A SELECTION OF FOREST CONDITION INDICATORS FOR MONITORING

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Abstract. Regional monitoring and assessments of the health of forested ecosystems require indicators of forest conditions and environmental stresses. Indicator selections depend on objectives and the strategy for data collection and analysis. This paper recommends a set of indicators to signal changes in forest ecosystem distribution, productivity, and disturbance. Additional measurements are recommended to help ascribe those changes to climate variation, atmospheric deposition, and land use patterns. The rationale for these indicators is discussed in the context of a sequential monitoring and assessment strategy.

1. Introduction

There are worldwide concerns that forest condition is deteriorating and climate is changing because of anthropogenic influences such as air pollution and deforestation. In the United States, Congressional and public concerns are evidenced by calls for increased monitoring in the Forest Ecosystems and Atmospheric Pollution Research Act of 1988 and in the 1990 amendments to the Clean Air Act. This monitoring will be long term and regional to address ecological and environmental issues such as air pollution and climate change. An important design consideration is the selection of measurements and indicators to guide data collection and to set up the necessary assessments.

The discussion of criteria for ecological indicators does indeed seem to be a 'spring ritual' (Rapport, 1990). Criteria are needed to choose among more indicators than can ever be implemented. Measurement selection might be better termed a 'rite of passage' for a design team, because a small number must be selected and not everyone will be satisfied. Compare, for example, the data needed for assessments of air pollution effects at the international scale (e.g., UN, 1989) and at the stand-level scale (e.g., Schulze, 1989), or the

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variety of existing monitoring systems (e.g., NSEPB, 1985; Magasi, 1988; Nordic Council of Ministers, 1988). Although no single example can settle the issue, this case study of indicator selection may help other design teams in the future.

2. A Sequential Forest Monitoring and Assessment Strategy

Forests are continually exposed to a changing array of natural (competitive, climatic, biological, and chemical) and anthropogenic (disturbance and pollution) stresses (Woodman and Cowling, 1987). Against this background of poorly understood and interacting disturbances and stresses, the regional effects of climate change and air pollutants can be subtle and difficult to identify (Smith, 1981). A strategy based on the detection of unusual, regional, and important changes in forest condition followed by progressively more detailed studies to explore those changes is often recommended to solve this problem (e.g., CEQ, 1987; UN, 1987; Schaeffer *et al.*, 1988; Addison, 1989; NRC, 1989). Monitoring gives just observational data, and a combination of inductive and deductive approaches may be needed to elucidate specific cause-effect relationships (Oren *et al.*, 1989).

The point of departure for our case study is a similar ecological monitoring and assessment strategy (Messer, 1990) that fits within an overall ecological risk assessment paradigm. Applied to forest indicator selection, the important elements of the monitoring strategy are as follows:

(1) The first objective of monitoring is to identify ecological resources whose condition is deteriorating widely or rapidly;

(2) Indicators are used to classify the status of ecological resources and to gauge the stresses placed on those resources;

(3) Indicators are related to societal values and are derived from knowledge of regional ecological processes;

(4) Interpretations of associations among indicators suggest but do not necessarily diagnose regional cause-effect relationships;

(5) A multi-stage, systematic sample includes large landscape sampling units and smaller plot sampling units;

(6) Routine, long-term, and large-scale monitoring of selected indicators is supplemented by more intensive research when warranted by changing ecological conditions.

3. Requirements of Indicators – Some Details

A multi-dimensional suite of indicators is required to monitor several aspects of forest condition. Many measurements are needed to comprehensively characterize ecosystem structure, function and process (e.g., Schaeffer *et al.*, 1988) or a single aspect of condition such as biodiversity (e.g., Noss, 1990). But only a few key indicators should be used in regional monitoring (Agren, 1984; Johnson, 1988; Schaeffer *et al.*, 1988; Hunsaker and Carpenter, 1990). Ideally, this small set addresses many dimensions of forest condition such as sustainability, productivity, aesthetics, contamination, utilization, diversity, and extent. If only a few aspects of forest condition are monitored, then important ecological changes could be overlooked.

