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From Siberia to the Black Sea by GPS-tracking – conservation implications of Red-breasted Goose *Branta ruficollis* seasonal movements

Nicky Petkov[1], Mikhail Iliev[1,2], Ivan Zuban[3,4], Alexey Timoshenko[3] and Tomas Aarvak[5]

[1]Conservation Department, Bulgarian Society for the Protection of Birds, Bulgaria; [2]Vertebrates Department, National Museum of Natural History, Bulgaria; [3]Association for the Conservation of Biodiversity of Kazakhstan, Kazakhstan; [4]Department of Biology, Manash Kozybayev North Kazakhstan University, Kazakhstan and [5]Science Department, BirdLife Norway, Norway

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Corresponding author:
Nicky Petkov;
Email: nicky.petkov@bspb.org

Summary

The Red-breasted Goose *Branta ruficollis* is a globally threatened migratory species that faces increasing pressures from habitat loss and climate change along its flyway between Siberia and the Black Sea. This study presents detailed insights into the annual migratory patterns of the species based on GPS telemetry data collected between May 2019 and February 2023. We tracked 41 individuals fitted with GPS transmitters, of which 23 provided data spanning at least one full migratory season. The resulting dataset of over 150,000 GPS positions revealed fine-scale patterns of seasonal movement across a total area of 3.6 million km^2. There was a nearly equal temporal division among seasonal phases. At the population level, the spring and autumn migration windows lasted 96 and 97 days, respectively, while individual completed journeys averaged 93.0 days in spring and 98.3 days in autumn. Migration pathways featured distinct, non-overlapping spatial corridors and key staging areas identified in northern Kazakhstan and the Orenburg region of Russia. Red-breasted Geese travelled an average of 17,725 km annually, with peak movement in April–May and September–November. Wintering birds occupied three discrete core areas within a larger wintering extent (116,751 km^2): coastal Romania (with adjacent areas in Bulgaria and Ukraine), the Sivash area in Crimea, and the Veselovskoie region in southern Russia. The data also enabled inferences about breeding success and moulting periods, confirming high breeding site philopatry and no evidence of major previously undocumented wintering areas. The findings directly supported conservation planning, including the designation of temporary hunting restrictions in priority staging areas. This study highlights the conservation value of GPS tracking for delineating core and critical seasonal habitats, assessing threats, and informing flyway-scale management strategies essential for the long-term survival of the Red-breasted Goose and other long-distance migratory waterbirds.

Introduction

To ensure effective conservation actions for migratory birds, mapping their current ranges and spatiotemporal migration patterns is increasingly important. Studies of such patterns have shown that the seasonal ranges of migratory species are well explained by prevailing climatic factors, suggesting that global distributions and annual movements of migratory birds from distinct breeding to wintering areas are more or less in equilibrium with the current climate (Somveille et al. 2020). Rapid climate change is already affecting species ranges and migration routes and interfering with the timing of seasonal resource availability upon which migratory species depend, significantly affecting global migration patterns and potentially changing migratory behaviour (Zurell et al. 2024). For example, for Arctic-breeding geese, autumn drought can make feeding habitats unavailable and desiccate shallow steppe lakes used as nocturnal roosts and daytime drinking sites. Geese may then have to cover greater proportions of their route over shorter periods without opportunities to refuel, with potentially adverse consequences. Such changes are especially critical when considering conservation actions for rare, declining or threatened species such as our focal species, the Red-breasted Goose *Branta ruficollis* (Pallas, 1769). This species is classified as Vulnerable on the IUCN Red List, facing significant declines due to various threats across its extensive migratory flyway. The species has suffered a large and rapid decline in population size since 2000 and is highly concentrated at relatively few sites, thus increasing its vulnerability to multiple threats (BirdLife International 2025).

The Red-breasted Goose is a long-distance migrant that breeds in Arctic Russia, primarily on the Taimyr and adjacent peninsulas. It migrates south along the Ob Valley, with important

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stopover sites in northern Kazakhstan, and then west along the north and west coasts of the Black Sea, through Russia and Ukraine (Cranswick et al. 2012). The majority of the population currently winters in Bulgaria, Romania and Ukraine, on the Black Sea coast. Throughout the annual cycle, the species occurs almost exclusively in just five countries, namely Bulgaria, Kazakhstan, Romania, Russia and Ukraine. Monitoring and research on the species have been undertaken throughout the flyway since the 1960s; however, compared to most other Western Palearctic goose species, it remains little studied (Cranswick et al. 2012). Despite the species' distinctive morphology and high field detectability, historical population estimates have lacked rigorous survey protocols and should be interpreted with caution and be considered approximate. Following coordinated counts in Bulgaria and Romania, and occasionally in Ukraine, conducted since the 1990s, a broad consensus has emerged that the global population size is approximately 90,000 individuals, following a steep decline in the early 2000s (Dereliev 2006). During migration, they mix with other goose species and use several sites within different regions, which creates challenges for survey methods and interpretation of the count data, and thus hampers the derivation of species-specific totals (Cuthbert et al. 2018). In addition, in recent decades there has been a tendency for Red-breasted Geese to short-stop and disperse more in the winter period. For instance, in milder conditions, some birds may now spend considerable parts of the winter in southern Russia (Simeonov et al. 2014, Harrison and Hilton 2015, Iliev et al. 2023). If this change is a result of climate change, as noted for other species (e.g. Nuijten et al. 2020, Linssen et al. 2023, Heldbjerg et al. 2024), these patterns may be exacerbated in the future. Rapid climate change is already affecting species ranges and migration routes while disrupting the temporal synchronization between bird arrival and seasonal peak resource availability, which can trigger severe ecological mismatches and drive long-term population declines in migratory birds (Saino et al. 2011, Zurell et al. 2024).

