WATERBIRDS AS BIOINDICATORS OF WETLAND CHANGE: ARE THEY A VALUABLE TOOL?

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SUMMARY

It has long been appreciated that waterbirds might function as indicators of ecosystem (particularly wetland) health. The support of wildlife, including waterbirds, is recognized as one of the important functions of wetlands. This paper examines the potential of waterbirds as bioindicators by defining bioindicators, evaluating those aspects of waterbird biology which might be useful as bioindicators, and considering how waterbirds might be used to indicate the ecological changes that occur in wetlands.

A bioindicator is a biological measure of exposure to, or a measure of the effect of, anthropogenic environmental stressors. Bioindicators are integrative, relatively inexpensive, and functionally pertinent. Bioindicators may be derived from biological function at any level of biotic organization. Suborganism bioindicators are particularly valuable because they can demonstrate stressor exposure or effect prior to that stressor having an adverse effect on the organism or the population. Population level bioindicators are of particular concern to wetland managers because they possess high ecological relevance, in other words they relate directly to wetland values of importance to humans. They also measure long-term responses to chronic stressors, such as a a gradual change in wetland functioning. Potential bioindicators of wetland change derived from waterbird biology include mixed function oxidases, porphyrins, xenobiotic burdens, egg shell thinning, presence/absence, population indices, and reproductive competency.

Suborganism bioindicators show considerable promise, especially when related to confined groups of organisms such as non-migratory or breeding populations. A suite of potential bioindicators, applicable to eggs and chicks, has the promise of being indicative of both exposure to and the effect of many contaminants. There is a need for additional studies of reproductive period bioindicators in different wetlands. Population level data show special promise as sentinel bioindicators. Depending on the species and the wetland, in some cases, changes in population indexes can be related to specific wetlands and in other cases, additional study of explanatory hypotheses are needed to determine the causes of population index change. Nonetheless population bioindicators can be a signal of wetland functional failure. There is a need for additional studies of how population indices in a wetland relate to the underlying functional attributes. Indicators of reproductive competency may have potential to signal wetland change that is related to food supplies, and the hydrological and hydraulic conditions determining food availability. Reproductive success, such as the growth or mortality of chicks, can be a sensitive indicator of wetland conditions. Changes in the pattern of reproductive competency can indicate a trend in change of wetland function. More study is needed on the relationship of reproductive competency to food supplies and the hydrological functioning of wetlands. Waterbird bioindicators must be carefully investigated and then carefully selected and used. When changes are found, a careful and scientifically valid study of the explanatory hypotheses is usually needed. But given this care, specific waterbird bioindicators show promise as tools for detecting wetland change.

INTRODUCTION

It has long been thought that waterbirds might function as indicators of ecosystem (particularly wetland) health (Bluset *al*. 1977; Custer and Osborn 1977; Adamus and Stockwell 1983; Williams 1985; Rose 1992). Waterbird species are large, obvious, and popular. The support of wildlife, including waterbirds, is recognized as one of the important functions of wetlands. Much information already exists on the presence or numbers of waterbirds at many wetland sites, both on summering and wintering grounds. The use of waterbirds as bioindicators of wetland change would encourage the integration of wetland monitoring into existing and proposed waterbird monitoring programmes, the primary goal of which is the conservation and management of those populations. Furthermore, the presence of internationally important numbers or types of waterbirds on a wetland are important criteria for Ramsar site designation. The continued presence of these birds may be an indication of the continued importance of a site.

This paper aims to examine the issue of waterbirds as bioindicators. To evaluate the utility of waterbirds in this role, it is necessary to define carefully what we mean by bioindicators and to evaluate those aspects of waterbird biology which might be useful as bioindicators. Then we can consider how waterbirds might be used to indicate the ecological changes that occur in wetlands.

RESULTS AND DISCUSSION

Bioindicators

Indicators are a useful way of assessing environmental health. To argue using an analogy: assessing the health of a person is accomplished by measuring body temperature, calculating a cholesterol ratio, or determining the presence of pathogens. From the presence of a large number of pathogens, we infer the existence of a disease. Similarly, assessing the health of the economy is accomplished by measuring the money supply, calculating the Gross Domestic Product, or counting the number of unemployed workers. From the presence of large numbers of unemployed former executives we infer a weak economy.

