



Viewpoint

Seabirds as indicators of aquatic ecosystem conditions: A case for gathering multiple proxies of seabird health

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ABSTRACT

The use of seabirds as sentinels of the condition of aquatic ecosystems has been well-established. Large environmental perturbations to aquatic food webs (e.g., chemical contamination, overfishing, particulate pollution) have all been detected or monitored by tracking seabirds at colonies. However, seabirds may elicit more subtle, sublethal responses that can also be used to track ecosystem health, or the health of seabird populations. In this article, we advocate for field researchers to plan *a priori* to collect a broader suite of samples when handling seabirds, and to reach out for collaboration with specialists (e.g., parasitologists, wildlife veterinarians). Collectively, such efforts will greatly improve our ability to establish baseline physiological and chemical levels for seabirds, against which we can detect future changes in aquatic ecosystems.

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1. Introduction

From tropical to polar regions, aquatic ecosystems change in response to natural cycles and anthropogenic stressors (Aebischer et al., 1990; Pauly and Maclean, 2003; ACIA, 2005). Seabirds are integral components of aquatic ecosystems. They forage over large geographic areas and feed at different trophic levels, and thus are often considered to be effective monitors of the condition and health of aquatic systems (Cairns, 1987; Furness and Camphuysen, 1997). Indeed, seabirds have been used to monitor pollution (Borgå et al., 2005, 2006; Braune et al., 2005; Elliott et al., 2005), sizes of fish stocks (e.g., Frederiksen et al., 2007), and effects of fisheries management practices (Véran et al., 2007; Einoder, 2009). Moreover, seabirds show ecological responses to changes in aquatic productivity (Frederiksen et al., 2006) or climate change (Thompson and Ollason, 2001), and thus monitoring of their populations or reproductive success provides an index of marine ecosystem responses to perturbation. Seabirds can be used as proxies to assess the impact of stressors on the spatial and temporal status of aquatic environments. For example, bird tissues can be used to assess levels and bioaccumulation of pollutants. When environmental conditions deteriorate, stress in seabirds may be manifested through reductions in reproductive effort, breeding success or sur-

vival. As migratory species, the health and success of seabirds may be affected by both local conditions near their breeding colonies (e.g., Duffy, 1983; Kuzyk et al., 2003) and by factors far from these locations (e.g., Bustnes et al., 2003; Pierce et al., 2004). Thus, by monitoring seabirds, we have the potential means to assess conditions across large aquatic regions.

Studies have shown that seabirds can show both dramatic responses to environmental change, e.g., seabird die-offs or “wrecks”, as well as much more subtle, sublethal, physiological effects. Seabird responses of the latter type are more useful in providing an early-warning indicator of ecosystem change. Seemingly benign activities, such as tourist visitation to penguin colonies, can elicit a stress response, indicated by higher baseline corticosterone levels in breeding birds (possibly associated with lower reproductive success; Ellenberg et al., 2007). White blood cell profiles, notably heterophil:lymphocyte (H:L) ratios, reflect immune status in birds, and are influenced by acute or chronic stress on individuals (e.g., Vleck et al., 2000). Contaminant levels may be associated with higher intensity of parasitic infections or reduced immune function (e.g., Grasman et al., 1996a; Grasman and Fox, 2001; Wayland et al., 2001, 2002), but there may also be positive, synergistic relationships between parasites and contaminants if parasites remove contaminants from bird tissues (e.g., Malek et al., 2007).

Furthermore, as highly mobile vectors, aquatic birds can move parasites and disease vast distances (e.g., Winker et al., 2007), potentially introducing pathogens to populations lacking immunity (e.g., Parker et al., 2006). Ongoing environmental changes could facilitate the establishment of these pathogens and parasites

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in regions where they were previously excluded (Marcogliese, 2001), which could have dramatic effects on local populations.

