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Biological monitoring and ecological prediction: from nature reserve management to national state of the environment indicators

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13.1 INTRODUCTION

The techniques for biological monitoring are well-developed, as shown by examples in the preceding chapters. This chapter will explore two further issues: firstly, how do we decide what to measure, and secondly, what do we do with the data once it is collected? By examining these questions, we may make modifications to our biological monitoring programmes and growing computer databases. To restate, the issues which I propose to address are the following.

1. The selection of the state variables to be monitored. With more than a million species on the planet (Myers 1985; May 1989) we cannot possibly monitor each. Moreover, given predictions that a quarter may be extinct by the end of the next century we cannot possibly monitor even the threatened ones. How do we choose what to monitor? I will suggest a greater emphasis be placed upon macro scale state variables.
2. The interaction between monitoring and decision making. Monitoring is by its very nature *post hoc* – that is, it can only tell us what has already happened. But to wisely manage the biosphere, we need to predict future events. What is the relationship between biological monitoring, prediction, and decision making?

13.2 CHOOSING THE STATE VARIABLES TO MONITOR

13.2.1 Scale consideration

What do we monitor? Our first response is often to select a target species and begin to record its abundance through time. Target species can be selected for three reasons.

1. The species itself is of interest and we wish to measure our success in managing for it (e.g. Giant Pandas, Reid 1989).
2. The species is undesirable, and we wish to monitor our success in eradicating it (e.g. Purple Loosestrife in Canada, Thompson *et al.* 1987).
3. The species is an indicator of environmental conditions, and we are monitoring it because it is an indicator of the state of health of a particular habitat or environment (e.g. Meadow Beauty, Keddy *et al.* 1989).

Since the planet has millions of species (Myers 1985; May 1989), it seems that in most cases a species by species approach will leave the biologists outnumbered by species to be monitored. This suggests we need to place emphasis upon indicators of the state of health of entire ecosystems (Rapport *et al.* 1981; Ryder and Edwards 1985; Stokes and Piekarz 1987; Rapport 1990).

To give a concrete example, and one different from those discussed elsewhere, consider the problems in conserving the Atlantic coastal plain flora on the east coast of North America (Keddy 1985; Keddy and Wisheu 1989a; Wisheu and Keddy 1989a). What should be monitored to measure our success (or lack thereof) of conservation efforts in this region? A species by species approach would be time-consuming, and in the Canadian context, there are neither the trained staff, nor the financial resources to do this properly. However, a single species such as the showy pink-flowered Plymouth Gentian (*Sabatia kennedyana*) indicates species-rich coastal plain communities (Keddy 1985). Monitoring the abundance of this species may therefore measure the state of health of coastal plain communities in general.

But perhaps there is something even easier to measure than the abundance of Plymouth Gentians. We know that there are several environmental variables which can be used to predict the distribution of these species: naturally fluctuating water levels and sand shores (Keddy and Wisheu 1989a). Cottage development and all-terrain vehicles are key threats. Perhaps simply the number of lakes without dams and with less than ten cottages on them would be a simpler index still, and this sort of data might be collected by satellite or aerial photographs.

The choice of state variable will vary with the scale of the problem. At one end of the scale we may well be interested in monitoring the abundance of Plymouth Gentians in a single nature reserve. But at the other end of the scale, we may be interested in monitoring the state of health of Canadian wetlands as a whole, or the state of health of our entire natural environment, in which case no single state variable will suffice. In the case of wetlands, we would need to consider a hierarchy of scales (Table 13.1); each might require a different state variable to monitor its status.

As a guide to selecting appropriate state variables, Rapport (1990) suggests that in general we can recognise nine classes of information which provide symptoms of ecosystem distress: abnormalities, primary productivity, nutrients, species diversity, instability, disease prevalence, size spectra and contaminants. The challenge will be to provide simple means to measure these and to provide clear standards which must be achieved to maintain ecosystem health.

