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Multi-Sensor Logger Tracking Reveals the Threats of Offshore Windfarms to Passerine-Sized Birds

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ABSTRACT

Offshore wind energy is a cornerstone of the transition to renewable energy, yet its rapid expansion raises concerns for wildlife. These concerns notably involve small migratory birds whose movements across marine barriers and therefore potential interactions with offshore wind turbines remain poorly understood. Here, we deployed hundreds of miniature multi-sensor loggers on 14 small (12–80 g) bird species from eight families near the N-E Atlantic (Western France and the United Kingdom). We obtained useful data from 13 species and were able to reconstruct their migratory timing, trajectories and flight altitudes with high precision. From 137 sea-crossing flights across the English Channel and the Bay of Biscay, we reveal that most species crossed these maritime barriers almost exclusively at night and routinely at altitudes below 300 m above sea level, overlapping with turbine rotor-swept zones, thereby exposing them to multiple threats, including collision risks and displacement through barrier effects. These findings highlight the critical need to include passerine-sized migrants, often overlooked in biodiversity assessments, in environmental impact studies prior to offshore wind farm installation, as well as in monitoring protocols during the operational phase. Moreover, our study provides a proof-of-concept of the utility of multi-sensor loggers to integrate small bird migration ecology into windfarm planning and sustainable energy transitions.

1 | Introduction

Generating electricity from wind power is currently a key solution to meet rising energy demand while limiting human-driven global change. While land-based wind farms conflict with other land uses, offshore wind farms (OWFs) can harness strong, steady winds at sea without competing for land and provide large-scale reliable renewable energy (Nitsch et al. 2019; Wang et al. 2019; Kempton et al. 2007). In this context, OWF number and capacity has been growing quickly worldwide, with operational capacity exceeding 85 GW in 2025 and projections suggesting that global offshore wind power could reach 250 GW by 2030 (Gauld et al. 2022; GWEC 2025).

In the European Union, cumulative offshore wind capacity reached over 21 GW in 2024, and member states have set ambitious goals of approximately 110 GW by 2030 and 315 GW by 2050 to support climate and energy targets (Gauld et al. 2022;

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Bilgili et al. 2023; Beiter et al. 2022; Curley et al. 2025; European Commission 2025). Moreover, OWFs have been increasing steadily in height over the past decades with current projects planned in European waters being expected to reach heights up to 300 m (Gauld et al. 2022; Bilgili et al. 2023; Beiter et al. 2022; Curley et al. 2025). In order to ensure that offshore wind energy develops sustainably, it is crucial to assess its potential impacts on flying wildlife and to identify effective mitigation strategies (Gauld et al. 2022; Hüppop et al. 2006; Drewitt and Langston 2006; Schippers et al. 2020; Conkling et al. 2022; Watson et al. 2025). Current research has mainly focused on large species such as seabirds or shorebirds (Watson et al. 2025; Furness et al. 2013; Weiser et al. 2024; Schwemmer et al. 2023; Schwemmer et al. 2023; Desholm and Kahlert 2005), while little is known about smaller flying animals like small birds or bats (Hüppop et al. 2006; Drewitt and Langston 2006; McGuire and Guglielmo 2009). Yet, the few studies on sea crossings by small bird species have shown variable and context dependent flight altitudes but concerning regular low altitude flights suggesting potential deleterious interactions with future OWFs at individual levels, and by extension, populational levels (Norevik et al. 2023; Liechti et al. 2013; Brabant et al. 2015; Rime et al. 2023; Dufour et al. 2026; Rhyne et al. 2026; Doniol-Valcroze et al. 2026).

To address this concerning knowledge gap, multiple projects and initiatives are underway and combine methods such as GPS telemetry, radar tracking, land and marine surveys and acoustic monitoring (Hüppop et al. 2006; Drewitt and Langston 2006). GPS technology miniaturization has greatly advanced our ability to track animal movements and has proven to be useful to study OWFs' threat to flying fauna. Unfortunately, for most species under 80 g, which make up a large fraction of global avian diversity, GPS devices remain too heavy to allow routine, individual-level tracking. For such small bird species, radar and nocturnal acoustic monitoring can provide valuable insights into migratory activity and behavior (Liechti et al. 2013; Béasse et al. 2025). Radar studies from various regions have established that most passerine-sized migrants fly across broad altitudinal ranges, typically between 200 and 1000 m (Hüppop et al. 2006; Dokter et al. 2010; Mateos-Rodríguez and Liechti 2012). However, radar systems face significant limitations for assessing OWF risks. Geographically, radar coverage is often restricted to coastal fringes or specific offshore areas, leaving vast "blind spots" across open seas where bird trajectories remain unmonitored (Nilsson et al. 2019). Moreover, even within their range, radars frequently fail to detect birds at low altitudes due to the earth's curvature and sea surface clutter (Desholm and Kahlert 2005; Desholm et al. 2006), precisely the zone where the risk of collision with turbine blades is maximal. Finally, radars lacks the taxonomic resolution to distinguish between species or sometimes to filter out insects (Dokter et al. 2010), and cannot capture fundamental individual parameters, such as precise take-off sites or species-specific crossing strategies (Liechti et al. 2013). Until recently, the only viable option for small bird tracking was the use of light-level geolocators, which revolutionized the field by being cost-effective, minimally invasive and suitable for small-bodied species (Brlík et al. 2020; Stutchbury et al. 2009; Lisovski et al. 2012; Lisovski and Hahn 2012; Lisovski et al. 2020). However, while providing valuable insights into broad migration patterns, spatial resolution remained very limited (approx. 150–200 km). VHF-based telemetry systems (e.g., MOTUS network) can effectively document trajectories across wide spatial scales, provided that a geographically comprehensive receiver network is available, but neither system provides information on flight altitude (Mitchell et al. 2025; Loring et al. 2020). Therefore, finely tracking the movements of small birds at individual levels raises unique challenges which are hardly matched by currently available technology, limiting our understanding of how small birds interact with offshore environments and potential OWFs.

