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DOI: https://doi.org/10.3897/arphapreprints.e152093

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ABSTRACT

Understanding the movements of alien species in newly colonized territories is crucial for addressing the challenges posed by global transformations and threats to biodiversity conservation. In this study, we used mark-resight data to investigate the dispersal movements of the sacred ibis in Italy, which were virtually unknown until now. We analyzed data from 357 colour-ringed ibises, the majority of which were marked as nestlings, including six hybrids with the African spoonbill. Resightings revealed a tendency towards philopatry, with most observations occurring within 10 km of the original colony. However, some individuals traveled much farther, with maximum recorded distances exceeding 300 km from the ringing site. The average long-distance travel speed was 15.4 km per day. Movement directions showed clustering along both the North-South and East-West axes, influenced by colony location. Landfills emerged as significant feeding sites, particularly in winter. Age class had a significant negative effect on dispersal distance, whereas timing of hatching showed a positive effect. Despite the apparent pronounced tendency towards philopatry, the high dispersal potential of the sacred ibis suggests the possibility of rapid territory expansion and colonization of areas far from natal colonies. These findings provide the first evidence of the

dispersal capability of the sacred ibis outside its natural range and should be used to inform management actions aimed at mitigating the potential effects of this invasive species.

INTRODUCTION

The increasing spread of invasive alien species (IAS) is considered one of the major drivers of biodiversity loss in the Anthropocene (Park 2004). This spread can vary considerably depending on species ecology and environmental conditions, ranging from a slow and localized process to the rapid colonization of extensive areas (Liu et al. 2014; Cameron and Bayne 2015). The rate, mode, and circumstances of this process depend on several factors, including species-specific dispersal strategies. In IAS, these strategies may differ from those observed in their native range and may also shift during the invasion process. Furthermore, when tracking invasion patterns, it is crucial to consider the potential increase in activity levels or exploratory behavior of the alien species (Burstal et al. 2020).

The sacred ibis (*Threskiornis aethiopicus*; class: Aves), native to sub-Saharan Africa and Iraq, has been present in Europe as an alien species since the 1970s, following repeated escapes from aviaries and wildlife parks (Yésou and Clergeau 2005). The presence of these escaped individuals complicates efforts to determine whether other birds could have arrived spontaneously from their native range (Cocchi et al. 2023). While the likelihood of isolated immigrants appears low, it is not implausible, as observed in other highly dispersive avian species and hypothesized by Marion (2013). In Europe, breeding in the wild has been confirmed in France, Germany, Italy, Portugal, Spain, Switzerland, and the Netherlands (Robert et al. 2013; Yésou et al. 2017). In Italy, the species has been recorded since the 19th century (Arrigoni degli Oddi 1929), but until the early 2000s, it was not yet considered naturalized (Brichetti and Fracasso 2003). The exact origin of the Italian population remains uncertain. However, since the 1990s, the population has been reinforced by numerous accidental releases and escapes from zoos in Italy and neighboring countries (Cocchi et al. 2023) and possibly by individuals dispersing from the expanding French population (Cucco et al. 2021).

This exotic and relatively easy-to-maintain bird is commonly kept in zoological gardens, wildlife centres, and private parks. The risk of escapes and subsequent population growth remains a concern, particularly in non-EU countries where the keeping of alien species is not regulated. In recent years, over 10,000 individuals have been counted in captivity across

Europe. Currently, 142 facilities in EU countries and 34 in non-EU European countries house sacred ibises (Zootierliste, n.d.).

Until the early 2000s, the few recorded sacred ibises were concentrated in northwestern Italy. However, since 2006, their expansion has been continuous and exponential, initially across a large area of the Po Valley and later, with increasing frequency, into at least 14 regions of central and southern Italy, including the major islands of Sicily and Sardinia (Cucco et al. 2021; Ercole et al. 2021). Beyond the core population in northwestern Italy, in the past five years, the species has established thriving colonies in central and northern regions (Scarton and Valle 2020; Cucco et al. 2021). This geographical expansion has been accompanied by an exponential increase in numbers, from around 70 individuals with sporadic nesting until 2010, to 1,249 breeding pairs and over 11,000 wintering individuals in northwestern Italy by 2019 (Cocchi et al. 2023).

Regulation 1143/2014 of the European Parliament requires Member States to implement measures for managing IAS, including provisions to prevent their introduction and control their spread (European Parliament and Council 2014). Since 2016, the sacred ibis has been listed as an IAS of Union Concern, meaning it is subject to management measures and restrictions on keeping, importing, selling, breeding, and releasing into the environment. This classification is primarily due to its predation on amphibians and the eggs of native bird species, as well as its potential competition for breeding sites with native species such as the Eurasian spoonbill (*Platalea leucorodia*), colonial herons, and egrets. In response, Italy approved a national management plan for the species in 2023 (Cocchi et al. 2023), aiming to eradicate, reduce, and control the population in the Po Plain while preventing its expansion into currently unoccupied areas.

However, the effectiveness of a species management plan—both in terms of economic cost and technical feasibility—relies on a comprehensive understanding of the target species' ecology, population dynamics, and distribution. One critical factor in this context is dispersal, which significantly influences the extent and pace of invasion. Without robust quantitative ecological data clarifying the mechanisms driving species demography, developing a targeted control strategy and evaluating its effectiveness may be challenging, if not impossible.

In this study, we analyse a 19-year capture-mark-resight dataset to assess the dispersal capacity of the sacred ibis outside its native range. We also evaluate the role of dispersal in the context of the management strategies applied to this invasive species of Union Concern.

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METHODS

a. Mark-resight data.

From 2004 to 2023, a total of 357 nestlings and fledged ibises were marked with metal rings provided by the Italian Ringing Scheme and a yellow plastic ring with a unique 2- or 3-digit alphanumeric code. These colour-rings can be read from a distance of up to 100 metres using a telescope or digital images taken with a telephoto lens. Nestlings (n = 321) were marked in five colonies located either in inland locations (Desana and Valbrembo) or coastal wetlands (Comacchio and Ravenna) (Table S1 in Supplementary material, Figure 1). Most of the fledged birds were accidentally caught in cages originally intended for anatids and herons at the Casalbeltrame ringing station (province of Novara), and occasionally in colonies during nest monitoring.

