

Opportunities and challenges for new technologies in seabird population monitoring

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Abstract

Monitoring of seabird population size and demography has for decades relied on observer-based methods. While such methods have allowed the accumulation of extensive, standardized time series, while typically involving both volunteer and professional observers, they often suffer from uneven coverage across species and locations, as well as limited replicability. Technological advances, in the form of, for example, visual and/or thermal imagery collected either by permanently situated automated cameras or remote-sensing technology, acoustic data loggers, or automated presence/absence biotelemetry systems, show great potential for overcoming the limitations of observer-based methods and extending coverage of monitoring programmes to more difficult circumstances and species. However, there are challenges and risks associated with the introduction of technology-based monitoring such as initial costs, data storage, post-processing of the large amounts of data, and potential alienation of experienced fieldworkers. We review the issues that agencies responsible for seabird monitoring should consider before introducing technology-based monitoring to complement existing methods, and we provide a set of recommendations and potential future research directions.

Keywords: seabirds; monitoring; technology

Background—the need to monitor seabirds

Seabirds are among the most threatened groups of birds globally (Croxall et al. 2012), with an estimated mean 70% decline in population size over the period 1950–2010 across monitored populations (Paleczny et al. 2015). Collectively, they are exposed to many different threats, the most widespread being predation from invasive species, bycatch in fisheries, and climate-mediated changes, including extreme weather events and changes to bottom-up processes that affect primary productivity (Dias et al. 2019, OSPAR 2023). Moreover, marine ecosystems are under increasing pressure from human activities (Halpern et al. 2008). Many seabird species are relatively easy to observe (though some challenges are discussed below) and their behaviour and demographic performance are strongly affected by prey availability (Montevecchi 1993, Par-

sons et al. 2008). Therefore, seabirds are often used as indicators of marine ecosystem health (Lescroël et al. 2016). Seabird monitoring also contributes to holistic assessments of marine ecosystems at regional scales (Dierschke et al. 2022, Frederiksen et al. 2022, OSPAR 2023, Thompson et al. 2024). Thus, there is a need for consistent, replicable, and affordable methods for monitoring seabird populations, both to understand their status and to enable large-scale inferences on ecosystem state (Cairns 1987, Piatt et al. 2007, Brisson-Curadeau et al. 2017).

Current approaches

While many single seabird populations have been monitored for many decades using a variety of approaches, the first stan-

dardized large-scale, cross-species surveys were established in the 1980s in Britain and Ireland through the Seabird Monitoring Programme (Tasker 2000). This programme served as inspiration for many other countries and regions which, over the next decades, developed their own monitoring schemes such as the Canadian Seabird Colony Monitoring Programme (Gaston *et al.* 2009) and the Norwegian SEAPOP (Anker-Nilssen *et al.* 2015). Consequently, to a large extent, monitoring of seabird populations and their demography follows procedures established more than 40 years ago (Walsh *et al.* 1995). Population size, breeding productivity and annual survival have generally been monitored using direct visual observations (but see below for passive integrated transponders), using the skills of volunteers as well as professional field-workers. Although visual-based methodologies often require labour-intensive fieldwork, they typically involve relatively little post-processing, making it feasible to produce annual updates of population size and demography even when using field personnel with limited analytical training.

Despite their widespread success, there are drawbacks to the observer-based methods widely used in seabird monitoring (Mitchell and Parsons 2007). Sources of observer bias are often unknown and challenging to identify in field observations, which can make data and subsequent inference non-comparable and therefore challenging (or impossible) to scale up to broader temporal or spatial scales (Schmidt *et al.* 2023). An inherent issue with observer-based data is also that they are difficult to document systematically and can have limited reproducibility, although programme-specific protocols have been developed to attempt to address this issue (e.g. the SMP Handbook; Walsh *et al.* 1995). Finally, given the labour-intensive nature of these methods, sample sizes are generally small, which can lead to imprecise estimates and/or estimates that are only representative of a small area or are based on brief snapshots of observations (Sims *et al.* 2006).

