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ORIGINAL ARTICLE

First year-round movement tracking of the Mediterranean Gull (*Ichthyaetus melanocephalus*) in Europe: insights and conservation recommendations for declining population

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Abstract

This study examines the Mediterranean Gull (*Ichthyaetus melanocephalus*), utilizing GPS/GSM transmitters year-round for the first time on this species. The research covers habitat use, migration patterns, and breeding behaviors, tracking 19 birds captured at breeding colonies in Poland. To capture the birds and fit transmitters, we selected representative locations: islands in dam reservoirs, gravel pits, rivers, and lakes. Mediterranean Gulls nested mainly in colonies of Black-headed Gulls (*Chroicocephalus ridibundus*). By tracking birds with transmitters, we identified nine additional breeding sites within Poland, the Czechia, and Germany. We determined the mean length of phenological periods: breeding (76, April 10–June 26), autumn migration (11, June 26–July 7), winter (261, July 5–March 23), and spring migration (18, March 23–April 10). According to residence sites analysis, cropland was the most frequently used habitat during breeding (52.9%), while the open sea was predominant in winter (25.8%). We identified key wintering areas: the English Channel, the Utrecht–Antwerpen area, the North Sea coast, and the Irish Sea coast. One individual wintered along the coast of Portugal and near Malaga in Spain. An interesting discovery was the longer spring migration than autumn what involved visits to multiple potential breeding sites, leading to the mapping of a network of potential breeding areas. This underscores the need for proactive habitat protection and comprehensive conservation strategies. Given the Mediterranean Gull's migratory behavior and lifecycle, the study advocates for it as a model for conserving migratory waterbirds.

Keywords Conservation strategies · Breeding colonies · Waterbirds · GPS/GSM telemetry · Habitat use · Migration patterns · Anthropogenic pressures

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Zusammenfassung

Die erste ganzjährige Nachverfolgung der Bewegungen der Schwarzkopfmöwe (Ichthyaetus melanocephalus) in Europa: Einsichten und Schutzempfehlungen für die abnehmende Population

Diese Studie untersucht die Schwarzkopfmöwe (*Ichthyaetus melanocephalus*) und hat zum ersten Mal bei dieser Art ganzjährig GPS/GSM-Transmitter eingesetzt. Unsere Forschung umfasst Habitatnutzung, Zugmuster und Brutverhalten und basiert auf der Verfolgung von 19 in Brutkolonien in Polen gefangenen Vögeln. Um die Vögel zu fangen und die Transmitter zu befestigen, suchten wir repräsentative Standorte aus: Inseln in Stauseen, Kiesgruben, Flüssen und natürlichen Seen. Schwarzkopfmöwen brüteten hauptsächlich in Kolonien der Lachmöwe (Chroicocephalus ridibundus). Durch das Verfolgen besenderter Vögel identifizierten wir neun weitere Brutorte in Polen, Tschechien und Deutschland. Wir ermittelten die durchschnittliche Länge phänologischer Perioden: Brut (76, 10. April–26. Juni), Herbstzug (11, 26. Juni–7. Juli), Winter (261, 5. Juli–23. März) und Frühjahrszug (18, 23. März–10. April). Gemäß einer Aufenthaltsortanalyse waren Kulturflächen das am meisten genutzte Habitat während der Brutsaison (52,9 %), während das offene Meer im Winter vorherrschte (25,8 %). Als Hauptüberwinterungsgebiete ermittelten wir den Ärmelkanal, das Gebiet um Utrecht und Antwerpen, die Nordseeküste und die Küste der Irischen See. Ein Individuum überwinterte entlang der portugiesischen Küste und in der Nähe von Malaga in Spanien. Eine interessante Entdeckung war, dass der Frühjahrszug länger dauerte als der Herbstzug; ersterer schloss Besuche mehrerer potenzieller Brutorte ein, was uns die Kartierung eines Netzwerks möglicher Brutgebiete erlaubte. Dies unterstreicht die Notwendigkeit proaktiven Habitatschutzes und umfassender Schutzstrategien. In Anbetracht von Zugverhalten und Lebenszyklus der Schwarzkopfmöwe empfehlen wir diese Art als Modell für den Schutz ziehender Wasservögel.

Introduction

Birds seasonally migrate due to changes in food availability and the abundance of feeding grounds (Dingle and Drake 2007). During the Holocene period, birds developed specific migratory patterns involving predictable seasonal movements to optimize survival and reproduction (Alerstam et al. 2003). However, in the Anthropocene epoch, characterized by significant human impact on the environment (Dirzo et al. 2014), these patterns are being altered. We are observing the emergence of new and altered animal movement patterns in response to rapid climate changes and habitat modifications (Boere and Taylor 2004; Xu et al. 2017).

Climate change has prompted range shifts in many bird species (Pavon-Jordan et al. 2015; Marchowski et al. 2017, 2020). While a logical consequence of global warming in the northern hemisphere would be a northward shift of northern species, this phenomenon is not universal. In many instances, species are indeed moving northward (Lehikoinen et al. 2013), but there are also observed cases of species expanding southward (Keller et al. 2020; Marchowski et al. 2022). Migration patterns may even reverse due to new food resources and milder conditions in the north, with birds nesting in the south migrating northwards after breeding (Ławicki 2014). These examples illustrate that changes in annual bird migration patterns are complex and not easily predictable. The simplistic notion that populations are shifting north solely due to climate change does not fully align with observed realities.

In an era of significant anthropogenic pressure and progressive defaunation, species conservation should be a priority (Dirzo et al. 2014). Effective protection of migratory species requires conservation efforts across their entire range (Esler 2001). The current model for protecting migratory species is inadequate as it fails to ensure the protection of key areas across their entire range (Runge et al. 2015). In times of changing bird migration patterns, it is crucial to understand and update knowledge on new movement directions and identify key areas during breeding, migration, and wintering periods (Berthold et al. 2003; Bibby 2003). Birds face numerous challenges during breeding, migration, and wintering, including habitat loss, pollution, food resource depletion, and the impacts of climate change, which can exacerbate these challenges by directly affecting species and indirectly through further adversely impacting habitat loss and food availability. Although key areas in many populations' life cycles may seem well-established, a deeper understanding of detailed migration routes and stopovers is essential to comprehend the drivers behind population declines, especially as these factors may change under a changing climate (Quillfeldt et al. 2021).

A notable example of a species that has undergone changes in its range and migration pattern in recent decades is the Mediterranean Gull (*Ichthyaetus melanocephalus*), a West Palearctic species primarily distributed in Europe (Burger et al. 2020). Despite the range expanding northwestward in recent years, the overall population trend is declining (BirdLife International 2019). According to the criteria of the International Union for Conservation of Nature (IUCN), the Mediterranean Gull is classified as a least concern (LC) species. The population in Europe is suspected to be decreasing by less than 25% over a period of 30.3 years (three generations); therefore, it does not qualify for a higher threat category than LC. The declining trend is also evident in the Polish population, with a 6.4% decrease in breeding population size from 2007 to 2020 (Zieliński et al. 2022).

In Poland, the Mediterranean Gull is a rare breeding bird; the average number of breeding pairs is approximately 60 in 2015 to 2020 (Zieliński et al. 2022).

Initially, the main breeding grounds were in southeastern Europe, around the northern Black Sea and Sea of Azov (Ardamadskaya 1999). Currently, many breeding colonies are in central Europe, in some sites around the Baltic Sea, the British Isles, and Ireland, with new colonies emerging in Spain, France, Belgium, and the Netherlands (Balmer 2020). Considering that most of the global population of this species resides in Europe, it is crucial to investigate the factors contributing to its decline. According to the Birds Directive, species with their main range in Europe should be treated with priority under this European legislation, which is responsible for protecting birds within Europe (Directive 2009).