The first nestlings were ringed in the southern Po Delta, where the sacred ibis settled in a large mixed heronry, breeding in close association with Eurasian spoonbills and other colonial waterbirds (Volponi, 2020). In fact, the very first ringed nestlings were hybrids from a mixed pair formed by a male sacred ibis and a female African spoonbill (*Platalea alba*) nesting in a flooded *Salix* bush (Volponi et al. 2008). In 2016-2018, nestlings were ringed at the colony situated within the Valbrembo zoological park (province of Bergamo), where free sacred ibises bred on tall coniferous trees (Castiglioni, 2017). There, ringing was only possible by approaching the nests from a mobile aerial platform during tree maintenance work. More regular and intensive ringing started in 2017 in the colony inside the large coastal lagoon of Comacchio (province of Ferrara) where ibis nests were built on the ground, again close to the spoonbills nests. In addition, a small number of nestlings were ringed from ground nests in the Desana colony, located near the city of Vercelli in an area of intensive rice cultivation.

Most of the resighting data came from the observation of colour-ringed birds and to a lesser extent (less than 2% of the total number of records) from the recovery of dead birds. Birdwatchers, wildlife photographers and amateur ornithologists provided most of the observations outside the ringing sites. Such observations were often reported via social media or, secondarily, directly to the Italian ringing scheme or to the ringers themselves. Searches for ringed birds were regularly carried out during visits to known ibis colonies, heronries and their surroundings. Other resightings were obtained from images taken by camera traps used to monitor nests in the Comacchio colony.

Resightings of individuals marked as nestlings and seen in or near the ringing site were only included in the analysis if they occurred after 40 days of marking, in order to exclude records before fledgling. Data collection for resightings ended on 30 September 2024.

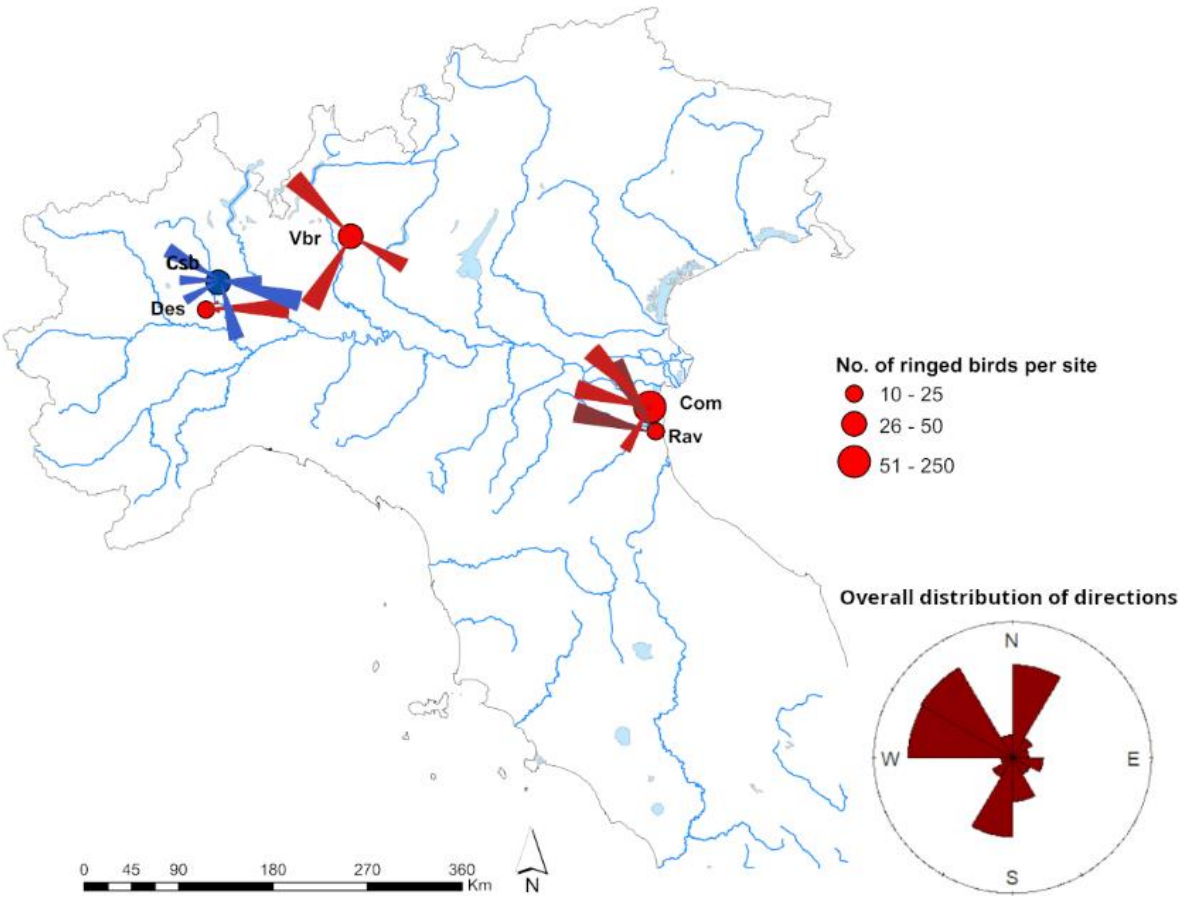

Figure 1. Map of ringing sites in Northern Italy and the corresponding movement directions observed. The size of each dot is directly proportional to the number of individuals ringed. Red dots represent breeding colonies, while the blue dot marks the location of the Casalbeltrame ringing station. Abbreviations: Com: Comacchio; Vbr: Valbrembo; Csb: Casalbeltrame; Des: Desana; Rav: Ravenna. The circular plot in the bottom-right corner illustrates the overall distribution of movement directions for resighted birds.

b. Movement Analysis.

