THE POTENTIAL OF ECOLOGISTS TO ENHANCE OUR UNDERSTANDING OF SEABIRD HEALTH

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ABSTRACT

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Ecologists play a pivotal role in the detection and investigation of population changes in seabirds and by doing so have significant potential to contribute to enhancing knowledge of seabird health. This review highlights key examples in the literature where ecologists have employed diligent passive health surveillance and/or undertaken targeted investigations of seabirds, strategies that have augmented our knowledge of seabird health at individual and population levels. Within the context of One Health, an integrated approach to perceiving and managing health, this review amalgamates veterinarian and ecology disciplines by summarising auxiliary metrics of clinical health that may be considered for incorporation into ongoing fieldwork. A focus on effective surveillance will advance understanding of disease processes impacting seabird health.

Key words: passive, active, surveillance, One Health, auxiliary sample

INTRODUCTION

Seabirds are among some of the most threatened taxa globally (Dias *et al*. 2019) and are commonly regarded as biological indicators of ecosystem health (Frederiksen *et al*. 2007). They serve as engineers and regulators of the terrestrial environments where they nest and the marine environments that sustain them, through inputting nutrients, physical disturbance (Ellis 2005, Duda *et al*. 2020), and top-down biomass consumption (Cury *et al*. 2011). They are conspicuous indicators of highly variable marine environments and are thus the subject of long-term research programs investigating ecological trends (Micol *et al.* 2001, Inchausti *et al*. 2003, Einoder 2009, Rolland *et al*. 2009, Ainley *et al*. 2010, Lahoz-Monfort *et al*. 2013, Chambers *et al*. 2015). Research programs routinely include general census and breeding phenology, such as number of breeding pairs and reproductive success (Micol & Jouventin 2001), mass and body condition (Tella *et al*. 2001, Robinson *et al*. 2005), foraging effort (Cohen *et al*. 2014, Berlincourt *et al.* 2015), and survivorship or dispersal through mark-recapture investigations (Sandvik *et al.* 2005, Votier *et al*. 2008). However, clinical seabird health often receives less focus in longitudinal studies. This prospective review considers the value of placing greater focus on auxiliary health metrics in long-term seabird monitoring programs to enhance effective health surveillance.

Health is broadly described as a state of normal functioning, with poor health and disease being integral components of ecosystem functioning (Brooks *et al*. 2008). These natural processes may be exacerbated, or go undetected, with the co-occurrence of other factors such as resource competition, human disturbance, or climate extremes (Heard *et al*. 2013). Achieving a holistic understanding of wild seabird population health can be challenging because the recovery rates of carcasses is low (Pacioni *et al*. 2015). Moreover, ubiquitous pathogens that cause mass mortality events are rare, and cryptic subclinical diseases that have individual and population level impacts often go undetected (Barbosa 2010). In addition to other compounding threats, subtle variation in individual health may contribute to population dynamics by influencing demographic parameters such as mortality, recruitment, or fecundity (Preece *et al*. 2017, Will *et al.* 2020). Adaptive management can employ intervention strategies on health perturbances to alleviate the impacts of pervasive threats. For example, avian insecticide has been applied to Shy Albatross *Thalassarche cauta* chicks to reduce the prevalence of vector-transmitted pathogens, a procedure that has led to overall increases in chick survival (Alderman *et al.* 2017); and food supplementation of Magnificent Frigatebird *Fregata magnificens* chicks has reduced nutritional stress and improved body condition, preventing individuals from succumbing to recurrent herpesvirus outbreaks (Sebastiano *et al.* 2019).

