AN ABSTRACT OF THE THESIS OF

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Abstract approved: _

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Forest management requires classification of forest stands into groupings or types based on structural similarities, even when structure varies continuously along gradients. Managed, mixed-species, multi-aged forest stands often display complex structures containing extreme variation in trees size, density, and species composition, and as a result have diverse canopy structures. A classification of these stands is quite challenging and has usually been done rather subjectively. The first objective of this study was to identify and apply an effective methodology to classify stand structures in mixed-species, multi-aged stands. Cluster analysis provided an approach for objective classification of stands based on a set of structural variables available from typical inventory data. A commercial forest ownership in northern California comprised the target population. Stands investigated were primarily mixed-species, multi-cohort stands that had been managed predominantly using single tree selection methods, resulting in a diverse range of vegetation structures. Crown area profile (cross-sectional crown area per relative stand height) (Dubrasich et. al 1997) served as basis for the classification since it embodies the size, density, and crown structure attributes necessary to characterize complex stands. The stand types identified were then fully characterized and differentiated from each

other with respect to various attributes allowing realization of the full benefit of the classification developed. The second objective was to fully characterize the stand types identified through cluster analysis. Three categories of attributes were regarded as most important for making silvicultural decisions in the target mixed conifer forests: 1) size distribution and density, 2) canopy structure, and 3) growth dynamics.

A Biological Classification and Characterization of Structure in Managed, Mixed-species, Multi-aged Stands

by

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A Biological Classification and Characterization of Structure in Managed, Mixed-species, Multi-aged Stands

1 Introduction

1.1 Introduction

A significant amount of quantitative silvicultural research has been conducted in even-aged stands of western Oregon and Washington, in large part because this area hosts some of the most productive forestland in the world. However, a vast area of forestland to the south and east of this region hosts many mixed-species, multi-cohort forest stands. Research in these forest types is often more meager since they are less productive and extremely variable in structure. As a result, quantification of stand structure in these forests types is often insufficient for assessing multiple resources and implementing multi-objective management.

Current vertical and horizontal dimensions of forest stands impose significant consequences on future stand dynamics. These dimensions include categories such as average size, stand density, crown structure, species composition, and spatial distribution, all of which together dictate stand structure (Oliver and Larson 1996, O'Hara et al. 1996). Managed forest stands that contain a single species and age class, such as Douglas-fir plantations in the Pacific Northwest, have relatively simple stand structures. A size attribute (for example, quadratic mean diameter) and a density attribute (for example, stand basal area) are typically sufficient to distinguish structural differences between two stands.

On the other hand, managed, mixed-conifer forests of eastern Oregon and northern California are much more complex in nature. They generally contain multiple tree ages and sizes, diverse canopy structure, and numerous tree species. These stands typically contain two to six conifers as well as hardwood components. The unique physiological characteristics of each species, such as differences in shade tolerance and foliage dynamics, contribute to the complexity of these stands. An average size and density attribute alone are not sufficient to distinguish significant differences in stand structure among these complex forests. Two stands could have identical basal area and quadratic mean diameter, yet differ in size class variety and species composition. Thus, more complete characterization of structure is needed to adequately predict the biological behavior of mixed-species multi-aged stands.

Despite the predominance of gradients in stand structure rather than distinct types, design and implementation of forest management plans require classification of stands into groupings based on biological similarity. Few efforts have assessed the adequacy of classifying stands in these complex forest types. Several additional tree and stand level attributes are needed, beyond those typically used for pure even-aged stands. If structural differences and their biological consequences could be identified, managers would have better insight into appropriate residual structures to meet management objectives. The purpose of this study was to identify and characterize stand structural types on the basis of various stand components in managed mixed-species, multi-cohort forest stands in northern

California. Chapter 2 addresses objective 1 as specified below, and chapter 3 addresses objective 2. Chapter 4 summarizes the general results and conclusions, and makes several coarse recommendations about application of the results and the utility of the described classification approach.

1.2 Objective 1

The need to classify stands into structural types arises from such activities as spatial analysis of landscapes for wildlife habitat diversity and habitat juxtaposition; timber supply analysis and forecasting for large geographic areas; establishment of targets for, and monitoring attainment of, historical range of variability; and expedient assessment of various non-timber values for entire ownership or parts of ownerships. Stands traditionally have been assigned to timber types based on species composition, average tree size, and some measure of density, such as crown closure, to facilitate classification from aerial photographs (Bell and Dillworth 1997). In stands that are more complex than typical even-aged stands, the timber type classification may also allow for layers or cohorts of the same or different species. However, timber type assignments can be quite subjective and they stress only commercial components; hence, the true structural differences between some can be quite small and between others quite large. Since structural classification of forest stands is typically done by only average size, density, and species composition, the resulting types are often based on economics or convenience rather than ecological processes (Kimmins 1987, O'Hara et al.1996). Classification of stand structure should be based on objective biological criteria that fit the objectives of forest management. Thus, the first objective of this study was to identify and apply an effective clustering methodology to classify stand structures in mixed-species, multi-aged stands.

In complex stands a biological classification of stand structure must include several attributes to sufficiently identify gradients. Simple species mix, average tree size, and stand density measures do not provide enough information in these forest types. Because much of the diversity in these stands is correlated with the distribution of crown layers, measures of canopy structure can reveal a significant amount of information about complex stand structure (Dubrasich et al. 1997), allowing for a more thorough biological depiction that can be related to numerous forest resources.

Information on general classification of stand structural gradients has apparently enjoyed limited application or success. Cluster analysis is one nonbiased method which can be used to objectively form groupings based on similarities between variables of interest. However, cluster analysis is not a single, standardized procedure with well laid-out rules; hence, numerous possible pathways for analysis are apparent (Anderberg 1973). Four key decisions that have to be made for an effective cluster analysis include: 1) selection of variables on which the classification is based, 2) selection of cluster analysis method, 3) identification of the desired number of clusters, and 4) interpretation of the groupings. Since the combination of variable sets, clustering methods, and number of clusters creates an almost infinite number of possibilities, these combinations have to be reduced to a reasonable set given the problem at hand. In this application, possibilities were eliminated through literature review or exploratory analyses of widely varying combinations. The final evaluation of clustering efficacy was based on a reduced set of possibilities to allow some comparison of relative performance.

Due to the subjectivity involved in cluster analysis procedures, and the difficulty in interpreting the results, a single category of stand attributes was selected to evaluate performance. Specifically, different attributes of the crown area profile (Dubrasich et al. 1997), were selected from the perspective that they embodied many important ecological attributes of the stands that controlled the dynamics of such resources as wildlife habitat and timber volume. In essence, crown area profile depicts the cross-sectional area of all live crowns within the stand at 1-ft height intervals.

Although these crown area profiles have biological appeal, there is also a need to classify stands quickly through standard inventory data. Discriminate function analysis was performed by incorporating more common structural variables into the classification process, facilitating grouping of stands into the original types based on crown area profile. Various combinations of structural variables were tested to determine which set provide the best discriminating power for classifying new stands into crown area profile types.

1.3 Objective 2

To realize the full benefit of the classification developed, the stand types identified must be fully characterized and differentiated from each other with respect to many attributes. This differentiation can be accomplished by summarizing important and distinguishing features through the average and variability of size, density, crown structure, and growth characteristics.

In multiple-objective forestry (i.e. balancing timber production, wildlife habitat, aesthetics, diversity, etc.) a significant amount of information is required to sufficiently characterize stand value. The complex structures of mixed-species, multi-cohort forests are particularly difficult to quantify. Canopy structure is one attribute that can reveal a significant amount of information about mixed-species, multi-cohort stands in a multiple-objective context. Dubrasich et. al (1997) computed crown area profiles (cross-sectional crown area per relative stand height) and porosity measures (between crown open space) to characterize complex stand structures in southern Oregon. They found these profiles to be useful tools in comparing stands and describing wildlife habitat potential. These canopy measures combined with simple structural indicators can help evaluate and distinguish between the composition of various complex stand types.

One primary concern on commercial forestland is achieving the balance between timber production and wildlife habitat requirements. Structural differences and growth trends for stands could provide managers with information needed to design residual stand structures. Species diversity and composition, plant density, foliage density, horizontal foliage diversity, pore space distribution, canopy volume, and degree of canopy closure are all important dimensions of wildlife habitat. If a biologist had reliable information about how these components differed between stands, for example, then sound judgements could be made with respect to providing habitat on a landscape level.

The second objective of this study was to characterize the stand structure types identified in the first part. Three categories of attributes were regarded as most important for making silvicultural decisions in the target mixed conifer forests: 1) size class distribution and density, 2) canopy structure, and 3) growth dynamics.

1.4 Past Work - Vegetation Classification

The objective of vegetation classification is to identify distinct groups of vegetation units or communities that are sufficiently homogeneous to allow reliable statements about a group's general vegetative structure. Classification infers that natural groupings do exist and are distinct enough to justify partitioning of gradients in structure and composition (Kimmins 1987).

Vegetation classification can be approached several different ways. Three primary methods are: 1) dominance type, 2) habitat type, and 3) physiognomic classification. Each method requires different approaches and different vegetation information. Ultimately, the classification should be driven by management goals and objectives.

Dominant vegetation typing was a standard practice early in forest classification. This classification was based solely on dominant species or forest cover type, dominance being defined primary by size or density (Kimmins 1987). These systems were primarily implemented to get a measure of the presence or absence of an economically important tree species (O'Hara et al. 1996). Dominant vegetation classification leads to easy implementation and understanding since usually a single easily-identifiable species is the focus of the typing efforts. The drawback to this method is that a significant amount of information about a forest system is unknown and actual biological processes are ignored (Wellner 1989). This is especially true as the structural complexity of a stand increases, since dominant cover types may be reveal little about actual structure or ecosystem processes.

Daubenmire's habitat type system was one of the first vegetation classification methods applied to Northwest forests. This system involves initial grouping based on overstory composition, with subsequent grouping by dominant understory vegetation. The assumption in this system is that the vegetation patterns over time are moving toward a stable climax plant association. (Daubenmire 1952, Daubenmire and Daubenmire 1968). The resulting classes are named for the dominant overstory/understory combination and identified by various indicator species. One difference between this system and dominant typing is that habitat classification is based on potential vegetation rather than current vegetation, thus placing significance on the climax species rather than early seral stages. A shortcoming of habitat typing is that it assumes the climax community will eventually succeed and become stable in the ecosystem, which may be an arbitrary assumption (Pickett and McDonnell 1989, Sprugel 1991). A development towards an actual stable climax community is often rare because of natural disturbance patterns (fire, insect and pathogen outbreaks) or management activities (fire suppression, harvesting). In addition, the stand information available from a habitat typing is often too general to make sound management decisions.

Physiognomic classification can be based on simple life form or direct description of vegetation structure. Classification by vegetation structure was first discussed by Kuchler (1947) and subsequently improved by Dansereau (1951, 1957). Both characterized vegetation using six components: growth form, size, species, leaf shape and size, leaf texture, and ground coverage. These attributes lead to categories which were subsequently characterized by a descriptive formula and diagrams of vegetation structure. A similar approach was applied in tropical forest description and classification with profile diagrams to deal with the extreme complexity of these forests (Davis and Richards, 1933 and 1934). This method depicted vertical structure and differentiation along environmental gradients. Others have used a physiognomic approach to describe various stand developmental stages in the Pacific Northwest (Thomas 1979, O'Hara et al. 1990, Oliver and Larson 1990). The shortcomings of some of the above approaches were that they incorporated only one structural dimension or do not include enough components such as crown structure to adequately distinguish the biological differences among complex forests stands.

This project took a physiognomic or stand structural approach to classifying forest stands. However, this study incorporated more detailed aspects of size, density, species, and vertical canopy structure to quantitatively determine natural groupings of stands.

1.5 Setting

Groupings developed under objective classification criteria should reflect natural classes, but end-use application must also be considered. While this project attempts to classify stands on a biological structural basis, the context of the classification, including both data available and intended application should be kept in mind.

The plot data analyzed were sampled from industrial forest land where primarily single tree or group selection methods are applied. Between natural ecosystem dynamics and legacies of past management, these forests have evolved into a very complex state of numerous size classes, high species diversity, and highly variable distribution of canopy layers. Effective forest management requires that a multitude of factors be evaluated before silvicultural strategies can be implemented on these lands. Simple volume or basal area estimates do not provide adequate information to make informed silvicultural decisions particularly in multi-resource management of these complex stands. Of particular concern for industrial-based forestry in these areas is the ability to harvest profitably while keeping stands productive and meeting stand structural regulations for wildlife habitat; hence, accurate but streamlined stand structural characterization is essential. Currently, the stands are classified by size, density, and dominant species component. Although this typing is easily determined from an inventory cruise, it lacks the information to further depict differences among structural types in these forests.

A basic principle of forest management is that a good silvicultural prescription leaves the stand in better condition after treatment than prior to entry. Continued productivity in these mixed-species, multi-aged stands is essential for sustainable forestry. A stable, continuous flow of timber under uneven-aged management is assumed to be obtained over repeated cutting cycles. This sustained productivity may not always be the case since stagnant clumps of trees, often interrupted by skid trails, are frequently left in the residual stand and, hence, contribute to the complex nature of these stands. Continued productivity of the stand relies on a strong response of the residual trees after each entry. However, it is uncertain how different components of the residual stand respond to harvest entries. This response will depend on pre-cut structure and post-harvest structure, and will be partly addressed by looking at relative volume growth among different structural groups.

Wildlife habitat assessment also require more accurate portrayal of stand structure and its variation across the landscape. Meeting habitat regulations requires some insight into crown structural attributes that are correlated with other stand structural features. These could include measures of crown closure, canopy layering, as well as overall size and density. A classification that provides the necessary structural information and allows for quick evaluation of forested landscapes can is urgently needed.

2 An Approach to Biological Classification of Stand Structure using Cluster Analysis

2.1 Introduction

Forest management necessitates classifying stands into structural types, despite the fact that stand structure varies continuously with respect to various key attributes. These key attributes of stand structure, from a forest management perspective, include but are not limited to: species composition, size distribution, and relative density (Oliver and Larson 1996, O'Hara et al. 1996). Other attributes such as vertical complexity, canopy structure, or vertical foliage distribution are assumed to be correlated with other more easily measured tree and stand dimensions.

The need to classify stands into structural types arises from such activities as spatial analysis of landscapes for wildlife habitat diversity/juxtaposition, timber supply analysis/forecasting for large geographic areas, establishment of targets and monitoring attainment of historical range of variability, and expedient assessment of various non-timber values for landscapes representing entire ownership or parts of ownerships. Stands traditionally have been assigned to timber types based on species composition, average tree size, and some measure of density such as crown closure to facilitate classification from aerial photographs (Bell and Dillworth 1997) . In stands that are more complex than typical even-aged stands, the timber type classification may also provide for layers or cohorts of the same or different species. Timber type assignments can be quite subjective, and the true structural differences between some can be quite small and between others quite large. Since structural classification of forest stands is primarily done with only average size, density, and species composition, the resulting types are often based on economics or convenience rather than ecological processes (Kimmins 1987, O'Hara et al. 1996). There is a need for an objective classification of stand structure based on biological criteria that also fit the objectives of forest management.

In complex mixed-species, multi-cohort stands a biological classification of stand structure must include numerous attributes to sufficiently identify differences among structural types. Simple species mix, average tree size, and density measures do not provide enough information. Because much of the diversity in these stands is represented in the vertical distribution of crown layers, and because this distribution has important implications for many resources, a measure of canopy structure can reveal a significant amount of information about stands (Dubrasich et al. 1997),. Thus, incorporating canopy diversity allows for a more thorough depiction of biologically relevant aspects of stand structure.

Cluster analysis is a multivariate technique which can be used to reveal natural groupings based on similarities between variables of interest (Johnson 1998). Numerous methods of cluster analysis have been proposed, and determining which are appropriate for use in stand structural forest classification can be challenging. When standard Euclidean distance is applied to measure dissimilarities between observations, the hierarchical clustering method is generally the preferred procedure and the most widely available in statistical computer packages (Anderberg 1973, Johnson 1998). Under this category of cluster analysis are numerous algorithms, the primary ones being single-linkage, complete-linkage, minimum variance, and average linkage. Even a brief literature review reveals that there is not a widely accepted set of algorithms by which to identify natural groupings in a data set (Anderberg 1973). For cluster analysis to be valid it should be able to recover the cluster types suspected to be present by field intuition and recognized to be useful given the intended application. If the clustering criteria and clustering method are not a match then the grouping or cluster classification will be distorted (Milligan 1981). Objective classification techniques (for example, cluster analysis) to identify stand structural types has apparently experienced limited application or success. The objective of this paper is to identify and apply an effective clustering methodology for classifying stand structures in mixed-species, multi-aged stands.

2.2 Study Area and Data

This study was conducted on commercial forestland located in the Klamath River basin and Scott Valley in northern California (approximately 42° 25' N latitude, 122° 45' W longitude). The land base ranges in elevation from approximately 3000 to 6000 feet, annual average precipitation varies from 25 to 45 inches, the average frost-free period is about 125 days, and the average July maximum and January minimum temperatures are 85°F and 12°F, respectively.

The soils vary but typically are a gravelly loam or gravelly coarse sandy loam, being low to moderately deep and well drained. The stands investigated represent a typical industrial land base, and the stands have received repeated stand entries. As a result, this ownership contains stands of widely varying and complex structure. The forests in this area include several major tree species and cover a wide range of size classes, and application of a single tree selection system has resulted in a diverse range of vegetation structures. The primary conifer species are *Pseudotsuga menziesii* (Douglas-fir), *Abies concolor* (white fir), and *Pinus ponderosa* (ponderosa pine), while secondary conifer species include *Abies magnifica* (red fir), *Calocedrus decurrens* (incense cedar), and *Pinus lambertiana* (sugar pine). For this analysis, the collection of "other conifers" will include red fir, incense cedar, sugar pine, and Jeffrey pine (*Pinus jeffreyi*), while hardwoods mainly include *Quercus kelloggii* (California black oak), *Quercus chrysolepis* (canyon live oak), *Arbutus menziesii* (Pacific madrone) and *Quercus garryana* (Oregon white oak) (Randall et al.1994).