Data from resightings were analysed to derive quantitative metrics of ibis movement and dispersal. To perform the analysis, when more than one resighting of the same individual occurred within the same month, only the one furthest from the ringing site was retained. Specifically, we (i) calculated both the orthodromic distance and direction between an individual marking site and each resighting location; (ii) calculated the average travel speed using the method of Smith and Munro (2011), which involves dividing the distance travelled by individuals covering significant distances (>150 km in our case) in a short period of time (<4 months) by the number of days elapsed; (iii) calculated the percentage of resightings per habitat to highlight any differences in occurrence among habitat types; (iv) checked whether, if an individual was resighted in a breeding colony, the latter was its hatching colony or not, to explore the possible tendency for philopatry or reproductive exchange among different colonies; (v) estimated how age class and hatching time of resighted individuals affected their travel distance, using Generalized Linear Mixed Model (GLMM) fitted using restricted maximum likelihood (REML). We used age groups and hatching time (or "brood class") as predictive variables and ring code (i.e. individual) as random factor to avoid pseudoreplication. This analysis was performed using the R (R Core Team, 2022) package lme4 (Bates et al. 2015). All classes were determined only for birds marked as nestlings. Age classes 1-, 2-, 3-, and 4-year old or older were categorised as follows: 1) birds resighted the same year they hatched, 2) birds resighted the year following their hatching, 3) birds resighted two years after hatching, and 4) birds resighted three or more years after hatching. We considered three brood classes: early broods (nestlings marked before 15 May), intermediate broods (nestlings marked between 16 May and 30 June), and late broods (nestlings marked from 1 July).

We used the Rao's spacing test (R package circular; Agostinelli and Lund, 2024) to test whether the calculated directions were randomly distributed or clustered. This analysis was performed by first considering the total movements and then separately examining the movements of birds ringed in coastal (provinces of Ravenna and Ferrara) and inland sites (provinces of Bergamo, Novara and Vercelli).

RESULTS

Mark-resight.

In total, 491 resightings were achieved during the study period, representing 138 different individuals (38.7% of the total number of individuals ringed). The year with the highest number of resightings (234) was 2024, with 64 different individuals. There were no resightings before 2006 and none in 2015. The vast majority of resightings involved live birds, but six concerned birds were found dead. Of these, three died of natural causes, two were shot, and one died as a result of a severe weather event. One of the shot birds was killed by a poacher in 2009, and the other by a wildlife ranger during a culling in Friuli-Venezia Giulia in 2023. Apart from the authors and ringers, 71 observers reported 215 resightings from 68 localities, spread across eight administrative regions and 19 provinces. Ringed birds were resighted at ibis and heron colonies, daytime aggregations, night roosts, and feeding sites in various habitats, including natural wetlands, ditches and canals, agricultural fields, and artificial environments (e.g. landfills, dung heaps). Most resightings were made at landfill sites (41.2%) and breeding colonies (38.8%) (Figure 2). In 97.8% of cases, where resighting occurred at a breeding colony, it was the same colony where the individual was ringed as a nestling.

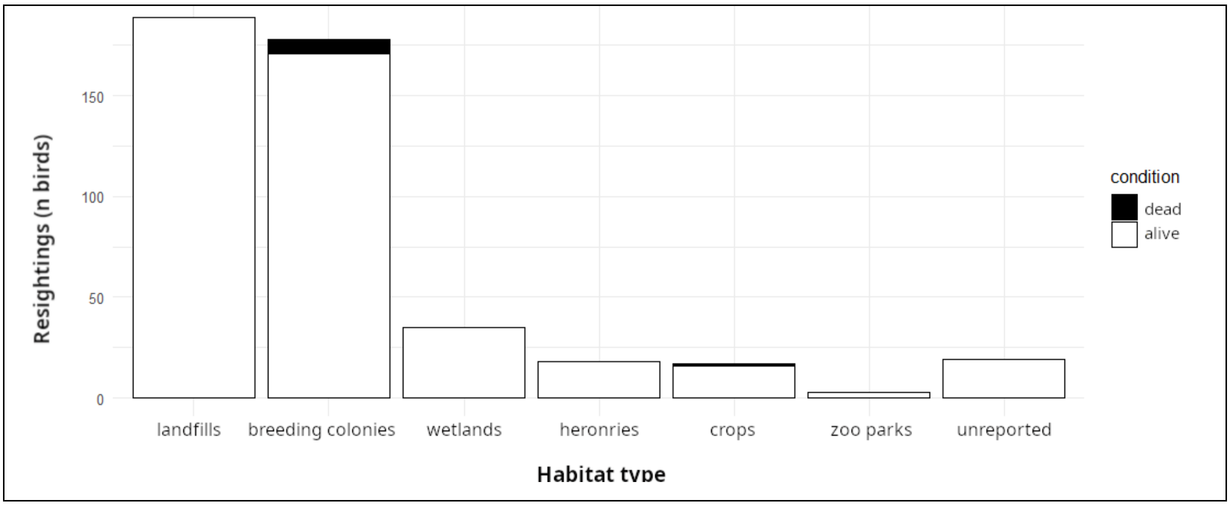

Figure 2. Number of resightings per habitat type. Recovery of dead individuals are shown in black.

Movement Analysis.

a. Dispersal distances.

Local movement after fledging, calculated as the mean orthodromic distance, was 40.97 km (SD = 58.33 km). However, the longest orthodromic distance travelled by an individual was 358.48 km, and five birds travelled distances of over 250 km. The movements of hybrid individuals were much more restricted, with an average dispersal of 3.5 km and a maximum orthodromic distance covered of approximately 13 km. Around 42.7% of resightings (excluding hybrids) occurred within 10 km of the ringing location (Figure 3). The average travel speed calculated for birds covering long distances (i.e. >150 km) in a short (<4 months) time was found to be 15.4 km per day, with the highest speed achieved by an individual covering 316.7 km in just over 3.5 months (26.6 km per day).

