Scanning the skies for migrants: Conservation-focused opportunities for a pan-European automated telemetry network

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Abstract

Accelerated biodiversity loss during the Anthropocene has destabilised functional links within and between ecosystems. Migratory species that cross different ecosystems on their repeated journeys between breeding and non-breeding sites are particularly sensitive to global change because they are exposed to various, often ecosystem-specific threats. As these bring both lethal and non-lethal population impacts, many migratory species are declining, making this group especially vulnerable to global change.

To mitigate their decline, research at a continental and flyway scale is required to adequately monitor changes in the demographic processes of populations and understand the needs of migratory species, during all parts of the annual cycle. The Motus Wildlife Tracking System (Motus) could provide a solution to data gaps that exist particularly for small and migratory species. Motus is an automated telemetry system for animal tracking, which originated in North America. It provides a collaborative network by using the same VHF radio frequency for all tracked individuals, in combination with an individual tag identifier. Motus can provide information on movements made by individuals of the smallest bird and bat, and even larger insect species, thus aiding our understanding of aspects of their migration that could impact demographic parameters.

Here we emphasise conservation-focused research opportunities, with a particular lense on European migrant taxa. We highlight examples from the existing network, and identify geographical gaps in the network which need to be filled to track continent-wide movements. We conclude that Motus is a useful tool to produce individual-level migration information for a variety of small-bodied taxa, and that a

drive to expand the network will improve its ability to conservation plans for such species.

Introduction

Biodiversity loss driven by land use change, exploitation of natural resources, and affected further by climatic disruption, is a defining feature of the Anthropocene (Sala et al. 2000). A decline in habitat availability and significant disruption to ecosystem structure, reducing critical services such as biomass production, pollination and pest control, has led to declines in a wide range of taxa globally (Jaureguiberry et al. 2022). The impacts of anthropogenic development do not just manifest through physical changes, i.e. habitat loss, but also through increases in zoonotic and vector-borne diseases (Jaureguiberry et al. 2022), and pest outbreaks. These impacts affect species' distributions, abundances, fitness, and consequently their ability to complete their life cycle successfully (Bellard et al. 2012).

Of particular concern are migratory species, which serve as ecological indicators and direct providers of vital contributions to ecosystem functioning, including biomass production, pollination, pest control (Bauer and Hoye 2014, Satterfield et al. 2020). Migratory species experience a variety of environmental conditions on their seasonal, sometimes trans-hemispheric journeys (Turbek et al. 2018, Zurell et al. 2018; Horton et al. 2020; Howard et al. 2020). Rapid changes in land use and configuration, throughout their annual cycle, can mean that their requirements for reproduction and survival are no longer met (Birnie-Gauvin et al. 2020, Marcacci et al. 2022, Rigal et al. 2023). There are also additional threats such as hunting (Jiguet et al. 2019), augmentation of ecological barriers (Gauld et al. 2022), as well as increasingly unpredictable climatic patterns decoupling the phenology of ecologically linked species (Iler et al. 2021, Clarke et al. 2022).

Understanding the factors impacting the population status of migratory species, i.e., the changes in vital rates that drive population growth or decline, is essential (Morrison et al. 2016). These species face challenges which directly conflict with the multi-factorial optimisation of migration, which form often inherited, integrated migration strategies (Åkesson and Helm 2020; Schmaljohann et al. 2022, Fattorini et al. 2023). Phenotypic flexibility and genetic change through heritable traits (‘micro-evolution’) can facilitate some adjustments and adaptations (Hiemer et al. 2018, Ozsanlav-Harris et al. 2024). However, many migratory species cannot respond to changes at a sufficiently rapid pace, meaning that population declines are widespread (Both et al. 2006, Wilcover & Wikelski 2008, Frick et al. 2017, Rosenberg et al. 2019, Vickery et al. 2023).

The Convention on the Conservation of Migratory Species (CMS; Resolution 12.26) highlights the need for a multi-species, flyway level perspective in terms of research into population declines (UNEP/CMS 2020, Frick et al. 2020, Marcacci et al. 2022, Chowdury et al. 2023, Vickery et al. 2023). However, gathering sufficient data from a robust number of individuals from different populations, is extremely challenging (Morrison et al. 2016; McKinnon and Love 2018). Research at a flyway scale is complicated and reliant on international collaboration (Nadal et al. 2020; Vickery et al. 2023, Serratosa et al. 2024). This is particularly the case for our smallest species, namely migratory passerines, waders and swifts, bats, and insects, whose size and behaviour have rendered them difficult to study (Wikelski et al. 2007, Fiedler 2009, Bridge et al. 2013). Infact, we are only now beginning to properly quantify the volumes of migratory insects crossing the continent (Hawkes et al. 2024), and the impact of this moving biomass is still little understood (Chapman et al. 2015).

Where are the knowledge gaps in the study of small migratory species?

Currently, we have little detailed spatial and temporal information on small bird, bat and insect migration. Broad scale migration patterns across Europe, including concentrations of both avian and insect migrants passing through marine and mountainous regions, have been identified using radar (Bruderer & Jenni 1990, Bruderer & Liechti 1999, Nilsson et al. 2019, Weisshaupt et al. 2021, Hirschhofer et al. 2024). Yet radar data, derived from echo signatures, largely do not allow us to tease out species-specific and indeed individual-level variation in large-scale movements (Schmaljohann et al. 2008, Zaugg et al. 2008), which would facilitate links to demography, physiology and ecology.

