significance as food for seabirds in the North Sea. *Marine Ecology Progress Series* 136, 1–11.

Hunt GL and Furness RW (eds) (1996) *Seabird/Fish Interactions, with Particular Reference to Seabirds in the North Sea*. ICES Cooperative Research Report No. 216. Copenhagen: International Council for Exploration of the Sea.

Jones LL and DeGange AR (1988) Interactions between seabirds and fisheries in the North Pacific Ocean. In: Burger J (ed.) *Seabirds and Other Marine Vertebrates: Competition, Predation and Other Interactions*, pp. 269–291. New York: Columbia University Press.

Montevecchi WA, Birt VL and Cairns DK (1988) Dietary changes of seabirds associated with local fisheries failures. *Biology of the Ocean* 5: 153–161.

Robertson G and Gales R (eds) (1998) *Albatross Biology and Conservation*. Chipping Norton: Surrey Beatty & Sons.

Springer AM, Roseneau DG, Lloyd DS, McRoy CP and Murphy EC (1986) Seabird responses to fluctuating prey availability in the eastern Bering Sea. *Marine Ecology Progress Series* 32: 1–12.

Tasker ML, Camphuysen CJ, Cooper J, *et al*. (1999) The impacts of fishing on marine birds. *ICES Journal of Marine Science* 57: 531–547.

SEABIRDS AS INDICATORS OF OCEAN POLLUTION

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Background

As wide-ranging, upper and multi-trophic level consumers, marine birds can provide useful indication of ocean pollutants. Seabirds are the most visible marine animals, and individuals, chicks, and eggs are relatively easily sampled, often nonlethally, over wide oceanographic regions. Birds also appeal to the general public who often go to great lengths to protect them. Hence, there is opportunity to help preserve marine ecosystems by monitoring and protecting sea birds and the habitats and prey on which they depend.

Pollutants are assayed to measure levels or rates of change of environmental pollution and to assess biological effects including those on humans. Both nominal and ordinal (qualitative) and interval and ratio (quantitative) measurements are possible. However, physiological, behavioral, taxomonic, and seasonal variations can limit the usefulness of different avian assays in reflecting variation in environmental levels of ocean pollution. Quantitative assays can be problematic because pollutants and other environmental stresses frequently occur in combination in indicator organisms, so it is often difficult or impossible to delineate the effects of a specific pollutant. The problem is complicated when different pollutants have synergistic or additive effects. Hence, determining the most appropriate assay for a pollutant to be monitored and then calibrating the assay are critical problems in all bio-monitoring programs.

Pelagic seabirds such as albatrosses and petrels can provide information on oceanic food webs, whereas coastal and littoral species such as auks and terns can provide information on inshore trophic interactions. Birds that feed at different trophic levels, such as gannets on large pelagic fishes, cormorants on benthic fishes, and sea ducks on bivalves, can be targeted to address different monitoring questions.

Many problems associated with pollution in the ocean are the result of nontarget organisms being affected by chemical management tools. Agricultural and forestry practices have been major sources of organochlorine and of other pesticide and herbicide treatments that affect birds and other nontarget organisms. Assays using marine birds also yield information about industrial chemicals, heavy metals and radionuclides. Pollutant levels reflect toxin sources in regional as well as local environments and are frequently high in estuaries and adjacent waters. Moreover, many chemical and metal pollutants are transported atmospherically, as well as aquatically, over great distances from contact zones – often to pristine polar regions. The movements of contaminated animals can also carry pollutants from source interactions to distant sites. Marine oil pollution is a global problem that results from both highly publicized spills and more extensively from long-term chronic low levels of illegal discharges. In both of these situations, research with seabirds has provided scientists with a means of studying and quantifying biological effects and of raising public awareness and concern about ocean health. Discarded and lost fishing gear and plastics are relatively recent and highly persistent sources of marine pollution that are increasing with expanding global use.

History

Widespread uses of synthetic chemicals following World War II rapidly created environmental problems. Extensive application of organophosphate pesticides poisoned many nontarget animals. Some of the first indications of their harmful effects came to light during the 1960s, many from studies of birds. Resultant public outcries were largely responsible for the banning of DDT and other organochlorine pesticides in North America and Europe. As organochlorines were phased out, background environmental levels soon decreased, and the reproductive success of brown pelicans and ospreys increased to pre-pesticide levels.