Table 13.1 The choice of state variable for monitoring requires consideration of geographic and biological scales. In the case of wetlands, we might use a different state variable for each of the following scales of interest

Geographic scale
global
biogeographic region
country
state/county
watershed
individual nature reserve
Biological scale
all wetlands
specific wetland habitat
functional group of organisms
selected species

13.2.2 The Canadian situation

In Canada there is a large land base and small population size, exactly the opposite situation from the UK and Europe. Canadians therefore have had to think carefully about what should be monitored and at what scale (e.g. Stokes and Piekarz 1987; Bird and Rapport 1986). Environment Canada now has a State of Environment Reporting Branch to deal with biological monitoring at the national scale. Environmental monitoring is a category somewhat broader than biological monitoring, and includes three sets of environmental data (Stakeholder Group on Environmental Reporting 1987):

1. environmental assets (e.g. natural resource stocks);
2. agents of environmental change (e.g. resource harvest and depletion);
3. environmental quality (e.g. levels and trends of pollutants).

An alternative framework for the development of environment statistics has four categories (United Nations 1989):

1. Social and economic activities, natural events (e.g. use of natural resources, waste loadings).
2. Environmental impacts of activities/events (e.g. resource depletion, change in environmental quality).

3. Responses to environmental impacts (e.g. pollution control, resource management).
4. Stocks, inventories and background conditions (e.g. biological resources, energy stocks).

Table 13.2 Environmental databases available for State of Environment reporting in Canada (from Keddy and McRae 1989)

Category	*No. of databases*
I. Environmental assets	
Water resources	3
Land resources	5
Wildlife	7
General	7
II. Agents of environmental change	
Waste generation and disposal	
Mining and smelting	3
Manufacturing	4
Municipal	2
Transportation	1
PCBs	3
Stored waste	1
Ocean dumping	2
Emissions – air	2
Environmental restructuring	
Urbanisation	1
Harvesting	
Agriculture	1
Hunting and trapping	1
Pesticide applications	1
General	3
III. Environmental quality	
Air	1
Water	3
Wildlife populations (plants and animals)	3
Landscape	1
Perceptions	1
General	4
IV. Other (indirectly related to environmental evaluation)	8

The document cited above lists a comprehensive series of indicators for each of these four categories.

There are growing numbers of databases which include the data for environmental monitoring. Friend (1988) listed 32 database categories suitable for this task. They include biological information on variables such as fish harvests, population sizes of migratory birds, and pesticide residues in organisms. A more recent inventory for the State of Environment Reporting Branch (Keddy and McRae 1989) identified 55 databases within Environment Canada alone. These range (Table 13.2) from avian census plots (non-game bird counts on permanent plots in various habitat types across Canada) to the national air pollution surveillance network (continuous monitoring of common air contaminants).

The following examples illustrate some of the biological variables being monitored in Canada, with emphasis upon larger scale biological variables.

13.2.3 Ducks and wetlands

Environment Canada has a long history of interest in waterfowl, in part because of the hunting lobby, and in part because of Canada's obligations

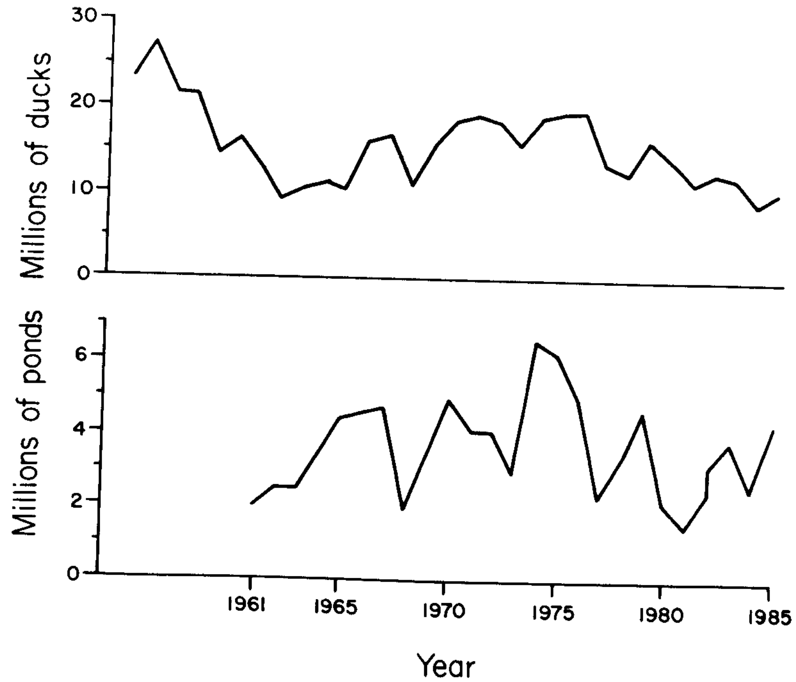

Figure 13.1 Number of ducks, and number of ponds, on the Canadian prairies for approximately the last 25 years (Bird and Rapport 1986).

under the Migratory Birds Convention Act. Figure 13.1 shows the number of ducks in the Canadian prairies as a function of time. There is clearly a problem. These data are particularly interesting, however, because we can consider ducks as bioindicators of wetlands. These data therefore may tell us of the declining state of health of prairie wetlands (Figure 13.1, bottom). We may be far more interested in the state of health of wetlands as a whole than any single group of species in them.