In contrast, several million individuals have been marked using metal or colour rings across Europe (Du Feu et al. 2016), contributing to our fundamental ecological knowledge of bird movements. Yet recapture, recovery, or resighting probability is often low (across 32 European level ringing schemes recovery rate for *all species combined* varied from 0.6 – 7.6%; Baillie 1995), particularly on the wintering grounds (only one of 49 Hoopoe *Upupa epops* and four of 121 Wryneck *Jynx torquilla* ringed in Europe and subsequently recovered, were found on the African continent; Reichlin et al. 2009), and highly variable amongst species and locations (Thorup et al. 2014).

Many of the disadvantages of the aforementioned methods can be addressed by tracking individuals and indeed, following their migratory movements. Flack and colleagues (2022) stress several major data-deficient migration research areas that could be filled by employing tracking, including how information on bird migration can be used to facilitate better conservation and management strategies. There are also other fundamental biological processes that would benefit from individual tracking. These include dispersal; more nomadic, non-breeding movements (Snell et al. 2018; Mckinnon et al. 2019); as well as pre- and post-breeding movements (Mukhin et al. 2005, Züst et al. 2023).

However, individual tracking of small migrants requires tracking devices weighing only 3-5 % of an individual's body weight (Barron et al. 2010), which excludes most tracking technology on the market (Figure 1; Bridge et al. 2011, McKinnon & Love 2018). Radio-tracking, however, has already reached masses of under 0.5g, and the Motus Wildlife Tracking System (hereafter Motus, Taylor et al. 2017) is producing tags equivalent to, and lower than, the weight of the smallest geolocators. Here, with Motus as a methodological basis, we focus on conservation and demographic-specific knowledge gaps in the study of small migratory birds, bats and insects.

Motus – Automated VHF tracking technology

Motus originated in Canada as a partnership between Acadia University and Birds Canada (Taylor et al. 2011, 2017), and its spread across the Americas is a great success story of collaborative research (see https://motus.org). The initiation of Motus in Europe has been later and its growth slower, but there is now a dense network of stations along the coasts of Germany and the Netherlands, and to a lesser extent in Sweden, Denmark, Belgium and the UK, with a number of additional stations in other countries, and on offshore research and energy platforms.

Motus exploits a network of passive VHF receivers (Figure 2), aligned on the same frequency, which continuously receive and record uniquely-coded signals of tagged individuals, using directional Yagi antennae, without the need for recapture

(Mitchell et al. 2015; Taylor et al. 2017; Mckinnon et al. 2019; Imlay et al. 2020). The lightest tags currently available weigh 0.13 g and have a maximum interval between pulses of 29 s, which can provide 20-22 days of data. Researchers are able to select from among a number of options and device parameters (burst interval, battery or solar power, attachment and antenna type), in line with their specific question (Figure 1). With the Motus system, it is now possible to track movements of light insects, such as the monarch butterfly (Knight et al. 2019, Wilcox et al. 2021).

Motus is already producing important insights into the movements of birds, bats, and insects. For example, Gómez et al. (2014) and Zenzal et al. (2021) revealed the intricacies of strategies of birds crossing the Gulf of Mexico; and Brunner et al. (2022) discovered several unknown aspects of migratory connectivity and ecology in the elusive Swainson's warbler *Limnothlypis swainsonii*. Studies in Europe are now beginning to understand more about the migratory and pre-migratory movements of Nathusius pipistrelles *Pipistrellus nathusii* (Bach et al. 2022, Briggs et al. 2023) and sea-crossing of thrushes (Brust et al. 2019). The existing work suggests myriad areas for future studies that would benefit greatly from using automated VHF telemetry. These examples show that Motus can be a tool to obtain a ‘holistic’ view of species’ ecology, by gathering data on groups and time periods (e.g. juvenile fledging) previously understudied (Martell et al. 2023).

How Motus can help to address knowledge gaps in migratory taxa movement

To understand population change and guide conservation measures, we need data on key population parameters, which necessarily require long-term, broad spatial scale, annual cycle data collection (Satterfield et al. 2020). Yet, funding, time, and staff resources, and the vast areas over which migration occurs, make this difficult (Lefevre and Smith 2020). A relatively low-cost, collaborative, spatially dispersed network of Motus stations can essentially create a vast open-air laboratory. Taylor et al. (2017) presented a detailed account of the benefits and opportunities of Motus, as well as areas that require further development and investment, but we address here the key strengths and challenges that we perceive in relation to pertinent conservation focused questions and in the context of other tracking devices.

Firstly, receiving stations can be placed anywhere (see Figure 2b) and be controlled remotely, and this autonomy means that data capture efforts are less limited by researcher effort, in contrast to commonly used methods such as bird ringing (Griffin et al. 2020; Flack et al. 2022). Fixed positioning of the receiving stations, along with a unrestricted recording period, also enables standardized data collection and reduces observer-bias (Griffin et al. 2020). Secondly, there is no requirement to recapture the birds to retrieve data, which can be recorded by one or more stations. In this way, Motus reduces bias encountered in studies where all information derives only from the fraction of successfully recaptured individuals (as with data loggers). Another benefit is that tracking occurs in near real time, as long as receivers are able to transfer data to the server quickly.