Organochlorines have low solubility in water and high environmental persistence. They were replaced largely by water-soluble organophosphates, carbomates, and other compounds that are less environmentally persistent and rapidly metabolized, but that may still be highly toxic to nontarget organisms. Many organochlorines are still used in South America, Asia, and Africa and affect the avifauna that migrate to and from these areas from other regions where these pesticides have been outlawed. Organochlorines accumulate in lipid (i.e. are lipophilic) and can bio-accumulate throughout an animal's life, as well as bio-amplify across trophic levels. Hence, effects of organochlorines and other lipophilic pollutants (e.g. methyl-mercury) are often most evident and can be best monitored through effects on top predators especially birds. However, lipophilic pollutants tend to covary, and an animal's lipid levels change seasonally as well as with food stress. In this respect, chicks can yield useful relatively immediate local assays of environmental toxins. Eggs can be useful assays, although their pollutant loads can also be influenced by food conditions and clutch sequence. For pollutants that are water soluble, it is normally more useful to use bio-monitors at lower trophic levels.

Bio-assay Calibration

The sampling of different species, life stages, age classes, and tissues have different utilities with respect to assaying different pollutants over different time and space scales. Dry-weight analyses are important for comparative purposes to control for variation in the water contents of tissues. Different classes of pollutants are addressed in separate sections below.

Organochlorines

DDT (dichloro-diphenyl-trichloroethane), its primary and stable metabolite DDE, and cyclodienes (dieldrin, aldrin, heptachlor) were used in insecticide applications. Many birds of prey and fish-eating birds accumulated organochlorines up to orders of magnitude above those in their prey and up to a million times greater than background environmental levels. Females often shunt some of their toxic burdens into eggs, and some organochlorines can decrease avian egg viability even at very low concentrations. DDT via DDE was identified as the agent responsible for the shell thinning of brown pelican eggs in the western USA and of osprey eggs that resulted in the species' precipitous decline in the eastern USA during the 1960s. DDE inhibits enzymatic (ATPase) activity in the shell gland preventing calcium transport, causing shell thinning and hence breakage during incubation. Relatedly, dieldrin, a powerful neurotoxin, was deemed responsible for the population crash of peregrine falcons in the UK. Organochlorines, PCBs, and other toxins have been detected in birds and other animals in polar regions as a result of atmospheric transportation.

PCBs

PCBs (polychlorinated biphenyls) are industrial compounds that were used in paints and as fluids in electrical and mechanical equipment. They have long-term persistence and wide dispersal in the marine environment, including polar regions. They too are lipophilic and hence bio-accumulate and magnify in higher levels of food webs. They seem to be highly toxic to seals and marine mammals, although not to birds. PCB production was greatly decreased during the 1970s, and assays with avian tissues or eggs could prove informative for levels of contamination in marine food webs. Because most of the PCBs produced are either at refuse sites or still in use, it is important to continue to monitor their presence, effects and environmental dispersion. Terns are the most sensitive seabird species known to the toxic effects of PCBs.

Heavy Metals

Copper, mercury, lead, and cadmium produce the most serious forms of heavy metal pollution in marine environments. Pollutant levels generally parallel those of regional environments with highest levels being found in the Mediterranean, intermediate levels around the British Isles, and lowest levels in northern Norway and eastern Canada. Many metals, particularly copper, mercury, and lead, and the chemical tributyltin (TBT) have been incorporated into marine paints as anti-fouling agents. These biocides are lethal to bivalves and have resulted in their elimination from many benthic communities.

Metals tend to accumulate in very specific body tissues (e.g. cadmium in kidneys) and assays are usually targeted precisely. Avian eggs also provide useful assays of some metals and have been found to exhibit oceanographic trends in mercury contamination.

Interestingly, birds shunt body burdens of mercury and perhaps tributyltin to growing feathers that are molted annually. Assays of mercury levels in feathers permit the assessment of both spatial and temporal fluctuations in contamination. Feather assays of methyl-mercury are attractive for many reasons: (i) removing selective feathers is harmless to the animal, (ii) feathers can be easily sampled and stored without freezing or other preparation, (iii) feathers can be simultaneously collected over large oceanographic regions, (iv) the metal burdens of the same individuals can be compared in successive years, (iv) historical trends in pollution can be obtained by analyzing feathers from museum specimens.

Mercurial relationships with feathers are particularly interesting in that inorganic mercury that is deposited atmospherically, like other heavy metals, adheres to feather surfaces and can be measured. In comparison, methyl-mercury that is derived from food sources is incorporated into the keratin structures of feathers. The use of small body feathers from circumscribed plumage sites, such as the scapulars, is proving most amenable for comparative analyses. Mercury levels in the feathers of adults tend to be more variable than those of nestlings that are accumulated during a brief period from food obtained in the vicinity of the nest. The same holds for eggs.

Mercury levels in the feathers of puffins, shearwaters, and skuas have increased during the past century in the UK. Levels in the Baltic sea birds also increased from the beginning of the twentieth century, and this trend was attributed to the extensive use of alkyl-mercury as a seed treatment in Scandinavia. Mercury levels in the feathers of auks in the North Atlantic during the 1970s and earlier were much lower than those of auks in the Baltic Sea, reflecting the higher pollutant levels there.

