlap with a significant percentage of the current population distribution but not in the 2070-ssp5 scenario, when projected population distribution is more restricted. This highlights the potential risk of White Storks to become endangered again.

This study provides relevant information that can be used in strategic planning for the management of wildlife which rely on landfills. Landscape-scale planning for restoration and conservation of wetlands, as well as pastures and meadows, should be a priority in areas adjacent to landfills in addition to a gradual landfill closure process. Furthermore, periodical monitoring programs of breeding populations along with GPS tracking of fledglings and breeding individuals are excellent tools to evaluate population dynamics and determine changes in habitat use (Rodríguez et al. 2012, Bouten et al. 2013).

Conclusions

In summary, our model projections of White Stork breeding population showed a strong reduction in range of distribution and habitat suitability of this species in all future scenarios in the absence of landfills. This reduction could become dramatic when we consider the extreme emission pathway and human population expansion (ssp5). However, landfill closure does not necessarily imply the collapse of the White Stork population. Gradual changes in landfill management, protection of natural feeding areas, and a reduction in environmental pollution and greenhouse gas emissions may contribute to White Stork conservation and may likely allow their population to adjust to landfill closures with no severe declines.

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Ethics statement

All methods and procedures adhere to Complutense University Guidelines and we have permits for fieldwork from the Dirección General de Biodiversidad y Recursos Naturales Área de Conservación de Flora y Fauna (Consejería de Medio Ambiente, Vivienda y Agricultura).

Conflict of interest statement

The authors declare no conflicts of interest.

Author contributions

Alejandro López-García was responsible for conceptualization, data curation, formal analysis, investigation, writing of original draft, writing, revising and editing, visualization. Diego Gil-Tapetado was responsible for methodology, formal analysis, writing of original draft, revising and editing, visualization. And José I. Aguirre was responsbile for conceptualization, investigation, methodology, revising and editing, supervision.

Data availability

Analyses reported in this article can be reproduced using the data provided by López-García et al. (2023).

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Figure 1. Map of our study area, the Community of Madrid. Rivers and water bodies are represented in blue and the Municipality of Madrid by the dark grey area in the center of the map. The protected natural areas of this region are marked in green. Landfills are represented by triangles and numbered: (1) Colmenar Viejo, (2) Alcalá de Henares, (3) Las Dehesas, and (4) Pinto.

Figure 2. Habitat suitability in 2021 **(A)** and in future scenarios **(B)**. Maps (**B**) show a decrease in the maximum habitat suitability in future, which are even more pronounced in extreme emission pathway scenarios (ssp5). Landfills are represented by white triangles. High suitability is represented in red and low suitability in blue.

Figure 3. Importance of the variables considered in our models: in 2021 (**A**) and in 1984 (**B**) with different algorithms: general linear model (GLM); artificial neural network (ANN), classification tree analysis (CTA), Random Forest (RF), maximum entropy (MaxEnt), generalized additive model (GAM), and the ensemble model (Mean). Landfill is the most important variable independently of the algorithm that we use. Variables: Landfill = distance to the nearest landfill; Water distance = distance to water bodies; Length power lines = length of the power lines; Agri = percentage of agricultural crops; Arable = percentage of arable lands; Index Forest = coverage of forest and density of trees; Pasture & AF = percentage of pastures and agro-forestry areas; Urban distance = distance to urban areas; Human dens = density of human population; Isotherm = Isothermality; Max temp = Maximum temperature of the warmest annual quarter; Cold quarter precip = precipitation of the coldest annual quarter.

Figure 4. Differences in the environmental variables between the presence points and absence points. Outliers with a value more than 1.5 times the interquartile range are shown as circles.

Figure 5. Changes in potential breeding population distribution of White Stork in Community of Madrid in absence of food availability from landfills and with different climate change future scenarios (ssp1 and ssp5). Landfills are represented by white triangles. Names corresponding to each landfill can be found in Figure 1.

Table 1. Predicted future habitat suitability variation considering different environmental variables under each respective climate-change scenario. *** Indicates the significance $p <$ 0.001.

