BEST PRACTICES FOR USING DRONES IN SEABIRD MONITORING AND RESEARCH

ALICE J. EDNEY[1], TOM HART[2], MARK J. JESSOPP[3,4], ALEX BANKS[5], LUCY E. CLARKE[6], LAURE CUGNIÈRE[2],
KYLE H. ELLIOT[7], IGNACIO JUAREZ MARTINEZ[1], ALEXANDRA KILCOYNE[8], MATTHEW MURPHY[9],
RUEDI G. NAGER[10], NORMAN RATCLIFFE[11], DANIELLE L. THOMPSON[12], ROBIN M. WARD[13] & MATT J. WOOD[6]

[1]Department of Biology, University of Oxford, Oxford, Oxfordshire OX1 3SZ, United Kingdom (alice.edney@biology.ox.ac.uk)
[2]Oxford Brookes University, Gypsy Lane, Headington, Oxford, Oxfordshire OX3 0BP, United Kingdom
[3]School of Biological, Earth & Environmental Sciences, University College Cork, Cork T23 N73K, Ireland
[4]MaREI Centre, Environmental Research Institute, University College Cork, Ringaskiddy, Cork P43 C573, Ireland
[5]Natural England, Exeter, Devon EX1 1QA, United Kingdom
[6]School of Natural and Social Sciences, University of Gloucestershire, Cheltenham, Gloucestershire GL50 4AT, United Kingdom
[7]Department of Natural Resource Sciences, McGill University, Montreal, Quebec, H9X 3V9 Canada
[8]Natural England, Leeds, West Yorkshire LS11 9AT, United Kingdom
[9]Natural Resources Wales, Bangor, Gwynedd LL57 2DW, United Kingdom
[10]Institute of Biodiversity, Animal Health and Comparative Medicine, University of Glasgow, Glasgow, Lanarkshire G12 8QQ, United Kingdom
[11]Biological Sciences Division, British Antarctic Survey, Cambridge, Cambridgeshire CB3 0ET, United Kingdom
[12]University of Aberdeen, Aberdeen, Aberdeenshire AB24 3FX, United Kingdom
[13]NIRAS UK, Cambridge, Cambridgeshire CB3 0AJ, United Kingdom

Received 23 March 2023, accepted 23 June 2023

ABSTRACT

EDNEY, A.J., HART, T., JESSOPP, M.J., BANKS, A., CLARKE, L.E., CUGNIÈRE, L., ELLIOT, K.H., JUAREZ MARTINEZ, I., KILCOYNE, A., MURPHY, M., NAGER, R.G., RATCLIFFE, N., THOMPSON, D.L., WARD, R.M. & WOOD, M.J. 2023. Best practices for using drones in seabird monitoring and research. *Marine Ornithology* 51: 265–280.

Over the past decade, drones have become increasingly popular in environmental biology and have been used to study wildlife on all continents. Drones have become of global importance for surveying breeding seabirds by providing opportunities to transform monitoring techniques and allow new research on some of the most threatened birds. However, such fast-changing and increasingly available technology presents challenges to regulators responding to requests to carry out surveys and to researchers ensuring their work follows best practices and meets legal and ethical standards. Following a workshop convened at the 14th International Seabird Group Conference and a subsequent literature search, we collate information from over 100 studies and present a framework to ensure drone-seabird surveys are safe, effective, and within the law. The framework comprises eight steps: (1) Objectives and Feasibility; (2) Technology and Training; (3) Site Assessment and Permission; (4) Disturbance Mitigation; (5) Pre-deployment Checks; (6) Flying; (7) Data Handling and Analysis; and (8) Reporting. The audience is wide-ranging with sections having relevance for different users, including prospective and experienced drone-seabird pilots, landowners, and licensors. Regulations vary between countries and are frequently changing, but common principles exist. Taking-off, landing, and conducting in-flight changes in altitude and speed at ≥ 50 m from the study area, and flying at ≥ 50 m above ground-nesting seabirds/horizontal distance from vertical colonies, should have limited disturbance impact on many seabird species; however, surveys should stop if disturbance occurs. Compared to automated methods, manual or semi-automated image analyses are, at present, more suitable for infrequent drone surveys and surveys of relatively small colonies. When deciding if drone-seabird surveys are an appropriate monitoring method long-term, the cost, risks, and results obtained should be compared to traditional field monitoring where possible. Accurate and timely reporting of surveys is essential to developing adaptive guidelines for this increasingly common technology.

Key words: drones, seabirds, remote sensing, monitoring, disturbance

INTRODUCTION

In the past ten years, the use of aerial drones has seen enormous uptake in environmental biology (Nowak *et al*. 2019). As platforms have become easier to fly, smaller, and more affordable, drones have become an increasingly cost-effective method of gathering finer spatial and temporal resolution data from the air. The number of publications on Web of Science referring to 'drone,' 'unmanned aerial,' 'unmanned aircraft,' 'remotely piloted aerial,' or 'remotely piloted aircraft' has increased by approximately 40% from 2015 to 2020 (Hyun *et al*. 2020). While drones are known under a variety of terms, including unoccupied aerial vehicles (UAVs), unoccupied aerial systems (UAS), and remotely piloted aircraft systems (RPAS), they are all characterised as small powered aerial vehicles that can be flown remotely or autonomously and carry a payload (Rush *et al*. 2018, Johnston 2019, Edney & Wood 2021). Here, we refer to all of the above as 'drones,' as the term is simple and in widespread use by non-specialists (Chapman 2014).

Seabirds are one of the most threatened groups of birds, so effective monitoring is needed to understand reasons for decline (Croxall *et al*. 2012). While detailed protocols exist for manually surveying breeding seabirds (Walsh *et al*. 1995), challenges remain, such as access, viewing, disturbance, and cost (both time and money), which has often limited the scale of monitoring efforts (Carney & Sydeman 1999, Mitchell & Parsons 2007, Paleczny *et al*. 2015, Rush *et al*. 2018). Drones are providing opportunities to overcome some of these challenges and have been used for monitoring of a variety of seabird species and for a range of purposes, including measurement of abundance, distribution, and breeding success (Edney & Wood 2021).

Drones can access areas that are difficult or dangerous for fieldworkers to reach, which means entire breeding populations may be surveyed, rather than sub-plots due to access or time restrictions for fieldwork (Rush *et al*. 2018). They are often able to survey areas faster than direct field observations with the naked eye or binoculars and are also capable of surveying larger areas than can be captured on-site with handheld cameras, although this depends on suitable weather for flying (McClelland *et al*. 2016). Furthermore, drones can be less disruptive than ground counts, as less time is spent in animals' territory and observation is from the air rather than the ground (Sardà-Palomera *et al*. 2012). These advantages are becoming particularly apparent in the face of disease outbreaks, such as highly pathogenic avian influenza (HPAI), where fast and non-invasive monitoring is needed to track rapidly changing populations (Millar 2022, Cunningham *et al*. 2022). Nonetheless, using drones for seabird monitoring is not without difficulties.

Public perception of drones can be an issue for survey work due to privacy concerns, an association with the military, the idea of drones 'ruining' the natural landscape, encouraging tourists to fly drones in nature reserves, and potential disturbance to wildlife (Vacca & Onishi 2017, Johnston 2019, Dukowitz 2019, Duporge *et al*. 2021). Novices attempting survey work without adequate knowledge of aviation regulations or animal behaviour are at risk of breaking the law and putting people and wildlife in danger (Krause *et al*. 2021). Yet, the steps to acquire this knowledge and the necessary qualifications can be unclear and time-consuming, and hence, there is a need to synthesise the current state of knowledge.

A workshop was convened at the 14th International Seabird Group Conference 2018 to discuss the use of drones in seabird monitoring and research and to develop guidance to ensure practitioners and researchers are confident that flights are legal, safe, and obtain the results required (Wood 2022). This review focuses on eight key steps the workshop identified for this to happen: (1) Objectives and Feasibility; (2) Technology and Training; (3) Site Assessment and Permission; (4) Disturbance Mitigation; (5) Pre-deployment Checks; (6) Flying; (7) Data Handling and Analysis; and (8) Reporting. An advanced literature search collated information from over 100 studies that had not previously been brought together in one place. As a result, the overall audience is broad, with specific sections having more or less relevance for different users. The presentations from the workshop can be viewed online (Wood 2022).

LITERATURE SEARCH

We performed an advanced search using scientific search engines Web of Science and Scopus on 13 February 2023, for published studies containing keywords: 'seabird,' 'waterbird,' or 'penguin,' and 'UAV,' 'UAS,' 'RPAS,' 'Unmanned Aerial Vehicle,' 'Unmanned Aerial System,' or 'Remotely Piloted Aircraft System.' We repeated this search using the Google Scholar search engine to identify grey literature, including conference papers and unpublished reports. Collated sources were screened and included in the final dataset if the study used drones to monitor/research seabirds, and personal communications were added. Scientific reviews summarising others' research were excluded. The final dataset synthesised information on study aim; seabird species; life-history stage; assemblage; drone type; drone engine; image/video analysis method; disturbance information; and comparison with traditional monitoring techniques (Table A1 in Appendix, available on the website).

The literature search yielded 114 relevant studies, with the first study using drones to monitor abundance of a seabird colony being published in 2012 (Sardà-Palomera *et al*. 2012). Since then, the number of publications on this topic has steadily increased over time (Fig. 1A). Most studies focused on breeding seabirds (84%) and measured their abundance (57%), although the diversity of study objectives has increased as the technology has developed (Fig. 1B). Further results are discussed within the eight-step framework detailed below.

FRAMEWORK

Objectives and Feasibility

Clear objectives are needed to determine whether drones are an appropriate monitoring method. While drones can offer a number of advantages compared to ground surveys and other aerial techniques, they may not be necessary, and the total time, cost, and disturbance incurred should be compared for each survey method (Tables 1, 2). The training and licensing procedure can take time and resources that may be better allocated elsewhere. Occasionally, cameras on long poles can achieve similar results (McDowall & Lynch 2017), and for large species, satellite imagery may be available to count a population (Fretwell *et al*. 2017). The type of drone needed will also inform whether drones could be used, as they have a range of battery capacities, purposes, prices, and disturbance risks. This is an important first consideration when deciding whether drones are the most effective survey technique for a given task.

Technology and Training

Choice of technology

There are many factors to consider when choosing a drone, including transportation, take-off and landing requirements, manoeuvrability, battery life, wind stability, temperature tolerance, water resistance, and sensor payload requirements. Drones commonly used for wildlife surveys can be classified into two main types: fixed-wing and multi-rotor (Table 3; Verfuss *et al*. 2019, Dunn *et al*. 2021). Out of 114 drone-seabird studies, 81% used multi-rotors. They are typically smaller, more manoeuvrable, and easier to fly, enabling easier transportation (e.g., in a rucksack), take-off from small spaces (e.g., boats), and reduced disturbance risk (see section 'Disturbance Mitigation'). Fixed-wing drones may be more efficient for colonies containing many individuals (tens of thousands) and spread across large areas (km) because higher flight speed and longer flight duration means they can cover a larger area per survey, although such colonies can also be surveyed with multi-rotors given sufficient batteries and time (Raoult *et al*. 2020, Lyons *et al*. 2019). Improved battery endurance in recent years means survey coverage is more likely to be limited by regulations restricting flying Beyond Visual Line of Sight, rather than battery power.