Another issue is that some species are more challenging to monitor due to limited accessibility of their habitats (e.g. remote offshore islands) and/or the type of nesting site (e.g. burrow/crevice nesters). This can lead to a bias in the species included in an ecosystem-based monitoring programme and, thus, contribute to reduced representativity. Furthermore, a lack of trained volunteers or funds for employing professional staff have limited the implementation of seabird monitoring in low-income countries, resulting in strong biases in our understanding of worldwide variation in seabird population trends (Paleczny *et al.* 2015).

New approaches

Recently, technological advances have led to the development of a range of increasingly automated, and often also autonomous, monitoring systems, some of which have been tested in seabird colonies (Hentati-Sundberg *et al.* 2025). These systems include passive or intelligent sensors as well as automated pipelines for data collection, storage and processing. A non-exhaustive overview of examples of such systems being used in seabird monitoring is briefly described here.

Time-lapse photography of cliff-nesting seabirds is increasingly used to measure phenology and breeding success (Merkel *et al.* 2016, Black 2018, De Pascalis *et al.* 2018, Edney *et al.* 2025) and motion-triggered cameras have been employed to re-sight colour-ringed individuals for survival studies and to identify nest predation events (Brides *et al.* 2018,

Johnston *et al.* 2020). Specifically, in-nest cameras (e.g. Hereward *et al.* 2021) are useful for monitoring of burrow-nesting species. Surveys using uncrewed aerial vehicles (UAVs) can reach, and so collect data from, remote colonies that are difficult or impossible to access for observer-based methodologies, e.g. sea stacks, steep-sided cliffs, and extensive areas of a flat or inhospitable terrain (Rush *et al.* 2018, Dunn *et al.* 2021, Edney *et al.* 2023). Data from UAVs can be used to measure breeding success and phenology as well as estimate numbers and distributions of birds present (Edney and Wood 2021), ground-nesting and cliff-nesting species for example, but also have the potential to collect data on other biological parameters such as body size and occurrence of disease outbreaks (Tyn dall *et al.* 2024, Stone and Davis 2025). Cameras equipped with thermal imaging capabilities can improve detectability of cryptic and burrow-nesting species, as well as nests that may be difficult to see in visible imagery due to vegetation or terrain (Lee *et al.* 2019, McKellar *et al.* 2021). Satellite imagery is being adopted for population estimation of ground-nesting species (Hughes *et al.* 2011, Fretwell *et al.* 2012, 2017, 2021, Larue *et al.* 2024, but see Attard *et al.* 2025), while acoustic monitoring has been used for counting burrow-nesting species (Buxton *et al.* 2013, Borker *et al.* 2014, Oppel *et al.* 2014). Biotelemetry systems that provide presence/absence information can provide data to parameterize key demographic metrics including survival and dispersal, both of which are major knowledge gaps in seabird ecology, particularly for pre-breeding age classes (Frankish *et al.* 2021, O'Hanlon *et al.* 2021, Yanco *et al.* 2025). Some of these systems have been used for decades, e.g. RFID PIT tags/transponders (Le Bohec *et al.* 2007, Dehnhard *et al.* 2014, Horswill *et al.* 2014) and radio-tracking (Kissling *et al.* 2015). However, recent advances in automation, through large networks of coordinated receivers and uniquely digitally coded transmitters (e.g. the Motus Wildlife Tracking System: Taylor *et al.* 2017; ATLAS: Beardsworth *et al.* 2022; Sigfox: Wild *et al.* 2023; Icarus: Krongdorff *et al.* 2022), have the potential to enhance data gleaned from ringing, as well as overcoming the limitations and biases associated with observer-based methods. In addition to biotelemetry's primary aim of improving our understanding of animal movement, these emerging technologies can gather information on other data types to provide key insights into causes of changes in population sizes and the demographic rates underlying them (Rishworth *et al.* 2014)).

Such non-observer-based methods allow for repeated measurements with potentially reduced (time and monetary) investment after the initial setup phase. They also enable more standardized data collection and processing, as well as monitoring of otherwise difficult-to-monitor species (e.g. cavity- and burrow-nesters) or locations. The data collected by these technology-based methods may also be easier to standardize, since images, recordings etc. can be collected automatically at precise schedules, frequencies, and/or locations. Furthermore, methods that do not depend on observer availability can also optimize timing of data collection, which can be an issue when there is annual variability in breeding phenology and if the timing of fieldwork at colonies is inflexible or must be planned far in advance.

