Environmental Monitoring Issues

" Even unmanaged ecosystems are characterized by combinations of stability and instability and by unexpected shifts in behaviour from both internal and external causes. That is even more true of ecosystems managed for the production of food or fiber. Data are sparse, knowledge of processes limited, and the act of management changes the system being managed. Surprise and change are inevitable."
(Walters & Holling 1990)

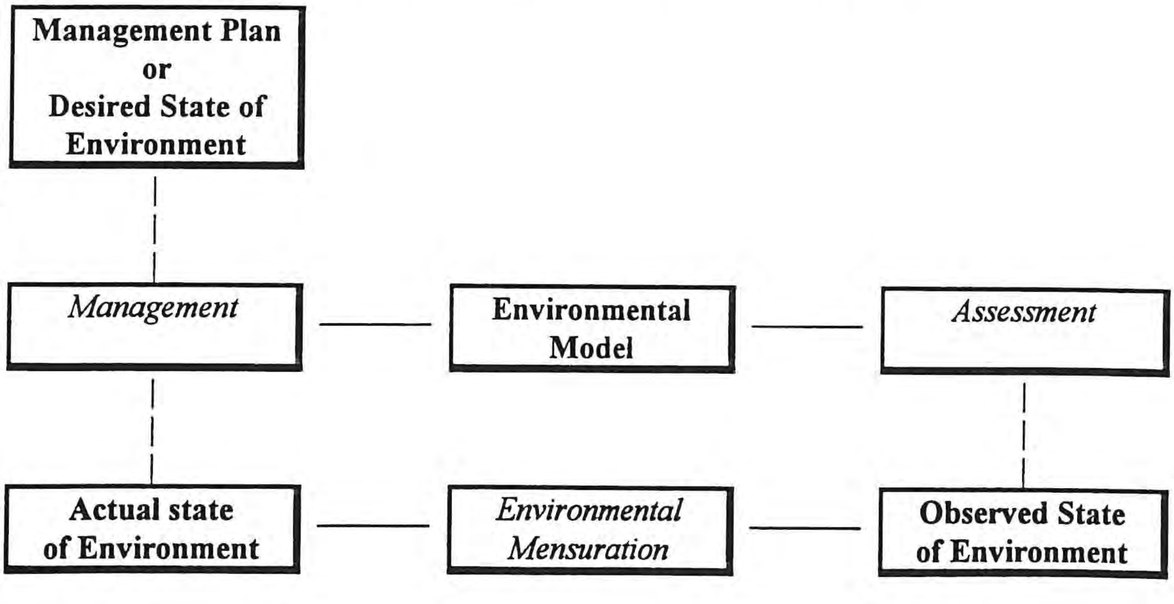
I. Introduction

This document is intended to raise issues in environmental monitoring (EM) for discussion. It is restricted to scientific rather than political issues (although of course both are important). Good background discussions of EM may be found in CALM policy document #28, and in Hopkins (unpubl.). Given that these background documents exist, I will not review the importance or objectives of EM, but assume that they are understood.

In my view the context of environmental monitoring programs (EMPs) is often poorly delineated, so the remainder of this section and section II provide a view of the EMP process designed to highlight the issues that are discussed in sections III and IV.

Figure 1 shows a model of EM: this is a hybrid of the models of Constable (1991) and Hopkins (unpubl.). It seeks to clarify two points which often cause confusion in EMPs: (i) the actual and observed states of the environment are not the same thing; and (ii) assessment is a process of itself that could potentially lead to different conclusions based on the same data, depending on the assessment methods. This separates the data from the subsequent analysis and interpretation.

Fig. 1. The context of environmental monitoring, adapted from Constable (1991) and Hopkins (1989). Physical entities are in bold, and processes in italic. The environmental model may not exist explicitly, but is nonetheless an entity on which management decisions are based. Flows of data are indicated by arrows.



II. Phases in the EM process

The phases in an EMP may be summarised as follows:

Task	**Responsibility**
1. Set up EM Program Steering Committee (EMPSC). The EMPSC: • Defines objectives • Allocates staff • Is responsible for program management	Management
2. Define indicator variables and critical values. Set allowable limits for monitored variables	Scientific staff Management
3. Specify sampling regime and replication, timing, controls, covariates, power, etc.	Statistician Scientific staff Operations
4. Design information management system (IMS)	Info Systems Specialist Operations
5. Construct IMS	Operations Info Systems Specialist
6. Collect and store data	Operations
7. Analyse data	Scientific staff Operations
8. Interpret results	Scientific staff
9. Implement findings	Management

Phases 6-9 are an ongoing process and may conveniently be thought of as an open-ended environmental impact experiment.