One could argue that the number of ducks is a poor choice to measure health of prairie wetlands – it may be much simpler to measure acreage of wetlands directly from satellite photographs. But an advantage to monitoring ducks is that they may be integrating both the quantity and the quality of wetlands. Increasing pesticide use may be reducing wetland quality (Sheehan *et al.* 1987). On the other hand, the decline in duck populations might also be caused by overhunting in the US – in which case the duck population sizes are telling us little about the state of health of prairie wetlands. In fact, the data probably integrate the effects of declining area of wetland, declining quality of wetland, and increased hunting pressure as well as many other unknown factors.

13.2.4 Great Lakes fisheries

Changes in the Canadian Great Lakes illustrate the scale and rate at which freshwater ecosystems are being altered by human activities. Figure 13.2

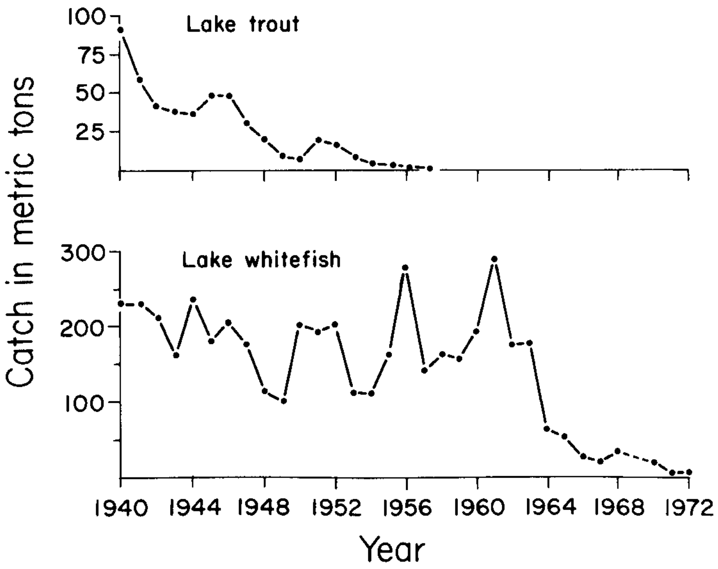

Figure 13.2 The decline in commercial yields of two species of fish in Lake Ontario since 1940 (after Christie 1974).

shows declines of two important commercial species over time. Christie (1974) has discussed such changes, and has attributed them to human impacts including overfishing, eutrophication, dams and the introduction of exotic species. We might ask, however, whether there are indicators of the state of health of Great Lakes fisheries beyond species by species enumerations. Figure 13.3 shows two indicators which illustrate overall changes in fish community structure over the last century. The top panel shows that large benthic species such as lake trout and sturgeon