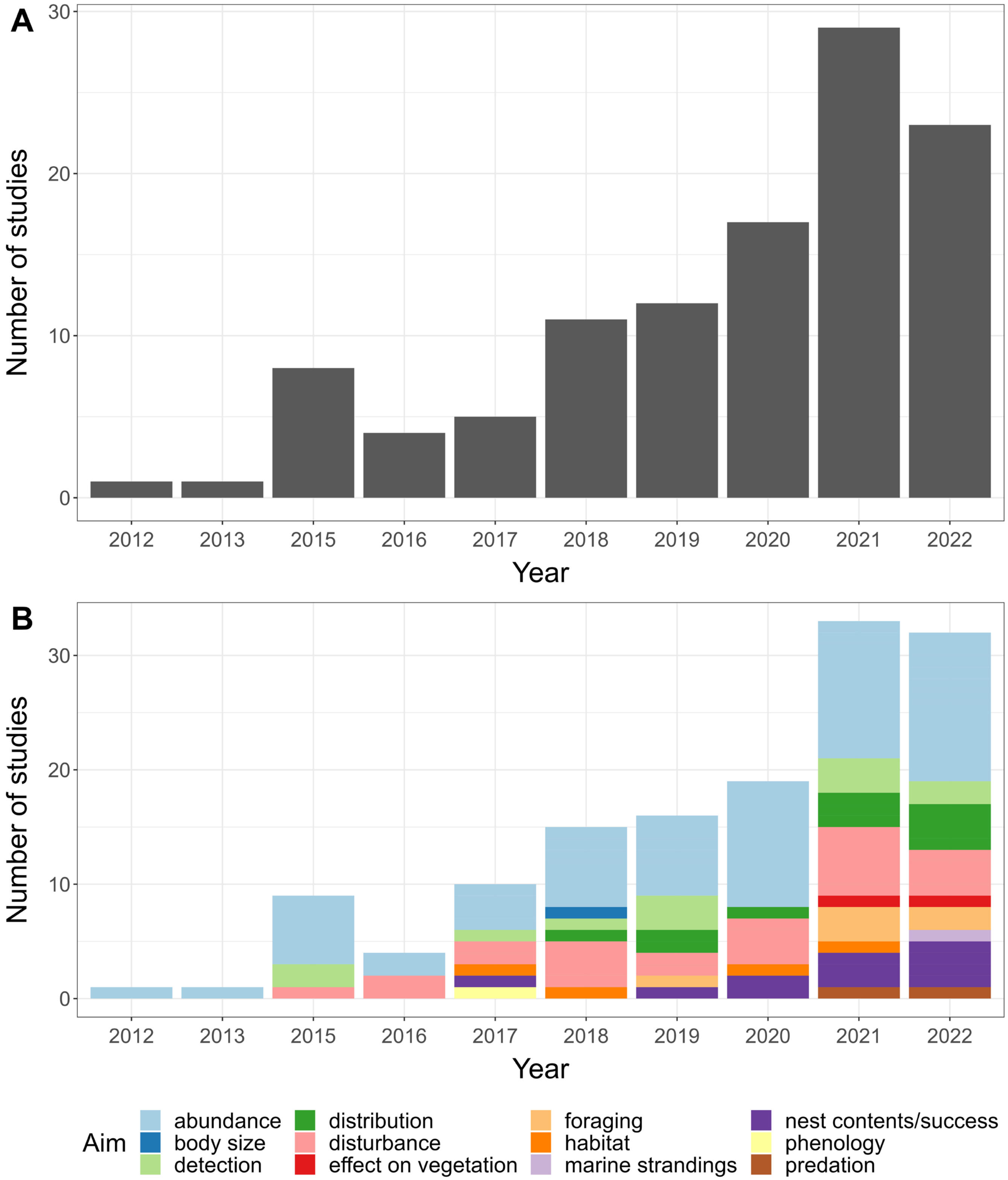

Fig. 1. (A) Number of studies that have used drones to monitor/research seabirds each year from 2012–2022 (n = 114), as identified from our literature search. (B) Number of studies that used drones to monitor/research seabirds each year from 2012–2022, where the study aim has been categorised into one of twelve groups (n = 140, studies with multiple aims have been included more than once [i.e., once per aim]). Data from 2023 were excluded because the year is not yet complete.

The type of payload will also affect drone choice. In the past, commercial multi-rotors have commonly used a digital camera that takes Red Green Blue (RGB) images and videos (Johnston 2019, Raoult *et al*. 2020), but they are increasingly carrying additional

TABLE 1
Advantages and disadvantages of using drones to monitor seabirds compared with ground-based field observations; adapted from Edney & Wood (2021)

Advantages	Disadvantages
• Operate at locations and times when field observations would be near-impossible. For example, remote locations (e.g., survey small islands from a boat), onshore and offshore, difficult terrain (Rush *et al*. 2018, Scarton & Valle 2022). • Surveying from a boat can avoid landing on remote islands, reducing risk posed to researchers from difficult boat landings in some cases, and minimising biosecurity risks and wildlife disturbance (Dickens *et al*. 2021). • Reduced nest and site disturbance compared with walk-through surveys (Rush *et al*. 2018). • Cover large areas in a short time (Valle & Scarton 2021b, Corregidor-Castro *et al.* 2022) • Combine habitat mapping and seabird occupancy from images, to investigate how habitat features affect populations (Oosthuizen *et al*. 2020). • Georeferenced photographs allow for accurate geolocation of colonies and nests within and between seasons (Pfeifer *et al*. 2019). • Permanent record viewable any number of times, available for independent verification, and re-analysis when new research questions and techniques become available (Thaxter & Burton 2009, Buckland *et al*. 2012, Hodgson *et al*. 2018). • Annotating images can improve accuracy of counts when presented with a large number of individuals, whereas field observers might find it hard to keep track of birds that have/have not been counted (Hurford 2017, Hodgson *et al*. 2018)	• Reduced use in areas with limited electricity and internet, which may be needed to charge batteries and update software. A fuel-powered generator may be required (Radjawali *et al*. 2017, Nowak *et al*. 2019). • Vulnerable to damage or loss of control in adverse weather conditions, whereas field observations can often occur in more inclement weather. For example, small drones are unable to operate in windy conditions, and low temperatures can reduce battery life or prevent take-off for some models (e.g., DJI). Waiting for the right conditions can make survey times longer than direct counts, and survey cancellations waste the opportunity costs of travelling to the site (Chabot *et al*. 2015, McClelland *et al*. 2016) • Large amount of data to handle and analyse, and processing and analysis requires specialised training and software (Rush *et al*. 2018). • Data quality depends on operator skill, and environmental and meteorological conditions during flight. Birds flying over/in front of the colony could obscure the objects of interest behind them in images (Nowak *et al*. 2019). • Animals may modify their behaviour in response to a flying object, increasing intraspecific aggression, predation of eggs or chicks, and nest abandonment. Some birds (e.g., raptors) may also attack the drone, and drone crashes in the colony could injure or kill birds (Borrelle & Fletcher 2017, Brisson-Curadeau *et al*. 2017, Rush *et al*. 2018). • If an image is not clear, there is no opportunity to return/wait for a bird to move, unlike in the field. For example, field observers may wait for an adult to shift position to determine whether an egg/chick is present in the nest, but this is not possible when viewing an image afterwards (Walsh *et al*. 1995). • Local, national and regional administrative regulations can affect possibility of data acquisition (Chabot *et al*. 2015, Nowak *et al*. 2019). • Upfront cost of training and purchasing a drone makes surveys more expensive than field observations (e.g., using notebook, pencil and binoculars) for one-off or a small number of surveys; and multiple flights may be required to cover larger areas, increasing survey time (Albores-Barajas *et al*. 2018).

TABLE 2
Advantages and disadvantages of using drones to monitor seabirds compared with aerial surveys from occupied aircraft; adapted from Edney & Wood (2021)

Advantages	Disadvantages
• Manoeuvrable, so can operate over small areas and monitor small objects (Nowak *et al*. 2019). • Greater control over the scale, quality, and temporal and spatial resolution of images (Thaxter & Burton 2009, Korczak-Abshire *et al*. 2019, Nowak *et al*. 2019) • Flexible angles of view can observe birds in a range of habitats and help reduce missed counts, especially when combined with thermal cameras to locate cryptic nests (Villegas *et al*. 2018, Shewring & Vafidis 2021). • Portability and limited launch requirements allow operation in most locations and terrains, including from boats (Goebel *et al*. 2015). • Cost-effective (short survey time, low purchase, and operation costs; Bibby *et al.* 2000, Buckland *et al*. 2012, Rush *et al*. 2018, Villegas *et al.* 2018, Nowak *et a*l. 2019, Scarton & Valle 2022).	• Reduced use in areas with limited electricity and internet, which may be needed to charge batteries and update software. A fuel-powered generator may be required (Radjawali *et al.* 2017, Nowak *et al*. 2019). • Operation generally limited to direct line of sight, which can prevent surveys of certain areas (e.g., headlands) from land. This requires the drone to be flown from a boat. • More affordable (usually smaller) drones have sensors that take lower resolution images and often have lower battery life, increasing the number of flights needed to survey a given area, and thus survey time (Nowak *et al*. 2019).

sensors, such as active infrared (short wavelength infrared), thermal (mid-long wavelength infrared), and hyperspectral (wavelengths across the electromagnetic spectrum). Thermal sensors can be useful for detecting birds with cryptic colouration in environments where the animal's reflection in the visible wavelengths contrasts with the surrounding's reflection (Lee *et al*. 2019, Lethbridge *et al*.

TABLE 3
Comparison of multi-rotor and fixed-wing drones

Multi-rotor	Fixed-wing
• Length usually from 35 to 150 cm and can normally be folded for transportation (e.g., can carry in a rucksack) (Johnston 2019).	• Wingspan usually from 90 to 350 cm but can exceed 20 m (Johnston 2019).
• Small multi-rotors (often < 250 g) typically require less pilot training as they present a lower risk when flying.	• Larger size means additional training and permits often needed.
• Can take-off and land vertically in small areas (e.g., from the deck of a small boat) and from rugged terrain (Johnston 2019, Raoult *et al*. 2020).	• Often require launcher or runway for take-off, although some (expensive) models can take-off vertically (Chabot *et al*. 2015).
• Agile manoeuvring and hovering and easier to fly. Allows image capture at appropriate angles for surveying cliff nesting seabirds, due to the aspect of the cliffs (Linchant *et al*. 2015).	• Lower manoeuvrability cannot remain stationary in flight. Harder to fly or require pre-programmed flight (e.g., SenseFly eBee X).
• Safer because they remain hovering when the control sticks are released. This means the pilot can let go in the event of an incident and allow the drone to hover while they regain composure and control.	• Cannot hover, must be kept flying at all times, meaning problems can arise quickly.
• Sound level is normally below the background noise from animals (e.g., seabird colony), ocean waves and wind (Goebel *et al*. 2015, Irigoin-Lovera *et al*. 2019).	• Sound level of fixed-wing drones with petrol engines is greater than multi-rotors and can increase substantially with drone size (Christie *et al*. 2016). Electric fixed-wing drones have comparable sound levels to multi-rotors.
• Lower speed and shorter flight duration (~20 min) so cover smaller area per survey (Colefax *et al*. 2018, Rees *et al*. 2018).	• Higher speed and longer flight duration (≥ 45 min), so cover larger area per survey (Rees *et al*. 2018).
• Aerodynamically less stable, especially in windy conditions; although most reasonable sized multi-rotors perform well in moderate breeze (e.g., DJI Mavic 2 Enterprise Advanced is stable up to 29–38 km/h, Beaufort scale 4 to 5) (Goebel *et al*. 2015, Colefax *et al*. 2018, Corcoran *et al*. 2021).	• Aerodynamically stable, less vulnerable to the effects of wind (Goebel *et al*. 2015, Corcoran *et al*. 2021).
• Carry a limited range of sensors, often only one or two, so have to select the 'best' sensor(s) to carry prior to take-off (e.g., DJI Mavic 2 Enterprise Advanced has RGB and thermal sensors).	• Carry and capture from a greater range and number of sensors, due to their larger size. This includes carrying larger, heavier sensors which will reduce ground sample distance (GSD).

2019, Corregidor-Castro *et al*. 2021). Most multi-rotors stabilise the payload with gimbals to improve image and video quality, especially when flying at higher speeds, while fixed-wings rarely use gimbals as their flight is more stable (Gašparović & Jurjević 2017, Brinkman & Garcelon 2020).

