CONTINUOUS ADAPTIVE MONITORING OF STATUS AND TRENDS IN ECOSYSTEM CONDITIONS[1]

R.L. Czaplewski[2]

ABSTRACT. Adaptive management uses an experimental approach in the stewardship of our natural resources. This paper advocates the complementary concept of "*adaptive monitoring*" to observe and evaluate the outcomes of these experiments. Adaptive management acknowledges that decisions must be made in spite of imperfect understanding of their consequences; likewise, *adaptive monitoring* is designed to accommodate the unknown objectives and technologies of the future. *Adaptive monitoring* must be extremely flexible to accommodate constant change in natural resources and management paradigms, in addition to changes in societal priorities. Like any monitoring endeavor, it must be credible, timely, efficient, relevant to management objectives, produce intelligent assessments and evaluations, and support informed decision-making. *Adaptive monitoring* must consider multiple management objectives, multiple spatial and temporal scales, multiple ecosystems and environmental features, multiple social dimensions and economic conditions, multiple institutions and publics, and integration of multiple technologies. This paper envisions an *adaptive monitoring* technology that uses remotely sensed data and geographic information systems, multiple frames to extensively monitor different systems with probability samples, a few intensively studied experimental sites, and information on social and economic systems. These components are integrated through models, statistics, information management, and interdiscipinlary analyses. Application of adaptive management principals is in its infancy, and the concept of *adaptive monitoring* is even less well developed. However, the Annual Forest Inventory System is presented as a preliminary example of an emerging *adaptive monitoring* system. This system represents an evolution of the existing Forest Inventory and Analysis system to produce more timely information, quickly respond to new issues and concerns, and incorporate more efficient technologies in remote sensing, modeling, and statistics.

INTRODUCTION

Ecosystem management envisions an adaptive system that requires timely monitoring information to continually improve resource management (e.g., Walters 1986, Grumbine 1994, ESA 1996). Monitoring is crucial to mitigate risks caused by the uncertain outcomes of adaptive management, and to make better decisions in the future by learning from successes and failures of past decisions.

The concept of "*adaptive monitoring*" originated during development of an interagency monitoring design to support adaptive management that was mandated by the Forest Plan in the Pacific Northwest (USDA/USDI 1994, Tolle and Czaplewski 1995, Mulder et al. 1995, Ringold et al. 1995). Before adoption of this regional plan, management of public forests in the range of the spotted owl was halted by lawsuits and injunctions. In

[1] A paper presented at the session Forest Ecosystems: Measuring, Monitoring, Modeling at Multiple Scales at the SAF National Convention held in Portland, Maine; October 28-November 1, 1995

[2] Raymond L. Czaplewski, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, 240 W. Prospect Road, Fort Collins, CO 80526

an order issued on December 21, 1994, United States District Judge William L. Dwyer affirmed the legality of the Forest Plan. However, Judge Dwyer stressed that "[m]onitoring is central to the plan's validity... If it is not funded, or not done for any reason, the plan will have to be reconsidered. If the plan as implemented is to remain lawful, the monitoring ... will have to be faithfully carried out, and adjustments made if necessary." Therefore, the courts and society, in addition to the natural resources professions, recognize that monitoring is integral to responsible adaptive management.

The purpose of this paper is to propose the concept of "*adaptive monitoring*" to support responsible decision-making and adaptive management. Criteria and components of *adaptive monitoring* are introduced, although many of these generally apply to any sort of intelligent monitoring. The monitoring design for the Pacific Northwest Forest Plan (USDA/USDI 1994) motivated the concept of *adaptive monitoring* (Mulder et al. 1995); however, this design has not been implemented. Therefore, *adaptive monitoring* is explained in more tangible terms with an example from the Forest Inventory and Analysis (FIA) Program of the USDA Forest Service. The FIA program has generated strategic information on the nation's forests, beginning in the 1930's (Powell et al. 1994). The current design, which emerged in the 1950's, provides estimates of forest conditions at the State- and sub-State levels on a 10- to 20-year cycle. The Annual Forest Inventory System (AFIS), which is currently being tested in Minnesota, provides more current FIA information at approximately the same cost and average precision. Although AFIS is an incomplete example of a single *adaptive monitoring* effort, it does demonstrate many of the following principles.

PRINCIPLES OF ADAPTIVE MONITORING

Management of natural resources involves issues and concerns that constantly change because of environmental, social, economic, and judicial dynamics. Management of natural resources encompasses multiple goals and objectives; multiple ecological and social systems; multiple spatial and temporal scales; multiple land ownerships and agencies that manage public lands; and multiple publics and users of monitoring information. Priorities change, funding fluctuates, new technologies emerge and mature, scientific knowledge evolves, and management paradigms shift. *Adaptive monitoring* must be extremely flexible to provide relevant information in this ever-changing environment.