Recent technological advances are beginning to change this picture: Miniature (<0.5 g) and cost-effective multi-sensor loggers now also integrate barometric and accelerometric sensors. The rich datasets delivered by such loggers along with recently developed analysis tools that account for local meteorological and barometric conditions now allow us to track i) geographic location with unprecedented accuracy (approx. 50 km against 150–200 km for light level-tracking), ii) precise flight activity periods, and importantly iii) altitudinal movements (Nussbaumer et al. 2023; Nussbaumer et al. 2023; Rhyne et al. 2024; Sjöberg et al. 2018). These innovations could theoretically allow us to better assess risks and develop solutions that support the coexistence of anthropogenic infrastructures and flying biodiversity. Using such technology to bridge current knowledge gaps therefore appears promising for designing offshore wind solutions that are sustainable and compatible with biodiversity conservation (Hüppop et al. 2006; Drewitt and Langston 2006). In this context, this study was designed as a proof-of-concept of the effectiveness of multi-sensor loggers for tracking small migratory birds and estimating their flight altitude and timing of sea crossings to understand how these birds use airspace that may overlap with OWFs. To explore this issue, we focused on the maritime areas of the English Channel and the Bay of Biscay, where the French government is currently developing and planning additional OWFs by 2035 and 2050 (Figure 1). This focus is particularly timely given the documented long-term declines of many migratory species along the Afro-Palearctic flyway, underscoring the need for improved understanding of potential cumulative pressures across their migratory routes (Vickery et al. 2023). We considered an ecologically and phylogenetically diverse species panel encompassing both short and long-distant migrants, not to only focus on classically tracked trans-Saharan migrants as shorter migrants could behave differently. A total of 375 individuals from 14 small migratory bird species from eight families were tagged with 0.5 g multi-sensor loggers at strategic coastal or insular sites to maximize the number of recorded sea-crossing flights. Using state-of-the-art analytical methods (Nussbaumer et al. 2023; Nussbaumer et al. 2023), we reconstructed individual trajectories, identified flights over marine areas, and estimated both the timing and the altitude of these flights from barometric data. This framework allows us to quantify how often birds fly below the altitudes corresponding to the maximum height of offshore wind turbines and thus provide the empirical basis needed for assessing potential interactions and associated risks (e.g., collision or displacement) between small migratory birds and OWF developments.

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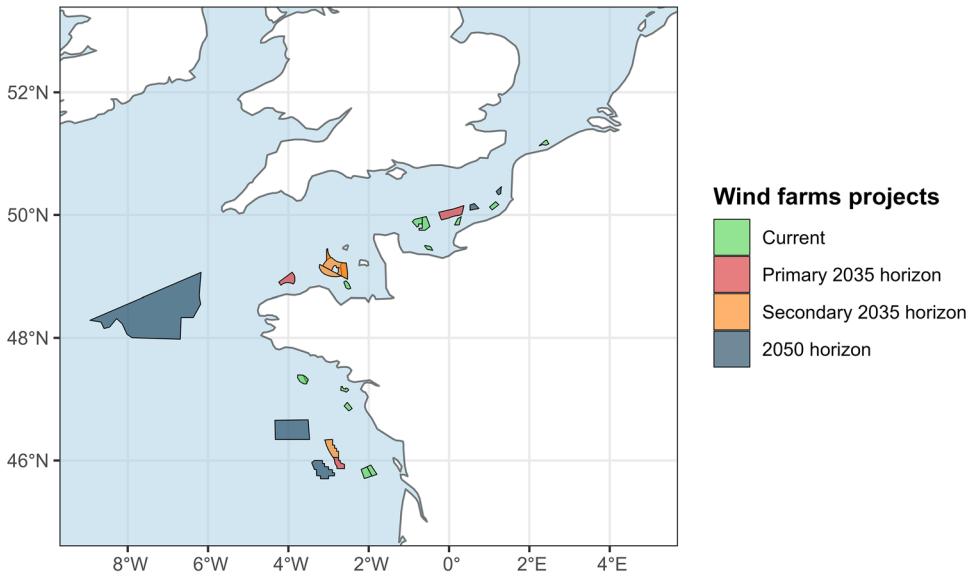

FIGURE 1 | Current (already operating, currently being implanted or having received implantation authorization) and projected windfarm implantation areas in the French Economic Exclusive Zone (from https://www.eoliennesenmer.fr/). For a broader and interactive view of European Offshore Wind Farm planning, see https://map.tgs4c.com/offshorewind/.