Another way to overlook changes is to focus attention only on diagnosing and interpreting known cause-effect relationships. The emphasis on detecting regional changes in overall condition without necessarily explaining them suggests an emphasis on integrative measures of condition (e.g., Materna, 1984; Smith, 1984; Waring, 1984) rather than specific and precise bioindicators (c.f., Ratsep, 1990). For a given dimension of condition, a composite and complementary set of integrative indicators may be needed to account for buffering or compensatory changes (Cairns and van der Schalie, 1980; Munn, 1989). Some additional explanatory measures may be necessary to improve the precision of change detection or to narrow the range of plausible causes of abnormal condition. But the highly specific measurements that are needed to answer questions such as 'the effect of stress *w* on attribute *x* in forest *y* through mechanism *z*' would not be considered for routine monitoring.

So that monitors can evaluate the relevance of observed changes, indicators must relate to environmental values that people care about. Because these values are not typically amenable to direct measurement it is common to represent them as 'endpoints' (Suter, 1990) that can be evaluated in terms of indicators. Forest monitoring is primarily concerned with endpoints of forest condition rather than of environmental stresses (Messer, 1990). A prototype endpoint is 'good forest health' defined, for example by 'normal' biological conditions (Johnson, 1988; Munn, 1989). Biological normality can refer to site-specific trends, regional average or representative conditions, or a best attainable status. Thus, endpoints can be defined from remeasurements of permanent monitoring locations, from field surveys, or from research at either pristine or representative locations. Characteristics of the population frequency distributions of an indicator may be useful endpoints.

In some situations it will be useful to define 'indices' as the quantity to be monitored. For example, an indicator value corresponding to a healthy condition may change over time for a given forest, or, if the same indicator is constrained by different ecophysiological processes in different forests, a range of indicator values will be obtained even when conditions are normal everywhere. To get comparable values, the indicators will have to be standardized as quantitatively comparable 'indices' of condition that relate actual to expected condition for each recognized category of forest. Models are required to incorporate auxiliary data and estimate expected condition. Such models have been shown to improve the precision and accuracy of monitoring (Hirsch *et al.*, 1982; Radford and West, 1986; Sparks, 1987).

Whether or not a change will be detectable depends partly on the scale of the indicators relative to the scale of the change phenomena of interest (Overton, 1977; O'Neill *et al.*, 1986). Climate change, air pollution, forest decline, and other regional phenomena are best monitored on a regional basis. Model-based extrapolation of a few intensively monitored sites to a regional scale is not regional monitoring. Furthermore, since time and space scales of ecological processes seem to be linked (O'Neill *et al.*, 1986), regional monitoring will probably utilize seasonal, annual, or longer remeasurement cycles

(Messer, 1990). Knowledge of finer-scale temporal variability often contributes little information about longer-term changes.

Under the monitoring strategy, data analysis has an 'early warning' phase to detect changes and an 'exploratory analysis' phase to associate patterns of change with patterns of environmental stresses. In the early warning phase, indicator (or index) patterns and trends give quantitative signals of conditions. Indicator selections optimized for early warning analyses would minimize the occurrence of false negatives (i.e., type II error rate) because the goal is to detect changes. But the more powerful indicators may be relatively more sensitive to environmental change, and this will tend to increase the number of false positives (i.e., type I error rate). A compromise must be reached, and type I error rates should be reduced by incorporating auxiliary data known to be important.

Additional exploratory analyses seek plausible causes for observed changes. In some cases, indices can be decomposed into their component measurements for exploratory analyses (e.g., Walworth and Sumner, 1987). In other cases, the signals for each indicator can be combined in interpretive analyses such as 'fingerprinting' (MacCracken and Moses, 1982) or 'pattern recognition' (e.g., Simmleit and Schulten, 1989). In most cases, full interpretations will require additional measurements, but there is no way to predict the specific data requirements. To augment existing auxiliary data bases, a few additional measurements should be made that help to discriminate among classes of causal agents through correlative or synoptic analyses (Wallace, 1978). These preliminary analyses will then suggest more specific analyses or follow-up studies to diagnose specific causes (Treshow, 1984).

Appropriate measurements can also be identified based on the probable total cost of monitoring all forest land in the U.S. Consider a relatively sparse network with 3500 monitored sites*. If the average annual per-site expenditure for travel, measurements, laboratory analyses, reporting, and administration is ~\$3000, then the total annual budget required for monitoring is ~\$10.5 million. Plot density and remeasurement frequency can be optimized for a given budget, but the total budget is not likely to increase by an order of magnitude. The implication is that appropriate indicators have to be relatively inexpensive and only a limited number of highly interpretable indicators can be realistically implemented.

