REVIEW

Colonial Waterbirds as Bioindicators of Environmental Change

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Abstract.—As ecosystems become increasingly affected by human activity, the need to monitor, evaluate, manage, and remediate ecological change will increase. Because of the complexity of ecosystems, it is likely that the use of biological indicators (bioindicators) will similarly increase. This paper reviews the potential utility of using aspects of colonial waterbird biology as indicators of environmental change in their supporting ecosystems. Characteristics of colonial waterbirds that support their use in bioindication include aspects of their basic biology, the extent of biological understanding of that biology, human interest, and historical precedent.

The justification for using biological indicators to understand ecosystem level human impacts has theoretical underpinnings in systems theory, ecosystem theory, and hierarchy theory. Bioindicators may be derived from any level of biological organization. Two levels of indicators, suborganismal bioindicators (biomarkers, biochemical indicators) and population/community/ecosystem indicators, each have distinctive strengths and weaknesses. Traditionally, bioindicators derived from colonial waterbirds have included contaminant burden and population numbers. However, certain suborganismal bioindicators also seem appropriate for development within this group of birds. Difficulties in using colonial waterbirds as indicators include their large size, wide ranging habits, difficulty of approach and capture, and migratory patterns.

Potentially appropriate colonial waterbird bioindicators include genotoxicity, mixed function oxidases, metallothionein induction, tissue concentration of contaminants, egg shell quality, other physiological responses, histopathology and teratology, growth, behavior, reproductive performance, mortality, presence/absence, distribution, and population indices. Several of these potential bioindicators may be used during the nesting period when the adults, eggs, and young are concentrated at specific colony sites. At this time, chicks and eggs can be effectively sampled and adults are often concentrated at foraging sites. The use of multiple indicators during nesting, especially those related to population indices, hematology, contaminant burdens, and reproductive competency, have special promise. *Received 26 May 1993, accepted 17 October 1993.*

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The management of ecosystems rather than individual species is taking a forward position in environmental conservation. To meet local, national, and international goals for ecosystem conservation, there is an increasing need to assess ecosystem conditions and changes and to judge when such changes require active management. How this is to be accomplished is not yet particularly clear (Schindler 1987, Mayer *et al.* 1992, Peakall 1992, Lyne *et al.* 1992, Peakall and Shugart 1993, Fossi and Leonzio 1993). What is clear, however, is that, in assessing changing conditions within an ecosystem, measuring (or even identifying) all its components, functions, properties, or values, is impossible. As a result, selected components will have to serve as indicators of wider conditions. Biological components serving this function are called biological indicators (hereafter bioindicators).

National and international programs to monitor environmental conditions are under discussion or implementation worldwide. Among these are the Environmental Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency, the Biomonitoring of Environmental Status and Trends (BEST) program of the U.S. Fish and Wildlife Service, the National Contaminant Biomonitoring Program of the U.S. Fish and Wildlife Service, the Commission for Bioindicators of the International Union for Biological Sciences (Jeffrey and Madden 1991), the Global Environmental Monitoring System of the United Nations Environment Programme, and the international waterfowl census of the International Waterfowl and Wetland and Research Bureau. Two recent initiatives deserve special note. In the United States, a new agency, the National Biological Survey of the U.S. Department of the Interior, is being organized, one of whose missions is to conduct scientifically valid monitoring of flora and fauna and their environmental conditions. Internationally, implementing the Ramsar Convention will require the Contracting Parties accept standards for monitoring wetlands of international importance (Ramsar 1988, Kushlan 1993). Bioindicator selection has been and will continue to be a consideration in all such surveys and monitoring programs.

Birds will play important roles in future biomonitoring schemes, if for no other reason than because they have been used this way for many years (Lower and Kendall 1990, Peakall 1992). Pesticide contamination has been well studied in bird species, and birds have also been used as indicators at the population level. In some cases, several species or a guild of bird species have been used together as indicators (Farmer and Adams 1989, Adamus and Brandt 1990) as was recommended by Cairns (Cairns 1983, 1984, Cairns and Pratt 1986). However, the use of bird populations for environmental monitoring has been vigorously questioned (Temple and Wiens 1989). Morrison (1986 p. 444) concluded that "The current and widespread practice of using individual [bird] species and groups of species (guilds) as indicators of environmental change is clearly inappropriate in most situations." In the face of divergent opinions as to their feasibility given their past and expected future use as bioindicators, the utility of using various groups of birds as biological indicators deserves explicit evaluation.

Colonial waterbirds (i.e., herons, storks, ibises, pelicans, cormorants, gulls, terns, and marine birds) often have been used (or proposed) as indicators of habitat conditions (e.g., Blus *et al.* 1977, Custer and Osborn 1977, Ohlendorf *et al.* 1978, 1979a, b, Anderson *et al.* 1980, Ricklefs *et al.* 1984, Boersma 1986, Cairns 1987, Batty 1989, Lower and Kendall 1990, Fox *et al.* 1991a, Oatley *et al.* 1992, Furness and Nettleship 1991, Custer *et al.* 1991, Montevecchi and Berruti 1991). However, use of this ecological group of birds as bioindicators has not been reviewed nor have the relative values of potential bioindicator variables been examined comprehensively. As increasing numbers of papers are being published on colonial waterbirds in their role as environmental indicators, it becomes of value to consolidate, synthesize, and evaluate information presently available.

The purpose of this paper, then, is to review the potential utility of colonial waterbirds as bioindicators of ecological change in their ecosystems. I will consider both suborganismal and superorganismal variables as potential bioindicators and contrast their value. I also discuss a unifying theoretical basis for the use of bioindicators and discuss how colonial waterbirds might best be used in this way. Such a synthesis seems timely given the rapid development in the field and the current interest of state, federal, and international agencies in developing long-term inventory and monitoring programs.

A CONCEPTUAL BASIS FOR BIOINDICATION

Although characteristics of various organisms are frequently proposed as indicators of environmental conditions, the theoretical and conceptual foundations of such proposals deserve more explicit justification than is usually provided. Among the conceptual bases for bioindication are: climax theory, ecosystem theory, systems theory, and hierarchy theory.

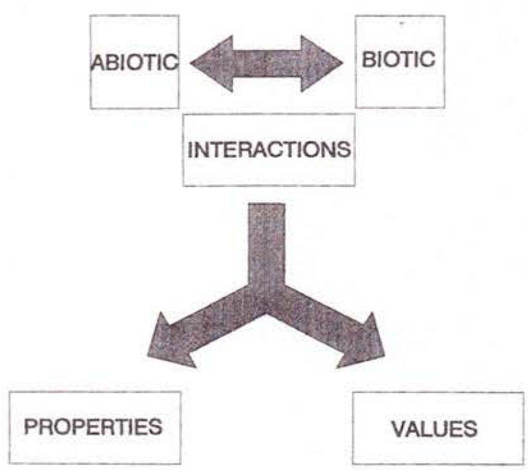

Figure 1. An ecosystem is composed of abiotic and biotic components and their interactions. These components produce the ecological properties and human-related values attributable to the ecosystem. Indicators may be drawn from among any of these five ecosystem attributes.

Table 1. Levels of biotic organization and potential bioindicators for colonial waterbirds at various levels.

Suborganism	DNA adduct formation
	Strand breakage
	DNA methylation
	Sister chromatid exchange
	DNA content
	Mixed function oxidases
	Metallothionein induction
	Contaminant accumulation
	Egg shell quality
	Thyroid function
	Esterase activity
	ALAD inhibition
	Retinoid accumulation
	Haem biosynthesis
	Hematology
	Histopathology
	Teratology
Organism	Growth
	Behavior
	Reproductive performance
	Mortality
Population	Presence/Absence
	Distribution
	Population indices
Community	Community bioindicators
Ecosystem	Ecosystem bioindicators

The concept of bioindicators probably first became widely used following Clements' (1920) identification of plant species as community indicators within his overall concept of plant community succession (Clements 1920, Morrison 1986).

The concept of ecosystem level indicators derives from ecosystem theory (Odum 1962, 1963): in the highly integrated and homeostatic natural ecosystem, ecosystem functioning supports species, and certain aspects of these species, in turn, should be able to indicate the functioning of their ecosystem. In that natural ecosystems also do work (Odum 1983), some ecosystem functions may possess values from a human perspective. It was on these bases that governments and agencies long ago made "indicator species," "endangered species," and "critical habitat" the cornerstones of natural resources management (Moore 1966, Council on Environmental Quality 1972, National Academy of Sciences 1978, Morrison 1986, Hunsacker and Carpenter 1990). More recent focus on "biodiversity" is a multispecies derivation of the concept that species and ecosystems are intimately related.