Variables	**Estimate**	**SE**	***t* value**	***p***	
2050-SSP1					
Water distance	–0.001	0.001	–48.775	<0.0001	***
Power lines	0.002	0.001	9.644	<0.0001	***
Agri	–0.090	0.004	–21.205	<0.0001	***
Arable	–0.123	0.003	–45.552	<0.0001	***
Index forest	–0.151	0.006	–23.697	<0.0001	***
Pasture & AF	0.028	0.003	9.496	<0.0001	***
Urban distance	–0.001	0.001	–33.216	<0.0001	***
Human dens	–0.002	0.001	–29.331	<0.0001	***
Isotherm	1.002	0.096	10.398	<0.0001	***
Max temp	–0.023	0.088	–0.261	0.794	
Cold quarter precip	–0.017	0.002	–7.886	<0.0001	***
2050-SSP5					
Water distance	–0.001	0.001	–43.818	<0.0001	***
Power lines	0.001	0.001	8.465	<0.0001	***
Agri	–0.056	0.004	–14.451	<0.0001	***
Arable	–0.093	0.002	–37.476	<0.0001	***
Index forest	–0.118	0.006	–19.988	<0.0001	***
Pasture & AF	0.033	0.003	12.103	<0.0001	***
Urban distance	–0.001	0.001	–37.163	<0.0001	***
Human dens	–0.002	0.005	–33.776	<0.0001	***
Isotherm	1.113	0.098	11.408	<0.0001	***
Max temp	–0.277	0.083	–3.326	<0.001	***
Cold quarter precip	–0.018	0.002	–8.711	<0.0001	***
2070-SSP1					
Water distance	–0.001	0.001	–46.248	<0.0001	***
Power lines	0.001	0.001	9.152	<0.0001	***
Agri	–0.075	0.004	–18.27	<0.0001	***
Arable	–0.116	0.003	–44.126	<0.0001	***
Index forest	–0.143	0.006	–22.944	<0.0001	***
Pasture & AF	0.031	0.003	10.808	<0.0001	***
Urban distance	–0.001	0.001	–33.194	<0.0001	***
Human dens	–0.002	0.001	–31.616	<0.0001	***
Isotherm	0.719	0.096	7.459	<0.0001	***
Max temp	0.096	0.085	1.120	0.263	
Cold quarter precip	–0.019	0.002	–9.474	<0.0001	***
2070-SSP5					
Water distance	–0.001	0.001	–38.505	<0.0001	***
Power lines	0.001	0.001	9.671	<0.0001	***
Agri	–0.052	0.004	–13.945	<0.0001	***
Arable	–0.073	0.002	–30.837	<0.0001	***
Index forest	–0.098	0.007	–17.294	<0.0001	***
Pasture & AF	0.035	0.003	13.355	<0.0001	***
Urban distance	–0.003	0.001	–38.42	<0.0001	***
Human dens	–0.002	0.001	–39.513	<0.0001	***
Isotherm	1.395	0.104	13.41	<0.0001	***
Max temp	–0.602	0.086	–7.013	<0.0001	***

Cold quarter precip	–0.013	0.002	–6.461	<0.0001	***

Variables: Water dist = distance to water bodies; Power lines = length of the power lines; Agri = percentage of agricultural crops; Arable = percentage of arable lands; Index forest = coverage of forest and density of trees; Pasture & AF = percentage of pastures and agro–forestry areas; Urban distance = distance to urban areas; Human dens = density of human population; Isotherm = Isothermality; Max temp = Maximum temperature of the warmest annual quarter; Cold quarter precip = precipitation of the coldest annual quarter.