In our study, we aimed to describe the annual cycle of Mediterranean Gulls using telemetry data, filling the gap in knowledge about their year-round movements. We focused on tracking the movements of 19 Mediterranean Gulls from breeding sites in Poland. As locations for capturing birds and installing transmitters, we selected the primary types of habitats used as nest sites by this species in Poland, specifically islands on rivers, gravel pits, and lakes. Initially considered the frontier of the species' northward expansion (Zielińska et al. 2007), recent monitoring suggests a stabilization or moderate decline in this population, indicating that Poland may represent the northeastern edge of their distribution (Zieliński et al. 2022). This study is the first to describe the year-round movement of Mediterranean Gulls using GPS/GSM tags at breeding site. There is one prior study on Mediterranean Gull but focused on the reproductive events instead the year-round migration period (Picardi et al. 2020).

Existing knowledge about their habitat selection during breeding and wintering is limited (Cramp and Simmons 1977), with general observations indicating a variety of habitats including coasts, estuaries, harbors, marshes, inland lakes, fields, and grasslands. Mediterranean Gulls are typically found in coastal lagoons, steppe lakes, and open lowland marshes with sparse vegetation, avoiding barren sands (Burger et al. 2020). They also inhabit coastal salt marshes, particularly in Northwest Europe (Blamer 2020). Remarkably adaptable, Mediterranean Gulls have recently expanded their range into new areas with different climates and vegetation (Blamer 2020; Burger et al. 2020). Our article seeks to provide updated information on the habitat use of this predominantly European gull species.

Our study specifically aims to address the following research questions:

(i) Movement patterns: This section is designed to analyze and compare the durations and migration rates of autumn and spring migrations, as well as to ascertain the lengths of the breeding and wintering periods. In addition, it seeks to identify a generalized migration pattern for the species under study.

(ii) Habitat selection: This segment delves into the clarity of habitat use patterns across the breeding season. It explores the coexistence of Mediterranean Gulls in colonies with other bird species, including gulls and terns, and aims to identify these frequently associated species. Moreover, the study endeavors to determine the use of habitats by Mediterranean Gull during various phenological phases, such as breeding, autumn migration, spring migration, and wintering, across different habitats, which encompass rivers, agricultural fields, and landfills.

(iii) Identification of important sites: This goal centers on pinpointing critical locations that hold significant importance for the species throughout the breeding, migratory, and wintering phases. Furthermore, it evaluates how these essential stopovers, wintering, and breeding sites are safeguarded by legal protection.

Materials and methods

Selection of breeding sites for the study

Established breeding colonies, where the Mediterranean Gull has consistently nested since the beginning of Polish state monitoring in 2007, were selected as study sites (Zielińska et al. 2007, 2022). The sites represent various nesting habitats, including islands on rivers, gravel pits, dam reservoirs, and natural lakes at the following specific locations: Wykowo (52.433, 19.811), Arciechów (52.327, 20.084), Zastów Karczmiski (52.329, 20.073), Skoki (52.5866, 19.3669), Nysa Reservoir (50.4412, 17.2080), Rynskie Lake (53.905, 21.479), and Januszkowice (50.377, 18.142). After confirming Mediterranean Gull presence by a telescope from a shore-based observation point, the islands were accessed using floating equipment. Nest and adult bird counts were conducted using traditional methods, which involves determining the species composition of the colony and the number of individual species. First, adults are counted from a distance, then the nests are counted directly. For large colonies, transect sampling or sample plots are used (Chylarecki et al. 2015). Field surveys, including nest inspections, were carried out on clear, windless, and rain-free days and completed before 7 p.m. to minimize disturbance pre-dusk. At least two field inspections, with a 14-day interval, were conducted during 9 to 31 May in years 2020 to 2022 to assess Mediterranean Gull and other species numbers, counting nests with eggs or chicks and categorizing by species. For a small number of nesting sites without visible nests, estimates were based on confirmed or probable breeding which means counting adult birds in the colony (Bibby et al. 2000). Drones were utilized for counting in large colonies following the approach in Marchowski (2021).

Breeding sites selected

In this study, Mediterranean Gulls chosen for tagging nested in seven locations, all of which were breeding in colonies of Black-headed Gull (*Chroicocephalus ridibundus*) on islands. Four locations had natural habitats, such as islands on lakes or rivers, while the remaining three were in artificially created habitats like water reservoirs on gravel pits or dam reservoirs. The average colony size of the Black-headed Gull was 4700 pairs, ranging from 452 to 10,429 (Table 1). These colonies also hosted other species of gulls and terns, including Caspian Gulls (*Larus cachinnans*) averaging 275 pairs (range 0–1924), Common Terns (*Sterna hirundo*) averaging 64 pairs (range 0–124), Common Gulls (*Larus canus*), European Herring Gulls (*Larus argentatus;* Table 1; GIOŚ 2023).

Catching and tagging birds

Most birds were captured in breeding colonies using nest traps as a breeding adult or by hand in the case of chicks. Birds already bearing metal and plastic rings were noted, and unringed birds were fitted with a metal ring on the left tarsus and a plastic ring with an alphanumeric code on the right tarsus. All birds were then equipped with GPS/GSM loggers. The devices were placed on nine females, nine males, and one young bird of unknown sex. In terms of age classes, one bird was in its first calendar year of life. The exact year of birth was known for five birds, which were aged 2, 3, 7, 9, and 13 years. For the remaining 12 birds, the approximate age was known, ranging from "after two years" to "after eleven years". Specifically, there were seven birds aged "after two years", two birds "after seven years", one bird "after three years", one bird "after ten years", and one bird "after eleven years" (see Table S1 for more details). These activities, including capturing, ringing, and approaching the breeding colony, complied with the legal regulations in Poland and were conducted under valid licenses and permits.

We used solar-powered INTERREX GPS-GSM-ACC 2G/4G loggers, each weighing 8.4 g, for 19 gulls. These devices, utilizing GPS for location tracking and GSM for data transmission, were attached with Teflon harnesses featuring sliding clamping rings for size adjustment, based on the methods of Klaassen et al. (2008) and Lameris et al. (2017, 2018). According to additional data of 32 Mediterranean Gull (no logger attached, treated as the reference weight) caught by one of the authors (PZ), the mean weight was 307 g ± 8 SD, so logger mass made up for 2.74% ± 0.07% of the reference bird mass. In our study, we included a control group of 20 birds that were ringed but not equipped with GPS/GSM devices. These control birds were observed using a telescope from a distance, and their behavior was visually compared with that of the tagged individuals. No significant differences in behavior were noted between the two groups, suggesting that the birds with transmitters behaved naturally. This approach allowed us to ensure that the data retrieved from the tags are representative of the birds' natural behavior and to address any potential welfare concerns associated with the use of harnesses. The GPS/GSM tags used in our study were configured allowing for data collection intervals ranging from 5 min to 1 day. The tags operated also in "BOOST mode", optimizing data collection and transmission frequency based on the bird's activity and charging conditions, increasing data frequency to every 1 min during optimal conditions, while it extended to 60 min during periods of rest or sleep. Our recorded transmission (total = 1,026,742) intervals frequencies were 1 min (49.1%), 2 min (24.9%), 3–10 min (15.8%), 11–20 min

Table 1 Breeding colony site types chosen by Mediterranean Gull (*Ichthyaetus melanocephalus*) in Poland, along with other co-nesting species

Breeding site	Hab. 1	Hab. 2	Year	Species associated with the breeding colony					
				LARMED	LARRID	LARCAN	LARCAC	LARARG	STEHIR
Wykowo #C	N	river	2020/21	3	1,800	4	0	0	124
Arciechów #C	N	river	2020/21	2	1,250	30	0	0	60
Zastów Karczm. #D	N	river	2021	2	3,450	0	1,924	0	15
Skoki #C	A	gravel pit	2021	6	10,429	1	0	0	124
Nysa #A	A	reservoir	2020	6	5291	0	0	0	53
Rynskie #E	N	lake	2022	10	10,000	0	0	8	73
Januszkowice #B	A	gravel pit	2021/22	1	452	0	1	0	0

Hab. 1—habitat type: natural (N), artificial (A). Hab. 2—specific habitat type. Species codes: LARMED—Mediterranean Gull, LARRID—Black-headed Gull, LARCAN—Common Gull, LARCAC—Caspian Gull, LARARG—Herring Gull, STEHIR—Common Tern (GIOŚ 2023)

(0.7%), 21–40 min (0.7%), 41–79 min (8.3%), 80–120 min (0.2%), and over 120 min (0.3%).