Camera specifications are important as well, as they will affect ground sample distance (GSD; the distance between two consecutive pixels in the image on the ground; small GSD means higher spatial resolution and more image detail) and risk of motion blur (O'Connor *et al*. 2017, Hayes *et al*. 2019, Mustafa *et al*. 2019). O'Connor *et al*. (2017) provide worked examples of how to achieve high-quality images by considering imaging configuration (pixel size, focal length, sensor size, and flight height) and exposure settings (ISO, aperture, shutter speed, focus and flight velocity). In summary, the GSD should be less than one-fifth of the size of the features of interest, and the flight height needed to obtain the required GSD can be calculated using:

$$\mathrm{GSD} \approx \frac{\mathrm{H \times S_{det}}}{\mathrm{f}}$$

where H is flight height, f is focal length, and S_{det} is width per pixel on the sensor (pixel pitch). If the required flight height is unsafe and may lead to disturbance (see 'Disturbance Mitigation'), then lens focal length or sensor resolution could be increased to mitigate the challenge of maintaining GSD while operating at increased altitude. Motion blur should be kept < 1.5 times the GSD, and the required flight speed or shutter speed to achieve this can be calculated using:

$$\mathrm{b} = \frac{\mathrm{v \times t}}{\mathrm{GSD}}$$

where b is motion blur (in pixels), v is velocity, and t is shutter speed. In general, choosing cameras with larger sensors (to maximise sensitivity and reduce GSD) and minimum effective focal lengths of 24–35 mm (to minimise errors due to lens distortion), and optimising ISO (to ensure shutter speed is fast enough to minimise motion blur), will help provide suitable image quality at appropriate flight heights and speeds (O'Connor *et al*. 2017). Once the drone and payload have been chosen, it is important to consider how the specifications will affect flight training and permissions.

Flight regulations and training

Each operation should ideally have two people, a pilot and a visual observer, to aid with situational awareness given the pilot's attention is divided between aircraft and screen (Dickens *et al*. 2021). Flight regulations vary by country and the nature of flights (examples in Table A2 in Appendix, available on the website),

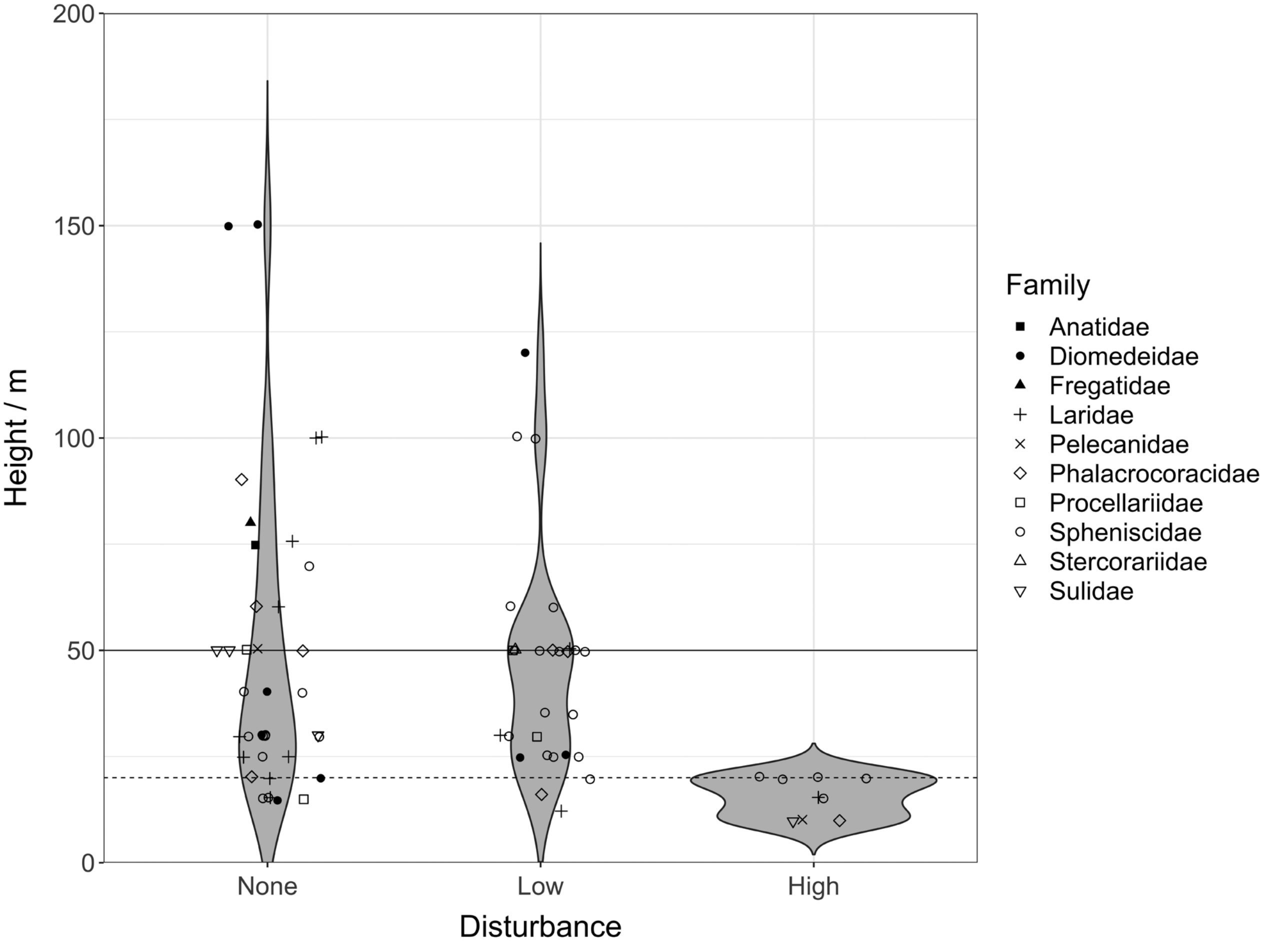

Fig. 2. Violin plot of height above breeding ground-nesting seabirds at which a multi-rotor drone induced no (n = 38), low (n = 28), or high (n = 9) adverse behavioural responses for different seabird families (n: Anatidae = 1, Diomedeidae = 9, Fregatidae = 1, Laridae = 13, Pelecanidae = 2, Phalacrocoracidae = 8, Procellariidae = 4, Spheniscidae = 32, Stercorariidae = 1, Sulidae = 4). Flying at ≥ 50 m height (solid line) led to almost no disturbance. High disturbance only occurred when the drone flew ≤ 20 m height (dashed line). Data is available in Table A5, from studies summarised in Table A4 (see Appendices, available on the website). Disturbance categories were defined as: none = no behavioural response; low = a minor adverse behavioural response (e.g., vigilance); high = a marked increase in adverse behavioural response (e.g., escape).

but in general, drones > 250 g should be registered and have the registration number on the device, and pilots need certification to show they understand how to fly safely and legally (although in some regions, commercial work with < 250 g drones also requires relevant certification). This normally means taking a theoretical and sometimes practical flight assessment and flying ≤ 120 m high due to regulatory airspace restrictions and > 50 m from built-up areas and people (Table A2). This makes drone-seabird surveys in urban areas, like urban gull studies, challenging (Ross *et al*. 2016, Rush *et al*. 2018). Special permission and further qualifications are needed for these more complex operations that impinge on general regulations, including flying Beyond Visual Line of Sight and flying with larger drones, typically > 25 kg (Table A2; Blight *et al*. 2019).

Site Assessment and Permission

Pre-site assessment

A pre-site assessment should be completed to assess whether the site is suitable for the designated work (Table A3 in Appendix, available on the website). This should include details of the landscape to decide whether the objects of interest will be visible in drone images. Seabird nests may be camouflaged, hidden by vegetation and rocky outcrops, or be underground, with small entrance holes hard to see from the air (Albores-Barajas *et al.* 2018, Dickens *et al*. 2021). It should also document features that could affect site access (e.g., tidal forecasts for island surveys) or be a hazard to drone flight, namely physical obstructions (e.g., pylons, buildings), restricted areas in the vicinity (e.g., classified airspace and military operations), habitation and recreational activities, public access, and environmental regulations, as well as phone numbers to contact Air Traffic Control (ATC) at nearby aerodromes/airports if the pilot loses control of the drone.

It is also important to consider optimal survey date and time in relation to the study species and survey objectives, as seabird breeding colony attendance varies on a daily and yearly cycle, so restricted site access could bias data collected. For example, many species display diurnal variation in colony attendance; Brisson-Curadeau *et al*. (2017) found that the number of Thick-billed

Murres *Uria lomvia* counted in drone images increased throughout the day before peaking at 20h00. Because the number of birds present in the colony also changes through the breeding season and this differs among species, the optimal survey timing best reflecting, for instance, the breeding population size, needs careful consideration (Walsh *et al*. 1995).

Permissions

Provided the site is suitable for the planned survey, it is essential to get the necessary permissions to fly the drone at a specific site and time over the target species, beginning with permission from the landowner or local land manager. Several countries have banned drones in National Parks, including the United States, Canada (also banned in provincial parks in eight out of ten provinces), and South Africa due to disturbance concerns and potential use by poachers (Table A2; Dukowitz 2019); although permission for research purposes may be granted by the countries' aviation authorities. Further consideration may be required for areas of any site that are sensitive to disturbance.

In the United Kingdom, most major seabird colonies are protected as Sites of Special Scientific Interest (SSSI), with many additionally protected as Special Protection Areas (SPAs). Every SSSI has a list of potentially damaging operations which can include the 'use of vehicles or craft likely to damage or disturb breeding seabirds' (Natural Resources Wales 2021, Nature Scot 2021); where such sites are also SPAs, conservation objectives (including those relating to minimising disturbance) must not be undermined by planned activity. It is also important to consider impacts on other 'features' of these protected sites, like other bird species or particular habitats, that could result from seabird surveys.

Some seabird species are granted specific protection from disturbance when breeding, meaning it could be illegal to disturb them at certain times of year, although licenses can be applied for in some jurisdictions. For example, a license is required if you cannot avoid disturbing birds listed in Schedule 1 of the Wildlife and Countryside Act 1981 when they are nest building and rearing young in the UK (GOV.UK 2015).

Even if additional licenses are not required, an ethics-related permit evaluating effects of potential disturbance by surveys on both target and non-target species' welfare may be requested by the research institution, funding body, or publisher if the study is later published. Whether animal welfare protocols are needed where drone work does not disturb wildlife is unclear, but possible direct and indirect environmental impacts must be considered during planning so the disturbance risks can be mitigated.

Disturbance Mitigation

Contamination and biosecurity

Contamination to the surrounding environment could occur from drone components shattering during collision and loss of drones in inaccessible locations where they cannot be retrieved, such as at sea. Anthropogenic debris can be physically hazardous to wildlife through entanglement, ingestion, alteration of habitats, or transport of non-native and pathogenic species (Engler 2012, Rochman *et al*. 2016, Roman *et al*. 2020). It can also be chemically hazardous if chemical constituents adsorbed onto the debris are transferred to organisms by direct ingestion or via the food web (Engler 2012, Rochman *et al*. 2016). Although the contribution of crashed drones to environmental pollution are minimal compared to that from other sources, these risks highlight the need for pilots to receive sufficient training to be competent, so the possibility of collision/loss is minimised.

Another concern when surveying seabirds is biosecurity, especially for birds breeding on remote islands. Introduction of invasive species and disease can have severe adverse consequences on seabird breeding success (Grimaldi *et al*. 2015, Martin & Richardson 2017, Caravaggi *et al*. 2018, Dias *et al*. 2019), so if drones can monitor populations without needing to go ashore, they can mitigate these risks (Dickens *et al*. 2021, Dewar *et al*. 2022). When drones do need to land, a landing pad should be used and the drone cleaned between sites to minimise spread of pathogens and non-native seeds and spores upon landing or in case of collision/loss (COMNAP 2021).

Wildlife disturbance

Another potential environmental impact is disturbance to breeding seabirds due to an unfamiliar aerial object in their territory, which may be perceived as an aerial predator (Mustafa *et al*. 2017, Mapes *et al*. 2020). This could disrupt behaviours like feeding, preening, and breeding, but it could also result in loss of nest contents. Adult seabirds displaced by a disturbance could knock eggs or chicks from nests, expose eggs or chicks to predation and the elements, or result in adults abandoning their breeding attempt (Borrelle & Fletcher 2017, Brisson-Curadeau *et al*. 2017). Seabird colonies are often densely packed, with many birds occupying the surrounding airspace, and collision or crash landings could injure or kill individuals (Brisson-Curadeau *et al*. 2017, Ellett *et al*. 2021). Even if birds do not flush in response to the drone, they may still be stressed by its presence and experience other behavioural or physiological changes (Weimerskirch *et al*. 2018). This also applies for non-target species, such as marine mammals and raptors, which may be adversely affected by drone flight (Junda *et al*. 2015, Palomino-González *et al*. 2021). It is therefore essential that studies take appropriate measures to minimise disturbance to wildlife and monitor disturbance during surveys so that operations can cease if required (Hodgson & Koh 2016).