Although scientists often advocate the use of seabirds as biological monitors based on successes with this approach (e.g., Einoder, 2009), there are also challenges with the interpretation of results. Specifically, it can be unclear whether changes in an observed metric in seabird monitoring reflect local or large-scale environmental perturbation. Part of this problem is attributable to a lack of baseline data regarding physiological norms, diet composition, contaminant levels, as well as other factors that could provide useful insights into environmental conditions (similar issues arise with marine mammals; Burek et al., 2008). Baseline information is necessary to discern the normal variation around “health” parameters in healthy and stressed birds, but such baseline values are lacking across species’ ranges. In other cases, baseline data are available for only one or two metrics from a study, rather than a more desirable, comprehensive suite (e.g., Parker et al., 2006). Common indices of seabird health remain largely unstudied (or unreported), and in particular, few research programs appear to have made simultaneous observations of multiple indices of health. Chown and Gaston (2008, p. 1469) argued that “knowledge of physiological variation is required to understand organismal responses to and influences on environmental change”. This is an important issue limiting our understanding of how seabird health parameters can be used to assess the impact of environmental stressors on the state of ecosystems.

Fortunately, the paucity of baseline data is slowly being remedied. For example, the number of scientific papers reporting baseline levels of contamination in marine birds is increasing (including at least 22 papers in *Marine Pollution Bulletin*, 2003–2007). However, we contend that a more comprehensive, baseline sampling of seabirds would be relatively easy to acquire as part of existing monitoring programs, and could provide a much stronger indication of how aquatic systems are being affected by environmental change. Moreover, these additional collections would provide important, ancillary data to address gaps in our knowledge of seabirds (e.g., migration routes, population structure; Smith et al., 2003).

2. The advantages of range-wide, baseline “health” data

By definition, baseline studies set the benchmark against which future information is compared, and are a critical part of both theoretical and applied research. Some scientists either fail to publish these data (Clapham, 2005), or would argue that baseline ecological, toxicological or physiological data are not novel enough to merit publication as relatively few journals have outlets targeted for this information (but see *Marine Pollution Bulletin: Baseline*). However, we would argue that such baseline data are of critical importance. The lack of accessible, regional baseline “health” data is apparent in the Birds of North America species accounts (<http://bna.birds.cornell.edu/bna>). These are invaluable, well-cited “state of knowledge” reports on the natural history of each avian species that breeds in North America, but also serve as a gap analysis on missing information for most species. Notably, data on species’ physiology and contaminant levels are sparse and even well-studied species have major information gaps concerning their basic ecology.

Failing to publish or make accessible baseline data is a problem, but an equally egregious situation, and one made by most of us, including the lead author of this article (Mallory et al., 2004a, 2005), is to consider only the focal study when gathering new samples, and to not make full use of specimens during fresh sampling or prior to their disposal. While certain “baselines” can be established using archived specimens and modern analytical technolo-

gies (e.g., Thompson et al., 1992; Newsome et al., 2007; van der Pol and Becker, 2007), other spatial and temporal baseline data cannot be gathered without fresh specimens (Fox et al., 2007a,b). This is particularly true when considering physiological differences (or local adaptations) of broadly distributed species (e.g., Chown et al., 2004).

Macrophysiology consists of investigating variation in physiological traits over large geographic and temporal scales (i.e., different, range-wide baselines), and the ecological implications of this phenotypic variation (Chown et al., 2004). Such a broad approach is common practice in studies examining the ecology or behavior of species (e.g., Salomonsen, 1965), and to some extent in research on regional contamination of species (Borgå et al., 2005, 2006; Fox et al., 2007a,b, 2008). Despite the utility of physiological indices in capturing or explaining subtle effects of environmental stress on birds (e.g., Vleck et al., 2000; Fox et al., 2007a,b), regional investigations of seabird health and physiology remain few. Data on baseline seabird health and physiology are available principally from studies where there are conservation concerns (e.g., Sagerup et al., 2000; Verreault et al., 2004; Ellenberg et al., 2007), and do not appear to have been part of many standard sampling protocols during routine field operations (e.g., mark-recapture studies). This is unfortunate, because much of the information that could be gained does not require destructive sampling of birds, so once they are “in hand” for banding or morphometrics, it generally takes relatively little extra time and effort to acquire important ancillary samples (Table 1). Because the health and physiological tolerances of seabirds (and all other wildlife) are intimately linked to the adaptations necessary to survive in the organism’s environment, our failure to record these data limits our ability to discern the subtle effects that environmental change can have on these species.