Lastly, the spatial scale of detections is in the order of several kilometres, rather than orders of magnitude higher as with geolocators (Taylor *et al.* 2017), although new multi-sensor tags have shown substantial improvements in positional accuracy (Nussbaumer et al. 2023). Pinpointing specific sites for targeted conservation efforts is important, given that limited, localised stopover site use could induce higher vulnerability in certain migrating species (Bayly et al. 2013; Gómez et al. 2014). Motus’ potential to help create species actions plans in this way has been recognised outside of the research community, and recommendations for its use to monitor understudied small species are included in the records from COP13 on the Convention of Migratory Species (UNEP/CMS 2020). Widespread adoption of Motus by conservation and research organisations, who may then allow others to install Motus stations on their land, could vastly improve network coverage.

Still, there are some caveats. Most Motus studies do not report a 100% detection rate; reporting rates are closer to 50-70% (Crewe et al. 2020), even when the tags are deployed close to a receiving station. Potential reasons for this are: habitat type and topography, weather conditions, characteristics of the antennae and the flight altitude and orientation of the animal in relation to the antennas of the receiver (Crewe et al. 2020). Furthermore, the network of stations is still patchy and this low spatial coverage does not yet allow continuous tracking across the continent in Europe, and is particularly sparse where data are lacking the most in eastern Europe. With this opinion paper, we hope to further spark the collaborative spirit of Motus to create a denser network in Europe and resemble the situation in North America.

Obtaining demographic information using Motus

Understanding when and where differences in population processes occur, is notoriously difficult (Doerr and Doerr 2005; Border et al. 2017, Telensky et al. 2020). Migrating species are diverse in their timing, routes, distance and speed, but most employ repeated, alternating migratory and stationary periods for resting, recovering and fuelling (Alerstam et al. 2003; Åkesson and Hedenström 2007; Schmaljohann et al. 2022). Differences among species in the location and timing of these patterns may affect how pressures accumulate and carry over, and therefore how strongly their populations are impacted by interacting environmental changes (Sawyer *et al*. 2009, Patchett *et al*. 2018, Nadal et al. 2022; Rueda-Uribe et al. 2022).

Quantifying variation in a number of different life history processes, primarily survival, mortality, emigration/ immigration (dispersal), as well as immediate behavioural responses to environmental stressors, can then direct conservation efforts for these populations and/or species (Gómez et al. 2021, DeMars et al. 2023). In the following sections, we address these different life history processes, identifying the most profitable opportunities to expand our knowledge of small species migration, using Motus.

Survival and mortality

Survival and mortality clearly affect population dynamics, altering age and sex structure (Schorcht et al. 2009), and affecting future reproduction (Saracco et al. 2008). Within migratory species, variation in survival among populations can be linked to alternative routes and their different pressures (Hewson *et al.* 2016). Pressures can create pinch points, which may lower fitness and increase mortality (Dhanjal-Adams et al. 2017), particularly those that support high numbers of ‘co-migrants’ (multiple species moving through major sites and corridors simultaneously – Cohen et al. 2021). The convergence of otherwise spatially segregated populations at single locations may also have additional consequences for disease transmission (Cohen et al. 2021).

Focusing Motus station placement at key staging areas, bottlenecks and barriers, in closely-packed ‘fence’ or ‘curtain’ formation (Figure 3) would provide ‘checkpoints’ for tagged migrants, leading to the comparison of local apparent survival rates along and among different routes for multiple populations of different species, and under a range of environmental conditions. Because of the single frequency strategy, ‘hits’ from different individuals of different species can be collated with ease to denote flyway-level site importance. Stations on either side of barriers could also provide insights into how migratory animals assess the scale of the barrier in front of them (Figures 3, 4).

If there are sufficient stations along a route (and adequate numbers of tagged individuals), then obstacles that slow down or terminate migration can be identified. Parameters derived from flights of individuals tracked with Motus such as speed, routes (Brust et al. 2019, Brunner et al. 2022; Linhart et al. 2023), can allow comparisons among individual birds, bats or insects of different populations, and those that orient across and around barriers (Woodworth et al. 2015; Brust and Hüppop 2022). Currently little is known about locations of high mortality across Europe for small migrating taxa (acknowledged by Serratosa et al. 2024, specific locational information and cause of death is limited to larger migratory species with accurate positional loggers). For migratory insects, incomplete trajectory information, including locations of stopover sites and wintering areas hinders the implementation of any conservation plans (Chowdury et al. 2021). This need should encourage us to place receiving stations at known – and suspected – locations of stopover and potential mortality (e.g. Figure 4b).

Dispersal, immigration and emigration

Juvenile and post-breeding dispersal are critical but understudied fundamental biological processes, consisting of the initial process of emigration from a breeding site, and the subsequent immigration to another the following season (Matthysen & Clobert 2012). Data are particularly needed from young individuals to assess when juveniles make decisions about breeding site settlement (Doerr and Doerr 2005; Mukhin et al. 2018). For species with discrete breeding sites restricted by habitat, some populations may display genetic structure that could increase and become inbred with further habitat loss and climate change (Day et al., 2023). Understanding how these populations are connected through immigration and emigration is important for deciding what conservation measures might be useful (Driscoll et al. 2014).