Measuring and reporting disturbance

Existing studies vary in their measurement and reporting of disturbance, from research aimed at specifically testing and documenting drone-seabird responses (e.g., Rümmler *et al*. 2016, Brisson-Curadeau *et al*. 2017, Weimerskirch *et al*. 2018, Rümmler *et al*. 2018, Irigoin-Lovera *et al*. 2019, Krause *et al*. 2021, Rümmler *et al*. 2021) to ecologically focused studies that recorded responses as a by-product (e.g., Sardà-Palomera *et al*. 2012, Korczak-Abshire *et al*. 2016, Albores *et al*. 2018, Rush *et al*. 2018, Mustafa *et al*. 2018, Blight *et al*. 2019, Rexer-Huber *et al*. 2020, Scarton & Valle 2021, Dunn *et al*. 2021, Mattern *et al*. 2021). From our literature search, 72/114 studies (63%) provided some measure of disturbance and gave 132 'sub-studies,' for example, by measuring more than one species' and/or life-history stage responses, with different drone specifications and/or flight parameters. These are summarised in Table A4 (see Appendix, available on the website) with the aim of interpreting general guidance for best practice in measuring, reporting, and minimising disturbance. Out of 132 sub-studies, 50%

reported a change in seabird behaviour in response to drone flight, although this should be interpreted with caution due to a lack of standardised protocol for measuring and quantifying disturbance.

Several studies have compared the proportion of birds displaying specific behaviours before, during, and after a drone flight (Table A4). These behaviours are often associated with a disturbance score (typically, resting = 0, vigilance = 1, agonistic = 2, and escape = 3), which is used to determine whether drone flight causes adverse behavioural reactions (Korczak-Abshire *et al*. 2016, Rümmler *et al*. 2016, Mustafa *et al*. 2017, Rümmler *et al*. 2018, Weimerskirch *et al*. 2018, Barr *et al*. 2020, Krause *et al*. 2021). While this method is useful, studies often compare behaviour during drone flight to behaviour a short period (namely a few minutes) before and after drone flight, meaning the longer-term context of behavioural change is missing (Chabot *et al*. 2015, Barr *et al*. 2020). Seabirds show vigilance, agonistic, and escape behaviours across the breeding season in response to predators and competitors, and so the consequences of increased vigilance, agonistic, and escape behaviours due to drone flights might be minimal in comparison, but this is a topic that warrants future work.

Conversely, some studies recorded only the proportion of birds flushing in response to the drone (Sardà-Palomera *et al*. 2012, Reintsma *et al*. 2018), as escape behaviours may be more likely to have a significant fitness cost than vigilance, for example, due to energetically costly flight responses, loss of eggs or chicks by nest predation or exposure, and nest desertion (Brisson-Curadeau *et al*. 2017, Jarrett *et al*. 2020). Therefore, making comparisons between studies can be difficult due to different methods of categorising disturbance; for example, a study measuring changes in vigilance might report adverse behavioural reactions to drone flight, whereas a study only recording escape responses would not. It is also important to recognise that changes in behaviour do not necessarily have fitness consequences.

Even if a behavioural response is not observed, individuals might suffer physiological changes (e.g., heart and respiratory rates, hormonal stress response) due to drone flight (Weimerskirch *et al*. 2018), which studies rarely measure. To our knowledge, only two studies have investigated seabird physiological responses; one reported an increased heart rate in both parent and chick King Penguins *Aptenodytes patagonicus* during drone flights (Weimerskirch *et al*. 2018), while the other found no change in Common Eider *Somateria mollissima* heart rate (Geldart *et al*. 2022; Table A4). Quantifying these impacts may result in additional stress if birds need to be handled to attach loggers, such as heart rate monitors and respirometers.

Studies should also consider drone-seabird responses relative to disturbance from 'traditional' monitoring methods, such as ground counts (Mustafa *et al*. 2018). The pilot and visual observer do not need to be in close proximity to nesting seabirds during drone surveys, and so disturbance is likely to be reduced, especially compared with walk-through surveys (Chabot *et al*. 2015, Rush *et al*. 2018, Rümmler *et al*. 2021). It is therefore essential to consider the trade-off between the value of the data collected against potential disturbance from all methods of data collection.

Responses vary depending on a range of factors including drone features (e.g., size, shape, colour; Mulero-Pázmány *et al*. 2017), flight technique (including take-off/landing location, altitude, approach angle, flight pattern; Vas *et al*. 2015), target species (Borrelle & Fletcher 2017, Barr *et al*. 2020), life-history stage (e.g., breeding vs. non-breeding; Brisson-Curadeau *et al*. 2017), age (e.g., adult vs. chick; Rümmler *et al*. 2021) and location (e.g., distance to an aerodrome affecting habituation to air traffic; Blight *et al*. 2019). Two studies investigated whether the sound of a multi-rotor drone was responsible for seabird behavioural changes, but both reported that the drone was no louder than ambient noise from the seabird colony (Table A4; Goebel *et al*. 2015, Irigoin-Lovera *et al*. 2019). We recommend detailed reporting of the equipment, flight methods used, and level of disturbance observed, as shown in Table A4, in all data published from drone surveys to help increase understanding of species' responses to different drone platforms in a range of environments and situations, leading to improved methods to minimise impacts (Hodgson & Koh 2016, Barnas *et al*. 2020).

Minimising disturbance

Summarising the disturbance data presented in Table A4, we find that for multi-rotor surveys of breeding ground-nesting seabirds, taking-off and landing 50 m from the study area (Brisson-Curadeau *et al*. 2017, Mustafa *et al*. 2017, Rümmler *et al*. 2018) and flying at greater than 50 m above the colony ($n = 75$, Fig. 2) is likely to have limited impact on many seabird species. If flight altitude or speed needs to be changed, the drone should be flown to the side of the colony and adjusted there, as vertical approach can cause more pronounced behavioural reactions than horizontal approach (Mustafa *et al*. 2017, Rümmler *et al.* 2018, Rush *et al*. 2018). For multi-rotor surveys of breeding cliff-nesting seabirds, the guidance is less clear due to few available studies ($n = 9$, Table A4), although flying at least 50 m horizontal distance from the cliff face is likely to prevent visible disturbance of species like guillemots and kittiwakes (Brisson-Curadeau *et al*. 2017, Park *et al*. 2020, Bishop *et al*. 2022, TH and AJE pers. comm, RMW pers. comm).

Nevertheless, when flying at a new site, a precautionary principle should always be adopted in the absence of evidence (Hodgson & Koh 2016), and so we recommend that a trial is conducted to determine appropriate flight parameters (Mulero-Pázmány *et al*. 2017). Since there is a trade-off between image resolution and disturbance, we suggest starting at a height that is unlikely to cause disturbance and then working down to the maximum height (completing all changes in altitude away from the colony) at which the ground sampling distance is sufficient to accurately identify individuals without altering behaviour of both target and non-target species (Rush *et al*. 2018, Rexer-Huber *et al*. 2020, Duporge *et al*. 2021, Dunn *et al*. 2021). Flying higher will also give greater coverage in images and videos, requiring fewer passes over the colony, and extra altitude gives the pilot more time to move the drone away in the event of a problem.

Some researchers have suggested that post take-off, flying over the colony a few times can allow birds to habituate to the drone prior to the survey (Chabot *et al*. 2015, Reintsma *et al*. 2018, Rümmler *et al*. 2018). Equally, surveying sub-colonies that seem more sensitive to disturbance last, after they have seen calmer sub-colonies surveyed without incident, can reduce disturbance (e.g., Lesser Black-backed Gull *Larus fuscus*, MJW pers. comm). However, other studies have not observed short-term habituation, with seabird responses remaining the same after multiple flights during the same and consecutive days (Brisson-Curadeau *et al*. 2017, Mustafa *et al*.

2018, Rümmler *et al.* 2018). Therefore, habituation flights might not reduce disturbance and only use up battery/opportunity time without justification of data collection. Instead, it is more important that an observer with seabird knowledge monitors the birds' behaviour and informs the pilot if flight needs to be adjusted or ceased due to disturbance (Junda *et al*. 2015, Hodgson & Koh 2016, Mulero-Pázmány *et al*. 2017, Mustafa *et al.* 2018).

Pre-Deployment Checks

The pilot is responsible for having the necessary materials and supplies, and for ensuring both themselves and the drone are fit to fly in the local operating conditions on the day. Table A6 (see Appendix, available on the website) provides an example pre-deployment checklist to help achieve this, and extensive guidance can be found in operations manuals.

For seabird surveys, it is especially important to monitor local weather conditions leading up to the survey, as coastal sites are often windy and subject to sudden changes in weather (Duffy *et al*. 2018, Raoult *et al*. 2020). Poor conditions (cold, precipitation, fog, glare, high wind speed) can decrease visibility, reduce the pilot's ability to control the drone, and distort or blur images (Raoult *et al*. 2020, Doukari *et al*. 2021). Maximum wind speed should be measured on-site using an anemometer, as winds > 20 km/h can reduce the stability of multi-rotors (Bevan *et al*. 2015, Duffy *et al*. 2018, Raoult *et al*. 2020). A secondary landing site should be identified in case changing conditions prevent landing at the take-off location. For example, if worsening sea state prevents a boat landing, the drone should be landed remotely and recovered on land.

During set-up, the pilot must check that there is a global positioning system (GPS) signal, and that the compass and inertial measurement unit (IMU) are calibrated away from metal objects or other sources of interference. When operating from boats, it can be useful to ask the skipper to turn off radars during take-off and landing. The drone home point should also be set as the controller, not the take-off location, so if the batteries become low and the 'return to home' failsafe is activated, the drone returns to the boat's current location and not over the ocean. For surveys of cliff-nesting seabirds, where take-off and landing are from the clifftop, the 'return to home' failsafe must also be changed, so the drone flies vertically upwards above the clifftop, then horizontally to the landing point. Not all drones have object avoidance settings (Raoult *et al*. 2020), so the standard 'return to home' will return the drone to its take-off location via the shortest possible route: a diagonal upwards slope into the cliff.

Flying

Flying from a boat is sometimes recommended when surveying cliff-nesting seabirds (e.g., Bishop *et al*. 2022, TH and AJE pers. comm., IJM pers. comm.) so direct visual contact can be maintained throughout flight, signal is maintained between the drone and controller, and the risk of pilot and observer standing too close to the cliff edge is removed. Furthermore, updrafts can be substantial at clifftops, making take-off and landing difficult (Duffy *et al*. 2018, Rexer-Huber *et al*. 2020). Surveying from a boat can also avoid landing on remote islands, minimising biosecurity risk and further wildlife disturbance (Dickens *et al*. 2021), as well as the risk posed to researchers by difficult boat landings. Taking off from a boat is best done from an observer's hand rather than the deck of the vessel (Johnston 2019).

During take-off, the area downwind of the drone should be clear, as GPS compensation is only effective when it is a few feet above the ground, making the drone initially vulnerable to drift from wind gusts. Once airborne, a lawn-mower (grid) flight pattern is advised, with 70%–80% forward/backward overlap and 60% sideways overlap to prevent gaps in the stitched image (Parker & Rexer-Huber 2020). The flight pattern can be pre-programmed with autonomous flight planning software (e.g., Map Pilot) and the same plan used over multiple years, making surveys repeatable, saving both preparation time for subsequent surveys and allowing assessment of temporal changes. However, this requires downloading the maps in advance for offline use when in the field (Dickens *et al*. 2021) and also relies on knowing the precise location of the target animals, which is not always possible if observing foraging behaviours, or if breeding colonies expand, contract, or shift location, as often occurs with penguins (Dickens *et al*. 2021). Manual flight is sometimes more appropriate, and the flight pattern chosen should be practiced in advance. If a bird starts interacting with the drone, the pilot should either continue slowly flying away from the area of disturbance until mobbing stops, or altitude should be immediately increased while remaining below any aviation flight height restrictions (often at ≤ 120 m high, but this varies by jurisdiction; Table A2) to avoid further interactions. This contrasts with most non-bird emergency responses where altitude would be lowered, such as if a low-flying aircraft passed by.