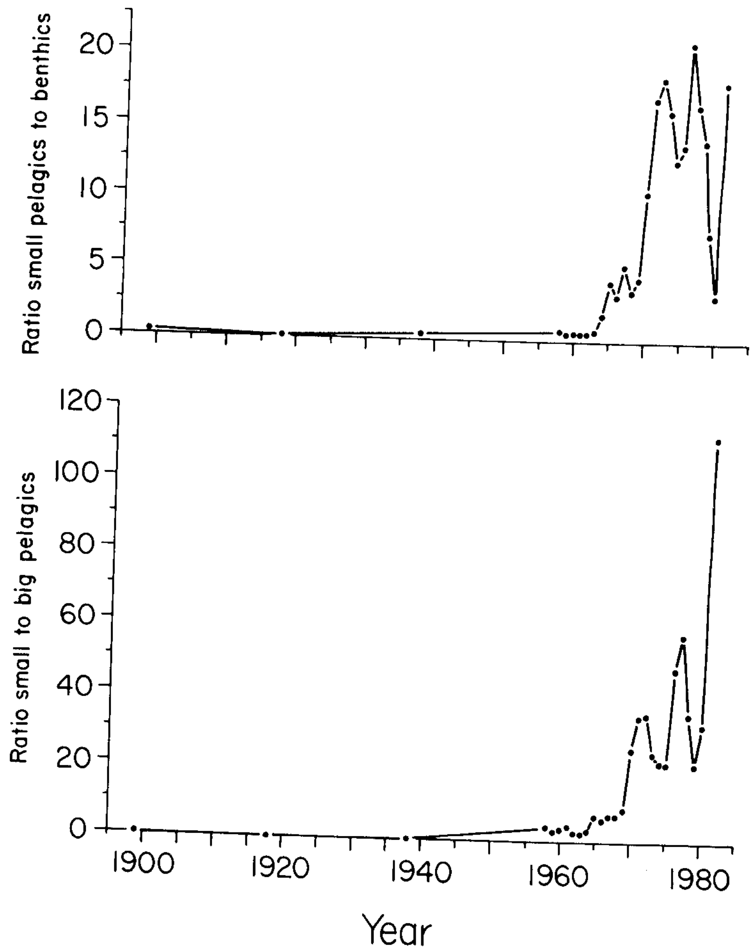

Figure 13.3 Changes in the state of Great Lakes ecosystems as measured by changes in composition of Lake Ontario fish communities. Small pelagics include smelts and alewife; benthics include lake whitefish and sturgeon; big pelagics include blue pike and lake herring (after Rapport 1983, Table 6).

predominated early in this century, but they have now been replaced by small pelagics such as smelts and alewife. The bottom panel shows that pelagic species have been shifting in composition; early in the century, big pelagic species such as blue pike and lake herring were most common; now they have been replaced by small pelagics such as smelt and alewife. While such indicators do not provide information on single species, they may be far better for monitoring the overall state of health of freshwater ecosystems. Regier *et al.* (1988) and Rapport (1989) have discussed the extent to which similar patterns are found in the Baltic Sea. More generally, the tendency for stress to eliminate larger species seems to be a common feature of ecosystem distress (Rapport *et al.* 1985; Rapport 1989, 1990).

13.2.5 Endangered species

There are approximately 5092 species of plants and vertebrate animals known from Canada (Pollard and McKechnie 1986). Of these, 95 species or subspecies are considered threatened, endangered, extirpated or extinct by the Committee on the Status of Endangered Wildlife in Canada (Table 13.3) – approximately 2% of our biota. A simple biological measure of environmental health would be the number of species falling into these categories (Figure 13.4). At present, a plot of number of species in this category against time would not be a reliable way of monitoring biological health. First, invertebrates are conspicuously absent. Second, many species are not listed by COSEWIC simply because there is little money to support the work needed to prepare the reports to have species officially listed! That is, the number of such species is currently underestimated for financial reasons,

Table 13.3 Monitoring threatened wildlife in Canada. Status designations by the Committee on the Status of Endangered Wildlife in Canada as of April 1989

Category (status)	*Birds*	*Mammals (terrestrial)*	*Mammals (marine)*	*Fish*	*Plants*	*Amphibians and reptiles*	*TOTAL*
Rare	16	13	3	22	18	1	73
Vulnerable	0	1	1	8	1	2	13
Threatened	7	5	2	10	18	–	42
Endangered	8	3	5	3	17	1	37
Extirpated	—	2	2	2	1	–	7
Extinct	3	1	1	4	—	–	9
TOTAL	34	25	14	49	55	4	181

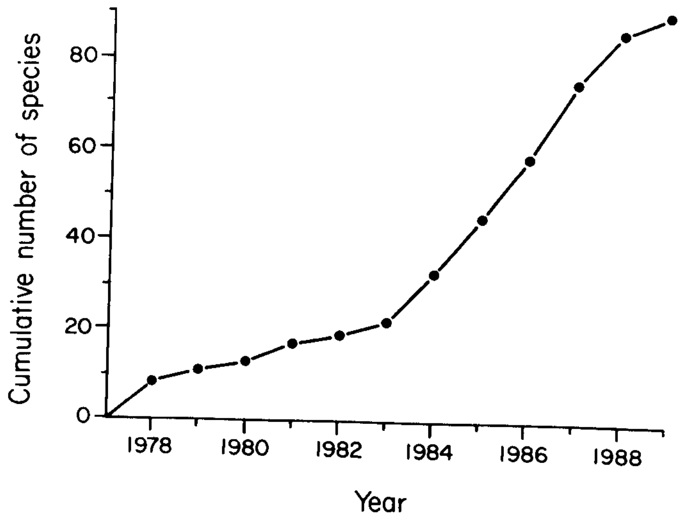

Figure 13.4 Cumulative number of species designated by COSEWIC (Committee on the Status of Endangered Wildlife in Canada) as threatened, endangered, extirpated or extinct in Canada. 'Species' can mean subspecies or geographically restricted population in COSEWIC data, but where a species was designated more than once in such categories, it was counted only once for this figure. Only plants and vertebrate animals are currently considered by COSEWIC.