Contemporary processes that are a threat to all seabird species have been systematically reviewed (Dias *et al*. 2019), the most pervasive of which are invasive alien species, bycatch, hunting, climate change, and disturbance. Interestingly, pathogens and disease are reported as threats that impact very few species, and a similar report published over a decade ago (Croxall *et al*. 2012) did not list pathogens as a factor threatening populations at all. Conversely, diseases and pathogens have been reviewed and highlighted as a key threat in the context of penguins (Ropert-Coudert *et al*. 2019). In recent months, highly pathogenic avian influenza outbreaks have decimated entire populations of seabirds in the northern hemisphere (Dewar *et al*. 2022, Ramey *et al*. 2022), highlighting the considerable role that pathogens and diseases have on individuals and populations. Impacts of terrestrially-based invasive species are widely considered a high priority threat due to direct predation or habitat loss (Dilley *et al*. 2016, Cleeland *et al*. 2020). However, the associated exposure to novel pathogens and subsequent threat of disease is rarely mentioned (Dias *et al*. 2019) despite its potentially significant impact on individual and population health (Duignan 2001, Barbosa 2010). Seabird health can also be affected by pathogen transmission between seabirds and alien species, such as the dissemination of *Toxoplasma gondii* from felines (causing toxoplasmosis) or *Pasteurella multocida* from poultry (causing cholera); however, this source of disease is rarely addressed by ecological monitoring programs (Leotta *et al*. 2003, Ploeg *et al*. 2011, Poulle *et al*. 2021, Campbell *et al*. 2022). The majority of the literature that reviews seabird health as it relates to infectious agents primarily describes impacts on threatened albatross and petrels (Uhart *et al*. 2018), Antarctic species (Kerry *et al*. 1999, Barbosa *et al*. 2009, Woods *et al*. 2009, Barbosa 2010, Grimaldi *et al*. 2010, Diaz *et al*. 2017, Smeele *et al*. 2018, Wille *et al*. 2020), and penguins (Clarke *et al*. 2000, Duignan 2001, Grimaldi *et al*. 2015).

Pollution is recognized as another prominent threat to the health of seabirds (Dias *et al*. 2019). The widely publicised and overtly disturbing consequences of oiling, plastic ingestion, or entanglement are directly linked to reduced seabird health or survival (Ryan 2018, Puskic *et al*. 2020). Other pollutants have less overt effects on the health of individual seabirds. Heavy metals, trace elements, and persistent organic pollutants artificially enter waterways from anthropogenic sources (Shahidul Islam *et al*. 2004), bioaccumulating within higher order predators and leading to immunosuppression and endocrinological inhibition (Sagerup *et al*. 2009, Blévin *et al*. 2014, Fort *et al*. 2015, Megan 2018, Sebastiano *et al*. 2020, Soldatini *et al*. 2020, Sonne *et al*. 2020, Thébault *et al*. 2020, Sebastiano *et al*. 2021). Toxicity from persistent substances, which are now globally widespread and ubiquitous within marine environments (Carravieri *et al*. 2020, Chastel *et al*. 2022), is increasingly being investigated in relation to sublethal perturbances to the health of wild free-living populations. Correlations between delayed egg loss, reduced body condition, and toxicity from persistent organic pollutants in Great Skuas *Stercorarius skua* have shown overall lowered juvenile survival (Bustnes *et al*. 2015). Mercury toxicity, known to effect the function of the hormone-regulating pituitary gland, has been correlated with egg neglect in Snow Petrels *Pagodroma nivea* (Tartu *et al*. 2015), breeding sabbaticals in Black-legged Kittiwakes *Rissa tridactyla* (Tartu *et al*. 2013), and shorter telomere lengths leading to reduced life expectancy in Cory's Shearwaters *Calonectris borealis* (Bauch *et al*. 2022). Increased toxicity burden has been suggested as a contributing factor to seabird wrecks along North Atlantic coasts; the highest heavy metal concentrations ever reported in seabirds was recorded in multiple species during a winter wreck in this region (Fort *et al*. 2015). While the direct aetiology of beach cast carcasses is impossible to infer from such an investigation, it is likely that the cumulative impacts of multiple stressors on individual health are leading to immunosuppressed individuals, which may decrease resilience within a changing world. This synergistic interplay of multiple threats directly impacting clinical health has been noted through a case study on tropical seabird populations of French Guiana (Sebastiano *et al*. 2022). The authors also explored causative links between toxicity burden (Sebastiano *et al*. 2017) and nutritional stress (Sebastiano *et al*. 2018) to disease prevalence and found acutely severe consequences of both contributing factors. These findings highlight the urgent need to understand and mitigate these multifactorial threats.

