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Percent Canopy Cover and Stand Structure Statistics from the Forest Vegetation Simulator

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Year 2000: ***young forest, multistrata***
Canopy cover 35 percent

Year 2140: ***old forest, single stratum***
Canopy cover 74 percent

Abstract

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Estimates of percent canopy cover generated by the Forest Vegetation Simulator (FVS) are corrected for crown overlap using an equation presented in this paper. A comparison of the new cover estimate to some others is provided. The cover estimate is one of several describing stand structure. The structure descriptors also include major species, ranges of diameters, tree heights, and heights to crown base for as many as three significant height strata. From these data a structural class is assigned to the stand using concepts defined by O'Hara and others (1996) with some subsequent enhancements. An FVS keyword for applying and tuning the classification is documented along with information for FVS Event Monitor users. An illustration of the structural classification is presented.

Keywords: FVS, Prognosis Model, crown cover, stand structure classification.

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Percent Canopy Cover and Stand Structure Statistics from the Forest Vegetation Simulator

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Introduction

Estimates of percent canopy cover generated by the Forest Vegetation Simulator (FVS, also known as the Prognosis Model for Stand Development, Stage 1973; Wykoff and others 1982) are corrected for crown overlap using an equation presented in this paper. Canopy cover percent has been identified as an indicator of wildlife habitat for deer and elk (Thomas and others 1979) and is an output of the COVER and SHRUBS Extension to FVS (Moeur 1985). A review of other methods used to estimate canopy cover is presented with comparisons to the new method. Appendix A describes an algorithmic foundation for the new method in detail.

Descriptors of stand structure have become an increasingly important consideration in prescribing management actions to preserve wildlife habitat and watershed values. Traditional FVS-generated outputs that describe the distribution of tree crowns comprising a stand are available to users of the COVER and SHRUBS extension. It reports the horizontal and vertical crown distribution by 10 foot tall slices of the canopy. A new report has been added to the FVS output describing stand structure. New computations are used to search for up to three distinct canopy strata. For each significant stratum, the canopy cover, major species, ranges of diameters, tree heights, and heights to crown base are displayed. From these data a structural class is assigned to the stand using concepts presented by O'Hara and others (1966) with some subsequent enhancements. The new output report is illustrated below with a description of the classification scheme and an overview of the supporting methods. Appendix B describes the classification procedure in detail.

Features added to FVS that support using these new tools are documented.

Percent Canopy Cover

Stand percent canopy cover is the percentage of the ground area that is directly covered with tree crowns. Generally, the crown area of a tree is computed using the formula for a circle as a function of crown radius. Crown radius is estimated using formulae that are different for each FVS geographic variant. The stand percent crown cover without accounting for crown overlap is computed using equation 1:

$$C' = 100(\sum p_i a_i)A^{-1} \tag{1}$$

where:

C' = percent canopy cover without accounting for overlap,
p_i = trees per acre for the i^{th} sample tree,
a_i = projected crown area for the i^{th} tree in ft^2/acre, and
A = ft^2/acre (43560).

To correct for crown overlap, D. Satterlund (in Moeur 1986, p. 344) suggested a computing procedure to estimate incremental additions of total canopy cover. Moeur reported that Satterlund's method produced estimates 13 percent greater than ground-based observations.

McGaughey, in a program called PERCOVE, (1997a) computes percent canopy cover by first placing the sample trees from an FVS projection onto a two dimensional grid. The crown circle of each tree is projected on the grid and the proportion of the grid cells covered by the circles of one or more trees is the proportion of canopy cover. PERCOVE is capable of representing several spatial distributions of trees, and it allows users to specify canopy strata for which independent estimates are computed.

Because PERCOVE must follow the execution of FVS, the cover predictions it generates cannot be used to guide management within FVS using rules evaluated by the FVS Event Monitor (Crookston 1990).

Furthermore, as the density of the dot grid increases (necessary for accurate estimates), the computer time required to run the program can become burdensome.

To solve these problems, a new method was created for use in FVS that is based on established techniques. This approach is fast, accurate for a large class of problems, and is part of FVS, so that the values computed can be easily reported in FVS outputs and made directly available in the Event Monitor. The new method is now used in the COVER and SHRUBS Extension to FVS (Moeur 1985).

The new method starts with the assumption that trees are randomly located within the stand. This assumption is midway between the extremes of equidistant spacing that might characterize the early distributions of stems in a plantation and the clumped distributions that might characterize the latter stages of a group-shelterwood applied repeatedly and to old forests (Moeur 1993). To many observers this random distribution of points in space appears clumpy. A logical next step would be to generate a hypothetical stem map, assign crowns, and project this map of crowns onto a dot grid as done in PERCOVE. Appendix A outlines a simplified stem map approach that does not include exact stem placement. The technique has several desirable properties outlined in the appendix.