2 | Material and Methods

2.1 | Study Species and Logger Deployment

We fitted 375 multi-sensor loggers on 14 species (11 passerines and three non-passerine species) in different locations in France and the United Kingdom during the 2021–2024 breeding seasons (Table S1). Tagged species selection was primarily constrained by ethical guidelines limiting equipment mass to less than 5% of the bird's body mass (Brlík et al. 2020; Barron et al. 2010; Kenward 2001), which restricted the inclusion of smaller species: the lightest species being the Sedge Warbler and the Pied Flycatcher weighing approximately 12 g (birds under this mass limit were not equipped). Fieldwork logistics, species availability, and abundance further constrained our sample. Although this resulted in a panel primarily composed of nocturnal, insectivorous, and long-distance migrants, we included additional short-distance migrants to maximize ecological and phylogenetic diversity. Birds were captured and tagged under a license delivered by the MNHN-CRBPO (reference PP1245) and approved by the Animal Experimentation Ethics Committee Cuvier (reference DEE2025-68-140) in France, and under permits issued by the British Trust for Ornithology and granted by the Special Methods Technical Panel (project codes 15/11s; 875; 2728; 12234; 12338; 12340) in the Uk. Adult breeding individuals (1-year-old or more, i.e., birds that already performed one complete migratory journey) were caught using mist nets, spring-traps or falling traps depending on the species' ecology and were measured and marked with a metal ring and an engraved color ring or a combination of colored rings to facilitate their recapture. We fitted each bird with a multi-sensor CARP30Z11136-7-DIP logger (weight with harness = 0.6–0.7 g, Migrate Technology Ltd.) programed to record continuously (from deployment to recovery) ambient light intensity and temperature (every 5 min) as well as activity data and atmospheric pressure (every 20 min). Loggers were attached to the birds using custom leg-loop harnesses made from elastic "magic-stretch" string (⌀ 0.7–1 mm depending on species). We did not use control groups of untagged birds, but previous works showed a limited impact of this kind of tagging on small migratory bird fitness (Brlík et al. 2020; Lathouwers et al. 2022; Arlt et al. 2013). In subsequent years, the same individuals were searched for and recaptured to retrieve their tag.

2.2 | Migratory Journey and Flight Alti Inference

To determine if, where, when and how birds crossed the marine areas of interest, we modeled the trajectory of each tracked bird following the approach implemented in the *GeoPressureR v3.4* R package (Nussbaumer et al. 2023; Nussbaumer et al. 2023). We followed all the steps to reconstruct the birds' most likely trajectories as described in the manual of the package (Nussbaumer and Nussbaumer 2024): We reconstructed individual trajectories using the *geopressuretemplate_graph()* function, carefully checked the consistency of the outputs and iteratively corrected the data labelling if needed (Nussbaumer and Nussbaumer 2024). Last, we considered the *path_most_likely* output of the *GeoPressureR* pipeline to identify the flights during which the birds crossed a maritime barrier. For birds tagged in the UK, identifying flights across the English Channel (spanning c. 35 to 250 km) was straightforward, as any movement between the UK and mainland Europe necessitates a distinct maritime crossing. Conversely, crossing the Bay of Biscay (c. 300–500 km) is optional, as birds can bypass the sea by following the coastline over land. To ensure a conservative classification, any flight connecting Northern Spain with Western France or two different regions of Western France was only categorized as a "Bay of Biscay crossing" if at least 50% of the total distance was covered over open water (Dufour et al. 2026). This threshold prevented shorter coastal hops from being misclassified as major maritime crossings. For identified sea-crossing flights, the temporal altitude profile along the trajectory was computed by converting the barometric

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pressure measured by the tag (sampled every 20 min) to altitude via the barometric equation. These altitude estimations were corrected using the local ground-level pressure and temperature retrieved from the ERA5 reanalysis dataset (Hersbach et al. 2020) along the path using the dedicated *pressurepath_create()* function which allows to reach an estimated 20–50 m (i.e., 2–5 hPA) maximal error (Nussbaumer et al. 2023).

To test for potential species, season, and geographic effects on sea-crossing flight altitude we fitted Bayesian linear mixed-effects models using the *MCMCglmm* R package (Hadfield 2010). To evaluate the variation in the OWF collision risk, we considered the proportion of time spent flying below 300 m a.s.l. as the response variable. We included the season (Autumn/Spring) and the marine barrier (English Channel/Bay of Biscay) as categorical fixed effects, along with their interaction. We initially tested species identity as both a fixed and a random effect. Because including species as fixed effect did not yield significant differences between individual species and overparameterized the model, we retained species as a random effect to account for phylogenetic non-independence and intrinsic inter-specific variability. Phylogenetic non-independence was accounted for by constraining the species covariance matrix using an ultrametric phylogenetic tree containing the 11 considered species build using the *clootl* R package (Miller et al. 2026; McTavish et al. 2025). To control for repeated measures, individual bird identity was included as a random effect. Parameters were estimated using 20,000 iterations (with a burn-in of 3000 and a thinning interval of 10). Given the results of these models (see Section 3), post-breeding (autumn) or pre-breeding (spring) migration flights were treated separately because season appeared to influences the strategy of migratory birds (more generally flights in spring are often shorter and more direct; Nilsson et al. 2013).