Temporary plot data for 783 stands were summarized at the stand level. A majority of the stands were mixed-species, multi-cohort stands representing approximately 50,000 acres of managed timber land. The original plot data included species, dbh, total height, and crown ratio for each tree. These data were collected from randomly located variable-radius plots. Stand -level data were summarized by the CACTOS growth and yield model into diameter classes (2-6, 6-10, 10-14, 14-18, 18-22, 22-26, 26-30, 30-34, 34+ (inches)). Several stand-level structural variables were then computed from these summaries to further quantify stand structure. During plot measurement the stands were classified into traditional timber types based on tree size, density, and major species. Table 2-1 summarizes the average attributes and their standard deviations for all 783 stands.

Table 2- 1– Average, standard deviation, and range of five standard attributes for 783 stands

	Average	Standard deviation	Range
Basal Area (sq. ft/acre)	87.48	45.11	10 - 373
Trees/acre	199.63	120.24	3 - 1014
Quadratic Mean Diameter (in.)	9.78	3.55	4 - 29
Stand Density Index	144.36	66.89	13 - 503
Average Height (ft.)	74.38	17.30	31 - 148

2.3 Analysis Methods

Cluster analysis is not a single, standardized procedure with well laid-out rules; hence, numerous pathways for analysis are possible (Anderberg 1973). Four key decisions that have to be made in cluster analysis include: 1) selection of variables on which the classification is based, 2) selection of cluster analysis method, 3) identification of the desired number of clusters, and 4) interpretation of the groupings. Since the combination of variable sets, clustering methods, and number of clusters creates an almost infinite number of possibilities, these combinations have to be reduced to a reasonable set given the problem at hand. In this application, possibilities were eliminated through literature review or exploratory analyses of widely varying combinations. The final evaluation of the clusters presented below was performed on the reduced set of possibilities to allow some comparison of relative performance.

Because of the subjectivity involved in cluster analysis procedures, and the difficulty in interpreting the results, a single stand attribute was selected to evaluate performance. This stand attribute, crown area profile (Dubrasich et. al 1997), was selected from the perspective that it embodies many important ecological attributes that are important in the context of many forest resources, including wildlife and timber. Crown area profile is a representation of the cross-sectional area of all live crowns within the stand. Crown area profiles were computed by 1-ft intervals to provide representation of structure in the target population.

Although these crown area profiles have biological appeal, there is also a need to be able classify stands with standard inventory data. Thus, discriminate function analysis was also performed by incorporating more conventional structural variables that would be readily available for classification of new stands into the original groupings based on crown area profile. Various combinations of structural variables were tested to determine the set providing the best discriminating power for assigning new stands to a crown area profile type.

2.3.1 Variable selection

Variable selection is an important first step in cluster analysis, both in regard to the total number of variables selected and the types and grouping of variables retained. If several variables measuring the same factor are included in the analysis then that element may have a greater influence in the resulting clustering if other general factors are not represented equally (Anderberg 1973). The balance of influence among potential factors in complex mixed-species, uneven-aged stands has not been extensively explored. To a certain extent, the clustering variables should be related directly to the purpose to which the resulting classification will be directed. Because most of the primary resources of interest in the current application are related directly to crown and canopy structure, variables describing crown area profiles were selected as the basis for clustering. Several sets of variables were tested to determine which resulted in the best separation and groupings of the crown area profiles by minimizing the within cluster variation.

The five sets evaluated are defined in Table 2-2 below. CAP20 is the stand crown area summed on a 20- foot height interval basis by the five major species groups –ponderosa pine, Douglas-fir, white fir, hardwood, and other conifer. Crown closure is the stand crown closure by species (same species grouping just described). Crown volume is the stand crown volume by species. V_CAP and V_SPCAP are the variances of the stand crown area profile across species and variance of crown area profile by species, respectively.

Table 2- 2 – Description of variable sets used in cluster analysis

Variable set	Description
CAP20	Crown area by 20 ft. height intervals by species
CC	Crown closure by species
CV	Crown volume by species
V_CAP	Variance of crown area profiles
V_SPCAP	Variance of crown area profiles by species

Preliminary analysis indicated that Ward's clustering algorithm was one of the more promising algorithms and that approximately 10 clusters would meet the intended application, hence, this algorithm and number of clusters were held constant during variable subset selection.

Two procedures were used to determine the influence of each variable. First, boxplots of each variable by cluster were analyzed. This showed the distribution of the stands (observations) by cluster with respect to each variable. The goal here was to get a quick estimate of variables maximizing separation of observations into clusters. The greater the separation between clusters the more discriminating power the variable has in assigning stands to clusters. This procedure narrowed the possible sets of variables down to five, then further testing was performed to reduce the pool of choices; specifically, within-cluster variation was computed to indicate the degree of variability and consistency within clusters. The weighted, mean coefficient of variation of crown area at each height interval proved effective for measuring relative variability. The coefficients of variation were weighted by the number of stands (observations) in each cluster.

2.3.2 Clustering method selection

Numerous methods have been applied to calculate distance matrices and to form clusters (Johnson 1998). The selected method should be appropriate for identifying the expected groupings in the data (Anderberg 1973). Euclidean distance is the most common approach for measuring dissimilarities between observations and is the most widely available measure in statistical computer packages (Anderberg 1973, Johnson 1998). Hierarchical agglomerative clustering methods have been grouped into four major categories: single-linkage, complete-linkage, minimum-variance, and average linkage (Pielou 1984).

Prior knowledge of stand structural classification by cluster analysis was limited, so an arbitrary number of clusters and variable sets identified in the previous step were chosen to evaluate differences between methods. In an effort to match characteristics of the algorithm and the type of data and intended application, the methods were narrowed down to six possibilities: single-linkage, centroid, complete-linkage, Ward's minimum-variance, flexible-beta, and average linkage. This range of algorithms covered the variety of available algorithms and have been previously applied for specific objectives.

In single-linkage and complete-linkage the two clusters to be joined at any step are ascertained exclusively by the distance between two individual observations in each cluster. Therefore, a cluster is always depicted by only one of its observations, and this observation is always extreme (either minimum distance for single-linkage or maximum distance for complete-linkage) rather than a characteristic observation from the cluster it represents. For single-linkage this typically results in chaining in which few individual clusters absorb a large proportion of the observations, and objectiveness is lost (Pielou 1984). Milligan (1981) evaluated different clustering methods through Monte Carlo analysis of data containing clusters of known shape and size. Ward's method proved superior for most applications, while single-linkage consistently performed poorly. Average-linkage also performed well, but slightly below Ward's and flexible beta.

Because of the complex structure in mixed-species, multi-cohort stands and known gradients in structural attributes, considerable overlap between clusters was expected; hence, the selected clustering method had to perform well for overlapping clusters in this application. Milligan's (1981) testing showed that Ward's method gave good results with overlapping clusters, while unweighted average-linkage did not. In fact, they recommended that any evaluation of methods include Ward's and unweighted average-linkage algorithms, since these are the most widely used and most widely understood methods.

Formal within-cluster variability facilitated comparison of five methods: 1) complete-linkage, 2) centroid, 3) unweighted average-linkage, 4) flexible beta, and 5) Ward's minimum variance. A promising variable set from the previous step was selected and the number of clusters was set to ten, ensuring consistent comparison between algorithms.

2.3.3 Determining number of clusters

As with selection of both variable sets and the clustering method, determining the optimal number of groupings is very subjective, but should be directed in part by intended application of the resulting classification. Cluster analyses yield a range in the number of clusters from one to the number of observations in the data set. The analyst must make a choice of the number of clusters retained and interpreted (Johnson 1998, Milligan and Cooper 1985). One approach is to maximize the distance between clusters while explaining a significant amount of clustering variation. Although some overlapping of observations between clusters cannot be avoided, an effective cluster analysis will minimize the overlap (Anderberg 1973). However, as the number of clusters decreases the distance between them increases so that if maximizing distance was the only criteria then one or two clusters would be chosen. This result clearly has no practical value for distinguishing observations, and is misleading since prior experience has likely revealed that observations can be grouped. As mentioned above, however, too many groups renders the results impractical for the application since the initial objective usually is to simplify the data.

Four criteria were used to evaluate the optimal number of clusters. These included the pseudo F statistic, pseudo t^2 statistic, cubic clustering criterion (CCC), and R^2 (Johnson 1998). The number of clusters was selected by identifying general agreement among the four statistics. With discrete data, the CCC and pseudo F statistics are expected to increase with the number of clusters, therefore local peaks rather than overall maximums were desired to determine the proper number of clusters. As the number of clusters decreases so does the amount of variation captured by the clustering. Thus, for R^2 the optimal was that number at which fewer clusters resulted in a significant decrease in the amount of explained variation (R^2) (Johnson 1998). Therefore, a combination of the following criteria will result in the optimal number of clusters: 1) local maximum of CCC, 2) local maximum of pseudo F, 3) relatively high R^2, and 4) a small value of the pseudo t^2 followed by a larger value.

2.3.4 Evaluation criteria

After completion of the previous three steps, final evaluation of the cluster analysis was accomplished by both graphical and numerical techniques. Validation and interpretation of any cluster analysis can be difficult because of the subjectivity involved in each step, particularly when several types of variables exist with which to describe the classification. Some of this subjectivity is unavoidable with stand structure classification as well, particularly in these complex stands. Crown area profiles by species served as the primary basis for evaluation of the analysis since they depict the end result of previous stand and crown dynamics, including species composition and relative size distribution, which are the major characteristics of any stand and should help quantify the attributes of those with complex structure. Thus, the final classification was selected to minimize within- and between-cluster variation on the basis of crown area profiles.

Within-cluster variation was measured by the coefficient of variation of crown area among one-foot height intervals. The distance between clusters was also important; however, it is not valid to apply techniques such as ANOVA to test for differences between clusters. Clustering methods maximize the separation between clusters and observations are not assigned randomly to clusters; hence, the assumptions of parametric or nonparametric tests are severely violated (Anderberg

1973). Because alternative tests have some significant shortcomings, discriminate function analysis (Johnson 1998)was applied to evaluate between-cluster variation. Specifically, the misclassification rates in discriminate analysis give a measure of overlap between clusters. The same variables from the corresponding cluster analysis were evaluated in each discriminate analysis.

2.3.5 Relative performance of traditional timber-typing

A measure of the objectivity and relative performance of traditional timber typing was also desired to assess the need for, and efficacy of, the clustering approach developed for the study area. The traditional timber types are based roughly on major species component, size, and density. The performance of assigned timber types was also judged through misclassification rates from discriminate function analysis of the same crown area profile variables.

2.3.6 Classifying new stands

The goal for the landowner is to quantify stand structure based on standard inventory data and to assign new stands to an appropriate structural type. Various combinations of structural variables based on the standard inventory data were input into discriminate analysis to determine the combination that resulted in the lowest misclassification rates. The optimal variable set was then established as the criteria by which newly inventoried stands can be classified.

2.4 Results

2.4.1 Preliminary cluster analysis evaluation

From preliminary evaluation of variable sets, V_SPCAP was eliminated because it resulted in the highest relative variability of crown area profiles (Table 2-3).

Table 2- 3 - Within cluster variability for five alternative variables set based on ten clusters from 783 stands. Ward's method was applied for cluster assignments.

Variable set	Weighted-mean coefficient of variation
CAP20	309.86
CC	313.63
CV	332.45
V_CAP	345.52
V_SPCAP	461.55

Based on CAP20 variable set and ten clusters, the flexible beta and Ward's minimum variance methods exhibited far less within cluster variation than the other methods (Table 2-4).

Table 2- 4 – Within-cluster variability for five alternative clustering algorithms based on ten clusters from 783 stands. Clustering was based on CAP20 variable set.

Clustering Method	Weighted-mean coefficient of variation
Flexible beta	287.55
Ward's minimum variance	309.27
Centroid	488.94
Complete	499.36
Average	502.63

CCC, pseudo F, pseudo t^2, and R^2 revealed no single number of clusters to be optimal (Figures 2-1, 2-2, 2-3, 2-4). Together these statistics seemed to suggest that the appropriate number of classes occurred in a range between about 8 and 25. With respect to R^2 (Figure 2-1) the amount of variation explained by the clustering decreased considerably below 8-9 particularly for the CC -Ward's and CC -flexible beta variable-algorithm combinations. Eight classes were also judged to be minimal for practical application. The gain in explained variation was trivial for each additional cluster in excess of 25. The goal was to reduce the number of classes while explaining a relative high amount of variation.

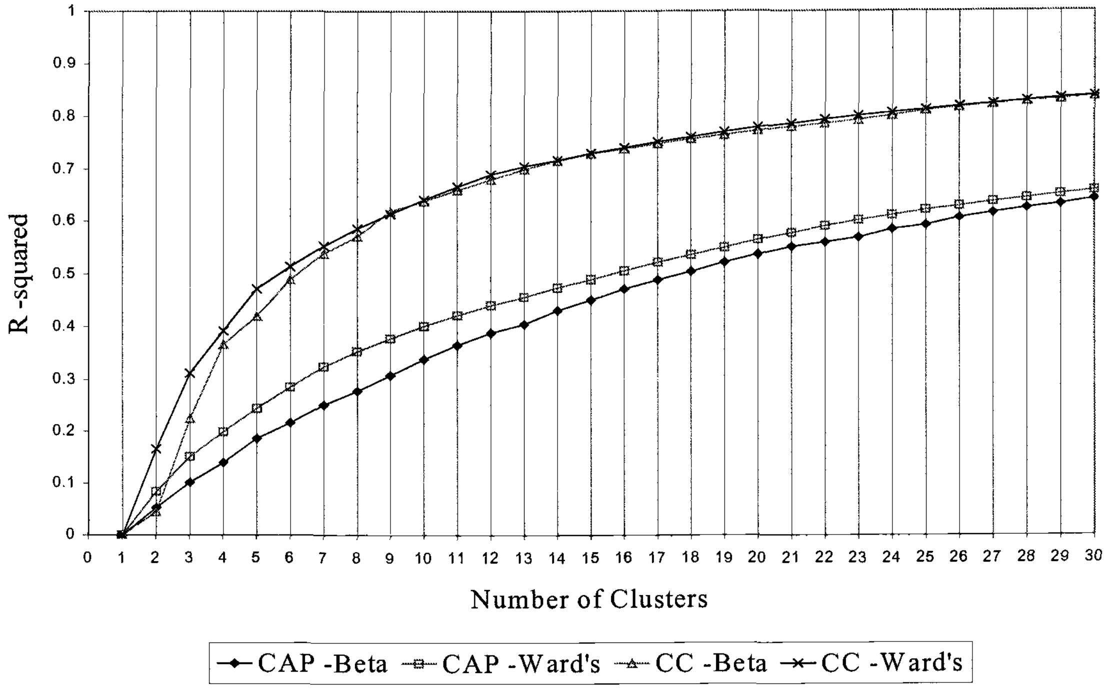

Figure 2- 1 –Proportion of initial variation among stands explained by clustering relative to the number of clusters produced

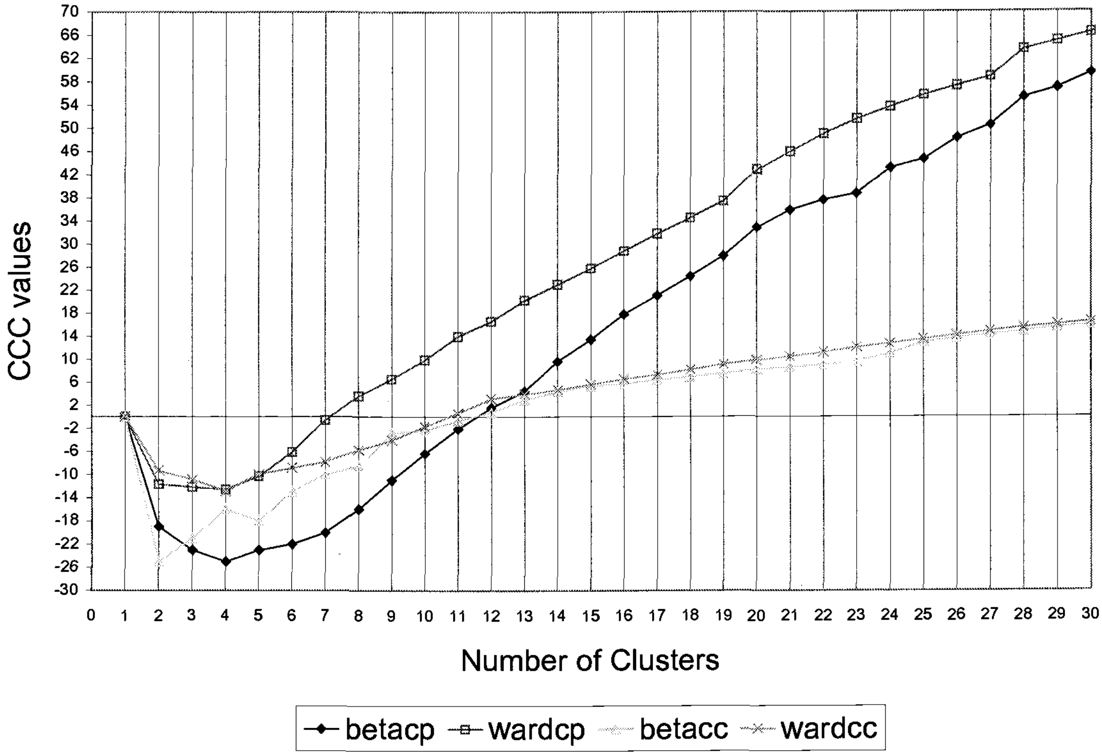

Figure 2- 2 – Cubic clustering criterion statistic for determining optimal cluster number. Appropriate number of clusters are found where local peaks occur.