Figure 1 displays the results using the simplified stem map approach detailed in Appendix A plotted against results using the equation that does not account for overlap (equation 1). The data for the comparison were produced using FVS to generate estimates of cover for 447 plots from the north Idaho Forest Inventory Assessment data (Woudenberg and Farrenkopf 1995). These data are a systematic sampling of conditions in north Idaho. Two estimates were made for each plot, one for the inventory year and another for 80 years later. Because no difference in behavior between these two estimates was detected, they are not distinguished in the figure.

The tight fit in figure 1 suggested a search for a mathematical basis for the relationship. The analytical solution for the problem is available from the theory of geometrical probability for randomly located figures on a plane (Mack 1954, cited in Kendall and Moran 1963, section 5.56 on p. 116). Furthermore, the mathematical derivation holds for arbitrary convex figures as well as for circles. Therefore, equations that directly predict projected crown area regardless of crown shape could be used in place of those that assume the crowns are round. Equation 2 estimates the percent canopy cover that accounts for overlap (illustrated as the solid line in fig. 1).

$$C = 100\,[1 - \exp(-.01\,C')] \qquad (2)$$

where:

C = percent canopy cover that accounts for overlap,
and
C' = equation 1.

The same function is known in tree physiological literature as the Beer-Lambert law—a commonly used relation for calculating the absorption of light by foliage (see Waring and Schlesinger 1985, p. 12; or see Jones 1992, p. 15). In the Beer-Lambert law, foliage is measured by leaf area index which replaces C' in equation 2. By introducing a coefficient other than unity multiplying the argument of the exponential, the Beer-Lambert law generalizes the mathematical result to allow for non-random distributions. The ability to represent uniform distributions and some spe-

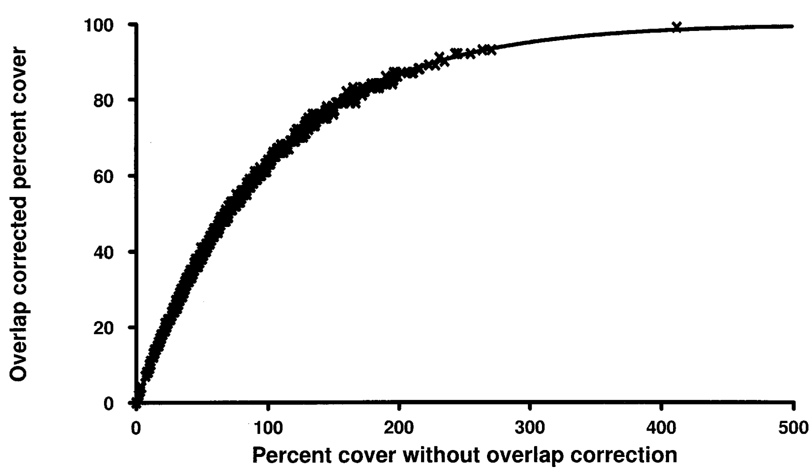

Figure 1—Percent cover with overlap correction plotted over cover without correction for 447 plots from the north Idaho FIA data. The formula for the line is $y = 100\,[1 - \exp(-x/100)]$; see equation 2.

cial attraction and repelling of canopies (so as to clump trees or clump openings, as the case may be) would depend on empirical relations not currently available. Early experience shows that little accuracy would be gained by including more refinements.

Figure 2 illustrates the relationship between estimates made with the new method (equation 2, the x-axis) and those made using PERCOVE (the y-axis). The solid lines in the graphs are 1:1 reference lines.

PERCOVE estimates differ from estimates using equation 2, and the differences are different for the inventory-time estimates as compared to those made after 80 years of simulated time. Regression lines characterize these differences as follows: for the inventory time estimates the formula $y = 3.27 + 0.927x$ ($r^2 = 0.91$) is the best fit; for 80 years of simulated time $y = -4.65 + 1.03x$ ($r^2 = 0.99$) fits best; and for all data taken together $y = 1.56 + 0.94x$ ($r^2 = 0.94$) fits best.

It is clear that PERCOVE estimates are about 4 percent lower than those generated by our method after 80 years of simulated time (versions of PERCOVE prior to April 1998 have slightly higher bias). These estimates have much lower variance compared to those made at inventory time indicating that PERCOVE benefits from increased sample sizes coincident with longer projections in FVS (attributable to in-growth and the FVS record tripling logic).

Stand Structure

The stand structural classification generated by FVS is based on concepts described by O'Hara and others (1996). Stage and others (1995) applied these rules in analyses using FVS simulations to support the Columbia River Basin Succession Model (CRBSUM, Keane and others 1996). Stage (1997) has augmented the classification rules to accommodate users concerns and experience with several alternative classification rules (Warren and others 1997). The method presented in this report incorporates further refinements of these rules particularly for cases that arise from sparse sampling of the stand and for poorly stocked stands.

