A Conceptual Model for Defining and Assessing Condition of Forest Stands

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ABSTRACT / Determining what indicators can be used to measure forest health has been much discussed but largely unresolved in the forestry literature. A model is presented in which the condition of a stand is quantified relative to a suitable target condition based on a preselected set of stands that, in the opinions of the managers, meet management objectives. Each stand was characterized by a list of variables that were selected from the existing forest database. We termed these characterizations stand profiles. Profiles of inventory data for 28 stands, each managed for either wildlife habitat or timber production in the Wallowa-Whitman National Forest in eastern Oregon, USA, were used to develop this model. Healthy stands were represented by points in multidimensional scaling space that fell within the bounds of a 65% kernel density estimation of the distribution of stands preselected for each management objective. Stands falling outside these bounds were, by definition unhealthy, and the distance from the bounds is a measure of degree of unhealthiness. Operationally, the objectives of silvicultural manipulations would be to maintain or move points to within the target space by selectively manipulating the values composing stand profiles. The direction and length of the trajectory associated with manipulations is an indicator of the effect of management actions. More work needs to be done to develop and validate this method.

Indicators are "measures of condition, processes, reaction or behavior that provide reliable shorthand for complex systems" (DPIE 1995). Much has been written about what characterizes good indicators of the condition of the environment (McRae and others 1995, Johnson 1988) or forest (Lewis and others 1996), and how they should be selected (Ritters and others 1990). According to Angermeirer and Karr (1994), for example, indicators should be responses to stress, easily measured and evaluated, distinguishable from natural variation, and societally significant. To manage their forests effectively, managers must have good indicators.

In contrast to forests, air and aquatic ecosystems have been the subject of much work on development of indicators to measure effects of pollution (Root 1967; Severinghaus 1981; Landres 1983; Morrison 1986). Many of these indicators are based on single variables, which describe limited portions of the system and may not portray the functional and structural complexity of the ecosystem (Karr 1987). Karr (1981) introduced a multivariate metric referred to as an index of biotic integrity that was composed of measures for species abundance, composition, richness, trophic and reproductive function, and condition. The index of biotic integrity has been widely used in aquatic systems to describe impact on fish communities (Lyons and others 1995). Field and others (1982) introduced a method for assessing differences among aquatic communities described with multiple characteristics using similarity indices coupled with multidimensional scaling. Individual communities were represented as points in multidimensional scaling space. Multidimensional scaling (MDS) is a nonparametric multivariate analysis where differences are visually represented in *n*-dimensional space by the distance between points (Kruskal and Wish 1978); the greater the distance between points, the less similar are the entities that the points represent. Changes in the state of a community can be measured by the length and direction of the trajectory of movement of points in multidimensional space. This method has been widely used for assessing the impact of pollutants on communities characterized by multiple variables (Clarke 1993).

The USDA Forest Service is making a notable effort to develop indicators of forest health as part of an ecosystem-based management approach to decision making. In 1991, the Forest Service Northern Region introduced a management philosophy called "managing for sustaining ecological systems" (SES). In this

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management philosophy, forest condition is assessed by comparing the current ecological state to a range of values specified for a number of variables. Variable ranges were estimates based on professional opinion. The ecological elements measured differed for different spatial scales. At the stand scale, the following elements were assessed: water quality, hydrology, fish/aquatic systems, fire/fuels regime and risk, threatened and endangered species viability, forest insects and pathogens, nutrient cycling/long-term soil productivity, and successional community structure/composition. In 1992, the Blue Mountains Restoration Panel adopted the SES approach for evaluating forest health at the river-basin scale. The panel used the following elements as indicators: (1) percent of stands that were early seral; (2) late seral parklike; (3) late seral tolerant multistory; (4) ponderosa pine, high density, low vigor; (5) lodgepole pine, high density, low vigor; (6) available fuels; (7) juniper grasslands; (8) riparian shrub cover; and (9) streambank stability (Caraher and Knapp 1994).