Successful *adaptive monitoring* requires much more than flexibility. Like any successful monitoring effort, *adaptive monitoring* must be up-do-date; precise; consistent; credible to scientists, decision-makers, and citizens; understandable; accessible and user-friendly; exciting; well documented and of known quality; and efficient. But most important, *adaptive monitoring* must provide relevant information to support the decision-making process. This requires clear and detailed articulation of management goals and objectives; translation of these into monitoring objectives and criteria; selection of measurable indicators that quantify status, changes and trends relative to the management goals; design of efficient technical systems to collect those data; a clear vision on how those data will be analyzed to produce relevant evaluations and assessments; and a mechanism to regularly modify monitoring objectives, priorities, methods, and techniques if necessary. Effective prioritization of monitoring efforts requires regular dialog among managers, scientists, and technical specialists. As adaptive management causes refinements in management direction, and even shifts in management paradigms, the priorities, objectives and implementation of *adaptive monitoring* must respond in synchrony.

The specific vision of *adaptive monitoring* expounded in this paper employs four major technical components: remote sensing and geographic information systems (GIS) to provide synoptic coverage; extensive probability samples of numerous monitoring sites to reduce cost of detailed and high-quality data; a few intensively studied experimental sites (e.g., Long-term Ecological Research Sites) for the highest-quality research data and to support development of prediction models; and data on social and economic systems:

① Remote sensing and GIS provide comprehensive coverage of all sites (e.g., 0.1-ha pixels) within the entire region. Remotely sensed imagery permits monitoring of spatial characteristics at landscape scales (e.g., forest fragmentation); historical imagery is available for retrospective studies and detection of gross changes in land cover; and the cost is reasonable for broad areas. GIS permits spatial integration of data on land cover, terrain, ecoregions and climatic patterns, anthropogenic features (e.g., roads, clearcuts), major disturbances (e.g., catastrophic fires), *etc.* Although the spatial quality of GIS data is very high, the accuracy and detail of GIS data for each and every pixel or polygon are poor.

② Probability sampling makes more accurate and detailed measurements feasible for a small number of pixels, polygons, plots or sites that cover the same broad geographic areas (e.g., a 1-ha plot for each 1000- to 10,000-ha segment of the landscape). For example, re-measurement of permanent plots can accurately detect subtle changes in forest structure and processes (e.g., species composition, regeneration, individual tree mortality, gap dynamics, changes in down woody debris) that are not reliably detected with remote sensing. Sample plots can be registered in a GIS to assess accuracy of GIS data and develop GIS models (e.g., crude maps of habitat; potential natural vegetation; and micro-climate, such as average soil moisture and mean annual temperature). Different sampling frames are required for different types of environmental features: terrestrial ecosystems; rare features (e.g.; "old-growth" forests, rare species); perennial streams, rivers, and their riparian buffers; intermittent streams and their riparian buffers; standing water bodies and their riparian buffers; wetlands and their riparian buffers; roads; bridges; past management projects (e.g.; timber sales); large past disturbances (e.g., catastrophic fires); ridgelines; protection buffers for rare species; *etc.* Monitoring priorities might dictate intensification of sampling efforts into certain geographic areas (e.g., timber-sale areas v. habitat reserves) or types of ecosystems (e.g., perennial streams and riparian buffers v. intermittent streams and riparian buffers).

③ Intensively-studied experimental sites provide the highest quality data, but the cost of such sites limits their number (e.g., one 1,000-ha site for a 1,000,000-ha physiographic province). Such sites provide case studies that can advance scientific understanding of ecological processes and response of ecosystems to management actions. Hypotheses and mathematical models developed at these few sites can be tested on the more representative probability sample of extensive monitoring plots.

④ Census data, questionnaires, sample communities, *etc.* for socio-economic monitoring.

All of these components require dependable institutional support in the form of competent and innovative staff; modern information management; professional quality assurance systems; training and documentation; expert statistical design of sampling systems and complex data analysis; independent assessment and evaluation of monitoring results; critical and open scientific peer review; and performance evaluations by decision-makers and other users of monitoring results.

Adaptive management can occur at many scales. Spatial scales range from individual sites (e.g., 5-ha timber sale, 5-km road project, 10-ha protection buffer), to watersheds (e.g., 500- to 50,000-ha), to broader administrative units and physiographic provinces (e.g., 500,000- to 2,000,000-ha), and to the entire region (e.g., the 10,000,000-ha range of the northern spotted owl). Adaptive management can apply to hundreds or thousands of individual sites. It might not be feasible to fund adequate monitoring for each of these numerous sites.