3 | Results

3.1 | Logger Recovery and Analysis

We resighted 98 (26%) and recaptured 84 (22%) of the 375 tagged birds (Table S1), which fits with the general resighting and recapture rates in similar studies (Brlík et al. 2020; Lathouwers et al. 2022; Arlt et al. 2013). Resighting rates varied between species (and between sites for a given species), with the highest being for Northern Wheatears (50% in the UK and 55% in France) or Meadow Pipits (35%) and the lowest for European Nightjars (5%). A limited number of loggers had technical failures, and one was lost by the bird (Table S1). Based on retrieved tag data, not all individuals migrated: all three Common Reed Buntings and six out of seven Meadow Pipits remained sedentary, staying at their tagging site throughout the non-breeding season. The aerial feeding behavior of Common Swifts and Barn Swallows prevented the assignation of flight periods to migratory or stopover phases using accelerometric or barometric data and therefore the reconstruction of precise year round trajectories (see Nussbaumer et al. 2023; Nussbaumer et al. 2023). For those species we therefore estimated the potential exposure to OWFs by converting migratory period (swallows: April and September; swifts: April and August; Dupuy and Sallé 2022) barometric measurements recorded during flight into altitudes. The estimation of flight altitude obtained from barometric pressure for those two species tagged in Brittany and therefore potentially crossing the Bay of Biscay showed strong differences between species: Common Swifts spent only about 25% of their daytime flights and 15% of nighttime flights below 300 m a.s.l. while Barn Swallows spent about 50% of their nighttime flights and 70% of their daytime flights below 300 m a.s.l. (Figure S1). The final dataset for our study therefore represented data from 65 multi-sensor loggers from 11 species for which precise migratory tracks were reconstructed using the *GeoPressureR* package.

3.2 | Regional and Seasonal Differences in Sea-Crossing Flight Altitudes

The Bayesian linear mixed-effects model revealed a significant interaction between the season and the maritime area ($pMCMC < 0.001$; Tables S2 and S3). The baseline proportion in autumn in the Bay of Biscay is estimated at 53% (95% CI [29%; 80%]). The effect of spring varies according to the region: in the Bay of Biscay, it leads to a significant decrease in the proportion (estimated at –19%, CI [–30%; –7%] compared to autumn) resulting in 34% of the birds' flight time being below 300 m a.s.l. On the other hand, this proportion increases in spring within the Channel area (+29%, CI [+13%; +46%] via the interaction term). Consequently, the estimated proportion for the spring season across the Channel is 58% (CI [29%; 87%]). Finally, individual-level variance accounts for 14.2% (CI [3.3%; 27.3%]) of the total variance, confirming the relevance of including bird identity as a random effect to avoid pseudo-replication.

3.3 | English Channel Crossing Flight Characteristics

Thirty-three flights were identified for the post-breeding (autumnal) migration period (Figure 2A; Table S2) and 27 for the pre-breeding (spring) migration period (Figure 2A; Table S2). During both seasons multiple birds (notably Northern Wheatears and Pied Flycatchers but note that these species are the most represented ones in our dataset) migrating southward from the UK crossed the Channel before also crossing the Bay of Biscay or vice versa during their northward migration in spring. On the other hand, none of those birds crossed both water bodies during the same flight as all made a stopover in Western France between the two crossings. In autumn, all English Channel crossings occurred at night, departing from southern England or Wales shortly after dusk (take-off hours regarding sunset hour: mean = +43 min, SD = 27 min) and reaching northern France before dawn, or very occasionally just after (landing hours regarding sunrise hour: mean = –61 min, SD = 223 min; Figure S2). Similarly, spring departures from Northern or Western France occurred just after dusk (take-off hours regarding sunset hour: mean = +56 min, SD = 50 min). While flights generally ended in southern England or Wales before dawn, a few were prolonged for a few hours past sunrise (e.g., Tree Pipits, see Figure S2, landing hours regarding sunrise hour: mean = –22 min, SD = 260 min). Channel crossings by our study species panel occurred within a rather narrow seasonal windows with most of the post-breeding flights occurring in August (except for one late Northern Wheatear and the European Nightjar which crossed in mid-September), while most of the pre-breeding flights occurred between mid-March and