Nevertheless, there are also several challenges in the use of technological approaches, such as the costs of equipment as well as data storage and processing. The collection of very large datasets requires development of algorithms for advanced and time-consuming post-processing. This has natu-

rally led to a growing number of studies developing machine-learning algorithms, for example to identify individual birds or nests in images and videos (e.g. Descamps et al. 2011, Williams and DeLeon 2020, Jenkins et al. 2024).

Aim

Although many relevant issues thus have been discussed in the literature, a general overview of opportunities and challenges associated with new technologies in monitoring was lacking. To address this, we held a workshop on 'How can technology enhance seabird monitoring programmes?' at the 16th International Seabird Group Conference in Coimbra, Portugal, on 2 September 2024. In this paper, based on discussions at the workshop, we aim to provide a brief assessment of the potential use of new technologies in standardized colony-based seabird monitoring programmes (see the examples in Table 1). Through four focussed questions and a series of examples, we outline the opportunities and challenges associated with these technologies. Our approach is conceptual, and we do not review the suitability of specific technological developments with respect to monitoring seabird demography in detail. Instead, we provide recommendations for how organizations in charge of seabird monitoring programmes may assess whether specific technologies should be added to their toolbox and how to implement them.

What are the benefits of introducing technology-based methods in seabird monitoring programmes?

The expected benefits of integrating new technologies into seabird monitoring can be grouped into two main categories: (1) monitoring of parameters that have been challenging to measure until now and (2) more efficient, less disturbing, and more precise measurements of commonly recorded parameters leading to improved comparability and more comprehensive coverage. Focusing on the latter aspect, technology can allow for scaling up of data collection, enabling more comparable measures between sites. In addition to facilitating more regular and standardized monitoring in existing schemes, technologies can allow us to monitor populations for which it was not possible using observer-based approaches. For example, autonomous recorders could allow monitoring to be extended to situations that previously have been difficult to monitor, such as species which are highly challenging to count visually (e.g. they nest underground, are nocturnal or highly cryptic).

The use of technologies such as UAVs or autonomous recorders can also minimize human disturbance while maximizing data acquisition (Edney et al. 2025). In regions where both volunteers and professional observers are in short supply, a reduced team of observers may deploy recorders in a single visit and return several weeks or months later to collect the data. At the same time, observer disturbance of target birds could be reduced to the time when technologies are deployed (and retrieved if needed) compared to when multiple days, weeks or months of disturbance may be required for observer-based methods. Additionally, the training of personnel for setting up equipment can be less intensive than training an observer to, for example, count a population with high accuracy while minimizing disturbance.

Autonomous detectors can also yield monitoring data that are more standardized (provided open-source algorithms are used to process raw data) and with reduced error or bias compared to observer-based methods (DeLeon et al. 2023, Brusa et al. 2024). While observer-based methods focus on techniques to minimize observer bias, technology-based methods have largely overcome this problem and should rather focus on how to obtain a (statistically) representative design of the observed systems. Raw data could also be stored indefinitely for potential future re-analysis using updated algorithms or for other research purposes. Thirdly, directly transmitted data from autonomous recorders might allow for near real-time assessment of e.g. feeding rates as a proxy of prey availability, as well as increased opportunities for public engagement (Hentati-Sundberg et al. 2023, Purdie 2024, Edney et al. 2025).

What challenges do seabird monitoring programmes encounter when introducing new technologies?

