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Monitoring for conservation

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Human-mediated environmental changes have resulted in appropriate concern for the conservation of ecological systems and have led to the development of many ecological monitoring programs worldwide. Many programs that are identified with the purpose of 'surveillance' represent an inefficient use of conservation funds and effort. Here, we revisit the 1964 paper by Platt and argue that his recommendations about the conduct of science are equally relevant to the conduct of ecological monitoring programs. In particular, we argue that monitoring should not be viewed as a stand-alone activity, but instead as a component of a larger process of either conservation-oriented science or management. Corresponding changes in monitoring focus and design would lead to substantial increases in the efficiency and usefulness of monitoring results in conservation.

Monitoring, efficiency and Platt (1964)

It has been four decades since the publication of 'Strong inference' by Platt [1], which dealt broadly with the conduct of science, focusing on the crucially important step of discriminating among competing hypotheses. He criticized the unfocused collection of detailed data that are perhaps generally relevant to the investigation, but not directed at hypothesis discrimination. His paper has been hugely influential and is widely cited as an important contribution to the philosophy and conduct of science.

Here, we offer a perspective on the conservation and monitoring of biological resources that we believe to be analogous to Platt's critique of scientific investigation. This perspective contrasts two approaches to obtaining information for conservation, namely targeted (or focused) monitoring and omnibus surveillance monitoring. Targeted monitoring is defined by its integration into conservation practice, with monitoring design and implementation based on *a priori* hypotheses and associated models of system responses to management. By surveillance monitoring, we mean monitoring that is not guided by *a priori* hypotheses and their corresponding models.

A frequent justification for surveillance monitoring is that more information about a system must be useful to its management. Although this premise is true to some degree, it does not address the key issues of effectiveness and efficiency. Just as Platt argued that the rate of learning can be increased by focusing scientific investigation on discriminating among competing hypotheses, we believe that the effectiveness of conservation can be greatly increased by focusing monitoring efforts on crucial information needs in the conservation process.

Monitoring for active conservation

As an active process of decision making to achieve objectives, conservation is rooted in decision theory, sharing an intellectual foundation with many other disciplines [2,3]. Essential elements in a framework for informed decision making include objectives, potential management actions, models of system response to management actions, measures of confidence in the models, and a monitoring program providing estimates of system state and possibly other relevant variables [4–6]. There are several approaches to structured decision making and informed management. We focus here on 'adaptive management' because it is designed specifically to deal with the uncertainty that characterizes most problems in biological conservation [6–8]. Adaptive management is an iterative process that integrates monitoring directly (Box 1).

Roles for the different elements of an informed decision process are clearly defined in adaptive management. In particular, monitoring is used in three key steps. First, estimates of system state are used in the decision analysis to produce state-dependent decisions. Second, system state is frequently a component of the objective function itself, and estimates are needed to assess progress towards this objective. Finally, estimates of system state and perhaps other variables (e.g. system vital rates) are needed for comparison against model predictions for the purpose of discriminating among competing models of system response. This comparison constitutes the scientific step in adaptive management.

Understanding the roles of monitoring in an informed conservation process helps to guide the design of monitoring programs. Monitoring data are not gathered with a vague hope that somehow they will prove useful for conservation. Instead, monitoring focuses on precisely the information needed to make conservation decisions (Box 2).

Monitoring for science

In some situations, the monitoring of a biological system is needed before active management, so as to improve the biological understanding on which such management can be based. In such cases, the focus of monitoring is not necessarily to make state-dependent decisions or assess the degree to which conservation objectives are being met. Rather, it is to produce estimates of system status and other attributes that can be compared against model-based predictions for the explicit purpose of learning (Box 3). Just as Platt [1] argued that scientists should focus on

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Box 1. Informed decision processes and adaptive management

Informed decision processes typically include five essential elements: objectives; potential management actions; models of system response to management actions; measures of confidence in the models (model-specific probabilities summing to 1 for all of the members of the model set and reflecting relative degrees of faith in model predictions); and a monitoring program providing estimates of system state and possibly other relevant variables [4–6].

The first two components, objectives and potential management actions, are based on the value judgments of a community of interest. All relevant stakeholders should be involved in the development of objectives and, to a lesser extent, of available management actions. This development can be facilitated by social scientists but is largely outside the scope of ecological science. Conditional on agreement about objectives and potential actions, the remaining components are the purview of ecological scientists and technical experts, working closely with decision makers. Models and their associated measures of confidence are needed as a basis for predicting system responses to management actions, and monitoring is required to estimate system states (and perhaps other quantities) through time.