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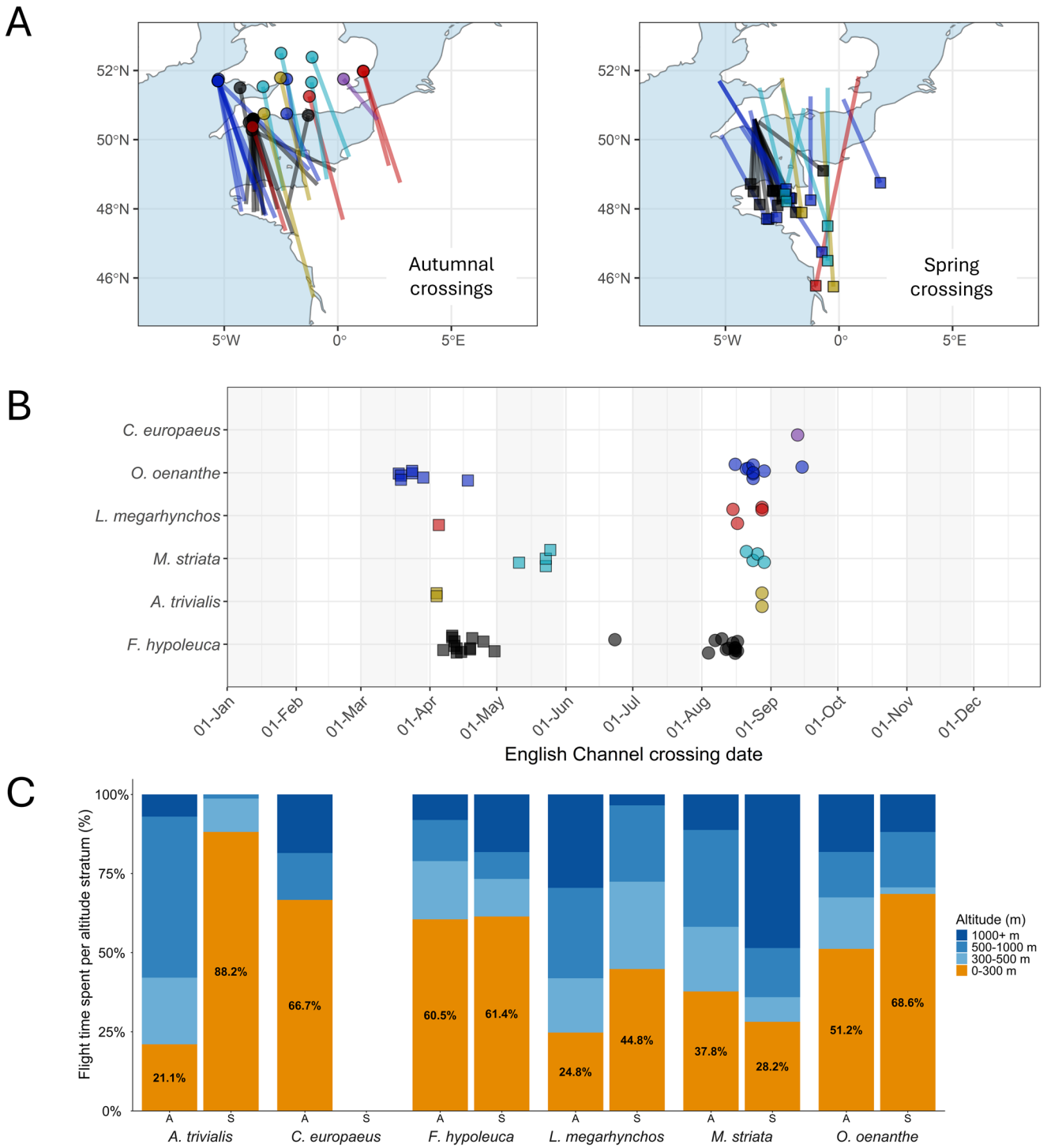

FIGURE 2 | (A) Representation of the flights across the English Channel identified in this study for post-breeding migration (left panel) and pre-breeding migration (right panel). (B) Timing distribution of the sea crossing flights (day of departure) across the English Channel. Colors correspond to species and shapes correspond to migratory periods (squares: Pre-breeding migration and circles: Post-breeding migration). (C) Proportion of marine crossing flight time by altitude stra according to season (A: autumn and S: spring) and species (see Table S2 and Figures S2 and S3 for details). Turbine rotor-swept zone altitude (i.e., below 300 m a.s.l.) is indicated in orange.

late April except for the Spotted Flycatcher (mid-May; Figure 2B). Flight altitude during sea crossings varied considerably between species, between individuals, and within flights, during both migratory periods (Figure 2C). Almost all birds spent a substantial proportion (mean = 53.3% *SD* = 27.4% across all species; Figures 2C, S2, and S3; Table S2) of their sea-crossing flights below 300 m, that is, within the height of wind turbine blades. This proportion of low altitude flight varied between species (max across both seasons: Pied Flycatcher mean = 60.9% *SD* = 26.2%; min: Common Nightingale mean = 29% *SD* = 21.1%) and seasons (autumn across all species: mean = 48.8% *SD* = 25.5%; spring across all species: mean = 59.3% *SD* = 29%; Figure S2).