An important caution about the use of feathers for historical analysis is that if the species' diet has changed trophic levels (as occurs at times) over the study period, this could influence the levels of metals in the feathers. Hence it is most conservative in historical reconstructions to target specialist species with narrow dietary breadths. However, stable isotopic determinations of trophic level can also be derived from feathers to assess possible dietary changes.

Fish absorb mercury directly from water through their gills and can also be used to assess contamination by heavy metals. However, unlike fish, birds do not bio-accumulate mercury over their lifetimes and so offer different assaying possibilities. Evidence suggests that mesopelagic and deep-water fishes accumulate higher levels of mercury than epipelagic and coastal fishes. These findings have led to the hypothesis that inorganic mercury is converted to methyl-mercury in low oxygen environments in deep oceans and that this may facilitate uptake in these fishes and then hence by the birds that prey on them. Research is ongoing.

Lead weights used by fishers and lead shot used by hunters are major sources of contamination. Lead concentrations are highest in estuarine and inshore areas, and lead toxicity has been responsible for mortality among swans, marine waterfowl, and seabirds. This mortality has attracted considerable public attention that is resulting in (albeit too slowly) the replacement of lead with nontoxic materials. Blood and enzyme analyses can be used to assess environmental lead levels. Eiders often exhibit high levels of copper in livers and appear to be the best potential avian species for assaying this metal in marine environments. Cadmium and other metals that are not lipid soluble are not assayed in feathers, so there is no advantage in assaying birds compared to other taxa. All atmospherically deposited metals can be evaluated by accumulations on feather surfaces.

Oil Pollution

Chronic illegal discharges of unsegregated ballast and bilge water and tank flushes at sea pose long-term environmental problems for birds and other marine organisms. Unlike highly publicized situations involving tanker spills, oiled birds found on beaches are often the first and sometimes the only evidence that a pollution event, likely illegal, has occurred. Standardized beach bird surveys have generated robust intra- and inter-regionally comparable databases for decades. However, these surveys appear to be possible only in regions inhabited by large numbers of pursuit-diving birds (auks, penguins) that are highly vulnerable to oil at sea (**Figure 1**). Surveys have shown divergent trends in oil pollution in different regions: decreasing in the north-east Atlantic and increasing in the north-west Atlantic. Oil pollution is extensive in the Mediterranean where, owing to an absence of auks, beach bird surveys have not proven tractable.

Once oiled, birds often swim to shore to get out of the cold water at high latitudes and to attempt to

Figure 1 A murre entangled in a small piece of net (on left) and an oiled murre, both recovered on a beach on the south coast of Newfoundland.

clean their plumage on land. Carcass trajectories are influenced by winds and currents. The numbers of oiled birds that are recovered on shore are fractions of those oiled at sea, and estimates of these proportions are being assessed by experiments involving the release of drift blocks at sea. Most oiled seabirds come ashore on beaches exposed to dominant wind directions. Such geographic features are essential considerations in selecting beach bird survey sites.

Species composition can at times be indicative of the distance of a pollution event from the coast. For example, murres tend to be oiled farther from shore than dovekies and sea ducks, and when the composition of oiled species changes from the former to the latter it can reflect the shoreward movement of an oil slick. Gas chromatographic and mass spectrometric techniques have been used to 'fingerprint' the compositions of hydrocarbons removed from oiled seabirds and have been used in efforts to prosecute specific ships alleged to have polluted. There is also the possibility of 'marking' oil shipments so that they could be identified in the case of discharge or spillage. Separators have to be installed as mandatory equipment on ships to promote oil recycling, in much the same way as anti-pollution devices have been legislated for automobiles. However, until binding, enforceable international agreements require the recycling and discharging of used oil at land-based flushing facilities, hydrocarbon pollution in the world's oceans will be a fact of life and death.

Radionuclides

Radionuclides (e.g. cesium) are released from weapon testing and use and from industrial accidents, such as those associated with power-generating facilities. As is the case with many other pollutants, specific radionuclides are taken up in specific tissues. These chemicals are monitored in shellfish with concerns for human consumption. Hence, shellfish predators including shorebirds, gulls, and sea ducks are likely the best avian species to assay with reference to this source of pollution. Seabirds could potentially provide useful indications of the bioavailability of certain radionuclides over global oceanographic regions.

Plastic

Plastic biodegrades slowly, is very environmentally persistent and occurs in all of the world's oceans. The replacement of twine nets with synthetic monofilament nets has extended the existence of lost and discarded nets adrift at sea that entangle and kill many fish, birds, and mammals (**Figure 1**). The levels of mortality associated with these by-catches can be very high and produce large-scale negative population effects.