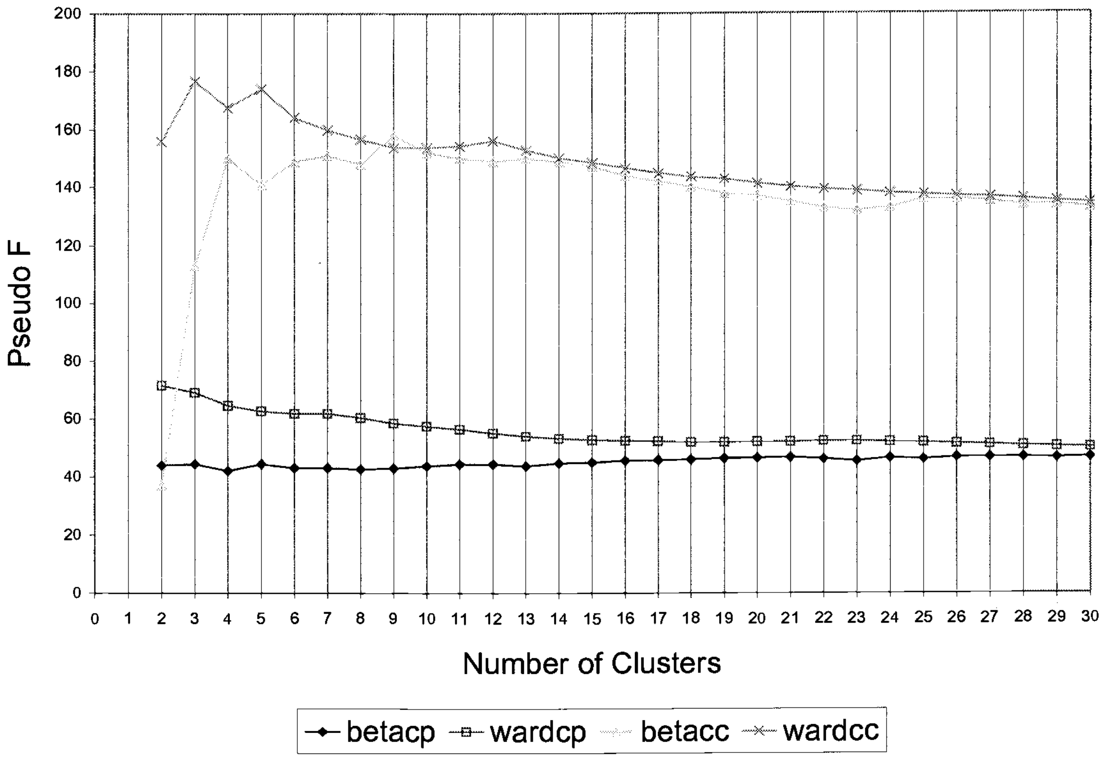

Figure 2- 3 – Pseudo F-statistic for determining optimal cluster number. Appropriate number of clusters are found where local peaks occur.

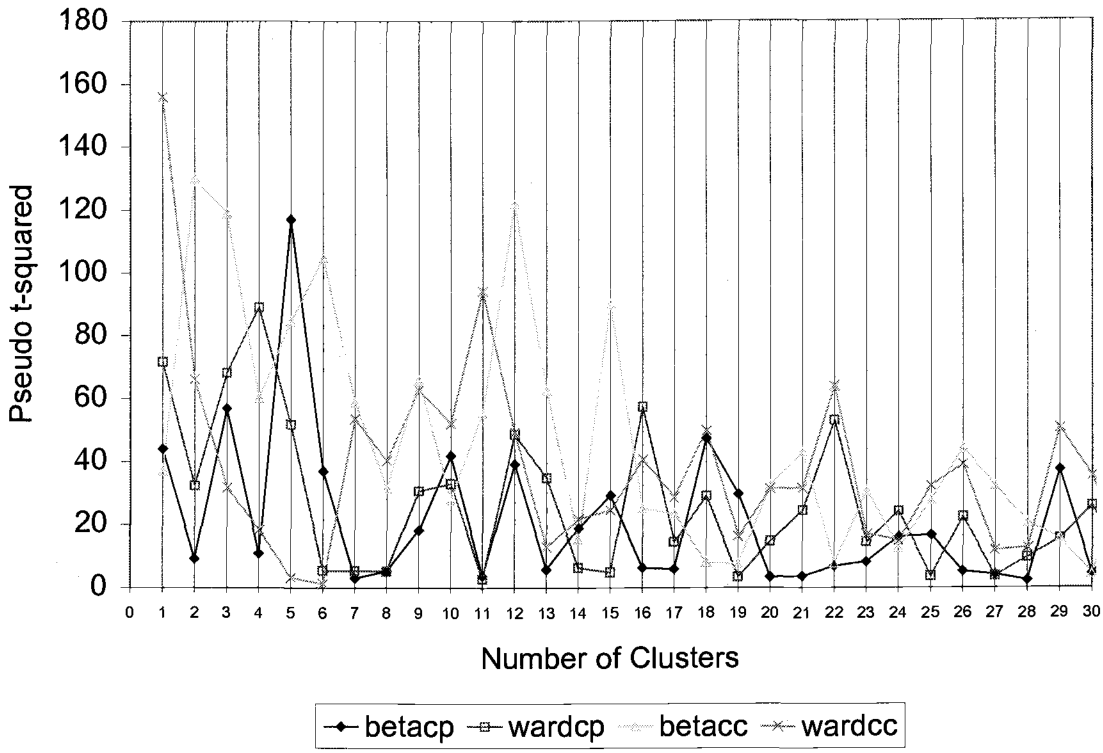

Figure 2- 4 – Pseudo t^2 statistic form determining optimal number of clusters. A small value of this statistic followed by a larger value indicates an appropriate cluster number.

2.4.2 Final Clustering Evaluation

The four top variable sets and two top clustering algorithms were retained in the final evaluation. The flexible beta method with the CAP20 variable set by far minimized within-cluster variation, as measured by weighted mean coefficient of variation (Table 2-5). Cluster overlap as measured by misclassification rates in the discriminate function analysis for the CC -flexible beta method was the lowest (14%), while CAP -flexible beta was the highest at 61% (Table 2-5). The flexible beta method in combination with the CAP20 variable set was selected as the best approach for identifying stand structural types.

Table 2- 5 –Within- and between-cluster variation for six combinations of variable sets and clustering algorithm.

Clustering Scenario	Weighted-mean CV	Misclassification rates by DFA
CAP -flexible beta	227.76	0.6142
CC -flexible beta	285.92	0.1432
CAP -Ward's	309.86	0.2209
CC -Ward's	313.63	0.3181
CV -Ward's	332.45	
CV -flexible beta	333.33	
V_CAP -flexible beta	342.08	
V_CAP -Ward	345.52	

With the optimal classification method and variable set determined, the appropriate number of clusters was reexamined. The four indices (CCC, pseudo F, pseudo t^2, and R^2) could not support or refute any particular number of clusters between 8 and 25. Therefore, the final number of classes remained at 10, from the standpoint of practical consideration and combined assessment by the four indices.

The misclassification rates for the CAP-beta approach indicated similar overlap between clusters as between the traditional timber type assignments using the CAP20 variable set (Table 2-6). Even using standard inventory variables which the timber type were originally based on (% basal area by species –species component, SDI -density, average stand height - average size) to more objectively compare misclassification rates between the two classifications resulted in less overlap for the new clustering approach (Table 2-6).

Table 2- 6 –Misclassification rates for discriminate function analysis of clusters vs. timber types, based on CAP variable set and standard timber type inventory variables.

Classification method	CAP-beta variable set	Standard variables
Timber type classification	62.3%	62.5%
Cluster classification	61.4%	40.1%

2.4.3 Classification of new stands

Final cluster assignments were based on the flexible beta method with the CAP20 variable set, producing 10 clusters. Standard inventory data were analyzed to determine their ability to discriminate among the structural types classified by the CAP-beta classification. Various sets of the inventory variables (Table 2-7) were evaluated to determine the set yielding the lowest misclassification rate. The best set of variables included: 1) Stand Density Index, 2) percent basal area of ponderosa pine, Douglas-fir, and white fir, 3) total crown closure, 4) trees per acre, and 5) average stand height. Approximately 35% of the stands were misclassified, as opposed to 61% based on the CAP20 variable set. Therefore, the standard variable set was retained for computing the final discriminate function for new stand classification.

Table 2- 7 – Means of alternative inventory variables used in discriminate function analysis for new stand classification.

Inventory Variables	Cluster #									
	1	2	3	4	5	6	7	8	9	10
1) Basal Area/ac	76.7	58.1	85.6	101.4	110.5	56.3	74.8	139.0	128.3	162.0
2) Stand Density Index	157.1	234.9	171.8	309.7	219.0	122.1	233.8	220.3	272.8	162.4
3) Trees per Acre	10.0	6.9	10.2	8.3	11.0	10.4	8.1	12.2	10.4	14.9
4) Quadratic Mean Diameter	126.5	108.1	142.9	174.8	179.8	93.0	134.0	212.7	211.6	210.8
5) Total Stand Height	55.1	46.3	53.5	56.1	57.8	51.9	45.2	79.7	57.7	176.5
6) Variance of Total Height	75.1	61.4	68.8	65.4	79.8	72.0	67.1	87.1	83.8	115.1
7) Variance of Average DBH	797.1	614.3	587.2	772.3	814.5	702.1	729.5	844.7	908.1	1741.8
8) %Basal Area-ponderosa pine	20.3%	44.3%	22.9%	37.7%	40.4%	6.1%	14.2%	2.8%	10.8%	3.8%
9) %Basal Area-Douglas-fir	44.3%	32.2%	30.1%	23.1%	33.8%	26.4%	64.0%	29.7%	66.4%	48.4%
10) %Basal Area-white fir	15.2%	5.2%	11.0%	3.7%	9.2%	54.6%	9.1%	48.8%	9.3%	27.9%
11) Total Crown Closure(%)	50.1%	42.7%	52.9%	68.2%	67.6%	40.0%	61.5%	88.0%	93.9%	85.8%

2.5 Discussion

The goal of this research was to objectively classify complex stands on a structural basis. Crown area profiles by species was the criterion selected to portray the structural complexity of stands in a manner relevant to most if not all forest resources. Crown area profile depicts the composite result of the major structural aspects of a stand: crown/canopy structure, species composition, size distribution, and stand density.

Crown area profiles, when broken down into vertical strata, depict the diameter and height distributions of the stand (for example, if a significant amount of crown area occurs under 30 ft., the stand has a significant small size class component). When broken out by species, crown area profiles portray species composition, including the vertical distribution of species (for example, white fir occupies a majority of the crown area under 30 ft. and, hence, is a key understory component).

Stand structure relates directly to fundamental forest resources that are the targets of multiple-objective forestry (O'Hara et al. 1994). Overall stand and canopy structure are important determinants of wildlife habitat. Many animal species require specific structural features (such as multi-species canopies, a few large overstory trees, etc.) (Hayes et al. 1997, Hayes et al. 1998), which can be assessed with crown area profiles. In addition, features such as microclimatic and hydrological properties of forest stands can be evaluated given crown structure (Kimmins 1987, Russell et al. 1989) information provided by the profiles. Factors influencing natural regeneration dynamics are controlled directly by crown dynamics: light distribution to the understory, seed fall, physiological features of various species, etc. (Smith 1997) . Finally, if related to growth mechanisms, these profiles imply the potential for timber production.

Crown area profiles, however, do not necessarily capture all of the characteristics of stand structure. The horizontal spatial arrangement of trees is largely ignored. The arrangement of trees can be clumpy, regular, or a combination of both. Also, the profiles are simply a static representation of stand structure. Forest stands are constantly changing, and how well crown area profiles capture the past and potential dynamics of stands is difficult to interpret. The information contained in the profiles may be enhanced when combined with information on how stands develop into other structural types including those that may not be not represented in the current data. Finally, it is unknown how difficult it is silviculturally to maintain or create certain structural types. Harvesting costs, regulations, and changes in current markets and policies all play a role in determining desired stand structures and the ease of obtaining them.

One type of classification can not necessarily provide all of the information needed to manage for multiple-resource objectives (Kimmins 1987). Oliver and Larson (1996) developed a system to describe stand development through four structural stages. O'Hara et al. (1996) further quantified these developmental stages for northwest forest vegetation classification. These systems use a stand dynamic or developmental approach to forest classification rather than quantifying stand structure in a static state. Some typings may provide more specific data on a single management objective, such as timber or wildlife habitat, but not both. Timber type classification based on predominant species (Bell and Dillworth 1997), along with rough average size and density estimates do not integrate enough structural features to evaluate other forestry objectives. In addition, timber type classification applied in mixed-species forests can result in a large number of classes due to the numerous combinations of species mixes, densities, and average sizes in stands. For example, under the current approach the land base used in this study has over thirty different types, which includes only overstory typings (many more combinations exist when understory structure is considered). This leads to difficulty when making broad-based land management decisions. Other typings may be broad-based enough to provide information to serve numerous management purposes or goals. O'Hara et al. (1996) advocate a integrated, biologically-based classification system representing ecological conditions and processes that can be flexible for multiple forestry objectives.

To realize the full benefit of any stand structural classification, the stand types created must be characterized and fully differentiated from each other with regard to their desirability to meet a given resource objective. The classes therefore acquire value only after summarizing important distinguishing features from which managers can infer mean size, density, crown structure, and growth, as well as their variability.

3 Characterization of Stand Structural Types Identified Through Cluster Analysis of Crown Area Profiles

3.1 Introduction

In multiple-objective forestry a significant amount of information is required to characterize stand features pertinent to the resources being managed (for example, timber, wildlife habitat, aesthetics, diversity, etc.). This information need is especially critical in mixed-species, multi-cohort forests where complex structures are difficult to describe with only a few indices. If structural differences are to be recognized between these complex stand types, numerous stand dimensions must be included. Simple species mix, density, and average size variables are often not enough to sufficiently detect differences between these stands, and they do not provide enough information to evaluate success in meeting multiple objectives. Canopy structure offers an unusually large amount of multi-resource information about mixed-species, multi-cohort stands. For example, complex stand structures in southern Oregon have been characterized with crown area profiles (cross-sectional crown area at different heights within the stand) and porosity measures (between crown pore space) (Dubrasich et. al 1997). These canopy measures incorporate important information that is relevant to virtually any forest resource that may be the target of management in complex stand types.

One primary challenge on commercial forestland is balancing timber production with wildlife habitat requirements. In mixed-species, multi-aged stands structural differences have clear implications for growth potential and, hence, growth expectations for a given residual structure. Growth and yield models sometimes fall short of accurately predicting growth because too little information is available for detailed stand characterization. Likewise, models often do not summarize enough information to properly assess wildlife habitat directly. The structural makeup of a stand including species diversity and composition, plant density, foliage density, vertical and horizontal foliage diversity, pore space distribution, canopy volume, and degree of canopy closure, are all important dimensions of animal habitat. If a biologist had some information about how these components differed between stands and landscape, then sound judgements could be made with respect to potential wildlife habitat at both the stand and landscape levels.

To plan efficiently, managers have to group stands with characteristics that are similar relative to the resources of concern. The objective of the initial phase of this study was to objectively classify complex mixed-species, uneven-aged stands through cluster analysis. The next step, and the objective of this chapter was to more fully characterize the clusters from a variety of perspectives. Three categories of attributes important to making silvicultural decisions were analyzed for each structural type: 1) size distribution and density; 2) canopy structure; and 3) growth.

3.2 Study Area and Data

This study was conducted on commercial forestland located in the Klamath River basin and Scott Valley in northern California (approximately 42° 25' N latitude, 122° 45' W longitude). The land base ranges in elevation from approximately 3000 to 6000 feet, annual average precipitation varies from 25 to 45 inches, the average frost-free period is about 125 days, and the average July maximum and January minimum temperatures are 85°F and 12°F, respectively. The soils vary but typically are a gravelly loam or gravelly coarse sandy loam, being low to moderately deep and well drained. The stands investigated represent a typical industrial land base, and the stands have received repeated stand entries. As a result, this ownership contains stands of widely varying and complex structure. The forests in this area include several major tree species and cover a wide range of size classes. These stands have been primarily harvested through single tree selection methods resulting in a diverse range of vegetation structures. The primary conifer species are *Pseudotsuga menziesii* (Douglas-fir), *Abies concolor* (white fir), and *Pinus ponderosa* (ponderosa pine), while secondary conifer species include *Abies magnifica* (red fir), *Calocedrus decurrens* (incense cedar), and *Pinus lambertiana* (sugar pine). For this analysis, the collection of "other conifers" will include red fir, incense cedar, sugar pine, and *Pinus jeffreyi* (Jeffrey pine), while hardwoods mainly include *Quercus kelloggii* (California black oak), *Quercus chrysolepis* (canyon live oak), *Arbutus menziesii* (Pacific madrone) and *Quercus garryana* (Oregon white oak) (Randall et al.1994).

Temporary plot data for 783 stands were summarized at the stand level. A majority of the stands were mixed-species, multi-cohort stands representing approximately 50,000 acres of managed timber land. The original plot data included species, dbh, total height, and crown ratio for each tree. These data were collected from randomly located variable-radius plots. Stand -level data were summarized by the CACTOS growth and yield model into diameter classes (2-6, 6-10, 10-14, 14-18, 18-22, 22-26, 26-30, 30-34, 34+ (inches)). Several stand-level structural variables were then computed from these summaries to further quantify stand structure. Crown attributes were computed based off crown width equations from the general study area. During plot measurement the stands were classified into traditional timber types based on tree size, density, and major species. Table 3-1 summarizes the average attributes and their variability for all 783 stands sampled with temporary plot data.

To aid in the growth analysis phase of the study, various growth components were computed from permanent growth plot data. This data base contained 49 0.1- or 0.2-acre fixed-radius plots representing the same geographic region and structural conditions as the temporary plots described above. Dbh, total height, and crown ratio were recorded for each species. Volume periodic annual increments were computed for a single 7-year growth interval (1991-1997). Table 3-2 summarizes the initial (1991) conditions for the 49 plots.

Table 3- 1 – Average, standard deviation, and range of five standard attributes for 783 stands

	Average	Standard deviation	Range
Basal Area (sq. ft/acre)	87.48	45.11	10 - 373
Trees/acre	199.63	120.24	3 - 1014
Quadratic Mean Diameter (in.)	9.78	3.55	4 - 29
Stand Density Index	144.36	66.89	13 - 503
Average Height (ft.)	74.38	17.30	31 - 148

Table 3- 2 - Average, standard deviation, and range of four standard attributes for 49 permanent plots

	Average	Standard deviation	Range
Trees/acre	347.6	227.7	60 - 945
Basal area/acre (sq. ft.)	119.8	67.9	8.6 - 335.2
Quad. mean diameter (in.)	8.6	3.0	3.4 - 16.4
Stand Density Index	234.0	127.6	24.2 - 587.7

3.3 *Characterization of stand structural types*

3.3.1 Size and density characteristics

Size class distribution is a standard way to evaluate structure in forest stands. Typically this distribution is constructed by presenting the trees per acre by diameter class. Since species composition is a significant classification criterion in these mixed-conifer stands, diameter distributions by species were evaluated for each cluster. The species components were broken up into Douglas-fir (DF), white fir (WF), ponderosa pine (PP), hardwoods (HW), and other conifer (OC), the latter of which primarily consisted of incense cedar, sugar pine, and red fir. These species distributions produced finer, more detailed characterization of stand structure than if all species were lumped. To obtain a more general index of size differences, quadratic mean diameter was also computed for each type. This allowed for a quick look at average size of trees between clusters. Stand Density Index was also tabulated for each cluster, and mean basal area per acre was computed by species provided an illustration of species contribution to stand density within each structural type.