SURVEILLANCE BEGINS IN THE FIELD

Knowledge of the heath of wild seabird populations is advancing through targeted investigations that are usually published in veterinary journals (Smith *et al*. 2008, Parsons *et al*. 2016, Park *et al*. 2021, Tucker-Retter *et al*. 2021), although this area of research is expanding in the ecological literature (Gamble *et al*. 2020a, 2020b, Wilkinson *et al*. 2022). Investigations often examine variation in clinical health parameters of 'healthy' populations that are free from overt pathogen outbreaks. These investigations establish reference ranges and lead to cross-sectional views of population health. Although health diagnostics are carried out by specialised pathologists, effective surveillance begins in the field, and ecologists and managers play key roles in the detection of health perturbances in seabird populations (Ryser-Degiorgis 2013, Preece *et al*. 2017).

Seabird ecological studies often focus on populations and their interactions, using individual-based approaches to make inferences about the broader population (Barbraud *et al*. 2011). Often, less consideration is given to individual health in a more introspective clinical sense, perhaps reflecting a perception that health is merely an absence of disease. This focus does not allow for the detection of subtle non-lethal variations in individuals (Stephen 2019). Targeted health investigations are often reactive and revolve around the response and control of pathogen-disease outbreaks (Alley *et al*. 2004, Cooper *et al*. 2009, Fullick *et al*. 2022). These studies often occur in the absence of baseline knowledge of basic physiological parameters and adequate reference ranges of what constitutes a healthy population (Kophamel *et al*. 2021). Consequently, management or intervention actions are often made based on limited information (Deem *et al*. 2008, Woods *et al*. 2019). The dissemination of population-specific baseline data, particularly data derived from healthy individuals, is fundamental to identify spatial or temporal trends in physiological parameters, and to infer any perturbances to these parameters in healthy individuals in the future (Hawkey *et al*. 1989, Edwards *et al*. 2006, D'Amico *et al*. 2014, De Mas *et al*. 2015, Valle *et al*. 2020).

Long-term studies are imperative for effective health surveillance and the identification of 'normal' functioning (Micol & Jouventin 2001, Weimerskirch *et al*. 2003). For example, as part of an on-going 35+ year monitoring program, unusual observations of lesions on Marion Island Wandering Albatross *Diomedea exulans* warranted a targeted epidemiological investigation, resulting in the detection of avian pox (Schoombie *et al*. 2018). These findings generated a retrospective analysis of similar abnormalities, revealing historical incidences of similar outbreaks. Ecologists working in the field are perhaps an underutilised resource for understanding seabird health, and they have tremendous potential to enhance understanding and reveal insights into individual and population health through the collection of auxiliary information (Mallory *et al*. 2010, Bestley *et al*. 2020).

The scope of this prospective review is to discuss the utility of auxiliary metrics of health through key examples in the literature that have progressed our knowledge in this field. This manuscript provides an exploration of biological information that can be collected relatively easily and incorporated into routine monitoring activities undertaken by seabird ecologists. The goal is to encourage ecologists to collaborate with veterinarians and to consider the incorporation of a passive health surveillance initiative in on-going monitoring programs. The intent is not to undermine the value of wildlife health professionals, but to amalgamate disciplines to advance understanding of disease processes and health in seabirds. The One Health concept calls for interdisciplinary approaches to maintaining and managing healthy populations and emphasises the interconnectedness of the health of our environment, animal, and human populations (Destoumieux-Garzón *et al*. 2018). Although this concept is not new, segregation between the veterinary and ecology disciplines persists in the literature (Manlove *et al*. 2016). Ecology investigations can evolve through the consultation and collaboration of veterinarians at all project stages. This involvement can be as simple as seeking prior advice regarding procedures and equipment or involving a specialised wildlife health professional in part of the field team. Partnerships with wildlife veterinarians can be established through wildlife veterinarian associations, wildlife health networks, rehabilitation clinics, or zoos and aquariums.