4. A Selection of Forest Condition Indicators

Distribution, disturbance, and productivity are an important but small subset of ecological and social values about forests. Given these or other values, the process suggested by Schaeffer *et al.* (1988) for defining ecosystem health contains criteria that could be applied to the indicator selection process. Table I lists these and other criteria that help to decide upon particular indicators of forest condition. Taking into account these criteria, the dimensions of concern, and the monitoring strategy, five indicators are

* For comparison, this is 50–100 times less dense than existing U.S. forest inventory networks (Hazard and Law, 1989).

TABLE I

Some desirable attributes of indicators of forest condition (after Schaeffer *et al.*, 1988)

1.	Is not dependent upon the presence, absence, or condition of a single species.
2.	Is not dependent upon a census or inventory of many species.
3.	Reflects knowledge of 'normal' changes, for example due to succession or other sequential changes.
4.	Is one of several indicators that collectively represent a set of end points, but is not redundant.
5.	Is dimensionless, single-valued, and monotonic in relation to a defined range of condition.
6.	Has known statistical properties.
7.	Responds to stresses, but is resistant to wild data and insensitive to poor sampling design.
8.	Can be decomposed into indicators of more specific definitions of forest condition.
9.	Is practical and feasible.
10.	Is comparable among classes of forest, for example among forest type, size, and density classes.
11.	Integrates responses and has a stable value for several months each year and over a geographic area as large as the sample unit.

recommended to detect changes in forest condition:

(1) landscape pattern
(2) visiual symptoms
(3) tree foliar nutrients
(4) soil nutrients
(5) stand growth efficiency.

Measurements needed for particular expressions of these indicators and auxiliary data needed to better interpret them are discussed in the following section.

4.1. Landscape Pattern

A suite of measures of landscape pattern is needed to describe the distribution and extent of different forest types, patterns in vegetative and physical habitat structure, and characteristics and degrees of natural and human-induced disturbance. The wide scope of this definition makes the indicator potentially the most complicated of all proposed in this paper. Thus, 'landscape pattern' here refers to a number of indices that can be used to monitor various aspects of changes in landscape features.

Our ability to represent landscape ecophysiological processes by indicators is uncertain, and only suggestions can be made here. Some examples include horizontal indices such as connectivity (Forman and Godron, 1986), dominance, contagion, and fractal dimension (O'Neill *et al.*, 1988). Connectivity measures the association of corridors (e.g., migration routes) within a landscape. Dominance is a measure of the extent to which one or a few patch types (e.g., cover type, land use type) dominate the landscape. Contagion is a measure of the extent to which patch types are aggregated or clumped, and fractal dimension is a measure of the edge complexity of patches in a landscape. Examples of vertical landscape indices are the Habitat Layer Index (Short and Williamson, 1986) Patton's (1975) diversity index.

Other landscape pattern indices may be used to classify regions with respect to potential stresses, for example drought, land use, or air pollution. Such indices could be estimated from models of interactions between static landscape features and dynamic weather and pollution stresses. This procedure would suggest broad regions where changes in forest condition could be expected.

4.2. VISUAL SYMPTOMS

The adage that 'one can learn a lot by just looking' seems to apply to forest monitoring. If trained personnel visit ground plots, it is easy to justify an on-site inventory of signs and symptoms of damage, disease, and stress. Most types of chronic environmental stresses will eventually lead to a change in overall health that is visible to a trained observer. Typical observations are relatively inexpensive and repeatable. In any event, it is probably more difficult to justify *not* 'just looking' than to deal with concerns about the bias and variability of these types of measurements.

Visual symptoms can include a potentially large number of measurements and observations. A common international index summarizes the foliation of individual trees in late summer (UN, 1987). Each sampled tree receives a score based on the percentage of normal foliation, and individual tree scores are then combined to estimate a visual symptoms indicator for a given monitoring location, forest type, or region. Other techniques for observing and scoring foliation have been described (e.g., Anderson and Belanger, 1986; Alexander and Carlson, 1988; Millers and Lachance, 1989). Common summary indices of pests and pathogens report percentages or areas of affected populations.