Since some individuals provided data for 2 or 3 seasons, we obtained a total of 32 full-year tracks (see Fig. 1a—the same colors indicate the same individuals in different years). For autumn migration, we had 27 complete migration tracks from 16 individuals (2 migration tracks from 2 birds were excluded from the migration analyses because they did not cover the full migration). During the wintering period, we had 14 wintering complete tracks from 10 individuals (14 incomplete wintering tracks from 14 individuals were excluded from further analysis). For spring migration, we had 14 complete migration tracks from 10 individuals. For the breeding season, we had 11 full breeding tracks from 8 individuals (19 incomplete breeding tracks from 18 individuals were excluded from further analysis).

Data processing

Initially, our dataset underwent a filtering process using the *atlastools* package (Gupte et al. 2022) within R (R Core Team 2023). We retained records with a horizontal dilution of precision (HDOP) of 20 or lower and with at least 3 satellite connections, ensuring the spatial data's integrity. Subsequently, we analyzed distance metrics by calculating the speed and turning angles for each individual. We identified distances as anomalies based on a threshold set at the 90th percentile of these metrics, after which they were filtered.

To standardize periods between records, the dataset was thinned to a 30-min interval, summarizing mean values of longitude, latitude, and date time. For each individual, we calculated the distance from their initial location to each of their subsequent records using the Haversine formula (see Fig. S1 in electronic supplementary materials), implemented via the *geosphere* package (Hijmans 2022). Clustering techniques were then applied to categorize data into distinct behavioral states, differentiating between stationary and moving phases in *EMbC* package (Garriga et al. 2019).

Migration pattern

To analyze seasonal variations in movement, we segmented the data according to different seasonal patterns, using manually obtained time stamps (dates) to discern breeding, migrations and wintering period across seasons.

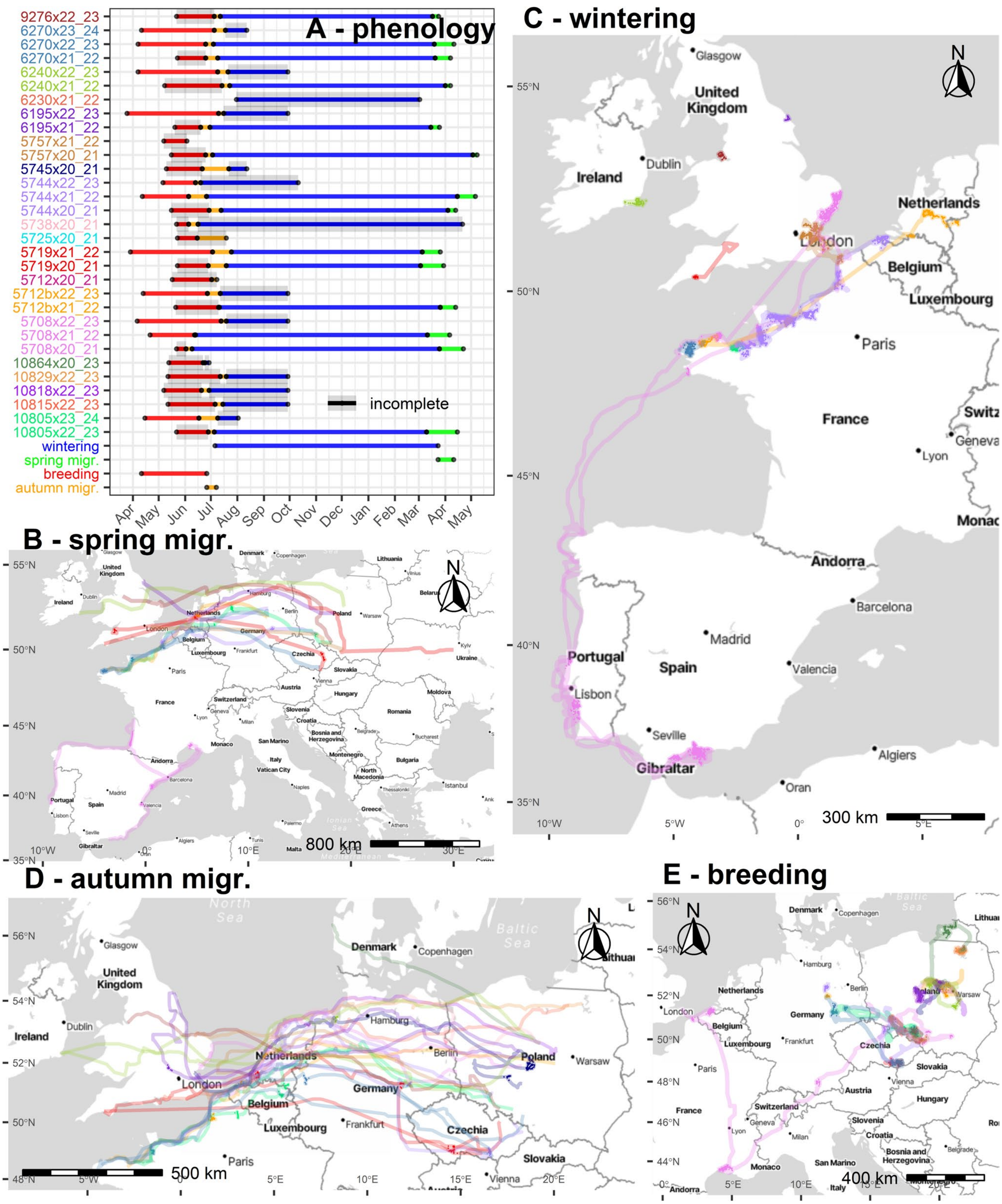
The onset of autumn migration was defined as the bird's last day at the breeding colony, marked by traveling over 60 km (Gilg et al. 2023), with pre-migratory excursions excluded from migration duration. However, in some cases, birds travel longer distance after possible breeding failure, and these routes and new breeding sites were included as breeding season. Autumn migration ended upon arrival at the initial wintering location (distance traveled lower than 60 km, but mostly lower than 10 km, see Fig. S1, which clearly shows a horizontal line for most birds), although some gulls may visit multiple sites during winter. Conversely, spring migration began when the bird left its wintering location (traveling over 60 km) and concluded upon return to the breeding colony, excluding post-migration trips. These periods were manually determined based on distances presented in Fig. S1.

Residence sites analysis

To identify residence sites, first we extracted specific clusters of moving/nonmoving types of records from the dataset using expectation–maximization binary clustering for behavioral annotation (Garriga et al. 2016). We filtered for the stationary records which were categorized by the EMbC algorithm as low velocity/low turn (LL), and low velocity/high turn (LH) as these likely represent behaviors such as foraging, standing, and other short-step movements. Then we calculated the residence time of individuals within a 25 km radius of each position (Borrmann et al. 2021), using the *getRecursions* function in the *atlastools* package, which considers both spatial and temporal aspects of movement. To refine our data on residence time, we filtered out short-term visits lasting less than 1 h. For each residence point, we aggregated total residence time, the time of the first visit, and the number of revisits. We segmented the data into residence patches, defined by spatial and temporal thresholds: (1) a distance threshold of 10 km between positions; (2) a 50 km distance threshold between clusters of positions; (3) a 2-day time difference threshold between clusters; (4) a minimum of 30 positions to qualify as a residence patch. We selected these thresholds by checking different values and then we visually inspected results to ensure that these residence patches matched the clusters of stationary birds. This spatial computation was conducted using the *atl_res_patch* function in the *atlastools* package (Gupte et al. 2022). We separately computed residence patches for spring and autumn migration (to identify stopover sites) and for breeding and wintering sites. For all analysis, we used only complete phenological periods (Fig. 1a, Table 3).