More fundamentally, I suggest that bioindication derives its theoretical basis from general systems theory (Von Bertalanffy 1968, Odum 1983). That is, given a system of parts interacting according to some set of processes, the condition of the system should be predictable from the status of state variables and processes connecting them. Systems also have emergent properties, attributes unique to that level of biotic organization. System variables, flows and controls, and emergent properties all might be measured as indicators to assess system functioning.

Another concept underlying bioindication is that of hierarchy. The universe including biotic entities is divisible into scales of organization that consist of nested levels having differing but inter-related properties (Webster 1979, Odum 1983, Farmer and Adams 1989). Although the division of the biotic world into a hierarchy of complexity is a well accepted concept among biologists, it is not agreed whether functioning at the higher levels of complexity is a summation of functions at lower levels (the reductionist paradigm) or involves emergent properties that are more than the sum of the parts (the systems paradigm).

Bringing these underlying concepts together, we can say that if an ecosystem is composed of abiotic and biotic components and their functional interactions, potential indicator variables may be drawn from any of an ecosystem's abiotic or biotic components or their functional interactions, its emergent properties, or pertinent human values (Fig. 1). Furthermore, indicator variables may be drawn from any hierarchical level, and those drawn from one level may relate to other levels (Table 1).

A robust theoretical base notwithstanding, indicators need to work in practice to be useful. Confidence in the value of using indicators in ecological systems is gained from their success in other systems. The use of bioindicators to assess environmental conditions is analogous to the use of numerical indicators to assess the condition of the economy (Kushlan 1993). Bioindicators (or economic indicators) are of value to the extent that they can measure some important condition of the ecosystem (or economy) and to lesser degree the extent they can provide information that can be used to predict future conditions of the ecosystem (or the economy). The widespread agreement on the use of specific economic indicators is based on their having an acceptable theoretical basis and their past success (albeit imperfect) in monitoring economic conditions. In contrast, specific bioindicators fail to enjoy such universal acceptance because their theoretical basis has been less well appreciated, the success of most has yet to be so convincingly demonstrated and because no consensus has developed that specific indicators work. Conceptually, however, much of the basis of the economic and environmental uses of indicators is similar. Furthermore, given that the functioning of ecosystems is less theoretical than the functioning of economies, the success of indicators in ecology might be expected to be even greater (G. Fox, Canadian Wildlife Service, pers. comm.).

Bioindicators are the living subset of a wider array of possible indicators for ecosystems, which by definition also consist of abiotic components. A robust monitoring and assessment program would use both abiotic indicators and bioindicators, as might be appropriate (Zonneveld 1983). Moreover, a monitoring scheme appropriate to management needs might be accomplished solely with a very few abiotic variables (e.g., water depth, water quality) although bioindicators are usually needed as well to assure that the abiotic indicators are reflecting a biotic reality. In this sense, it is of value to recognize the importance of the concept of bioavailability. With respect to contaminants, for example, the amount present in the environment is far less important than the amount that organisms actually come in contact with, i.e., their bioavailability.

Bioindicators can function in two interacting ways (Mayer *et al.* 1992). A bioindicator may reflect "exposure": that an organism has been in contact with a stressor, even if the stressor is no longer effective. A bioindicator also may reflect "effect": that is, the degree to which an organism has been impaired by or responds to a stressor. Of course, a bioindicator may function both ways. To illustrate with a colonial waterbird example, numbers of feeding storks may be reduced in a wetland as the result of a short-term flood event. After the water recedes, the storks, who had moved elsewhere during the flood, are not present. The change in the number of birds is an indicator of exposure to high water conditions. In another case, storks may be permanently extirpated from a wetland after thirty years of reproductive failure caused by excessive high water brought about by water management authorities. The lack of birds in this case shows an effect of chronic high water conditions.

Another important concept underlying the use of bioindicators is that of stress. One definition of a stressor is any stimulus that elicits an adverse response at any level of biotic organization: organism, population, or ecosystem Selye 1956, Thorpe and Gibbons 1978, Pickering 1981). Stressors are not necessarily unnatural; stress and stressors are part of the normal life of any organism Selye 1956, Adams *et al.* 1989). Selection of bioindicators can take advantage of the ways organisms or ecosystems naturally respond to stress. Biomarkers, for example, are measurable cellular or biochemical functions that are affected by stressors, especially in a dose-dependent manner (National Research Council 1987).

Another concept of importance in using bioindicators is that of the multivariable system. An ecosystem is inherently multivariate, in that it has any number of dependent and independent variables. Any given bioindicator is a dependent variable in a system with multiple independent variables. The instantaneous value of a variable may be due to the combined action of many of these independent and codependent variables. This concept is vitally important in interpreting the meaning of a change in variable value. For remediation to occur, cause and effects need to be understood. This may take additional study, correlation analysis, or evaluation of relative importance as discussed by Ludwig *et al.* (1992).

Bioindicator development has generally followed two somewhat different approaches. The first approach uses animal populations to assess the condition of their habitat (e.g., National Academy of Sciences 1978, National Research Council 1987 Goldsmith 1991). The other approach seeks to use physiological and biochemical responses to stress to assess stress (Kendall 1982, McCarthy and Shugart 1990, Goldsmith 1991, Huggett *et al.* 1992, Peakall 1992). Traditionally the two approaches represent different disciplines, wildlife biology (concerned primarily with population biology) and environmental toxicology (concerned primarily with physiology). These fields have different histories, perspectives, tools, vocabulary, and until recently different disciples. However, the basic concepts underlying the two approaches, as discussed previously, are the same. So it is imperative to give full consideration to a complete repertoire of potential biological indicators in selecting indicator variables.

BIOINDICATOR SELECTION

Selection of bioindicator variables from all the biological components that could be measured, estimated, or calculated should involve a number of considerations. These include: (1) choosing response variables that may be correlated with higher level (ecosystem) characteristics; (2) ensuring that the selected variables reflect the risk or hazard associated with the changes detected (Cairns 1980, Burger and Gochfeld 1992a, Lipton *et al.* 1993); (3) choosing variables that relate to specific human values (economic, health, aesthetic placed at risk by a change (Crossland in press)); and (4) selecting variables that are relatively economical and logistically feasible. In each application, the feasibility and prospects of potential bioindicators require specific development.

One of the most fundamental considerations in selecting a bioindicator is understanding what it indicates. Because bioindicators need to be considered as dependent variables in multivariable systems, it may be difficult to discover cause-and-effect relationships between the dependent bioindicator variable and a single stressor. As noted above, a subsequent analysis of causality (by correlation analysis, experimental study, or epidemiological evaluation) is required to ascertain which of the many interacting processes might be causing the indicator to assume a particular value. Another consideration is the inherent variability of biological systems. Under nonstressed conditions, biological variables may vary widely, and it is critical to know if an observed value of a variable is within its expected range.

Despite these difficulties, bioindicators also have several useful characteristics. They can be robustly integrative, relatively economical, and functionally pertinent. The integrative properties of bioindicators balance the complication of their being dependent variables in a multivariable system. The quantitative value and trend of a bioindicator may be responses to the individual, simultaneous, and synergistic stimuli of multiple stressors in the environment. Bioindicators can integrate exposure to, or effects of, these multiple stressors over time and space. Bioindicators are economical because one bioindicator can be used to monitor many independent variables of the ecosystem. Biological indicators are pertinent because they can relate directly to important human values of ecosystems.

COLONIAL WATERBIRDS AS BIOINDICATORS

Several aspects of the biology of colonial waterbirds make them conducive to being bioindicators of environmental change. As top carnivores (Kushlan 1979), their responses can signal environmental changes occurring at lower trophic levels (Ankley *et al.* 1993). Their mobility and use of human-dominated environments (Kushlan 1986, Parnell *et al.* 1988) result in a high incidence of exposure to environmental contaminants that can cause toxic effects (Hill and Hoffman 1984, Hoffman 1990, Lower and Kendall 1990). Their wide geographic ranges permit comparisons of responses among sites, setting up natural experiments. Their communal roosting and nesting facilitate sampling large numbers of eggs, young, and adults. Their central place foraging strategy limits the activity ranges of nesting adults allowing inferences to be made about sources of stress. Some species depend on specific physical aspects of aquatic ecosystem function, such as hydrology or hydrography (Anderson *et al.*, Kushlan 1986, 1989a, thereby being potential indicators of changes in these fundamental ecosystem characteristics.

Another advantage is that the state of biological knowledge of many colonial waterbirds is fairly well developed (Hancock and Kushlan 1984, Croxall 1987, Burger and Gochfeld 1991a, Hancock *et al.* 1992, Kushlan 1992). A strong knowledge base allows comparison of "baseline" biology with that affected by environmental conditions. A particularly extensive data base exists on the occurrence and numbers of colonial waterbirds at many sites worldwide (e.g., Scott 1989). In some locations, such data are available over a span of decades (Spendelow and Patton 1988, Rose 1992).