Figure 1

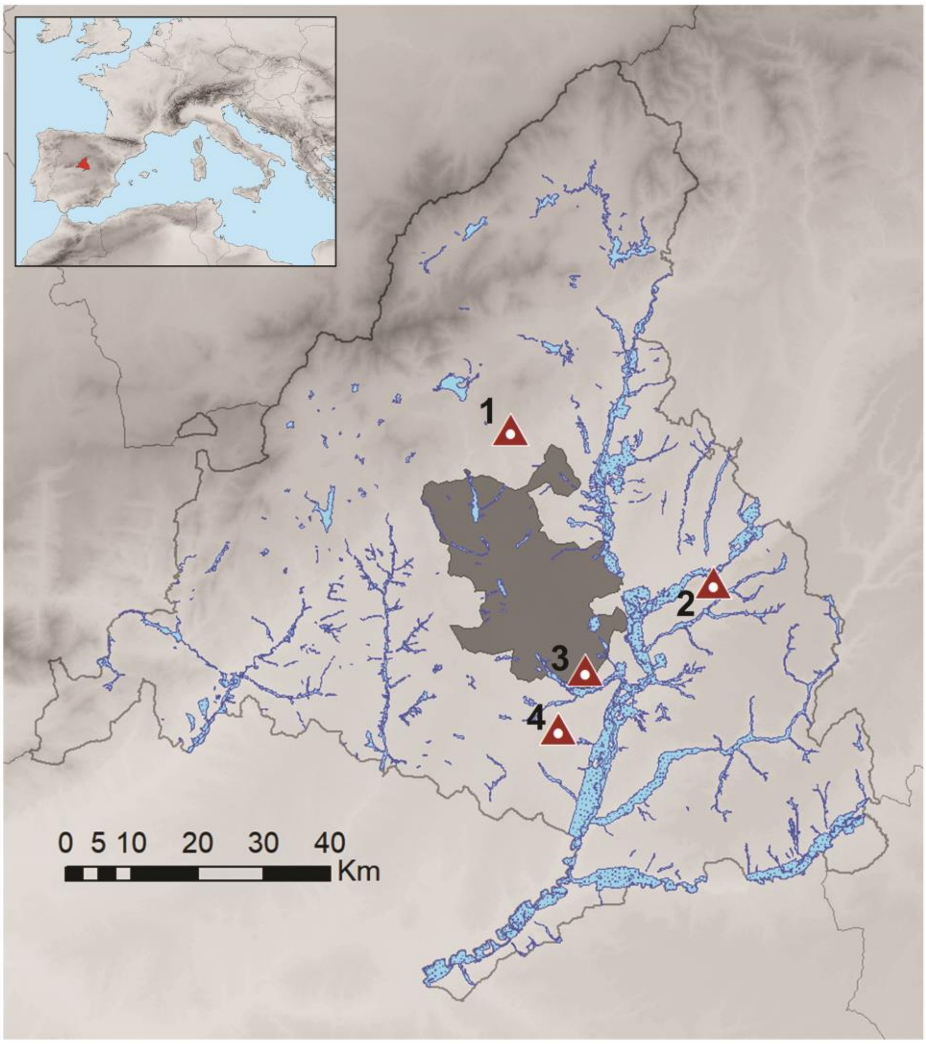


Figure 2

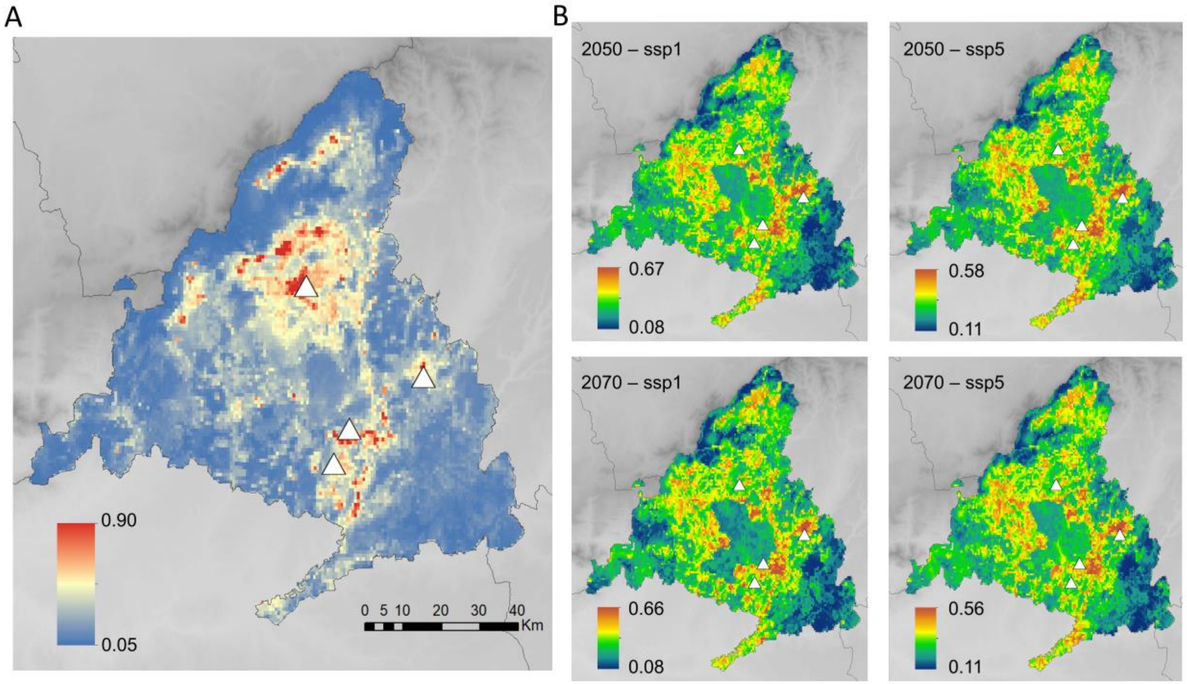