3.3.2 Crown dimensional attributes

Canopy diversity is a very informative structural indicator, especially in complex mixed-species, uneven-aged stands. Several aspects of canopy structure were calculated to condense canopy information into simplified form. First, crown area profiles were constructed by species, showing the amount of cross-sectional crown area at any given height in the stand (Dubrasich et al. 1997). In addition to canopy diversity, crown profiles reveal pertinent information about species, size, and density of stands. Variance of the crown area profiles (variance between heights) was computed to provide a measure of stand complexity; low variances indicating more complexity, while higher variances suggest simpler structures (Dubrasich et al. 1997).

Next, several features quantifying stand pore space distribution were computed. Dubrasich et al. (1997) defined total stand porosity as the amount of stand space (amount of 3 dimensional space below the tallest tree in the stand) unoccupied by crown. In this application, porosity is only the unoccupied space between crowns, and does not include unoccupied space within the crown. In addition to total stand porosity, porosity profiles were plotted, to show the percent of crown pore space at any given height in the stand. Height at minimum areal porosity was also tabulated, which reveals the height of maximum crown closure. Next, the mean range of total porosity was computed. The vertical height of crown within this range gives a measure of uniformity of the distribution of pore space for each cluster. Finally, total crown closure by species was computed as a final method of distinguishing between clusters.

3.3.3 Growth characteristics

Two sources of volume growth measures were used to evaluate relative productivity for the clusters. Permanent growth plots were used to calculate total cubic foot volume periodic annual increment (PAI). Since the permanent growth plots were not part of the classification analysis it was necessary to determine the clusters to which each plot belonged. Results from discriminate function analysis in the original cluster data allowed for classification of new observations. The discriminate function reported previously (chapter 2) resulted in a misclassification rate of 35%, giving the permanent plots an 65% chance of being classified correctly. Once classified, the average volume PAI and standard errors were summarized for each cluster.

Because of the low number of permanent plots (44) and the chance of plots being classified incorrectly, a second type of PAI growth average was calculated to further evaluate the clusters: Scribner board foot volume PAI's predicted by the CACTOS growth and yield model, served as expected productivity estimates for each plot. Means and standard errors within a cluster were also computed for these predicted volume growth rates. Finally, because there is error in growth estimates from both model prediction and the permanent plots, the two methods of volume growth were compared.

3.4 Results

3.4.1 Size and density characteristics

Diameter distributions by species revealed strong differences between the ten stand structural classes. Trees per acre were represented for individual observations (stands) as a percentage of total trees per acre for each particular stand (Figures 3-1 to 3-10).