Assessing environmental health uses the same process. This is accomplished by measuring productivity, calculating a diversity index, or determining the presence of sensitive species.

So indicators provide an important way to monitor the status and changes in complex interactive systems. The trend of the indicator is often as important as its instantaneous value. For a good indicator, the trajectory of change should reveal an underlying trend in the same direction as the functions being monitored.

At the present time, the use of various specific ecological indicators is less universally accepted than the use of indicators in medicine or economics. Nonetheless, the use of biological indicators is increasingly well appreciated, and significant progress has been made within the past decade in discovering and evaluating bioindicators. Considerable research efforts are being made at the present time.

There is also a fundamental theoretical concern when using indicators to assess wetland change. This can be illustrated using the statistical concepts of independent and dependent variables. In nearly all cases, a biological indicator is the dependent variable. The environmental factors that control wetland function are the independent variables. When we measure an indicator, we are measuring dependent variables of a multivariate system, leaving undetermined which of the independent variables has changed. Thus care must be taken in interpreting indicators because in many cases it is not clear what is causing the indicator to behave as it does. To continue the analogy, consider the divergent reasons that are given by experts to explain a change in a stock index or GDP, and the number of opinions offered as to the direction of future trends in these indices. It is for this reason that the detection of an adverse trend in a bioindicator, often needs to be followed by the development and testing of explanatory hypotheses.

A bioindicator may be defined as a biological measure of exposure to, or a measure of the effect of, anthropogenic environmental stressors.

Bioindicators can function in two ways (Mayer *et al.* 1992). A bioindicator of exposure reflects the fact that an organism has been in contact with a stressor, even if the stressor is no longer present. A bioindicator of effect reflects the fact that an organism has been impaired by a stressor. Of course a given bioindicator may usefully reflect both.

A bioindicator of exposure may show that an organism has been in contact with a contaminant, whereas a bioindicator of effect will show impairment due to that exposure. Similarly, waterbird numbers may be reduced in a wetland due to a short-term event such as a flood. After the water recedes the waterbirds, who moved elsewhere during the flood, may not return. The lack of birds is an indicator of exposure to high water levels. Alternatively, waterbird numbers may be reduced in a wetland, due to ten years of reproductive failure, the result of excessively high water levels brought about by management action. The lack of birds is an indicator of the population effect of continued high water levels.

Another component of the definition is that of "stressors." A stressor is an environmental condition that creates an adverse response in an organism. This concept is an extension of the stimulus-response paradigm that underlies much of our understanding of biological systems. In its environmental use, it derives from the seminal work of Seyle (1956). Biological stress is a robust concept that can be used at any level of organization (Thorpe and Gibbons 1978, Pickering 1981). Stressors may be thought of as a natural component of the life of an organism (Seyle 1956). However, "bioindicators" involve only artificial, anthropogenically derived stressors. The related term "stress" is to be avoided or explicitly defined in each application, as it has been widely used both as the stimulus and the response.

Ecosystems are defined as being composed of both biotic and abiotic components, and the interactions between them. Thus there are biotic indicators, abiotic indicators and functional indicators. There is no *a priori* reason why biological indicators should be more suitable than non-biological indicators of ecosystem condition or change. In many applications, it might be more appropriate to measure an abiotic indicator, such as some aspect of hydrology, hydraulics, or water chemistry, rather than a biotic indicator.

In most cases a proper monitoring system will probably include both bioindicators and nonbiological indicators. This is because in order to test explanatory hypotheses, it often helps to conduct a correlation study to search for relationships between bioindicators that are suggesting system changes and physical and chemical indicators that may suggest the causes.

Nonetheless, there are very good reasons for using bioindicators, namely that they are integrative, relatively inexpensive, and functionally pertinent.