Walker and Boyer (1994) present a qualitative model for forest conditions that is similar to Field and others (1982) method using MDS. In this model, the natural range of variability is represented by an area defined in two-dimensional space. According to Walker and Boyer (1994), "continuous processes/growth, mortality, species interactions, responses to weather, and small scale disturbances change the condition of a stand within the confines of the natural variability boundary. At times, the stand is changed to fall outside of these bounds, whereupon a force (management action) needs to be applied to restore its original condition or establish a different system." The objective of the present study is to quantify the model presented by Walker and Boyer (1994) by combining the multivariate approach described by Caraher and Knapp (1994) with the multidimensional scaling method developed by Field and others (1982). How the resulting model might be used as an indicator of forest condition was examined as a pilot study using data from an established National Forest stand inventory database.

Model Development

The Blue Mountains of northeastern Oregon were chosen for this study because of the recent concern for the health of the forests there (Wickman 1992). Forest managers at the Baker District of the Wallowa-Whitman National Forest were asked to select groups of stands that represented examples of different target conditions (or management objectives) listed in their forest plan. Subsequently, 28 stands were identified. The management objective for 15 of these stands was timber production; the objective for the other 13 stands was wildlife habitat. Both of these objectives are general terms that have many definitions. For example, stand conditions suitable for cavity-nesting birds differ from those suitable for elk. Managers did not specify what was meant by timber production or wildlife habitat in this study. The selection of these stands was left entirely to managers who routinely make field management decisions. The specific decision criteria used by them to select management targets were not examined. The model is intentionally based on the assumption that managers make thoughtful good decisions about stand objectives.

Data characterizing each of the 28 stands were acquired from the existing database at the Wallowa-Whitman National Forest. Initially, 208 variables were chosen for each stand, which was the maximum number of variables that could be processed by the available software. Each stand was thus characterized as a list of several variables, which we called a stand profile.

To simplify subsequent analysis, the number of variables within stand profiles was reduced using an analysis based on classification and regression tree (CART). CART estimated the relative importance of each of the 208 variables for distinguishing between target management objectives (Breiman and others 1984). For this analysis, the preselected management objectives (wildlife habitat and timber production) were used as the dependent variables, and all profile variables were used as candidate predictor variables. Variables that this analysis indicated had no importance for distinguishing between the management objectives were eliminated from subsequent analysis. Six predictor variables had greater than 0% relative importance for distinguishing management objectives; CART needed none of the other 202 variables to distinguish between the two management objectives. The significant variables included: periodic annual increment of the 9–13.9-in. DBH class interval (DBH9CFPA), total basal area of the 5-in. DBH class (BAAS57), periodic annual increment of the 5-in. DBH class (DBH5CFPA), total number of merchantable trees per acre (TREASMER), periodic annual increment of the 7-in. DBH class (DBH7CFPA), and average DBH of the >14-in. DBH classes (DBH6AVG). In practice, unless all forest objectives were represented in a particular analysis, variables having no importance in one analysis should not be eliminated from another analysis.

Because even with shortened stand profiles, an analysis involving several stands would quickly become unmanageable due to the large number of values, we used MDS as a method of data reduction to facilitate the analysis. To do this, a Pearson correlation matrix, which estimates correlation between stands and calculates these values from profiles composed of the shortened variable list for all possible pairs of stands, was used as input data for MDS (Kruskal and Wish 1978). Output was a two-dimensional graph where each point represented an individual stand; spacing between points is a measure of similarity between stands.

Stands managed for the same objectives should have similar profiles and should cluster together in MDS space. The bounds of this space represent the range of stands that are suitable for a specific objective (see Figure 1 below). To establish these bounds, we used the kernel density estimation method using SYSTAT (SPSS Inc., Chicago, Illinois), which generates a contour representing the continuous density distribution of points in two-dimensional space. We coined the term core range of variability (CRV) for the space bounded by the kernel density estimator. In this study, the CRV was graphically visualized in MDS space as the region within the bounds of a 68% kernel, which was the default setting in SYSTAT. The distribution of stands previously selected by managers for the different objectives was compared to the space bounding the CRV. Points outside the CRV represent stands that are not currently in a condition suitable for a specified objective. The CRV is meant to be equivalent to the natural range of variability shown in the Walker and Boyer (1994) model.