Below, we provide two examples of seabird research where broad regional assessments of health metrics have begun to elucidate not only problems for seabird populations, but also broader issues of aquatic ecosystem change. These examples are both from regions in the Northern Hemisphere (i.e., Arctic, North American Great Lakes). We point out that there are many long-term seabird research sites distributed around the Southern Ocean (e.g., Antarctica and sub-Antarctic – Lormée et al., 1999; Takahashi et al., 2004; Angelier et al., 2006; Holmes, 2007; Wheeler et al., 2009), southern Indian Ocean (e.g., Crozet Islands – Weimerskirch et al., 2005), southern Pacific Ocean (e.g., New Zealand – Weimerskirch, 1998), and tropical regions (e.g., Hawaii – Fisher, 1969; Crawford and Cooper, 2003; Africa – Lewis et al., 2006), as well as many others from sites elsewhere in the northern hemisphere (e.g. Wanless et al., 2007; Hipfner, 2008). The questions of interest and types of sampling and monitoring that are permitted will clearly vary by region and species. Our intent in the following examples was simply to illustrate the benefits of expanded sampling for seabird health metrics, using sites or projects with which we were most familiar.

2.1. Examples from the Arctic

Long considered pristine, the Arctic is a marine region currently experiencing rapid environmental change, attributable to long-range transport of pollution (Braune et al., 2005), climate change (ACIA, 2005), and development pressures associated with industrial resource exploration and extraction. Marine food webs of this region tend to biomagnify contaminants, such that top level predators like seabirds can have relatively high contaminant burdens, despite being remote from pollution sources. There is marked geographic variation in contaminant levels around the circumpolar Arctic (Borgå et al., 2005, 2006), even within species or trophic levels. In glaucous gulls (*Larus hyperboreus*) breeding at Svalbard and Bear Island near the Barents Sea, relatively high concentrations of

Table 1

Most projects involving handling of seabirds can gather a basic suite of samples rapidly, which can immediately or eventually provide insights into numerous aspects of the species' ecology as well as the aquatic environment. Such baseline information is critical for broad assessments of the condition and changes in aquatic ecosystems.

Sample	Data provided	Time to acquire (min)	Amount of sample	Reference examples
<i>Non-destructive</i>				
External morphometrics	Index of body condition (structural size, body mass, obvious irregularities)	2	n/a	Robertson et al. (2001), Gaston et al. (2005)
Feathers	Isotopes, certain contaminants, DNA, hormones	0.5	<10	Thompson et al. (1992), Gupta et al. (1996), Smith et al. (2003), Bortolotti et al. (2008)
Blood	Isotopes, fatty acids haemoparasites, leukocyte profiles, contaminants, DNA, hormones	2	1 drop for smearsMore for other work	Grasman et al. (1996a, 2000a), Vleck et al. (2000), Edwards et al. (2006)
Eggshell powder	DNA			Egloff et al. (in press)
<i>Destructive</i>				
Tissue morphometrics	Index of health (e.g., immune organs), isotopes, fatty acids, contaminants, DNA	≥30	Whole organism	Grasman et al. (2000b), Braune et al. (2005), Fox et al. (2007a,b, 2008)
Parasites	Biodiversity, index of health, contaminants, diseases, DNA	≥60	Whole organism	Wayland et al. (2001, 2002), Mallory et al. (2007)