Users of structural classifications should be aware that arbitrary division of essentially continuous variables, such as tree size, into broad classes can introduce undesirable artifacts in any planning process (Haight and others 1991; Philpot and others 1998). We recommend that continuous metrics of stand structure, like the number of strata and the size of trees in the uppermost stratum, be retained along with the class itself. The interpretation of the structural class is aided when this additional information is part of the analysis and is part of the classification output. Tuning the classification rules may be necessary to meet the needs of a particular application. In general, the structural classifications are best for interpretive purposes only.

The new Structural Statistics report (fig. 3) lists the nominal d.b.h. and height, the heights of the tallest and shortest trees, the crown base height, percent

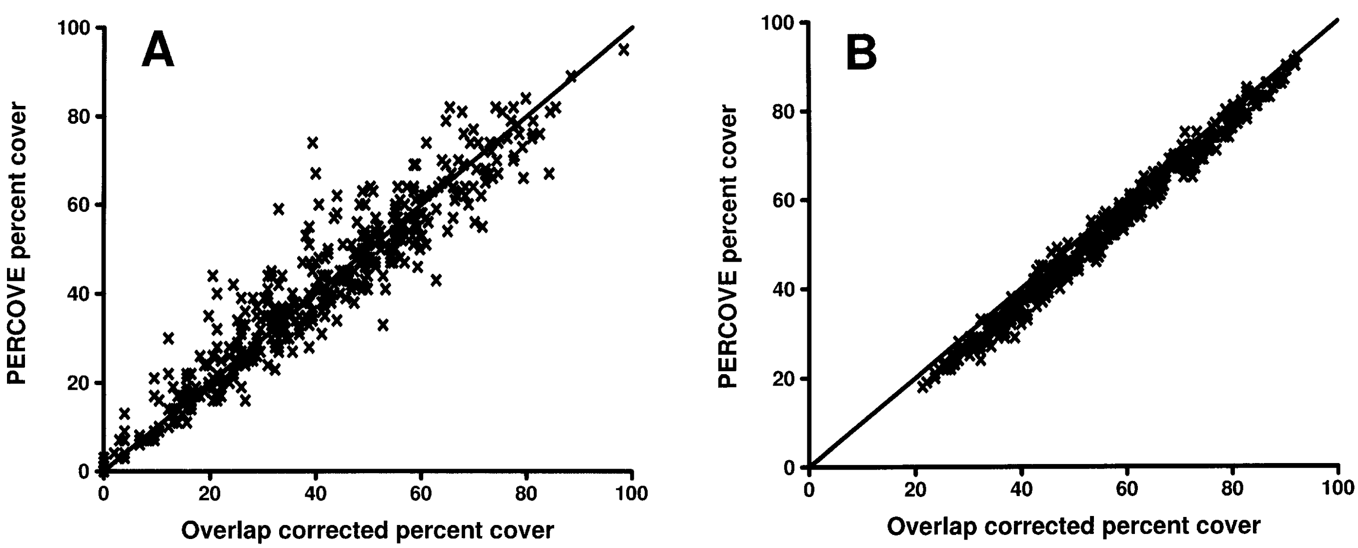

Figure 2—Percent cover estimates from PERCOVE (McGaughey 1997a) plotted over those made with equation 2, **"A"** for inventory time and "**B**" for 80 years later. PERCOVE estimates are generally lower and the variance of the estimates made for the inventory year are higher than the variance made for the stand after 80 years of simulated growth.

```
Structural statistics for stand: 15316     MgmtID: NONE

         ------------ Stratum 1 ------------ ------------ Stratum 2 ------------ ------------ Stratum 3 ------------
     Rm        ---Height-- -Crown- -Major- C        ---Height-- -Crown- -Major- C        ---Height-- -Crown- -Major- C N Tot Struc
Year Cd  DBH  Nom  Lg  Sm Bas Cov Sp1 Sp2 D  DBH  Nom  Lg  Sm Bas Cov Sp1 Sp2 D  DBH  Nom  Lg  Sm Bas Cov Sp1 Sp2 D S Cov Class
---- -- ----- --- --- --- --- --- --- --- - ----- --- --- --- --- --- --- --- - ----- --- --- --- --- --- --- --- - - --- -----
1990  0  17.6  88  95  84  49   6 GF  --  2   4.5  24  26  22  10  13 WH  --  1   1.5   9  10   8   3   4 GF  --  0 2  22  3=UR
2000  0  19.8  99 106  94  54   7 GF  --  2   7.1  32  38  28  13  26 WH  --  1   2.0  13  14  10   4   6 GF  --  1 3  35  4=YM
2010  0  21.7 108 117 103  60   8 GF  --  2   9.8  41  49  33  17  38 WH  --  1   2.9  19  21   2   4   8 GF  DF  1 3  47  4=YM
2020  0  23.6 117 125 113  64   8 GF  --  2  11.6  50  60  41  21  46 WH  --  1   4.3  25  28   4   7   9 GF  DF  1 3  55  4=YM
2030  0  25.3 125 132 121  72   8 GF  --  2  13.5  59  69   1  13  60 WH  GF  1    .0   0   0   0   0   0 --  --  0 2  63  6=OM
2040  0  26.9 133 139 129  79   9 GF  --  2  14.1  63  77   2  18  65 WH  GF  1    .0   0   0   0   0   0 --  --  0 2  68  6=OM