We can derive differential rates of emigration and immigration of a species of interest, among different locations (le Roux and Nocera 2021) through comprehensive tagging campaigns (ethical considerations of such projects notwithstanding – Soulsbury et al. 2020), supported by groups of Motus stations around key breeding sites. Using Motus, juvenile Blackpoll warblers (*Setophaga striata*), Kirtland’s Warbler (*Setophaga kirtlandii*) and Barn Swallow (*Hirundo rustica*), have been shown to make large exploratory movements upon fledging prior to migration (Brown and Taylor 2015, 2017; Evans 2018; Cooper and Marra 2020). Questions remain about the function of such exploratory movements (Züst et al. 2023), in particular because long-distance dispersal to new breeding sites appears to be rare overall, although potentially underestimated given the difficulty of monitoring such movements. It is unclear how this exploration may relate to range expansion and individual or species responses to climate change (Driscoll et al. 2014).

Motus can facilitate local to large scale, low effort tracking, and its ability to expand spatially and temporally beyond the capabilities of manual VHF tracking can increase the power of both juvenile fledging studies (Cox et al. 2012), and medium-long distance post-breeding dispersal (Evans et al. 2018, Hayes et al. 2024). Practical conservation decisions could benefit from understanding how far and in what direction juveniles disperse, and how individual phenotypes and condition levels (Morales et al. 2010) might lead to differential survival based on fledging strategy (Evans et al. 2020) and surrounding habitat quality (Hayes et al. 2020). Knowledge of this variation within and among species, gained by observing dispersal movements using Motus, could drive conservation measures that would facilitate population stability (Travis and Dytham 2013; Niebuhr et al. 2015, Endriss et al. 2019).

Identification of Stopover sites

We can identify the importance of stopover sites with strategic placement of Motus stations. Smetzer and King (2018) used a regional Motus network at the Gulf of Maine of the United States, and identified the use of a major staging area for Blackpoll warblers (*Setophaga striata*) and Red-eyed Vireos (*Vireo olivaceous*). The directional information collected by Motus showed that tagged individuals originated from multiple breeding populations across the North American continent, demonstrating the area’s importance to the two species nationally. Such a study could be carried out at similar areas in Europe such as in the large natural wetlands in the Bay of Biscay, and the Strait of Gibraltar (Figure 4b), and therefore could be used to focus conservation resources.

Understanding migratory decisions

Motus can facilitate a ‘quasi-experimental’ approach as proffered and demonstrated by Goymann et al. (2010) and Schmaljohann and Klinner (2020), and can extend capture-mark-recapture studies such as that undertaken by Knoblauch et al. (2021) and Menz et al. (2022), on dragonflies and moths respectively. Studies on insects have shown reliance on both celestial and sun compasses, as with birds

(Åkesson et al. 1996), and that there is significant selection of favourable winds, to facilitate their journeys over and around barriers (Menz et al. 2022).

When numerous individuals subject to the same external conditions are tracked at the same time, this may then allow estimation of conditions when most individuals migrate (Delingat et al. 2008, Schmaljohann & Klinner 2020), as well as better understanding of 'optimal' strategies (Åkesson et al. 2002, Hedenström 2008). Such fundamental understanding of migration processes can also help to prioritise important locations to target for conservation or management.

Exploring the evolution of migratory routes via vagrants

Motus could also play a role in improving our understanding of vagrants, for example how they act as potential agents of evolution of new migratory routes and/or of range expansion (Dufour et al. 2022). Their influence on population change has only been explored in a few cases, for example that of Richard's Pipit (Dufour et al. 2023). For example, small songbirds, travelling in a westerly direction from Siberian breeding grounds, and are hard to track because of their small size and distant, widespread, less accessible breeding grounds (Dufour et al. 2021). Such knowledge gaps could be addressed using Motus by detecting departure directions of vagrants. Motus can collect data on unsuccessful phenotypes, i.e. individuals that would not be recaptured anyway. Studies could investigate the fate of vagrants in the north-western parts of Europe (e.g., the UK and Republic of Ireland, Helgoland; Thorup et al. 2012), and a potential candidate for this research might be the Yellow-browed warbler (*Phylloscopus inornatus*), as suggested by Dufour et al. (2022).

Obtaining individual responses to environmental stressors

Motus studies of individuals can also address identifiable conservation concerns, and detect how animals respond to specific forms of anthropogenic or environmental disruption. Obstructions, such as wind turbines, can incur extra fitness pressure from detours, as well as direct mortality. Impacts are still largely unquantified on migratory populations of birds (Marques et al. 2021) and bats (Lagerveld et al. 2014, Bach et al. 2022, although see Serratosa et al. 2024). Motus has been used to track Nathusius pipistrelles (*Pipistrellus nathusii*) migrating along the coast and to islands (Bach et al. 2022). Using Motus in combination with acoustic monitoring (Lagerveld et al. 2023), we can localise the interaction of individuals with near- and offshore infrastructure, through careful placement of receiving stations on substations and energy platforms (Loring et al. 2019, Willmott et al. 2023).