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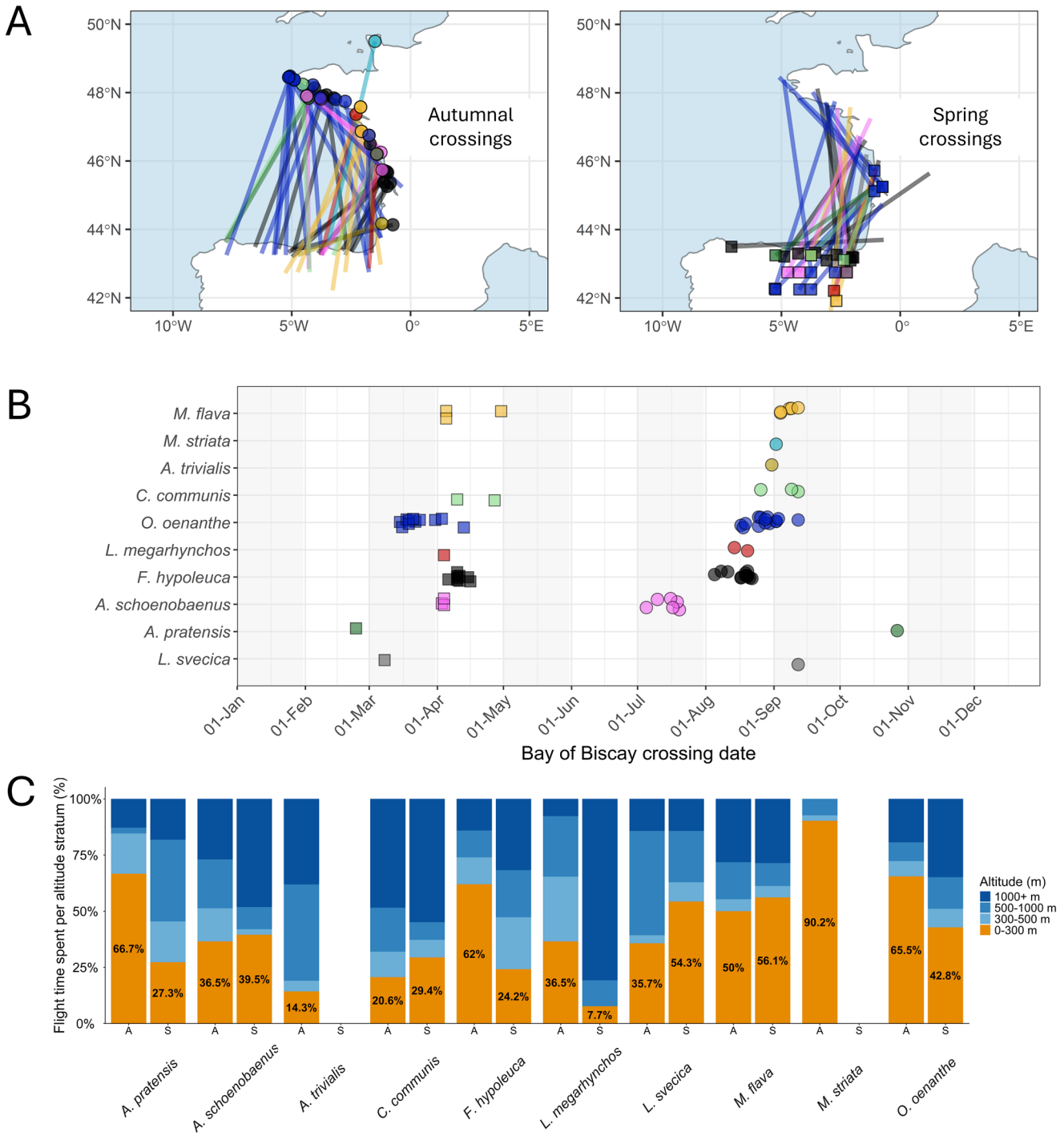

FIGURE 3 | (A) Representation of the flights across the Bay of Biscay identified in this study for post-breeding migration (left panel) and pre-breeding migration (right panel). (B) Timing distribution of the sea crossing flights (day of departure) over the Bay of Biscaye. Colors correspond to species and shapes correspond to migratory periods (squares: Pre-breeding migration and circles: Post-breeding migration). (C) Proportion of marine crossing flight time by altitude class according to season (A: autumn and S: spring) and species (see Table S2 and Figures S3 and S4 for details). Turbine rotor-swept zone altitude (i.e., below 300 m a.s.l.) is indicated in orange.

3.4 | Bay of Biscay Crossing Flight Characteristics

Although most birds tagged on the French Atlantic coast crossed the Bay of Biscay, some individuals followed the coastline instead of crossing. Forty-six flights were identified for the post-breeding (autumnal) migration period and 31 for the pre-breeding (spring) migration period (Figure 3A; Table S2). In both autumn and spring, birds generally departed after dusk (autumnal take-off hours regarding sunset hour: mean = +68 min, *SD* = 110 min; spring take-off hours regarding sunset hour: mean = +88 min, *SD* = 148 min) and crossed the Bay of Biscay within the night, landing before dawn or just after (autumnal landing hours regarding