Adaptive management is a type of sequential decision process designed especially for use in the face of uncertainty [5–8]. At each decision point, the task is to determine an appropriate management action for the resource system of interest. The action is based on a conservation objective, the estimated state of the system, and the models (and associated credibility measures) predicting system responses to the different possible actions. Optimization methods can be used to select the desired management action [2,3,6,8], but less formal approaches (e.g., simulation [25]) also are available. The selected action is then taken, and the system is driven to a new state that is estimated via the monitoring program. Comparison of an estimate of the new state against model predictions leads to decreasing credibility measures ('weights') for models that are poor predictors, and increasing weights for models that predict well [5,6,8,26,27]. This step focuses on discriminating among competing hypotheses [6,26,27]. At the next decision point, a new decision is made, using the new estimate of system state and the updated model weights, and the sequence of monitoring, assessment, and decision making is reiterated through time.

information from experiments that enable discrimination among competing hypotheses, we argue that monitoring programs should help discriminate among hypotheses about environmental and other variables that can be manipulated in active conservation.

The effectiveness of monitoring conducted in preparation for active conservation should be evaluated in the same manner as for any other scientific process, the only distinction being the nature of the hypotheses (those of potential use to conservation) under consideration. The following assertion by Platt [1] is especially relevant to ecological monitoring: "Biology, with its vast informational detail and complexity, is a 'high-information' field, where years and decades can easily be wasted on the usual type of

Box 2. Adaptive harvest management of mid-continent mallard ducks *Anas platyrhynchos* in North America

A formal adaptive approach has been used in North America for the setting of mallard hunting regulations since 1995, and it provides a successful model of informed decision-making for biological resources in the face of uncertainty [4,6,23,27,28]. This approach to harvest management includes the five essential elements for informed management (Box 1). Management objectives are to maximize cumulative harvest over a long time period (thus assigning value to duck populations in the future and insuring conservation), while devaluing harvest when predicted population size falls below a threshold (the North American Waterfowl Management Plan goal of 8.8 million breeding mallards). Management actions include four regulatory packages specifying daily bag limits and season lengths for each of the four major North American flyways.

Four models of system response to harvest management are included in the model set. These models reflect two different hypotheses about the translation of hunting mortality into effects on annual duck survival (compensatory mortality reflecting minimal effects of hunting and additive mortality reflecting maximal effects of hunting mortality), and two hypotheses about the strength of density-dependent relationships defining reproductive rates (weakly and strongly density-dependent). At the initiation of this management process in 1995, all four models (representing all possible combinations of these four hypotheses) were given equal credibility weights of 0.25, indicating no greater faith in the predictions of one model than in those of any other. Monitoring programs for mid-continent mallards include an extensive aerial survey, the Waterfowl Breeding Population and Habitat Survey (Figure I), to estimate breeding population size and number of wetlands in Prairie Canada (an important environmental covariate), a preseason banding program to estimate rates of survival and harvest, and a harvest survey program (consisting of a mail questionnaire component and a waterfowl parts component) to estimate harvest and (combined with band recovery data) preseason age ratio [27].

The Waterfowl Breeding Population and Habitat Survey provides estimates of system state that are used for two primary purposes: (i) in the spring of each year, the new estimate of population size is compared against predictions made the previous spring corresponding to each of the four models. These comparisons are combined with the model weights from the previous year to update the weights. Learning thus occurs when weights become large for some models, giving them more credibility and thus more influence in the decision process, and small for others; (ii) using methods of optimal stochastic control, survey results are used in conjunction with the models and their updated weights to develop an optimal state-dependent regulatory strategy. The decision about which set of harvest regulations to implement thus depends on system state, as defined by estimated numbers of ducks and ponds. The Waterfowl Breeding Population and Habitat Survey is thus a continental monitoring program that is an important component of the harvest management decision process. Estimated duck and wetland abundances from this survey have clearly defined roles within the decision process.

Figure I. Surveying mid-continent mallard ducks *Anas platyrhynchos.* The Waterfowl Breeding Population and Habitat Survey is conducted yearly by the US Fish and Wildlife Service and Canadian Wildlife Service in cooperation with other federal, state and provincial resource management agencies as a means of estimating waterfowl and wetland abundance over ~3.6 million km^2 of breeding habitat in Canada and the USA.

Box 3. Monitoring for conservation science: generation of system dynamics

The key step in science is the comparison of model-based predictions against observed system dynamics. There are several approaches to generating these dynamics, and the selected approach is a primary determinant of inferential strength. Consider a situation in which habitat characteristics are believed to be important to the dynamics of a species, such that large-scale habitat management is possible. Competing hypotheses involve population responses to habitat change, and learning advances via comparison of hypothesis-based predictions against actual population responses. In active conservation processes, system dynamics are generated by the management actions themselves, sometimes via experimental manipulations. For example, different habitat management practices could be imposed on different experimental units. Random allocation of treatments to experimental units and replication within each treatment type define a true manipulative experiment capable of providing strong inferences [6,29,30].