There has been much speculation as to whether the observed decline in the species is genuine or whether the birds have made a major shift in wintering grounds and thus now spend the winter elsewhere. Individual birds or smaller groups are frequently seen in many countries in Europe, the Caucasus region and even in Asia, but these are vagrant birds outside the species' normal range (Cranswick et al. 2012). Interestingly, large-scale changes in distribution are not unprecedented for this species. Historically, the Red-breasted Goose exhibited a markedly different wintering distribution; until the late 1960s, the majority of the global population wintered along the western shores of the Caspian Sea, heavily concentrated around Kyzyl-Agach Bay in Azerbaijan, as well as parts of northern Iran. However, sweeping Soviet agricultural reforms during this era replaced extensive winter wheat fields across the Caspian region with non-forage cash crops such as cotton and vineyards (Cranswick et al. 2012). This rapid loss of primary food resources forced a dramatic, species-wide migratory shift westward to the northwestern Black Sea coasts of Romania, Bulgaria and Ukraine, where intensive cereal grain cultivation provided a viable alternative wintering refuge. This historical precedent highlights the extreme sensitivity of the species' migratory strategies to localised agricultural shifts.

Tracking devices that monitor individual birds throughout the annual cycle provide detailed information on migration timing and routes, stopover sites and habitat use, and have supported effective conservation measures for a range of species (Davidson et al. 2020, Teitelbaum et al. 2023). Remote tracking can therefore clarify whether undocumented wintering areas exist, whether short-stopping contributes to large between-year differences in abundance, and how birds use wintering, staging and breeding sites, including the number and distribution of sites, throughout the annual cycle.

Winter distribution and abundance vary substantially within and between years in response to weather conditions. In mild weather, Red-breasted Geese occur farther north, whereas extreme cold pushes them farther south along the Black Sea coast (Dereliev 2000, Harrison and Hilton 2015). Growing evidence indicates that waterbirds are responding to climate change by shifting and redistributing their ranges, with declines in numbers wintering farther south matched by increases farther north (e.g. van Roomen et al. 2012, Lehikoinen et al. 2013, Pavon-Jordan et al. 2019, Amano et al. 2020, Solokha and Lokhman 2021).

Migratory birds may also need to adjust the timing of critical periods of their annual cycle (such as migration, breeding and moult) in response to climate change. Migration timing and the location and quality of stopover sites influence other parts of the life cycle of migratory birds, especially for geese, which are capital breeders and must acquire body stores en route to breeding areas to invest in reproduction (Drent et al. 2007). To maximise reproductive output, geese need to minimise spring migration duration, arrive and nest as early as possible in optimal body condition by occupying the highest-quality territories (Drent and Daan 1980, Thomas 1988, Kokko 1999, Bêty et al. 2003, Moore et al. 2005). As the geese are less time constrained during autumn, it is expected that spring migration should be shorter (Nilsson et al. 2013, Schmaljohann 2018, Deng et al. 2019), partly because they are not constrained by having to reach a predetermined breeding site in time (Linssen et al. 2023). Evidence from detailed tracking of Arctic-breeding geese indicates that spring migration can take significantly longer than autumn migration because spring transit is dominated by extensive fueling stopovers required for capital breeding, whereas autumn migration relies on selective, wind-assisted rapid movements (Kölzsch et al. 2016). However, as climate change and urban encroachment make habitats unavailable to geese, the duration of, and difference between, spring and autumn migration will change significantly.

Recent studies have demonstrated that the response of geese to climate-driven advances in spring depends heavily on their flyway geography. For instance, while island-bound Arctic migrants with long, non-stop flights over sea struggle to adjust their migration timing to fine-scale regional climate cues (e.g. Svalbard Barnacle Geese *Branta leucopsis*; Tombre et al. 2008), overland continental migrants exhibit different adaptive constraints. Continental Russian Barnacle Geese have significantly advanced their spring migration to track earlier green-up across the mainland, yet still encounter a phenological mismatch because their Arctic egg-laying dates have not advanced at the same pace, thus reducing offspring survival (Lameris et al. 2018). Because the Red-breasted Goose shares the same extensive continental Eurasian flyway, understanding its seasonal timing and capacity to dynamically adjust to changing stopover conditions is critical to predicting similar phenological bottlenecks.

Climate change has altered both migration timing and routes; delays and northward shifts in autumn waterfowl migration have been reported worldwide (e.g. Andersson et al. 2022, Thurber et al. 2020). Because national census frameworks and population indices rely heavily on fixed-calendar standardised count windows, these phenological shifts directly undermine monitoring effectiveness by decoupling survey dates from actual peak bird abundance.