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sunrise hour: mean = +50 min, *SD* = 166 min; spring landing hours regarding sunrise hour: mean = −29 min, *SD* = 186 min; Figure S4). The migrant Meadow Pipit was the only individual to perform mostly diurnal crossings (Figure S4). As expected, flights across the Bay of Biscay were generally longer than those across the English Channel and more frequently extended into the following day before land was reached. In both seasons, these prolonged flights often coincided with distinct altitude drops after sunrise, which consequently increased the proportion of flight time spent below 300 m a.s.l. during the day (Figures S4 and S5). Crossings of the Bay of Biscay for our species sample were concentrated between late March and late April in spring (the Meadow Pipit and the Bluethroat were earlier migrants). On the other hand, autumnal crossings of the Bay of Biscay mostly span between mid-July and mid-September except for the late migrating Meadow Pipit (late-October, Figure 3B). Similarly to crossings of the English Channel, flight heights over the Bay of Biscay largely varied between species and individuals but also within flights during both migratory periods (Figures 3C and S4). Most birds spent a substantial part (mean = 46.7% *SD* = 27.8% across all species; Table S2; Figures 3C, S3, and S4) of their sea-crossing flights below 300 m, that is, at the height of wind turbine blades. This proportion of low altitude flights varied between species (max across both seasons: Northern Wheatear mean = 61.3% *SD* = 36.8%; min: Common Nightingale mean = 21.0% *SD* = 23.8%) and seasons (autumn across all species: mean = 53.6% *SD* = 28.6%; spring across all species: mean = 36.8% *SD* = 23.6%; Table S2; Figures S3 and S4).

4 | Discussion

Our study unambiguously demonstrates that our phylogenetically and ecologically diverse panel of passerine-sized birds, consisting largely of nocturnal migrant as most small landbirds (Dufour et al. 2026), fly routinely within the rotor-swept zone (0–300 m a.s.l.) of OWF turbines (Gauld et al. 2022; Bilgili et al. during their sea crossing flights. These results provides clear evidence that small migratory birds, which represent extremely large numbers of individuals (Woodward et al. 2020), may face a substantial collision risk in OWF areas, consistent with evidence previously reported for larger species (Watson et al. 2025; Furness et al. 2013; Weiser et al. 2024; Schwemmer et al. 2023; Schwemmer et al. 2023). Using data from our large-scale deployment of multi-sensor loggers we reconstructed high-resolution altitudinal flight profiles for 65 individuals from 11 species representing five families. This dataset provided 137 sea-crossing flights over the English Channel and the Bay of Biscay, two major marine migratory ecological barriers (Figures 2 and 3). These trajectories reveal some consistent patterns in the timing, routes, and altitudes of sea crossings. For the diverse species panel we studied, most crossings occur at night, potentially reducing collision avoidance opportunity due to limited obstacle detectability, and regularly at altitudes below 300 m a.s.l. Moreover and in line with previous studies (Norevik et al. 2023; Dufour et al. 2026), we show that diurnal prolongation of long sea crossing flights is associated with clear altitude drops (Figures S2, S4, and S5), often immediately after dawn, and therefore with an increase in the proportion of low (<300 m a.s.l.) flight altitudes. The occurrence of such events in our dataset proved to be rather scarce, which is potentially linked to the equipment site locations, the width of the studied marine barriers or the ecology of the studied species. Conversely, this behavior have been shown to be more common during the crossings of larger marine barriers (e.g., the Mediterranean Sea; Dufour et al. 2026), a type of context in which it could be particularly deleterious as the daytime low altitude portion of these flights is expected to occur at the end of the crossing, closer to the coast, where flight through OWFs is more likely (Beiter et al. 2022; Dufour et al. 2026).

The implications of these findings for OWF planning and management are immediate. On a global scale, our results offer empirical and methodological foundations to refine environmental impact assessments (EIAs) and motivate the deployment of targeted mitigation strategies, such as the installation of future OWFs outside major migratory corridors when possible or the implementation of adaptive turbine shutdowns during main migration periods. Applying the approach presented here to other regions where numerous bird migrants cross marine barriers such as the Mediterranean, North Sea, Baltic Sea, Gulf of Mexico, or Gulf of Alaska could help to delineate global patterns of high collision-risk zones, as well as potential risk accumulation along flyways or migratory corridors. Integrating these insights into the planning and expansion of OWFs will be essential to ensure the conservation of small migratory birds. The combination of the fine spatio-temporal resolution of our dataset with radar-based monitoring notably opens promising avenues for predictive modeling notably to identify peak migration events. Last, while tagging diverse species at this scale remains logistically and financially demanding for standard EIAs, our results provide a practical reference to calibrate more accessible monitoring tools (e.g., radars or passive acoustic monitors), offering a flight behavior baseline that remains transferable even when direct tagging is not feasible. Integrating these insights with meteorological data and context will be essential to identify which conditions are linked with sea-crossing initiation (see Rüppel et al. 2026) or potentially associated with elevated collision risk, such as tailwinds or reduced visibility (Nilsson et al. 2019; Van Doren and Horton 2018; Aschwanden et al. 2018; Nilsson et al. 2018). Within our focal study regions of the English Channel and the Bay of Biscay, our high-resolution trajectories reveal that broad-front nocturnal migration dominates across most of the region rather than being confined to restricted, predictable corridors. Consequently, from a spatial planning perspective, our results indicate that no specific sector within these marine areas can be considered inherently "low-risk" for small night-migrating birds based on spatial avoidance alone. This widespread spatial overlap between bird flights and proposed OWF developments suggests that local EIAs in the Channel and the bay of Biscay areas should likely shift their focus from spatial zoning to fine-grained temporal mitigation. Given that most crossings occur at night and within the rotor-swept zone (0–300 m a.s.l.), effective local management in these specific basins will heavily rely on macro-scale automated curtailment (i.e., temporary turbine shutdowns). Crucially, our empirical tracking data suggests that these mitigation measures should be seasonally targeted during the key migration windows identified for the monitored species. For such strategy the considered spring passage should broadly span from March to late May, and the autumn passage from August to September (but see earlier or later short-distance migratory species). Within these seasonal periods, the precise, real-time activation of curtailment during peak migration nights