Bioindicators are integrative in that they usually are responses to multiple, individual, simultaneous, and perhaps synergist stressors in the environment. In the case of wetlands these stressors may be contaminants, nutrient pollution, hydrological changes, drainage and habitat loss, or wetland habitat alteration. At a given time, each stressor separately and together may affect the quantitative value and trend of a bioindicator. So bioindicators integrate the exposure to or the effects of many stressors.

Bioindicators similarly integrate the effects of a single stressor both temporally and spatially. Waterbirds are potentially long-lived and relatively mobile species. They can be affected over their lifetime and in multiple locations. Thus a bioindicator may integrate the effects of stressors over both time and space.

Economy is one consideration when using an integrative bioindicator. Bioindicators are responding to a suite of stressors over time and space and therefore it may be possible to measure a single bioindicator, rather than all the possible causes or stressors. Cost is always an issue, and it is often less expensive to count plants or animals than conduct extensive chemical analyses or hydrological monitoring.

Bioindicators are pertinent because they relate directly to wetland values important to humans. In the present discussion, this includes the role of wetlands in wildlife and waterbird conservation. If artificial stressors affect waterbirds, the wetlands will have lost some of their value in the human landscape. The lack of a demonstrated effect is also a very pertinent aspect of bioindicators in relation to the human values of wetlands. A contaminant or a hydrological alteration that does not have a measurable biological effect would not cause a decrease in that value, and may not be a matter of concern. Taking the example of a contaminant: it is not necessarily the presence or concentration of a xenobiotic that is of importance but its availability and its effect. If a contaminant is sequestered in the sediment and is not available to the animal then it has no biological effect at that level. Chemico-indicators generally do not distinguish availability from concentration, whereas bioindicators generally measure availability as revealed through effect. In this way bioindicators can be functionally pertinent in ways that physical indicators are not.

Bioindicators may be derived from biological function at any level of biotic organization (Table 1). Within this hierarchy of organization, the weakest bioindicators tend to be those at the organism level. The growth or death of a single organism has little predictability because it is idiosyncratic, due to the many factors influencing its life. However, when these same measures are made at a population level they can become valuable indicators. Mortality of a test population is the basis of the LD 50 toxicity bioassay. It has been demonstrated that behaviour is affected by stressors, but again the behaviour of an individual organism may be unrepresentative.

Table 1. Potential bioindicators for waterbirds at various levels of biological organization.

Suborganism	Molecular
	Physiological
	Histopathololologic
	Immunological
	Xenobiotic Burden
Organism	Growth
	Death
	Behaviour
Population	Presence/Absence
	Distribution
	Population Size
	Reproduction
	Energetics
Community	Species Assemblages
	Species Richness
	Diversity
Ecosystem	Energy and Material Flow
	State variables

Suborganism bioindicators are particularly valuable because they can demonstrate stressor exposure or effect prior to their adverse effect on the organism or the population (Huggett*et al.* 1992). This is a reflection of the extensive accommodative abilities of organisms. For example, DNA alterations, acetylcholinesterase inhibition, tissue distribution of a xenobiotic chemical, or histopathology may be detectible in a group of test organisms, prior to a reduction in growth rate or life span. This characteristic is extremely important, because it provides "predictability." That is, these indicators can signal future events or conditions that are more detrimental than those measured. The detection of exposure or effect should lead to a prediction of future effects, and in a practical sense could encourage corrective action.

It is important to note that at the present state of knowledge, the extent of this "predictability" has limitations. Suborganism bioindicators thus far have shown some predictability with respect to the future effect at the organism level. However thus far, changes in suborganism bioindicators have shown a poor correlation with higher level effects, those at the population, community, or ecosystem levels (PCE effects) (Mayer *et al.* 1992). This result, although disappointing, should not be unexpected in that organisms have many ways of accommodating sublethal stressors. These accommodations dull, postpone, or modify the direct expression of exposure to stressors at the population level, unless the stressor produces an overwhelming effect. Future study will undoubtedly uncover suborganism indicators that will be predictive of higher level effect, but the current lack of certainty is one reason why it remains valuable to seek bioindicators functioning at the higher levels of organization.