4.3. FOLIAR NUTRIENTS

This indicator is used to identify imbalances in tree nutrient concentrations. Healthy functioning depends on a sufficient supply and the proper balance of critical nutrients in foliage, and imbalances may signal imbalances in other ecosystem functions. Environmental stresses can change nutrient flux rates by reducing the uptake of nutrients from the soil, by increasing nutrient leaching from foliage, or by changing the within-plant allocation of nutrients. These effects may be reflected by changes in foliar nutrient ratios that are better indicators of balance in comparison to the sufficiency of particular nutrients in relation to critical concentrations or normal ranges (e.g., Ingestad, 1962 and 1979; Timmer and Stone, 1978).

Many methods can be considered for collecting foliage samples, but none are inexpensive and it is therefore difficult to control the many sources of variation at a given location (Turner *et al.*, 1978). A minimum laboratory analysis would determine the concentrations of N, P, K, Ca, and Mg per unit of dry weight. If possible, specific leaf weight (dry weight per unit leaf area) and the concentrations of S, Fe, Mn, Zn, Cu, Na, B, and Al should also be determined.

Full interpretation of nutrient dynamics requires sampling during different phenological stages over several consecutive years, and coincident soil chemical measurements (Oren and Schulze, 1989). For monitoring regional changes, an index is needed that would permit less frequent sampling. One possible summary index that is based on nutrient ratios is the overall DRIS (Diagnosis and Recommendation Integrated System) index (Beaufils, 1973; see Walworth and Sumner, 1987). DRIS is a system for defining normal nutrition and diagnosing nutrient requirements to achieve optimum plant condition. It considers many nutrient ratios simultaneously, and provides a summary statistic describing the overall nutritional balance in relation to an independently defined population of healthy trees. DRIS has been tested extensively in agronomic crops (Walworth and Sumner, 1987) and has been applied to the analysis of forest nutrition (Truman and Lambert, 1980; Leech and Kim, 1979 and 1981; Ward *et al.*, 1985; Kim and Leech, 1986; Schutz and devilliers, 1987; Svenson and Kimberley, 1988; Lozano and Huynh, 1989; Hockman and Allen, 1990; Needham *et al.* 1990) and diagnosis of tree damage and quality (Schaffer *et al.*, 1988; Hockman *et al.*, 1989).

4.4. Soil Nutrients

This indicator is used to identify imbalances in soil nutrients. Although the quantitative balance of soil nutrients is less important than foliar nutrient balance for the growth of trees, changes in ratios brought about by differential leaching, weathering, or deposition of nutrients to the soil may indicate changes in other ecosystem functions. An index of soil nutrients can be constructed by using the DRIS approach described earlier (Beaufils and Sumner, 1976; Evanylo *et al.*, 1987).

In application, soil pedon descriptions should be completed for all soil series at each monitoring location. Soil samples should then be obtained once every five to ten years and portions of the samples saved. The recommended laboratory analyses from the forest floor horizons include pH, total N, total extractable P, cation exchange capacity, total C, percent base saturation, and exchangeable K, Ca, Mg, Fe, Mn, Zn, Cu, Na, and Al. For mineral horizons, analysis for pH, cation, exchange capacity, percent base saturation, extractable P, pyrophosphate-extractable Al, Fe, and Mn, exchangeable K, Ca, S, Mg, Fe, Mn, An, Cu, Na, and Al, and total S should be performed.

4.5. Growth Efficiency

This indicator identifies net changes in the ability of trees to maintain themselves in an ecosystem. Because growth is a relatively low-priority sink for assimilated carbon, tree growth rates usually decrease preceding the death of individuals; decreasing growth rates thus may be evidence of regional changes in forest productivity (e.g., Sheffield *et al.*, 1985). A sensitive indicator of ecosystem productivity is growth efficiency, expressed as a ratio of actual tree growth to capacity for growth (Waring *et al.*, 1980; Waring, 1983). Stressed systems should exhibit a reduction in growth efficiency before community structure changes (Waring and Schlesinger, 1985) and as a precursor to damages from biotic agents (Christiansen *et al.*, 1987).

A suitable expression of growth efficiency for monitoring is net stemwood volume growth divided by an index of light absorbed by the forest canopy, on a per unit area basis. Periodic remeasurement of live trees is commonly used to estimate periodic stemwood volume growth. Measures of light absorption can come from measurements of light transmittance or from structural parameters such as leaf area index. Some of these indices can be estimated from satellite imagery by forming ratios of appropriate wavelengths from various sensors (e.g., Rock *et al.*, 1986; Tucker and Sellers, 1986; Running and

Nemani, 1988). An efficient method to measure light transmittance directly is described by Pierce and Running (1988).