PASSIVE SURVEILLANCE

In the absence of an apparent health concern to target investigative methodology (e.g., mass mortality or obvious morbidity), ecologists in the field also strive to enhance passive surveillance of health during routine population monitoring. A potential pitfall of such an objective is that sampling naturally selects for the overtly clinically healthy individuals of a population because discovery rates of sick or deceased individuals are low (Mörner *et al*. 2012). However, as already described, studying health in healthy individuals still has value; Mallory *et al*. (2010) advocate for a proactive approach to health monitoring of seabirds as sentinels of marine ecosystem health through the collection of auxiliary physiological proxies of individual health across spatial and temporal scales during routine fieldwork. By adding an element of health information to already existing ecological monitoring, this may elucidate the subtle non-lethal impacts that stressors have on individuals. This may work to disentangle chronic or acute stressors and to correlate population-level changes to health perturbances. Of key significance to capturing the variability of individual health within a population is understanding what is considered 'healthy.' This information provides a reference against which any perturbances can be measured. Perhaps the incorporation of a health score card that a fieldworker can use to rapidly assess an individual's physical, behavioural, and neurological status can assist in detecting perturbances. Additionally, the routine collection and storage of auxiliary biological samples from individuals (Table 1) as part of on-going monitoring programs would be invaluable for retrospective health investigations and for the discovery of novel infectious and non-infectious disease-causing agents within a system (Schoombie *et al*. 2018).

Body condition as an estimate for fat reserves provides a primary indication of individual health, and several approaches to infer body condition can be considered (Brown 1996, Labocha *et al*. 2012). A decline in body condition is typically the first sign of a perturbance to health and has been correlated with parasitism, pathogenic agents (Sebastiano *et al*. 2019, Sanz-Aguilar *et al*. 2020), reduced immunocompetence (Tella *et al*. 2001), habitat loss (Burton *et al*. 2006), and pollutant load (Eckbo *et al*. 2019). Additionally, observations of any physical or behavioural abnormalities should be explored and can only be ascertained through on-going monitoring. Observations of parasites can also be used to infer important health information; for example, opportunistic scat collections can assist with examinations for endoparasites through faecal floats and morphological identification or DNA metabarcoding. The collection of ectoparasites in nest material or during routine inspection can be used as an ongoing surveillance tool for the parasites themselves and the pathogens they can transmit. Systematic assessments of parasite infestations have been directly linked to cause of death (Gauthier-Clerc *et al*. 1998, Bergström *et al*. 1999, Gamble *et al*. 2020b) and disease transmission (Wang *et al*. 2014, Vanstreels *et al*. 2016b, Khan *et al*. 2019) in seabird species.

Haematological indicators of health can reveal significant information because blood is considered the single most informative, non-destructive tissue that can elicit an understanding into whole-organism functioning (Maceda-Veiga *et al*. 2015). In a recent review of methodology used for wildlife health assessments on vertebrate species, haematology was highlighted as the most commonly applied tool (Kophamel *et al*. 2021). Just one drop of blood, smeared on a glass slide and fixed with methanol *in situ*, can reveal critical information about cell functioning, an individual's stress response, the presence of disease-causing hemoparasites, or genotoxic effects (Samour 2006, Vanstreels *et al*. 2015, Montero *et al*. 2016, Menéndez-Blázquez *et al*. 2021). There is value in considering the incorporation of this standard health parameter into surveillance. However, ethics must be considered for any invasive procedure such as blood extraction. To minimize disturbance to the seabird, this auxiliary health sample should only be considered in conjunction with blood sampling that is already being carried out. Blood extraction of any amount has associated risks and should only be conducted by appropriately trained individuals. A blood smear is cheap and easy to collect and can be stored long-term if fixed and stained correctly (Houwen 2002). Differential counts of white blood cells (leukocytes) and their relative proportions can signify inflammation or infection, highlighting individuals within a population that may be immunocompromised or chronically stressed. The relative proportions of different blood cells in a sample can also assist in disease aetiology (i.e., bacterial vs. viral infection). Leukocyte ratios have been correlated with periods of intense energy demand such as moulting or breeding (Mortimer & Lill 2007, Palacios *et al*. 2018) and with injured birds (Vleck *et al*. 2000), suggestive of life stages where individuals may elicit an innate immune response and could therefore be vulnerable to disease processes. Furthermore, blood smears are vital in the detection of hemoparasites, which are capable of transmitting pathogens (Valkiūnas *et al*. 2008). For example, blood smears have detected *Plasmodium*, which can cause highly infectious avian malaria (Clarke & Kerry 2000, Vanstreels *et al*. 2016b), and hemoparasites transmitted by ticks like *Babesia* sp. in penguins (Vanstreels *et al*. 2015, Montero *et al*. 2016).