Other situations might impose constraints on manipulative studies. For example, an investigator might learn that habitat changes are to be carried out as part of a forest management plan. Monitoring could be conducted on areas to be treated as well as on control areas. This approach takes advantage of manipulations carried out by others, so random allocation of treatments to experimental units is not possible. Such constrained designs can be useful [6,30], although they produce weaker inferences than do true manipulative experiments.

Some science-based monitoring programs are not designed around system manipulations, but rely on natural variation in environmental and other factors to generate system dynamics. Data are collected for some period of time, and investigators look retrospectively at the resulting time series in an effort to learn about system dynamics via induction [9]. This observational approach is likely to produce weak inferences, primarily because of the large number of potential hypotheses that can be invoked to explain any time series [6,9,31,32]. In fact, a retrospective approach is best viewed as a means of generating hypotheses. Nicholson [24] characterized as 'a gross misunderstanding of scientific method' the 'widespread idea that the facts of nature can be revealed by observation and experiment alone, so avoiding the pitfalls and labour of thought'.

With observational monitoring, we favor designs based on management-oriented hypotheses about system dynamics. In our habitat management example, we might establish strata reflecting different levels of the habitat variable of interest, and distribute most of the monitoring effort to strata reflecting habitat contrasts. Such a design could include a stratum (e.g. of intermediate habitat) not perceived to be especially useful in hypothesis discrimination. This stratum could be sampled at low intensity for the purpose of contributing to a secondary objective of surveillance. Even in cases where it is not possible to identify sampling strata based on hypothesis discrimination, management-oriented hypotheses can still be used to guide the identification of useful covariates to include in the monitoring effort.

'low-information' observations or experiments if one does not think carefully in advance about what the most important and conclusive experiments would be." Our recommendation is simply to design monitoring with the aim of making the resulting data as useful to conservation and science as possible.

Surveillance monitoring

Surprisingly, monitoring for decision making or science does not appear to be widely used in conservation biology. Instead, a different approach is taken, involving omnibus surveillance monitoring of biological populations and communities [9]. Surveillance monitoring is frequently characterized as 'omnibus' because of its potential use for many different purposes and its inclusion of many different species and locations. However, it is not a focus on multiple species and large areas that distinguishes surveillance monitoring from targeted monitoring; rather, it is the role of management-oriented hypotheses in guiding the monitoring efforts. The distribution and intensity of sampling, the attributes to be monitored and the field procedures to be used can all be informed by extant theory and the hypotheses that underlie a monitoring design, irrespective of its scale. By failing to build directly on the relevant theory and hypotheses, surveillance monitoring ignores the value that these can confer to the relevance and efficiency of the monitoring effort.

Surveillance monitoring is often justified by claims that it provides at least some information about biological systems of interest, and that more information is useful for conservation. In some cases, recent challenges [9] have led to a sharper focus on tracking system states and detecting trends as a way of recognizing declines in species abundance. The detection of a decline is viewed as a trigger for active conservation and as a mechanism for setting conservation priorities.

This view of conservation monitoring differs substantially from targeted monitoring. Here, we provide a critique of surveillance monitoring, prefaced by two points. First, we are not suggesting that all existing surveillance monitoring programs be abolished. In some cases, a reallocation of effort in an ongoing monitoring program might be warranted, but we view our recommendations as being most relevant to the establishment of new monitoring programs. Second, we acknowledge that surveillance monitoring does provide useful information for conservation. However, the important issue is efficiency, that is, whether the approach provides the most information for effective conservation, given our limited resources for monitoring (see Platt's [1] analogous arguments about rate of learning).

A critique of surveillance monitoring

Surveillance monitoring in conservation typically involves a two-step process. First, population declines are identified by means of a statistical test of a null hypothesis of no decline versus a decline. Following the statistical detection of a decline, either of two actions is recommended as a second step. One is to initiate active conservation immediately, and the other is to initiate studies to understand the 'cause' of the decline, followed by active conservation. Key to both is the detection of a population decline as a trigger for initiating management actions. We believe that this approach to monitoring is inefficient and frequently ineffective.