Human interest in colonial waterbirds and their habitats is another reason to consider using them as bioindicators of ecological change. Wildfowl, including colonial waterbirds, are of high recreational and aesthetic value to humans. This has been codified, for example, in that the listing and continuance of a site as a wetland of international importance under the Ramsar Convention is based primarily on migratory waterfowl populations (waterfowl include colonial waterbirds in this context) (Ramsar 1988). The prominent role played by colonial waterbirds in the passage of early wildlife protection (e.g., Migratory Bird Treaty Act of 1916) and in the establishment of national refuges and parks (Frohring *et al.* 1988) reflects their significant heritage value to humans.

Historical precedent also is a reason to consider using colonial waterbirds as bioindicators. Government agencies, non-governmental organizations, and legions of naturalists have monitored populations of nesting colonial waterbirds for decades. Population decreases of the American Wood Stork (*Mycteria americana*) and other wading birds in the Florida Everglades revealed changes in ecosystem function caused by water management (Kushlan and Frohring 1986, Kushlan 1987). Population decreases in Brown Pelicans (*Pelecanus occidentalis*) signaled excessive pesticide contamination in their feeding areas (Anderson and Risebrough 1976, Schreiber 1980). The endangered status of many storks and ibises in Asia suggests the extent and nature of environmental degradation there (Hancock *et al.* 1992). Colonial seabirds have been used as bioindicators of their pelagic food resources and, by extension, of hydrographic conditions (Anderson *et al.* 1980, Schreiber and Schreiber 1984, Furness and Nettleship 1991). They have also been explicitly proposed for use as bioindicators of ecosystem-level contamination and function (e.g., Fox *et al.* 1991a, Oatley *et al.* 1992).

POTENTIAL COLONIAL WATERBIRD BIOINDICATORS

Many aspects of colonial waterbird biology appear to be potentially useful as bioindicators. The use of some is based on detailed studies using colonial waterbirds, whereas others have been studied only in other species. In this section, a hierarchical approach will be taken to examine potential bioindicators at both the suborganism-organism level (SO bioindicators) and population, community, and ecosystem level (PCE bioindicators).

Genotoxicity

Environmental contaminants, radiation, and other factors are known to be correlated with observable genetic damage (Lower and Kendall 1990, Shugart 1992, Lyne *et al.* 1992, Theodorakis *et al.* 1992). In fact, DNA damage may be one of the earliest bioindicators of exposure to genotoxic contaminants such as polycyclic aromatic hydrocarbons (PAH's), contaminants that are hard to detect because they are quickly excreted in birds, yet their genotoxic damage can be assessed. Somatic dysfunction, genetic defects, reproductive impairment, and second generation responses are some expected results of genotoxic agents.

To date, DNA damage has been studied primarily in fish and mollusks, organisms that are in prolonged contact with contaminated sediment. Birds, however, tend to be exposed to lower levels of contamination and would not be expected to be so readily affected (G. Fox, pers. comm.). However, recent studies of mollusk-feeding eiders (*Somateria mollissima*) indicated DNA damage (G. Fox, pers. comm.), suggesting that food-chain effects may be detectable in this way. Another matter of concern is that chromosome analysis is difficult in birds (J. Bickham, Texas A&M University, pers. comm.).

Several measures of genotoxic effects are available and more are being developed. The most frequently used measure of DNA damage is strand breakage (Shugart 1988). Another measure is the relative concentration of DNA and RNA/DNA ratios in various tissues, particularly in liver tissue and blood (Hoffman *et al.* 1993). Blood cell DNA can be assessed using flow cytometry (George *et al.* 1991, Bickham *et al.* 1992, Bickham 1993). DNA adduct formation, occurring due to the covalent binding of contaminants to the DNA, has been used as a bioindicator primarily in fish (Shugart *et al.* 1987) but could be applied in colonial waterbirds as well. Methylation of DNA, a reflection of genetic activity, can be an indicator of reduced gene activity due to contaminants (Shugart 1990). The exchange of DNA by sister chromatids has been linked to contaminants. Other genotoxicity related approaches include analyses of mutation rates and chromosomal proteins.

Only a few of these genetic bioindicators have been thoroughly studied in colonial waterbirds, but several are under development. Strand breakage has primarily been used in fish, but recent studies have been conducted on Double-crested Cormorants, (*Phalacrocorax auritus*), gulls, and Great Blue Herons (*Ardea herodias*) (S. D'Surney, University of Mississippi, pers. comm., G. Fox, pers. comm.). DNA methylation studies also are currently underway in cormorants and Great Blue Herons (S. D'Surney, pers. comm.). Sister chromatid exchange has been field tested in Herring Gull (*Larus argentatus*) embryos, although no effects were found (Ellenton and McPherson 1983, Ellenton *et al.* 1983). Mutation rate analysis and chromosomal protein analysis are both currently being studied in Great Blue Herons (S. D'Surney, pers. comm.). T. W. Custer (U.S. Fish & Wildlife Service, pers. comm.) found that Black-crowned Night-Heron (*Nycticorax nycticorax*) chicks from petroleum-contaminated sites had a greater variation in DNA content than did those from comparison sites.

Mixed Function Oxidases (MFOs)

MFOs are components of the monoxygenase enzyme system (P450 cytochrome superfamily) that detoxifies contaminants through transformation of organic molecules to less toxic, more water soluble forms (Ortez de Montallano 1986, Payne *et al.* 1987, Rattner *et al.* 1989, G. Fox, pers. comm.). MFO activity can be induced by exposure to several contaminants, such as PCBs, dioxins, furans and related chemicals (T. W. Custer, pers. comm.). As a result, elevated MFO activity can be used as an indicator of exposure.

Recent studies have demonstrated FO induction in colonial waterbirds, supporting their use as bioindicators (Knight and Walker 1982, Ellenton *et al.* 1985, Boersma *et al.* 1986, Hoffman *et al.* 1987, Ronis *et al.* 1989, Bellward *et al.* 1990). Peakall *et al.* (1987) examined changes in mixed function oxidase systems with age of Herring Gull (*Larus argentatus*) chicks and as correlated with contaminant levels.

Metallothionein Induction

Metallothioneins are members of a family of metal-binding peptides and proteins (Benson *et al.* 1990), apparently functioning to regulate essential metals, including detoxifying metals obtained from environmental contamination (Baer and Benson 1987, Benson *et al.* 1990). They are induced by metal contamination and such induction can be used an indicator of exposure to metals. However, interpretation may be difficult. Induction is hard to relate to a specific contaminant because metallothionein induction is not restricted to specific metals, including relatively nontoxic metals such as zinc. Even when metal-induced, they may not be indicative either of toxic metals or of impairment (D. Hoffman, U.S. Fish & Wildlife Service pers. comm.) Metallathioneins are also induced by other stresses, however, their normal function is unclear, and their variability is often high.

However, these metal-binding proteins are present in birds, and further study in colonial waterbirds may lead to broadly applicable indicators of stress, including those from metal contamination. Elliott *et al.* (1992) found metallothionein levels in kidneys of gulls, puffins, and storm-petrels were correlated with cadmium but not mercury.

Contaminant Accumulation

Colonial waterbirds have proven utility as indicators of environmental contamination (Hill and Hoffman 1984). As high trophic level carnivores, they accumulate many persistent contaminants, including organochlorine pesticides, metals, polychlorinated aromatic industrial chemicals, and radionuclides (Environment Canada 1991) to levels that can be accurately and reliably measured. Burdens of contaminants and their metabolites in tissue of colonial waterbirds are direct indicators of exposure (Melancon *et al.* 1992); and, at levels known to cause lethality in study organisms, they can be used to infer potential effects as well. These residues reflect actual availability of contaminants in the environment, and so are more ecologically relevant than environmental concentrations per se (G. Fox, pers. comm.).

General tissue burdens of organic contaminants have been well documented in colonial waterbirds (e.g., Gilbertson and Fox 1977, Vermeer and Peakall 1977, Sileo *et al.* 1977, Ohlendorf *et al.* 1978, 1979a, b, 1981, Miller *et al.* 1979, Fry and Toone 1981, Gochfeld and Burger 1982, Custer *et al.* 1983, Calambokidis *et al.* 1985, Risebrough 1986, Noble and Elliott 1986, Hoffman *et al.* 1986). Depending on the season and migration history of the birds, contaminant levels may indicate exposure on the local feeding grounds, on migration, or in wintering areas (Henny and Blus 1986, Henny *et al.* 1984, 1985). Responses of birds to halogenated aromatic hydrocarbons have been investigated in detail, and their effects and mode of action are understood (Nisbet 1980, Nisbet and Reynolds 1984, Eisler 1986a, b). Although DDT era pesticides have been banned in the United States for decades, residual effects are still uncovered (Ohlendorf and Marois 1990, Ohlendorf *et al.* 1981).