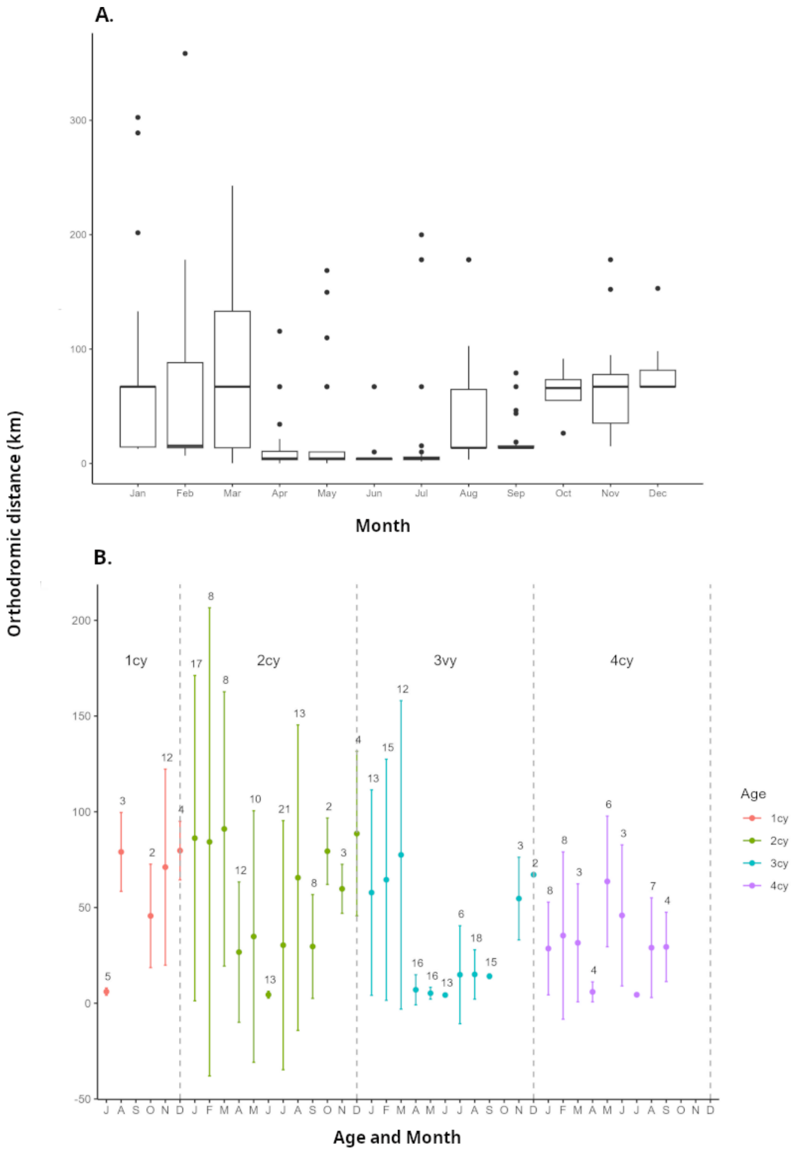

Figure 3. A. Mean orthodromic distance travelled by resighted birds, divided by month of resighting, without distinction by age class. B. Mean orthodromic distance (± standard deviation; in kilometers). Resightings are grouped by month and age class (calculated in calendar years, see methods). The numbers on each bar indicate sample size.

Results from the GLMM, revealed significant associations between distance travelled and both age and brood class factors (Figure 3, Table S). In particular, age group had a significant negative effect on distance travelled (mean effect and 95% CI = -29.28, [-50.99, -7.57], t value = -2.645 for age class 3 and -33.17, [-59.16, -7.18], t value = -2.502 for age class 4), suggesting that older individuals tended to travel shorter distances. Conversely, brood class 3 had a significant positive effect on distance travelled (mean effect and 95% CI = 51.49, [17.53, 85.45], t value = 2.968 for brood class 3), while brood class 2 effect was positive but not significant - indicating that only birds from the latest broods tended to travel longer distances.

b. Directions.

Rao's spacing test on the directions (in degrees) taken by resighted individuals significantly (t= 292.2, p<0.001) indicated that angular directions were not uniformly distributed in space. When considered all together, the dispersal paths of the ibises were not randomly directed; instead, they exhibited a clear clustering, predominantly directed towards the northwest and roughly along the north-south axis (Figure 1). Two individuals showed interesting commuting movements along the east-west axis between the Adriatic coast and the western Po valley.