III. Issues

The four major potential problem areas apparent from the EMP phases detailed above are:

1. Defining indicator variables.
2. Devising sampling regimes.
3. Designing and constructing an IMS.
4. Analysing data/results.

Each area needs to be considered carefully prior to establishing an EMP. These areas are discussed below:

1. Defining indicator variables.

The choice of variables to measure in an EMP is a source of considerable debate. Major considerations are:

Causative vs. symptomatic variables

Often it is tempting to measure symptoms (e.g. waterbird abundance, abundance of a CWR mammal), although putative or potential causative factors (e.g. water quality, introduced predator abundance) may be a more direct means of guaging environmental quality. Similarly, whether monitored variables should be biotic or abiotic is important. Within CALM, it is quite likely that biotic variables would be favoured. However, the tendency to measure variables within one's own area of expertise must be avoided.

Use of summary variables

Another temptation is to measure "summary" type variables, such as species diversity or richness. However, such measures are widely decried (e.g. Hurlbert 1971: "species diversity has become a non-concept": Eberhardt 1976: "there is little reason presently to expect species diversity indices to accurately reflect the well-being of the ecological system under study"; Keough & Quinn 1991: "The choice of biological indicator variables to be measured in detecting human impacts on the environment is a critical one. The usual community-level measures (species richness, diversity) generally have questionable theoretical justification, have no demonstrable causal links to the impact, and are dependent on the taxonomic expertise available."). Such measures probably have little place in monitoring programs.

Defining acceptable limits

Simply measuring and recording environmental indicator variables may constitute "environmental monitoring", but an effective EMP must define what acceptable limits for the measured variable. Similarly, what course of action will be taken should the indicator variable go outside these limits should be defined at the outset of the program. If no corrective action is possible, monitoring may be pointless! Defining acceptable limits may be difficult in the absence of a detailed knowledge of the desired state of the environment (fig. 1).

One proposed solution is that a monitored site be deemed undisturbed if the distribution of some measured variables on the site are equal to the distributions on an undisturbed reference site; i.e. that the two sites are "bioequivalent". This approach is particularly useful where there is little or no prior knowledge of the values or variability of monitored variables on a site, or if the site is already subject to putative impacts. However, this doubling of sampling intensity immediately increases the cost of monitoring. A possible solution to this problem is to monitor a small set of reference sites to be used as comparisons for all monitored sites within a region.

2. Devising sampling regimes. Sampling strategies must be the most efficient possible, and must be able to reliably detect environmental change. Devising an optimal sampling regime is a trade-off between α, β, Δ, n and σ; these parameters are outlined in the subsections below. The details of this trade-off is known as statistical decision theory, and below I only outline the important issues in this field of study.

This trade-off has rarely been explicitly considered other than in large scale monitoring projects where considerable expense is involved, and detailed consideration of the trade-offs involved is important in maximizing return for a given cost. However, it is now widely recognised that setting the levels for these parameters *a priori* is essential to an effective and efficient EMP (Green 1993).

Power and sampling effort

Power is an essential consideration in monitoring studies: "Understanding statistical power gives three ways to improve EM and to inform decisions about actions arising from monitoring. First, it allows the most sensitive tests to be chosen from among those applicable to data. Second, preliminary power analysis can be used to indicate the sample sizes necessary to detect an environmental change. Third, power nalysis should be used after any nonsignificant result is obtained in order to judge whether that result can be interpreted with confidence or the test was too weak to examine the null hypothesis properly. Power analyses are, however, essential to designing sensitive tests and correctly interpreting their results. Low power can be disastrous for EMPs." (Fairweather 1991).

It is well known that failing to reject a null hypothesis is not proof that the null hypothesis is true. Unless sampling is sufficiently intense, it will be possible to detect only gross changes in measured variables. This fact is well known as a "cop-out" for the unscrupulous seeking to bypass environmental monitoring requirements by "fixing" the outcome of such monitoring; i.e. by undertaking an EMP of very low intensity, even gross changes in measured variables will not be statistically significant. Given that there is often confusion amongst managers of the distinction between practical and statistical significance, such low-powered monitoring programs provide a result of "no significant change" even when substantial environmental change is being caused.

Equally culpable are those who, albeit with honest intent, institute EMPs without investigating the power of the sampling design used. Many sampling designs and analyses proposed in the environmental end ecological literature are likely to be of very low power (Brian McArdle, pers. comm.), although the power of many commonly used designs has not yet been formally investigated. EMPs employing such designs thus fail to deliver on their stated intent: i.e. an efficient means of detecting environmental change.