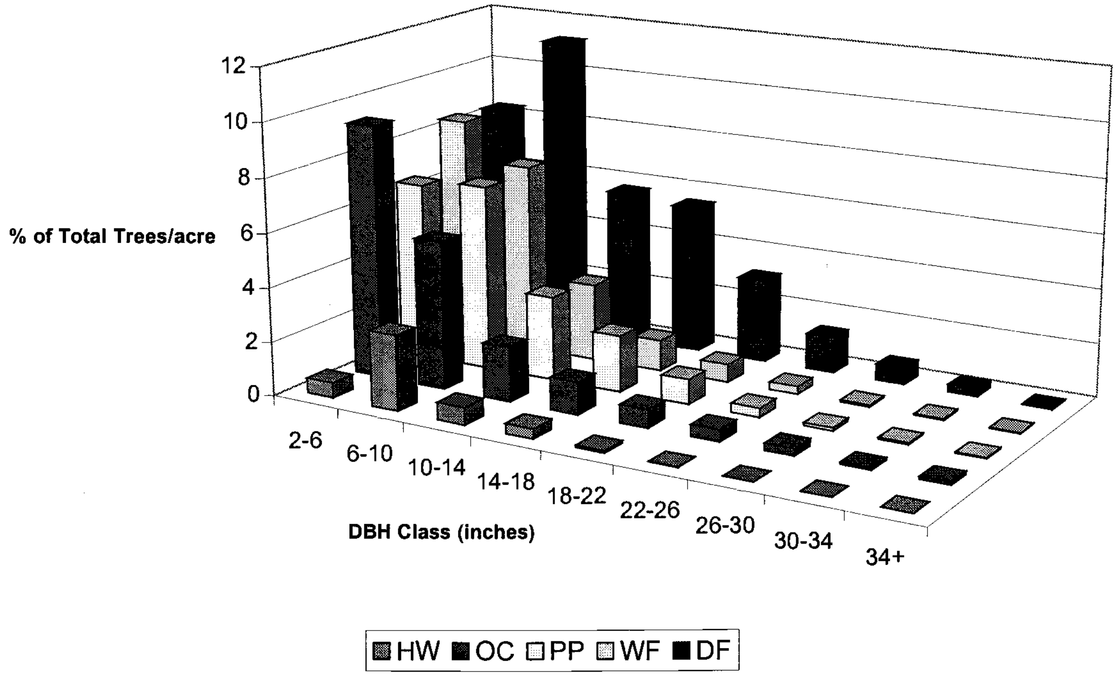

Figure 3- 1 – Relative diameter distribution of plots in cluster #1, by species

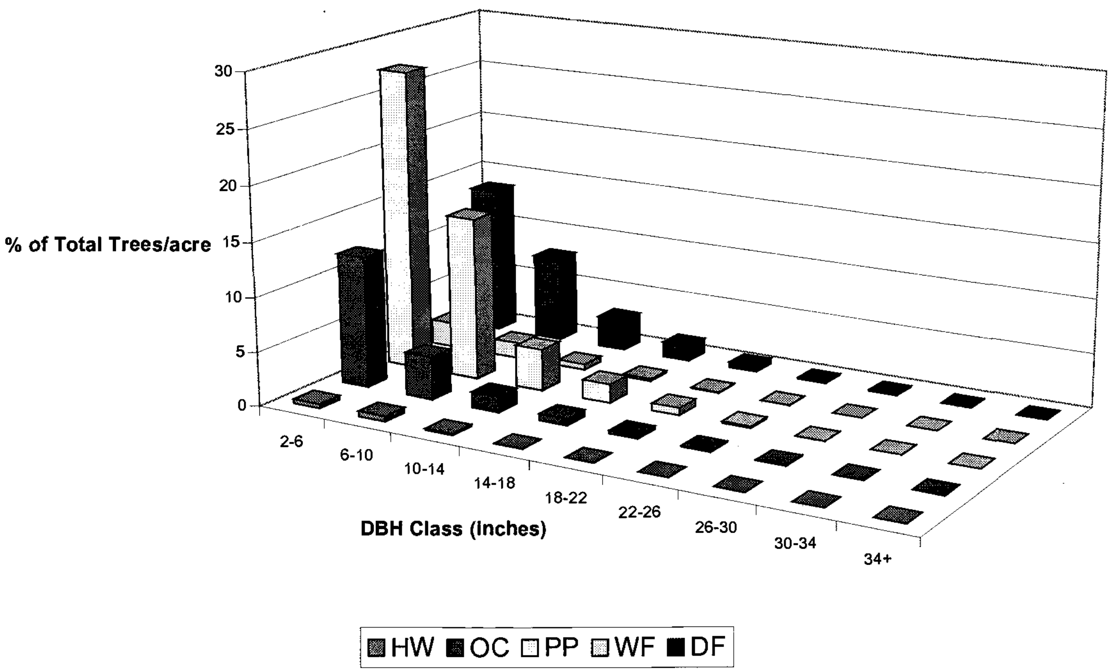

Figure 3- 2 - Relative diameter distribution of plots in cluster #2, by species

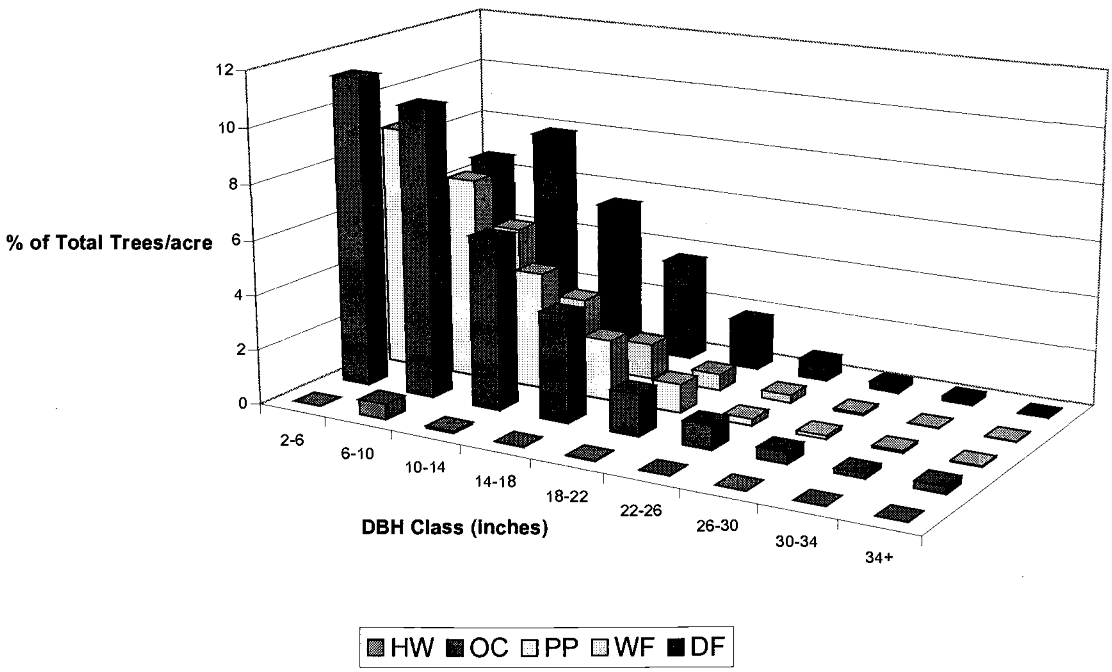

Figure 3- 3 - Relative diameter distribution of plots in cluster #3, by species

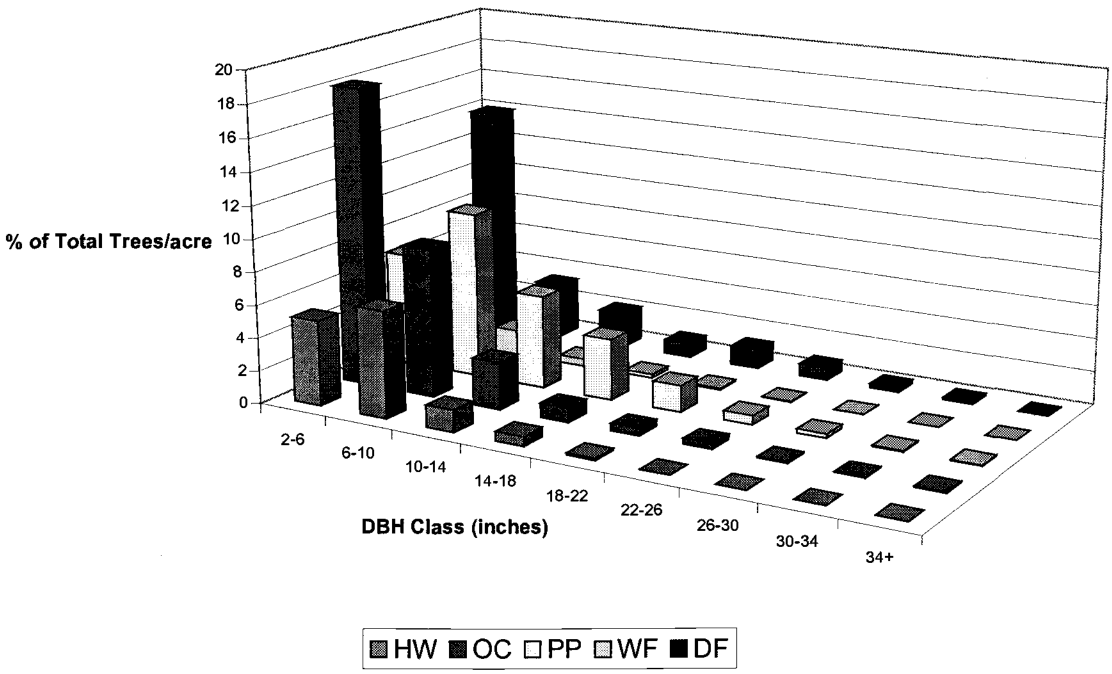

Figure 3- 4 - Relative diameter distribution of plots in cluster #4, by species

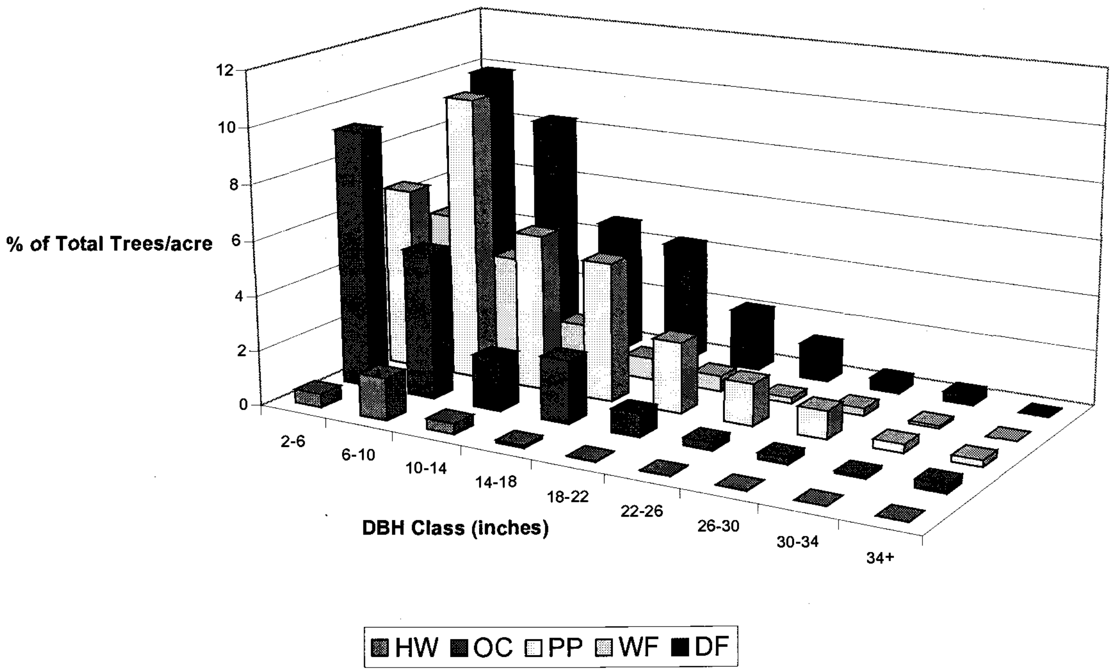

Figure 3- 5 - Relative diameter distribution of plots in cluster #5, by species

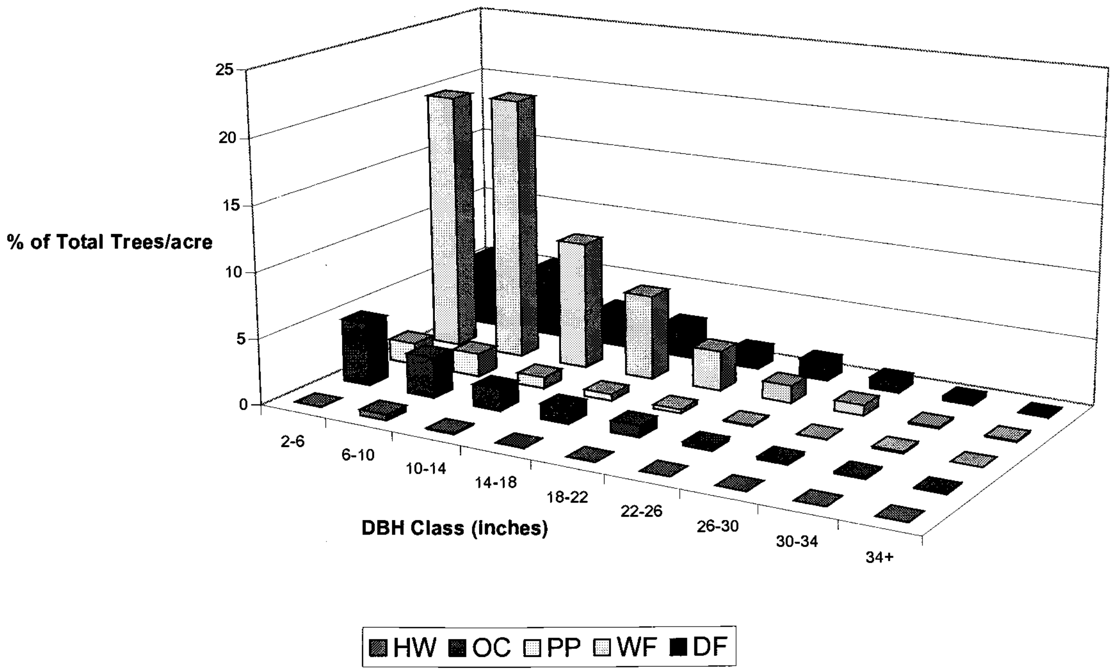

Figure 3- 6 -Relative diameter distribution of plots in cluster #6, by species

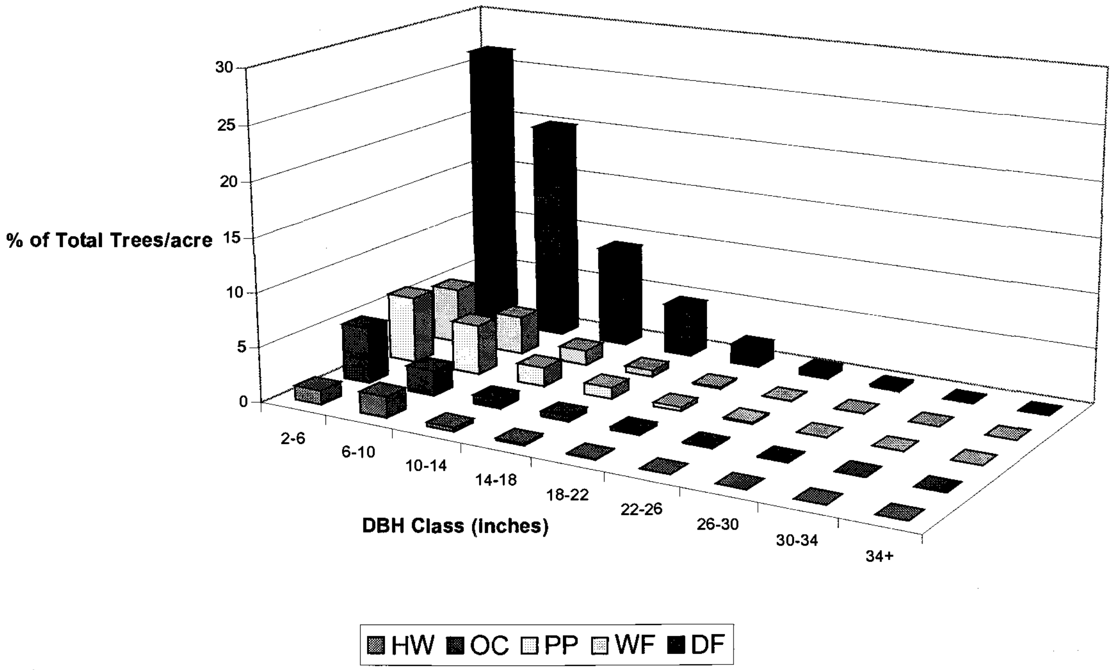

Figure 3- 7 - Relative diameter distribution of plots in cluster #7, by species

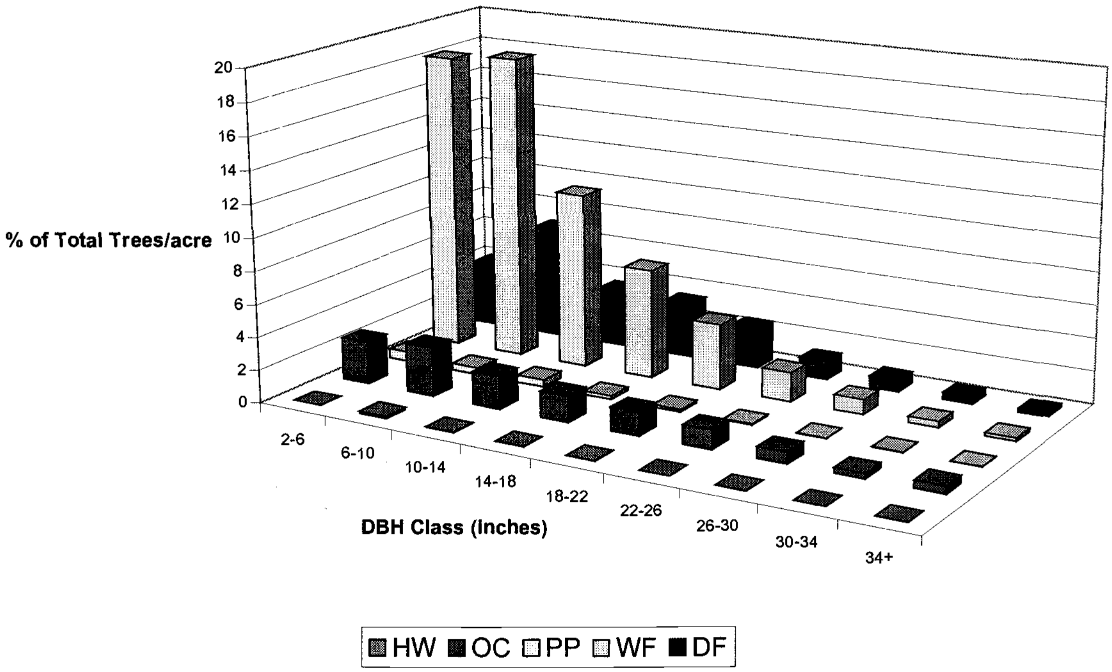

Figure 3- 8 - Relative diameter distribution of plots in cluster #8, by species

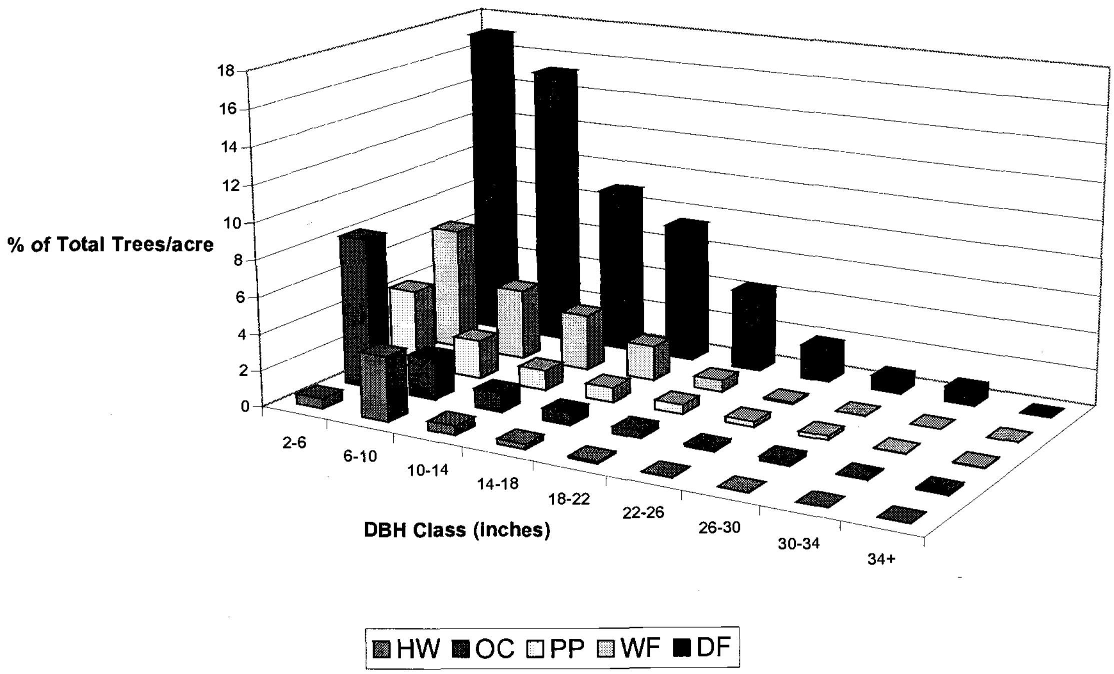

Figure 3- 9 - Relative diameter distribution of plots in cluster #9, by species

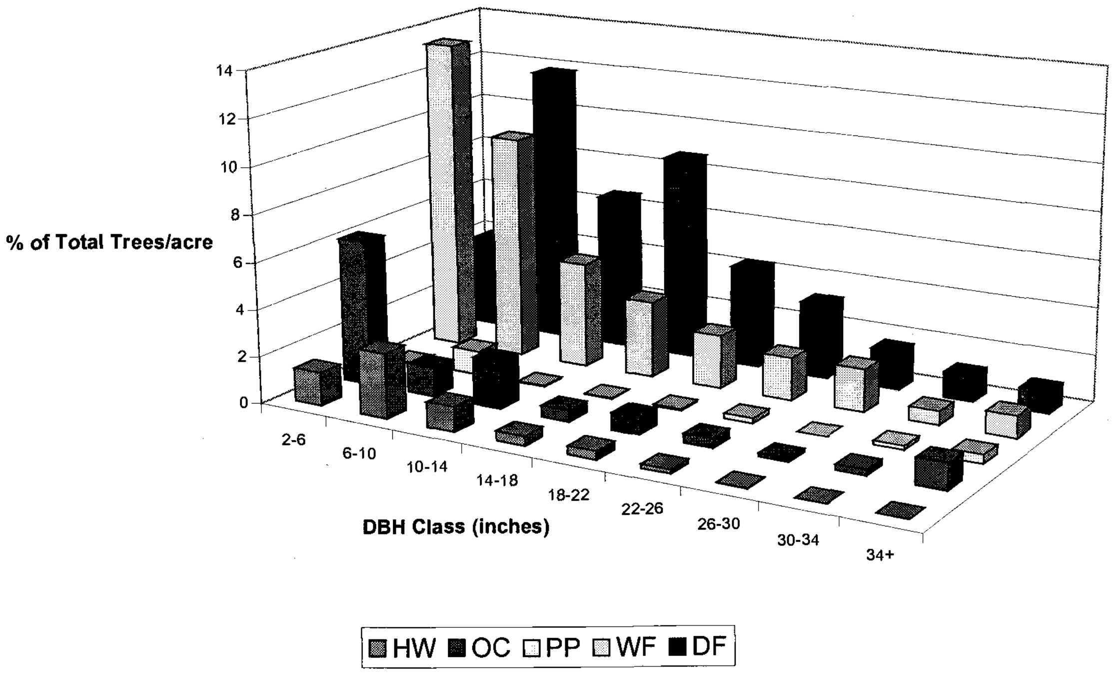

Figure 3- 10 -Relative diameter distribution of plots in cluster #10, by species

Diameter distributions by species revealed some key indicators in differentiating between clusters. Where a species group was a clear dominator, separation between clusters was evident. For example, from Table 3-3 clusters 7 and 9 were Douglas-fir dominated and clusters 6 and 8 were white fir dominated. Each can be further separated by looking at upper size class differences. Clusters 2 and 3 are distinguished by dominance of ponderosa pine and other conifer, respectively.

Table 3- 3 –Summary of species distribution by size class

Structural type	Understory		Midstory		Overstory	
	Dominate species	Size class	Dominate species	Size class	Dominate species	Size class
Cluster #1	DF/WF/PP/OC	2-10	DF	10-18	DF	18-34
Cluster #2	PP	2-10	PP/DF/OC	10-18	PP/DF	18-26
Cluster #3	OC/PP/DF	2-10	OC/DF/PP	10-18	OC/DF	18-34+
Cluster #4	OC/DF	2-6	PP/OC/HW	6-18	PP/DF	18-34
Cluster #5	DF/PP/OC	2-10	PP/DF	10-18	PP/DF/OC	18-34+
Cluster #6	WF	2-10	WF	10-18	WF/DF	18-34
Cluster #7	DF	2-10	DF	10-18	DF	18-30
Cluster #8	WF	2-10	WF	10-18	WF/OC/DF	18-34+
Cluster #9	DF	2-10	DF	10-18	DF	18-34
Cluster #10	WF	2-6	WF	6-18	DF/WF/OC	18-34+

Average quadratic mean diameters (QMD) also differs among structural groups (Table 3-4). For example, cluster 10 is characterized by large diameters, while cluster 2 is depicted by small diameters. However, the range in these averages is relatively small and variability is moderate, so statistically significant differences are small. Overall density characteristics were summarized with Stand Density Index (SDI), (Table 3-4). Clusters 8, 9, and 10 have relatively high SDI's, while and clusters 2 and 6 have low densities. Basal area distribution by species also suggests strong differences between structural types (Figure 3-11). Wide ranges between clusters were evident in both total basal area and basal area by species.

Table 3- 4 – Average quadratic mean diameter and Stand Density Index by cluster

Cluster #	QMD	Coefficient of variation	SDI	Coefficient of variation
1	10.02	0.278	126.49	0.355
2	6.91	0.138	108.11	0.352
3	10.23	0.245	142.86	0.271
4	8.31	0.367	174.80	0.451
5	11.02	0.351	179.82	0.311
6	10.36	0.393	93.03	0.386
7	8.08	0.230	133.95	0.308
8	9.08	0.357	212.74	0.325
9	10.38	0.350	211.65	0.365
10	14.91	0.338	210.78	0.496

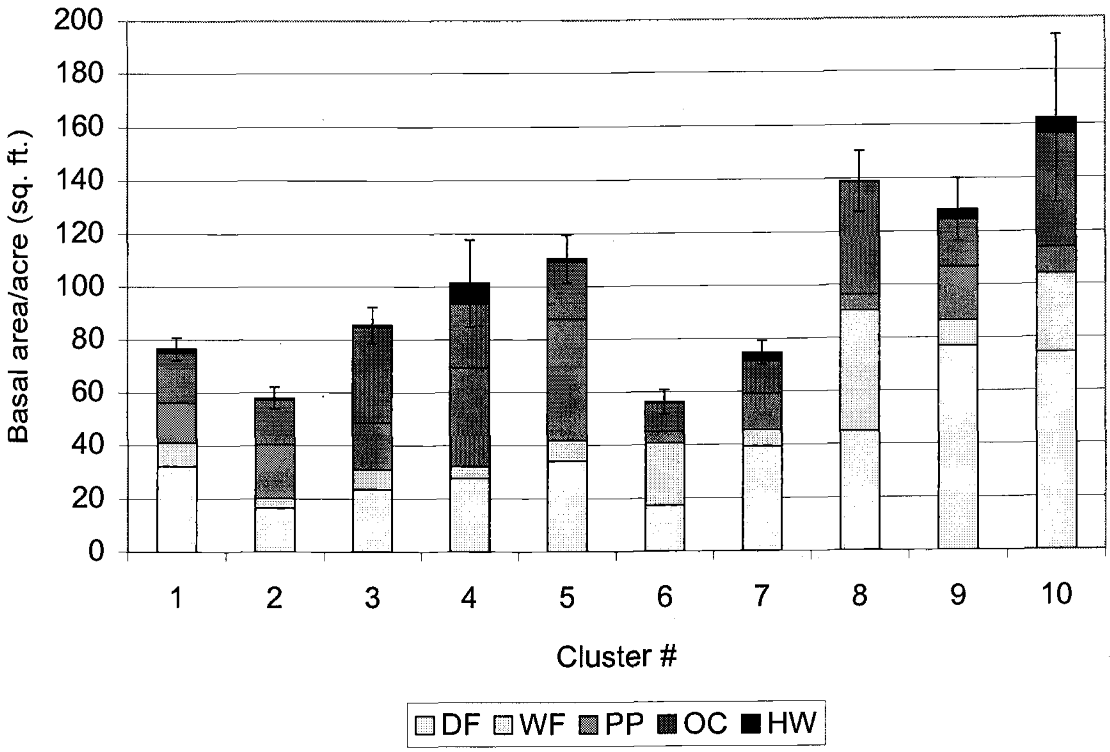

Figure 3- 11 – Mean basal area of structural types by species along with standard error bars of the total mean basal area (bar length = 2 standard errors in each direction).

3.4.2 Crown dimensional attributes

Figure 3-12 shows crown area profile curves for the 10 clusters, with all species lumped. Several of the curves appear to be similar, with only clusters 8, 9, and 10 showing large crown areas relative to the others, as is consistent with their larger SDI's. Height variances (Table 3-5) not only revealed differences between clusters but also gave a measure of degree of vertical complexity in the canopy arrangement. Higher variances indicate simpler structures while lower variances suggest more complexity. Cluster 10 had in the lowest variances indicating greater structural diversity than the rest of the clusters.

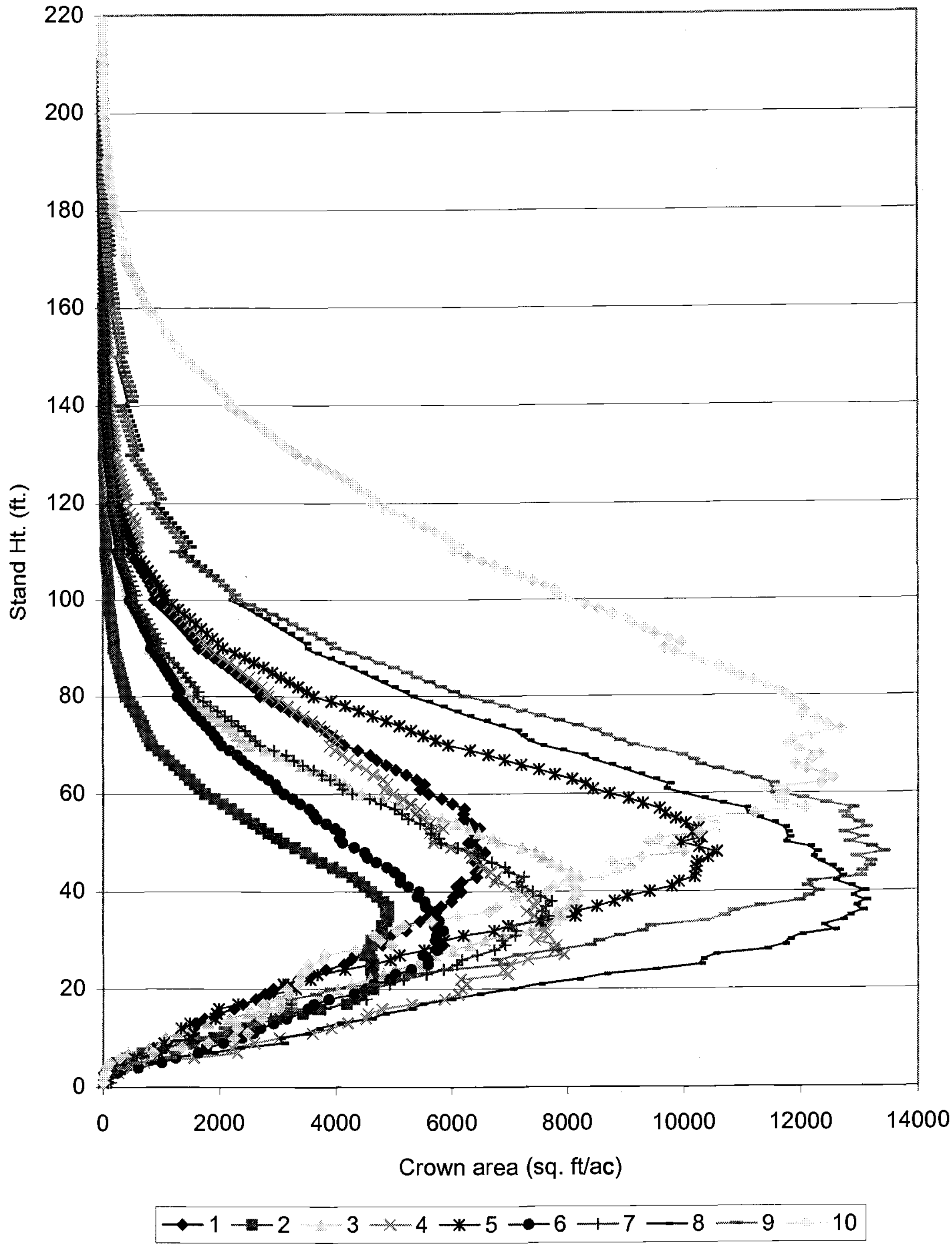

Figure 3- 12 – Crown area profiles by cluster

Table 3- 5 – Variance of Crown Area Profiles ranked smallest to largest. The lower the value the higher the degree of stand complexity (Relative normalized variance = 100,000*normalized variance).