Statistical hypothesis testing

Our first objection concerns the unfortunate misuse of methodology for statistical hypothesis testing. Statistical testing is best applied in an experimental context of hypothesis formulation and testing, rather than the determination of which management action to take, and when. The point of statistical testing in surveillance monitoring is to recognize a negative trend in abundance when it occurs, by asking whether data correspond more closely to a model that assumes a negative trend than to a model that assumes no trend. Sometimes lost in the statistical details is the operational objective of the testing procedure, which is to retain a null hypothesis of no trend unless there is sufficient evidence (i.e. a preponderance of sample data) to confirm the alternate hypothesis of a negative trend. In that sense, the procedure is a test not only of a hypothesized pattern underlying the data, but also of the ability of the statistical procedure itself to recognize that pattern, conditional on the available data. Also lost is the fact that the test is not necessarily informative about the appropriate choice of management actions once a pattern is confirmed.

Management decision making is best viewed not as a statistical test, but as a problem in structured decision analysis that is conditional on conservation objectives and a set of alternative actions [6]. Structured decision making typically yields decisions that are state dependent, requiring periodic estimates of abundance (rather than of trends). Even if decisions are based on annual trend statistics, it is unlikely that the two-step surveillance approach articulated above (i.e. wait until a 'significant' negative trend is detected and then act) would be optimal. Using the result of hypothesis testing as a trigger for management action inserts unnecessary arbitrariness and subjectivity into the decision process, and thereby yields suboptimal decisions.

Time lags

A second objection to surveillance monitoring involves the time delay inherent in the two-step approach to conservation. When trend detection is viewed in a hypothesis-testing context, detection of significant declines frequently requires several years [10]. Rather than framing monitoring in a context of decision making that accounts for uncertainty in estimating system states [6], surveillance monitoring requires the amassing of enough data to provide strong evidence of a decline in state before action is taken. Resulting delays can result in crucial changes in extinction probabilities, with potentially dire conservation consequences [10–12]. By treating management decisions as problems of decision analysis rather than of hypothesis testing, conservation programs can avoid these unnecessary time lags.

Costs and resource availability

A third objection to the two-step approach to surveillance monitoring concerns the cost of monitoring, and the need to make the best possible use of available resources for monitoring. Because surveillance monitoring programs are not embedded directly in active conservation, they are not designed to be maximally useful in discriminating among competing hypotheses about system responses to management. Surveillance monitoring is focused on the discovery and/or confirmation of declines, and the crucial issues of causes and remedies for a decline are not addressed. These issues must therefore be addressed through follow-up investigation. The combined cost of both activities can easily exceed that of a monitoring effort that is designed from the outset to focus on conservation (including potential causes and remedies of declines).

Causes of decline

A final objection to a two-step surveillance approach involving trend detection concerns the focus of the second step on identifying the causes of declines. Although diagnosing the cause of a decline can be useful, such knowledge is not by itself essential to good management. The key issue for management is not the cause of a decline, but the most effective remedy for it. Often, but not always, recognizing a cause can help in identifying potential remedies but, ultimately, it is the remedy that is the focus of management. Thus, active conservation programs such as adaptive management involve predictions about which actions are likely to reverse a decline, but might or might not address its cause(s). What they do address is the most effective action to take, pursuant to management objectives.

Surveillance monitoring: arguments and rejoinders

Proponents of surveillance monitoring often emphasize the use of trend estimates for planning and setting conservation priorities, with the declines found through monitoring used to prioritize follow-up actions [13]. However, substantive declines are frequently recognized through information sources other than surveillance monitoring. In fact, surveillance monitoring typically provides weak inferences about species that are neither abundant nor widespread, the very species that are most in need of priority attention. For example, the US Federal Register (http://www.gpoaccess.gov/) provides recent examples in which results of surveillance monitoring programs were considered and then found to have been of little use for the listing of species as endangered [14]. Historically, targeted monitoring programs have been developed for such species, to focus more effectively on specific conservation issues.

Not only are surveillance monitoring programs ill-suited for assigning trend-based priorities, but the utility of trend as a mechanism for prioritization can also be questioned. Objectives in an integrated conservation framework might also involve differential weighting of species (i.e. prioritization), with priorities based not on trends but on taxonomic status, endemism, geographical range, economic utility, and/or other factors [9]. Rates of species declines enter the conservation process automatically via state-dependent decisions, rather than as part of the objective. In addition, so many conservation problems have already been identified that it seems logical to devote substantial conservation resources to their solutions rather than to additional prioritization.