Other anthropogenic disruptors are (agro-) chemicals such as neonicotinoids, which can impair the progress of migration (Cabrera-Cruz et al. 2020). Eng *et al.* (2019) used Motus tracking to show responses to neonicotinoid ingestion by White-crowned sparrows (*Zonotrichia leucophrys*), whereby migrating birds on stopover are severely impaired in their ability to put on fat, vital for migration, despite significantly increasing the length of stopover. In contrast, Wilcox et al. (2021) found no impairment of Monarch butterflies *Danaus Plexippus* when tracked with Motus, after being given the neonicotinoid Clothianidin.

Further, artificial light at night (ALAN) poses a potential thread for migratory birds (McLaren et al. 2018, Smith et al. 2021). From large-scale radar analyses we know that night-migratory birds are attracted to bright areas (Horton et al. 2023), where birds can be drawn into potential ecological traps (i.e., inadequate stopover sites that might present higher risk of mortality; disorientation; Van Doren et al.

2021). However, the extent of this effect on individuals has not been examined, yet, which poses a suitable question to apply Motus tracking. Similarly, anthropogenic electromagnetic radiation (“electrosmog”) has been shown to disrupt the magnetic compass of night-migratory songbirds (Engels et al. 2014). As this was observed in the lab environments with caged birds, it poses the question whether ‘electrosmog’ is also a hazard for freely moving birds in the wild. Once properly understood, appropriate mitigation and conservation can be designed and further tested to reduce the environmental impact of humans on migratory animals in the future.

Combining Motus tracking with physical samples

Motus movement data can be collected alongside physical samples (e.g., feathers, morphological measurements, blood and faeces). Such samples can help us understand links between physical condition and site quality, for example by measuring stopover time, habitat use, direction of departure, and correlating with immune function (Schmaljohann & Naef-Daenzer 2011, Hegemann et al. 2018, Brust et al. 2022). Additional genetics could be particularly valuable if information on putative origin of individuals could also be inferred (Ruegg et al. 2014), thus shedding light on the genetic architecture underlying migratory patterns in different populations (Bossu et al. 2022, Sharma et al 2023). Blood and faecal samples could be used to monitor pathogen prevalence, which can be linked to physical condition, population origin, and subsequent movement decisions (Taylor et al. 2011, Neima et al. 2020), all of which may give insights into population declines and predict responses to global climate and habitat change (Saura et al. 2014, Anderson et al. 2019).

Practical next steps: the logistics of developing Motus for flyway level research

Currently, there are vast areas across the European continent that are not yet covered by Motus, but the collaboration of researchers in North America has demonstrated that it is possible to obtain a near-continent-wide network of Motus stations. One major challenge European researchers encounter is the lack of a single frequency the tags emit the signal. Whilst in a number of European countries the frequency of 150.1 MHz is authorised either temporarily or permanently for wild animal telemetry tracking, in others only an alternative frequency is permitted. Although multi-frequency detection by Motus receivers is possible, for example introducing the licence-free frequency 434 MHz alongside the commonly used 150.1 MHz frequency in Europe, it incurs additional expense for extra equipment.

A second challenge is achieving sufficient spatial coverage by Motus stations. The progress of a continent-wide network comprised of potentially hundreds of different stakeholders across many nations is a big task and will require a strategic placement plan (Lefevre and Smith 2020), concentrating on coastlines, barriers or bottlenecks (Figures 3, 4). A complementary focus on regional-scale networks, which can feasibly be funded as part of a discrete project, is also necessary, essentially forming a dual bottom-up/ top-down approach (Taylor *et al*. 2017, Griffin et al. 2020). Regional projects could be structured in such a way that they ‘fill in’ gaps while meeting study-specific design features. Key clusters of stations could be efficiently positioned according to detection likelihood, but focusing on areas where we have little information collated (Griffin et al. 2020).

Lastly, the amount of data harvested from Motus is huge and will likely continue to grow alongside other biologging data (López-López 2016) and will require the continued development of appropriate statistical tools. Complex Bayesian modelling frameworks to appropriately analyse Motus data have been developed, and have been tested in limited circumstances, e.g., modelling movement offshore related to avian wind turbine interactions (Cranmer et al. 2017; Baldwin et al. 2018). Extending the applicability of these methods and developing integrated frameworks with multiple data types would enable researchers to make better use and further inferences about migratory parameters that can inform conservation (Gregory et al. 2023).

These challenges can only be solved in the long term, with a coordinated, international, collaborative effort. Platforms are needed to bring together multiple research groups to develop joint funding applications and to work together for the benefit of the wider Motus community. This community must contain academics, policymakers, government officials, and conservationists, who can develop well-defined, focused study objectives. The involvement of a diverse number of stakeholders, not just to share the cost burden and coordination responsibilities, but also to ensure fair data sharing, and the direct integration of such data into policy and conservation actions (UNEP 2020, Gregory et al. 2023; Guilherme et al. 2023).