The following procedures illustrate how this model might be used to develop management prescriptions aimed at improving the suitability of stands for selected objectives. Mean cluster profiles were composed using average values for each variable across all stands within each cluster (Table 1). Stands that fell outside the bounds of the CRV were compared to the mean cluster profile of the target cluster to determine which variables were most different. The values of these variables were changed to simulate a silvicultural manipulation aimed at moving the outlier stand back into a CRV for a chosen objective. To quantify the effects of these manipulations, the multidimensional scaling procedure described above was repeated using profiles that incorporated adjusted variables. The direction and length of an arrow from the preadjusted location of the selected stand to its new location was used to illustrate and assess the expected effect of these manipulations. This trajectory would be used as a measure of the impact of any silvicultural manipulations.

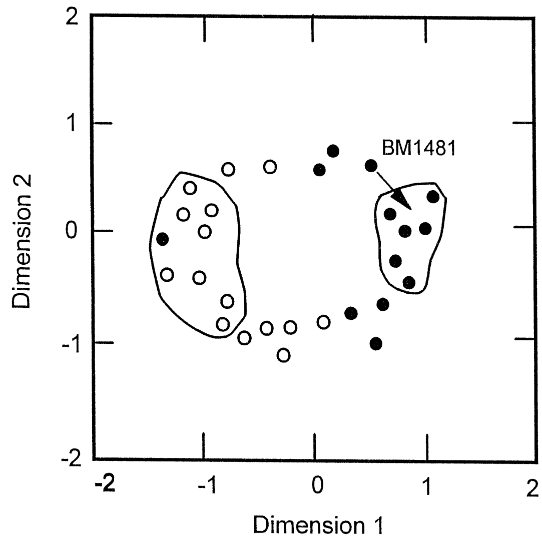

Figure 1. Based on vegetation profiles, 28 stands were analyzed for similarity/dissimilarity using multidimensional scaling (MDS) coupled with kernel density contour plots. Each dot represents a single stand. The thick lines define outer bounds of groupings defined by cluster analysis. The arrow signifies the trajectory or direction and magnitude of change that resulted from silvicultural manipulations of stand BM1481. Dark dots represent stands chosen as wildlife habitat, and empty dots represent stands chosen for timber production.

Results

Stands associated with wildlife habitat grouped toward one half of the MDS graph, and those associated with timber production grouped to the other half (Figure 1). The spread of points was slightly broader for timber production, indicating that a broader range of stands was suitable for this objective. Similarly, the size of the CRV was bigger for the timber production objective. For wildlife habitat, six stands fell within the CRV and seven fell outside of it. For timber production stands, eight were inside and seven outside of its CRV.

The stand designated BM1481 was selected to examine how manipulation of the stand profile could alter a stand's position in MDS space. Originally, this stand was designated for wildlife habitat, but it fell outside the CRV that bounded that cluster (Figure 1). A comparison of the current profile of BM1481 with the mean cluster profile for the wildlife objective showed that the total number of merchantable trees per acre (TREASMER), average DBH of the >14-in. DBH class (DBH6AVG), and the periodic annual increment of the 9–13.9-in. DBH class interval (DBH9CFPA) were the variables most out of range (Table 2). A silvicultural prescription could reduce the total number of relatively

Table 1. Mean cluster profiles for timber production and wildlife habitat based on vegetation characteristics[a]

	Management objective	
Variable	Timber production	Wildlife habitat
BAA57	2.5	11.5
DBH5CFPA	6.0	15.5
DBH6AVG	20.5	16.5
DBH7CFPA	9.5	31.5
DBH9CFPA	9.0	13.0
TREASMER	64.5	113.5

[a]Variables include: periodic annual increment of 9–13.9-in. DBH class (DBH9CFPA), basal area of 5-in. DBH class (BAAS57), total number of merchantable tree sper acre (TREASMER), periodic annual increment of 7-in. DBH class (DBH7CFPA), periodic annual increment of 9-in. DBH class (DBH9CFPA), and average DBH of the >14-in. DBH class (DBH6AVG).