Movement metrics analysis

We calculated various metrics related to migration and residence duration. These metrics included start and end dates to illustrate each phenological period's variability (breeding autumn migration, wintering area and spring migration), duration in days for the average length of each period, and *n* for the number of complete tracks analyzed. Total migration distance and linear direct distance were computed to measure the average cumulative migration distance per track and the mean linear direct distance between the first and last



points of each period, respectively. Travel speed per day was calculated as the mean travel speed per track. Total residence sites tallied the sum of all residence sites across tracks (residence sites during the breeding period indicated breeding sites, during the winter indicated wintering sites, and during autumn and spring migrations indicated stopover sites), while residence number and residence duration in days indicated the average number of residence sites per track and the

◂**Fig. 1** Phenology **A** and movement of Mediterranean Gull (*Ichthyaetus melanocephalus*). Panel **A**: Phenological events (obtained as averaged dates of complete tracks of each ID), including breeding (red), wintering (blue), spring migration (yellow), and autumn migration (green). The IDs of tagged individuals with the ID displayed on the x-axis and the corresponding season denoted by the second part of the ID, and the same colors indicate the same individuals across different years. Incomplete data are indicated by grey shaded strokes. Panels **B**–**E** show movement and residence sites in different phenological periods. Transparent lines show the movement tracks of tagged birds, and bold points indicate residence sites. The colors indicate tagged individuals from the panel **A**. Interactive maps of panels **B**–**E** and further details on phenology are available in the supplementary materials and Fig. S2

average duration at each site, respectively. The direction in degrees, analyzed using circular statistics through the *circular* package in R (Agostinelli and Lund 2022), represented the direction from the first to the last point in each period.

Habitat use analysis

To assess the Mediterranean Gull's habitat use at computed residence sites, we utilized land cover data from the CORINE Land Cover (CLC) inventory (CLC 2023). This dataset provides a detailed representation of the European landscape. We simplified the CLC classes into broader habitat categories (detailed description of the each category and which CLC classes were used are presented in Table S2): urban, landfills, urban green, arable land, grassland and meadow, heterogeneous agricultural, beaches, miscellaneous (forests because not suitable habitat), inland wetlands, coastal wetlands, inland waters, seawater. Next we computed percentage of habitat types in each of individual residence site in different phenological periods (what correspond to birds habitat use). We also calculated the percentage of use in residence site areas under the Birds Directive-Natura 2000 areas (Directive 2009).

For comparisons between different periods of habitat percentage within given habitat categories (separate analyses for each habitat type), we employed the nonparametric Kruskal–Wallis test (KW) and conducted post hoc analysis (Dunn test) when the main effect was significant.

Identification of important wintering sites

We applied spatial rasterization to analyze residence (only wintering sites) durations (number of days) and visit frequencies within specific geographic regions (overlapping wintering sites). Using the *rasterize* function (*raster* package; Hijmans 2023), we processed both the duration and overlapping areas, summing durations and counting overlaps within each 1 km × 1 km cell of intersecting polygons of wintering site area. This method visualized and quantified cumulative durations and visit frequencies, revealing spatial distribution patterns of hotspots.

To construct a hierarchical map of preferred areas, we generated hotspots representing stop-over sites in QGIS (QGIS Development Team 2023) and overlaid a layer of European protected areas under the Birds Directive (Directive 2009). We assessed legal protection of stop-over areas by comparing them with habitats defined by the CORINE Land Cover classification. This approach allowed us to determine the extent to which frequently used bird areas are protected within the Natura 2000 network.

For identifying other key sites, particularly breeding colonies, we conducted a detailed visual inspection of migration routes and clustering sites using transmitter data in QGIS software. Since the Mediterranean Gull is known for its lack of attachment to breeding colonies in Poland and often moves in search of convenient nesting places after brood loss, we focused on identifying potential new breeding sites. During migration, especially in spring, birds visit multiple locations that could be suitable for establishing colonies (Zielińska et al. 2007, 2022).

To process and visualize this data, we mapped migratory paths and key locations chosen by the birds. Clustering sites, which are areas of increased activity or prolonged stays, were identified by analyzing the frequency and duration of stops. We used the inverse distance weighting (IDW) method (Watson 1992; Bartier and Keller 1996) to create clusters and detect areas of point density. This method allowed us to observe clustering patterns and star-shaped routes indicative of nesting sites (Picardi et al. 2020). By observing these patterns, we aimed to identify new, previously unknown sites important for the species.

Results

Information regarding the periods from which the data comes can be found in Table S1 and is graphically presented in Fig. S1. In addition, we present a video showing when the transmitters were installed and how long the birds were tracked. The video can be viewed on the timeline online (Marchowski et al. 2023; Marchowski and Jankowiak 2024).

Through the analysis of behavior patterns, we identified nine additional Mediterranean Gull nesting areas within a geographic region encompassing breeding grounds in Central Europe, including Poland, eastern Germany, and the Czech Republic. These sites are distinct from the locations where GPS/GSM transmitters were originally installed (Table 2).

Table 2 Probable nesting sites of the Mediterranean Gull (*Ichthyaetus melanocephalus*) in Central Europe, identified through GPS/GSM transmitter data, separate from the initial transmitter attachment locations

No	Site	Country	Habitat	y	x
1	Mietków	Poland	Reservoir	50.95126	16.59792
2	Goczałkowice	Poland	Reservoir	49.92786	18.81539
3	Věstonická nádrž	Czechia	Reservoir	48.89651	16.59899
4	Mutěnické rybníky	Czechia	Fish ponds	48.8938	17.05726
5	Jeziorsko	Poland	Reservoir	51.83616	18.67931
6	Wsola	Poland	Fish ponds	51.49826	21.12161
7	Lipsk	Germany	Gravel pit	51.26731	12.28327
8	Barby	Germany	Gravel pit	51.95342	11.87445
9	Bertingen	Germany	Gravel pit	52.34734	11.80939

Phenological periods: duration and distances

The breeding period started around 10 April (± 11 SD) and ended on 26 June (± 13 SD), lasting approximately 76 days. This stage involved relatively shorter movements; birds changed breeding sites after breeding failures, visiting an average of three different breeding sites (or stopover sites if they did not start to breed), typically lasting 46 days. The predominant direction during this period was West-Northwest. For more details, see Table 3, Fig. 1a, e. The different breeding sites were located at varying distances from the previous breeding site (median = 95 km, 1st quartile = 66 km, 3rd quartile = 155 km, $n = 34$; for this computation, we included also incomplete breeding periods).

The autumn migration period, lasting 11 days (± 18 SD), began on 26 June and ended on 7 July. The gulls traveled an average of 1797 km in total, and 1241 km directly linear. The mean travel speed was 182 km/day with mostly one stopover, averaging 0.8, and a short stopover duration of average 3 days. The movement was primarily westward. For more details, see Table 3, Fig. 1a, d.

The winter period spans 261 days (± 21 SD), starting from 5 July and lasting till 23 March. The average travel speed was 20 km/day. The gulls made an average of three wintering sites (if excluding one unusual bird which had nine wintering sites per season in was in average two wintering sites). The average duration within each wintering site lasts about 150 days (± 90 SD). The direction of changing sites was predominantly West–Southwest. For more details, see Table 3, Fig. 1a, c.

Spring migration occurred from 23 March to 10 April, this 18-day period (± 22 SD) involved an average total migration distance of 2076 km and a direct linear distance of 1363 km. The mean travel speed was 144 km/day. Gulls averaged 1.6 stopovers with a mean duration of 7 days per stopover. The directional orientation of migration was East–Northeast. For more details, see Table 3, Fig. 1a, b.

Overall, the wintering period is the longest, with relatively short migration periods. Autumn migration was shorter than spring, with no significant difference in durations (Mann–Whitney U test = 76.5, $p = 0.068$). The general migration direction was West.