Important challenges associated with the introduction of technology-based monitoring techniques include maturity of specific techniques, data storage requirements, skills and competences as well as financial costs. Innovation in the use of technology has often arisen from the research community, where the focus has largely been around addressing a specific question(s), with less attention to how such methods could be rolled out as monitoring tools. Deciding when a technology is mature or cost-effective enough to deploy on a wider scale is not straightforward, particularly if the variable in question is already covered by observer-based methods. Should new methods supersede or complement previously more common, observer-based methods? Another consideration is to what extent observer-based methods should still rely on volunteers to ensure continuous/future engagement and awareness for the target species through wider participation (<https://conservationvolunteers.com.au/positive-impacts-of-citizen-science-for-conservation/>). International coordination of data collection will be important, as monitoring parameters should ideally be comparable across national borders to the greatest possible extent (although total comparability is likely not feasible). This is particularly important when combining data from multiple countries to derive indices or other measures of the status of seabirds at a larger regional scale. Other challenges relate to the associated vast increase in data storage and data management requirements, which depends on long-term funding sources (La Sorte et al. 2018). Finally, the costs of developing algorithms to efficiently process the large amounts of data are often underestimated, and there is a risk of an accumulation of unprocessed raw data.

The transition from more traditional observer-based monitoring to implementation of new technologies will also entail a major shift in the required competences of personnel, e.g. related to sensor technology, device deployment on birds, databases, programming and large-scale monitoring design. Implementing a new technology and using it to collect data in the field along with the subsequent processing of those data are two key steps that require quite different skills. In other words, substantial data are being collected with new technologies, at least in some cases, before open-source approaches for processing and incorporating these data are available and implemented in monitoring programmes.

Table 1. Examples of new technologies and their associated benefits, risks, barriers to adoption, and requirements for standardization

Method	Approach, and key variables monitored (<i>in italics</i>)	Additional benefits	Risks	Main challenges and barriers	Requirements for standardization
Fixed cameras	Time-lapse and motion-triggered cameras. Autonomous devices record photos of study plots or single nests at fixed intervals.	Minimizes observer disturbance. Within- or between-day variation in numbers present allows calibration of, for example, UAV-based total counts.	Analytical lag. Equipment failure resulting in years without data. Potential bias in site selection.	Power supply (battery or solar). Devices (memory card) often need to be retrieved at end of season. Post-processing of large datasets can be time-consuming and often require development of AI methods.	Best practice guidelines on the design of studies, incl. camera set-up, sampling frequency, etc.
Satellite imagery		Satellite-based imagery is used to estimate the population size of ground-nesting seabird species by acquiring high-resolution images of colonies from space.	Enables monitoring of colonies in remote or difficult-to-access areas. Large-scale, efficient monitoring can assist in mapping large-scale population trends.	High cost of satellite data, particularly for high-frequency monitoring. Potential for data gaps due to weather or satellite scheduling issues. Misinterpretation of data in challenging environments.	Cost and availability of high-resolution satellite imagery. Requires clear skies and good weather conditions for accurate imaging. Temporal and spatial resolution may not capture small species, small colonies or changes in population size immediately. Post-processing of large datasets can be time-consuming.
Bioacoustic recording			Autonomous devices record sound in colonies, and species-specific calls are identified subsequently.	Records all species present. Detection of nuisance species, e.g. non-native mammals.	Device failure. Analytical lag. The power of a device to detect species' calls may vary with environmental conditions and other factors. Time to process audio data (potentially including the development of new classifiers).

Table 1. Continued

Method	Approach, and key variables monitored (<i>in italics</i>)	Additional benefits	Risks	Main challenges and barriers	Requirements for standardization
Biotelemetry	Tags deployed on birds provide presence/absence information of individuals, thus collection of data on spatially explicit demographic metrics. <i>Survival</i> <i>Dispersal</i> <i>Phenology</i> <i>Breeding propensity</i>	Information on 'missing years'. (fledging to adult) Year-round spatially explicit monitoring. Bird movements (away from the colony) depending on the availability/location of infrastructure.	Possible tag effects on bird behaviour and demographic rates. Small sample sizes that may not be representative of the wider population. Bias towards high-income countries due to cost.	Size of tags restricting their use on smaller species. Long-term attachment methods and welfare considerations. Refinement of logger attachment methods and training. Data storage, incl. choice of repositories. Cost and maintenance of infrastructure.	Best practice guidelines for the design and implementation of tagging studies, incl. monitoring and reporting for possible device effects.
Thermal imaging	Handheld, fixed, or UAV-mounted thermal sensors record infrared photos. <i>Occurrence and abundance</i> <i>Distribution and activity</i> <i>Monitoring of disease outbreaks</i>	Useful for: <ul style="list-style-type: none">cryptic speciesdifficult vegetation and terrainadverse weather conditions, e.g. low light and visibility.night-based monitoringreduced background noise for easier AI-automated detection (single-band imagery)diseased or dead birds can be identified by temperaturedetection of mortalities	Lag of standardized postprocessing workflows. Possible disturbance from somewhat close approach due to coarse sensor resolution. Other heat sources, e.g. anthropogenic or natural thermal vents and reflective surfaces.	Requires relatively low ambient temperature, lower than the research object. Post-processing workflow and data conversions can be cumbersome. General coarse resolution (640 × 480) limits the useful operating range. However, fast evolving technology with more powerful sensors on the way (1280 × 1024).	Calibration of sensors and exploration of the effect of different types. Additional analysis of differentiation between species, life stages (chicks and adults) and activities (e.g. breeding and non-breeding).