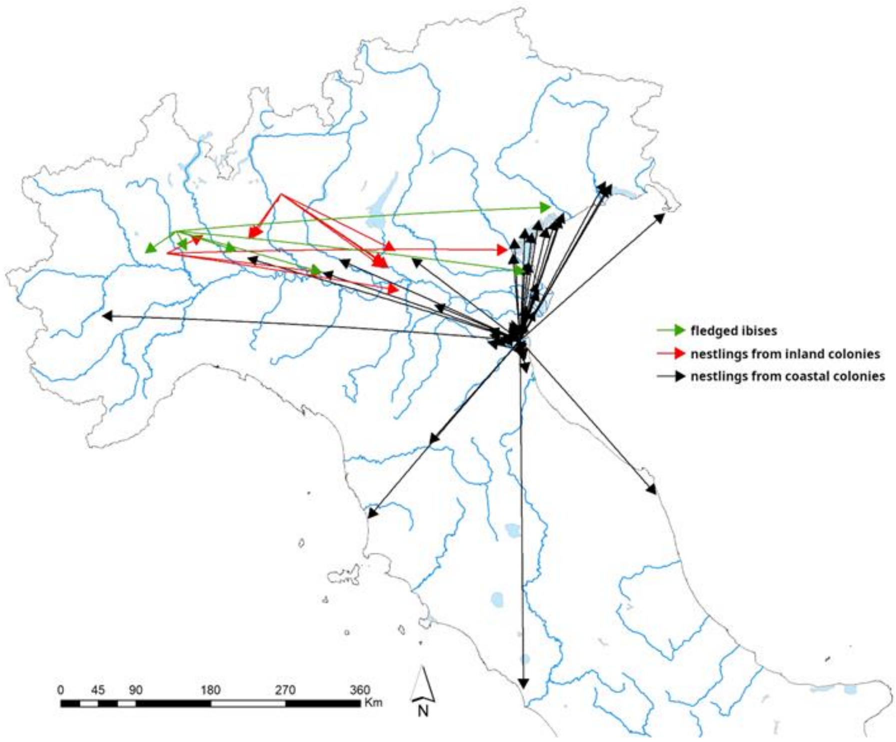

Figure 4. Movements of the Sacred ibises ringed in Italy. The colour of the arrows corresponds to individuals ringed as fledged birds (green) or as nestlings from inland (red) and coastal (black) colonies. The arrowheads indicate the recapture sites.

For both birds ringed in coastal and inland colonies, the directionality of movement was found to be non-random and highly clustered (assessed by Rao's spacing test, t = 237.6 for inland and 301.0 for coastal, both p<0.001). The Watson's two-sample test of homogeneity yielded a test statistic of 1.261 and a p-value of less than 0.001, indicating a significant difference between the directional movement angles of individuals ringed in coastal colonies compared to those ringed in inland colonies. This suggests distinct directional patterns between the sampled populations. While birds from inland colonies showed a prevalence of movement along the east-west axis, those ringed in coastal colonies showed a distinct directional trend along the north-south axis, accompanied by a secondary dispersal cluster towards the west-northwest direction. (Figure 2, 4).

DISCUSSION

Understanding the dispersal of alien species beyond their native range is crucial for addressing the challenges of managing them in a constantly changing environment (Webber and Scott, 2011). Although ringing has inherent limitations—such as potential sampling biases (e.g., certain age groups of birds being more likely to be resighted; Giuntini et al. 2023) and its inability to track entire migration routes, capturing only segments through resightings (Smith and Munro, 2011)— the exploration of movement ecology through ringing has consistently proven its worth (Baillie et al. 1999; Thorup et al. 2014; Dalui and Mondal, 2023). In this study, we used this technique to unravel previously unknown dispersal movements of this alien species during a period of population expansion outside its native range.

The analysis of resightings showed a rather pronounced tendency for adults and juveniles (probably during prospecting movements) to be philopatric towards the colony where they had been marked as nestlings. In fact, about half of the resightings occurred within 10 km of the ringing site. Specifically, whenever a bird was resighted in a breeding colony—the most common resighting habitat after landfills—was consistently the same breeding colony where the individual had been ringed. On the other hand, nest site fidelity is indeed quite characteristic of the species (Maillard et al. 2020), and has also been observed in the closely related Australian white ibis (*Threskiornis molucca*, Smith and Munro 2011). Nevertheless, we acknowledge the presence of possible bias in this result, as several resightings were obtained within the colonies of origin during nest monitoring. However, the large number of observers and their extensive geographical distribution (see Results) should help mitigate such bias.

In our sample, local post-fledgling dispersal consistently averaged less than 50 km. However, substantial movements of more than 350 km were documented as early as the first autumn-winter of life. The much shorter distances observed for hybrids, never exceeding 12 km and averaging less than 4 km, are not particularly surprising, as all hybrid observations were restricted to the first few months after fledging. Except for hybrids, the observed dispersal distances align with findings from other invasion areas, such as France, where ibises have dispersed over hundreds of kilometres (Clergeau and Yésou, 2006), and with patterns in their native range, where adult ibises travel significant distances during post-breeding dispersal, often accompanied by juveniles (Hancock and Kushlan, 1992). In Africa, the extent and direction of movements vary with seasonal rainfall. Ringing records indicate that birds ringed in South Africa have been recovered across a wide territory, reaching as far as Zambia, Botswana, and Namibia, with the most distant recovery recorded 1,474 km from the ringing site (Clark and Clark, 1979). Similarly, the Australian white ibis (*T. molucca*)—once considered a subspecies of *T. aethiopicus* (Hancock and Kushlan, 1992; Christidis and Boles, 2008) and now recognized as one of three species in the *Threskiornis aethiopicus* superspecies complex (Lowe and Richards, 1991)—frequently travels distances exceeding 300 km, with occasional movements surpassing 1,000 km (Smith and Munro, 2011).

The average dispersal speed we calculated appears to be particularly high. When considered alongside observations from other newly invaded areas and the inherently high mobility of ibises in their native range (Clark and Clark, 1979), this underscores the species' potential to expand across a significant portion of the Italian territory within a few years. Theoretically, our results suggest that ibises could traverse the entire length of Italy in less than three months. This finding aligns with the dispersal speeds calculated by Smith and Munro (2011) for *T. molucca*, where the fastest ringed individual traveled at an average speed of 14.5 km per day. It is also important to note that our estimated speed is likely conservative, as it remains unknown whether the resighted bird arrived at the resighting site on the day of observation or had been there for several days. This potential for range expansion is particularly relevant given the extensive suitable habitat available throughout Italy, as outlined by Cucco et al. (2021), much of which remains uncolonized.