A good example of the use of colonial waterbirds as bioindicators of contamination is the Great Lakes Herring Gull Egg Program, with data ranging back to 1974 (Mineau *et al.* 1984). This program has found substantial decreases in persistent organochlorine pesticide and PCB levels correlated with decreasing use of these materials. Although, it is generally found that persistent organic contaminants are below levels known to have lethal or sublethal effects (Fitzner *et al.* 1988, Henny *et al.* 1989, Mora 1991, Speich *et al.* 1992), recently developed *in vitro* bioassay techniques provided a correlation between PCB levels and cormorant egg mortality (Tillitt *et al.* 1992).

Great Lakes studies demonstrate the value of studying eggs and chicks at the nesting colony. They show that tissue burdens and uptake rates in chicks have special promise as bioindicators of site-specific contaminant bioavailability (Ankley *et al.* 1993).

Metals and other inorganic contaminants also accumulate in colonial waterbirds. These tend to accumulate in specific tissues, although low levels tend to affect multiple body systems (S. D'Surney, pers. comm.). Colonial waterbirds have often been assayed for tissue concentrations of lead, cadmium, arsenic, selenium, and mercury (Munoz *et al.* 1976, Vermeer and Peakall 1977, Hulse *et al.* 1980, Hutton 1981, Cheney *et al.* 1981, Gochfeld and Burger 1982, Howarth *et al.* 1982, Maedgen *et al.* 1982, Custer and Mulhern 1983, King and Cromartie 1986, Custer *et al.* 1986, Gochfeld and Burger 1987, Ohlendorf *et al.* 1988, Furness and Rainbow 1990, Thompson *et al.* 1991, Burger *et al.* 1992).

Results from the above studies indicate that levels of contamination in most colonial waterbirds remain in the nonlethal ranges. However, more subtle effects are being discovered. Laughing Gull (*Larus atricilla*) accumulation of lead and cadmium reflects concentrations in their diet (Reid and Hacker 1982). Lead and mercury ingestion has been linked to deaths in the Grey Heron (*Ardea cinerea*) and the White-faced Ibis (*Plegadis chihi*) (van der Molen *et al.* 1982 Hall and Fisher 1985). Elliott *et al.*'s (1992) recent study showing correlations of effects to cadmium levels was noted previously. Perhaps the most dramatic effect of an inorganic contaminant is that shown by the case study at Kesterson Reservoir, California, where increased levels of selenium were associated with multiple effects (especially embryo deformities) in noncolonial aquatic birds (Ohlendorf *et al.* 1986). This is also a prime example of how aquatic birds signaled an environmental change.

A promising new approach uses waterbird feathers to assess metal bioaccumulation (Furness *et al.* 1986, 1990, Burger and Gochfeld 1991b, 1992b, 1993, Burger *et al.* 1993). Feather concentrations may be an ideal bioindicator because feathers can be sampled nondestructively, are easy to obtain, and they are sensitive because birds tend to sequester metals in feathers (Braune and Gaskin 1987).

Radioisotopes are accumulated by colonial waterbirds through contaminated food chains, thereby providing an indicator of radiation contamination and movement of radioisotopes in the ecosystem (Domby *et al.* 1977). Their coloniality, accessibility, and central-place foraging are specific attributes that support their use as indicators of radionuclide pollution.

The above traits are particularly useful for all types of contaminant monitoring programs. Accumulation of contaminants in eggs and tissues of chicks and feathers of both chicks and adults can be sensitive indicators of exposure in the ecosystem supporting the nesting adults (Ohlendorf *et al.* 1978, Mineau *et al.* 1984, Custer *et al.* 1985, Henny and Blus 1985). Concurrently collected data on growth, survival, and teratology can be used to assess effect (Tumasonis *et al.* 1973, Mineau *et al.* 1984, Fox et al. 1991b,c). However, to the extent that birds avoid feeding in contaminated sites, they may not be able to reveal contaminated "hot spots" (Blus *et al.* 1985).

Egg Shell Quality

Egg shell thinning is a proven bioindicator of DDE/DDT contamination and has been well documented in colonial waterbirds (Blus *et al.* 1972, Anderson *et al.* 1975, King *et al.* 1978). Brown Pelicans and Double-crested Cormorants suffered reproductive failures due to eggshell thinning (Gress *et al.* 1973, Jehl 1973, Weseloh *et al.* 1983). This bioindicator is sensitive, relatively specific, and its mechanisms of action have been elucidated (Lundholm 1987). Fox *et al.* (1976) provided an nondestructive method for measuring egg shell quality. Breaking strength is a fairly precise measure as well (Bennett *et al.* 1988) and was field tested with a DDE-exposed population of White-faced Ibises Henny and Bennett 1990, (C. Henny U.S. Fish & Wildlife Services, pers. comm.).

In the California nearshore ecosystem, egg shell thinning coupled with contaminant accumulation in tissues signaled the extent of chlorinated hydrocarbon contamination and led to rapid corrective action (MacGregor 1974). Decreases in egg shell quality have been associated with reproductive failure and consequent population decreases. This suborganism bioindicator is one that has been shown to have demonstrable effects at the population level.

The usefulness of egg shell quality for monitoring a specific ecosystem is usually less straightforward in cases where the affected birds are highly mobile. Also, egg shell thinning may be affected by other stressors such as diet, metals, and temperature (Roland *et al.* 1973, Smith 1974, Lundholm and Mathson 1986). Thus, before a change in egg shell breaking strength can be ascribed to a particular stressor, additional studies should be undertaken. Nonetheless, it is an important bioindicator of bioavailability of specific kinds of contaminants.

Other Physiological Bioindicators

Contaminants and other stressors can be expected to elicit various types of physiological responses. Among systems known to be affected are thyroid functioning, retinol homeostasis, the haem synthetic pathway, as well the activities of various enzymes, such as cholinesterase, glutathione-S-transferase, and aminolevulinuc acid dehydratase (ALAD) (Peakall *et al.* 1981, McCarthy and Shugart 1990, Stegman *et al.* 1992, Hoffman *et al.* 1993). Many of these have been found in all animals so far tested but have not been extensively examined in colonial waterbirds until very recently. Because of the extensive work on these systems in other animals, their characterization in colonial waterbirds holds promise for extrapolation of results from other organisms.

The thyroid plays a central role in controlling metabolism, and contaminants have been shown to affect its function in colonial waterbirds, although species differ in response (Jefferies 1975). Thyroid function has been studied experimentally in PCB-exposed gulls and Black Guillemots (*Cepphus grylle*) and free living Great Lakes Herring Gulls (Moccia *et al.* 1986).

Acetylcholinesterase functions in neural transmission. The mode of action of organophosphate and carbamates pesticides, dioxin, and other compounds is to inhibit esterases. A 50% depression of acetylcholinesterase activity in the brain can be lethal (D. Hoffman, pers. comm.). As a result, acetylcholinesterase activity can serve as a biomarker of contaminant exposure and effect (Grue *et al.* 1983, Mackness *et al.* 1987, Mineau 1991, G. Fox, pers. comm.). Esterase effects have been well demonstrated in the field, especially with gulls and herons (White *et al.* 1983, White and Kolbe 1985, Smith *et al.* 1986, Custer and Ohlendorf 1989).

The metabolism and storage of retinol, an essential vitamin that cannot be synthesized by birds, can be affected by contaminants. Planar halogenated hydrocarbons, especially, alter the storage of hepatic retinoids (Spear *et al.* 1986, G. Fox, pers. comm.). Retinol is important in chick development and its concentration in egg yolk is readily determined. Its levels in chicks can be assessed through blood or liver samples (G. Fox, pers. comm.). It has been suggested that contaminants decrease levels of retinoids in Herring Gull yolk (Spear *et al.* 1986, 1990, Environment Canada 1991). This assay might be of value in monitoring exposure to compounds such as dioxins.

PCBs and metals can alter haem biosynthesis causing alteration in the amounts of porphyrins that accumulate in tissues. Fox *et al.* (1988) found that Herring Gulls from contaminated areas had higher liver concentrations of highly carboxylated porphyrins than did gulls from control areas. Porphyrin accumulation in colonial waterbirds is a potentially useful bioindicator of both exposure and effect (Gilbertson and Reynolds 1972, Koeman *et al.* 1973).