Final Outlook

In this time of transformation and ecosystem disruption globally, it is vital to work collaboratively to conserve migratory species efficiently. We need to work at the right scale to answer questions about how species are confronting environmental changes. Motus can provide data at a local, regional and intercontinental scale, on the movements of our smallest bird, bat, and even some insect species, without the need for recapture. With such data we can address conservation-relevant questions to fill the corresponding gaps in knowledge so that effective conservation measures can be more precisely formulated for the species in focus. Motus' features and capabilities make it an attractive and exciting prospect for exploring as yet unanswered ecological, evolutionary, and behavioural questions.

There is a significant amount of logistical and planning work to develop and grow the network to reach its full potential in terms of basic and applied science, but effort to grow the network, expand the collaboration between the involved parties and realize the thereout developed conservation strategies will result in benefits for birds, nature as a whole and ultimately, us as humans.

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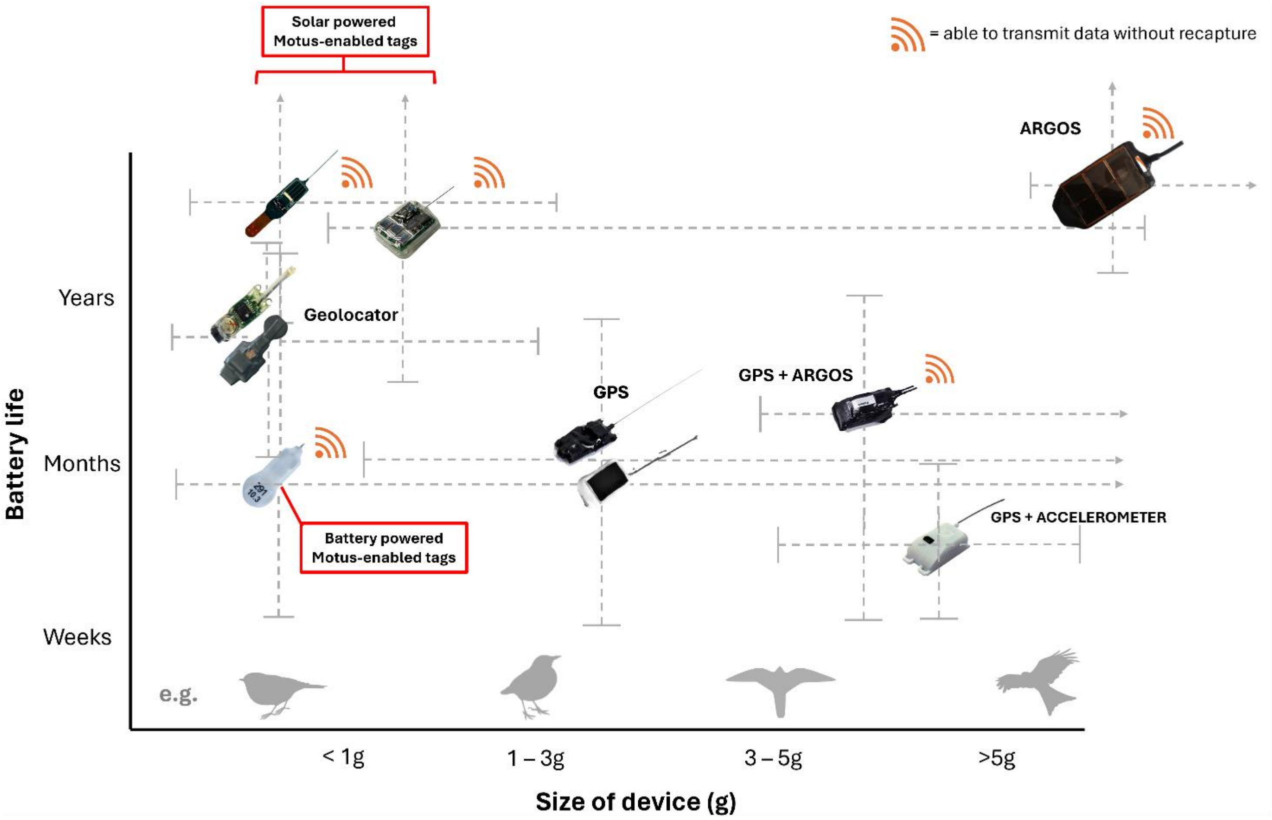

Figure 1: Capability and context of tags enabled for Motus. Icons indicate tag types and are positioned approximately in relation to their mean battery lifetime and size. Grey dotted lines represent variation on both axes taking into account programming influence on battery life and differences among and between device types. Orange ‘wifi’ symbols represent transmission capability.