Cluster #	Relative Normalized Variance
10	1.82
4	3.16
8	3.17
9	3.30
1	3.50
6	3.88
7	4.05
5	4.23
3	4.90
2	5.30

Composite crown area profiles (Figure 3-12) obviously do not depict species composition. However, plotting crown area profiles by species did reveal a significant amount of information about the differences between the clusters (Figures 3-13 to 3-22). The major crown area profile differences can be summarized as follows (Table 3-6)

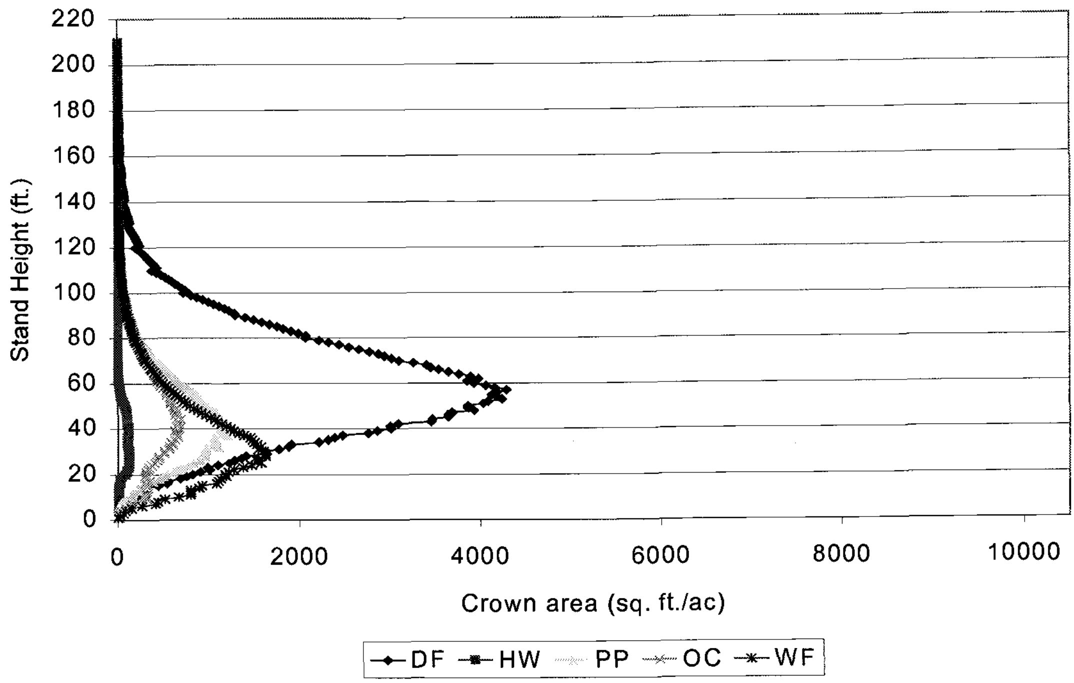

Figure 3- 13 - Crown area profile by species – Cluster #1

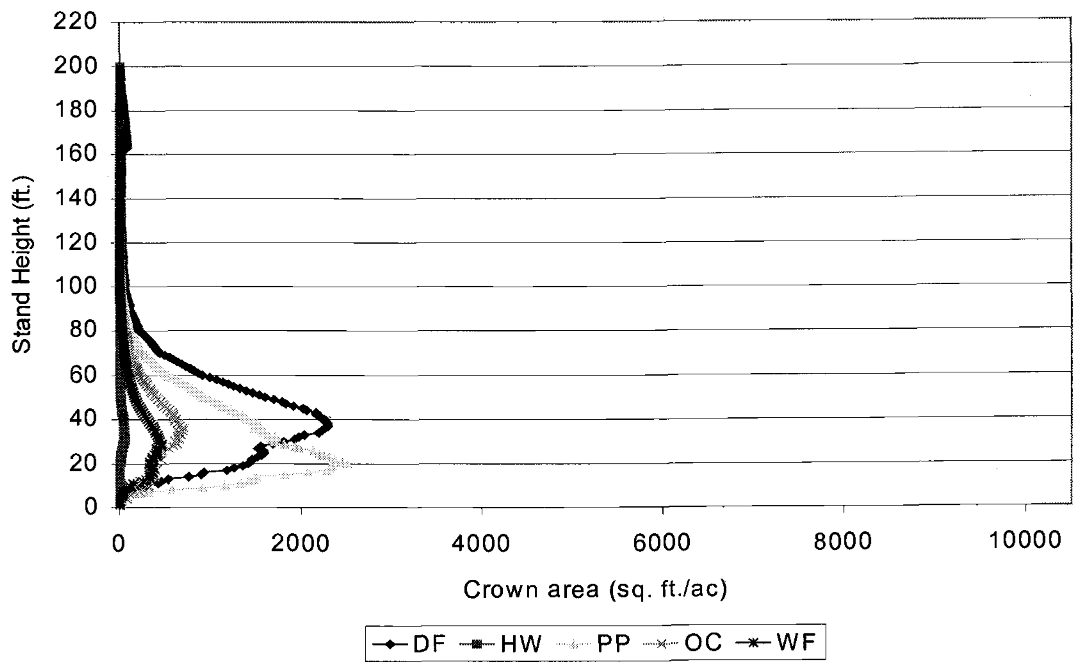

Figure 3- 14 - Crown area profile by species – Cluster #2

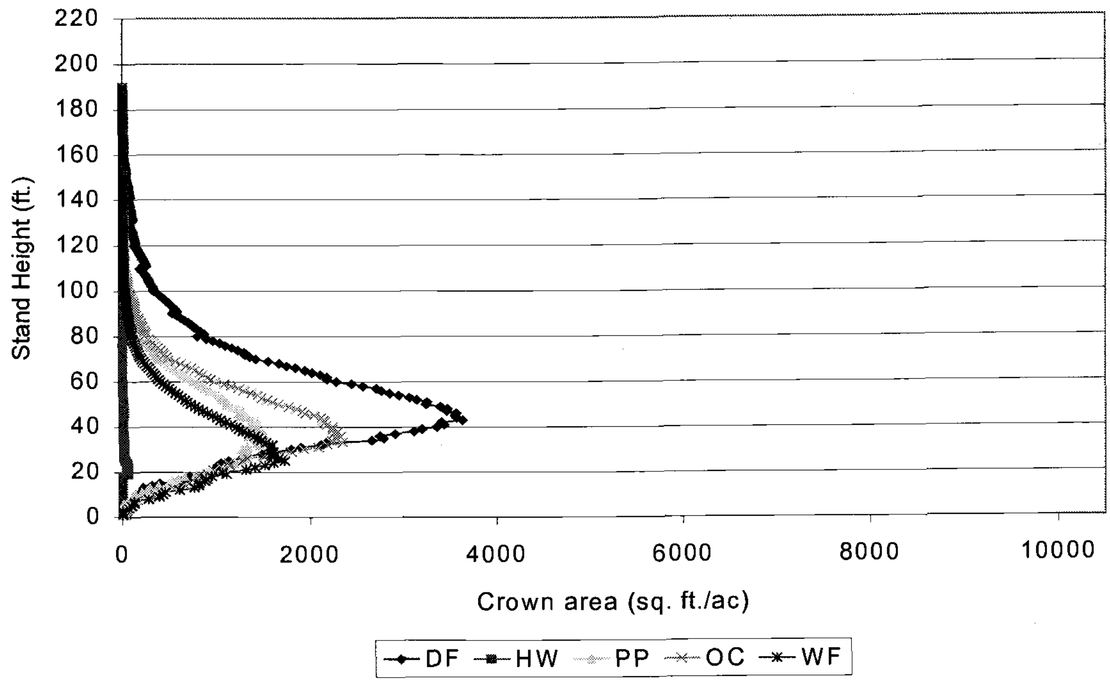

Figure 3- 15 - Crown area profile by species – Cluster #3

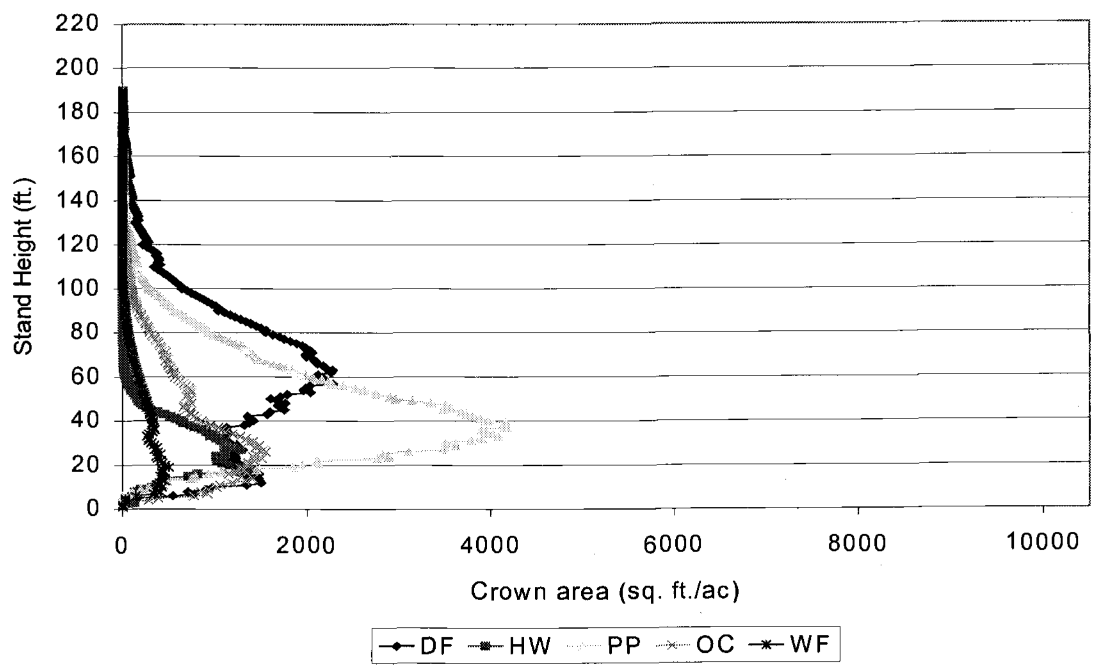

Figure 3- 16 - Crown area profile by species – Cluster #4

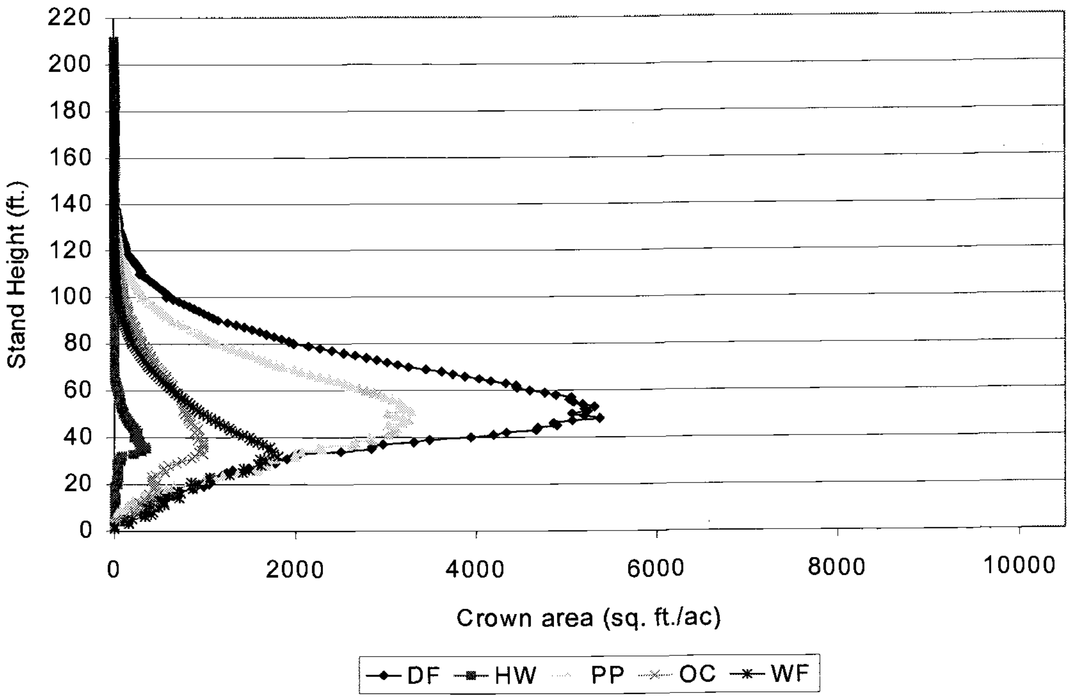

Figure 3- 17 - Crown area profile by species – Cluster #5

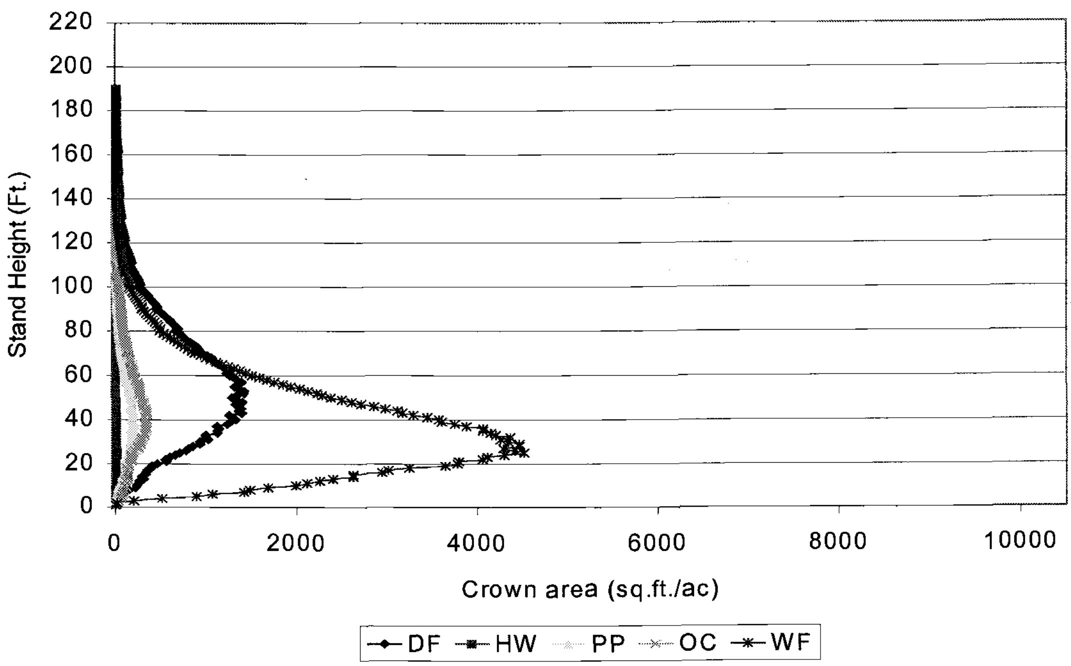

Figure 3- 18 - Crown area profile by species – Cluster #6

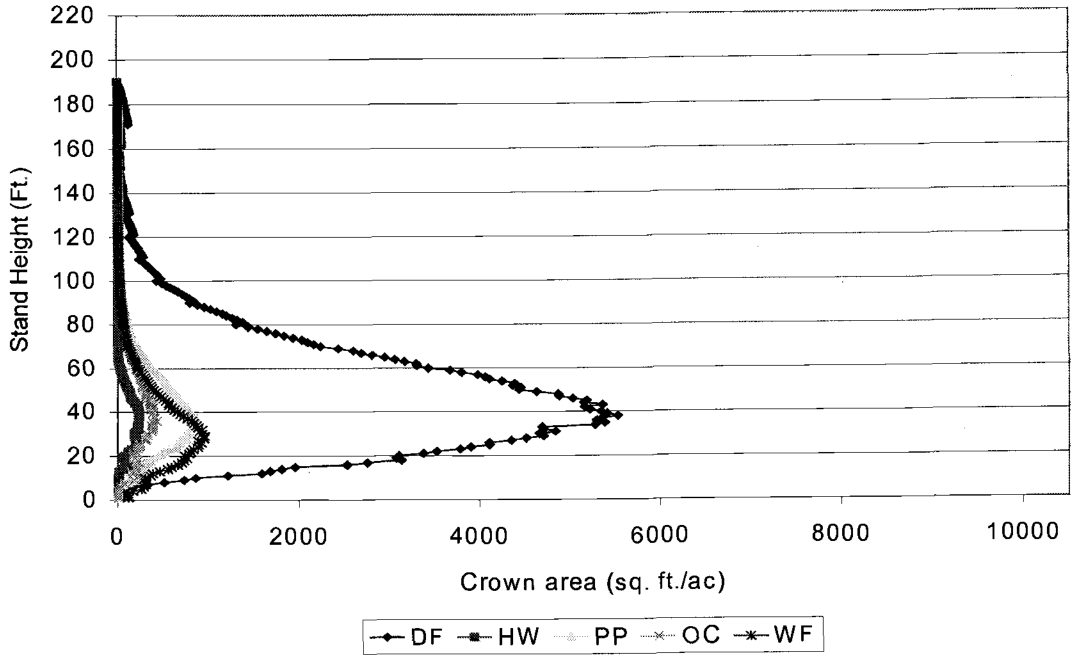

Figure 3- 19- Crown area profile by species – Cluster #7

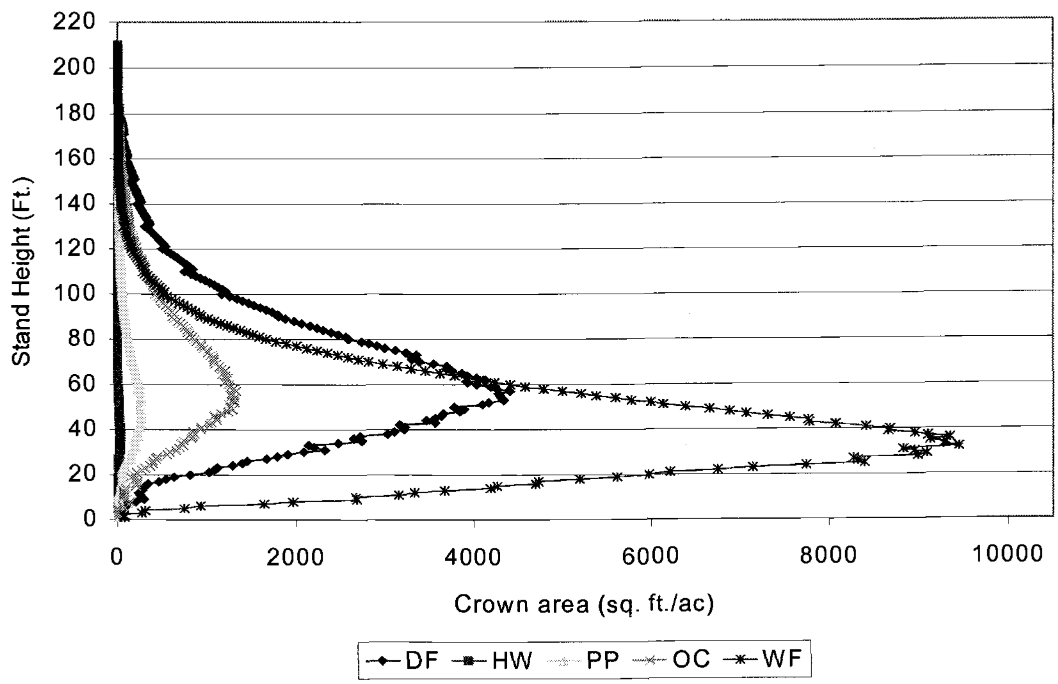

Figure 3- 20- Crown area profile by species – Cluster #8

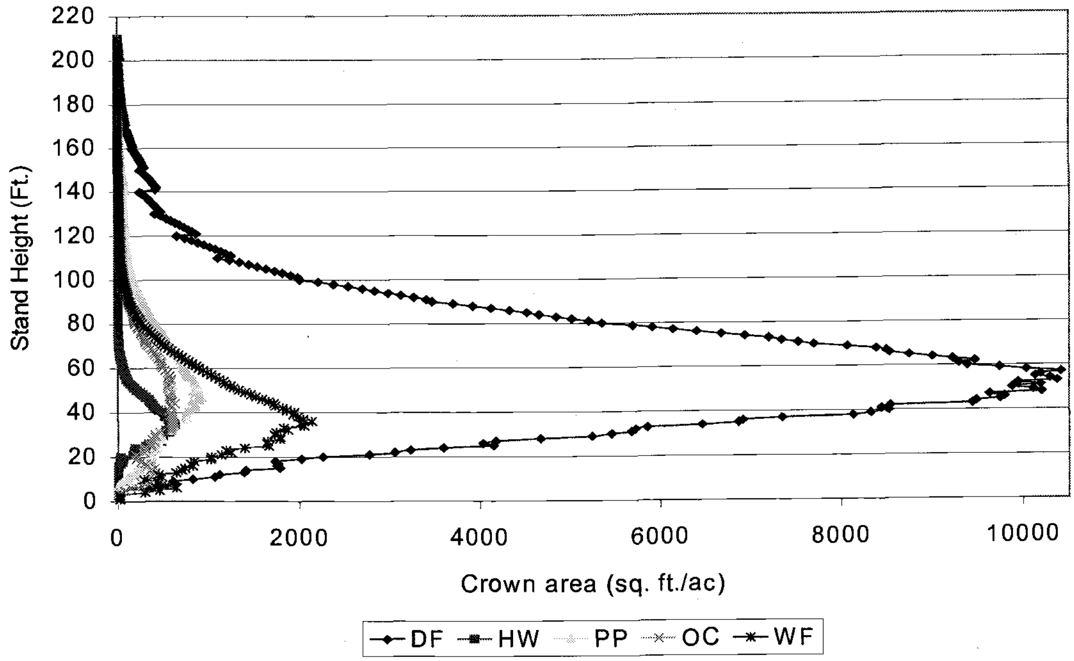

Figure 3- 21 - Crown area profile by species – Cluster #9

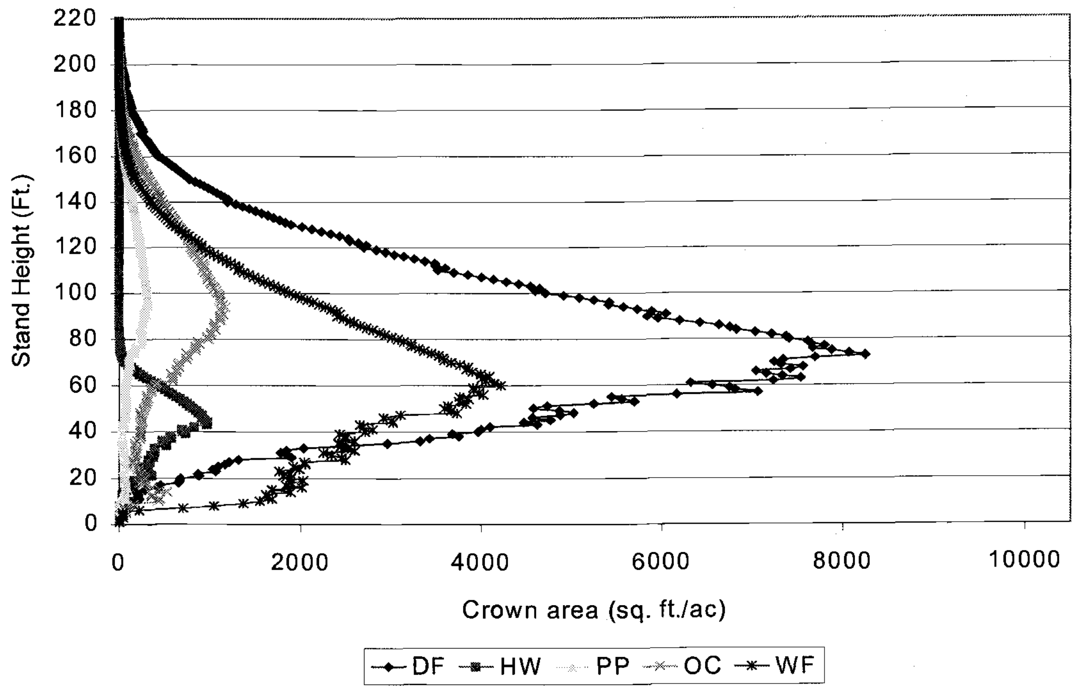

Figure 3- 22 - Crown area profile by species – Cluster #10

Table 3- 6 - Summary of canopy distribution by species

Structural type	Understory Dominate species	Midstory Dominate species	Overstory Dominate species
Cluster #1	WF/DF/PP	DF	DF
Cluster #2	PP	DF/PP	DF/PP
Cluster #3	PP/OC/DF/WF	DF/OC	DF
Cluster #4	DF/PP/OC/HW	PP	DF/PP
Cluster #5	DF/PP/WF	DF	DF/PP
Cluster #6	WF	WF	DF/WF
Cluster #7	DF	DF	DF
Cluster #8	WF	WF	DF/WF/OC
Cluster #9	DF/WF	DF	DF
Cluster #10	WF	DF/WF	DF/WF/OC

To gain information on the distribution of unoccupied space in the stand, several summarization's of pore space were explored. Total stand porosity (the percentage of unoccupied 3-dimensional space below the tallest tree) shows no clear differences between clusters (Table 3-7). The height of minimum areal porosity, which is also the point of maximum crown closure, is relatively high for cluster 10 (73 feet in stand height), but is low for clusters 2 and 4 (22 and 27 feet, respectively) (Table 3-8).

Table 3- 7 - Total porosity by cluster

Cluster #	Total porosity (%)	Coefficient of variation
1	93.4	0.03049
2	95.4	0.02028
3	92.8	0.02407
4	91.3	0.06133
5	90.9	0.03823
6	94.5	0.02556
7	92.7	0.02632
8	86.8	0.05607
9	86.6	0.07381
10	86.7	0.10426

Table 3- 8 – Height at which maximum crown closure occurs – point where areal porosity is least.