Other enzyme systems affected by stressors can serve as bioindicators (Westlake *et al.* 1983). ALAD, an enzyme involved in haem biosynthesis as discussed above, is specifically inhibited by metals especially lead (D. Hoffman, pers. comm.). In studies of lead poisoning in waterfowl, this blood enzyme has been shown to have a dose-dependent reduction in activity. ALAD should be applicable as a bioindicator of exposure and effect in colonial waterbirds (G. Fox, pers. comm.). Glutathione S-transferase and aryl hydrocarbon hydroxylase are other enzyme systems induced by contaminants (Ellenton *et al.* 1985, Pickett and Lu 1989, Hoffman *et al.* 1993). Hormones are also affected by stressors, and the concentration of various stress hormones (such as corticosteroids) can be used as a bioindicator of exposure and effect (Peakall *et al.* 1980a, Morimoto *et al.* 1987).

Hematology

Hematology offers exceptional potential for providing bioindicators (S. D'Surney, pers. comm.). Contaminant concentrations can be measured directly. DDE in plasma has been found to be correlated with exposure and body burden (Henny and Meeker 1981). Stressors can cause changes in morphology or activity of blood cells. Identifiable hematopoietic alterations can be traced to metals, including lead and mercury, and to PCB's (D. Hoffman, pers. comm.). In addition to morphological changes, blood can also be used for genetic level determinations, as discussed previously.

Because hematological techniques have not been applied to colonial waterbirds, considerable information on methods and evaluation is required. However, blood is one of the most easily sampled tissue, and multiple bioindicators can be extracted from the same sample. Because taking blood samples is relatively unobtrusive and unharmful to the birds being sampled, hematological bioindicators can be efficient and cost effective. One challenge is to determine the specific environmental correlates of hematological conditions, as these may be relatively nonspecific (G. Fox, pers. comm.).

Histopathology

Histological investigations are able to detect structural changes that can be related to environmental stressors. One example in colonial waterbirds is the change in the histology of the thyroid of Herring Gulls in the Great Lakes thought to be caused by contamination (Moccia *et al.* 1986, Gilbertson *et al.* 1991). Edema also is a known response to contamination stress (Hoffman *et al.* 1993). Histopathology can also be a part of blood and teratology evaluations.

Teratology

Physical defects in colonial waterbirds, particularly bill and other developmental defects in chicks, can be caused by contamination (Tumasonis *et al.* 1973, Gochfeld 1975, Gilbertson *et al.* 1977, 1991, Ludwig and Kurita 1988, Fox *et al.* 1991b, Hoffman *et al.* 1993, Yamashita *et al.* 1993). These are reviewed by Hoffman (1990). It has been proposed that such defects can be used to detect the presence of developmental toxicants in Great Lakes food chains (Fox *et al.* 1988, Mineau *et al.* 1984).

Teratological defects provide a sensitive indicator of hazards (Hill and Hoffman 1984) and studies of colonial waterbirds in the Great Lakes have provided some of the best evidence for their value as bioindicators (Gilbertson *et al.* 1976, Gilbertson and Fox 1977, Mineau *et al.* 1984, Gilbertson *et al.* 1991). The selenium-caused teratogenesis in (noncolonial) birds at Kesterson Reservoir, California is similarly a definitive demonstration of the utility of developmental defects as bioindicators (Ohlendorf *et al.* 1986, Hoffman *et al.* 1988). In almost all cases, to understand the origin of developmental defects residue analyses must also be conducted (C. Henny, pers. comm.).

Growth

Growth and condition are commonly used bioindicators in various animals (Adams 1990). Similarly, the growth of colonial waterbird chicks appears to be tightly related to prey availability and can be adversely affected by contaminants.

Prey populations may be assessed through the growth of Blue-footed Booby (*Sula nebouxii*) chicks (Ricklefs *et al.* 1984). Similarly, growth of young herons may be a sensitive indicator of water conditions in their feeding habitat (K. Parsons, Manomet Bird Observatory, unpubl. data. P. Frohring and J. A. Kushlan, unpubl. data).

Growth has been shown to be affected by lead in Common Terns (*Sterna hirundo*) in the laboratory (Gochfeld and Burger 1988). Oil decreases growth of Fork-tailed Storm-petrels (*Oceanodroma furcata*), Herring Gulls and Black Guillemots (Miller *et al.* 1978, Butler and Lukasiewiczs 1979, Peakall *et al.* 1980a, Heath 1983, Boersma *et al.* 1988). Dioxins and planar PCB congeners can cause wasting, as shown by studies of tern and gull chicks (Grasmen and Fox, pers. comm., Ludwig *et al.* 1993, Harris *et al.* 1993). However, contaminants do not always affect growth (Trivelpiece *et al.* 1984, Fry *et al.* 1986, Custer *et al.* 1986).

Behavior

Environmental stresses can alter bird behavior, especially neurotoxic contaminants such as lead and certain pesticides that affect the nervous system. In many cases, the normal behaviors of colonial waterbirds are sufficiently well documented to serve as a baseline for identifying stress-related deviations.

Both contaminants and habitat alteration affect behavior of colonial waterbirds (Burger and Shisler 1978, Fox *et al.* 1978, White *et al.* 1983). For example, food-handling behavior of Common Tern chicks was altered by injection with lead (Gochfeld and Burger 1988). Fox *et al.* (1978) and Kubiak *et al.* (1989) have shown that contaminants can alter the reproductive behavior of both Herring Gulls and Caspian Terns (*Sterna caspia*).

Reproductive Performance

Nesting success and other measures of reproductive performance of colonial waterbirds can be a bioindicator of effect for certain ecosystem conditions (Gilbertson and Hale 1974a, b, Gilbertson and Fox 1977, Mineau and Weseloh 1981, Kushlan 1989b, Kubiak *et al.* 1989, Fox *et al.* 1991a, b, c). For successful nesting to occur, suitable nest sites, cover, and food must be available over a specific period of time. A deficit in the availability of habitat or food can reduce the number and quality of chicks produced. Other factors such as weather and contaminants also can affect nesting success. Thus, in many cases poor reproductive performance is due to some aspect of the environment creating stress and, as a result, can be used as a bioindicator (Gilbertson *et al.* 1991).

Such bioindicators are valuable because reproductive performance is one of the most critical aspects of population dynamics. Temple and Wiens (1989) concluded that basic population parameters such as birth rates are among the most appropriate variables to use as bioindicators. Henny (1972) found that a change in recruitment rate was the variable that most affected population dynamics. Reproductive performance can be an early indication of population effects that appear later. Mora *et al.* (1993) have shown that the proportion of Caspian Terns recruiting to their natal colony in the Great Lakes was negatively correlated with the mean concentrations of PCBs in the plasma of the breeding adults.

A number of studies have demonstrated the link between reproductive performance and food supplies. The reproductive success of Brown Pelicans decreases when anchovy stocks decrease (Anderson *et al.* 1980). Similar situations exist between other seabirds and their fish stocks (Schaefer 1970, Crawford and Shelton 1978, Gaston *et al.* 1983, Furness 1984, McCall 1984, Cairns 1987, Hamer *et al.* 1991). The reproductive success of American Wood Storks in the Everglades depends on water level fluctuations to make food available during nesting (Kushlan 1989b). Such strong correlations provide a sound basis for using reproductive performance as an indicator of how an ecosystem functions to provide food.

Reproductive performance can be an indicator of contaminant effects and exposure because developing young are especially sensitive (Gilbertson and Hale 1974a, b, Gilbertson and Fox 1977, Osborn and Harris 1979, Kubiak *et al.* 1989, Peakall *et al.* 1980a, Fox *et al.* 1991a, b, c, Ankley *et al.* 1993). Colonial waterbird reproduction is adversely affected by oil, which both affects adults and is transported across the shell (McGill and Richmond 1979, Peakall *et al.* 1980b, Ainley *et al.* 1981, Holmes 1983, Parnell *et al.* 1984, Fry *et al.* 1986, Butler *et al.* 1988). It is also affected by chlorinated hydrocarbons (Anderson *et al.* 1975, Fox 1976, Gilbertson and Fox 1977) Ohlendorf *et al.* 1978, Weseloh *et al.* 1979, Nisbet 1980, Custer *et al.* 1983, Henny *et al.* 1984, Findholt and Trost 1985, Ohlendorf *et al.* 1985, Eisler 1986a,b, Hoffman *et al.* 1986, Brunstrom 1988, Elliot *et al.* 1989, Hart *et al.* 1991, Gilbertson *et al.* 1991, Tillitt *et al.* 1992), organophosphates (White *et al.* 1983, 1984), and metals (Fimreite 1974, Gochfeld 1980, Ohlendorf *et al.* 1986). Harris *et al.* (1993) showed improvement in hatching success, the number of young fledged, and length of incubation as contaminant residues decreased. Ford *et al.* (1982) found that reduced nesting success caused by oil contamination may be more important to population stability than are oil spills.