Table 3 Metrics of migration and residence sites in different phenological periods of Mediterranean Gull (*Ichthyaetus melanocephalus*)

Metric	Breed	Autumn	Winter	Spring
Start ± SD	10-Apr ± 11	26-Jun ± 12	05-Jul ± 13	23-Mar ± 17
End ± SD	26-Jun ± 13	07-Jul ± 13	23-Mar ± 17	10-Apr ± 14
Duration ± SD [days]	76 ± 17	11 ± 18	261 ± 21	18 ± 22
N completed tracks	11	27	14	14
N tagged ind	8	16	10	10
Total migr. dist. ± SD [km]	3,798 ± 1,937	1,797 ± 574	5,100 ± 4,336	2,076 ± 673
Direct. dist. ± SD [km]	271 ± 410	1,241 ± 341	341 ± 604	1,363 ± 387
Travel speed ± SD [km/day]	51 ± 24	182 ± 77	20 ± 15	144 ± 78
Total residence sites	31	21	42	23
Residence number ± SD	2.8 ± 2.2	0.8 ± 0.9	3 ± 2.8	1.6 ± 1.4
Residence duration ± SD [days]	46 ± 36	3 ± 2	150 ± 90	7 ± 3
Direction ± SD [o]	287 ± 1.53 WNW	278 ± 0.38 W	249 ± 1.63 WSW	76 ± 0.25 ENE

SD—standard deviation (standard deviation of duration was computed as the square root of the pooled variance of start and end date). Start and End—mean value of start or end of phenological period. Duration—mean duration time of phenological period. *n* completed tracks indicates the number of complete tracks. *n* tagged ind. shows the number of tagged individuals. Total migr. dist—mean total (summed) migration distance per track. Direct. dist.—mean linear direct distance between first and last point in given period per track. Travel speed—mean travel speed per track. Total residence sites—sum of all residence sites of all tracks (residence for breeding period indicate breeding site, for winter wintering site and for autumn and spring migration stopover sites). Residence number—mean stopover sites number per track. Residence duration—mean residence duration. Direction—direction from the first point to the last in a given period

Habitat use

Analysis of the Mediterranean Gull's habitat selection across various phenological periods revealed distinct uses (for details percentages habitat use and tests see Table 4, Fig. 2). During the breeding season, arable habitats which birds used as feeding grounds were the most selected, significantly higher than during autumn migration. Meadows and grassland were consistently important, peaking during autumn. Inland water and inland wetlands showed moderate selection throughout the year, with notable use during breeding and spring migration. Urban and urban green habitats had steady selection year-round, with a slight increase in autumn. The most used habitat during wintering was open sea waters.

Wintering areas

The primary wintering area along the English Channel was subdivided into eight sub-areas: three on the United Kingdom side and five on the continental side. Additional wintering sites were located along the North Sea coast in the UK, and on the coasts of the Irish Sea in both the UK and Ireland (Fig. 3). One individual's wintering area spanned the coast of Portugal and near Malaga in Spain's Mediterranean Sea (Fig. 3). The Utrecht–Antwerpen region in the Netherlands—Belgium area presented the most visits, with five individuals spending a total of 425 days there during winter. The longest single-site stay during winter was 511 days, recorded near Brest in France, involving two individual visits (Table 5, Fig. 3). All wintering areas were located along or near seacoasts, with river estuaries as preferred habitats in six cases (Table 5, Fig. 3).

Discussion

Movement patterns

Mediterranean Gulls display limited breeding philopatry; the individuals frequently visit new potential nesting locations following breeding losses and rarely nest in the same place consecutively (Zieliński et al. 2022). This behavior contrasts with their high fidelity to wintering areas (Carboneras et al. 2013). The significant duration of time spent at wintering sites (Marchowski and Jankowiak 2024; Fig. 1) and the limited breeding philopatry observed may corroborate the theory of bird migration evolution (Alerstam et al. 2003). According to this theory, birds initially inhabited warmer regions year-round. With some species exploring more resource-abundant yet seasonal environments at higher latitudes, migratory behaviors evolved to exploit these areas during breeding (Salewski and Bruderer 2007).

Table 4 Habitat use by the Mediterranean Gull (*Ichthyaetus melanocephalus*) across different phenological periods, indicating the mean percentage of habitat use (± SD), with statistical significance assessed by Kruskal–Wallis test (KW) and *p* values (*p*)

Habitat	Autumn	Breeding	Spring	Winter	KW	KW p	A-B	A-S	A-W	B-S	B-W	S-W
Arbl	35.7 ± 21.7	52.9 ± 15.4	34 ± 20	22.9 ± 17.9	34.10	***	*	NS	NS	**	***	NS
Beach	1 ± 0.9	0.2 ± 0.2	1 ± 1.5	0.9 ± 0.7	25.08	***	NS	NS	**	NS	***	*
Coastal wetlands	14.1 ± 11.6	4.8 ± 2.2	8.3 ± 8.9	14.4 ± 14.8	38.06	***	NS	NS	**	**	***	NS
HetAgri	8.1 ± 8.4	8.4 ± 5.9	12.5 ± 12.1	11.7 ± 10.8	4.71	NS						
InlWtr	8.9 ± 7.8	9.1 ± 7.9	5.1 ± 7.1	1.3 ± 2.3	55.52	***	NS	NS	***	**	***	**
InlWet	2.8 ± 4.1	2.7 ± 5.1	9.3 ± 7.5	3.4 ± 4.2	8.39	*	NS	NS	NS	*	NS	NS
Lndfll	0.3 ± 0.2	0.5 ± 0.5	2.2	0.1 ± 0.2	7.74	NS						
MdwGrss	17.6 ± 16.3	7.1 ± 6.8	16.7 ± 20.9	11.1 ± 11	7.24	NS						
Misc	6.9 ± 4.9	11.1 ± 6.3	4.3 ± 3.8	3.1 ± 3	35.42	***	**	NS	NS	***	***	NS
SeaWtr	12 ± 14.5	2.5 ± 1.3	17.2 ± 15.6	25.8 ± 27.4	56.01	***	NS	NS	***	**	***	**
Urbn	16.5 ± 12.5	9.5 ± 6.1	11.6 ± 11.8	13 ± 11.5	4.32	NS						
UrbnGrn	2.7 ± 2.5	0.8 ± 0.9	2.7 ± 2.9	1.8 ± 2.1	3.11	NS						
N2K	22.2 ± 21.5	16.4 ± 12.5	19.1 ± 14.4	23.1 ± 16.5	3.44	NS						

Arbl Arable lands, *Beach* beaches, *CstlWet* coastal wetlands, *HetAgri* heterogeneous agricultural areas, *InlWtr* inland waters, *InlWet* inland wetlands, *Lndfll* landfills, *MdwGrss* meadows and grasslands, *Misc* miscellaneous habitats, *SeaWtr* sea water, *Urbn* urban areas, *UrbnGrn* urban green areas, *N2K* Natura 2000 areas, *NS* non-significant

The other column indicates post hoc analysis (Dunn test) between periods and performed when the main effect was significant. A-B: autumn vs breeding, A-S: autumn vs spring, A-W: autumn vs winter, B-S: breeding vs spring, B-W: breeding vs winter; S-W: spring vs winter. The overall percentage is above 100 because percentages are averaged from different residence sites