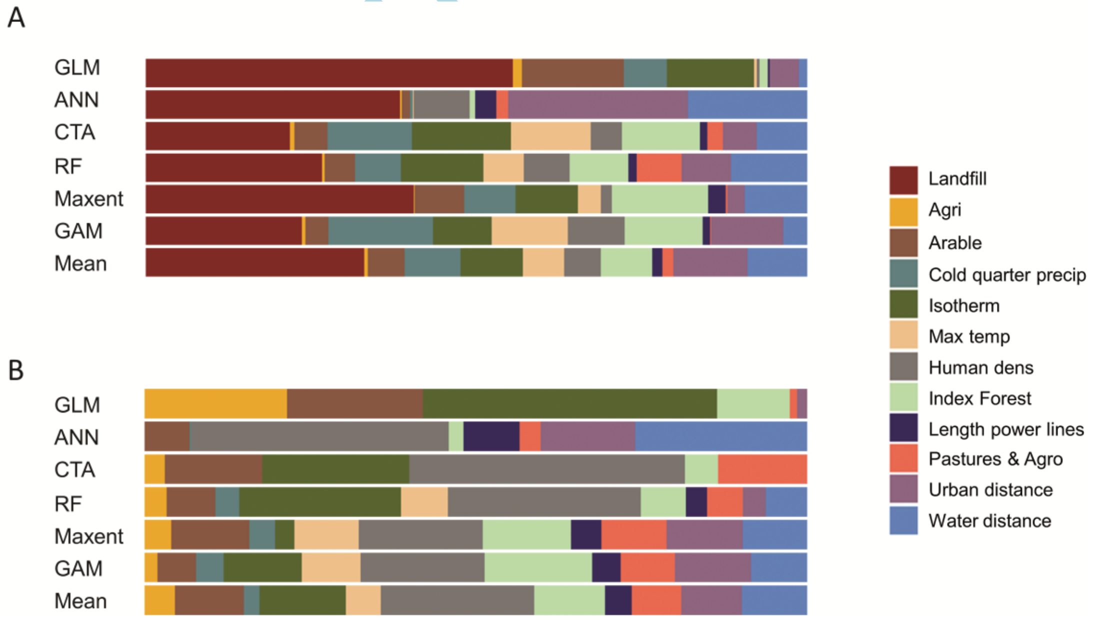
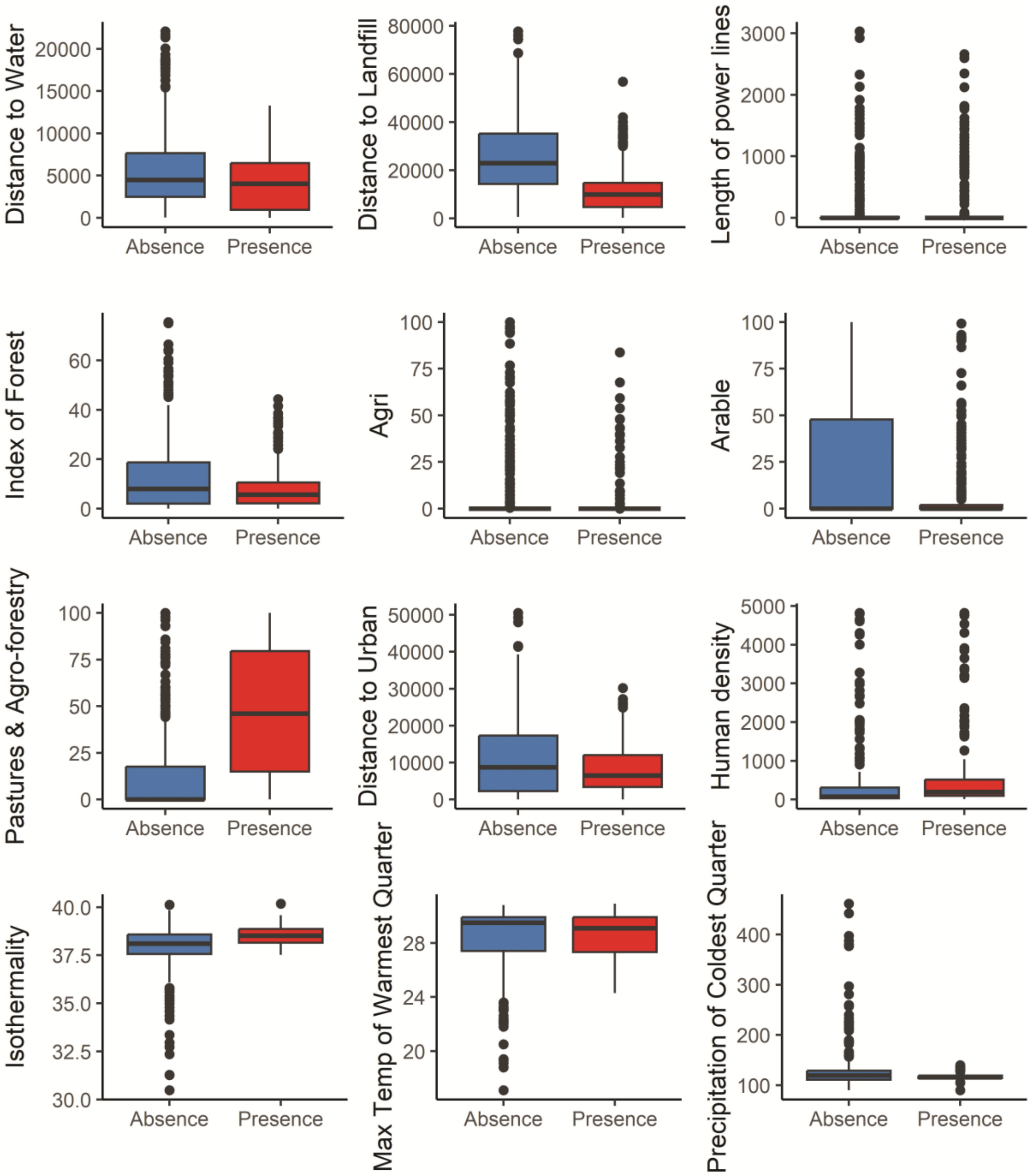