Reproductive performance can be assessed by using a number of bioindicators, each with its own particular value. These include infertility, fecundity, embryo morbidity and mortality, hatching success, contaminant burdens, nestling survival, and fledging success. They also include aspects discussed previously, such as developmental defects and post-embryonic growth and development. Behavior, as discussed subsequently, has also been advocated as a potential bioindicator. These include behaviors associated with courtship and pairing behavior and success and such outcomes as the frequency of female-female pairs (Fry *et al.* 1987).

Reproductive success related to contaminants has been proposed for ecosystem monitoring (Gilbertson *et al.* 1991), although it should also be noted that some studies have not found reproduction to be inhibited by apparently high availability of contaminants (Connors *et al.* 1975, Custer *et al.* 1986). One advantage of reproductive performance bioindicators is that they can be evaluated and compared at several times during the nesting period. This allows assessment of changing conditions or the use of rates of change of various bioindicators.

Mortality

Mortality can provide information of value in environmental assessment, whether using specific cases or calculations of population mortality. Bird mortality has often been recognized as a signal of broader environmental problems. Although death of a single bird provides little information, massive or repeated instances of mortality can be considered to be an assay, analogous to typical toxicology bioassays. Long-running surveys of dead birds, e.g., beached bird surveys, have been run along standard routes (Stenzel *et* *al.* 1988). Oatley *et al.* (1992) suggested that banding recovery rates of Cape Gannets (*Sula bassanus*) (i.e., percent of banded birds found dead and reported to the Bird Banding Laboratory) could be used as an indicator of environmental conditions.

Mortality of nestlings and young may be particularly indicative of conditions, as discussed under reproductive performance. As noted, recently developed bioassays found a correlation between egg mortality in cormorants and PCBs levels (Tillitt *et al.* 1992).

Colonial waterbird mortality has provided evidence of poisoning, oil contamination, pesticide effects, and disease (Koeman *et al.* 1973, Tumasonis *et al.* 1973, Parslow and Jeffries 1973, 1977, Vermeer and Vermeer 1975, Weise *et al.* 1977, Ohlendorf *et al.* 1981, Zinkl *et al.* 1981, Hill and Fleming 1982, Boellstorff *et al.* 1985, Brand *et al.* 1988, Page *et al.* 1990, Crawford *et al.* 1992). One of the most common examples of poisoning is by orthophosphate pesticides (White *et al.* 1979, Zinkl *et al.* 1981, Hill and Fleming 1982, White and Kolbe 1985). Among other contaminants, mercury was implicated in winter starvation of Grey Herons (van der Molen *et al.* 1982). Studies of oil contamination in colonial waterbirds suggest the importance of long-term mortality effects. Trivelpiece *et al.* (1984) demonstrated the effects of oil on Leach's Storm-petrel (*Oceanodroma leucorhoa*) survival.

Determining the cause of death is often difficult, for example, in distinguishing primary oil effects (Carter and Page 1988). The recovery of dead birds must often be followed by forensic or ecological studies to relate the mortality to a specific environmental stressor. Other difficulties in using bird mortality as a bioindicator include locating corpses before they decay, separating the many potential causes of mortality, and dispersal of ill birds from the initial source of stress.

Presence/absence

The presence and persistence of a colonial waterbird species at a site indicates that the ecosystem is suitable for it at some level. Therefore, it is an appropriate bioindicator of those conditions that the bird requires. C. Henny (pers. comm.) notes that many of the colonial waterbird species in the western United States are now primarily found on Federal and state wildlife refuges, suggesting the importance of appropriate habitat conditions. It is possible to evaluate habitat use in terms of suitability from a number of perspectives (Soots and Parnell 1975, Schreiber and Schreiber 1978, Erwin 1980, Frohring and Kushlan 1986).

Presence does not mean that all aspects of a bird's needs are met; a bird may be present but not reproducing. Presence also depends on having a regional waterbird population pool available to make use of an ecosystem. If birds are at very low density in an area their absence in a particular spot may not reflect habitat quality (van Horne 1983). Also, colonial waterbirds often have many choices of feeding or nesting sites and birds may not be present in all suitable places at a particular time. Thus, the absence of a species at the time of sampling does not prove that ecosystem conditions are unsuitable for it.

Distribution

Changes in the ranges of colonial waterbirds may be affected by changes in habitat quality and mortality rates. In Florida, the shift of nesting American Wood Storks northward has been interpreted to be the result of ecosystem changes in the more southerly portion of the range (Ogden *et al.* 1987). Recent expansions of the Double-crested Cormorant in the North American Great Lakes have been attributed to release from DDT-era suppression (T. W. Custer and C. Henny, pers. comm.). Of course, distributional changes are generally long term and may relate to purely natural processes such as climate change. Distribution changes may prove hard to distinguish from short-term fluctuations in occurrence.

Population Indices

Colonial waterbird population data provide more information than presence/absence data alone. There is a substantial information base on colonial waterbird numbers (Spendelow and Patten 1988, Rose 1992), especially at colony sites. Censuses of colonial waterbirds in their breeding colonies in the U.S. Great Lakes over 40 years demonstrated changes in numbers and dispersion (G. Fox, pers. comm.). Thus, given trends in appropriate indices over time and space, the underlying population trends should be inferable.

Such populations trends can be caused by environmental changes. For example, changes in the nesting numbers of several fish-eating colonial waterbirds in Florida Bay suggested the effect of a common stressor related to food abundance or availability (Kushlan and Bass 1983, Powell 1983, Kushlan and Frohring 1985). Similarly, other populations may respond directly to changes in food stocks (Vader *et al.* 1990).

There are, however, major difficulties in using colonial waterbird population indices as bioindicators of ecosystem change. Low accuracy and/or precision in most count data for colonial waterbirds have been noted (Kushlan 1992). In many cases, there is a poor relationship between count data and the underlying population. Counts that are really indices are misused often as population estimates. A specific difficulty is the mobility of the species. As noted previously, the presence of many birds at a site is often an indicator of good environmental conditions, however, the presence of only a few birds may not reflect poor environmental conditions because conditions elsewhere may be influencing bird numbers at the monitoring site. For instance, poor wintering conditions may reduce nesting population numbers the following season, which in no way reflects the local situation. The many factors affecting population density at a particular site suggest that it may be difficult to relate population data to overall habitat value (van Horne 1983).

Most problematic is that, when a downward trend of a population index is detected, it may not be possible to know what is causing the trend. To do so often requires causality studies. Changes in population indices of colonial wading birds in the Everglades are related to changes in wetland hydrology (Kushlan and Frohring 1986, Kushlan 1987, Frohring *et al.* 1988). In most cases, however, correlative information is lacking.

Population index changes in wintering colonial waterbirds are limited and usually even harder to understand than those on the breeding grounds. Because of their mobility, variability in timing, and multiple habitat options, population indices of colonial waterbirds generally would have little relationship to changes in a single ecosystem.

Community Bioindicators

Species assemblages, species richness, species diversity, similarity indices, guild indices, and integrity indices are community level bioindicators often used in other groups of organisms (Bernstein 1986, Kingston and Riddle 1989, Adamus and Brandt 1990). They are seldom used in colonial waterbirds. Nonetheless, changes in ecosystem functioning could be expected to alter patterns of colonial waterbird community structure over time. Differences in the number and relative abundance of colonial wading bird species in the Florida Everglades and Venezuelan llanos appear to reflect differing hydrological conditions (as well as evolutionary history) in these two similar ecosystems (Kushlan *et al.* 1985). But these differences emerged over long periods. It is likely that concerns over a decrease of an individual colonial waterbird species would overshadow concern for changes in community indices.

Ecosystem Bioindicators

Some colonial waterbirds have very specific food chain requirements. For example, the American Wood Stork requires relatively large fish whereas the American White Ibis (*Eudocimus albus*) requires small invertebrates (Ogden *et al.* 1976, Kushlan 1979). A well-functioning ecosystem would be supplying requirements for all species.

Food taken can be assessed by sampling food consumption, which is relatively easy in many colonial waterbirds because the chicks readily regurgitate their meals. Seabirds may be useful as samplers of the fish stocks present in their feeding environment (Duffy and Siegfried 1987, Furness and Barrett 1991 but see Hunt *et al.* 1991). Problems of differential digestibility and variation in prey availability need to be considered to relate these data back to food chain alterations.

Other ecosystem-level functions, such as bioenergetics, community respiration, or decomposition rates, also should be affected by environmental stressors and so should be able to serve as bioindicators (Pratt 1990). Because of its importance, energy taken by, or available to, nesting birds should be indicative ecosystem conditions (Kushlan 1977). To the extent that energy is limiting during nesting, energy restrictions at this stage of the annual cycle may be crucial to population stability.