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

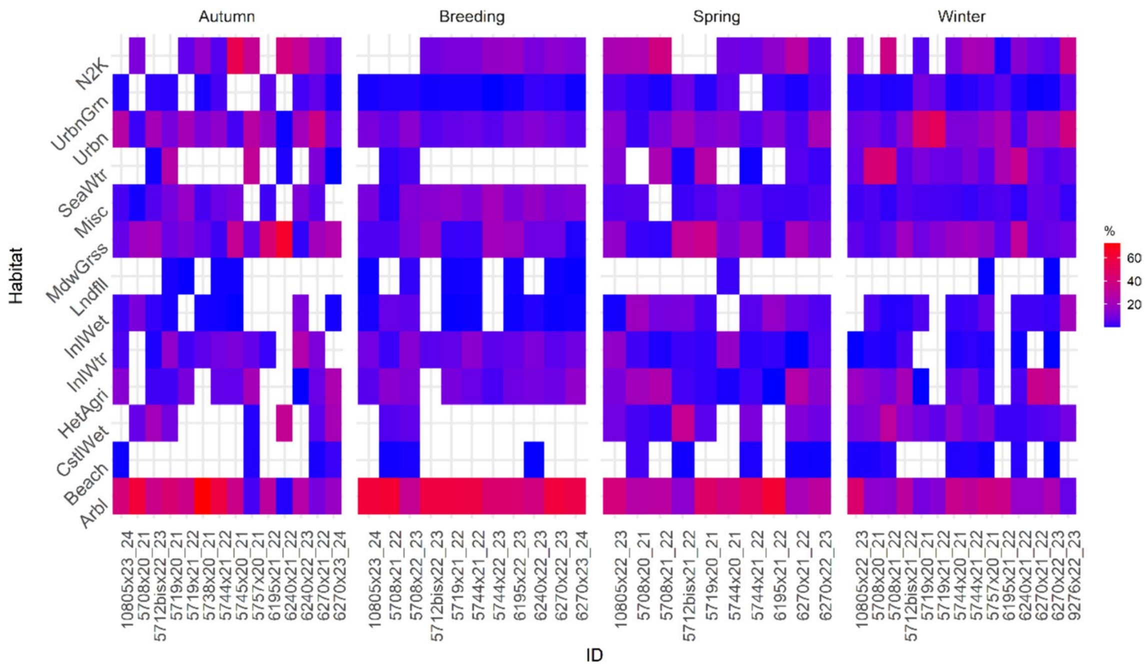


Fig. 2 Heat map visualization of habitat utilization by tagged Mediterranean Gulls (*Ichthyaetus melanocephalus*) throughout different seasons. Each tile represents the mean percentage use in a specific habitat type by an individual bird, with the ID of the tagged bird displayed on the x-axis and the corresponding season denoted by the second part of the ID. Habitat types are abbreviated on the y-axis for clarity: Arable lands (Arbl), beaches (Beach), coastal wetlands (CstlWet), heterogeneous agricultural areas (HetAgri), Inland waters (InlWtr), inland wetlands (InlWet), landfills (Lndfll), meadows and grasslands (MdwGrss), miscellaneous habitats (Misc), sea water (SeaWtr), urban areas (Urbn), urban green areas (UrbnGrn), and Natura 2000 areas (N2K)

Mediterranean Gulls, spending most of the year in river estuaries, coastal regions, and open sea areas in Western and Southern Europe (Fig. 1), exemplify this. They seek optimal breeding sites annually, yet consistently return to their established wintering grounds (Carboneras et al. 2013).

The behavior of individual 5708 (in the third calendar year of life) exemplifies a pioneering pattern in the expansion of the species into new areas. This demonstrates how Mediterranean Gulls are changing their breeding and wintering ranges, as supported by sightings of breeding birds ringed in Poland in Western European breeding colonies (Zieliński et al. 2022). Tracking individual birds allows for a nuanced understanding of population structure and evolutionary dynamics. It shows that while most birds are conformist (in this context, birds wintering in Western Europe), a minority are pioneers seeking new opportunities. Immatures or sub-adult birds may be more prone to such behavior than fully adult birds, but this aspect should be further investigated. This pioneering individual, for example, wintered in atypical locations, including the northern coast of Africa (Fig. 3), did not return to its original breeding ground, and explored potential nesting sites in southwestern Europe, demonstrating a departure from established behavioral patterns.

The generally accepted ecogeographic pattern indicates that species in the Northern Hemisphere are expanding northward in response to climate change (Hampe and Petit 2005; Lagerholm et al. 2017; Santangeli et al. 2017). However, this trend is not universal, as some species are expanding southward. In Europe, for instance, the Common Merganser (*Mergus merganser*; Marchowski et al. 2022) and the Whooper Swan (*Cygnus cygnus*; Sikora and Marchowski 2023), and in North America, the Tree Swallow (*Tachycineta bicolor;* Siefferman et al. 2023) exemplify this contrary movement. For Mediterranean Gulls, our observations (Fig. 3), combined with the results of Zieliński et al. (2022) and bird ringing returns from the Polish Bird Ringing Center, suggest a shift from using Poland as a transit breeding site (probably from South-East) to expansion into Western and South-Western Europe. Initially, the Mediterranean Gull's breeding population in Poland was expected to increase due to the expansion of the species (Zielińska et al. 2007), yet studies over the years have noted a decline (Zieliński et al. 2022). The phenomenon of shifting breeding and wintering grounds across the entire range warrants further investigation, presenting a valuable opportunity for future research.

Poland, positioned at the North-Eastern edge of the Mediterranean Gull's range, seemingly functions as a transit route

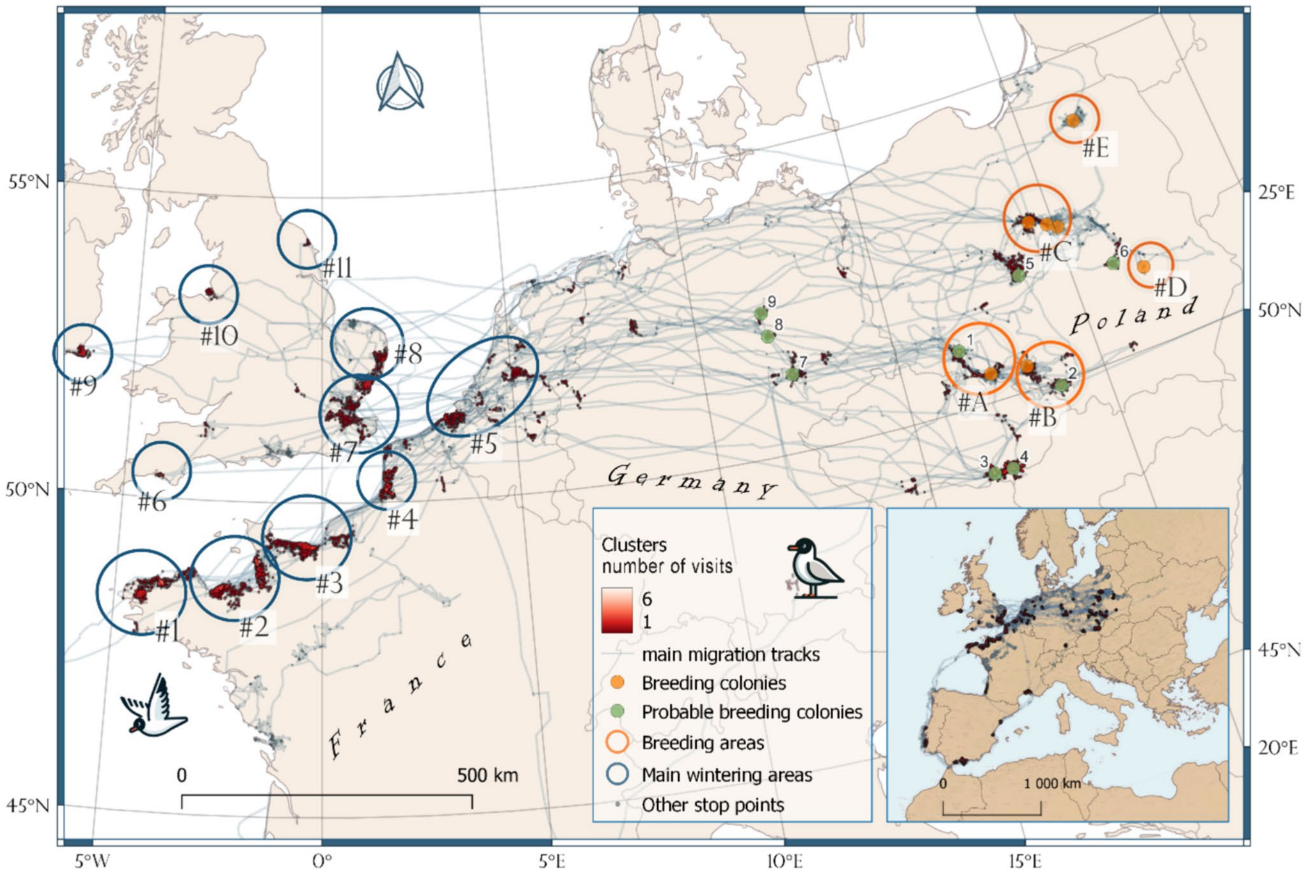


Fig. 3 Key areas of nesting, wintering grounds, probable nesting sites, migration stopovers, and movement tracks of the Mediterranean Gull (*Ichthyaetus melanocephalus*) in Central Europe. The main wintering sites are highlighted with navy blue circles (#1–#11, refer to Table 5 for details). The breeding areas where GPS/GSM transmitters were installed are marked in orange (#A—#E, see Table 1 for details) and exact colonies where transmitters have been set (orange points). Green points represent probable colonies that have been identified based on bird behavior patterns other than those at transmitter sites (see Table 2)