Passive health monitoring through the collection and analysis of carcasses is at the forefront of any sort of disease surveillance regime and should be considered among the simplest of practices an ecologist could implement in their field program (Mörner & Beasley 2012, Pacioni *et al*. 2015). This practice is key in opportunistic and early disease detection, as well as for ongoing monitoring of existing disease, though additional biosecurity precautions must be followed if there is reason to suspect the involvement of an infectious agent (Dewar *et al*. 2022). Long-term investigations into the mortality of Yellow-eyed Penguins *Megadyptes antipodes* have revealed underlying infections by aspergillosis and avian malaria (Alley *et al*. 2004). Similarly, opportunistic investigations

TABLE 1
Review of auxiliary samples which may be collected during ecological monitoring that can enhance capability for effective health surveillance and associated health applications

Sample type	Applications for health insights	Applicable references and examples
Blood	Haematology, biochemistry, molecular biology, endocrinology (corticosteroid), immunology, toxicology, serology, parasitology, stable isotopes (diet)	Barbosa *et al*. 2006, Barbosa *et al*. 2007, Mitchell *et al*. 2008, Gilbert *et al*. 2013, Herborn *et al*. 2014, Campbell 2015, Maceda-Veiga *et al*. 2015, Minias 2015, Vogt *et al*. 2020, Colominas-Ciuró *et al*. 2021
Carcass	Aetiology (histopathology, toxicology, microbiology, parasitology), metadata may lead to disease investigation	Vidal *et al*. 2012, Jerez *et al*. 2013, Tavares *et al*. 2016, Vanstreels *et al*. 2016a, Vanstreels *et al*. 2019, Ventura *et al*. 2021
Eggshell	Toxicology, bacteriology	Burger *et al*. 1995, Pérez De Vargas *et al*. 2020, Kuepper *et al*. 2022
Feather	Toxicology, endocrinology (corticosteroid), stable isotopes (diet)	Jaspers *et al*. 2007, Jerez *et al*. 2011, Koren *et al*. 2012, Rutkowska *et al*. 2018, Jaspers *et al*. 2019, Will *et al*. 2019
Morphometrics	Body condition, fitness	Jacobs *et al*. 2012, Labocha & Hayes 2012, Reusch *et al*. 2022
Parasite	Parasites themselves can impact host e.g., cause anaemia or can act as a vector for pathogen transmission.	Thompson *et al*. 2010, Watson 2013, Matos *et al*. 2020, Dharmarajan *et al*. 2021
Preen gland oil	Toxicology, endocrinology (corticosteroid)	Jaspers, 2008, Solheim *et al*. 2016, Yamashita *et al*. 2021
Scat	Stable isotopes (diet), parasitology, microbiome	Dewar *et al*. 2014, McInnes *et al*. 2017, Mykhailenko *et al*. 2020, Cabodevilla *et al*. 2022
Swab (cloacal, oropharynx)	Microbiome, pathogens, parasitology	Fereidouni *et al*. 2012, Dynowska *et al*. 2013, Stenkat *et al*. 2014, Barbosa *et al*. 2016

into beach cast Little Penguin *Eudyptula minor* carcasses have revealed the previously undocumented infection of disease-causing *Haemoproteus* sp. parasites (Cannell *et al*. 2013). While in both instances it is impossible to determine the definitive causes of death, the post-mortem investigations conducted by specialised pathologists revealed key insights into disease processes likely at play in both penguin populations. This information forms the foundation for conducting a targeted disease assessment, which can be applied to other populations. As an initial step, tissue samples of organs should be collected from fresh carcasses if timely processing can be achieved and samples kept cool; in cases where processing is delayed, tissue samples should be fixed in 10% formalin in sample jars. Alternatively, or additionally, collaboration with veterinary schools through the provision of carcasses could be a fundamental step in achieving effective surveillance. The incorporation of a passive health surveillance toolkit (Fig. 1) that can be included in an ecologists' field kit would enable the opportunistic collection of fresh specimens and should be considered. This would enhance the capacity for any disease diagnosis or the identification of health perturbances.