Thousands of plastic pellets litter each square kilometer of ocean surface and often accumulate at fronts. Many marine animals ingest plastic, especially small particles of industrial plastics such as styrofoam. Ingestion can create gastrointestinal problems and result in mortality. Petrels appear most vulnerable to small bits of plastic. PCBs and other toxic chemicals often adhere to the surfaces of plastic debris and hence can also increase the contaminant burdens of animals that ingest plastic. Some seabird species incorporate plastic strapping, netting, line, and other solid objects collected from the ocean surface into nests. Cormorant and gannet nests with plastic built into them have increased in recent decades, reflecting increased plastic pollution at sea.

Acid Rain

Acid precipitation of industrial releases of sulfur dioxide, ammonia, and nitrogen oxides has generated many environmental problems. Most of these have been evidenced in terrestrial and freshwater environments. However, as the generation of this pollution increases, effects are to be expected in marine environments.

Conclusion

As pollutant inputs to the environment continue to accelerate, diversify, and combine in novel ways, new effects on marine birds will be detected and new avian bio-assays will continue to be developed and needed. A healthy and diverse avifauna supported by a natural diverse prey base is indicative of a well functioning and healthy marine environment. Decreases in avian diversity are evident in regions with increased pollution levels. Nature abhors vacuum and life proliferates, but biodiversity creates the fabric of life that sustains the natural functioning of large-scale ecosystem processes. For the sake of the oceans and for our own benefit, it is essential to do everything possible to understand human-induced threats to the world's oceans and with or without that understanding to protect and preserve them.

See also

Anti-fouling Materials. Atmospheric Input of Pollutants. Chlorinated Hydrocarbons. Metal Pollution. Oil Pollution. Pollution Control. Pollution: Effects on Marine Communities. Pollution, Solids. Radioactive Wastes.

Further Reading

Furness RW and Greenwood JJD (eds) (1993) *Birds as Monitors of Environmental Change*. London: Chapman and Hall.

Furness RW and Rainbow PS (eds) (1990) *Heavy Metals in the Marine Environment*. New York: CRC Press.

Poole A (1987) *The Osprey*: A *Natural and Unnatural History*. Cambridge: Cambridge University Press.

Ratcliffe DA (1967) Decrease in eggshell weight in certain birds of prey. *Nature* 215: 208–210.

Spitzer PR, Riseborough RW, Walker W *et al*. (1978) Productivity of ospreys in Connecticut – Long Island increase as DDE residues decline. *Science* 202: 203–205.

SEALS

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Taxonomy

The seals, or Pinnipedia, are the suborder of the Carnivora that includes the Phocidae (earless or 'true' seals), Otariidae (eared seals, including fur seals and sea lions) and the Odobenidae (walrus). They are related to the bears, based on a common ancestry with terrestrial arctoid carnivores (**Figure 1**). The otariids retain more of the ancestral characteristics than the other two groups but all have a more or less aquatic lifestyle and display highly developed morphological and physiological adaptations to an aquatic existence.

The Pinnipedia are made up of 34 species and 48 species/subspecies groupings (**Table 1**). However, with the advent of new methods based on DNA analysis for examining phylogeny and also because of new methods used to track animals at sea many of these groupings are questionable. Several groups that were thought to have been different species have overlapping ranges and are likely to interbreed. It seems most probable that the southern fur seals (*Arctocephalus* sp., Table 1) are not distinct species. Conversely, some of the North Atlantic phocid pinnipeds that are classified as single species are likely to be better represented as a group of subspecies. The gray seal is a particular example in which three genetically distinct populations (NW Atlantic, NE Atlantic and Baltic) are recognized.

Distribution and Abundance

The greatest diversity and absolute abundances of pinnipeds occurs at temperate and polar latitudes (Table 1). Only three phocid seal species, the monk seals, are truly tropical species and all of these are either highly endangered or, in one case, may be extinct. Among the otariids, fur seals and sea lions extend their distributions into the tropics but their absolute abundance in these locations is low compared with the populations at higher latitudes.

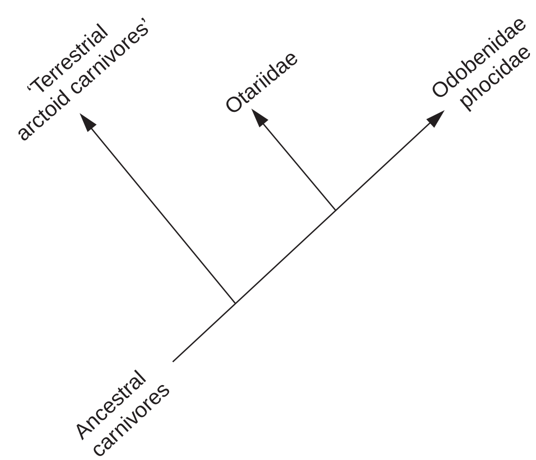

Figure 1 Pinniped phylogeny from a cladogram based on postcranial morphology. (Reproduced from Berta *et al*., 1989.)