Traditionally the global population size of the Red-breasted Goose has been estimated from the International Waterbird Census (IWC, Sayoud et al. 2017) or targeted counts conducted on its wintering grounds. Efforts to undertake coordinated surveys began in the early 1990s and have continued to the present day, particularly in Bulgaria, Romania and Ukraine (Cranswick et al. 2012). However, recent short-stopping in Russia has made it increasingly difficult to derive population estimates from winter counts. In some mild winters, birds range widely from southern Russia to the northern and north-western Black Sea coast (Iliev et al. 2023). Surveying this area effectively is logistically difficult, particularly because of the war in Ukraine, and would require substantial funding and personnel. Counts at autumn staging areas in northern Kazakhstan therefore emerge as an alternative option for assessing the size of the population (Cuthbert et al. 2018). However, logistical difficulties also affect monitoring in this area. Red-breasted Goose numbers at roosting lakes are therefore extrapolated from recorded counts, which may produce under- or overestimates of population size. For instance, the birds are mobile and use multiple sites, but the logistics on the ground mean that a synchronised census of all major wetlands is not possible and birds might be overlooked or counted multiple times.

Early GPS-tracking studies provided only limited insights into the species' movements (Vangeluwe et al. 2012, Todorov et al. 2024). We therefore aimed to expand this work by deploying GPS transmitters on a larger sample of Red-breasted Geese to (1) provide a more detailed understanding of spatial and temporal variation during spring and autumn migration; (2) identify and quantify the use of important staging areas along the flyway, particularly in relation to breeding and wintering sites; (3) determine the duration and spatial extent of habitat use during different phases of the annual cycle (breeding, moulting, migration, and wintering); and (4) assess individual variation in migratory behaviour and breeding success in relation to habitat use.

Methods

Bird capture and deployment of transmitters

Between May 2019 and June 2022, we captured 94 Red-breasted Geese and fitted GPS transmitters to 31 birds in Kazakhstan, 9 birds in Bulgaria and one in Romania. The Romanian bird was a rehabilitated bird and provided limited data so it was not considered further in this analysis. Birds were captured with cannon nets under permit number 816/06.12.2019 issued by the Ministry of Environment and Water of Bulgaria, and the Ministry of Natural Resources in Kazakhstan. A total of 11 birds were fitted with GPS-GSM neck collars (five with 13.8 g INTERREX OMNI 2G C1 and six with 17.0 g Ornitela OrniTrack–NL40), all deployed in Kazakhstan. The remaining 30 birds were fitted with a harness backpack (11 with 22 g Microwave Telemetry solar-powered PTT, one with 9.5 g Microwave Telemetry solar-powered PTT, and 18 with 20 g Ornitela OrniTrack 20), of which nine were deployed in Bulgaria, one in Romania (not considered here) and 20 in Kazakhstan. The Microwave GPS PTT tags were programmed to collect a maximum of six fixes per day at the following local times: 00h00, 06h00, 10h00, 13h00, 18h00 and 21h00 to cover both day and night roost locations; data were transmitted once per day. The Ornitela GPS-GSM tags were programmed to take one GPS fix per hour, with longer intervals based on battery status (100–75%: 1 fix per hour, 75–50%: 1 fix every 3 hours, 50–25%: 1 fix every 6 hours, below 25%: 1 fix every 12 hours) and to transmit every 12 hours. The five Interrex tags were programmed to collect one GPS fix per hour. They initially transmitted data every 8 hours, which was adjusted to 12 hours within a week of the deployment.

The tracking devices provided from two to several hundred GPS fixes per day, depending on tag capacity and battery conditions (depending on the solar radiation reaching the built-in panel), resulting in individual datasets from 769 to 27,872 GPS locations. On average, all tags produced 24.5 GPS positions per day (range 5.5–137.3, SD = 32.2, n = 23). Excluding Interrex tags, the average was 10.3 fixes per day (range 5.5–19.7, SD = 6.6, n = 19). A typical tag from Ornitela (ID 201342) lasted 242 days and produced 4,593 fixes, averaging 19 per day. With the programmed schedule, this tag had a battery status of 70.5–79.7% over this period; with 19 fixes a day, the tracker spent between 69% and 77% of its total time above 75% battery level. Argos locations were not used directly in the analyses, but were inspected informally for discrepancies in the data (filtered for precision classes LC 3, 2, 1, 0).

In the analysis, we included only those tags/individuals that provided data for a minimum of one full season, whether spring, summer, autumn or winter, which also allowed analysis on a monthly basis. Birds with just a few months of data were excluded.

Tracking devices weighed less than 2% of body mass, well below the accepted 3% threshold for transmitters (Kenward 1987). Transmitters were mainly deployed on adult males (>1,500 g), although antenna-free tags and neck collars were also fitted to heavier females and subadults. Backpack harnesses, developed for the species by the Wildfowl and Wetlands Trust in 2010, were used for all backpack transmitters. With technological advances, we also employed neck collars to reduce handling time.

Low battery power levels and signal loss hindered the accumulation of data, especially in autumn and winter when day length was short and available sunlight was limited. Typically, transmitters also did not resume transmitting after extended off periods. We therefore only used tracks from which we obtained a full season of data, i.e. where the start and end of a season, for example spring migration, could be determined based on the GPS data (see below for definitions of seasons).

Of the 41 tagged individuals, 23 produced GPS data for a full season or longer (range 110–854 days, mean 297), with a total of 150,137 GPS positions (mean 6,528). At the time of analysis, six birds had been tracked for more than one year, and four still had functioning transmitters; together, these birds were tracked for 177 full months (mean 8.4 months). Five of the 23 individuals included in the analyses were aged at capture as second-calendar-year birds (i.e. hatched the previous summer), but were treated as adults, since geese stay throughout the year in extended family groups or flocks, and we expected them to behave like adults except within the breeding area where they would then follow non-breeding adults.