Proponents also emphasize the potential of surveillance monitoring to identify unanticipated problems, based on the assumption that its unfocused, omnibus nature preadapts the approach to recognize unanticipated events. Certainly, historical surveillance monitoring programs have been valuable in identifying unanticipated declines, for example of farmland bird species in Great Britain [15]. But no monitoring program, whether targeted or surveillance, can be assured of consistently registering unanticipated events. Furthermore, the large number of extant conservation issues, and the finite resources available to address them, argues against designing monitoring programs solely to recognize unanticipated problems, even if it were clear how to do so. Detection of unanticipated declines is a by-product of targeted monitoring programs developed as components of specific management processes. For example, declines of pintail ducks *Anas acuta* in North America during the late 1970s and 1980s were clearly identified by the Waterfowl Breeding Population and Habitat Survey [16]. However, this detection of an unanticipated problem was a secondary product of a survey developed to inform management decisions. Similarly, monitoring programs designed to discriminate among competing scientific hypotheses will not be blind to dynamics that are beyond the scope of those hypotheses.

Finally, proponents see surveillance monitoring as cost-effective, because the approach frequently includes large numbers of species over extensive geographical areas. Conversely, they criticize conservation-focused monitoring as being too narrowly focused. However, this view reflects a misunderstanding about focused monitoring, as it can readily include large geographical areas and groups of species. In either case, it is not possible to monitor effectively all biological species everywhere that they occur, and some selection of species and areas of interest is always required as a matter of good survey design [17].

Caveats

The most difficult aspect of our recommendation is the need to develop detailed hypotheses and associated models of system response to management actions. Hypotheses about the dynamics of biological populations and communities are likely to be more complex than many of the hypotheses considered by Platt [1]. Hypotheses about responses of communities and ecosystems will typically involve numerous interactions and will probably be especially difficult to develop. Even with single populations, the applicability of one hypothesis versus another might depend on the ecological context [18]. However, potential difficulties associated with system complexity and context dependence do not absolve us of the need to develop hypotheses and associated models. The ability to make predictions about system response to management actions is not optional in decision making, and current ecological problems do not allow us the luxury of postponing conservation and management until some future time when we are more comfortable with model development. Indeed, even if we begin the management process with a set of models that contains no good predictor, informed management will provide opportunities for revision of existing models and development of new ones.

In some parts of the world, previous ecological study has been so limited that development of hypotheses and associated models will be especially difficult. In such situations, the collection of baseline information through surveillance monitoring might be warranted as a means of generating initial hypotheses about system behavior. However, even in situations of limited previous ecological study, the use of targeted monitoring is worthy of consideration [19]. Indeed, in the absence of extensive baseline monitoring, hypotheses based on ecological theory have proven to be useful in designing monitoring and conservation programs. For example, basic principles of predator–prey relationships led to the prediction that tiger Panthera tigris densities should be determined largely by densities of prey species. A spatial monitoring program of tiger and prey densities throughout India provided evidence supporting specific predictions [20]. This work has led directly to major conservation efforts in selected areas designed to increase prey numbers (e.g. through actions such as reducing poaching) [21] and to associated monitoring programs to inform these efforts.

Conclusions

If surveillance monitoring can be an inefficient use of scarce conservation funding, it also can become a form of political and intellectual displacement behavior [22], or worse, a deliberate delaying tactic. We are all familiar with situations in which declarations of a need for 'more study' appear to be stalling tactics, with crucial actions delayed for reasons that have little to do with information needs. From a somewhat less cynical perspective, it is much easier to postpone a difficult decision for reasons of inadequate information than to engage in an informed decision-making process. The development of *a priori* hypotheses and their associated models is intellectually challenging, often requiring substantial time and effort [23,24]. It is much easier to establish surveillance monitoring programs based on a putative need for additional 'baseline' information, and therefore postpone the careful thought that goes into hypothesis formulation and analysis. Our hope is that an emphasis on focused monitoring programs will decrease the incidence of inadvertent displacement behavior and deliberate delaying tactics, while increasing attention on science and its use in conservation.

We conclude with a statement by Platt [1]: '...in numerous areas that we call science, we have come to like our habitual ways, and our studies that can be continued indefinitely. We measure, we define, we compute, we analyze, but we do not exclude. And this is not the way to use our minds most effectively or to make the fastest progress in solving scientific questions.' We in the field of conservation are also creatures of habit, and we emphasize historical uses of data as reasons for continuing surveillance monitoring programs and developing new ones. In partial response to such continuing programs, the public in many countries appears to view science as a never-ending story with little relevance to real-world problems.

The targeted monitoring approach presented here offers a different paradigm, and a more efficient approach to monitoring. The monitoring of biological resources, seen as a key component of active conservation and/or conservation science rather than as a stand-alone activity, inherits its design and focus from the larger conservation process, so as to ensure maximum utility of the resulting information. In times of limited conservation funding and almost unlimited conservation needs, we view the efficient use of monitoring effort to be vital to successful conservation.

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