However, it is feasible to monitor a representative sample of those sites. If this is a probability sample (e.g., a stratified random sample of timber sales), then it is possible to make scientifically defensible inferences about the overall outcomes of adaptive management at all sites in a region, province, National Forest, District, or some other broad domain, even though some of those sites are not directly monitored. Likewise, adequate monitoring of hundreds of watersheds might be not be feasible. *Adaptive monitoring* would take a probability sample of all watersheds, and use the sample to infer the outcomes of adaptive management for all watersheds in a broad domain.

Adaptive monitoring must consider the dilemma of multiple temporal scales that range from past conditions, to present changes, to conditions expected 50- to 500-years in the future. Existing monitoring data partially quantify conditions now and in the recent past. Historical aerial photographs and satellite images can help quantify some past conditions. Mathematical models can forecast future conditions. The validity of those models requires continual development, testing and improvement, which requires the few intensively-studied sites and numerous extensive sample plots (i.e., substitution of space for time).

Probability samples are less expensive and more feasible than monitoring every individual site or watershed, but this introduces uncertainty caused by random sampling errors. Probability sampling permits quantification of this uncertainty (e.g., confidence intervals, see Fig. 1). *Adaptive monitoring* would analyze the risk caused by this uncertainty; qualify evaluations and assessments based on this uncertainty; and possibly re-prioritize monitoring efforts by intensifying sampling in certain strata, thus reducing the greatest risks caused by this source of uncertainty.

Except for a few intensively studied experimental sites, *adaptive monitoring* does not use purposive sampling. A common example of purposive sampling is selection of a few stream reaches that appear to be representative, without some form of randomized sampling from all stream reaches. Although much can be learned from purposive sampling, these are case studies that require strong assumptions in order to make inferences about all stream reaches. These assumptions can not be defended by the sampling design, and usually can not be scientifically tested. Therefore, the results of purposive sampling are vulnerable to legal challenges. Probability sampling can be stratified to accommodate practical constraints and provide more credible information at approximately the same cost as purposive sampling.

Adaptive monitoring will use techniques that change over time in response to new objectives or technologies. Such methodological changes can affect the time-series of monitoring data; changes in the environment can be confounded with changes in data due to different techniques. This can disrupt monitoring of long-term changes and trends in the environment. However, statistical methods, such as regression or calibration estimators that model the association between results of the new and old methods, might mitigate this disruption. Regardless, changes in techniques are sensible only when the advantages are substantial, the change is critically reviewed by experts, and the change is consciously endorsed by the responsible program managers.

EXAMPLE OF ADAPTIVE MONITORING

Adaptive management is a relatively new practice in applied management of natural resources, and the concept of *adaptive monitoring* to support adaptive management is even less well developed. The following example demonstrates one effort to modify an existing monitoring system to serve goals and objectives that emerged after the system was originally designed.

The Annual Forest Inventory System (AFIS) is an adaptation of the current Forest Inventory and Analysis (FIA) system, which has been used to survey and monitor the nation's forestlands across all ownerships since the 1930's. AFIS replaces the 15- to 20-year FIA cycle in the North Central States with annual re-measurements of 1/15th to 1/20th of the FIA forest plots every year (Fig. 1). This avoids the large propagation of uncertainty that exists in traditional FIA estimates (e.g., broad confidence intervals prior to 1990 in Fig. 1), and substitutes more current estimates with less average uncertainty (e.g., post-1990 AFIS estimates in Fig. 1). AFIS uses interpretation of remotely sensed imagery on a 4-year cycle to detect those FIA plots that have manifested an unusual increase or decrease in vegetation (e.g., regeneration or timber harvest). Those FIA plots with notable change in vegetation constitute a stratum that is intensively remeasured in the field. The remaining FIA plots (i.e.., "undisturbed" plots) form a second stratum; the current condition of each FIA plot in this stratum is estimated with a growth/mortality/removal model (using past FIA field measurements as initial conditions), and a small sub-sample of these plots is re-measured in the field to quantify model prediction errors. The premise is that past field measurements of "undisturbed" FIA plots are useful predictions of their current conditions, as predicted by the growth/mortality/removal model.