and changes with time at present reflect the number of reports completed per year rather than the number of species being newly-threatened. Once this lag phase is finished, however, this would be a useful indicator. An allocation of a few hundred thousand dollars would probably be sufficient to finish candidate species (excluding invertebrates). Two species, the White Pelican and Wood Bison were recently downlisted from the endangered category, showing that percent of fauna listed by COSEWIC could also measure the success of recovery programs.

13.2.6 Protected land base

An ultimate cause of endangerment is generally habitat destruction (Ehrlich and Ehrlich 1981). A simple measure of our success in protecting habitat would have two components: the total area of land protected, and the degree to which this land base represents the natural diversity of Canada. In spite of our small population size and large area, Canada lags behind many countries in terms of total protected area in our parks system (Task Force on Park Establishment 1987). Parks Canada recognises 39 terrestrial and 29 marine

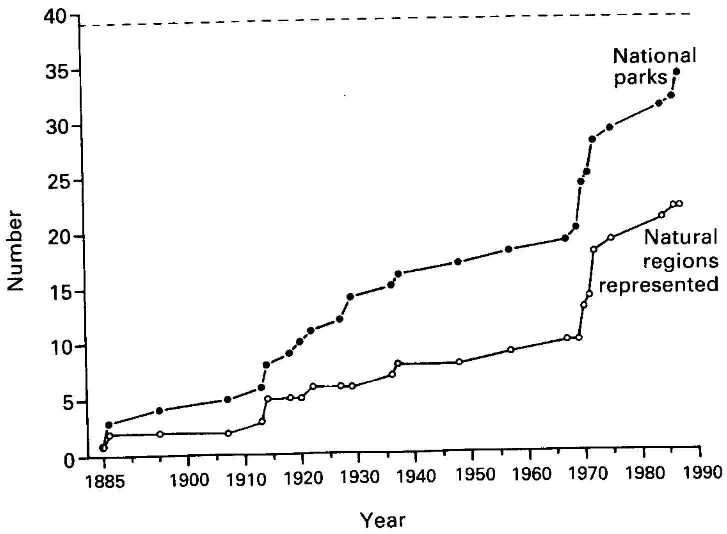

Figure 13.5 Monitoring the state of completion of Canada's national park system. The hatched line at the top represents the goal – complete representation of national park natural regions in Canada. While the number of national parks has slowly grown to 34 (solid dots), only 22 natural regions occur in a park (open dots). Moreover, some of these 22 natural regions are only partially represented, so that the parks system currently is less than half complete.

regions in the country, and Figure 13.5 shows that many of these important natural regions are not yet protected by National Parks (Taschereau 1985; Task Force on Park Establishment 1987). The World Wide Fund for Nature has just launched its national Endangered Spaces programme (Hummel 1989) which provides specific targets for each province to meet in order to ensure a national system of representative protected areas.

13.3 BIOLOGICAL MONITORING AT THE NATIONAL SCALE: TOWARDS STATE OF ENVIRONMENT INDICATORS FROM THE WORLD CONSERVATION STRATEGY

We need indicators of the biological health of a country in much the same way that the GNP of the country provides one measure of its economic health. No one indicator is sufficient, of course; even the GNP is supplemented by measures such as foreign exchange rates and unemployment rates. In the absence of measurable criteria for environmental improvement, we will have little way to judge whether our increasing expenditures on environment are really paying off. That is, are they really leading to measurable improvement in the state of environment? And at a

time when political parties are rushing to paint themselves green, indicators such as this would be a simple way for the public to tell whether a party's policies once elected matched its rhetoric. There is general agreement about neither the components of such measures nor their relative weightings (e.g. Inhaber 1974; Stokes and Piekarz 1987; Karr 1987; Liverman *et al.* 1988). One approach which might be considered is indicators based upon the World Conservation Strategy (International Union for Conservation of Nature and Natural Resources 1980). The World Conservation Strategy gives us three components of biological health of the planet: genetic diversity, sustainable utilisation and the maintenance of essential life support systems (Figure 13.6). Using indicators ('state variables') for these three components would provide relatively simple measures of environmental health that could be monitored annually and reported to a country or province without it. It might also be possible to combine these indicators into more general indices summarising one aspect of the state of environmental health, such as biodiversity (Figure 13.6). Other possible indicators are presented in a recent review prepared for the United Nations (1989).