persistent organic pollutants have been linked to altered hormone and immune function (Verreault et al., 2004), higher gastrointestinal parasite infection (Sagerup et al., 2000, 2009), and increased absence from the nest during incubation (Bustnes et al., 2001). Glaucous gulls in the Canadian Arctic generally have lower levels of contaminants than birds from Svalbard (Braune et al., 2002), but they also experience more extensive and persistent sea ice near their nesting areas, which may result in more limited access to food compared to birds from the Barents Sea. If the Canadian gulls are under greater environmental stress (i.e., shorter breeding season, more restricted access to food), contaminants at a lower level could conceivably have a proportionately greater effect on Canadian birds. Baseline health and incubation patterns of glaucous gulls have not been investigated in Canada. However, in a regional assessment of another marine bird, the common eider (*Somateria mollissima*), birds from the Canadian Arctic had similar or lower levels of contaminants than eiders around northern Europe (Mallory et al., 2004b). Even at these relatively lower levels of contamination, Wayland et al. (2001, 2002) found evidence of deleterious health effects on breeding eiders.

Overall, in our research on environmental and health issues in Canadian aquatic birds, baseline data are often not available for robust spatial or temporal comparisons (e.g., Mallory et al., 2004a; Edwards et al., 2005; Mallory, 2006; Robinson et al., 2008). However, there is evidence that some ecological, physical and physiological traits of broadly distributed species differ in the Arctic from conspecifics breeding in the southern part of the species' range. This is well-documented in the northern fulmar (*Fulmarus glacialis*). Breeding fulmars in the high Arctic have darker plumage and possess smaller bills than birds from the more southerly Boreal oceanographic zone (Mallory and Forbes, 2005). Many pollutant concentrations differ between fulmars breeding in these two regions (Braune et al., 2005; Borgå et al., 2006; Mallory, 2006), and the prevalence and intensity of various types of parasites are lower in the Arctic (Mallory et al., 2006, 2007). Finally, breeding phenology and behavior also differ across the species range, with breeding occurring later and in a compressed schedule in the Arctic (Mallory and Forbes, 2007; Mallory et al., 2008). Arctic fulmars accommodate this shortened breeding schedule by acquiring and managing their energetic reserves differently than Boreal fulmars (Mallory and Forbes, 2008), in other words, their biology is founded upon a different behavioral and physiological baseline.

This probably comes as little surprise to many ecologists. Undergraduate ecology courses teach us about many "rules" that describe variation in species morphological patterns across environmental gradients (e.g., Allen's Rule, Bergmann's Rule, Gloger's Rule). What has received much less attention is the possibility of

gradients in physiological or behavioural characteristics (e.g., Chown et al., 2004), but it is these data that might have the highest sensitivity to local adaptation (e.g., Hörak et al., 2001) and thus that are needed to improve the utility of aquatic birds as indicators of ecosystem change.

2.2. Examples from the Laurentian Great Lakes

Unlike the Arctic, the Laurentian Great Lakes have long been recognized as a region heavily affected by human activities. For example, contaminant studies on seabirds, in particular the herring gull (*Larus argentatus*), date back to the 1960s (Keith, 1966). Seabird contaminant studies on the Great Lakes were significant in terms of detecting new contaminants (Hallett et al., 1976, 1982; Norstrom et al., 1982; Gauthier et al., 2009), assessing spatial patterns, temporal trends, and sources (Hebert et al., 1999a for a review; Weseloh et al., 2006; Gauthier et al., 2008 for recent examples), and assessing health effects in wildlife (Fox et al., 2007a,b, 2008; Grasman et al., 1996b, 2000a,b). The latter studies have provided data for regional macrophysiological comparisons in seabirds. However, even larger scale comparisons are possible given that many of the same species are monitored in other parts of the world (e.g., Marth et al., 2000).

Most of the seabird samples that have been collected on the Great Lakes are stored in a frozen archive after original analysis. Such archives are invaluable in allowing broad-scale macrophysiological comparisons involving new techniques (van der Pol and Becker, 2007). Such retrospective studies on the Great Lakes have involved not only environmental contaminants, but also research directed at detecting alterations in seabird diets associated with ecosystem change (Hebert et al., 1999b, 2008a). At the heart of these changes are alterations in food web dynamics that stem from the introduction of non-native species into the Great Lakes. Such changes are important in regulating the quantity of food available to top predators, such as seabirds, and its quality. Diet composition can be important in affecting the health of individuals and in affecting the sustainability of populations through impacts on reproduction and adult survival (Hebert et al., 2002, 2008a,b, in press; Breton et al., 2008). Continued monitoring of food web change through a seabird "lens" will allow us to assess not only the impacts of exotic species but also other stressors that may become more important in the future, e.g., climate change.