Rapid developments in artificial intelligence (AI), like machine-learning algorithms, will likely contribute profoundly to more standardized and rapid processing in the coming years. For example, machine learning algorithms have been used to accurately identify and count seabirds in images, much faster than manual image analysis by a human (Hayes *et al.* 2021, Kellenberger *et al.* 2021). Building such algorithms requires appropriate computer infrastructure and often large training datasets, although volunteers already involved in seabird monitoring could be trained to annotate images to reduce researcher workload. Machine-learning algorithms might also be viewed as a ‘black box’ by ecologists, who may be able to use an existing algorithm, but do not have the necessary expertise to re-train and refine a model if the algorithm needs re-training, for example, to improve accuracy on images captured of a new species and/or at a new location. Agencies responsible for seabird management should therefore actively encourage collaboration between ecologists and data scientists to develop suitable algorithms and software in order to streamline development and improve efficiency.

Initial and longer-term maintenance costs of employing new technologies can be high (Tuia *et al.* 2022). These financial outlays include not just equipment purchase but also, for example, software and the training of the people using the equipment. Furthermore, depending on the specific technology and location, there may be a need for installing receiver stations, new power sources such as photovoltaics, and cabling and data transmission infrastructure (Hentati-Sundberg *et al.* 2023). Overall costs are thus often higher than expected and careful budgeting is crucial. In some countries, legal requirements may be a limitation to the deployment of some technologies (e.g. licenses to fly UAVs or deploy tags on birds). Some new technologies involve commercially developed equipment, and in such cases built-in proprietary software may prevent or at least hamper standardization of data processing pipelines, e.g. for digital aerial cameras used to count birds or cameras with built-in capacity for individual bird recognition.

What needs to be done to align and standardize data collection?

It is critical that the integrity and continuity of existing monitoring time series are not compromised when new technologies are implemented (Lavers *et al.* 2019). Old and new methods should therefore be run concurrently, at least at a subset of sites for several years, to allow comparability of old and new methods and ensure a smooth transition and limit risking the integrity of long-term time series (Freeman *et al.* 2007). This could also provide opportunities for upskilling of volunteers or professional fieldworkers, so that their experience is not lost. Development of, for example, conversion factors (Rodway *et al.* 2024) between old and new methods could also mean that a two-level approach with more and less intensively monitored sites—as currently used in some monitoring programmes—could be maintained. Furthermore, the application of new technological approaches should be accompanied by standardized protocols of data storage and processing, following the FAIR data principles (findability, accessibility, interoperability, and reusability), to maximize comparability of data, particularly when upscaling to larger spatial scales. There is a strong need for development of standardized protocols for employing new technologies, as well as for

data processing. The existing seabird monitoring handbook for Britain and Ireland (Walsh *et al.* 1995) is due to be revised, and the new version will include protocols for some new technologies. Developing an internationally applicable version of this handbook should be seen as a priority. Careful consideration is also needed around the extent to which existing databases can be adapted to facilitate entry of data collected by new technologies, or whether entirely new databases will have to be designed and built to accommodate such data. Again, the challenges of the two monitoring approaches differ, as observer-based methods are largely centred on minimizing observer bias while technology-based methods need to ensure representative and statistically sound study designs that answer the monitoring goals and associated study questions.

What are the risks of using new technology?