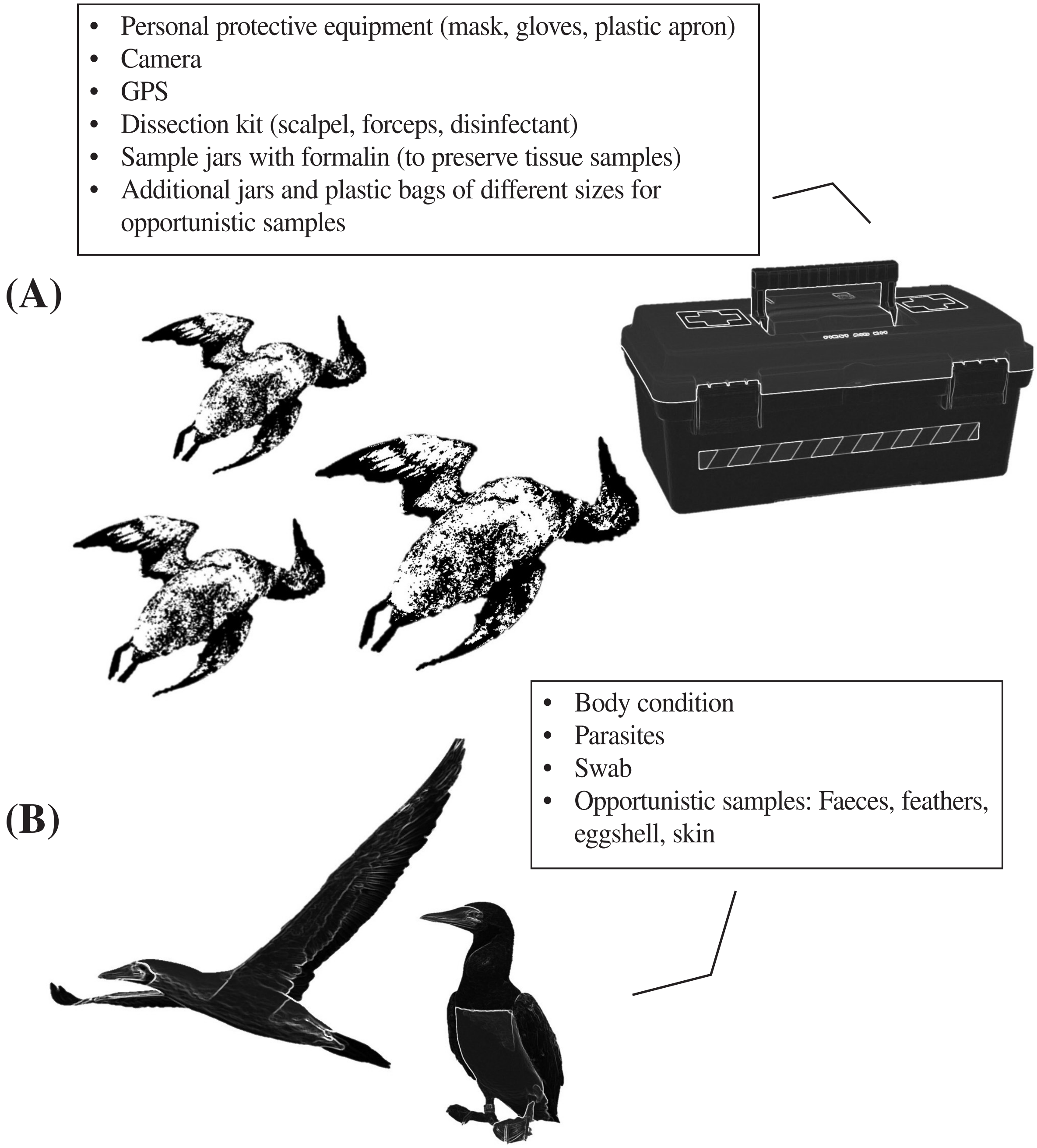
Further analysis may be performed on carcasses with conspicuous indicators of morbidity, such as lesions or obvious evidence of disease (Cannell *et al*. 2013, Pacioni *et al*. 2015, Martín *et al*. 2016). Additionally, biological samples from carcasses, such as fresh tissues, can have great value in the discipline of ecotoxicology. Toxic algal blooms associated with a marine heatwave are thought to be an added factor leading to mass seabird die-offs in the Gulf of Alaska, as established by targeted toxicological analysis from beach cast carcasses (Van Hemert *et al*. 2020). The organs from fresh carcasses collected during seabird 'wrecks' in the North Atlantic Ocean (wrecks generally attributed to extreme climatic conditions) have been opportunistically sampled for heavy metals, recording some of the highest toxicity levels reported in the species involved (Fort *et al*. 2015). The analysis of penguin bones collected opportunistically within rookeries has revealed higher concentrations of trace elements in a population subject to greater levels of human disturbance (Barbosa *et al*. 2013).