Table 2. Vegetation profiles for stand BM1481 showing current, mean cluster and adjusted profiles[a]

	Actual	Mean wildlife habitat	Adjusted
BAAS57	12.0	11.5	12.0
DBH5CFPA	15.0	15.5	15.0
DBH6AVG	18.0 (H)	16.5	16.0
DBH7CFPA	32.0	31.5	32.0
DBH9CFPA	25.0 (H)	13.0	25.0
TREASMER	419.0 (H)	113.5	144.0

[a]Variables include: periodic annual increment of 9–13.9-in. DBH class (DBH5CFPA), basal area of 5-in. DBH class (BAAS57), total number of merchantable trees per acre (TREASMER), periodic annual increment of 7-in. DBH class (DBH7CFPA), periodic annual increment of 9-in. DBH class (DBH9CFPA), and average DBH of the >14-in. DBH class (DBH6AVG). "H" signifies that the current values are high relative to the mean wildlife habitat, which is the desired target condition.

large stems in order to reduce TREASMER and DBH6AVG. Accordingly, TREASMER and DBH6AVG were changed in a simulation exercise from 419 trees/acre and 18 inches to 144 and 16, respectively. DBH9CFPA would be much less easy to manipulate in a real situation and its value was left unchanged. The resulting trajectory shows that the position of stand BM1481 changed with these simulated silvicultural manipulations and moved within the bounds of the CRV (Figure 1).

Discussion

Based on the above observations using limited data, we propose the following general model (Figure 2).

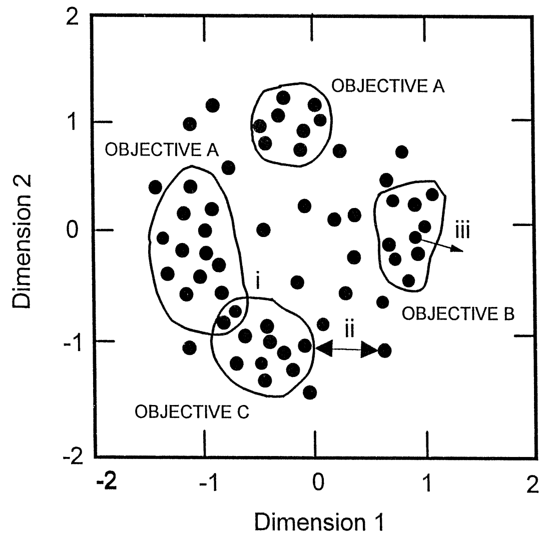

Figure 2. A hypothetical model of forest stand condition. Each point represents a single stand. Clusters of points surrounded by a line represent the core range of variability (CRV) associated with individual management objectives A, B, and C, respectively. The bounds of CRVs for two objectives overlap at point i; two stands within this overlapping space are suitable for either objective A or objective C. Trajectory ii represents the distance from the point in MDS space and the bounds of the CRV is a measure of how unsuitable the selected stand is for objective C; the stand can be made suitable by silviculturally manipulating its profile. Trajectory iii represents a change in the condition of a stand that makes its position in MDS space drift outside of the CRV of objective B; the distance beyond the edge of the CRV is a measure of impact.

Individual stands within the management area are presented as points in a decision space. Each stand has a profile of many characteristics that describe its current condition. The position of each stand within the decision space depends on the values of the variables that compose its profile. Each management objective has a desired condition, which is represented by its CRV. The width of a CRV indicates how broadly the desired condition of the associated objective is defined. The condition of a stand is a function of how suitable it is for a specified management objective. The bounds of the CRV are established by selecting a value for the kernel density estimator, and thus, the criteria of suitability can be loosened or tightened on the basis of this selection (Figure 3). Suitable stands fall within the preselected bounds of the CRV. If a stand were outside of this space, then silvicultural manipulations would be necessary, and the distance between this stand and the edge of the core range of variability would be a measure of the degree of unsuitability of a stand for a particular objective. CRVs may overlap, indicating that some

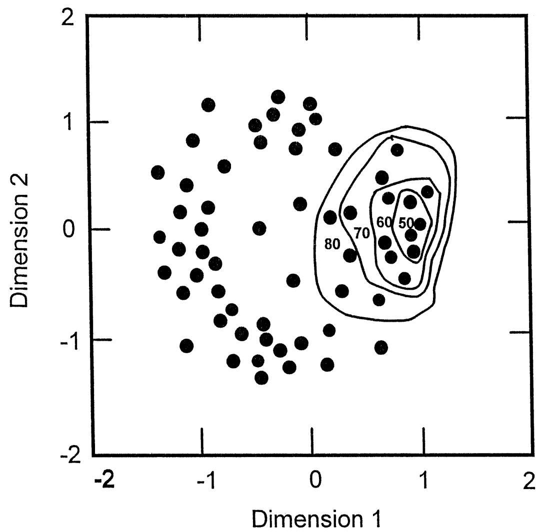

Figure 3. A hypothetical model showing the relative condition of various stands based on their placement in MDS space. Stands located within contours defined by relatively lower kernel density estimator values have relatively better conditions.