Data analysis

We divided the year into seasons. Spring extended from 1 March to 31 May, summer from 1 June to 31 August, autumn from 1 September to 30 November, and winter from 1 December to 28 February (29 February in a leap year). However, to use the GPS data to describe the periods of spring and autumn migration and duration of time spent on the breeding and wintering areas, we further divided the year according to the movement of each individual. We defined the end of spring migration and start of summer as when an individual bird arrived at the last staging site close to the nest site or breeding area. The end of summer and commencement

of autumn migration was set as the date when an individual undertook its first long flight southwards out of the breeding/moulting areas. Similarly, autumn migration was considered to have ended and winter started when a bird settled within the traditionally defined winter period, or at a site that would be used the following winter months. The start of spring migration was defined by the first long movement in an easterly or northward direction towards the breeding areas; these movements were typically >100 km.

The start and end of incubation were defined as when GPS positions narrowed and became stationary within a few hundred metres, in both females and males, clustered around an evident nest-site midpoint, with very few or no long excursions (>1 km). Nesting was judged as successful when an individual was confined to such a limited range for at least 27 days and without excursions >1 km during the following 30–40 days, when adults were presumed to be with their goslings. The breeding period was therefore defined as starting when incubation commenced until the first long flight of 10+ km when goslings had gained flight capability. Geese failing early during incubation usually leave to moult elsewhere, often flying several hundred kilometres. During active moult in late summer, individuals would again use confined areas, with no flights (defined as speeds >5–6 km h^{-1}). Moult end was defined as when flights were again undertaken (speed >25 km h^{-1}, distance >10 km).

Following the hierarchical framework of Zhang et al. (2024), key staging areas were identified by applying the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm in QGIS to group stopover locations by migration season. We retained locations with a recorded speed of 0. We utilised a spatial distance threshold of 1° (c. 110 km), which approximates the average distance a goose can cover in a 1.5-hour flight (cf. Zhang et al. 2024). Because raw tracking data featured variable fix rates (ranging from 2 to several hundred fixes per day), we chose not to downsample the dataset. This approach accepts that individuals with lower tracking frequencies may be locally underrepresented, but it preserves the maximum spatial resolution and fine-scale behavioural data of the remaining tracks, avoiding the loss of critical stopover sites that may occur when forcing the data into a uniform or standardised structure. High GPS fix rates were also more likely when birds were in flight, because the solar panels were exposed for longer; on the ground, resting birds and other activities could cause feathers to cover the panels partly or completely.

To filter out minor, short-term stops and isolate major regional staging complexes, we evaluated the core cluster selection using minimum point thresholds (MinPts). We established a high-density threshold of 250 points and a low-density threshold of 100 points per cluster. These thresholds were determined iteratively: 250 points represents the maximum threshold capable of delineating major, distinct regional concentration zones without merging the entire flyway into a single continuous polygon, while 100 points represents the minimum baseline required to capture localised stopover clusters before the output fragments into an uninterpretable number of minor spatial artefacts. Concave hull polygons were used to delimit winter, autumn, spring and summer ranges (QGIS 2023).

All GPS analyses and summary statistics were carried out in QGIS 3.32 Lima (QGIS 2023) and Microsoft Excel.

Results

Flyway movements

We obtained 177 full months of tracking data from the 23 tagged Red-breasted Geese (range per individual 3–27 months, mean = 8.4, SD = 6.6). On average, our tagged Red-breasted Geese travelled a mean of 17,725 km annually, with peak movement distances occurring during the spring and autumn migration periods (April–May and September–November) (Figure 1). The tracked birds travelled an average of 47.7 km d^{-1} throughout the study (range 25.8–75.7, SD = 10.9).