Although the assessment of carcasses may provide only a narrow window of insight into the individual and population health of seabirds, these opportunistic investigations enhance our knowledge and build a holistic picture, as well as catalogue the biological utility of seabirds as sentinels for environmental health. These insights assist in disentangling the multifactorial pressures that may be influencing population dynamics. Additionally, biological samples such as feathers, collected opportunistically and non-invasively from moulting penguins, have revealed heavy metal and trace element toxicity in this species (Jerez *et al*. 2011, Motas *et al*. 2021). The effectiveness of this opportunistic method of feather collection for toxicology analyses is equivalent to more invasive blood sampling methods (Finger *et al*. 2015), particularly for penguins that moult their entire plumage annually during a short period. Furthermore, the analysis of dried membranes from opportunistically collected Wilson's Storm Petrel *Oceanites oceanicus* eggs that were abandoned or hatched across an 18-year period revealed trends in persistent organic pollutant and heavy metal toxicity (Kuepper *et al*. 2022). Finally, an auxiliary scat sample, collected as fresh material or as a cloacal swab, can enhance pathogen investigations (Mykhailenko *et al*. 2020) or the identification of enteric parasites through DNA metabarcoding (McInnes *et al*. 2017).

Long-term sample archiving should be considered prior to collection. Some samples require few resources to preserve long-term (feathers, eggshells, blood smears, or formalin-fixed tissues), whereas others are more resource- and funding-dependant. In the absence of fresh carcasses or the ability to collect and preserve or store specimens, the value of gathering metadata regarding incidence and prevalence of deceased or sick individuals should not be overlooked, particularly in longitudinal studies. For example, observations of nestling mortality in the Black-browed Albatross *Thalassarche melanophris* of the Falkland Islands over a five-year period examined the spatio-temporal clustering of carcasses and age at death. Results have been suggestive of the occurrence of an infectious agent and warrant targeted investigation (Ventura *et al*. 2021). This proactive approach to passive health surveillance is the foundation for a targeted active health investigation and is key to preventing future disease outbreaks.

ACTIVE SURVEILLANCE

Active health surveillance investigations are targeted and require specialized advice from health professionals prior to sampling (Ryser-Degiorgis 2013). These investigations may occur in response to a specific event (often mass mortality), following observations



- Personal protective equipment (mask, gloves, plastic apron)
- Camera
- GPS
- Dissection kit (scalpel, forceps, disinfectant)
- Sample jars with formalin (to preserve tissue samples)
- Additional jars and plastic bags of different sizes for opportunistic samples

- Body condition
- Parasites
- Swab
- Opportunistic samples: Faeces, feathers, eggshell, skin

Fig. 1. (A) Contents of a passive health surveillance toolkit ecologists can include in field kits, and (B) some auxiliary metrics of health which may be collected during routine ecological monitoring of healthy individuals that can enhance the capacity for effective passive health surveillance.