"Predictability," the ability to signal future events, is a fundamental difference between most (but not all) bioindicators at the suborganism level and most (but not all) bioindicators at the PCE levels. The predictive, prospective characteristic of bioindicators operating at the suborganism level is lost or compromised by most bioindicators operating at higher levels of organization. There are two considerations.

The first consideration is that of scale. PCE bioindicators are detectable only after the ecosystem has been changed substantially. By the time a significant change in a population bioindicator is detectable, the combined stressors have exceeded the substantial capacity of the study populations to accommodate, and so they already have suffered reproductive failure, population changes, or community alterations by the time the bioindicator change is detected. These bioindicators tend not to predict changes as much as to measure them after they have occurred. This distinction between suborganism and superorganism indicators is not complete, of course, the important exceptions will be noted below. It does suggest a problem in using higher level indicators to predict future wetland change. However, PCE bioindicators can signal that the change has occurred or is underway.

The second consideration is that of integration. PCE level bioindicators also lose predictability for the same reason that they are valuable: they are highly integrative. These bioindicators may be responding to any number of stressors operating over time and space. As a result it is usually not possible to learn directly from the bioindicator which ecosystem function has been compromised. Given a firm understanding of the biology of a species, one can often infer reasonable hypotheses as to the causes. Similarly, concurrently collected environmental data can be searched for correlations. In either case, changes in PCE bioindicators lead to an explanatory hypothesis that must then be tested in a scientifically valid way.

Whereas waterbird bioindicators at the PCE levels may be sensitive to severe changes in wetlands, they often cannot lead directly to corrective action. By the time a deleterious pattern is detected, it is often sufficiently serious that immediate management is called for. Yet, because of the lack of causal relationships there may not be a consensus among experts and managers as to what should be done. It may not even be possible to pursue sequential hypothesis-testing research, as the populations may be so compromised that causal research is no longer possible.

The question of interpretative care is paramount. Because a bioindicator is defined as a measure of exposure to, or a measure of the effect of, artificial environmental stressors, it will not directly measure the overall health of a wetland, but rather it will indicate the changes which have occurred in the independent variables that function as stressors. It should be recognized that changes in these stressors may or may not have a significant effect on the overall functioning of a wetland or on its ability to fulfill a specific function in the human landscape. For example, if a contaminant adversely affected only the reproduction of a rare species, it is quite possible that all the other wetland functions might be unimpaired. Whether the rare species is a matter of concern depends more on the role that this wetland plays in conserving the species, the legal status of the species, and the stated purpose of the wetland than on the adverse effects on the ecosystem. This leads to the requirement to define the conservation functions of a specific wetland that need to be preserved and to choose the indicators that relate to those functions. The goal of a biomonitoring program must be known in advance.

The difficulties noted above in the use of waterbird bioindicators are not unique to waterbirds in wetlands. They are inherent to bioindicators at this level of biological organization. Nonetheless, PCE bioindicators are of particular use to wetland managers because they possess a high ecological relevance (in other words they are directly linked to wetland values for humans) and they measure long-term responses to chronic stressors (such as a gradual change in the function of the wetland (Adams *et al.* 1989).

Waterbirds as bioindicators

We now can examine some aspects of waterbird biology as bioindicator candidates. Table 1 suggests a number of types of appropriate bioindicators at several levels of biological organization. Each bioindicator has its own properties, reflects a specific stressor or suite of stressors, and enjoys differing achievable precision, accuracy, and predictability. Some of these potential bioindicators will be briefly and selectively noted.

At the suborganism level, waterbirds are being increasingly used to assess the presence and effects of contamination. At this level, waterbirds appear to have potential as bioindicators, in that they seem to respond to and are sensitive to many contaminants. As noted before, an advantage of measuring suborganism responses is their nonlethality and therefore their early warning potential. A disadvantage in using waterbirds is that the biology of many species makes them especially integrative. Those birds that are highly mobile and migratory may be affected by stressors in locations other than the wetland in which they are nesting or feeding at the time. Nonetheless, by careful study, the determination of cause and effect relationships is possible in specific situations (Fox 1991).