The likely main risk of applying new technology is a too abrupt transition from the established to the new approach. This can lead to several negative consequences, including interruption of existing time series, alienation of fieldworkers who may feel left out, overwhelmed, or undervalued, as well as a weakened connection between fieldworkers and data analysts/modellers. Maintaining traditional approaches at some sites, to ensure intercalibration, may be an opportunity to keep long-standing fieldworkers involved. Furthermore, if proper intercalibration of old and new technologies is not done, spurious trends in monitoring variables may result at a time when evidence-based conservation is more critical than ever. As new technologies gain more traction, it is increasingly important to document by which method each data point was gathered, as some fieldworkers might choose the method they subjectively find the best for each case, and deliver results based on multiple different methods. An additional risk is that new technologies, due to their high initial and in some cases running costs, may contribute to, rather than reduce, the existing imbalances between seabird monitoring in high-income and low-income countries.

Conclusions and recommendations

- (1) The introduction of new technologies in seabird monitoring programmes should be carefully planned and budgeted, with a particular focus on identifying medium- to long-term funding. Resources should be allocated in such a way that major national or global data gaps are prioritized. This could take into account any gaps in existing knowledge related to key demographic parameters (e.g. immature/juvenile survival or dispersal rates), species (e.g. those which are hard to monitor due to their breeding ecology), or spatial coverage (e.g. habitats or regions that are poorly covered).
- (2) Data storage infrastructure should be in place from the start, and resources should be allocated for long-term data management, post-processing, and analysis. Availability of data for sharing should be secured according to the FAIR principles.
- (3) Specific technologies should only be incorporated into monitoring programmes once they are sufficiently mature and standardized.
- (4) Both observer-based and new, more technology-focused methods should run concurrently at some sites to ensure

that resulting data are complementary and that old and new approaches are properly inter-calibrated.

(5) Volunteer and professional fieldworkers should be involved in decision-making on the implementation and use of new technologies and, whenever possible, they should be encouraged and receive training to take up these technologies. There will be sites and species that would benefit from the implementation of new technologies; however, where sites are currently monitored, they should be encouraged to retain the use of observer-based methods recognizing the added value of having people on the ground for validation and in terms of knowledge of the site and species of interest.

(6) An international manual of traditional and new seabird monitoring methods should be developed and—as far as possible—methods used should be standardized among countries. Existing international working groups (e.g. OSPAR/HELCOM/ICES Joint Working Group on Marine Birds, Circumpolar Seabird Expert Group) could play a part in encouraging standardization and collaboration.

Potential research directions

Emerging technologies have the potential to greatly increase our knowledge of seabird ecology beyond traditional metrics that have been captured by observer-based surveys and ringing effort. As these technologies become more integrated into seabird monitoring, research should focus on their potential to transform demographic and behavioural studies via cross-disciplinary initiatives and data integration. For instance, this could involve adoption of AI-based data processing of imagery, audio and thermal data to extract fine-scale demographic metrics such as chick provisioning rates. Technologies have the huge advantage of providing year-round data, which is especially advantageous for asynchronous breeders where in-person monitoring is challenging. The combination of demographic and movement data is also critical to understanding the impacts of the full range of pressures experienced on seabirds throughout their annual cycle and the likely impacts, from individuals to populations (O'Hanlon et al. 2023).

New research should also focus on validation of proxies of ecological drivers, e.g. using time-lapse imagery to infer prey availability, where climate proxies are currently often used, or disease outbreaks. Furthermore, coupling different sensor-types, e.g. UAVs with both thermal cameras and acoustics, can enable simultaneous monitoring of multiple species and/or nesting types in previously inaccessible habitats. Biotelemetry and tracking will benefit from continued miniaturization and reduced cost, meaning longer deployments and finer spatio-temporal resolution should allow us to study the non-breeding life stages and population connectivity in more detail. Integrating several data streams into cloud-based platforms will provide opportunities for adaptive monitoring frameworks and early-warning systems. Open-data platforms can also enable greater participatory science, particularly in currently under-monitored areas, contributing to more equitable science. At the same time, automation should also be balanced with fieldworker engagement and involve the co-development of open-source tools and protocols for transparent and standardized monitoring.

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