Indeed, while the species has primarily been recorded in northern Italy, recent years have seen an increasing number of regular sightings in central and southern regions (Nicoli et al. 2022; Pantalone et al. 2023; Fraticelli, 2024; Maio et al. 2024). Given the species' high mobility, it is reasonable to assume that its range expansion could impact countries near Italy that are either not yet colonized or only partially so. Colonies in northwestern Italy (e.g., Piedmont) could expand into neighboring France, where an eradication program has been in place since 2007, leading to a significant reduction in the French ibis population (Yésou et al. 2017). Moreover, ibises dispersing from colonies in other Italian regions may have already contributed to the colonization of nearby countries. For instance, the six immature birds that spent a few weeks in the Magadino Plain (Canton Ticino, Switzerland) in early 2021 (Mordasini, 2021) may have originated from colonies in Piedmont or Lombardy. Similarly, some of the at least 30 ibises observed in Corsica (France) in 2021 (CorseOrnitho, 2021) could have arrived from Tuscany, possibly following migrating Eurasian spoonbills that were present in the same coastal wetland at the time. Finally, at least one of the 12 individuals recorded in Slovenia in February 2024 (Maks Šešlar, pers. comm.) was confirmed to have been born and ringed in the Comacchio colony in 2023. The prevalence of movements along the east-west axis (and vice versa) in the Po Valley and northwards from the Emilia-Romagna colonies appears to be guided by the hydrographic network of the Po River and the sequence of wetlands along the northern Adriatic coast. Similar behaviour has been observed in spoonbills, herons, cormorants, and other colonial wading birds ringed in the Po Delta (Volponi S. unpublished data). Elsewhere, closely related species, such as the Glossy Ibis (*Plegadis falcinellus*), have been found to follow wetland flyways (Samroui et al. 2023). Additionally, sacred ibises within the same roost and colony seem to consistently maintain an awareness of local foraging areas from one day to the next. This is supported by the relatively stable and directional flight paths of birds departing in the morning (Evans et al. 1981) or returning at dusk (Volponi, unpublished data). This pattern may help to explain tendency of some ringed individuals to exhibit east-west commuting movements from their original coastal colony towards the core area of initial settlements (i.e., the western Po Valley). Such behaviour could be an extended form of the commuting movements between foraging areas and roosts characteristic of the species. However, it is important to note that typical commuting movements generally cover shorter distances (less than 1 km, Evans et al. 1981; Yésou et al. 2017) and are therefore likely distinct from the longer-range movements (several tens of kilometres) observed in this study. The most plausible hypothesis remains that these movements involve individuals returning in spring to their marking colony following breeding or prospecting dispersal.

The location of resightings underscores the key role of landfills as feeding sites and, more specifically, as winter hotspots. Across three winters (2021–2023), a total of 35 distinct individuals, accounting for 81 observations, were resighted at five landfill sites in the provinces of Cremona, Ferrara, Ravenna, and Venice. These sites, which hosted anywhere from a few dozen to over 1,000 ibises, served as foraging grounds where the birds scavenged a mix of animal, plant, and human waste alongside other bird species. The majority of ibises observed at landfills were juveniles and immatures, with adults present in smaller numbers. This suggests that landfills play a role in winter survival, particularly for younger individuals, which are generally more vulnerable to winter mortality.

The use of landfills as feeding sites by ibises has been documented in other populations. Clark and Clark (1979) noted that ibises tend to concentrate in areas where food is produced by human activities, such as animal farms and rubbish dumps. Clergeau and Yésou (2005) reported over 600 ibises feeding at a single landfill, while Marion (2013) identified landfills as the primary feeding grounds for the species in Brittany. Similarly, the Australian white ibis exhibits the same foraging behaviour in its native range. Smith and Munro (2011) found that landfills played a dominant role in the species' feeding habits, with over 90% of resightings occurring at these sites. Despite their ecological significance, the role of landfills as key feeding areas has not been previously highlighted in the Italian context. This is particularly important for population management initiatives, as the easy access and constant availability of food in landfills—especially during winter—can promote aggregation and enhance survival rates in large numbers of birds (Oro et al. 2013).

The analysis revealed a significant effect of age class on dispersal distance, which decreased with increasing age. This may reflect natal dispersal—i.e., the movement from the birth site to the site of first (or potential) reproduction—of immature birds (Greenwood and Harvey, 1982).

Although this might seem to contradict the observed philopatric tendencies, a plausible hypothesis, at least in our case study, is that juvenile ibises engage in extensive prospecting movements before returning to their natal colonies to breed, having gathered information on potential breeding sites during their first two years of life (Morales et al. 2010). This would also align with the observed non-random directionality of movements, which, as mentioned above, appears to follow the distribution of wetlands.

Even immature northern gannets (*Morus bassanus*), although highly faithful to their natal colony, tend to explore and assess the habitat quality of other colonies (Votier et al. 2011)—a behaviour also documented in the glossy ibis (Santoro et al. 2013).

By contrast, the observed positive effect of hatching time on dispersal distance is less straightforward. While no comparable analyses exist for the sacred ibis or other Pelecaniformes, Oudman et al. (2017) found a positive relationship between chick condition and hatching date in stable Eurasian spoonbill colonies in the Netherlands. Moreover, in several bird species, better body condition is associated with greater dispersal distances (Barbraud et al. 2003; Liu and Zhang 2008). However, this aspect requires further investigation.

Our data show that sacred ibises born in a single colony exhibit different dispersal behaviours and may be nomadic, as recorded in their native range (Clark and Clark, 1979) and in the closely related *T. molucca* (Carrick, 1962; Smith and Munro, 2011). These results have implications for the spread of this alien bird into new territories and the establishment of new settlements, highlighting the importance of understanding the movement ecology of alien species in order to prevent or mitigate potential negative impacts. At the same time, the high dispersal capacity of the sacred ibis can affect the effectiveness of management measures for this invasive species. Taking in consideration these results, a regular and effective monitoring programme should be implemented to enable adaptive resource management.

CONCLUSIONS

Our findings provide crucial insights into the dispersal patterns of the sacred ibis outside of its native range, demonstrating its high mobility and potential for rapid range expansion across Italy and beyond. This study represents the first attempt to analyse the dispersal dynamics of the species in Europe, offering novel data on its movements during a phase of population expansion. The observed dispersal distances, comparable to those documented in both the species' native and invasive ranges, underscore its ability to colonize new areas swiftly, facilitated by a network of suitable habitats and anthropogenic food sources such as landfills. Given the species' capacity for long-distance movements and its reliance on human-altered landscapes, targeted conservation actions, including habitat monitoring and population control measures, should be adapted accordingly. Ultimately, this study underscores the necessity of ongoing, large-scale monitoring to inform evidence-based management and mitigate the ecological impact of this expanding invasive species.