The state variables in Figure 13.6 were chosen because of their obvious value as indicators, and because the data are already available (Friend 1988; Keddy and McRae 1989), or could be collected relatively cheaply. We could therefore, if we wished, have biological monitoring of each nation, and each political unit within a nation, in relatively short order. These indicators and/or indices could be compiled by a non-profit organisation (such as the World Wide Fund for Nature). It might be best for government to delegate such responsibilities to avoid any suggestion of political interference in the annual

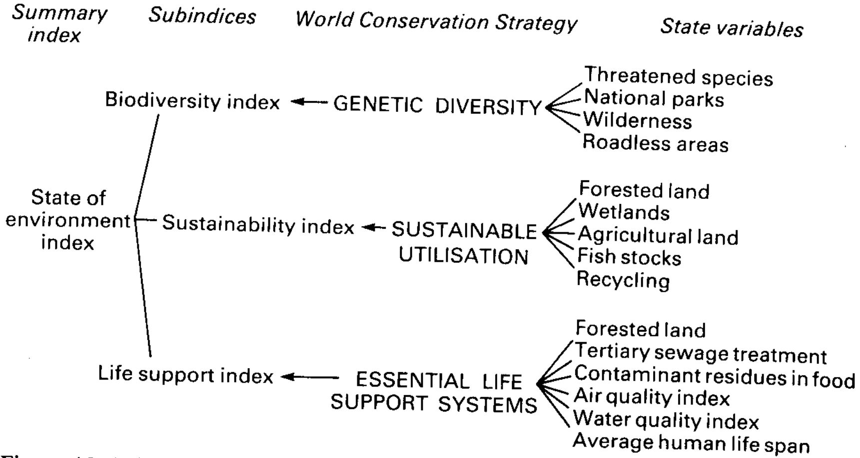

Figure 13.6 A series of indicators ('state variables') can be used to monitor the state of a nation's health according to the World Conservation Strategy. These indicators would provide quantitative measures of the success of environmental programs. It might also be possible to combine indicators into summary indices.

environmental audit, or it might be set up with the same independence as the Canadian Auditor General who evaluates federal expenditures for efficiency.

13.4 PREDICTION, MONITORING AND DECISION MAKING

13.4.1 Prediction

What is the relationship between monitoring and prediction and why does it matter? There are two reasons why prediction is important. First, it is an essential component in the maturation of ecology as a science (Rigler 1982; Peters 1980a,b). Second, and of greater importance for conservation, decisions we make today are guided by our expectations, or predictions, about their consequences in the future. To return to the economic analogy, accurate predictions are necessary to guide political decision making. If we increase personal income taxes on low income tax payers, what will be the change in the national seasonally-adjusted unemployment rate? As ecologists, we need to be able to make similar predictions. If the James Bay hydroelectric project (Phase 2) goes ahead, what will be the impact on coastal ecosystems? If Montreal spends money to install tertiary sewage treatment, how will aquatic communities downstream respond? If the climate warms by 1°C, how much marginal agricultural land in the prairies should be converted to pasture or abandoned? If Canada's remaining coastal forests are clear cut, what will happen to oceanic fisheries?

At present we are unable to make such predictions. This may have less to do with inherent ecosystem characteristics than with human behaviour: the emphasis in much of ecology is still upon description rather than prediction, perhaps because the foundations of ecology are still closely tied with natural history. It is beyond the scope of this chapter to explore in detail the different avenues which have been proposed for prediction, but the issue is explored further in Holling (1978), Peters (1980a,b), Rigler (1982), Starfield and Bleloch (1986) and Keddy (1989). A few generalisations are possible, however.