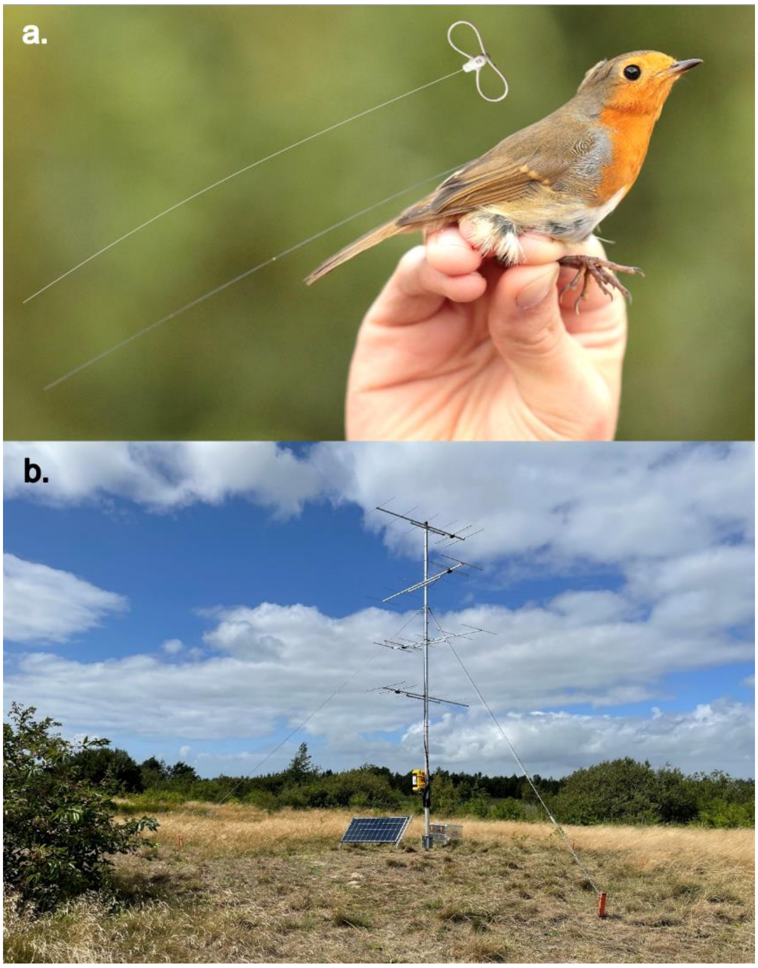

Figure 2a. European Robin (*Erithacus rubecula*) with attached radio transmitter with radio transmitter and attached leg-loop harness illustratively shown above the bird; b. a Motus receiving station (6m height), with 4 six-element-Yagi antennas pointing in four directions. The station is powered by solar, with a buffer battery (in aluminium box on ground). The electronics are installed in the small yellow box at the pole. Detailed information about tagging animals and building stations can be found at the Motus Webpage (motus.org/resources/) and from the regional Motus coordinators (motus.org/groups/regional-coordination-groups/). Photos: T.K.