Cluster #	Height at min. areal porosity	Min. areal porosity (%)
1	48	84.9
2	22	89.3
3	43	81.2
4	27	81.8
5	43	79.9
6	32	86.6
7	38	82.3
8	38	69.9
9	46	69.7
10	73	70.9

Not surprisingly, areal porosity profiles indicated that only cluster 10 are easily differentiated because it had less pore space than the other clusters (Figure 3-23). Mean total stand porosities ranged between 86% and 96%. The vertical height of crown within this range gives a measure of uniformity of the distribution of pore space for each cluster. Clusters 2 and 6 show the highest degree of pore space uniformity, while clusters 3, 5, 7, 8, and 9 had a more heterogeneous pore space distribution (Figure 3-23, Table 3-9).

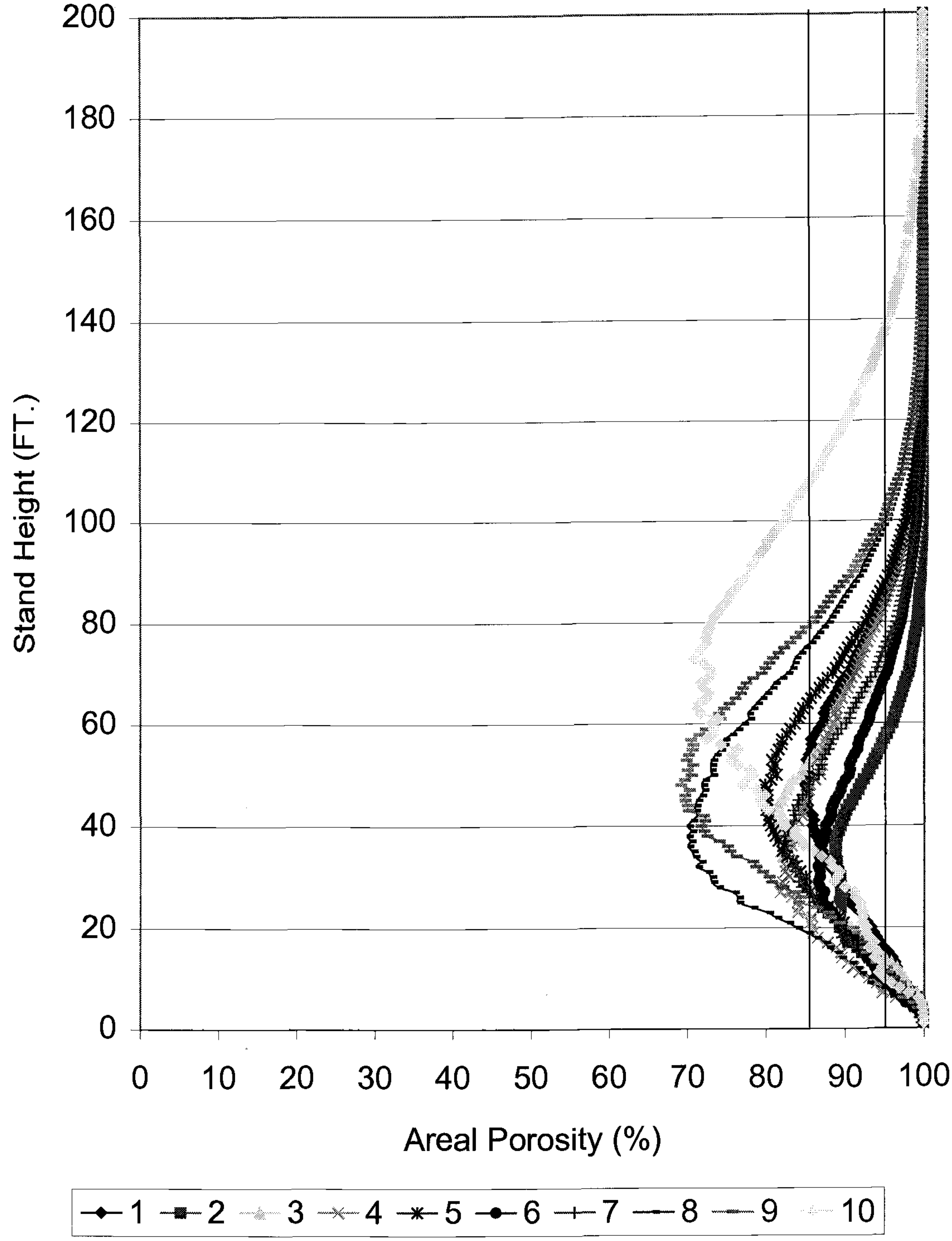

Figure 3- 23 – Areal porosity of all 10 clusters.

Table 3- 9 – Vertical height of canopy continuously occupying between 80 and 95% of areal porosity. Measure of uniformity of the vertical distribution of pore space.

Cluster #	Vertical canopy in mean range (ft)
1	35
2	56
3	26
4	45
5	30
6	72
7	33
8	32
9	28
10	39

Total crown closure by species depicted some of the major distinctions among clusters (Figure 3-24). These distinctions can be summarized as:

- **Cluster #1** - Total crown closure - 50%. Majority in Douglas-fir.
- **Cluster #2** - Total crown closure - around 42%. Even majority in Douglas-fir and ponderosa pine.
- **Cluster #3** - Total crown closure - around 52%. Majority in Douglas-fir and other conifer
- **Cluster #4** - Total crown closure - around 68%. Even majority in Douglas-fir, ponderosa pine, and other conifer. Hardwood component present.
- **Cluster #5** - Total crown closure – around 67%. Majority in Douglas-fir.
- **Cluster #6** - Total crown closure - 40%. Majority in white fir.

- **Cluster #7** - Total crown closure – around 62%. Clear majority in Douglas-fir.
- **Cluster #8** - Total crown closure - around 88%. Majority in white fir.
- **Cluster #9** - Total crown closure - around 93%. Clear majority in Douglas-fir. Some hardwood present.
- **Cluster #10** - Total crown closure - around 85%. Majority in Douglas-fir. Some hardwood present.

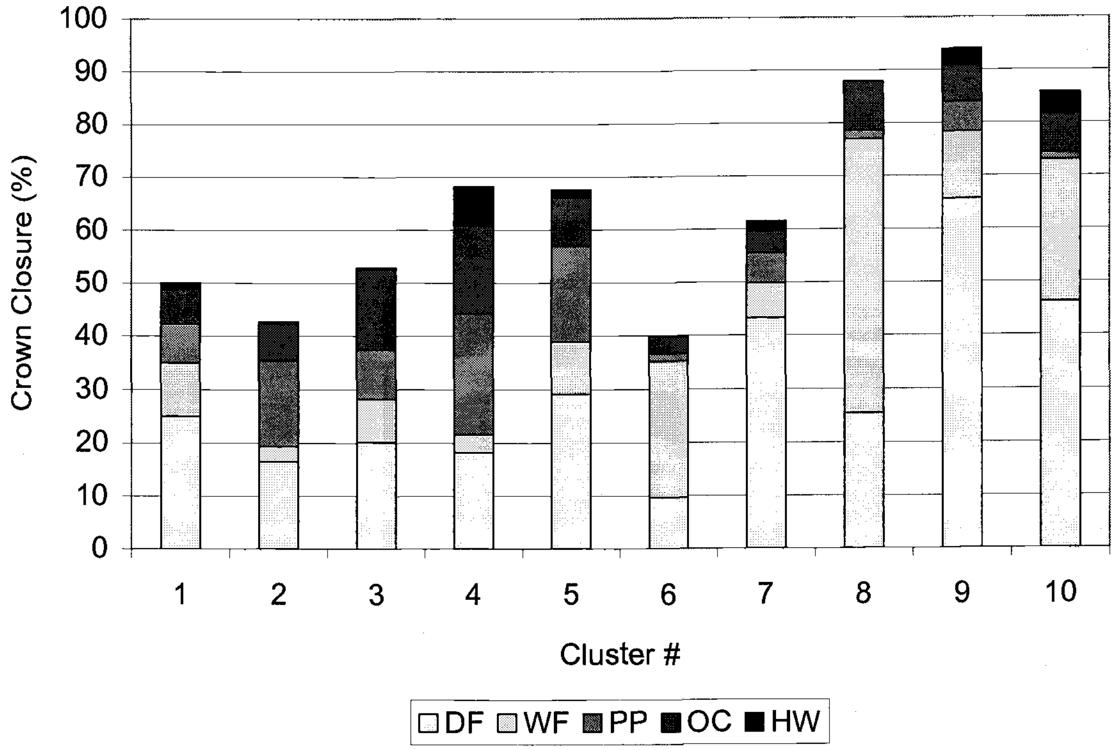

Figure 3- 24 - Crown Closure by species

3.4.3 Growth characteristics

Only clusters 2, 3, 4, 6, and 7 were represented by the permanent plots. Total cubic foot volume PAI varied from 59 to 128 (Figure 3-25). Permanent plots from cluster 4 showed relatively high growth rates for total cubic foot volume. Cluster 2 had the lowest growth. Cluster's 3, 6, and 7 showed moderate growth rates. However, as is evident from the standard error bars, the variability in these estimates is very high.