Landing must occur away from the study area to minimise disturbance (Rush *et al*. 2018). If landing on a boat, multi-rotors are better hand-caught (protective gloves and eye protection are essential) due to movement of the vessel on the water increasing the risk of the drone landing overboard. Hand-catching is also preferred in windy conditions when the drone might otherwise fall over upon landing. Figure 3 provides a summary of the conditions that should normally be met when flying drones to survey breeding seabirds. More detailed information on steps to take when flying is given in Table A6.

Data Handling and Analysis

Image processing

Survey images can be examined individually or stitched together to form a composite image. An orthomosaic (where overlapping photos are joined together with distortions removed to create a positionally accurate representation of the surveyed area) can be produced using photogrammetry software such as Agisoft Metashape, previously called AgiSoft Photoscan (https://www.agisoft.com/), or ESRI Drone2Map (https://www.esri.com/en-us/arcgis/products/arcgis-drone2map/overview) (e.g., Rush *et al*. 2018, Albores-Barajas *et al*. 2018). This is difficult for surveys of vertical seabird colonies, as the software is designed to create a georeferenced image in the horizontal plane (i.e., a map), rather than the vertical plane. Instead, images can be stitched without embedded location data, using software like Hugin (http://hugin.sourceforge.net/) by finding fixed reference points in the images to create a panorama (Ratcliffe *et al*. 2015, Valle & Scarton 2021a). Three-dimensional models of the surveyed area can be reconstructed from multiple overlapping drone images using structure-from-motion processing (e.g., Oosthuizen *et al*. 2020) in software like Agisoft Metashape (https://www.agisoft.com/) or

Pix4D (https://www.pix4d.com/). This has the advantage of capturing the 3D nature of cliff-based colonies.

Image analysis

After processing, images are analysed to obtain the measurements required. Thus far, manual image analysis has been most common (92/114 drone-seabird studies), where researchers examine the image and make the required measurement themselves (such as counting the number of nests, recording the stage of each nest, recording individual behaviours, etc.); however, because manual analysis is labour-intensive, semi-automated and automated methods are being increasingly applied (Shewring & Vafidis 2021).

a) Manual image analysis

Many drone studies involve counting objects (e.g., birds, nests) (Nowak *et al*. 2019), with 80% of studies from our literature search (91/114) measuring seabird abundance. Tools which allow users to label objects in an image and then automatically sum the number of labels of each 'type' can reduce counting errors (Ratcliffe *et al*. 2015, Hodgson *et al*. 2018). Suggestions for freely available software include ImageJ (https://imagej.nih.gov/ij/; e.g., Hodgson *et al.* 2018), DotDotGoose (https://biodiversityinformatics.amnh.org/open_source/dotdotgoose/; e.g. Scarton & Valle 2022), iTag (https://sourceforge.net/projects/itagbiology/; e.g. Ratcliffe *et al*. 2015), and QGIS (https://www.qgis.org/en/site/; e.g. Espíndola *et al*., 2023), while Adobe Photoshop's count tool (https://www.adobe.com/uk/products/photoshop.html) and ArcGIS (https://www.arcgis.com/index.html; e.g. Bishop *et al*. 2022) must be purchased. To improve manual analysis, grid cells can be overlaid onto photographs to allow systematic counts grid-cell by grid-cell (Hodgson *et al*. 2016, Albores-Barajas *et al*. 2018, Korczak-Abshire *et al*. 2019, Valle & Scarton 2021a), and images can be enhanced to improve clarity, such as by adjusting for shadows, highlights, and mid-tone contrast (Parker & Rexer-Huber 2020). It is recommended that counts are repeated by both the same and different people, so that intra- and inter-observer error can be calculated and reported to assess confidence in results (Gregory *et al*. 2004, Hodgson *et al*. 2016, Sinclair *et al*. 2017, Mallory *et al*. 2020).

The time required for manual identification and counting depends on the number of objects of interest in the image, image quality, and analyser experience, although it can be significant. Analysing images of Gull-billed Tern *Gelochelidon nilotica* colonies took 176 minutes, which was 3.5 times longer than the drone inspection and surveys themselves (23 and 27 minutes, respectively; Scarton & Valle 2021). Image processing time can be reduced by counting subsections of the image and scaling up to obtain a whole image estimate, provided counts from image sections are correlated (Sinclair *et al*. 2017).

For projects with large numbers of images to analyse, citizen scientists can represent a low-cost option to increase counting speed (Jones *et al.* 2018). The Zooniverse platform hosts over 50 active citizen science projects for free and has enabled annotations of over one million seabird images as part of the Penguin Watch and Seabird Watch projects (Zooniverse 2021).

b) Semi-automated image analysis

Semi-automated classification is a type of supervised classification, meaning it is user-driven and cannot identify birds without human assistance, but is less time intensive than manual image analysis (Fretwell *et al*. 2012). Commercial ArcGIS software is commonly used and has given 98% and 96% mean agreement between semi-automated and manual counts of Lesser Black-backed Gulls (Rush *et al*. 2018) and Herring Gulls *Larus argentatus* (Corregidor-Castro *et al*. 2021), respectively. More recently, free ImageJ software has enabled 99.1% agreement for Mediterranean Gulls *Ichthyaetus melanocephalus*, providing a low-cost alternative (Corregidor-Castro & Valle 2022).

Most semi-automated methods find a unique spectral signature for the target object (e.g., the head of a gull) that is used to identify all object occurrences in the image (Grenzdörffer 2013, Waluda *et al*. 2014, Edney & Wood 2021). This requires consistency in shape and colour of target objects and high contrast between objects and their background (Chabot & Francis 2016, Andrew & Shepard 2017, Hollings *et al*. 2018, Lyons *et al*. 2019). Animals with spectral properties similar to other species or the background—for instance, pale coloured gulls on guano-stained cliffs—will be harder to distinguish (Corregidor-Castro & Valle 2022). Thermal imaging may help overcome this problem, as endotherms tend to be warmer than their surroundings and should therefore stand out (Lee *et al*. 2019). Nevertheless, in cold environments animals are often well insulated, leaving only a few small thermal 'hotspots' that may be difficult to detect. In addition, differences in emissivity between animal tissue and substrate against which animals are viewed may mask the thermal difference between bird and background in thermal images (Witczuk *et al*. 2017).

c) Automated image analysis

Computer vision using deep neural networks (e.g., convolutional neural networks (CNNs)) is being increasingly used to automatically detect features in complex, ecological data (Christin *et al*. 2019, Jones *et al*. 2020, Hayes *et al*. 2021, Weinstein *et al*. 2022). However, accurate prediction of features, such as seabird location, abundance, and behaviour, will depend on technological constraints, environmental conditions, and ecological traits of target species (Corcoran *et al*. 2021). Detection is more accurate for images with uniform habitats, non-overlapping individuals of a single species, and individuals at rest rather than in flight (Dujon *et al*. 2021). Large training sets should improve detection and the network's ability to generalise to unseen imagery but are often unfeasible unless training annotations are outsourced to citizen scientists and/or micropayment sites (Arteta *et al*. 2016, Wang *et al*. 2019, Bowler *et al*. 2020). Lightweight CNN architecture, and incorporating knowledge of bird spatial distribution within colonies, can reduce the number of annotated images needed for training if species are abundant (e.g., Royal Terns *Thalasseus maximus*), but it is less accurate for species comprising < 10% of individuals (e.g., Caspian Terns *Hydroprogne caspia* and gulls; Kellenberger *et al.* 2021).

Automated image analysis can greatly increase efficiency compared to manual classification; Kellenberger *et al*. (2021) classified ~21 000 seabirds in 4.5 hours, compared to three weeks of manual annotation. Nonetheless, building machine learning algorithms takes time, money, and experience. This might present a direct barrier to some users and make manual/semi-automated techniques more cost-effective if the drone survey is a one-off or infrequent occurrence.

Assessing validity and accuracy of data

The accuracy of results must be assessed to ensure data derived from drone images is suitable for use. Here, we can consider two types of accuracy: ‘image-accuracy’ and ‘observer-accuracy’ (Edney & Wood 2021).

Image-accuracy is dependent on the image itself and whether it has captured all objects of interest, such as all active nests in the area being examined. It should predominantly be considered during the survey planning stage, as it will depend on image resolution (influenced by flight height and camera megapixels), weather conditions, and the landscape to be surveyed.

Observer-accuracy is the method’s (e.g., manual observer’s, computer’s) intrinsic ability to correctly perform the required task (e.g., identify and count nests in the image) (Edney & Wood 2021). For manual analysis, accuracy largely depends on user experience and the number of individuals in an image (Swanson *et al*. 2016, Jones *et al*. 2018). Large numbers of individuals increase the probability of some individuals being missed, although low numbers of individuals present fewer opportunities for the user to learn to recognise them (Swanson *et al*. 2016).

Ultimately, an accurate estimate is close to the ‘true’ result (e.g., the true count in the wild), which is unknown. However, comparing results from drone imagery with traditional (often ground-based) monitoring methods can help decide if drone technology is an appropriate monitoring tool for the study objectives. If results from drone and ‘traditional’ methods differ significantly, then the user needs to decide on the ‘most accurate’ result. For example, drone imagery may achieve more accurate counts of breeding Thick-billed Murres than on-site ground counts, as the drone flushes non-breeding birds from the cliff (Brisson-Curadeau *et al*. 2017). Conversely, drones might give less accurate counts of species nesting in dense vegetation (e.g., gulls, terns, Macaroni Penguins *Eudyptes chrysolophus*) compared to traditional walk-through surveys, as nests will be hard to observe in photographs, but could be spotted on the ground (Dickens *et al*. 2021). As well, it may be difficult to discriminate between birds sitting on nests and nearby birds not on nests (especially for gulls) and impossible to distinguish between occupied and unoccupied burrows for burrow-nesting species. Where nests or burrows are difficult to spot from the air, sample areas should be counted in the field and on images to estimate counting error so that a correction factor can be used to estimate the true number of nests or burrows in images. Occupancy analysis, such as manual burrow inspection or playback of conspecific calls at burrow entrances in a sample area, can then estimate the proportion of burrows that are occupied (Walsh *et al*. 1995, Arneill *et al*. 2019).

Ideally, drone counts should give either the same or more accurate results than traditional methods before adopting them as common methodology; however, accuracy must also be balanced against variables such as time, money, and disturbance. Albores-Barajas *et al*. (2018) estimated that drone surveys of burrowing seabirds missed 5.6 burrows for every 100 compared to ground counts but saved 68% in person-hours, including additional image processing time. The monetary cost was higher due to the price of the drone, but this approach would become increasingly cost-effective per extra survey completed. Drone surveys might also be preferred at the expense of some accuracy if they significantly reduce disturbance to breeding seabirds, provided they do not limit the ability to detect, for example, population trends. In some cases, drones may even provide the only option for monitoring, for instance, if an island cannot be landed on or the terrain is impassable on foot (Benemann *et al*. 2022).

Reporting

A post-survey report is encouraged to allow continued guideline development and is typically required by regulators to determine how the survey went. This review offers practical guidance on how to survey seabirds with drones and obtain accurate data, and Barnas *et al*. 2020 complements it by providing a standardized protocol for reporting the methods in peer-reviewed articles, which we recommend. The protocol outlines information that should be included in each of six sections: Project Overview; Drone System and Operation Details; Payload, Sensor, and Data Collection; Field Operation Details; Data Post-Processing; and Permits, Regulations, Training, and Logistics. Table A4 in the Appendix of this review further highlights key information that should be reported to help assess species’ responses to drones and minimise disturbance.