An important molecular bioindicator has been studied in seabirds, that of mixed-function oxidases. These are a family of enzymes that function to transform the structure of organic molecules. MFO production can be induced by exposure to xenobiotics and many other chemicals, so their presence can be an indication of exposure. The action of these enzymes presumably detoxifies foreign chemicals, but this can also increase toxicity or carcinogenicity through the transformation products. Recent studies have shown MFO induction in seabirds, supporting their use as bioindicators (Knight and Walker 1982, Ronis *et al.* 1989).

Porphyrin accumulation patterns in tissues can indicate the inhibition of porphyrin metabolism by xenobiotics, such as PCB and metals. The effects of lead on ducks has been well documented (Rattner *et al.* 1989). Such effects have been traced to changes in the food chain (Fox *et al.* 1988). This promises to be an important bioindicator of both exposure and effect.

Xenobiotic burdens have been well documented in several species and can be related to impaired reproduction (Gilbertson *et al.* 1977, Ohlendorf *et al.* 1979, Ohlendorf *et al.* 1981). The effects of halogenated hydrocarbons have been particularly well investigated, and the mode of action is understood. For wetlands that serve as feeding sites during nesting, the assessment of the changing burdens of chicks during the nesting period can be used to assess exposure and a study of teratology can be used to assess effect (Fox *et al.* 1991a).

Egg shell thinning is a well known bioindicator of chlorinated hydrocarbon pesticide contamination. *Pelecanus occidentalis* (Brown Pelican) is one of the more famous examples, but other waterbird species have also been well studied (Anderson *et al.* 1975; King *et al.* 1978). The values of this bioindicator include its sensitivity, the fact that its mechanisms of action are understood (Lundholm 1987), and the increasingly precise measures of effect, especially breaking strength, that have been developed (Bennett *et al.* 1988). The usefulness of this bioindicator for assessing wetland change is less well established, because of its highly integrative character. These birds are highly mobile, they can pick up their burden in locations other than the wetland of interest. Also, other stressors can affect egg shell morphology including diet, metals, and temperature (Lundholm and Mathson 1986; Roland *et al.* 1973; Smith 1974). Thus before change in bioindicators can be ascribed to changes in a specific wetland, additional studies are needed.

Most data regarding waterbirds have been accumulated at the population level, and the existence of these data is an important factor in our interest in waterbirds as bioindicators. Because of long-standing concern, derived from the importance of waterbirds in hunting and migratory bird treaties, waterbird surveys and censuses have been conducted for some time. Many censuses have entered the monitoring mode, and so a substantial backlog of population level data are available for evaluation.

One of the more accurate population level variables is presence/absence of waterbirds in a wetland, particularly the presence of a sensitive species. The presence of a waterbird species indicates that at some level the wetland is suitable for it. In this way the presence of a species can be viewed as an indicator of overall condition. There are, of course, many difficulties. One is that presence may be transient. Another is that one individual will count as much as 1% of the population in assessing wetland function. Furthermore a change from 1% of the population to one individual will not be distinguished by the indicator. Also, very importantly, the absence of a species does not prove that a wetland is unsuitable, given that so many factors outside the wetland may be contributing.

An example of the relationship of habitat character to sensitive species occurrence is that of *Tringa totanus* (Redshank), on a marsh reserve described by Roberts (1991). Investigating the correlations between habitat variables and *T. totanus* number led to the clearing of some scrub, thereby bringing *T. totanus* back to the reserve. It is informative to note that the birds did not use the scrub, yet it was the change in this habitat variable that affected their occurrence.

Presence/absence, of course, determines distribution, which may be affected in the long run by wetland change. In south Florida, the shift of *Mycteria americana* (Wood Stork), to nest further north is considered to be the result of wetland change. However, after thirty years of repeated reproductive failure in south Florida, *M. americana* is still present in the Everglades (Kushlan and Frohring 1986). Thus distribution changes are often long term. By the time the last bird has gone much will have changed, so the predictability of this bioindicator and its relation to responsive management action is increasingly small.