A
B
0.90
0.05
0 5 10 20 30 40
Km
2050 – ssp1
0.67
0.08
2050 – ssp5
0.58
0.11
2070 – ssp1
0.66
0.08
2070 – ssp5
0.56
0.11

Figure 3



A
GLM
ANN
CTA
RF
Maxent
GAM
Mean
B
GLM
ANN
CTA
RF
Maxent
GAM
Mean
Landfill
Agri
Arable
Cold quarter precip
Isotherm
Max temp
Human dens
Index Forest
Length power lines
Pastures & Agro
Urban distance
Water distance

Figure 4



Distance to Water
20000
15000
10000
5000
0
Absence
Presence
Distance to Landfill
80000
60000
40000
20000
0
Absence
Presence
Length of power lines
3000
2000
1000
0
Absence
Presence
Index of Forest
60
40
20
0
Absence
Presence
Agri
100
75
50
25
0
Absence
Presence
Arable
100
75
50
25
0
Absence
Presence
Pastures & Agro-forestry
100
75
50
25
0
Absence
Presence
Distance to Urban
50000
40000
30000
20000
10000
0
Absence
Presence
Human density
5000
4000
3000
2000
1000
0
Absence
Presence
Isothermality
40.0
37.5
35.0
32.5
30.0
Absence
Presence
Max Temp of Warmest Quarter
28
24
20
Absence
Presence
Precipitation of Coldest Quarter
400
300
200
100
Absence
Presence

Figure 5