CONCLUSIONS

In summary, drones offer many advantages for seabird monitoring and research. Time spent at a site is minimised if drones collect data faster than ground-based monitoring methods, and disturbance should be reduced as observers do not need to be in close proximity to seabirds. Furthermore, drones can minimise site travel and the potential to spread invasive species and damage vegetation. However, these benefits must be weighed against the costs, accuracy, operational utility, and potential impacts to seabird colonies and individuals. The recommendations outlined in this review are aimed at providing practitioners and researchers with a framework to ensure flights are effective, safe, and within the law. The need for accurate reporting and dissemination of operations is evident so we can continue to develop guidance for this comparatively new technology.

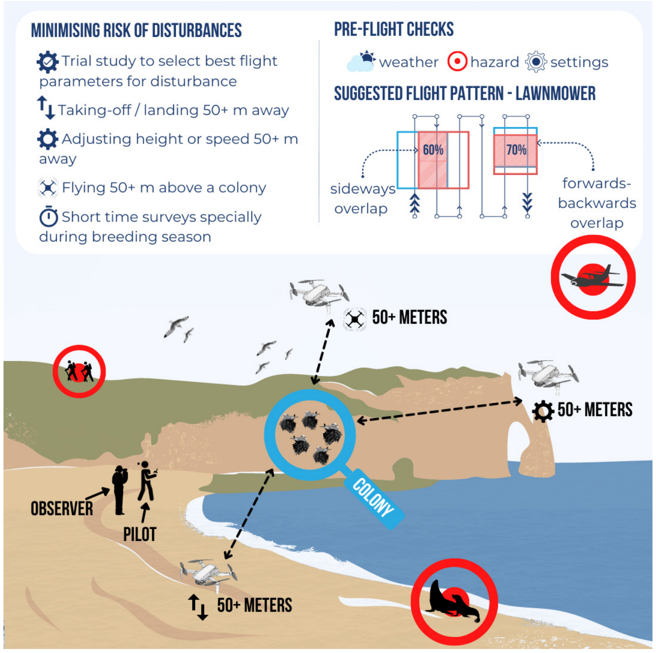

Fig. 3. Summary of the conditions that should be met when flying drones to survey breeding seabirds, including pre-flight checks, methods to minimise wildlife disturbance, and possible flight pattern.

ACKNOWLEDGEMENTS

This review was conceptualised at the *workshop Using UAVs in Seabird Research and Monitoring* at the 2018 International Seabird Conference, which was organised and led by MJW. We would like to thank everyone who attended the workshop and contributed ideas. The research was funded by the University of Gloucestershire's Environmental Dynamics and Governance RPA (to MJW) and Natural Environment Research Council DTP studentship (grant NE/S007474/1 to AJE). We are also grateful to Fiona Suttle and anonymous reviewers who provided valuable feedback on the manuscript.

REFERENCES

ALBORES-BARAJAS, Y.V., SOLDATINI, C., RAMOS-RODRÍGUEZ, A., ALCALA-SANTOYO, J.E., CARMONA, R. & DELL'OMO, G. 2018. A new use of technology to solve an old problem: Estimating the population size of a burrow nesting seabird. *PLoS One* 13: e0202094. doi:10.1371/journal.pone.0202094

ANDREW, M.E. & SHEPHARD, J.M. 2017. Semi-automated detection of eagle nests: an application of very high-resolution image data and advanced image analyses to wildlife surveys. *Remote Sensing in Ecology and Conservation* 3: 66–80. doi:10.1002/rse2.38

ARNEILL, G.E., PERRINS, C.M., WOOD, M.J. ET AL. 2019. Sampling strategies for species with high breeding-site fidelity: A case study in burrow-nesting seabirds. *PLoS One* 14: e0221625. doi:10.1371/journal.pone.0221625

ARTETA, C., LEMPITSKY, V. & ZISSERMAN, A. 2016. Counting in the wild. *European Conference on Computer Vision* 9911: 483–498. doi:10.1007/978-3-319-46478-7_30

BARNAS, A., CHABOT, D., HODGSON, A., JOHNSTON, D.W., BIRD, D.M. & ELLIS-FELEGE, S.N. 2020. A standardized protocol for reporting methods when using drones for wildlife research. *Journal Of Unmanned Vehicle Systems* 8: 89–98. doi:10.1139/juvs-2019-0011

BARR, J.R., GREEN, M.C., DEMASO, S.J. & HARDY, T.B. 2020. Drone surveys do not increase colony-wide flight behaviour at waterbird nesting sites, but sensitivity varies among species. *Scientific Reports* 10: 3781. doi:10.1038/s41598-020-60543-z

BENEMANN, V.R.F., ARAÚJO, L.D., FABBRIS, A.Z., MONTONE, R.C. & PETRY, M.V. 2022. Nesting distribution of Masked Booby *Sula dactylatra* at Trindade Island, western South Atlantic Ocean. *Marine Ornithology* 50: 189–195.

BEVAN, E., WIBBELS, T., NAJERA, B.M. ET AL. 2015. Unmanned aerial vehicles (DRONEs) for monitoring sea turtles in near-shore waters. *Marine Turtle Newsletter* 145: 19–22.

BIBBY, C.J., BURGESS, N.D., HILL, D.A. & MUSTOE, S. 2000. *Bird Census Techniques*. London, UK: Elsevier.

BISHOP, A.M., BROWN, C.L., CHRISTIE, K.S. ET AL. 2022. Surveying cliff-nesting seabirds with unoccupied aircraft systems in the Gulf of Alaska. *Polar Biology* 45: 17031714. doi:10.1007/s00300-022-03101-9

BLIGHT, L.K., BERTRAM, D.F. & KROC, E. 2019. Evaluating drone-based techniques to census an urban-nesting gull population on Canada's Pacific coast. *Journal of Unmanned Vehicle Systems* 7: 312–324. doi:10.1139/juvs-2019-0005

BORRELLE, S.B. & FLETCHER, A.T. 2017. Will drones reduce investigator disturbance to surface-nesting seabirds? *Marine Ornithology* 45: 89–94.

BOWLER, E., FRETWELL, P.T., FRENCH, G. & MACKIEWICZ, M. 2020. Using deep learning to count albatrosses from space: assessing results in light of ground truth uncertainty. *Remote Sensing* 12: 2026. doi:10.3390/rs12122026

BRINKMAN, M.P. & GARCELON, D.K. 2020. Applying UAV Systems in Wildlife Management. *Proceedings of the Vertebrate Pest Conference* 29.

BRISSON-CURADEAU, É., BIRD, D., BURKE, C. ET AL. 2017. Seabird species vary in behavioural response to drone census. *Scientific Reports* 7: 1–9. doi:10.1038/s41598-017-18202-3

BUCKLAND, S.T., BURT, M.L., REXSTAD, E.A., MELLOR, M., WILLIAMS, A.E. & WOODWARD, R. 2012. Aerial surveys of seabirds: the advent of digital methods. *Journal of Applied Ecology* 49: 960–967. doi:10.1111/j.1365-2664.2012.02150.x

CARAVAGGI, A., CUTHBERT, R.J., RYAN, P.G., COOPER, J. & BOND, A.L. 2019. The impacts of introduced House Mice on the breeding success of nesting seabirds on Gough Island. *Ibis* 161: 648–661. doi:10.1111/ibi.12664

CARNEY, K. M. & SYDEMAN, W. J. 1999. A review of human disturbance effects on nesting colonial waterbirds. *The International Journal of Waterbird Biology* 22: 68–79. doi:10.1111/jofo.12171

CHABOT, D. & FRANCIS, C.M. 2016. Computer-automated bird detection and counts in high-resolution aerial images: a review. *Journal of Field Ornithology* 87: 343–359. doi:10.1111/jofo.12171

CHABOT, D., CRAIK, S.R. & BIRD, D.M. 2015. Population census of a large common tern colony with a small unmanned aircraft. *PLoS One* 10: e0122588. doi:10.1371/journal.pone.0122588

CHAPMAN, A. 2014. It's okay to call them drones. *Journal of Unmanned Vehicle Systems* 2: iii-v. doi:10.1139/juvs-2014-0009

CHRISTIN, S., HERVET, É. & LECOMTE, N. 2019. Applications for deep learning in ecology. *Methods in Ecology and Evolution* 10: 1632–1644. doi:10.1111/2041-210X.13256

COMNAP (COUNCIL OF MANAGERS OF NATIONAL ANTARCTIC PROGRAMS). 2021. *Antarctic Flight Information Manual (AFIM)*. [Accessed at https://www.comnap.aq/air-operations on 31 March 2022.]

CORCORAN, E., WINSEN, M., SUDHOLZ, A. & HAMILTON, G. 2021. Automated detection of wildlife using drones: Synthesis, opportunities and constraints. *Methods in Ecology and Evolution* 12: 1103–1114. doi:10.1111/2041-210X.13581

CORREGIDOR-CASTRO, A. & VALLE, R.G. 2022. Semi-Automated counts on drone imagery of breeding seabirds using free accessible software. *Ardea* 110: 89–97. doi:10.5253/arde.v110i1.a7

CORREGIDOR-CASTRO, A., HOLM, T.E. & BREGNBALLE, T. 2021. Counting breeding gulls with unmanned aerial vehicles: camera quality and flying height affects precision of a semi-automatic counting method. *Ornis Fennica* 98: 33–45.

CORREGIDOR-CASTRO, A., RIDDERVOLD, M., HOLM, T. E. & BREGNBALLE, T. 2022. Monitoring colonies of large gulls using UAVs: from individuals to breeding pairs. *Micromachines* 13: 1844. doi:10.3390/mi13111844

CROXALL, J.P., BUTCHART, S.H.M., LASCELLES, B. ET AL. 2012. Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International* 22: 1–34. doi:10.1017/S0959270912000020

CUNNINGHAM, E.J.A., GAMBLE, A., HART, T. ET AL. 2022. The incursion of Highly Pathogenic Avian Influenza (HPAI) into North Atlantic seabird populations: an interim report from the 15th International Seabird Group conference. *Seabird* 34.

DEWAR, M. L., DR, WILLE, M., GAMBLE, A. ET AL. 2022. *The Risk of Avian Influenza in the Southern Ocean: A Practical Guide*. *EcoEvoRxiv Preprints*. doi:10.32942/osf.io/8jrbu

DIAS, M.P., MARTIN, R., PEARMAIN, E.J. ET AL. 2019. Threats to seabirds: A global assessment. *Biological Conservation* 237: 525–537. doi:10.1016/j.biocon.2019.06.033

DICKENS, J., HOLLYMAN, P.R., HART, T. ET AL. 2021. Developing UAV monitoring of South Georgia and the South Sandwich Islands' iconic land-based marine predators. *Frontiers in Marine Science* 8: 630. doi:10.3389/fmars.2021.654215

DJI. 2022. *Mavic 2 Enterprise Series*. Shenzen, China: DJI. [Accessed at https://www.dji.com/uk/mavic-2-enterprise/specs on 31 March 2022.]

DOUKARI, M., KATSANEVAKIS, S., SOULAKELLIS, N. & TOPOUZELIS, K. 2021. The effect of environmental conditions on the quality of UAS orthophoto-maps in the coastal environment. *ISPRS International Journal of Geo-Information* 10: 18. doi:10.3390/ijgi10010018

DUFFY, J. P., CUNLIFFE, A. M., DEBELL, L. ET AL. 2018. Location, location, location: considerations when using lightweight drones in challenging environments. *Remote Sensing in Ecology and Conservation* 4: 7–19. doi:10.1002/rse2.58

DUJON, A.M., IERODIACONOU, D., GEESON, J.J. ET AL. 2021. Machine learning to detect marine animals in UAV imagery: effect of morphology, spacing, behaviour and habitat. *Remote Sensing in Ecology and Conservation* 7: 341–354. doi:10.1002/rse2.205

DUKOWITZ, Z. 2019. *Drones in National Parks: What Every Drone Pilot Needs to Know*. Nashville, USA: The UAV Coach. [Accessed at https://uavcoach.com/drones-in-national-parks/ on 24 August 2021.]

DUNN, M.J., ADLARD, S., TAYLOR, A.P., WOOD, A.G., TRATHAN, P.N. & RATCLIFFE, N. 2021. Un-crewed aerial vehicle population survey of three sympatrically breeding seabird species at Signy Island, South Orkney Islands. *Polar Biology* 44: 717–727. doi:10.1007/s00300-021-02831-6.