Data on the numbers of waterbirds are available for many wetlands. These provide more information than just presence/absence data, but their accuracy is suspect. There are substantial inaccuracies and imprecisions in most count data for waterbirds, much of it unevaluated. Because of the difficulties in counting entire waterbird populations, population indices are particularly valuable, and the techniques for assessing changes in numbers, using population indices are increasingly well developed (Kushlan 1992). Given the trends in appropriate indices over time and space, the underlying population trends can be inferred signalling a predetermined level of change.

The major difficulties in using population indices concern integration due to mobility of the birds. Whilst the presence of a number of birds over time is an indicator of suitable conditions, the presence of a few birds may not be. This is because populations may be adversely affected by conditions elsewhere, or good conditions elsewhere may be attracting birds away from a perfectly adequate wetland of conservation interest. Tradition plays an undetermined role in a bird's choice of specific sites. Furthermore, as in all population level indicators, it is not usually possible to ascribe decreases in the index to specific changes in the wetland, unless concurrent data are collected or explanatory studies are undertaken. Good examples of the examination of explanatory hypotheses exist. Among the better known changes in waterbird populations are those in the Prairie pothole marshes and in the Everglades of North America (Poiani and Johnson 1991; Frohring *et al.* 1988; Kushlan 1987). In these examples well documented decreases in nesting waterbirds have been correlated with changes in wetland hydrology.

Population changes in wetlands used by wintering birds are harder to understand. Average counts have limited predictability due to local fluctuations, adverse census conditions, missing data and other matters (Rose 1992). Given the mobility of the species, these counts often have little relationship to changes in specific wetlands. They can and are used in managing waterfowl populations, especially for hunting mortality, and they can also indicate overall wetland conditions in the wintering area. However, as of yet, they have not demonstrated an ability to predict changes in specific wintering wetlands. In part this is because we know very little about wintering ecology, and so the testing of explanatory hypotheses is not well developed. Population level data could become more useful through additional research dealing with the causes and effects of the use of wetlands in winter.

Reproductive competency (nesting success) may be a superior indicator of wetland conditions and their change. Successful nesting requires, for example, changes in the water level to provide adequate food availability for foraging adults, over a suitably long period of time. In this respect, reproductive success functions more like suborganism level bioindicators because it provides information prior to population level effects, especially in long lived birds such as waterbirds. Difficulties include the limited segment of the nestling period available for analysis in some species, the difficulty of expressing reproductive success as a population based statistic (such as young per adult in the breeding population, as some may choose not to breed in a given year), the cost in manpower and logistics, and in some cases the adverse effect of the research on the nesting birds (Kushlan 1992). As in population statistics, indices that are appropriately collected over time can mirror changes in the environmental conditions where the birds are nesting. This is well demonstrated in the Everglades, where reproductive failures and population decrease can be attributed to hydrological conditions which exceed the capacity of the populations to accommodate them (Kushlan 1986).

Population level bioenergetics, especially the food taken by birds and food chain studies, should be indicative of environmental conditions (Kushlan 1977). However, since energy is often the most limiting factor during nesting, studies of reproductive competency may be a more straightforward way to approach energy limitations.

Community level bioindicators such as species assemblages, species richness, or diversity have not been used very often in waterbirds, probably because the individual species are identifiable, their specific habitat requirements are well known, and many species are themselves of management concern.

As indicators at ecosystem level, waterbirds are not necessarily the most appropriate measure of change. This is because waterbirds do not figure prominently in the flow of energy in most systems and if the requirement isto monitor changes in the pathways of energy flow, other indicators are usually more appropriate.

Assessing change in wetlands using waterbirds

Suborganism bioindicators may have considerable utility in waterbirds. The definitive studies of the responses of waterbirds to metals suggest that the many suborganism bioindicator systems, now available in other species, might be applicable to waterbirds as well. These bioindicators are particularly useful in assessing changes due to contaminants and to general stress. Further study is required to test many of these indicators in waterbirds.