In the simplest case, making predictions requires that we decide what we want to predict (the dependent variable), and then determine what independent variable will be the best predictor of the dependent variable. This approach raises important questions. First, what are the key state variables that we need to predict? One of our scientific problems is that we do not yet have a body of ecological models to tell us which variables are the key state variables for maintaining the state of health of our planet or measuring ecosystem 'integrity'. To use a medical analogy (Rapport *et al.* 1979; see also Rapport *et al.* 1981; Rapport 1990), we do not yet know whether to measure blood pressure, hair colour, weight, or smoking habits to predict life span. Lewontin (1974) has referred to this as 'the agony of community ecology'.

Similarly, we have few guides as to what state variables will be the best

predictors of our independent variables. The best predictor of future endangered species lists may be percent of ecoregions represented in national parks rather than simply percent of Canada's area devoted to parks. Working out the empirical relationships among such state variables would allow us to make such predictions (e.g. Rigler 1982).

We may find that in general, higher order (or macro level) variables will be easier to predict. To borrow an example from physics, the behaviour of individual molecules is very difficult to predict, but the ideal gas laws nonetheless provide clear empirical relationships among pressure, volume, and temperature. Prigogine and Stengers (1984) provide many examples of such relationships in emergent properties, as the title of their book, *Order out of Chaos*, suggests. I have argued elsewhere that this applies directly to community ecology (Keddy 1987).

Emphasising higher order state variables has another advantage: it tends to highlight general properties rather than site specific ones. This is necessary because there are insufficient resources for dealing with conservation issues on a case by case basis. Leary (1985) has discussed the importance of this transition, and presented a general model as a guide in the evaluation of government research (Figure 13.7).

A good example of this approach to prediction is the relationship between species richness (the dependent variable) and standing crop (the independent variable) in vegetation. Early work (Al-Mufti *et al.* 1977; Grime 1979) demonstrated an empirical relationship between these variables, with species richness reaching a maximum at intermediate levels of biomass. Since then similar relationships have been found in vegetation types including fens (Wheeler and Giller 1982), Pine savannas (Walker and Peet 1983) and

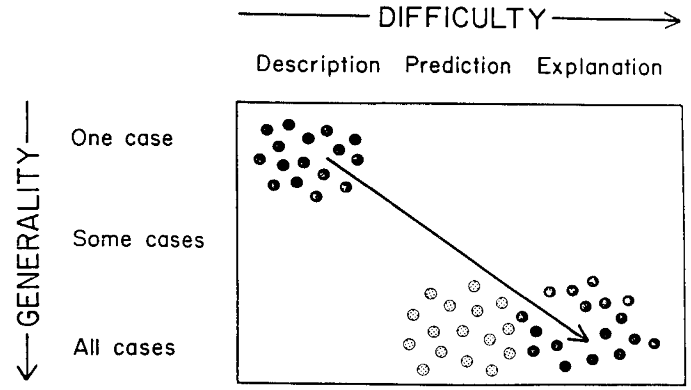

Figure 13.7 Two criteria for judging scientific progress (Leary 1985). Leary argues that we need to move from the upper left to the bottom right. For most conservation management, prediction (grey dots) would be the first priority (from Keddy and Wisheu 1989b).

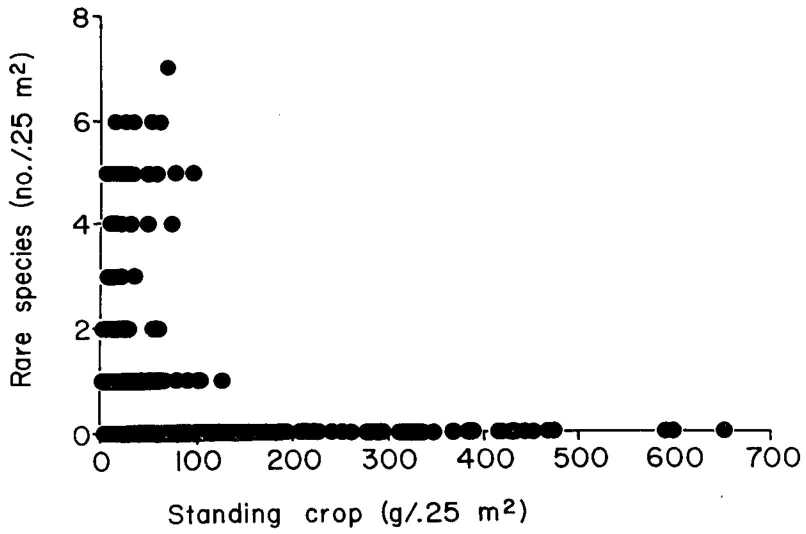

Figure 13.8 Vegetation biomass can be used to predict which wetland vegetation types do not support nationally rare wetland plant species. The number of nationally rare plant species in each of 401 quadrats from eastern Canada is plotted against quadrat biomass (dry weight). (Reproduced from Moore *et al.* (1989) with permission from Elsevier Publishers Ltd.)