4.6. Other Measurements

Experience has shown that location-specific site descriptions and maps, mensurational data, and soils data will be needed for routine monitoring (USDA Forest Service, 1985). Additional auxiliary data will be needed to incorporate regional patterns of weather, air pollution, and land attributes. Some of the needed auxiliary measurements of chemical exposure and deposition may be obtainable from existing monitoring systems (Table II). Weather data may also be accessed for daily and monthly information on precipitation (amount, form, and timing), temperature (averages, extremes, and frost-free period), and possibly incoming solar radiation (NOAA, 1987). Finally, topographic and elevation data bases (USGS, 1985 and 1987) may be useful in estimating or interpreting trends in environmental or forest conditions.

Forest monitoring will provide an opportunity to obtain specialized measurements of soil and foliar toxins to help discriminate changes caused by air pollution from those due to land use and climate change. These additional measurements would be made in two instances. First, they would be routinely made at a subset of representative monitoring locations to provide an extensive surveillance capability for detecting emerging problems. Second, they would be made as needed for intensive studies by using samples of soil and plant tissue obtained from selected locations. Appropriate expressions for these measurements would depend on the particular analyses.

5. Research Needs

Some questions about regional monitoring design will remain until experience reveals the

TABLE II

Examples of auxiliary chemical data

Wet Deposition		Dry Deposition	
Precipitation	Cloud/Fog	Gases	Particles
SO_4^{2-}	SO_4^{2-}	O_3	SO_4^{2-}
NO_3^-	NO_3^-	SO_2	NO_3^-
H^+	H^+	NO_2	H^+
NH_4^+	NH_4^+	NO_x	NH_4^+
Ca^{2+}	peroxides	HNO_3	CA^{2+}
Mg^{2+}		VOCs[a]	Mg^{2+}
peroxides		N_2O	
pesticides		CO_2	
trace metals		CH_4	
bioengineered products		CFCs[b]	

[a] Volatile organic compounds.

[b] Chlorinated fluorocarbons.

correct approaches. Our case study suggests one possible set of indicators that should be starting points for further development. The apparent emphasis on tree-based indicators reflects the fact that most experience is with those types of indicators. There is a need to identify additional environmental values of concern and to better represent the condition of forest fauna, soil, water, and non-tree vegetation.

Primary candidates for further consideration that require additional research to reduce the cost of measurement or to give a better ability to interpret effects upon forests are as follows:

(1) Tissue analysis for chemicals in mosses and lichens;
(2) Loading of nitrates in soil and surface waters;
(3) Phenology and decomposition of foliage;
(4) Faunal or habitat occurrence and relative abundance;
(5) Physical and biological processes of the soil;
(6) Stable isotopic composition of vegetation and soil biota.

Whereas national monitoring may at first be ground-based, remote sensing coupled with multi-stage sampling is probably a more efficient approach for monitoring regional change. Satellite technology is being developed rapidly and is aimed at the collection of global data bases of geographic, physical, and biological variables. Satellite systems offer a regional perspective and can measure some indicators that are not conveniently measured on the ground. Iverson *et al.* (1989) summarize tests of different sensors for measuring forest extent, succession, structure, damage, physiological parameters, and productivity. There will always be a need to calibrate remote observations with ground-based measurements, and the satellite-based global positioning system could be used for precise geodetic control.

Any selection of indicators should be tested as a complete set on a regional basis prior to full deployment in an operational monitoring system. This test would verify the representativeness of the sample, the interpretability of the set of indicators, and the power of the planned analyses. Realistic data would also then be available for simulation studies to compare techniques for exploratory pattern analysis and correlation with auxiliary data such as weather and air pollution.

6. Conclusion

There is a need for better systems to monitor forest condition in relation to the stresses imposed on forests by modern technology and utilization. In our view, the most sensible approach builds on the most successful aspects of existing systems and expands upon them over time. Two important opportunities in the U.S. are (1) the national forest inventory system of ground-based measurements (USDA Forest Service, 1985) and (2) emerging technologies in remote sensing that can provide a landscape perspective and linkage to global ecosystem assessments. Perhaps the greatest challenge is to provide for a sensible evolution of monitoring to complement changes in the demand for information and in the capabilities to provide it. Our selection is one view of a minimum set of forest condition indicators that could be measured in a practical monitoring system.

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