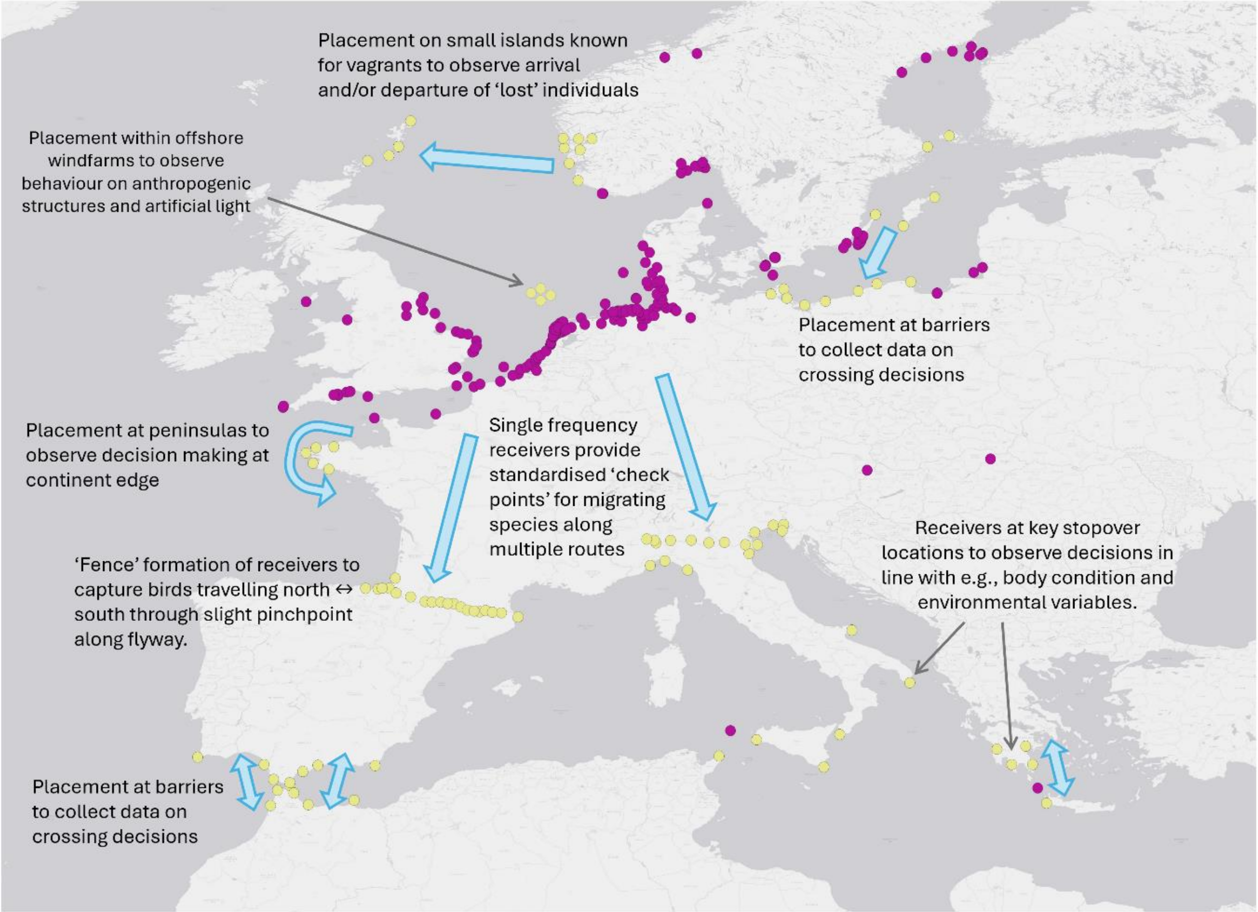

Figure 3: Current Motus receiving station network (purple dots) across the European continent, along with hypothetical future stations (yellow dots) to demonstrate potential to answer demographic and conservation-focused questions about bird migration. Blue arrows highlight flyways and movements of particular study interest.

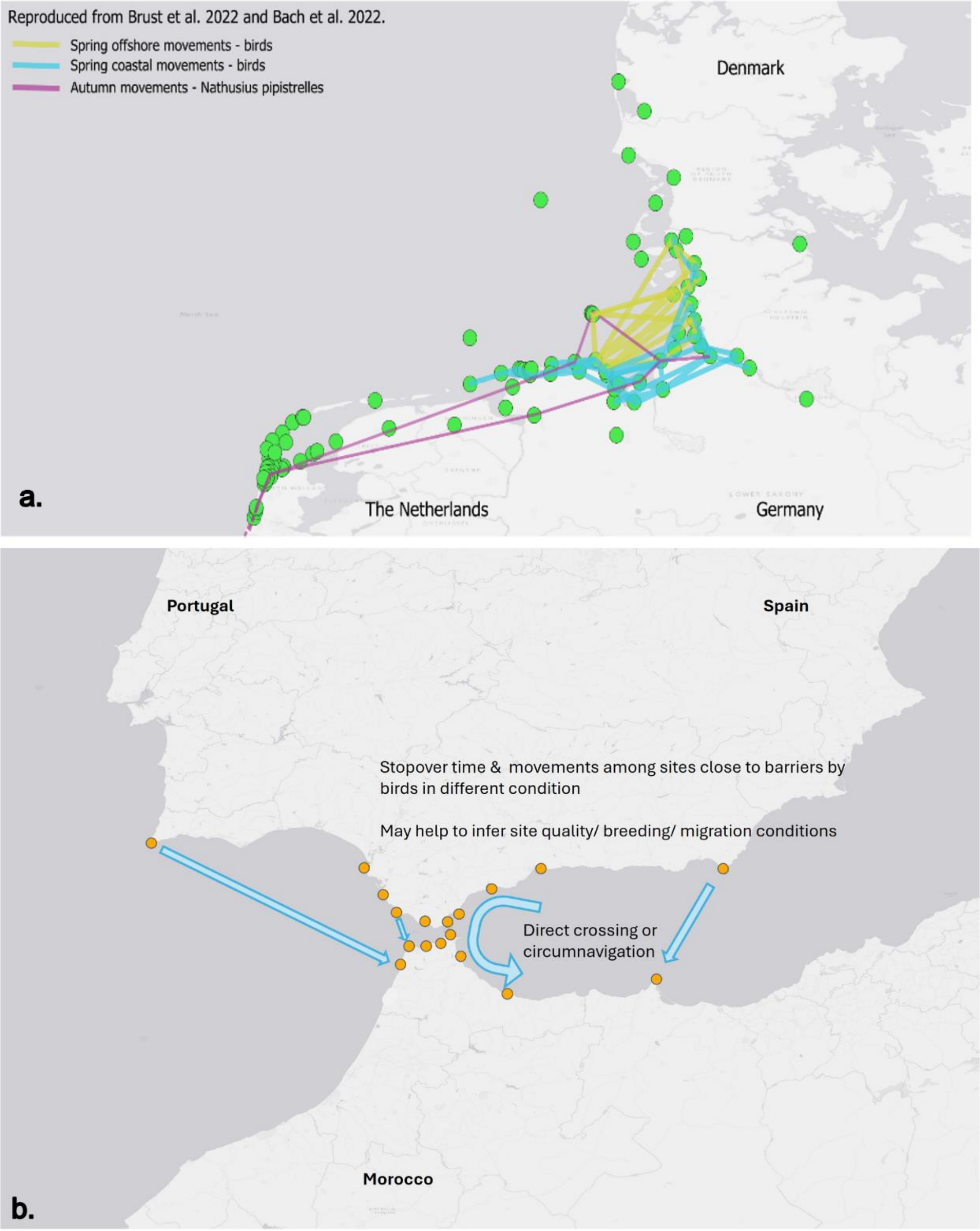

Figure 4: Studying behaviour of migrating animals at barriers; a: currently operational receiving stations (green dots) along the North Sea coast, and examples of tracks collected from birds and bats; b: examples of potential station placement (yellow dots) and data collection at Gibraltar, Iberian peninsula, where many thousands of migratory species will cross an important migratory barrier, the Mediterranean Sea. Blue arrows exemplify expected flight paths that could be detected by the set-up.