stands are suitable for multiple objectives. Furthermore, a given objective may have more than one CRV, and these may occur at different locations across the MDS space. Various disturbances will change the values of a stand's profile variables, and thus move the point associated with that stand. The trajectory formed by this movement in MDS space is an indicator of impact, and its direction and distance correspond to the magnitude of this impact. When the point moves from inside to outside a CRV, then there is a negative impact measured in terms of a specific management objective. In this way, impact should be able to be assessed for any management objective, including wildlife habitat, aesthetic value, recreation value, wilderness, biodiversity, as well as timber production.

Stand health is a function of stand condition. Forest health is much discussed among managers and users of forests (Sampson and Adams 1994), but not all agree with what it means. Kohb and others (1994) and O'Laughlin and others (1994) reviewed various definitions that have appeared in the literature. If we take the position that forest health is a function of suitability for achieving a specified management objective, then the health of a stand can be quantified relative to a suitable target condition; the more closely a stand fits the target condition, the healthier it is. This coincides with what Kohb and others (1994) termed the utilitarian definition of forest health, which states that "a forest is considered healthy if management objectives are satisfied and unhealthy if they are not." Unhealthy stands are represented by points that fall outside of the CRV, and the distance from the bounds of this space is a measure of degree of unhealthiness. The model accommodates the fact that health is not a binomial condition, but rather a continuous variable that depends on the chosen threshold values. In other words, a stand is not just healthy or not; it shows degrees of health.

The model developed above presents a way of assessing stand condition based on management suitability. The model is built on the basis of a preselected set of stands that in the opinion of the managers meet management objectives. An operational application of this method would identify well-defined populations with like objectives and randomly sample from these populations to obtain data for analysis. The requirement of this model is that the manager knows what the desired condition looks like. Determining stand objectives is as much an art as it is a science, and it depends on experience and knowledge of the underlying biological processes that impact forest resources. Data structure is imposed by the decision maker. Groups of stands suitable for different management objectives cluster together in different parts of this 2-D space. These regions vary in size and shape. In this way the model accommodates the fact that suitability has different meanings for stands with different objectives (Norris 1996).

O'Laughlin and others (1994) stated, "until appropriate indicators of forest ecosystem health have been selected, measured, and evaluated in a social context, objective judgements about forest health cannot be made." An important assumption made for this model was that different stands have specific, identifiable management objectives. Because different people have different ideas about what the objectives should be for management of forests (Jenkins 1997), their perceptions of suitability or health differ (Ritters and others 1990). Differences in opinion about the suitability for competing uses can be visualized in the model as overlapping CRVs in MDS space. This visualization might be useful for conflict resolution.

Operationally, the objectives of silvicultural manipulations would be to maintain or move points to within the target space by selectively manipulating the values composing stand profiles. The actual choice of which variables to adjust might depend on how effective, practical, and economical it is to adjust specific variables. Some variables, for example, could be manipulated more easily than others, and the manager might have to make compromises depending on the availability of resources. The direction and length of the trajectory associated with manipulations is an indicator of the effect of management actions. The change in distance between the arrow head and the bounds of CRV over time is a measure of effectiveness of the management action. Knowing when a target condition is achieved is just as important as establishing the target itself (Hobbs 1996).

Conclusions

The study described above examines a potentially useful method of simplifying the task of monitoring and evaluating forest stand conditions without the need for establishing new stand inventory procedures. It is based on a multivariate classification method that is designed to be used to assess stand health and develop silvicultural prescriptions in much the same way physicians use blood profiles to assess human health and prescribe treatments. Results suggest that profiling can be a useful decision support tool for assessing and monitoring stand conditions, formulating silvicultural prescriptions, and evaluating the effectiveness of management decisions. More work needs to be done to develop and validate the method.

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