Table 5 Main wintering sites of the Mediterranean Gull (*Ichthyaetus melanocephalus*), including habitat types at these sites, the total number of visits, and the cumulative number of days spent at each site

Id on the map (Fig. 3)	Site	Country	Habitat	Sum of visit	Duration in days	Individuals that visited the site
#1	Brest	France	Estuary	3	511	571 bis, 5708, 6270
#2	Saint-Brieuc	France	Coast	4	378	10,805, 5708, 5744, 6270
#3	Bayeux	France	Coast	3	425	6270, 5744, 5712 bis
#4	Abbeville	France	Estuary	5	437	6270, 5744, 5712 bis, 5757, 5708
#5	Utrecht–Antwerpen	The Netherlands–Belgium	Urban	6	425	6270, 5708, 5744, 6240, 5712 bis, 5719
#6	Plymouth	United Kingdom	Urban	2	441	5719
#7	Rochester	United Kingdom	Estuary	2	219	5757, 5708
#8	Ipswitch	United Kingdom	Estuary	5	397	5708
#9	Wexford	Ireland	Estuary	2	252	6240
#10	Liverpool	United Kingdom	Estuary	1	248	9276
#11	Scarborough	United Kingdom	Coast	1	258	6195

The sum of visits includes both visits from different individuals and multiple visits from the same individual if they appeared in a given place more than once for birds migrating from South-Eastern regions (Ukraine, Russia, Bulgaria, and Romania) to Western and South-Western Europe, including Belgium, the Netherlands, and France. Notably, South-Eastern Europe is experiencing a decline in numbers and range contraction, while Western Europe observes a population increase and range expansion (Balmer 2020). In conservation efforts, it is crucial to monitor populations at the edges of their ranges, as these areas frequently display the earliest signs of decline (Rogan et al. 2023). Despite being classified as LC by IUCN, the global Mediterranean Gull population is declining, a trend also observed in Poland, at the range edge (Zieliński et al. 2022). Negative changes are less apparent in central subpopulations (Rogan et al. 2023), underscoring the importance of understanding edge dynamics in conservation. Detailed knowledge of habitat selection, movement lengths during different phenological periods, and identification of stopover, breeding, and wintering areas is essential. This data can inform conservation strategies, ensuring the protection of critical habitats and supporting the species' overall survival and reproductive success.

Our transmitter data analysis highlights two critical phenological periods: breeding and wintering. Both spring and autumn migrations are relatively brief, making them less significant in duration compared to the longer periods. However, the short duration of these migrations does not diminish their importance. Although the likelihood of adverse events occurring during these brief migration periods is lower than during the extended breeding or wintering periods, migration remains a crucial phase for the birds. Notably, our findings challenge the prevalent theory that birds migrate faster in spring than in autumn (Fig. 1, Table 3) due to breeding ground competition and factors like increased daylight length (Nilsson et al. 2013; Schmaljohann 2018). For Mediterranean Gulls, spring migration was, on average, 7 days longer than autumn migration (Fig. 1, Table 3). Our findings reveal a distinct behavioral pattern wherein birds originating from wintering grounds embark on a search for suitable breeding sites. During this journey, they visit various potential locations, which explains why spring migration extends over a longer period compared to autumn. In autumn, birds committed to their permanent wintering grounds endeavor to return as swiftly as possible.

Habitat use

Our results reveal distinct habitat use across phenological periods, indicating the Mediterranean Gull's dynamic adaptation strategy to environmental changes throughout its annual cycle. A general pattern emerges that arable fields are consistently used for foraging year-round, with peak usage during breeding and reduced reliance during winter. These fields are also primary feeding grounds during autumn and spring migrations. Conversely, open seas are used in winter, while their utilization is minimal during breeding (Table 4, Fig. 2). A low use of sea areas during breeding is not surprising given that the breeding colonies are located inland (Zieliński et al. 2022). It should be noted that our analyses focus on comparing which habitats were used during each period, not on which habitats were preferred. This is because we did not compare habitat use to habitat availability; therefore, the analysis does not account for the availability of habitats to the gulls.

In examining the annual cycle of the Mediterranean Gull, we find that they spend the majority of the year, approximately 261 days, in their wintering grounds, predominantly utilizing open sea areas for feeding, and frequently inhabiting the estuaries of the English Channel rivers (Figs. 1, 3, Table 5). This observation underscores the necessity of conservation efforts in these regions. We analyzed the extent to which Mediterranean Gull wintering areas are under protection. Our findings show that during winter, 23.1% of significant habitats for the species fall under the European Natura 2000 network. However, it remains uncertain if the extent of this protection is sufficient or effective, and whether expanding these areas is feasible. Previous studies indicate that established protected areas might not adequately reflect the dynamic changes in species ranges (Pavon-Jordan et al. 2015; Marchowski et al. 2021). Our data suggest that Mediterranean Gulls prefer habitats like river estuaries and coastal areas near large cities, where they benefit from human activities such as fishing (Ramírez et al. 2015) and exploiting garbage dumps (Marchowski et al. 2016). The cessation of these activities might adversely impact the gull population. Moreover, simply expanding protected areas in wintering regions may not necessarily enhance the effectiveness of Mediterranean Gull conservation efforts.

The breeding season, although shorter than wintering (76 vs. 261 days), is crucial for the Mediterranean Gull's life cycle due to its impact on species productivity. The significance of habitat protection during this period is highlighted by Poland's Mediterranean Gull monitoring data, showing a 6.2% decline of the breeding population in protected areas versus a 16.9% decline in non-protected areas (Zieliński et al. 2022). We do not know exactly what the reason is, perhaps it is the better-quality habitats provided by Natura 2000 areas. The usage of Natura 2000 protected areas during breeding was 16.4% (Fig. 2, Table 4). Considering the trend of faster population decline outside protected areas during this period, enhancing habitat protection is imperative to mitigate population loss.

It is important to note that some Mediterranean Gull breeding habitats in Central Europe, like lakes and rivers (Table 2), are in natural areas where protection can be extended without likely social conflicts. However, Mediterranean Gulls also commonly nest in human-modified areas such as dam reservoirs, gravel pits, and fishponds (Tables 2, 4), where human interests can complicate protection efforts. This raises the question of whether area-based protection is sufficient for Mediterranean Gull breeding habitats. The growing impact of invasive species like the American Mink (*Neogale vison*) and Raccoon (*Procyon lotor*) on breeding waterbird populations in Europe highlights the need for active protection measures at Mediterranean Gull breeding sites. Active protection measures at Mediterranean Gull breeding sites can be beneficial. In recent years, active conservation efforts aimed at protecting waterbirds nesting on islands have proven effective (Jin 2021; Manikowska-Ślepowrońska et al. 2022; Marchowski et al. 2023). These include limiting predator access to nesting islands, both invasive and native, such as Red Fox (*Vulpes vulpes*), as well as protection and guarding, educational campaigns to limit human access to breeding areas, and efforts to mitigate the effects of water level changes and natural succession that deteriorate habitat conditions (Marchowski et al. 2023).