An interpretive difficulty remains due to the integrative character of these indicators. One approach to this difficulty is to use confined populations, such as nesting populations, their eggs, and chicks, or non-migratory species or populations. In this regard short-term trends in molecular or physiological responses, contaminant accumulation, teratology, and other effects in chicks may be among the more valuable bioindicators of wetland change. Another approach is to use epidemiological methods to determine cause and effect (Fox 1991; Fox *et al.* 1991b). A third approach is to conduct studies to test explanatory hypotheses, either simultaneously or following the finding of an adverse indication.

Population level bioindicators are also valuable. Substantial data bases are available at the population level and can be used as indicators of overall ecosystem suitability over the life span, annual cycle, and geographic range of waterbirds. But care has to be taken when ascribing changes to stressors at a local wetland, unless one can use bioindicators derived from a confined population. It is for this reason that the application of wintering population data for use as bioindicators remains problematic in context to a specific wetland site. The presence of a species sensitive to certain environmental conditions may be indicative of the presence of those conditions, but the absence of a sensitive species may or may not be indicative of the absence of those conditions.

To assess change in a wetland a bioindicator must relate to local stressors. This is one reason why reproductive competency is one of the most valuable population level indicators. These data are to a large degree site specific and they are usually sublethal with respect to the adult breeding population. Furthermore, bioindicators related to reproduction have a good chance of being correlated to, and predictive of, other population level responses, particularly subsequent population decreases.

Although the integrative aspect of most population level waterbird bioindicators makes measuring change in specific wetlands difficult, because they integrate the effects of stress over temporal and geographic scales, such bioindicators do show long-term responses of high ecological relevance. Thus the most robust use of waterbirds as bioindicators is as sentinels, one of three potential roles for bioindicator species (McCarthy and Shugart 1990). A sentinel is a species demonstrating the presence or extent of exposure to a stressor, in contrast to a surrogate - a species which indicates potential human exposure or effects and a predictor - a species which indicates future, long-term 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). This is another way of noting the lack of predictability inherent in using bioindicators associated with wide ranging species, usually monitored at the population level. Nevertheless, sentinel bioindicators are extremely valuable because they are highly integrative.

CONCLUSIONS AND RECOMMENDATIONS

With critical limitations, some aspects of waterbird biology may be useful as bioindicators of wetland change. The limitations are not exclusive to waterbirds, but are pertinent to the selection of any bioindicator, especially at the population level.

Suborganism bioindicators show considerable promise, especially in relation to confined populations or breeding populations. A number of bioindicatorshave been developed for other species, but their usefulness in waterbirds needs to be demonstrated. Encouragement should be given to the additional study of the usefulness in waterbirds of those suborganism bioindicators which have already been identified in other organisms. A suite of bioindicators, applicable to eggs and chicks, shows great promise of being indicative of both the exposure to and the effect of many contaminants. There is a need for further studies of reproductive period bioindicators in different wetlands.

Population level data show special promise as sentinel bioindicators. Depending on the species and the wetland, in some cases, changes in population indices can be related to specific wetlands, and in other cases, additional explanatory hypotheses are needed to determine the causes of population change. Nonetheless population bioindicators can signal the failure of a wetland function. Encouragement should be given to the study of how population indices in a wetland relate to underlying functional attributes. The study of case histories of past declines in population indices may be of value. The existing data bases should be examined for such cases. Additionally, the development of consistent population indices which could be used at different sites would be valuable in comparing changes among wetland sites.

Bioindicators of reproductive competency show promise in the identification of wetland change related to food supplies, and the hydrological and hydraulic conditions determining food availability. Reproductive indicators, such as chick growth or mortality, can be sensitive indicators of wetland conditions. Changes in the pattern of reproductive competency can indicate changes in wetland function. Encouragement should be given to further studies of the relationship between reproductive competency, food supplies and the hydrological functioning of wetlands.

Waterbird bioindicators must be carefully investigated and then carefully selected and used. When changes are found, careful, scientifically valid, studies of explanatory hypotheses must be undertaken. Given this care, specific waterbird bioindicators show promise as useful tools in detecting wetland change, and therefore of contributing to the conservation and management of wetlands.

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