of clinical symptoms of disease in individuals (Weimerskirch 2004, Schoombie *et al*. 2018), or when screening of individuals for antibodies to selected pathogens (Padilla *et al*. 2006, Tucker-Retter *et al*. 2021). Strict biosecurity measures and precautions, such as appropriate personal protective equipment, sanitisation of equipment, and meticulous personal hygiene should always be followed (Barbosa *et al*. 2021), especially if there is reason to suspect the involvement of an infectious agent (such as following a mass mortality event or amidst obvious morbidity; Dewar *et al*. 2022). More invasive sampling procedures, such as collection of swabs or blood extraction from wild free-living individuals—which are typically associated with active surveillance investigations—cause additional stress and disturbance. Therefore, which sampling techniques are proposed and whether they can be ethically justified in relation to project aims should be critically evaluated given the sensitive nature of seabirds to disturbance (Weimerskirch *et al*. 2002, Carey 2009). Furthermore, the specific methods, equipment, and storage required for the collection of any samples must be carefully considered in advance. Fresh biological samples, such as blood or genetic material, are highly perishable outside of the body. Advice from a pathologist or an epidemiologist should be sought to ensure that optimal collection and storage of samples is achieved.

For investigations into the exact aetiology of carcasses, accurate post-mortems require specialised assessment of fresh specimens by a pathologist (Artois *et al*. 2009). Targeted 'health evaluation' style investigations have been conducted on threatened penguin species to investigate the presence of potential disease-causing pathogens in wild free-living populations, often using serological methods (Karesh *et al*. 1999, Padilla *et al*. 2006, Travis *et al*. 2006, Smith *et al*. 2008, Parsons *et al*. 2016, Uhart *et al*. 2020). These assessments establish baseline knowledge of pathogens circulating among populations, with applications for adaptive management to prevent potential disease outbreaks in at risk populations, particularly colonial and threatened species. These investigations require a disease risk assessment to identify both the populations and pathogens of interest that have the potential to cause morbid disease outbreaks. Additionally, knowledge of, or access to, pathological analytical methods is also required. The World Organisation for Animal Health has developed guidelines for conducting species-specific disease risk assessments (Jakob-Hoff *et al*. 2014, OIE 2014), which builds the framework for targeted health objectives.

On-going targeted surveillance investigations of health can also assist in disentangling some of the multifactorial threats impacting seabird species. The decline of threatened Yellow-nosed Albatross *Diomedea chlororhynchos* breeding on Amsterdam Island has previously been attributed to bycatch from longline fishing. However, the ongoing passive surveillance of chick carcasses from fieldworkers over a 40+ year dataset detected suspicious mortality events that warranted targeted investigation (Weimerskirch 2004). The inquiry documented the aetiology and spread of the highly infectious avian cholera through serological analysis (Gamble *et al*. 2019, 2020a, Jaeger *et al*. 2019, Jaeger *et al*. 2020). This has resulted in the development of a vaccine and subsequent shifts in species management and research protocols to reduce the severity of disease outbreaks (Bourret *et al*. 2018). This case study is a shining example of ecologists implementing effective health surveillance within their field program, applying transdisciplinary collaborations leading to proactive disease management, and possibly preventing a future mass mortality event. This example emphasises the fundamental role that ecologists play in disease detection and the utility of long-term population trends and robust ecological data in fostering our understanding of perturbances to individual health and factors that influence species' declines.

CONCLUSION

It is likely that the cumulative impacts of multiple stressors on individual seabird health are leading to immunosuppressed individuals that may exhibit decreased resilience within a changing world. Ecologists can employ effective health surveillance during ongoing fieldwork, which is imperative for disease prevention and species management. As a primary step, surveillance can be achieved through the passive collection of metadata and fresh specimens from dead or moribund individuals. Additionally, the consideration of basic body condition, parasite-host observations, or the opportunistic collection of biological specimens can reveal significant insights into variability of individual health. Routine or opportunistic collection of eggshell, feathers, or scat samples have wide health applications and can serve as informative species or site-specific temporal baselines. Where feasible, the collection of a simple, yet highly informative blood smear will elicit valuable insights into individual function that can be incorporated if concurrent blood sampling procedures are planned. These observations are the building blocks for providing a holistic picture of individual and population health and disentangling the multifaceted processes threatening seabird populations.

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