However, with respect to ecosystem-level indicators, using colonial waterbirds is probably not the most appropriate bioindicator because of their mobility. Some groups, such as northern seabirds, may however be important in the flow of energy in certain systems (Wiens and Scott 1975). However, if the desire is to monitor changes in pathways of energy flow, other resident bioindicator groups would be more appropriate.

STRENGTHS AND WEAKNESSES OF BIOINDICATORS

What Bioindicators Mean

A common goal for most bioindicators is to predict effects at higher hierarchical levels, particularly ecosystem-level effects. Ecosystems include energy and biomass of its components and flows of energy and materials between them. The dynamics are driven by external forcing functions such as rainfall, sunlight and water flow, and controlled by feedback mechanisms maintaining homeostasis. If assessing ecosystem functioning were the only goal for using bioindicators, the most appropriate indicators would be values of state variables or flow rates between them, which would correspond directly to output of system models. However, these are seldom the variables chosen for biomonitoring because they are complex, difficult to measure, and have little appeal from a human perspective.

Biomonitoring is most pertinent and supportable when it involves organisms valued by people. Thus, colonial waterbirds have been used, and will continue to be, as bioindicators of environmental change. By monitoring factors other than state variables, one must realize that ecosystem function is not being measured directly but rather variables are being measured that are more remote from the direct effects of system disruption.

This paper has reviewed selected aspects of colonial waterbird biology that might be useful as bioindicators of environmental change in their ecosystems. Each bioindicator has its own properties, responds to a specific stressor or combination of stressors, and enjoys it own levels of precision, accuracy, and predictability. Choice of bioindicators is limited by the purpose of a monitoring program, human values associated with ecosystems being monitored, cost, understanding causalities, and social and political considerations. Limitations in interpretation need to be acknowledged so that indicators are not misused. Given these constraints, we should expect bioindicators to signal changes in environmental conditions, achieve some level of prediction at higher hierarchical levels, and detect effects prior to their having impact at the system level.

Bioindicator Characteristics

Bioindicators at the organismal level and below (SO bioindicators, often called biomarkers, bioeffects, or endpoints) differ in some ways from those at the higher hierarchical levels (PCE bioindicators).

SO bioindicators hold much promise, although their applicability to colonial waterbirds mostly awaits demonstration or perfection through additional study. Generally speaking, SO bioindicators have value in being prospective with respect to higher level changes; i.e., they can demonstrate nonlethal stressor exposure prior to homeostatic failure of the organism or ecosystem (Huggett *et al.* 1992). Thus, they should be able to provide early warning of future, more adverse effects. Another advantage of SO biomarkers is that they can eliminate or focus attention on specific contaminants and hence, reduce the costs and breadth of chemical analyses in subsequent studies (T. W. Custer, pers. comm.).

SO bioindicators applied to colonial waterbirds also can be problematic in that they are integrative, multifunctional, and often poorly understood biologically. They are integrative because they often involve multifunctional biochemical pathways and respond to multiple stressors, including natural ones (Stegman *et al.* 1992). In most cases, the pathways are poorly defined and the dose-response relationships are not well understood or are characterized over only a short range of values (C. Henny, pers. comm.). Furthermore, highly mobile colonial waterbirds can respond to stressors encountered at locations and times other than where the bioindicator value was measured. Because of their integrative properties in colonial waterbirds, results from SO bioindicators would usually need to be followed by additional evaluation of cause and effect (Fox 1991).

For all these reasons, predictability of SO bioindicators in real life situations has so far been somewhat limited, and they have shown poor correlation with higher level (PCE) effects (Cairns 1983, 1984, Cairns and Pratt 1986, Adamus and Brandt 1990, Mayer *et al.* 1992). In part, this is because few studies have examined bioindicators at both levels of organization simultaneously (G. Fox, pers. comm.). But, more fundamentally, that higher-level effects are rarely predicted from lower level effects should not be unexpected given the actions of homeostatic mechanisms at all hierarchical levels. Each level might be expected to be organized in ways to accommodate sublethal stressors, at least until some high threshold is exceeded. Such accommodations and defenses dull, postpone, or modify the direct expression of stressor exposure at the higher levels.

Two groups of SO bioindicators appear to hold special promise. First, those associated with contaminant accumulation and the molecular and physiological responses of organisms have indeed shown demonstrable population-level effects. Second, those associated with reproduction should have the power to predict subsequent population level responses. Future study will undoubtedly uncover suborganism indicators that can predict specific higher-level effects, but the current lack of specificity is one reason why it remains valuable to seek bioindicators that function at higher (PCE) levels of organization.

PCE level bioindicators can be especially integrative and pertinent. In colonial waterbirds which are long-lived, mobile, and wide ranging, bioindicator values may reflect the effects of many stressors that may have been experienced over long time periods in different locations. They are pertinent because they relate to ecosystem values of importance to humans, having economic, sociological, and political relevance. They also have a high degree of relevance to resource management because they reflect long-term responses to chronic stressors resulting from gradual changes in ecosystem functioning (Adams *et al.* 1989).

However, much of the inherently prospective characteristic of SO level bioindicators is lost by most bioindicators operating at the PCE levels of organization, owing to their inherent detectability, integration, and resiliency.

PCE bioindicators are detectable only after the ecosystem has changed substantially, by which time stresses have exceeded the accommodative capacities of homeostatic mechanisms. Populations may have already suffered reproductive failure, numerical fluctuations, or community shifts. Thus, PCE bioindicators tend to be retrospective rather than prospective, tending not to predict environmental changes but to measure them after they have occurred. Their retrospective character must be considered in planning use of PCE bioindicators.

PCE indicators are integrative, and so lose predictability for the same reason that they are valuable. Responding to multiple stressors and integrating stressors over time and space mean that it is usually impossible to learn which stressor may be causative, what ecosystem function may be compromised, or perhaps even which ecosystem is involved.

PCE bioindicators are resilient because of ecosystem level homeostasis. Ecosystems are characterized by interconnectiveness, redundancy, and feedback networks, such that ecosystem level changes are often not as predicted (Pratt 1990). By the time PCE bioindicator values exceed critical limits, it is likely that important ecosystem functions already will have been severely compromised.

Changes in PCE bioindicators often result in proposing explanatory hypotheses that must then be tested in a scientifically valid way. Given a firm understanding of a species' biology, one might infer reasonable hypotheses as to the causes. Previously collected environmental data can be scanned for correlations and for potential cause/effect relationships. However, it may not be possible to pursue sequential hypothesis-testing research when the ecosystem has been so altered that causal research is no longer possible. As a result, even when colonial waterbird bioindicators at the PCE levels may be able to show severe compromises in ecosystem functions, corrective action may not be possible.

One advantage of using both SO and PCE bioindicators with colonial waterbirds is that many are simultaneously measurable at colony sites. The simultaneous collection of bioindicator data enhances the opportunity to discover correlations among bioindicators. The sensitivity of developmental processes to disruption makes associated bioindicators particularly likely to show effects of environmental change. Furthermore, contaminent loading and reproductive performance bioindicators, both measurable at colony sites, have already demonstrated correlations to population level effects. Given the accessibility of eggs, young, and adults at the colony, the strengths of both levels of bioindicators can be maximized.

APPROACHES TO USING COLONIAL WATERBIRD BIOINDICATORS

Counterindications

Based on the above discussion, colonial waterbirds seem to have value in bioindicator monitoring, but under somewhat restricted circumstances that should be fully appreciated.

First of all, their biology makes colonial waterbird bioindicators particularly integrative. They are wide ranging and have the capacity to make choices among feeding and nesting sites and will not always sample the environment in a perfect way (Hunt et al. 1991). Thus it will not always be clear what an indicator is indicating, and follow up studies will often be required.

Second, they are large, not easy to handle, and are expensive to maintain in captivity. This constrains laboratory studies, their use in bioassay work, and capture and/or collection of adults in the field.

Third, counting colonial waterbird adults remains problematical. In some cases, counts can only be used as indices of underlying population fluctuations (Kushlan 1992). Furthermore, the use of counts, the most common sort of colonial waterbird data available, to assess habitat quality is suspect (van Horne 1983). In all cases, the severe statistical and sampling problems associated with environmental monitoring programs need to be dealt with (Spellerberg 1993).

These constraints notwithstanding, aspects of colonial waterbird biology appear to have some value as bioindicators. Suggestions for the development of bioindicator programs using colonial waterbirds are provided below.