Acknowledgements.

We thank the Ente Biodiversità Parco Delta del Po Emilia-Romagna (Comacchio, FE) and Mrs. Elisabetta Accatto (Desana, VC) for granting the access to the ringing colonies; Pietro Cassone and Alessandro Re for sharing the data of ibises ringed at Casabeltrame; Roberta Castiglioni, Marco Cucco, Davide Emiliani, Mauro Fasola and Daniela Mengoni for their assistance and invaluable help during ringing operation and search for ringed birds; the numerous birdwatchers, amateur ornithologists and photographers who provided a large amount of the ibis resightings.

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Marking of the Sacred ibises was carried out by ringers licensed by the Italian Ringing Scheme of ISPRA. Activities carried out after the year 2020 were concerted with the Italian Ministry of the Environment and the Piedmont and Emilia-Romagna Regional Administrations as a part of the management plan of this alien species.

REFERENCES

Arrigoni degli Oddi E (1929) Ornitologia italiana. Hoepli, Milano.

Agostinelli C, Lund U (2024) R package 'circular': Circular Statistics (version 0.5-1). URL https://CRAN.R-project.org/package=circular

Baillie SR, Wernham CV, Clark JA (1999) Development of the British and Irish ringing scheme and its role in conservation biology. Ringing & Migration 19(S1): 5-19.

Barbraud C, Johnson AR, Bertault G (2003) Phenotypic correlates of post-fledging dispersal in a population of greater flamingos: the importance of body condition. Journal of Animal Ecology 72(2): 246-257.

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67(1): 1-48. doi:10.18637/jss.v067.i01.

Brichetti P, Fracasso G (2003) Ornitologia Italiana 1. Gaviidae-Falconidae. Alberto Perdisa Editore, Bologna: 464 pp.

Burstal J, Clulow S, Colyvas K, Kark S, Griffin AS (2020) Radiotracking invasive spread: Are common mynas more active and exploratory on the invasion front? Biol Invasions 22: 2525–2543. https://doi.org/10.1007/s10530-020-02269-7

Cameron EK, Bayne EM (2015) Spatial patterns and spread of exotic earthworms at local scales. Canadian Journal of Zoology 93(9): 721-726.

Carrick R (1962) Breeding, movements and conservation of Ibises (Threskiornithidae) in Australia. CSIRO Wildlife Research 7(1): 71. https://doi.org/10.1071/cwr9620071

Castiglioni R (2017) Biologia riproduttiva di ibis sacro (Threskiornis aethiopicus) in provincia di Bergamo: risultati di 5 anni di monitoraggio – XIX CIO Torino 2017.

Christidis L, Boles W (2008) Systematics and taxonomy of Australian birds. CSIRO Publishing.

Clark RA, Clark A (1979) Daily and seasonal movements of the Sacred Ibis at Pretoria, Transvaal. Ostrich 50: 94–103.

Clergeau P, Yésou P (2006) Behavioural flexibility and numerous potential sources of introduction for the sacred ibis: causes of concern in western Europe? Biological Invasions 8(6): 1381-1388.

Cocchi R, Volponi S, Baccetti N (2023) Piano di gestione nazionale dell'ibis sacro Threskiornis aethiopicus (Latham, 1790). ISPRA e MASE. https://www.specieinvasive.isprambiente.it/images/Piani_di_gestione_approvati/piano_di_gestione_ibis_sacro_13_marzo_2023.pdf

Commission Implementing Regulation (EU) 2016/1141 of 13 July 2016 adopting a list of invasive alien species of Union concern pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council, 2016.

CorseOrnitho (2021) Attention: Spatule hongroise & Ibis africains @ Tanchiccia!!. http://corseornitho.canalblog.com/archives/2021/10/14/39177088.html (Accessed on 08/11/2011).

Cucco M, Alessandria G, Bissacco M, Carpegna F, Fasola M, Gagliardi A, Gola L, Volponi S, Pellegrino I (2021) The spreading of the invasive sacred ibis in Italy. Sci Rep 11: 86. https://doi.org/10.1038/s41598-020-79137-w

Dalui T, Mondal N (2023) Unlocking the Secrets of Bird Conservation through Ringing: A Review. Journal of Advanced Zoology 44(4): 559-562. https://doi.org/10.17762/jaz.v44i4.2065.

Ercole S, Angelini P, Carnevali L, Casella L, Giacanelli V, Grignetti A, La Mesa G, Nardelli R, Serra L, Stoch F, Tunesi L, Genovesi P (ed.) (2021) Rapporti Direttive Natura (2013-2018). Sintesi dello stato di conservazione delle specie e degli habitat di interesse comunitario e delle azioni di contrasto alle specie esotiche di rilevanza unionale in Italia. ISPRA, Serie Rapporti 349/2021.

Evans SM, Cantrell MA, Cram A (1981) Patterns of arrival and dispersal from a mixed communal roost of Sacred ibises and Marabou Storks. Ostrich 52(4): 230-234.

European Parliament and Council (2014) Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. Official Journal of the European Union, L 317, 4.11.2014, pp. 35–55. Available at: https://eur-lex.europa.eu

Fraticelli F (2024) L’Ibis sacro Threskiornis aethiopicus nel Lazio. Alula 31(1): 73–77. https://doi.org/10.60990/alula.2024.12

Gagliardi A, Volponi S, Tenan S, Preatoni D, Martinoli A (2023) Predators and prey: interactions between Sacred ibis (Threskiornis aethiopicus) and other species at nesting sites in northern Italy.

Giuntini S, Tattoni C, Gagliardi A, Martinoli A, Patocchi N, Lardelli R, Martinoli A, Preatoni DG (2023) Limnology for the ornithologist: effects of Lake Maggiore water level on migratory flows. Journal of Limnology 81(s2): 1-13.

Greenwood PJ, Harvey PH (1982) The natal and breeding dispersal of birds. Annual Review of Ecology and Systematics 13: 1-21.