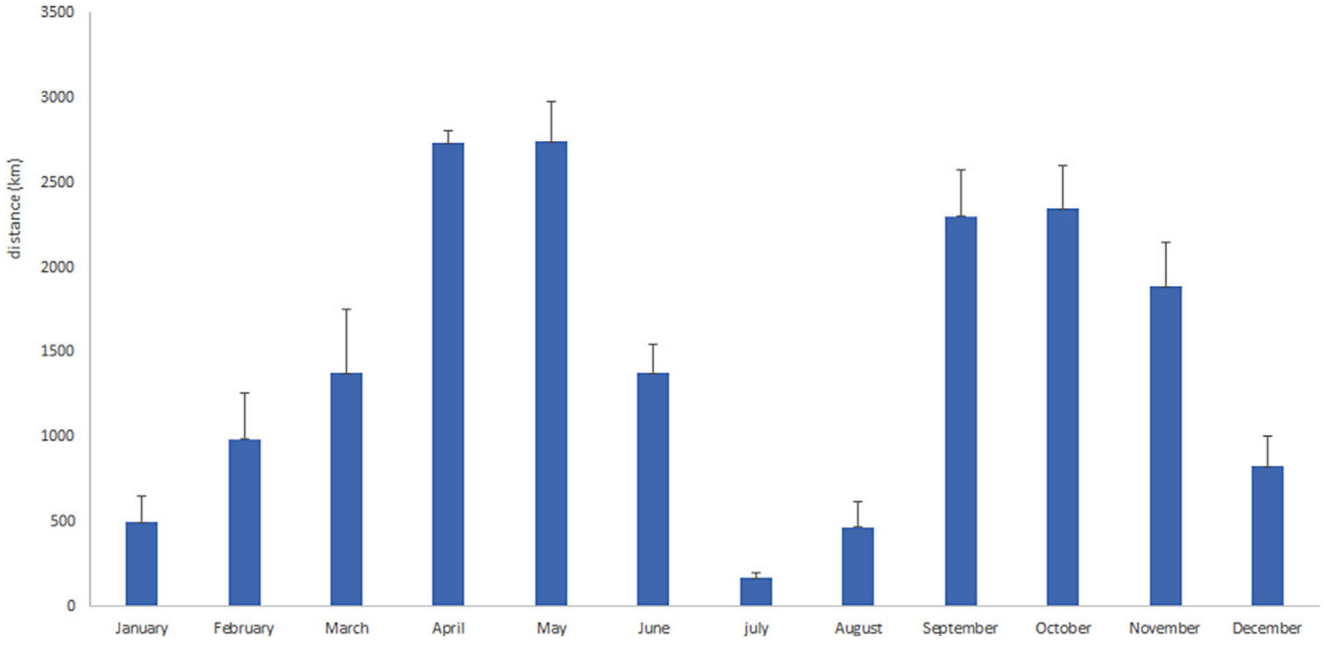

Figure 1. Average distance (+SE) travelled per month for 23 Red-breasted Geese tracked 2019–2023.

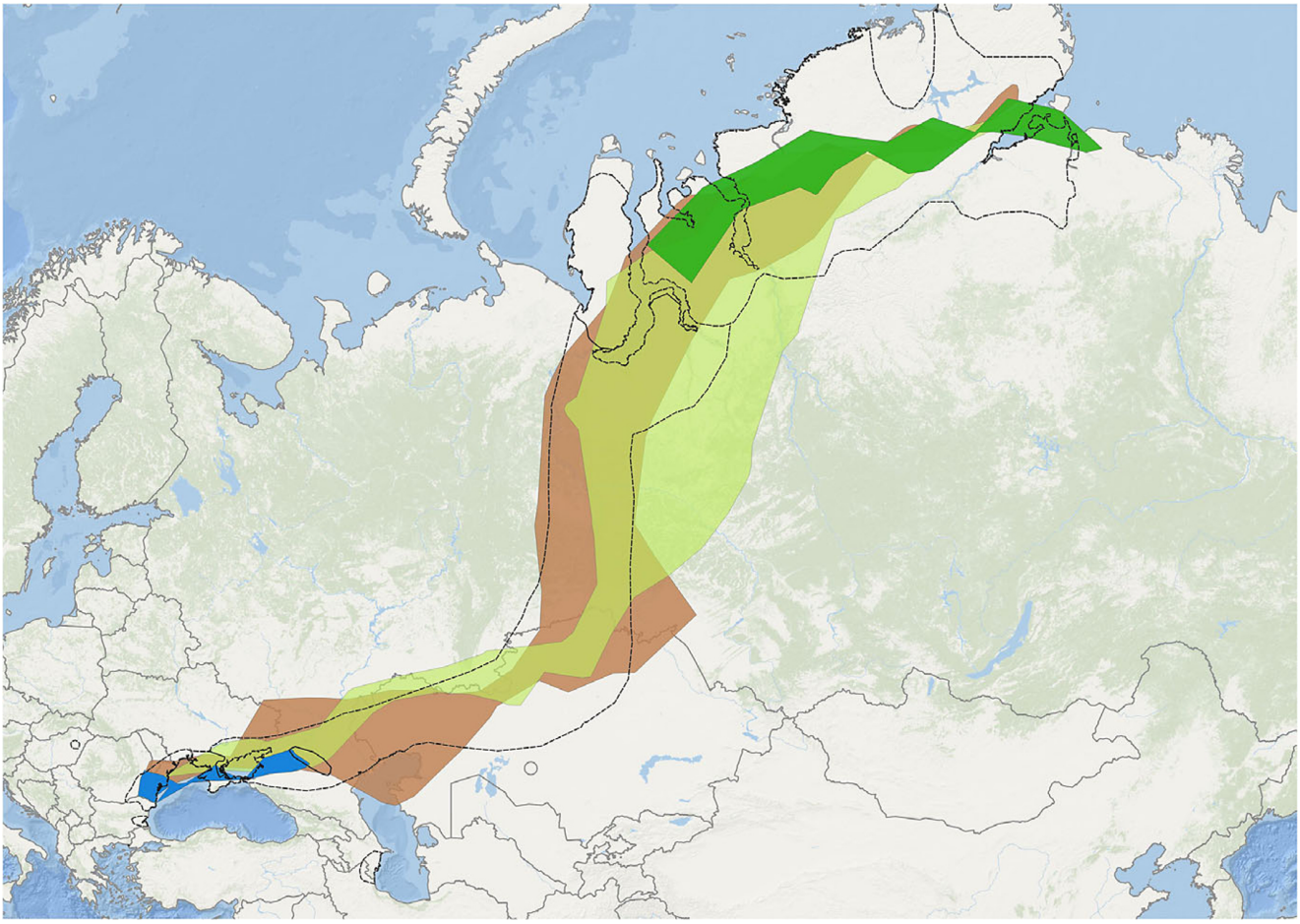

Figure 2. Red-breasted Goose flyway given as concave hull polygons. Summer (dark green), spring (light yellow), autumn (brown) and winter (blue) based on 177 full months with tracking data of 23 individuals. Dotted line is Red-breasted Goose distribution after BirdLife International (2025).