Clearly the sample size (n) employed in an EMP depends upon the inherent variability of the measured variable (σ, as estimated by the sample standard deviation s), and the size of the change (Δ) it is deemed necessary to detect. However, it is also necessary to consider with what reliability any environmental change is detected: this topic is related to "the burden of proof".

The burden of proof

Defining what constitutes sufficient evidence of extra-limital change in measured variables is a contentious issue. An analogous situation is the concept of the "burden of proof" in law. The legal concepts that a person is "innocent until proven guilty", and that a person must be proven guilty "beyond reasonable doubt" are well known. In essence, this means that the type I error rate (i.e. the probability of finding an innocent person guilty, denoted α) is set to a very low level. This is at the expense of the type II error rate, so that the probability of finding a guilty person not guilty (denoted β) must, inevitably, also be high. However, this trade-off is justified by the widely held opinion that it is better to set the guilty free than to falsely convict the innocent.

Although an entirely different arena, exactly the same considerations apply to environmental monitoring and environmental impact studies. Opinion in legal cases where damage to the environment is under investigation is changing from "innocent until proven guilty" to "guilty until proven innocent" (McDonald & Erickson 1993). Thus the null hypothesis in impact studies may be reversed from H_0: *there is no impact* to H_0: *there is an impact*, with the burden falling to those supposedly causing the impact to refute the latter null.

The attitude adopted on this issue has important ramifications for sampling strategies. For a given sampling effort, a monitoring program designed to be highly protective of the environment would require only "moderately" significant differences between observed and desired levels of the measured variables (say $\alpha < 0.20$). Such a constraint would result in a large number of "false alarms", but would ensure that any environmental change is detected with very high probability. Conversely, a monitoring program designed to detect only large changes in monitored variables would require "highly" significant differences (say $\alpha < 0.01$). Such a constraint would result in a low number of "false alarms", but would detect any environmental change with only low probability.

3. Designing and constructing an MIS.

Prior to development of the EM Management Information System (EM/MIS) the need for such a system will have been identified, the model would have been chosen, sampling regime defined as well as the variables to be measured, the types of measurements to be made, how they are to be measured and why.

The data will be of a corporate nature with users at different locations accessing the same source. Different users will also have different access rights and some data will be of a sensitive nature. The EM/MIS owner, custodians and users have to be identified and their responsibilities spelled out (eg. the owner will be responsible for granting access rights and priviledges to users).

Identification of the data/information content is the next issue to be addressed. This includes identifying the various data types, volumes, frequency of activity, levels of accuracy, who has what type of access and from where (ie. a data dictionary and data directory should be compiled).

After the various responsibilities for the data have been allocated, user requirements have to be identified and staffing issues have to be addressed. The composition of the development team has to be agreed to. Here, a formalised approach is recommended. This will require the setting up of a:

- STEERING COMMITTEE to oversee the direction and development,
- WORKING GROUP to attend to the technical details,
- DEVELOPMENT TEAM, comprising SID representative/s, end users and development staff.

No project of this nature can succeed without commitement to the project by management, the owners and custodians. Allocation of the right priorities and resources are also issues that have to be addressed.

Having committed resources, it will be necessary to agree to a time frame and to allocate a reasonable budget (management doesnt normally have a foggiest notion of what is involved and how much it will cost!) for the project. Development time will depend on the size of the project and will be costed out during the *system design* phase. If the anticipated completion date does not fall within the allocated time frame, it will be necessary to either change the scope of the project or allocate more budget to put more resources into the development phase.

After these have been set in place, *system development* and *implementation* can take place. This is a complex technical area with a lot of issues to be resolved. An important issue is resourcing (resources are required from all areas including end users and development personnel).

This section is further divided into processes, each with its own set of documentation and checkpoints, some process cannot be initiated until some others have concluded.

Because of the technical nature of the processes involved, no attempt will be made here to identify each of the various issues that have to be resolved. Rather, to give an indication of what is involved, the various processes are briefly outlined below:

- ***Definition of the EM/MIS Project.***

  This phase covers the following issues:

  - Definition of the project (problem)
  - Definition of the scope of the project
  - Developing an information plan for the project
  - Drawing up a data model to show relationships
  - Developing information flow diagrams
  - Producing a conceptual overview of the system
  - Establishing the end user requirements
  - Identifying all the users (& workstations)
  - Identifying interfaces to other related systems
  - Developing the technical specifications

- ***Design & Specification of the EM/MIS***

  This phase covers the following issues:

  - Data analysis (ie. data structures and relationships)
  - Evaluation of hardware & software platforms
  - detailed systems design (system specifications & programs specifications document)
  - design of input/output and screen formats
  - specification of each module and program in the system
  - specification of each interface.