Hancock JA, Kushan JA (1992) Storks, Ibises and Spoonbills of the World. Princeton University Press.

Liu Y, Zhang Z (2008) Research progress in avian dispersal behavior. Frontiers of Biology in China 3: 375-384.

Liu X, Li X, Liu Z, Tingley R, Kraus F, Guo Z, Li Y (2014) Congener diversity, topographic heterogeneity and human-assisted dispersal predict spread rates of alien herpetofauna at a global scale. Ecology Letters 17(7): 821-829.

Lowe KW, Richards GC (1991) Morphological variation in the sacred ibis Threskiornis aethiopicus superspecies complex. Emu 91(1): 41–45. https://doi.org/10.1071/MU9910041

Maio N, Fraissinet M, Pollaro F, De Luca C, Bolinesi F, Guarino FM (2024) New records of African Sacred Ibis Threskiornis aethiopicus (Latham, 1790) (Pelecaniformes:

Threskiornithidae) from Salerno Province. Bulletin of Regional Natural History 4(4): 5–8. https://doi.org/10.6093/2724-4393/10943

Marion L (2013) Is the Sacred ibis a real threat to biodiversity? Long-term study of its diet in non-native areas compared to native areas. Comptes Rendus Biologies 336(4): 207-220.

Morales JM, Moorcroft PR, Matthiopoulos J, Frair JL, Kie JG, Powell RA, Haydon DT (2010) Building the bridge between animal movement and population dynamics. Philosophical Transactions of the Royal Society B: Biological Sciences 365(1550): 2289-2301.

Mordasini E (2021) Ibis sacro raro in Canton Ticino e solo sul Piano di Magadino. https://www.youtube.com/watch?v=AtOnvxRY4_M&lc (Accessed on 01/09/2023).

Nicoli A, Di Masso E, La Grua G (eds) (2022) Ibis sacro, Annuario 2021. Quaderni di Birdwatching 39: 65.

Oro D, Genovart M, Tavecchia G, Fowler MS, Martínez-Abraín A (2013) Ecological and evolutionary implications of food subsidies from humans. Ecology Letters 16(12): 1501-1514.

Oudman T, De Goeij P, Piersma T, Lok T (2017) Colony-breeding Eurasian Spoonbills in The Netherlands: local limits to population growth with expansion into new areas. Ardea 105(2): 113-124.

Pantalone M, Ottorino Bai S, Sborgia M (2023) L’ibis sacro Threskiornis aethiopicus nelle Marche e in Abruzzo: presenza, habitat, ecologia e attività trofica nell’Italia centrale adriatica. Alula 30: 131–147. https://doi.org/10.60990/alula.2023.13

Park K (2004) Assessment and management of invasive alien predators. Ecology and Society 9(2). https://www.jstor.org/stable/26267679

Robert H, Lafontaine R, Delsinne T, Beudels-Jamar R (2013) Risk analysis of the Sacred ibis Treskiornis aethiopicus. Royal Belgian Institute of Natural Sciences, Brussels.

Samraoui B, Nedjah R, Boucheker A, Bouzid A, El-Serehy HA, Samraoui F (2023) Blowin' in the wind: Dispersal of Glossy Ibis Plegadis falcinellus in the West Mediterranean basin. Ecology and Evolution 13: e9756. https://doi.org/10.1002/ece3.9756

Santoro S, Green AJ, Figuerola J (2013) Environmental instability as a motor for dispersal: a case study from a growing population of glossy ibis. PLoS One 8(12): e82983.

Scarton F, Valle R (2020) L’Ibis sacro Threskiornis aethiopicus (Latham, 1790) in laguna di Venezia: una sintesi decennale (2010-2019) sulla presenza di una specie invasiva. Bollettino del Museo di Storia Naturale di Venezia 71: 113–121.

Smith AC, Munro U (2011) Local and regional movements of the Australian White Ibis Threskiornis molucca in eastern Australia. Corella 35(4): 89-94. https://opus.lib.uts.edu.au/handle/10453/18192#

Thorup K, Korner-Nievergelt F, Cohen EB, Baillie SR (2014) Large-scale spatial analysis of ringing and re-encounter data to infer movement patterns: A review including methodological perspectives. Methods in Ecology and Evolution 5: 1337-1350. https://doi.org/10.1111/2041-210X.12258

Volponi S, Emiliani D, Sighele M (2008) Nidificazioni ibride di spatola Africana (Platalea alba) a Valle Mandriole (RA). Quaderni di Birdwatching X: 20. https://www.researchgate.net/publication/381953989_Nidificazioni_ibride_di_Spatola_Africana_Platalea_alba_a_Valle_Mandriole_RA

ARPHA Preprints Author-formatted, not peer-reviewed document posted on 05/03/2025. DOI: https://doi.org/10.3897/arphapreprints.e152093

Votier SC, Grecian WJ, Patrick S, Newton J (2011) Inter-colony movements, at-sea behaviour and foraging in an immature seabird: results from GPS-PPT tracking, radio-tracking and stable isotope analysis. Marine Biology 158: 355-362.

Webber BL, Scott JK (2012) Rapid global change: implications for defining natives and aliens. Global Ecology and Biogeography 21(3): 305-311.

Yésou P, Clergeau P (2005) Sacred Ibis: a new invasive species in Europe. Birding World 18(12): 517-526.

Yésou P, Clergeau P, Bastian S, Reeber S, Maillard JF (2017) The Sacred Ibis in Europe: ecology and management. British Birds 110: 197-212.

Zoo Institutes (n.d.) Platalea leucorodia X Threskiornis sp. Hybrid / White spoonbill X Ibis in zoos. https://zooinstitutes.com/animals/white-spoonbill-x-ibis-4953/ (Accessed on 04/09/2023).

Zootierliste (n.d.) Sacred ibis (Threskiornis aethiopicus). Retrieved December 18, 2024, from https://www.zootierliste.de/en/?klasse=2&ordnung=208&familie=20805&art=2050507