Based on complete individual tracks, there was no significant difference (t = 0.65, df = 19, P = 0.52, SD = 8.069) between the individual duration of spring (93.0 days, SD = 10.1, n = 6) and autumn migration (98.3 days, SD = 18.5, n = 15).

The tracks compiled from spring and autumn migration covered areas of 2,007,695 km^2 and 2,511,285 km^2 respectively, but did not overlap perfectly (Figure 2). Spring migration followed a narrower corridor from the Black Sea to Kazakhstan and was generally approximately 400 km east of the autumn paths from Kazakhstan to the breeding area. Combined, the passage covered an area of 3,333,332 km^2, of which 24.7% was only used during spring (823,162 km^2) and 39.8% was only used during autumn (1,326,752 km^2).

Seasonal movements and timing

In summer and winter, the total geographic extent (minimum convex polygons) used was 165,825 and 116,751 km^2, respectively. Within this wintering range, the birds occupied three discrete core areas separated by 300–500 km from west to east: Romania together with limited cross-border areas in Bulgaria and Ukraine (19,714 km^2), the Sivash area in northern Crimea (842 km^2), and Veselovskoie, Rostov, Russia (275 km^2). The remaining area within the winter polygon represented the open space between these disjunct wintering sites, which might also be used by wintering Red-breasted Geese. The utilisation of these three distinct regions, particularly the eastern sites in Crimea and southern Russia, was consistent with recent observations of 'short-stopping' behaviour within the global population. The full geographic extent used by the Red-breasted Goose throughout the year covered an area of 3.6 million km^2 in this study, comparable to the range given by BirdLife International of 2.22 million km^2 (Figure 2) and the Critical Site Network (CSN; https://criticalsites.wetlands.org) flyway (4.4 million km^2). During the wintering period, 100% of our tracked individuals were located within the three core regions (coastal Romania/Bulgaria, Sivash, and Veselovskoie) known to regularly support >1% of the global population, confirming that our sample was highly representative of the known wintering distribution.

The DBSCAN clustering analyses showed little overlap between important spring and autumn staging areas close to the breeding region, but some overlap midway in Kazakhstan (Figure 3).

Red-breasted Geese spend near-equal amounts of time in the different phases of their annual cycle (Table 1). Population-level start and end dates showed that summer and breeding activities were the shortest (81 days, 22.3% of the year). The population-level autumn migration window covered 97 days (26.6%), wintering 90 days (24.8%) and spring migration window 96 days (26.3%). Spring migration started on average on 2 March (range 23 February–10 March, SD = 5.5, n = 9), summer/breeding period



Figure 3. Key seasonal staging areas identified by DBSCAN cluster analysis during spring migration (green polygons) and autumn migration (brown/beige polygons). High-density core clusters (≥250 positions per 1° spatial radius) are shaded light green (spring) and brown (autumn). Broader, low-density clusters (≥100 positions per 1° spatial radius) are shaded dark green (spring) and beige (autumn). Grey background lines show all individual GPS tracks. Staging regions: 1) Sivash, Ukraine; 2) Kalmykia, Russia; 3) West Kazakhstan; 4) Kostanay, Kazakhstan; 5) Northern Kazakhstan; 6) Lower Ob Valley; 7) SE Yamal; 8–9) Gydan (NW to SE); 10) Pyasina, Taymyr; 11) Khatanga, Taymyr.

Table 1. Spatiotemporal and phenological summary of tracked Red-breasted Geese across annual life-history stages

Seasonal phase	Population window (days)	Mean start date (range)	Individual duration (days ± SD, N)	Key regions & broad habitat type	General protection status
Spring migration	96	2nd March (23 Feb–10 Mar)	93.0 ± 10.1, 6	N. Kazakhstan and Kalmykia in Russia; shallow steppe lakes & agricultural matrix; in Kalmykia Manych Lake permanent wetland.	Ramsar sites present and KBAs/IBAs. In Kalmykia protected area, but hunting pressures exist. Goose spring hunting is prohibited in both KZ and RU (around Manych Lake).
Summer / Breeding	81	6th June (27 May–20 Jun)	81.4 ± 9.1, 20	Taimyr Peninsula, Russia; Arctic tundra river valleys	Variable - localised state nature reserves (Zapovedniks), but hunting pressure exists in some subarctic regions
Autumn migration	97	26th August (28 Jul–12 Sep)	98.3 ± 18.5, 15	North and Kostanay region in Kazakhstan, Orenburg region and Kalmykia in Russia; agricultural stopovers	Key staging hubs are KBA and/or Ramsar sites, managed as hunting estates. Some are regionally protected (Orenburg Russia) and in Kalmykia the main areas are part of biosphere reserve. In Kazakhstan some temporary hunting closures introduce, but it lacks substantial national legal protection.

started on average 6 June (range 27 May–20 June, SD = 5.6, n = 24), autumn migration started on 26 August (range 28 July–12 September, SD = 10.6, n = 22), with wintering period starting on average 1 December (range 4 November–27 December, SD = 17.4, n = 15).