DUPORGE, I., SPIEGEL, M.P., THOMSON, E.R. ET AL. 2021. Determination of optimal flight altitude to minimise acoustic drone disturbance to wildlife using species audiograms. *Methods in Ecology and Evolution* 12: 2196–2207. doi:10.1111/2041-210X.13691

EDNEY, A.J. & WOOD, M.J. 2021. Applications of digital imaging and analysis in seabird monitoring and research. *Ibis* 163: 317–337. doi:10.1111/ibi.12871

ELLETT, L., GIBBONS, S., GILBERT, J., CRUZ, J.G. & ISLAM, A. 2021. Navigating assumptions of wildlife viewing impacts. *Parks Stewardship Forum* 37: 546–551.

ENGLER, R.E. 2012. The complex interaction between marine debris and toxic chemicals in the ocean. *Environmental Science and Technology* 46: 12302–12315. doi:10.1021/es3027105

ESPÍNDOLA, W. D., CRUZ-MENDOZA, A., GARRASTAZÚ, A. ET AL. 2023. Estimating population size of red-footed boobies using distance sampling and drone photography. *Wildlife Society Bulletin* 47: e1406. doi:10.1002/wsb.1406

FRETWELL, P.T., LARUE, M.A., MORIN, P. ET AL. 2012. An emperor penguin population estimate: the first global, synoptic survey of a species from space. *PLoS One* 7: e33751. doi:10.1371/journal.pone.0033751

FRETWELL, P.T., SCOFIELD, P. & PHILLIPS, R.A. 2017. Using super-high resolution satellite imagery to census threatened albatrosses. *Ibis* 159: 481–490. doi:10.1111/ibi.12482

GELDART, E.A., BARNAS, A.F., SEMENIUK, C.A.D. ET AL. 2022. A colonial-nesting seabird shows no heart-rate response to drone-based population surveys. *Scientific Reports* 12: 18804. doi:10.1038/s41598-022-22492-7

GOEBEL, M.E., PERRYMAN, W.L., HINKE, J.T. ET AL. 2015. A small unmanned aerial system for estimating abundance and size of Antarctic predators. *Polar Biology* 38: 619–630. doi:10.1007/s00300-014-1625-4

GOV.UK. 2015. *Protected Species: When to Apply for a Licence To Survey, Film or Photograph Them*. London, UK: GOV.UK. [Accessed at https://www.gov.uk/guidance/protected-species-when-to-apply-for-a-licence-to-survey-film-or-photograph-them on 09 July 2021.]

GREGORY, R.D., GIBBONS, D.W. & DONALD, P.F. 2004. Bird census and survey techniques. In: SUTHERLAND, W.J., NEWTON, I. & RHYS, G. (Eds.) *Bird Ecology and Conservation: A Handbook of Techniques*. Oxford, UK: Oxford University Press, pp. 17–52.

GRENZDÖRFFER, G.J. 2013. UAS-based automatic bird count of a common gull colony. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-1/W2: 169–174. doi:10.5194/isprsarchives-XL-1-W2-169-2013

GRIMALDI, W.W., SEDDON, P.J., LYVER, P.O., NAKAGAWA, S. & TOMPKINS, D.M. 2015. Infectious diseases of Antarctic penguins: current status and future threats. *Polar Biology* 38: 591–606. doi:10.1007/s00300-014-1632-5

HAYES, M.C., GRAY, P.C., HARRIS, G. ET AL. 2021. Drones and deep learning produce accurate and efficient monitoring of large-scale seabird colonies. *Ornithological Applications* 123: 1–16. doi:10.1093/ornithapp/duab022

HODGSON, J. C., MOTT, R., BAYLIS, S. M. ET AL. 2018. Drones count wildlife more accurately and precisely than humans. *Methods in Ecology and Evolution* 9: 1160–1167. doi:10.1111/2041-210X.12974

HODGSON, J.C. & KOH, L.P. 2016. Best practice for minimising unmanned aerial vehicle disturbance to wildlife in biological field research. *Current Biology* 26: R404–R405. doi:10.1016/j.cub.2016.04.001

HODGSON, J.C., BAYLIS, S.M., MOTT, R., HERROD, A. & CLARKE, R.H. 2016. Precision wildlife monitoring using unmanned aerial vehicles. *Scientific Reports* 6: 1–7. doi:10.1038/srep22574

HOLLINGS, T., BURGMAN, M., ANDEL, M. VAN, GILBERT, M., ROBINSON, T. & ROBINSON, A. 2018. How do you find the green sheep? A critical review of the use of remotely sensed imagery to detect and count animals. *Methods in Ecology and Evolution* 9: 881–892. doi:10.1111/2041-210X.12973

HURFORD, C. 2017. Improving the Accuracy of Bird Counts Using Manual and Automated Counts in ImageJ: An Open-Source Image Processing Program. In: DIAZ-DELGADO R., LUCAS R., HURFORD C. (Eds.) *The Roles of Remote Sensing in Nature Conservation*. New York, USA: Springer International Publishing.

HYUN, C.-U., PARK, M. & LEE, W.Y. 2020. Remotely Piloted Aircraft System (RPAS)-based wildlife detection: a review and case studies in maritime Antarctica. *Animals* 10: 2387. doi:10.3390/ani10122387

IRIGOIN-LOVERA, C., LUNA, D.M., ACOSTA, D.A. & ZAVALAGA, C.B. 2019. Response of colonial Peruvian guano birds to flying UAVs: effects and feasibility for implementing new population monitoring methods. *PeerJ* 7: e8129. doi:10.7717/peerj.8129

JARRETT, D., CALLADINE, J., COTTON, A., WILSON, M. W. & HUMPHREYS, E. 2020. Behavioural responses of non-breeding waterbirds to drone approach are associated with flock size and habitat. *Bird Study* 67: 190–196. doi:10.1080/00063657.2020.1808587

JOHNSTON, D.W. 2019. Unoccupied aircraft systems in marine science and conservation. *Annual Review of Marine Science* 11: 439–463. doi:10.1146/annurev-marine-010318-095323

JONES, F.M., ALLEN, C., ARTETA, C. ET AL. 2018. Time-lapse imagery and volunteer classifications from the Zooniverse Penguin Watch project. *Scientific Data* 5: 180124. doi:10.1038/sdata.2018.124

JONES, F.M., ARTETA, C., ZISSERMAN, A., LEMPITSKY, V., LINTOTT, C.J. & HART, T. 2020. Processing citizen science- and machine-annotated time-lapse imagery for biologically meaningful metrics. *Scientific Data* 7: 1–15. doi:10.1038/s41597-020-0442-6

JUNDA, J., GREENE, E. & BIRD, D. M. 2015. Proper flight technique for using a small rotary-winged drone aircraft to safely, quickly, and accurately survey raptor nests. *Journal of Unmanned Vehicle Systems* 3: 222–236. doi:10.1139/juvs-2015-0003

KELLENBERGER, B., VEEN, T., FOLMER, E. & TUIA, D. 2021. 21 000 birds in 4.5 h: efficient large-scale seabird detection with machine learning. *Remote Sensing in Ecology and Conservation* 7: 445–460. doi:10.1002/rse2.200

KORCZAK-ABSHIRE, M., ZMARZ, A., RODZEWICZ, M., KYCKO, M., KARSZNIA, I. & CHWEDORZEWSKA, K.J. 2019. Study of fauna population changes on Penguin Island and Turret Point Oasis (King George Island, Antarctica) using an unmanned aerial vehicle. *Polar Biology* 42: 217–224. doi:10.1007/s00300-018-2379-1

KRAUSE, D.J., HINKE, J.T., GOEBEL, M.E. & PERRYMAN, W.L. 2021. Drones minimize Antarctic predator responses relative to ground survey methods: an appeal for context in policy advice. *Frontiers in Marine Science* 8: 648772. doi:10.3389/fmars.2021.648772

LEE, W.Y., PARK, M. & HYUN, C.-U. 2019. Detection of two Arctic birds in Greenland and an endangered bird in Korea using RGB and thermal cameras with an unmanned aerial vehicle (UAV). *PLoS One* 14: e0222088. doi:10.1371/journal.pone.0222088

LETHBRIDGE, M., STEAD, M., WELLS, C., LETHBRIDGE, M., STEAD, M. & WELLS, C. 2019. Estimating kangaroo density by aerial survey: a comparison of thermal cameras with human observers. *Wildlife Research* 46: 639–648. doi:10.1071/WR18122

LIEBER, L., LANGROCK, R. & NIMMO-SMITH, W.A.M. 2021. A bird's-eye view on turbulence: seabird foraging associations with evolving surface flow features. *Proceedings of the Royal Society B*. 288: 20210592. doi:10.1098/rspb.2021.0592

LIEBER, L., NIMMO-SMITH, W.A.M., WAGGITT, J.J. & KREGTING, L. 2019. Localised anthropogenic wake generates a predictable foraging hotspot for top predators. *Communications Biology* 2: 123. doi:10.1038/s42003-019-0364-z

LINCHANT, J., LISEIN, J., SEMEKI, J., LEJEUNE, P. & VERMEULEN, C. 2015. Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. *Mammal Review* 45: 239–252. doi:10.1111/mam.12046

LYONS, M.B., BRANDIS, K.J., MURRAY, N.J. ET AL. 2019. Monitoring large and complex wildlife aggregations with drones. *Methods in Ecology and Evolution* 10: 1024–1035. doi:10.1111/2041-210X.13194

MALLORY, M.L., DEY, C.J., MCINTYRE, J. ET AL. 2020. Long-term declines in the size of Northern Fulmar (*Fulmarus glacialis*) colonies on eastern Baffin Island, Canada. *Arctic* 73: 187–194.

MAPES, K.L., PRICOPE, N.G., BAXLEY, J.B., SCHAALE, L.E. & DANNER, R.M. 2020. Thermal imaging of beach-nesting bird habitat with unmanned aerial vehicles: considerations for reducing disturbance and enhanced image accuracy. *Drones* 4: 12. doi:10.3390/drones4020012

MARTIN, A.R. & RICHARDSON, M.G. 2017. Rodent eradication scaled up: clearing rats and mice from South Georgia. *Oryx* 53: 27–35. doi:10.1017/S003060531700028X

MATTERN, T., REXER-HUBER, K., PARKER, G. ET AL. 2021. Erect-crested penguins on the Bounty Islands: population size and trends determined from ground counts and drone surveys. *Notornis* 68: 37–50. doi:10.6084/m9.figshare.19709476

MCCLELLAND, G.T., BOND, A.L., SARDANA, A. & GLASS, T. 2016. Rapid population estimate of a surface-nesting seabird on a remote island using a low-cost unmanned aerial vehicle. *Marine Ornithology* 44: 215–220.

MCDOWALL, P. & LYNCH, H.J. 2017. Ultra-fine scale spatially-integrated mapping of habitat and occupancy using structure-from-motion. *PLoS One* 12: e0166773. doi:0.1371/journal.pone.0166773

MILLAR, G. 2022. *Drone Footage Reveals Devastating Impact of Bird Flu on The Bass Rock Gannets*. Glasgow, UK: The National. [Accessed at https://www.thenational.scot/news/20281829.drone-footage-reveals-devastating-impact-bird-flu-bass-rock-gannets/ on 11 August 2022.]

MITCHELL, P.I. & PARSONS, M. 2007. *Strategic Review of the UK Seabird Monitoring Programme*. Joint Nature Conservation Committee, Unpublished Report. Peterborough, UK: Joint Nature Conservation Committee.