3. Recommended baseline metrics

Wildlife monitoring programs are currently underway which could assess many of the physiological and ecological metrics

described above. Many bird banding programs already gather data on basic morphometrics including body mass/physical condition. Other types of monitoring projects have been initiated, such as sampling for avian influenza (e.g., Winker et al., 2007) or other diseases. In these projects, additional, non lethal sampling of tissues, such as a small amount of blood (only one drop is needed to make a blood smear) could provide considerable physiological data on the various species, including white blood cell profiles, blood parasites, and possibly contaminant levels (e.g., Parker et al., 2006). Similarly, a suitable sample of feathers could be collected that can provide data on foraging history, migration movements of birds, and population structure through genetics (e.g., Smith et al., 2003), as well as contaminants and stress indices (e.g., Gupta et al., 1996; Bortolotti et al., 2008). In cases where destructive sampling is planned, much more information can be gathered on endpoints such as endoparasite burden, disease exposure, and organ function.

For some types of samples, little is required in terms of extra equipment or special procedures other than a dry container or freezer space. However, for other sampling, such as certain contaminants, parasites, or diseases, tissue collection and storage does merit particular attention (e.g., avoiding contamination for chemical analyses, time windows for centrifuging blood), and thus investigators or collaborators must plan ahead and ensure field teams have the appropriate equipment and protocols (e.g., McLaughlin, 2001; van der Pol and Becker, 2007), and that animal care concerns have been addressed. Of course, the most important issue for all investigators should be that of conservation; some species or colonies may be particularly sensitive to disturbance, handling, or invasive procedures, or are sufficiently rare that risks associated with handling are unwarranted. Thus, investigators must balance conservation considerations with scientific need. An excellent example of a planned, robust sampling program with conservation goals is described by Parker et al. (2006), for avian studies on the Galapagos Islands.

With the costs and challenges of conducting field studies in many remote locations, it is unlikely that various specialists (e.g., toxicologists, parasitologists, veterinarians, geneticists, etc.) will independently travel and gather samples to investigate the broader ecological questions that we can now address with current analytical techniques from small samples. Thus, we argue that it is incumbent on field programs to use foresight and take a robust approach to sampling of seabirds (and hopefully many other organisms), as identified in Table 1. Some types of samples (slides with blood smears, feather samples) require little space and can be kept for years under minimal storage requirements, e.g., being kept dry. Other types of samples, such as those that need to be frozen, require more in the way of logistical planning but such tissues can serve as critical sources of tissues for retrospective analysis. Such archived samples are environmental “time-capsules” that can yield unforeseen information as new analytical methods become available (see also van der Pol and Becker, 2007). Careful thought regarding sample collection can provide great benefits from an environmental monitoring perspective allowing *a priori* or *ad hoc* investigations to evolve using field collected samples. Our experience is that specialists at universities or government institutions are usually pleased to collaborate when samples are provided. In fact, these types of projects are very suitable for post-graduate studies, and provide guaranteed data already gathered for the student.

4. Conclusion

We are not the first to call for more robust sampling as part of monitoring programs. For example, Smith et al. (2003), Burek et al. (2008), van der Pol and Becker (2007) and Chown and Gaston

(2008) have touted the need for biological samples, often tangential to the intended research project. However, we appeal here to the diverse community researching aquatic pollution worldwide, which includes many scientists that might be unfamiliar with the types of information needed in seabird work, as well as ornithologists. Broader geographic comparisons will require greater international cooperation concerning the integration of research programs. An excellent example of such integration is the Arctic Monitoring and Assessment Program that brings international researchers together and acts to coordinate their research activities. Through such programs, more systematic, baseline sampling of seabirds could be completed with little extra cost in time or financial resources, but these samples could provide critical data for assessing the effects of changes in our aquatic environments.

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