Breeding success and timing

Based on speed and concentration of locations over longer periods, it was possible to infer probable breeding success (successful or unsuccessful), and the start and end of the moulting period for non-breeders and failed breeders. The latter coincided with the start of autumn migration for successful breeders. For failed or non-breeders, moulting began on average on 3 July (range 28 June–17 July, SD = 7.0, n = 9). Among 20 complete summer periods for 15 adults, incubation was successful in 11 summers and failed in nine. In addition, of the six second-calendar-year birds, the one male seemed to have one successful incubation period, whereas there was none for the young females. One adult male that was tracked through three consecutive summers was successful during the first, failed in the second and succeeded the third summer. The breeding period, from when incubation commenced until the first long flight of 10+ km when goslings had gained flight capability, averaged 77.4 days (successful breeders, including the second-calendar-year male, n = 10, SD = 6.5). In four cases across the tracking period, distances between nest location could be measured for four individuals. For three individuals tracked in consecutive years, inter-annual nest-site distance was 94 m, 220 m, and 49.1 km, respectively. For a fourth individual tracked over a two-year interval—during which an intervening unsuccessful breeding attempt occurred—the distance between nest sites was 436.9 km. Even though the sample size was limited, these distances indicated high inter-annual nest-site fidelity among the tracked individuals.

Autumn staging and site use

Within the flyway, northern Kazakhstan and neighbouring Orenburg Oblast in Russia are particularly important. Of the 40 occasions during which birds were tracked through this area, 23 were complete and used for further analyses. In spring, Red-breasted Geese staged exclusively in Northern Kazakhstan Region for an average of 36.6 ± 5.2 SE days (n = 8, range 14.7–48.3 days) and each bird used approximately ten different lakes within one season (mean = 10.3 ± 2.5 SE, n = 8). In autumn they staged for 31.6 ± 2.82 SE days (n = 14, range 11.7–43.7 days), not significantly different from spring (t = 0.9273, df = 20, P = 0.36), but used significantly fewer lakes (mean = 0.8 ± 0.8 SE, n = 14; t = 2.484, df = 20, P = 0.02). Of the 15 autumn tracks, nine were exclusively in Kazakhstan and six were in Kazakhstan and Russia. Birds staged in northern Kazakhstan for 24.1 days (4.4 lakes), while staging in Orenburg Oblast, Russia, lasted 13.7 days (1.2 lakes). During the respective autumn staging periods, these six birds spent an average of 22 days in northern Kazakhstan (61.6%, range 11.9–31.9 days) and 13.7 days in Orenburg (38.4%, range 3.8–32.8 days).

A comprehensive database was developed on the 143 lakes where geese were counted during ground surveys in Kazakhstan up to 2021 (Cuthbert and Petkov 2022). Of these, 26 were used by the tagged geese. In addition, a further 28 new or previously unknown lakes/ponds were used for staging: 18 in spring and 10 others in autumn. Only one of these was used in more than one year. On summarising the number of staging days, independent of season but excluding Karatau Lake where birds were caught and released, Taldykol Lake in Kostanay Region was found to be the most important lake, accounting for 16.8% of all staging days. Zhetykol in Orenburg, Russia, accounted for 9.1% and Mamyrkol (+ Kepes) for 6.0%. Altogether, 19 lakes had more than 10 staging days counted from the GPS telemetry data. Regional totals were 259 staging days in Kostanay, 226 in North Kazakhstan, 78 in Orenburg (Russia), 31 in Akmola and three in Aktobe. The tracked individuals exhibited a mixed strategy within these staging regions: rather than remaining concentrated at a single waterbody, birds shifted dynamically between multiple nearby sites within a season, utilising an agricultural matrix of cereal crops adjacent to shallow steppe lakes which were used for roosting. Between years, birds spread across a wide network of available waterbodies, with low individual site fidelity to the same minor lakes between years, except for major regional hydrological hubs like Lakes Taldykol and Zhetykol.

Discussion

Annual chronology, flyway structure, and short-stopping

This study presents the most detailed spatiotemporal analysis to date of the annual migration of the Red-breasted Goose, a globally threatened species. GPS telemetry enabled high-resolution tracking of individuals across their entire annual cycle, revealing consistent use of three main wintering areas: coastal Romania, neighbouring areas in Bulgaria and Ukraine, the Sivash region in Crimea, Ukraine, and especially the Veselovskoie reservoir in southern Russia. Although our telemetry data did not support the existence of major undiscovered wintering sites during the study, the sample may not fully represent peripheral, low-density sites.

Crucially, our tracking data align with recent observations of short-stopping in southern Russia and Ukraine during winter, where over the past decade, birds have reached Bulgarian wintering grounds only during exceptionally severe winter weather (Iliev and Petkov 2015, Iliev et al. 2023). This provides strong empirical support for the hypothesis that climate-driven short-stopping is increasingly common. This shifting winter distribution has significant implications for migratory bird monitoring effectiveness, as climate-driven delays and range contractions can decouple standardised, fixed-calendar count windows from actual peak bird abundance (Thurber et al. 2020, Andersson et al. 2022). Consequently, traditional conservation boundaries, hunting pressure management, and international policy frameworks must adapt to these distributional changes.