MULERO-PÁZMÁNY, M., JENNI-EIERMANN, S., STREBEL, N., SATTLER, T., NEGRO, J.J. & TABLADO, Z. 2017. Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. *PLoS One* 12: e0178448. doi:10.1371/journal.pone.0178448

MUSTAFA, O., BARBOSA, A., KRAUSE, D.J., PETER, H.-U., VIEIRA, G. & RÜMMLER, M.-C. 2018. State of knowledge: Antarctic wildlife response to unmanned aerial systems. *Polar Biology* 41: 2387–2398. doi:10.1007/s00300-018-2363-9

MUSTAFA, O., BRAUN, C., ESEFELD, J. ET AL. 2019. Detecting Antarctic seals and flying seabirds by UAV. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* V-2/W5: 141–148. doi:10.5194/isprs-annals-IV-2-W5-141-2019

MUSTAFA, O., ESEFELD, J., GRÄMER, H. ET AL. 2017. *Monitoring Penguin Colonies in the Antarctic Using Remote Sensing Data.* Dessau-Roßlau, Germany: Umweltbundesamt. [Accessed at http://www.umweltbundesamt.de/publikationen on 31 March 2022.]

NATURAL RESOURCES WALES. 2021. *Sites of Special Scientific Interest (SSSI): Responsibilities of Owners and Occupiers*. Cardiff, UK: Natural Resources Wales. [Accessed at https://naturalresources.wales/guidance-and-advice/environmental-topics/wildlife-and-biodiversity/protected-areas-of-land-and-seas/sites-of-special-scientific-interest-responsibilities-of-owners-and-occupiers/?lang=en on 25 August 2021.]

NATURE SCOT. 2021. *Sites of Special Scientific Interest (SSSIs).* Inverness, UK: Nature Scot. [Accessed at https://www.nature.scot/professional-advice/protected-areas-and-species/protected-areas/national-designations/sites-special-scientific-interest-sssis on 25 August 2021.]

NOWAK, M.M., DZIÓB, K. & BOGAWSKI, P. 2019. Unmanned Aerial Vehicles (UAVs) in environmental biology: a review. *European Journal of Ecology* 4: 56–74. doi:10.2478/eje-2018-0012

O'CONNOR, J., SMITH, M.J. & JAMES, M.R. 2017. Cameras and settings for aerial surveys in the geosciences: Optimising image data. *Progress in Physical Geography: Earth and Environment* 41: 325–344. doi:10.1177/0309133317703092

OOSTHUIZEN, W.C., KRÜGER, L., JOUANNEAU, W. & LOWTHER, A.D. 2020. Unmanned aerial vehicle (UAV) survey of the Antarctic shag (*Leucocarbo bransfieldensis*) breeding colony at Harmony Point, Nelson Island, South Shetland Islands. *Polar Biology* 43: 187–191. doi:10.1007/s00300-019-02616-y

PALECZNY, M., HAMMILL, E., KARPOUZI, V. & PAULY, D. 2015. Population trend of the world's monitored seabirds, 1950–2010. *PLoS One* 10: e0129342. doi:10.1371/journal.pone.0129342

PARK, M. 2020. *Spatial distribution analysis of Black-legged Kittiwakes and Northern Fulmars in Svalbard coastal cliffs using remotely piloted aircraft system*. MSc Thesis. Seoul, South Korea: Seoul National University.

PARKER, G.C. & REXER-HUBER, K. 2020. *Drone-based Salvin's Albatross Population Assessment: Feasibility at the Bounty Islands*. Dunedin, New Zealand: Conservation Services Programme, Department of Conservation.

PFEIFER, C., BARBOSA, A., MUSTAFA, O., PETER, H.-U., RÜMMLER, M.-C. & BRENNING, A. 2019. Using fixed-wing UAV for detecting and mapping the distribution and abundance of penguins on the South Shetlands Islands, Antarctica. *Drones* 3: 39. doi:10.3390/drones3020039

RADJAWALI, I., PYE, O. & FLITNER, M. 2017. Recognition through reconnaissance? Using drones for counter-mapping in Indonesia. *Journal of Peasant Studies* 44: 817–833. doi:10.1080/03066150.2016.1264937

RAOULT, V., COLEFAX, A.P., ALLAN, B.M., ET AL. 2020. Operational protocols for the use of drones in marine animal research. *Drones* 4: 64. doi:10.3390/drones4040064

RATCLIFFE, N., GUIHEN, D., ROBST, J., CROFTS, S., STANWORTH, A. & ENDERLEIN, P. 2015. A protocol for the aerial survey of penguin colonies using UAVs. *Journal of Unmanned Vehicle Systems* 3: 95–101. doi:10.1139/juvs-2015-0006

REINTSMA, K.M., MCGOWAN, P.C., CALLAHAN, C. ET AL. 2018. Preliminary evaluation of behavioral response of nesting waterbirds to small unmanned aircraft flight. *Waterbirds* 41: 326–331. doi:10.1675/063.041.0314

REXER-HUBER K., PARKER K.A., PARKER G.C. 2020. *Campbell Island Seabirds: Operation Endurance November 2019*. Dunedin, New Zealand: Marine and Species Threats, Department of Conservation.

ROCHMAN, C.M., BROWNE, M.A., UNDERWOOD, A.J. ET AL. 2016. The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. *Ecology* 97: 302–312. doi:10.1890/14-2070.1.

ROMAN, L., KASTURY, F., PETIT, S. ET AL. 2020. Plastic, nutrition and pollution; relationships between ingested plastic and metal concentrations in the livers of two Pachyptila seabirds. *Scientific Reports* 10: 18023. doi:10.1038/s41598-020-75024-6

ROSS, K.E, BALMER, D.E, HUMPHREYS, E., AUSTIN, G., GODDARD, B. & REHFISCH, M. 2016. *Urban Breeding Gull Surveys: A Review of Methods and Options for Survey Design*. Thetford, UK: British Trust for Ornithology.

RÜMMLER, M.-C., ESEFELD, J., PFEIFER, C. & MUSTAFA, O. 2021. Effects of UAV overflight height, UAV type, and season on the behaviour of Emperor penguin adults and chicks. *Remote Sensing Applications: Society and Environment* 23: 100558. doi:10.1016/j.rsase.2021.100558

RÜMMLER, M.-C., MUSTAFA, O., MAERCKER, J., PETER, H.-U. & ESEFELD, J. 2016. Measuring the influence of unmanned aerial vehicles on Adélie penguins. *Polar Biology* 39: 1329–1334. doi:10.1007/s00300-015-1838-1

RÜMMLER, M.-C., MUSTAFA, O., MAERCKER, J., PETER, H.-U. & ESEFELD, J. 2018. Sensitivity of Adélie and Gentoo penguins to various flight activities of a micro UAV. *Polar Biology* 41: 2481–2493. doi:10.1007/s00300-018-2385-3

RUSH, G.P., CLARKE, L.E., STONE, M. & WOOD, M.J. 2018. Can drones count gulls? Minimal disturbance and semiautomated image processing with an unmanned aerial vehicle for colony-nesting seabirds. *Ecology and Evolution* 8: 12322–12334. doi:10.1002/ece3.4495

SARDÀ-PALOMERA, F., BOTA, G., VIÑOLO, C. ET AL. 2012. Fine-scale bird monitoring from light unmanned aircraft systems. *Ibis* 154: 177–183. doi:10.1111/j.1474-919X.2011.01177.x

SCARTON, F. & VALLE, R. 2021. Drone assessment of habitat selection and breeding success of Gull-billed Tern *Gelochelidon nilotica* nesting on low-accessibility sites: a case study. *Rivista Italiana di Ornitologia* 90: 69–76. doi:10.4081/rio.2020.475

SCARTON, F. & VALLE, R. G. 2022. Comparison of drone vs. ground survey monitoring of hatching success in the black-headed gull (*Chroicocephalus ridibundus*). *Ornithology Research* 30: 271–280. doi:10.1007/s43388-022-00112-2

SHEWRING, M.P. & VAFIDIS, J.O. 2021. Using UAV-mounted thermal cameras to detect the presence of nesting nightjar in upland clear-fell: A case study in South Wales, UK. *Ecological Solutions and Evidence* 2: e12052. doi:10.1002/2688-8319.12052

SINCLAIR, N.C., HARRIS, M.P., NAGER, R.G., LEAKEY, C.D.B. & ROBBINS, A.M. 2017. Nocturnal colony attendance by common guillemots *Uria aalge* at colony in Shetland during the pre-breeding season. *Seabird* 30: 51–62.

SWANSON, A., KOSMALA, M., LINTOTT, C. & PACKER, C. 2016. A generalized approach for producing, quantifying, and validating citizen science data from wildlife images. *Conservation Biology* 30: 520–531. doi:10.1111/cobi.12695

THAXTER, C.B. & BURTON, N.H.K. 2009. *High Definition Imagery for Surveying Seabirds and Marine Mammals: A Review of Recent Trials and Development of Protocols*. Thetford, UK: British Trust for Ornithology.

VACCA, A. & ONISHI, H. 2017. Drones: military weapons, surveillance or mapping tools for environmental monitoring? The need for legal framework is required. *Transportation Research Procedia* 25: 51–62. doi:10.1016/j.trpro.2017.05.209

VALLE, R.G. & SCARTON, F. 2021a. Drone-conducted counts as a tool for the rapid assessment of productivity of Sandwich Terns (*Thalasseus sandvicensis*). *Journal of Ornitholog*y 162: 621–628. doi:10.1007/s10336-020-01854-w

VALLE, R. G. & SCARTON, F. 2021b. Monitoring the hatching success of gulls Laridae and terns Sternidae: A comparison of ground and drone methods. *Acta Ornithologica* 56: 241–254. doi:10.3161/00016454AO2021.56.2.010

VAS, E., LESCROËL, A., DURIEZ, O., BOGUSZEWSKI, G. & GRÉMILLET, D. 2015. Approaching birds with drones: first experiments and ethical guidelines. *Biology Letters* 11: 20140754. doi:10.1098/rsbl.2014.0754

VERFUSS, U.K., ANICETO, A.S., HARRIS, D.V. ET AL. 2019. A review of unmanned vehicles for the detection and monitoring of marine fauna. *Marine Pollution Bulletin* 140: 17–29. doi:10.1016/j.marpolbul.2019.01.009

VILLEGAS, P., MENA, L., CONSTANTINE, A., VILLALBA, R. & OCHOA, D. 2018. Data imaging acquisition and processing as a methodology for estimating the population of frigates using UAVs. *2018 IEEE ANDESCON*, 1–4. doi:10.1109/ANDESCON.2018.8564660

WALSH, P.M., HALLEY, D.J., HARRIS, M.P., DEL NEVO, A., SIM, I.M.W. & TASKER, M.L. 1995. *Seabird Monitoring Handbook for Britain and Ireland*. Peterborough, UK: JNCC /RSPB /ITE / Seabird Group.

WALUDA, C.M., DUNN, M.J., CURTIS, M.L. & FRETWELL, P.T. 2014. Assessing penguin colony size and distribution using digital mapping and satellite remote sensing. *Polar Biology* 37: 1849–1855. doi:10.1007/s00300-014-1566-y

WANG, D., SHAO, Q. & YUE, H. 2019. Surveying wild animals from satellites, manned aircraft and Unmanned Aerial Systems (UASs): A Review. *Remote Sensing* 11: 1308. doi:10.3390/rs11111308

WEIMERSKIRCH, H., PRUDOR, A. & SCHULL, Q. 2018. Flights of drones over sub-Antarctic seabirds show species- and status-specific behavioural and physiological responses. *Polar Biology* 41: 259–266. doi:10.1007/s00300-017-2187-z

WEINSTEIN, B.G., GARNER, L., SACCOMANNO, V.R., ET AL. 2021. A general deep learning model for bird detection in high resolution airborne imagery. *Ecological Applications* 32: e2694. doi:10.1002/eap.2694

WITCZUK, J, PAGACZ, S., ZMARZ, A. & CYPEL, M. 2018. Exploring the feasibility of unmanned aerial vehicles and thermal imaging for ungulate surveys in forests - preliminary results. *International Journal of Remote Sensing* 39: 15–16. doi:10.1080/01431161.2017.1390621

WOOD, M. J. 2022. *Using UAVs in seabird research & monitoring: workshop at the 14th International Seabird Group Conference 2018*. [Accessed at https://doi.org/10.17605/OSF.IO/2MJVX on 28 January 2023.] doi:10.17605/OSF.IO/2MJVX

ZOONIVERSE 2021. *Welcome to the Zooniverse*. [Accessed at https://www.zooniverse.org/ on 11 November 2021.]