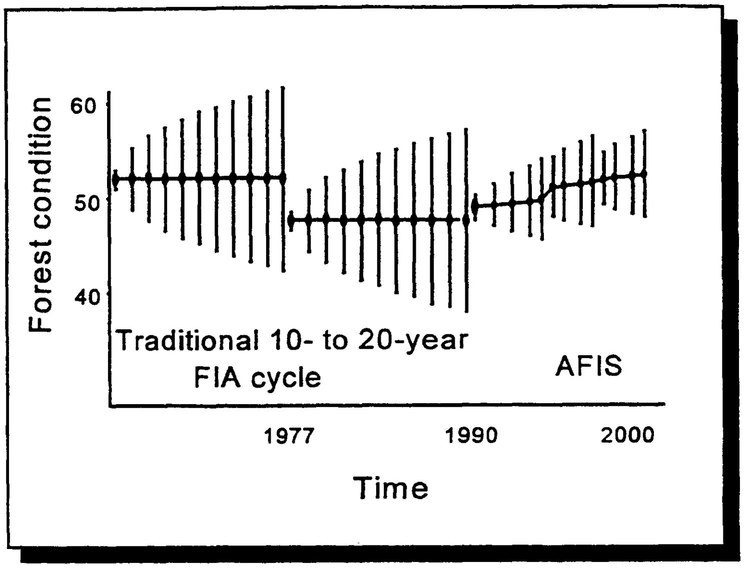

Figure 1. Hypothetical example of FIA and AFIS estimates (dots) with confidence intervals (vertical bars). The best available estimate is represented by a dot. However, the confidence interval illustrates the uncertainty with each estimate. For example, there might only be an 80% chance that the true forest condition is bracketed by the upper and lower bounds of the confidence interval (i.e., the vertical bars).

The Minnesota Department of Natural Resources began implementation of the AFIS pilot study in 1993, after several years of planning in cooperation with the USDA Forest Service. An informal consortium of users of FIA data in the Lake States has agreed to help fund the analyses and essential development activities that are necessary to complete this pilot study. A closely related pilot study began during the past year in Georgia, with the support of the State of Georgia, the forest products industry, and the USDA Forest Service. As these pilot studies near completion, the most successful components of both can be identified and combined to build the next generation of an *adaptive monitoring* system.

The success of AFIS relies directly on the performance of mathematical models that predict changes in forest conditions, which motivates continuous validation and improvement in those models. These same models can forecast future conditions and outcomes of adaptive management. Deviations of actual conditions on FIA plots from conditions predicted by historic models can be used to evaluate changes in forest health and the success of adaptive management. Potential causes of unexpected changes can be investigated, in part, by annual re-allocation of more monitoring efforts into those types of plots. The success of AFIS also depends strongly on the success of remote sensing to detect gross changes in forest conditions, which motivates continuous improvement of remote sensing methods and GIS models. Thus, *adaptive monitoring* naturally leads to continuous improvements in monitoring and evaluations.

ACKNOWLEDGMENTS

All of the concepts and examples used in this paper are the result of several major team efforts. Although the author was an active member of these teams, and many people contributed to the teams' success, the following individuals were especially essential in development of these concepts: Jim Alegria, Bill Befort, George Degan, Mark Hansen, Craig Mellin, Barry Mulder, Paul Ringold, Hans Schreuder, Ed Starkey, Tim Tolle. The following individuals provided essential support and encouragement: Jerry Hahn, Dave Heinzen, Neal Kingsley, Dan McKenzie, Ron McRoberts, Jerry Rose. Many of the components of adaptive monitoring were identified by the Forest Health Monitoring Program and the Environmental Monitoring and Assessment Program. The opinions expressed in this paper reflects the author's perspective as a team member, and other team members' opinions may differ.

LITERATURE CITED

ESA. 1996. The report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. Ecological Applications. In press.

GRUMBINE, R. Edward. 1994. What is ecosystem management? Conservation Biology, 1:27-38.

MULDER, B., J. ALEGRIA, R. CZAPLEWSKI, G. HAYSLIP, P. RINGOLD, E. STARKEY, and T. TOLLE. 1995. Effectiveness Monitoring: an interagency Program for the Northwest Forest Plan. Final Report to the Research and Monitoring Committee. USDA, USDI, EPA. Portland, OR.

POWELL, Douglas S., William H. MCWILLIAMS, and Richard A. BIRDSEY. 1994. History, change and the U.S. forest inventory, Journal of Forestry 92:7-11.

RINGOLD, Paul L., Jim ALEGRIA, Raymond L. CZAPLEWSKI, Barry MULDER, Timothy TOLLE, Kelly BURNETT. 1995. Ecosystem management-lessons in the design of an ecological monitoring strategy for the Forest Plan in the Pacific northwest. Ecological Applications. In press.

TOLLE, Timothy, and Raymond L. CZAPLEWSKI. 1995. An interagency monitoring design for the Pacific Northwest Forest Ecosystem Plan. pp. 293-307, In proceedings of the workshop Analysis in Support of Ecosystem Management, April 10-13, 1995, Fort Collins, CO. USDA Forest Service, Washington, D.C. 360pp.

USDA/USDI. 1994. Record of Decision for Amendments to the Forest Service and Bureau of Land Management Planning Documents within the Range of the Northern Spotted Owl. Portland, OR.

WALTERS, Carl. 1986. Adaptive Management of Renewable Resources. Macmillan Co., New York.