Identification of important sites

Developing a protection strategy for Mediterranean Gull breeding habitats is challenging due to their limited breeding philopatry (Zieliński et al. 2022). The focus should be on establishing a comprehensive protection system covering both known and potential breeding sites across their range. Behavior observation of movement tracks is crucial for identifying new breeding areas (Fig. 4). Our study identified nine such areas distinct from the transmitter locations in

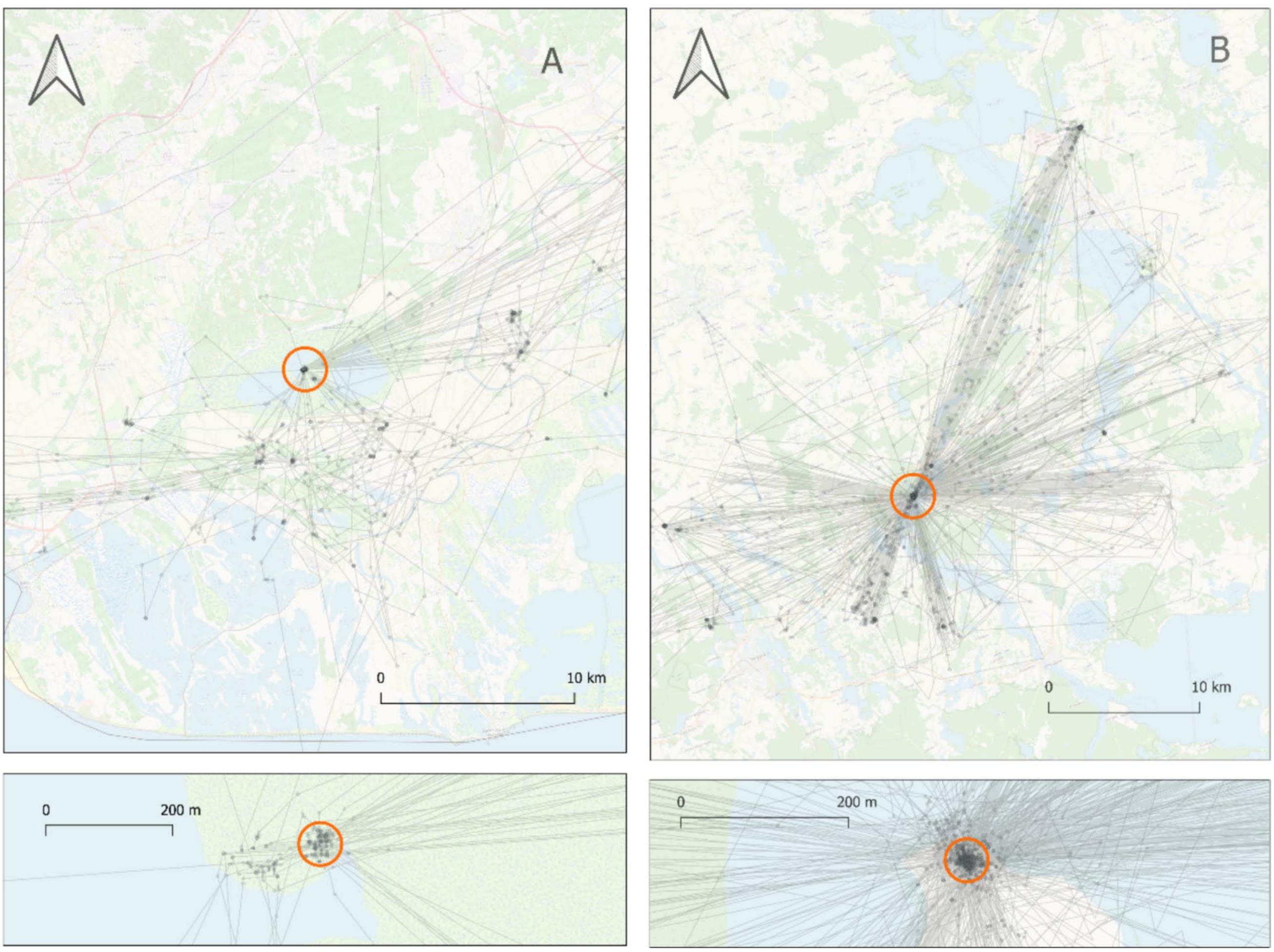


Fig. 4 Movement behavior patterns of Mediterranean Gull (*Ichthyaetus melanocephalus*) during the breeding season. A—an instance of exploring a new, potential nesting site without engaging in breeding activities, located in Camargue, France (individual 5708); B—a bird exhibiting breeding behaviors at Lake Ryńskie, Poland (individual 10,815). In panel B, a clearly visible pattern with one central point—the nest to which the bird returned and a star-type pattern of movement—is shown. Panel A illustrates a place potentially suitable for a nest, which the bird was likely "testing". Unlike panel B, panel A does not have one central point to which the bird returned; instead, numerous other clusters of points and irregular movement behavior are visible

Poland, the Czech Republic, and Germany (Table 5, Figs. 3, 4). Mediterranean Gulls may visit colonies briefly without breeding, providing clues to important reproductive sites. Birds may visit places suitable for breeding after the breeding season or after brood loss, and it is too late to breed or when they do not find a partner. Such presence in a site will be registered on the GPS track. This applies to both potential breeding sites and stop-over and wintering sites, which together will create a network of key sites for the species. For instance, individual 5708's behavior, tracked via transmitter on the Vistula River, illustrates exploration of new regions for wintering and potential breeding, deviating from traditional wintering near the English Channel to Portugal and Spain (Fig. 1c). During breeding season, it explored but did not breed at sites in Spain's Ebro estuary and France's Camargue region (Figs. 1e, 3, 4).

Expanding data analysis to include all potential breeding sites could enhance the network of Mediterranean Gull breeding areas in Europe, forming a basis for more effective species protection. Such a network can be established with transmitters on a small fraction of the population. Breeding sites must be given priority in the conservation strategy due to their critical role in the reproductive potential and, thus, the survival of the population. Although individual birds may exhibit weak attachment to specific breeding sites, these areas are regularly used by the species as a whole. Therefore, protecting these breeding sites is essential for the species' overall survival. In addition, it is important to note that the management within these protected areas is crucial; measures such as protection from predators and maintaining appropriate water levels will significantly benefit the species. Nevertheless, considering the Mediterranean Gull's attachment to wintering areas, appropriate protection of the most important wintering sites is also crucial.

Although our study did not directly observe Mediterranean Gulls nesting on rooftops, it is essential to address this phenomenon to provide a comprehensive understanding of the challenges in conserving the species. This primarily involves the European Herring Gull (Perlut et al. 2016), but also the Common Gull, the Black-headed Gull, and also the Mediterranean Gull (Przymencki et al. 2024). Such adaptation of gulls to exploit available habitats demonstrates their high ecological plasticity. At the same time, it poses challenges for the conservation of species, such as the Mediterranean Gull. The prevailing hypothesis explaining the selection of rooftops for nesting by gulls (Laridae) posits that the population growth rate exceeds the availability of territories in their traditional island habitats, indicating that rooftops may not constitute their preferred habitat (Dolbeer et al. 1990). Consequently, rooftops do not represent an optimal breeding environment, underscoring the necessity of prioritizing the protection of natural habitats, including islands in lakes and rivers, as primary conservation efforts.

The increasing use of non-traditional nesting sites by Gulls highlights their adaptability but also points to the pressures on their natural habitats. By incorporating this broader context, we underscore the need for targeted conservation efforts that prioritize natural breeding habitats while also monitoring and managing the use of urban environments by gulls. This holistic approach ensures that conservation strategies remain effective in the face of evolving ecological dynamics and habitat use patterns.

Conclusion

Employing GPS/GSM transmitters for monitoring, even in a small subset of the population, can enable precise mapping the network of key breeding colonies. Developing a comprehensive guide for best conservation practices, tailored to the primary breeding habitats, is necessary. Given the Mediterranean Gull's migratory nature and its extensive time spent in Europe, this species can become a model for conservation strategies applicable to migratory waterbirds in the European Union. A unified, Europe-wide approach to nature conservation policy would not only benefit the Mediterranean Gull but also other migratory species sharing similar habitats and threats.

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Authors' contributions ŁJ, PZ, and DM were responsible for designing the study. The field study was conducted by MS, JS, JSZ, and PZ. Databases for analysis were prepared by ŁJ, MS, JS, PZ, and DM. The analyses were performed by ŁJ with the help of DM. DM also took on the roles of writing the paper and supervising the work. All authors contributed to subsequent revisions.

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Data availability Raw data are available in the GitHub Pages repository. Links to the data can be found in the electronic supplementary materials.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical statement All procedures were conducted in accordance with valid licenses and permits, ensuring compliance with Polish legal requirements (License number MS: 345/2023, JS: 348/2023 according to decision of General Directorate for Environmental Protection nr DZP-WG.6401.2020; DZP-WG.6401.2021; DZP-WG.6401.75.2022.WW).

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