Multiple Approaches and Incorporation of Human Values

A bioindicator monitoring program should generally not be confined to one or a few prechosen variables, nor only to biological indicators (Zonneveld 1983). Too little is known about the causality and ranges of these bioindicators to predict with certainty which will be most valuable at some future date. Diversification of bioindicators avoids overspecialization and spreads the "downside" risk (Type II error) of not detecting any change when it occurs. This is the case in other hazard assessment programs as well. For example, monitoring a "triad" of chemical contamination, toxicity, and animal communities relative to sediment quality has been proposed (Chapman *et al.* 1987). Using a combination of variables, together and separately, to assess changes in both the ecosystem and in the populations of concern is preferred.

Defining what conservation functions or human values are to be preserved in a specific ecosystem is essential. Establishing goals for a bioindicator monitoring program in advance enhances the appropriate choice of bioindicators, provides a base standard with which to compare changes, and increases the probability that important changes will be detected in time.

After goals have been established, the final step is to closely and accurately monitor the indicators and their changes. In some cases, certain effects may have been predicted by *a priori* environmental impact statements or environmental assessments. To determine whether the effects exceed acceptable levels, they must be monitored and responded to appropriately.

With respect to colonial waterbirds, then, it is of particular value to identify suites of biomonitoring variables that could be of value depending on why these animals were chosen as bioindicators. I recommend four overlapping suites of biomonitoring: contaminants, blood sampling, breeding season, and population indices.

Monitoring Contaminants

As bioindicators of contamination, colonial waterbirds serve a sentinel function, one of three potential roles for bioindicator species (McCarthy and Shugart 1990). A "sentinel" demonstrates the presence or extent of exposure to a stressor, as contrasted with a "surrogate" that indicates potential human exposure or effects or a "predictor." That indicate future, longterm effects on the health of populations or the integrity of ecosystems. The distinction between sentinels and predictors is a crucial one. A sentinel species is used in a retrospective rather than prospective way (Lower and Kendall 1990). The highly integrative character of colonial waterbird bioindicators increase their value as sentinels of contamination in their ecosystems.

The experiences of using colonial waterbirds bioindicators of contamination in the North American Great Lakes show their value (Hill and Hoffman 1989). Gulls and terns have provided exceptional information on contamination, especially differences in contamination over time and among breeding areas. The Double-crested Cormorants explicitly have been proposed as a sentinel species in the North American Great Lakes (Fox *et al.* 1991a). Another proposal is to combine contaminant exposure and effects in an epidemiological approach stressing the inference of cause and effect relationships (Fox 1991, Fox *et al.* 1991b,c). One characteristic of the Great Lakes program has been the use of nesting colonies and of data gathered during nesting as the unit of comparison. One result of the program is to show that different species show different effects, suggesting the importance of choosing the monitoring species wisely. The Great Lakes approach can serve as a model for the use of colonial waterbirds in monitoring contaminants elsewhere.

Blood Samples

Blood sampling is a particularly promising approach to obtain repeatable bioindicator data in a nondestructive way. Blood sampling is relatively unobtrusive and nonlethal, usable on either nestlings or adults, and repeatable to assay changes in exposure or effect over time. Its nonlethality is not a trivial consideration where colonial birds are protected in ways that can inhibit research and monitoring activities. Nondestructive sampling may allow access when other methods might not.

This approach is still poorly developed in birds and considerable study needs to be conducted on methods of collection, preservation, and analysis (G. Fox, pers. comm.). Nonetheless, blood samples should be able to provide a suite of bioindicators, especially molecular and physiological bioindicators that can be very early indicators of exposure. Because avian haematocytes (unlike those of mammals) are nucleated, genetic material can be readily evaluated DNA content, DNA strand breakage, adduct formation, and degree of methylation can be assessed from blood samples. Flow cytometry may prove an easy and inexpensive approach to determining differences in DNA content (T. W. Custer, pers. comm.) Cell morphology, developmental abnormalities, stress hormone titer, contaminant levels, enzymatic activity, and contaminant levels are also readily measured.

Breeding Season Bioindicators

The nesting period of colonial waterbirds presents another opportunity for the use of bioindicators. Ready access to eggs, young, and even adults at colony sites facilitates simultaneous monitoring of a suite of variables. Either eggs or chicks or adults can be used, depending on the questions being asked and on the biology of the species.

Egg shell thickness and contaminant burdens are readily measured. Egg quality may reflect local contamination (Ohlendorf *et al.* 1979b, Nisbet and Reynolds 1984), but it may also reflect conditions in areas used by the adults prior to assembling at the colony site (Henny and Blus 1986). Eggs are readily obtained, although colony-site protection regulations may inhibit access (T. W. Custer, pers. comm.). A single egg can statistically represent the entire clutch (Custer *et al.* 1990) and the removal of a single egg does not affect population parameters (Henny *et al.* 1984).

Chick development is a sensitive indicator of environmental change. Unlike eggs, teratology and growth of chicks reflect current local conditions (Custer *et al.* 1991). Using chicks in the confined population of a nesting colony can compensate for the difficulties that colonial waterbirds present as wide-ranging species. Developing chicks can reflect local conditions via molecular or physiological responses, contaminant accumulation especially in feathers, behavior, teratology, and the suite of potential biomarkers available in blood samples. For example, Peakall *et al.* (1980b) studied the effects of oil contamination by repeated nonlethal sampling of growth and blood parameters in Black Guillemot chicks.

Perhaps the most definitive use of colonial waterbird as bioindicators during nesting has been in the North American Great Lakes. Gulls, terns and cormorants have all shown responses to contamination that can be measured in the nesting colony (Hoffman *et al.* 1990). A number of studies have demonstrated the relationship of bioindicators to contamination (Heinz *et al.* 1985, Hoffman *et al.* 1993), providing the basis for biomonitoring environmental conditions in the Lakes through the birds (Fox *et al.* 1991a).

Another promising approach is to decouple the effects of parental care from environmental effects by moving eggs to artificial incubators. This is particularly valuable for making intercolony or interyear comparisons. Hoffman *et al.* (1993) studied a suite of bioindicators of contamination collected from eggs, piped young, or eggs brought back to the laboratory. In comparisons between relatively contaminated and uncontaminated sites, they found expected trends in such bioindicators as reduced hatching success, morphological anomalies, teratogenicity, increased liver-to-body-mass ratio, decreased hepatic DNA concentration, and induction of liver microsomal aryl hydrocarbon hydroxylase activity. This study is a good model for the carefully controlled use of a suite of reproductive period bioindicators.

Bioindicators related to reproductive performance have special promise in signaling ecosystem changes related to food supplies, hydrology, and hydrography. Changes in reproductive variables, such as chick growth or mortality, can be sensitive bioindicators of changes in underlying ecosystem function. In fact, reproductive performance functions more like a SO level bioindicator than a PCE level bioindicator because it provides information prior to population-level effects, especially in long-ived birds such as colonial waterbirds. Reproductive indices appropriately collected over time can mirror changes in environmental conditions where the birds nest. This is well demonstrated in the Florida Everglades, where reproductive failures and population decrease can be attributed to hydrologic conditions exceeding the capacity of populations to accommodate (Kushlan 1986).

Population Indices

Although most population-level bioindicators are not very useful as bioindicators, trends in statistically valid population indices may have utility. Care must be exercised in trend use and interpretation relative to the long life spans, complex annual cycle, and wide geographic ranges of specific colonial waterbirds. That many population and census data bases are already available suggests the importance of using them if possible. If population indices are sufficiently documented changes should be evaluated in terms of their value as sentinels of environmental change.

Misuse of population data remains a serious concern (Kushlan 1992) and the difficulty of understanding causality remain vexing. Nonetheless, despite Morrison's (1986) misgivings noted in the introduction to this review, it does appear that population index data may have some biomonitoring value, particularly if they are associated with information from other bioindicators such as reproductive performance and if the questions asked are appropriate for the data. Thus, carefully-derived trends in population indices should be able to serve as an early warning of population changes and therefore suggest the need for additional research to seek causes of the change. Because of the eventual need for causal study, population indices need to be combined with long-term monitoring of bioindicator suites available during the breeding season and through blood sampling.

The Program

The needs of each biomonitoring program should be specific and explicit, so the first step is to identify the goals of the program, then to choose the most appropriate tools to achieve the goals, and finally to assess how the results compare to standards or to predicted outcomes. Within this context, colonial waterbirds seem of some value, especially during nesting. A suite of bioindicators including those associated with blood, chick growth, contaminant levels, and reproductive performance should provide a robust inter-correlated database to detect responses to stresses. Other critical values in the support system should also be monitored, such as food supplies, water quality, or hydrology in order to conduct correlation analyses after a response is detected. Given such carefully constructed monitoring schemes, aspects of colonial waterbird biology should continue to serve as sensitive bioindicators of environmental changes.

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