- ***Development of the EM Iinformation Management System.***

This phase covers the following issues:

- generation of test data for each program, module and system
- development of each program within the system
- unit testing for each program
- testing for each module
- testing for the entire system
- user acceptance testing
- development of user manual.

- *Implementation of the EM Iinformation Management System.*

This phase covers the following issues:

- Installation of the entire system onto a production platform (from development platform)
- Training end users to use the system
- identifying support staff and handing the system to them
- monitoring the system for a specified period to iron out teething problems.

Once the system has been developed and testing completed, the system will have be installed (ie. moved from a development environment to a production environment). At this stage, various control procedures have to be put in place, user documentation will have to be available and end users trained. The system will then have to be monitored for an agreed period of time to ensure that is operating well. The issue of handover of the system is an important one.

In addition, after implementation, provision must be made for changes in requirements, future changes and upgrades. Resources have to be allocated to address the following:

Who among the user/s will be responsible for operating the system,
Who among the operationsl staff will be responsible for supporting and maintaining the system,
Who among the technical staff will be responsible for modifying the system when new requirements surface, and
How will future changes & upgrades be effected?

It is only after all the above have been completed should the system be officially in production. The system will have been developed with limitations imposed by available hardware and software and strictly according to the scope and project definition. However, the hardware and software continues to develop at a rapid pace and, the scope and requirements will change in time. As such, all electronic systems are dynamic and have a fixed lifespan. The issue of resourcing for ongoing maintainence, enhancements and future upgrades are equally important issues to be addressed.

4. Analysing data/results. I have frequently encountered the opinion that once a study has been completed and written up, the project may be deemed "closed" and raw data safely destroyed. This is based upon the false supposition that an analysis is final. It is easy to find cases in EM (e.g. Manly 1993) where the use of different methods of data analysis result in markedly different conclusions. This fact re-emphasises the need for data maintenance, discussed in 3 above.

The lack of consensus on the best statistical methods for detecting environmental change has been noted by a number of authors; the subtitle of Carpenter's (1990) paper, "opportunities for innovation", demonstrates an optimistic attitude towards a need for better techniques.

IV. Practical problems

I will conclude by presenting some examples of where things have gone wrong. These examples are taken from papers presented by Cormack (1993) and Boyce (1993) respectively, and exemplify ecosystem-level and species-level monitoring programs.

The UK Environmental Change Network (ECN)

The aim of the ECN is to identify and quantify environmental changes associated with human activities, distinguishing these from natural variations and trends, and giving early warning of undesirable effects. The objectives of the ECN are to:

- obtain uniform and comparable data by means of measurement at regular intervals of environmental variables at a set of selected sites in the UK;
- provide for the integration and analysis of these data sets so as to identify environmental changes and to improve understanding of the causes of change;
- make these long-term data sets available as a basis for research and for prediction of possible future changes; and
- provide, for research purposes, a range of representative sites where there is good instrumentation and reliable environmental information.

The primary problems encountered in establishing and running the ECN are:

- the lack of involvement of a statistician in the design of the project;
- distinguishing natural and human-caused environmental changes;
- loss of momentum when key steering committee members retired;
- an inability to change measured variables or sampling regimes after setting up the program;
- a lost opportunity to reduce sampling effort in the early stages of the program by undertaking correlation analyses of measured variables, and reducing the number of variables accordingly.

Population monitoring and modelling of the northern spotted owl

The aim of this project is to model the population of a single species as a basis for adaptive management of the species. The objective is to conduct population viability analysis (PVA) of the species under different management regimes, with the objectives of:

- synthesizing all current knowledge into a PVA model, thus providing a statement of the current understanding of the system
- providing a single platform on which to investigate management options
- improve understanding of the system, highlighting areas of inadequate knowledge and thus guiding future data collection
- The primary problems encountered in establishing and running the PVA model are:

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Science and Information Division's Matt Williams and Mike Choo have prepared a discussion paper on the above (attached).

The paper analyses the important problems that need to be addressed and overcome before time and money is allocated to environmental monitoring.

I would be very interested to have your comments on the document. It would help if I could have these comments by 23 June.

Jim Armstrong per JR

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