freshwater shorelines (Wisheu and Keddy 1989b). From the point of view of conservation, this simple relationship has been valuable. Grime (1973) has discussed managing species-rich vegetation types in this context. Moore *et al.* (1989) show that biomass can be used to predict which wetlands will have nationally rare wetland plant species (Figure 13.8).

13.4.2 Monitoring and prediction

Monitoring is allied to prediction in two essential ways. First, in the model-building stage, it is only by making wrong predictions that we can build better models and monitoring is essential to determine whether our predictions were right or wrong. As in multiple regression techniques (e.g. Kleinbaum and Kupper 1978; Sokal and Rohlf 1981), adding in new independent variables will gradually increase the accuracy of predictions. Of course, no ecological model can be expected to produce prediction, so monitoring plays the more important role of providing an early warning system to advise us that the real world is beginning to deviate from our expectations. Consider species richness again. We may well know that to achieve maximum richness of chalk grassland, we need vegetation with biomass levels under 500 g m^{-2}.

We therefore plan grazing regimes accordingly. But if air pollution increases soil fertility, as is happening over much of Europe (Ellenberg 1988), higher than predicted levels of grazing may be needed to maintain the desired vegetation biomass. Furthermore, even if we maintained vegetation biomass constant, there might still be a shift towards species more tolerant of eutrophication (Ellenberg 1988), requiring us to devise yet another management strategy for our grassland. Monitoring therefore provides constant feedback to managers, and constant feedback for refining and reconstructing predictive models. Any political decision with an environmental component has an element of prediction, even if the simplest (and commonest) 'prediction' in the past has been that nothing of any consequence will be changed by the decision. With a growing environmental awareness by politicians and industrialists, there will be a growing interest in accurate predictions, or at least possible scenarios, to guide decision making.

13.4.3 Monitoring and decision making

Monitoring is the essential feedback link between humans and their environment. Once a decision is made, monitoring provides feedback about the consequences of that decision. It is therefore essential that there be well-established mechanisms for ensuring that the information gained from monitoring leads to modifications or even reversals of earlier decisions. If the right-hand arrow in Figure 13.9 is missing, we are losing the most important part of monitoring in both the scientific and political arenas.

The importance of feedback from monitoring applies at the complete range of scales as well. At the most local scale, the decision of a nature reserve manager may be to fluctuate water levels over a ten-year cycle to produce rich coastal plain vegetation in a lake (left arrow) (e.g. Keddy *et al.* 1989). The nature reserve management plan should then have a requirement that

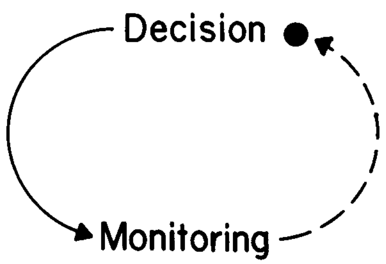

Figure 13.9 Monitoring records the consequences of environmental decisions. It is therefore important to have a feedback loop (hatched arrow) so that observations from monitoring can produce changes in social decisions as early as possible.

monitoring be carried out so that the merits of that decision can be evaluated, and the water level regime modified at a later date. At the large scale, the decision by the Quebec government to flood large areas of northern Quebec to generate hydroelectric power for the United States (the James Bay Project Phase 2) has the left-hand arrow, but the right-hand one is absent. There is no mechanism for removing the dams and restoring the environment if environmental quality deteriorates. Adaptive impact assessment (Holling 1978) and sustainable development will require such a feedback loop.

We can expect that in the future all environmental decisions, be they the management of a nature reserve or a national economy, will require environmental auditing both to guide initial decisions and to monitor projects as they progress so that modification is possible. Choosing the biological variables to monitor, and building the linkages and feedback loops to ensure that they influence societal behaviour, are two challenges which face us. As we address these two issues, biological monitoring will become an increasingly powerful tool for decision making at local, regional and national scales.

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