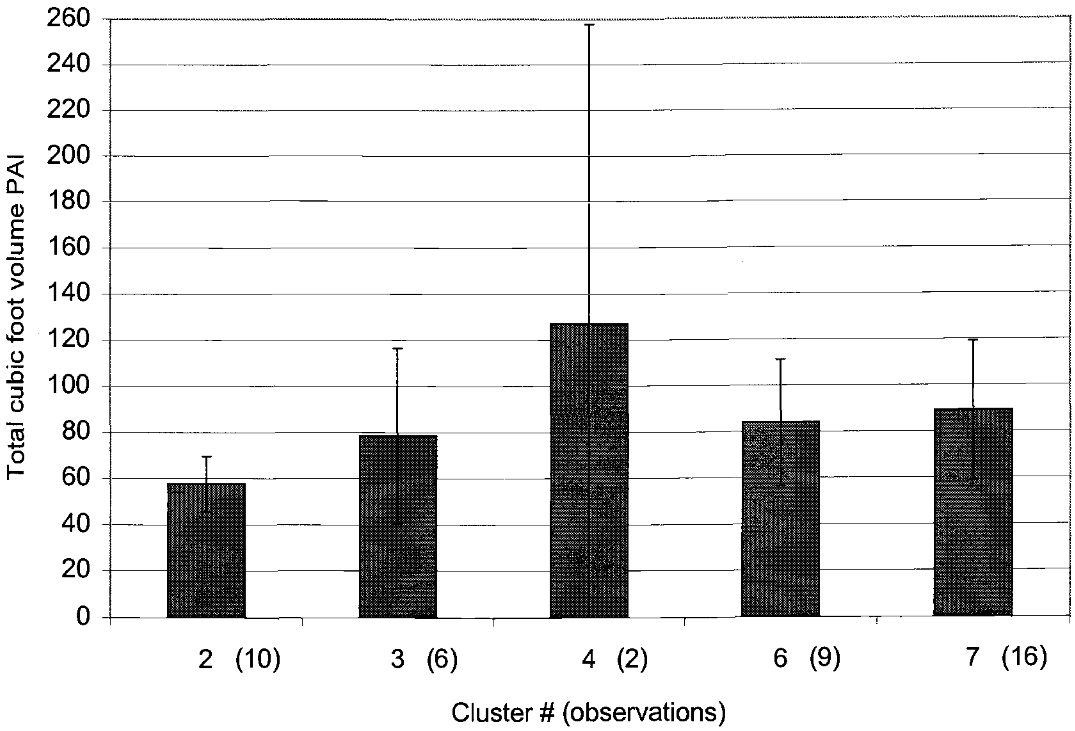

Figure 3- 25 – Total cubic foot volume PAI computed from permanent growth plot data along with standard error bars (bar length = 2 standard errors in each direction).

The expected PAI's (predicted by CACTOS) indicate that clusters 8 and 10 have superior growth, while clusters 2, 6, and 7 experience low growth rates (Figure 3-26). Standard error bars indicate relatively low variability, suggesting actual growth differences between some clusters exist.

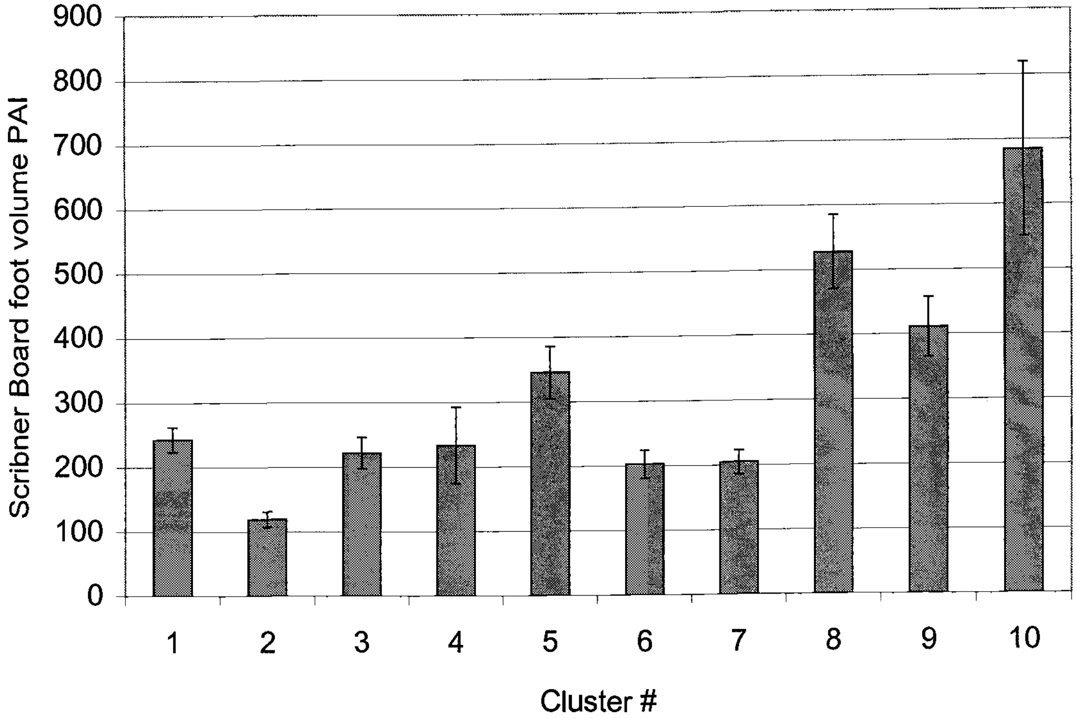

Figure 3- 26 - Scribner board foot volume PAI by cluster predicted by CACTOS growth and yield model along with standard error bars (bar length = 2 standard errors in each direction).

3.5 Discussion

Stand structure has most commonly been depicted by diameter distributions. This method usually works reasonably well since dbh distributions are often correlated with other stand and tree dimensions of interest. However, it is always better to deal with ultimate rather than proximate factors and, thereby, to have a stronger link between stand structure and function. Crown area profile has considerable appeal for relating more directly to the function of a given stand structure in producing various resource outputs.

Net primary production and ultimately timber production depends on vertical distribution of leaf area, which drives associated absorption of photosynthetic active radiation (PAR), respiratory losses, and limitations on gas exchange (Kimmins 1987, Russell et al. 1989, Smith and Long 1989, Long and Smith 1990). These processes are, therefore, closely related to crown area profile (CAP). The integral under the curve of CAP is crown volume which on the stand level is correlated with the relative illumination of foliage at a given level of relative height. The height of the peak in CAP indicates tree sizes and probable respiratory load and hydraulic limitations on net photosynthesis. These attributes are all therefore directly correlated to timber productivity, including both total volume growth and its distribution among species and size classes.

Likewise, the distribution of foliage within a stand, significantly affects wildlife habitat. Degree of vertical canopy layering plays an important role in favoring either canopy-nesters or shrub-nesting species. In an interior Columbia basin study where multistory canopies have closed (shading out understory vegetation) understory-nesters have shown declining numbers, while canopy-nesters showed increasing numbers (Saab and Rich 1997). Multi-layered canopies often provide forage for species associated with understory vegetation, either shrubs or small trees, and provide protection for different species at various heights in the stand (Hayes et al. 1995, Hayes et. al 1998). For example, forest birds that live within the canopy may need flight pathways in the midstory to hunt for prey, while needing overstory layers for protection from predators above. Tree species composition plays an important role in providing diverse wildlife habitat. Presence of hardwoods in conifer-dominated stands have been shown to favor some species birds, while some wildlife species favor particular conifer seeds as a significant forage contributor (Hagar et al. 1996, Benkman 1993). Differences between tree species in terms of characteristics such as needle lengths, branch size, bark texture, and susceptibility to pathogens (such as mistletoes) all contribute to specific wildlife niches.

Highly diverse, multistory forests have been shown to be aesthetically more pleasing than less diverse structures. Studies have shown that where residual structure includes some standings live trees, particularly compared to clearcuts, public sentiment is by far more strongly approving (Laughlin and Garcia 1986, Magill 1992).

3.6 Conclusions

In this study, numerous attributes were summarized in order to describe and differentiate between each of 10 structural classes. The ultimate goal was to gather information that would not only lead to distinct types but also facilitate multiple objective decision-making, particularly with respect to productivity and wildlife habitat. The 10 structural types allow for broad scale application in managing a large land base typical of many forest products companies and land management agencies. Each cluster displays a set of unique understory, midstory, and overstory characteristics. Standard attributes for each cluster are summarized in Table 3-10.

Table 3- 10 – Summary of standard attributes by cluster

Structural type	PAI (Board Feet)	Basal area/ac (sq. ft.)	Stand Density Index	QMD (inches)	Crown Closure (%)
Cluster #1	244	76.66	126.49	10.02	50.1
Cluster #2	119	58.11	108.11	6.91	42.7
Cluster #3	223	85.63	142.86	10.23	52.9
Cluster #4	234	101.38	174.80	8.31	68.2
Cluster #5	346	110.54	179.82	11.02	67.6
Cluster #6	203	56.27	93.03	10.36	40.0
Cluster #7	205	74.79	133.95	8.08	61.5
Cluster #8	528	138.96	212.74	9.08	88.0
Cluster #9	411	128.26	211.65	10.38	93.9
Cluster #10	685	162.01	210.78	14.91	85.8

Species composition, volume growth, size, and density information was provided in detail but can be condensed where more general application warrants less detail (Table 3-11). The structures represented by cluster 8 (WF/OC/DF) and cluster 9 (DF) are stands with relatively high densities and high productivity rates. Cluster 10 (DF/WF/OC)) stands are depicted by large average tree size, high density, and very high productivity rates compared to the other structural types. Cluster 2 (PP/DF), cluster 6 (WF/DF), and cluster 7 (DF) represent the other end of the spectrum, having low densities and low growth rates. Cluster 4 (PP) and cluster 5 (PP/DF/OC) fall between these two extremes. Cluster 1 (DF), and cluster 3 (OC/DF) could be generally described as structures with medium size trees, moderately-low densities, and moderately-low growth rates.

Table 3- 11 - Final summary for overall species, growth, size and density characteristics

Structural type	Major species overstory (understory)	Volume growth	Overall size	Overall density	Final general description overstory(density)/understory
Cluster #1	DF (DF/WF/PP/OC)	moderately low	medium	moderately low	DF(low)/mixed
Cluster #2	PP/DF (PP)	very low	small	low	PP-DF(low)/PP
Cluster #3	OC/DF (OC/DF/PP)	moderately low	medium	moderately low	OC-DF(low)/mixed
Cluster #4	PP (WF/PP/DF/HW)	moderately low	moderately small	moderate	PP(medium)/mixed
Cluster #5	PP/DF/OC (DF/PP/OC)	moderate	moderately large	moderate	mixed(medium)/mixed
Cluster #6	WF/DF (WF)	low	medium	low	WF-DF(low)/WF
Cluster #7	DF (DF)	low	moderately small	moderately low	DF(low)/DF
Cluster #8	WF/OC/DF (WF)	high	moderately small	high	WF-mixed(high)/WF
Cluster #9	DF (DF/WF)	moderately high	medium	high	DF(high)/DF-WF
Cluster #10	DF/WF/OC (WF/DF)	very high	very large	high	mixed(high)/WF-DF

4 Conclusions

Many current approaches to classification of forest stand into structural types arise from a subjective manner that ignores biological processes. This paper attempted to create an approach to objective classification and subsequent characterization of stand structure on a biological basis. The goal was to form structural classes based on ecosystem processes and functions (captured in crown area profiles) that fit the objectives of forest management.

Identifying structural classes in complex mixed-species, multi-aged stands is a difficult task since differences between stands lie along gradients rather than in distinct classes. Cluster analysis provided the best possible method for this type of classification, even though its procedures and interpretations are not always easily determined. The analysis indicated that using crown closure by species as the variable set with ten classes best minimized the within- and between- cluster variation on a crown area profile basis and, therefore, was used to form the structural types. Complete differentiation between types was not easily apparent, so full characterization of key structural attributes was completed revealing strong differences. Differences in average size, relative density, crown structure, growth potential, and particularly species composition were all apparent from the characterization.

The information gained from this project can be useful in several ways. First, the classification and characterization will be useful for forestry landowners in northern California for evaluating any broad-based objective requiring information about various stand structural features. Next, it provides a methodology for future classification of forest stands. Objective classification is difficult as is evident from the complexity in using cluster analysis. This paper outlined many of the pros and cons of this approach offering a solid basis for future classification. Finally, the project presented evidence of the overall usefulness of canopy structure in forestry. Not only is it an indicator of overall stand structure, it also provides a tool for evaluating many forestry objectives including; timber production, wildlife habitat, diversity, and aesthetics.

BIBLIOGRAPHY

Anderberg, M.R. 1973. Cluster Analysis for Applications. New York, Academic Press, Inc.

Bell, J.F., and J.R. Dillworth. 1997. Log Scaling and Timber Cruising. Revised Ed. Cascade Printing Co., Corvallis, Oregon. 444 p.

Benkman, C.W. 1993. Logging, conifers, and the conservation of conifers. Conservation Biology. 7:473-79.

Dansereau, P. 1951. Description and recording of vegetation upon a structural basis. Ecol. 32:172-229.

Dansereau, P. 1957. Biogeography, an Ecological Perspective. Ronald, New York. 394 pp.

Daubenmire, R.F. 1952. Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification. Ecol. Monogr. 22:301-330.

Daubenmire, R.F., and J.B. Daubenmire. 1968. Forest vegetation of eastern Washington and northern Idaho. Wash. Agric. Exp. Sta. Tech. Bull. 60. 104 pp.

Davis, T.W.A., and P.W. Richards. 1933 and 1934. The vegetation of Moraballi Creek, British Guiana: an ecological study of a limited area of tropical rain forest. J. Ecol. 21:350-384; 22:106-155.

Dubrasich, M.E., D.W. Hann, and J.C. Tappeiner III. 1997. Methods for evaluating crown area profiles of forest stands. Can. J. For. Res. 27: 385-392.

Hagar, J.C., W.C. McComb, and W.H. Emmingham. 1996. Bird communities in commercially thinned and unthinned Douglas-fir stands of western Oregon. Wildlife Society Bulletin 24:353-66.

Hayes, J.P., E.G. Horvath, and P. Hounihan. 1995. Townsend's chipmunk populations in Douglas-fir plantations and mature forests in the Oregon Coast Range. Canadian Journal of Zoology 73:67-73.

Hayes, J.P., S.C Chan, W.E. Emmingham, J.C. Tappeiner, L.D. Kellogg, and J.D. Bailey. 1997. Wildlife response to thinning young forests in Pacific Northwest. J. For. 95(8): 28-33.

Hayes, J.P., M.C. Adam, R.G. Anthony, W.H. Emmingham, D.M. Gomez, D.J. Larson, K.G. Mass-Hebner, N. Suzuki, W.G. Thies, D.J. Westlind, and J.M. Weikel. 1998. Effects of commercial thinning on stand structure and wildlife populations: A progress report, 1994-1997. Coastal Oregon Productivity Enhancement Program, College of Forestry, Oregon State University, Corvallis, OR.

Johnson, D.E. 1998. Applied Multivariate Methods for Data Analysts. Ed. 1. Duxbury Press, Pacific Grove, California.

Kimmins, J.P. 1997. Forest Ecology: A Foundation for Sustainable Management. Ed. 2. Prentice-Hall, New Jersey. 596 p.

Kuchler, A.W. 1947. A geographical system of vegetation. Geogr. Rev. (N.Y.) 37: 233-240.

Laughlin, N.A. and M.W. Garcia. 1986. Attitude of landscape architects in the USDA Forest Service. Toward the visual management system. Landscape Journal 5(2):135-139.

Long, J.N., and Smith, F.W. 1990. Determinants of stemwood production in *Pinus Contorta* var. *latiflia* forests: the influence of site quality and stand structure. J. Appl. Ecol. 27: 847-856.

Magill, A.W. 1992. Managed and natural landscapes: what do people like? Res. Paper PSW-RP-213. Albany, CA: Pac. SW Res. Stat. For. Serv., U.S.D.A. 28 p.

Milligan, G.W. 1981. A review of Monte Carlo tests of cluster analysis. Multivariate Behavioral Research. 16: 379-407.

Milligan, G.W. and M.C. Cooper. 1985. An examination of procedures for determining the number of clusters in a data set. Psychometrika. 50: 159-179.

O'Hara, K.L., P.A. Latham, P.H. Hessburg, and B.G. Smith. 1996. A structural classification for inland northwest forest vegetation. West. J. App. For. 11(3): 97-102.

O'Hara, K.L., C.D. Oliver, S.G. Pickford, and J.J. Townsley. 1990. A prototype decision rule base for planning and anticipating effects of silvicultural activities over broad areas. AI Appl. In Natur. Resour. 4:25-34.

O'Hara, K.L., R.S. Seymour, S.D. Tesch, and J.M. Guldin. 1994. Silviculture and our changing profession: Leadership for shifting paradigms. J. For. 92(1):8-13.

Oliver, C.D. and B.C. Larson. 1996. Forest Stand Dynamics. John Wiley and Sons, New York. 520 p.

Pielou, E.C. 1984. The Interpretation of Ecological Data. John Wiley and Sons, New York. 263 p.

Randall, W.R., R.F. Keniston, D.N. Bever, and E.C. Jensen. 1994. Manual of Oregon Trees and Shrubs. Ed. 5. OSU Bookstores, Corvallis. 305 p.

Russell, G., Marshall, B., and Jarvis, P.G. 1989. Plant canopies: their growth, form, and function. Cambridge University Press, Cambridge U.K.

Pickett, S.T.A., and M.J. McDonnell. 1989. Changing perspectives in community dynamics: A theory of successional force. Trends in Ecol. Evol. 4(8):241-245.

Saab, Victoria A. and T.D. Rich. 1997. Large-scale conservation assessment for Neotropical migratory land birds in the interior Columbia River basin. Gen. Tech. Rep. PNW-GTR-399. Portland, OR: U.S.D.A., For. Serv., PNW Res. Stat. 56p.

Smith, D.M., B.C. Larson, M.J. Kelty, and P.M.S. Ashton. 1997. The Practice of Silviculture. Ed. 9. Wiley, New York. 537 p.

Smith, F.W., and J.N. Long. 1989. The influence of canopy architecture on stem wood production and growth efficiency of *Pinus Contorta* var. *latiflia*. J. Appl. Ecol. 26:681-691.

Sprugel D.G. 1991. Disturbance, equilibrium, and environmental variability: What is 'natural' vegetation in a changing environment? Biol. Cons. 58:1-18.

Thomas, J.W. 1979. Wildlife habitats in managed forests: The Blue Mountains of Oregon and Washington. USDA For. Serv. Agric. Hand. No. 553.

Wellner, C.A. 1989. Classification of habitat types in the western United States. P. 7-21 *in* Proc. Land classifications based on vegetation: Applications for resource management, Ferguson, D.E., P. Morgan, and F.D. Johnson (eds.). USDA For. Serv. Gen. Tech. Rep. INT-257.