Divergent migration corridors and hydrological cues

While our data confirm the overall broad flyway structure previously suggested by historical literature on the Palearctic (Dementiev and Gladkov 1952, Cramp and Simmons 1977, Isakov 1979, Vangeluwe et al. 2012, Litvin 2014), the greater spatial precision revealed that spring and autumn migration corridors diverge substantially. This limited overlap suggests differing ecological requirements or constraints between seasons, likely linked to habitat availability, weather, and energetic demands.

During spring migration in Northern Kazakhstan, surface water availability for staging and drinking is strongly influenced by winter ice and snow accumulation, localised melting rates, and the subsequent formation of ephemeral wetlands. In early spring, larger permanent lakes are frequently ice-covered and largely unavailable to the geese. These transient water networks emerge with snowmelt

but dry rapidly, making precise migratory timing critical, while spatially uneven vegetation green-up rates further underscore how localised climatic anomalies can disrupt staging habitat availability. Together, these processes reinforce recent evidence that heterogeneous phenological shifts threaten network connectivity across waterfowl flyways (Si et al. 2015, Wei et al. 2024, Rogova et al. 2025).

Conversely, the similarity in migration durations between spring and autumn challenges existing assumptions of accelerated spring transit. Whereas long-distance Arctic migrants like Greater White-fronted Geese *Anser albifrons* take nearly twice as long in spring than in autumn due to multi-stop spring fueling strategies (Kölzsch et al. 2016), our tracked Red-breasted Geese exhibited remarkably balanced seasonal durations (93.0 days in spring vs. 98.3 days in autumn). This indicates that Red-breasted Geese face comparable temporal and environmental constraints during both migration seasons along their central Eurasian corridor. In autumn, the ecological pressures shift; frequent regional droughts can desiccate the shallow steppe lakes that geese require as safe nocturnal roosts and vital daytime drinking sites. Such droughts compress available staging space and alter migration schedules. Because reversing migration to fly back north is ecologically unviable due to rapidly declining temperatures at higher latitudes, widespread regional droughts force birds to compress their staging timelines, potentially reducing energy accumulation prior to their southbound flights. These distinct seasonal pressures demonstrate that protecting a single migratory corridor is insufficient; conservation measures must be season-specific.

High nest-site fidelity on Arctic breeding grounds

Despite our small sample size, the tracking data indicate high localised nest-site fidelity between consecutive years (94 m and 220 m in two pairs), alongside instances of substantial breeding dispersal (49.1 km between consecutive years and 436.9 km over a two-year period following an unsuccessful breeding attempt). Breeding dispersal in Arctic-nesting geese is strongly influenced by previous reproductive outcome, snowmelt phenology, and the spatial dynamics of protective nesting hosts such as Peregrine Falcons *Falco peregrinus* and Rough-legged Buzzards *Buteo lagopus* (Quinn et al. 2003). The large movement (436.9 km) observed following a failed breeding season is consistent with dispersal strategies in which individuals relocate across regional scales, potentially in response to localised nest loss or changes in raptor and owl territory occupancy. These findings suggest that, while Red-breasted Geese exhibit high site fidelity during successful consecutive breeding attempts, they retain substantial regional mobility that may allow them to abandon degraded or high-risk sites. Consequently, effective conservation cannot rely exclusively on protecting isolated historical nesting micro-sites; it should safeguard a broad network of suitable Arctic breeding habitats to accommodate such adaptive regional dispersal.

Translating telemetry into flyway-level conservation

The findings of this study improve our understanding of the Red-breasted Goose flyway by providing a more comprehensive delineation of its migratory range and highlighting key areas that are essential for the species throughout its annual cycle.

Through high-resolution GPS telemetry, we have identified highly localised and season-specific stopover areas in Kazakhstan, Russia, and Ukraine, many of which had not been previously recognised or adequately protected. These areas serve as crucial refuelling points during migration and are essential to maintaining energy balance, survival, and subsequent reproductive success across the annual cycle (Paxton and Moore 2017). Identifying the precise timing and spatial footprint of these staging periods facilitates optimised ground-survey designs and allows conservationists to target specific areas for protection, ensuring that essential migratory connectivity remains intact (Trierweiler et al. 2014, Gilroy et al. 2016, Hewson et al. 2016).

Taldykol Lake (Kostanay Region, Kazakhstan), Zhetykol Lake (Orenburg Region, Russia) and Mamyrkol Lake (Kostanay Region, Kazakhstan) emerged as the principal staging sites, together accounting for 31.9% of all recorded staging days. Taldykol and Mamyrkol are internationally recognised as Key Biodiversity Areas (KBAs), whereas Zhetykol forms part of the Shalkaro–Zhetykol Important Bird and Biodiversity Area (IBA) and has regional protection status. All three sites are managed as hunting estates during the autumn period, highlighting potential challenges for the conservation of these critical stopover sites. Nevertheless, several results from this study have already directly informed on-the-ground conservation planning and flyway-level management. Knowledge of peak staging periods has directly supported the implementation of protective measures, including the designation of temporary non-hunting zones or the extension of existing ones during peak migration waves in key areas of Kazakhstan and Russia as part of the LIFE for Safe Flight project. These GPS-informed spatial closures have significantly contributed to reducing anthropogenic pressure during critical fuelling phases. As human development and rapid agricultural land-use changes continue to threaten habitat quality across the flyway (Lei et al. 2019), the continuation of telemetry studies will be essential to monitor phenological mismatches (Saino et al. 2011, Lameris et al. 2018) and safeguard this vulnerable species under accelerating climate change.

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