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could further be dynamically triggered using local radar-based monitoring (see Van Doren and Horton 2018) which is ideally suited to detect mass movement events under risk-prone meteorological conditions.

4.1 | Limitations and Future Developments

Despite being the only suitable method for tracking both trajectories and altitude in small bird species, our approach still has limitations. First, precise geolocation with pressure data is only possible when birds are stationary at ground level (Nussbaumer et al. 2023). Flights are then assumed to be a straight line between two consecutive stationary periods or stopovers (Nussbaumer et al. 2023), which means that reconstructed trajectories may differ from those actually used by birds (e.g., following of the coast before crossing instead of direct crossing). Furthermore, the *GeoPressureR* approach is unsuitable for aerial foragers for which stationary foraging flights are extremely difficult to distinguish from migratory flights: Despite recovering tags from Common Swifts and Barn Swallows, we were only able to use the barometric data to reconstruct migration period flights altitude without being able to pinpoint potential sea crossings. Additionally, our sampling is logically dominated by long-distance and nocturnal migrants, as this represents the predominant migratory strategy in small birds (Dufour et al. 2026; Van Doren and Horton 2018), meaning that diurnal migrants (e.g., Fringillidae, Starlings) or some short-distance or facultative migrants are underrepresented in our dataset. Consequently, the flight altitudes and timings observed here may not fully reflect the strategies of all species that cross the studied marine barriers during the day or perform shorter migratory journeys. Last, as loggers need to be recovered, they are usually deployed on adult, often male, breeders because they are more likely to return to their breeding site. The migratory strategies of individuals that do not return (either because they emigrate or do not survive), of birds that are not recaptured, and of juveniles, despite their demographic importance in small short-lived species, remain largely unknown. Future technological advances such as remote data download or the addition of pressure sensors to further miniaturized GPSs may reduce some of these constraints. Until then, intensive and coordinated deployment and recapture efforts remain essential to maximize data recovery and representativity.

5 | Conclusion

By revealing that large numbers of small migratory birds, representing a substantial species diversity, routinely cross major maritime barriers at altitudes overlapping with turbine rotor-swept zones, our study demonstrates that OWFs pose a tangible and previously underestimated risk to this group. Our findings call for a precautionary approach to offshore wind energy development that explicitly integrates passerine migration ecology into OWF planning and management. Reconciling the urgent expansion of renewable energy with the conservation of already declining migratory bird populations (Vickery et al. 2023) will require informed OWF installation, targeted mitigation and adaptive management based on improved monitoring of small-sized migrants. Studies using multi-sensor loggers should characterize the meteorological conditions at departure that promote sea crossings, as this information would be critical to define weather-based curtailment rules for offshore wind turbines. Moreover, a better assessment of collision risks and the conditions leading to them is essential. This should be achieved not only by monitoring mortality and near-collision events within OWFs, but also by gaining a more comprehensive understanding of how birds behave when encountering turbines and notably the potential behavioral differences during day and nighttime encounters. Finally, our study demonstrates that miniature multi-sensor loggers currently provide the only viable approach to track individual, three-dimensional movements in small birds at a fine scale. Finally, this method appear to behighly complementary to other monitoring tools: while systems like radars, acoustic recordings, or visual observations are non-individual-based, and others like standard VHF (e.g., MOTUS) networks lack altitudinal data, our approach fills these gaps to better assess OWF threats to passerine-sized birds.

Author Contributions

Conceptualization: PDV, FJ. Funding acquisition: PB, FJ. Fieldwork planning and conduction: PDV, IB, FB, MB, GC, YC, RD, CE, SdG, CH, KL, FR, SS, FJ. Formal analysis: PDV, PD, RN. Writing: PDV. Revision of first and subsequent versions: PDV, PB, SdG, PD, FJ. All authors contributed to and agreed for the submission of the final version of the manuscript.

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Data Availability Statement

The dataset linked to this study is available on Zenodo under the dedicated Data Package format https://doi.org/10.5281/zenodo.17631331. The code and parameter values (*config.yml* file specifying general and individual settings such as deployment sites, crop dates and map extents and resolution) linked to this study are available on GitHub at https://github.com/Doniol-Valcroze/MIGRATLANE_GLS_ANALYSIS.

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Supporting Information

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