2050  0  28.3 139 145 136  86   8 GF  --  2  16.6  75  85   1  18  68 WH  GF  1    .0   0   0   0   0   0 --  --  0 2  71  6=OM
2060  0  29.5 146 151 142  91   8 GF  --  2  17.9  83  93   2  25  70 WH  GF  1    .0   0   0   0   0   0 --  --  0 2  72  6=OM
2070  0  30.8 151 156 148  97   8 GF  --  2  19.3  90 100   1  24  72 WH  GF  1    .0   0   0   0   0   0 --  --  0 2  74  6=OM
2080  0  32.2 157 161 155 102   8 GF  --  2  20.6  97 107  47  42  72 WH  GF  1   1.7  13  32   2   2   1 DF  LP  0 2  75  6=OM
2090  0  23.8 108 166  66  50  75 WH  GF  2   1.1   9  40   1   1   2 DF  LP  0    .0   0   0   0   0   0 --  --  0 1  75  2=SE
2100  0  24.5 112 170  76  54  75 WH  GF  2   5.7  50  50  50  37   0 PP  --  0   2.1  17  29   1   2   2 DF  LP  0 1  75  2=SE
2110  0  26.0 119 174  85  58  75 WH  GF  2   5.2  43  43  43  35   0 DF  --  0   1.7  13  26   1   1   1 DF  LP  0 1  75  5=OS
2120  0  27.0 125 178  95  62  74 WH  GF  2   5.9  41  41  41  24   0 DF  --  0   1.8  14  24   1   1   1 DF  LP  0 1  75  5=OS
2130  0  28.4 131 182 100  66  74 WH  GF  2   3.8  32  32  32  23   0 DF  --  0   1.0   8  19   1   0   1 DF  LP  0 1  74  5=OS
2140  0  29.4 136 186 100  69  74 WH  GF  2   3.6  25  25  25  13   0 DF  --  0   1.3  10  15   1   1   1 DF  LP  0 1  74  5=OS
2150  0  30.7 142 189  96  72  73 WH  GF  2    .9   7  24   1   0   1 DF  LP  0    .0   0   0   0   0   0 --  --  0 1  74  5=OS
2160  0  31.8 147 192 108  75  73 WH  GF  2   3.2  29  29  29  26   0 L   --  0   1.0   7  13   1   0   1 DF  L   0 1  73  5=OS
2170  0  32.9 151 195 136  77  72 WH  GF  2   5.3  36  36  36   4   0 LP  --  0   1.0   8  20   1   0   1 DF  LP  0 1  73  5=OS
2180  0  33.9 156 198 142  79  72 WH  GF  2   4.5  40  40  40  28   0 LP  --  0   1.2  10  21   1   1   1 DF  LP  0 1  72  5=OS
2190  0  34.7 159 201 145  81  71 WH  GF  2   1.0   8  27   1   1   1 DF  LP  0    .0   0   0   0   0   0 --  --  0 1  71  5=OS
2200  0  35.6 163 204 150  84  70 WH  GF  2   3.7  28  28  28   5   0 LP  --  0   1.1   9  17   1   1   1 DF  LP  0 1  70  5=OS
2210  0  36.8 167 207 155  86  70 WH  GF  2   3.3  27  29  27  10   0 L   DF  0   1.0   9  16   1   0   2 DF  LP  0 1  70  5=OS
2220  0  37.6 171 209 158  88  69 WH  GF  2   3.3  29  29  29  23   0 L   --  0   1.2  10  19   1   1   1 DF  LP  0 1  70  5=OS
2230  0  37.6 173 212 161  89  68 WH  GF  2   3.6  29  29  29  20   0 LP  --  0   1.5  12  18   1   1   1 DF  LP  0 1  68  5=OS
2240  0  38.4 176 214 164  91  67 WH  GF  2   1.2  10  24   1   1   1 DF  LP  0    .0   0   0   0   0   0 --  --  0 1  67  5=OS
2250  0  38.7 179 216 167  92  66 WH  GF  2   1.5  12  27   1   1   2 DF  LP  0    .0   0   0   0   0   0 --  --  0 1  66  5=OS
2260  0  38.1 180 218 170  94  65 WH  GF  2   4.7  43  43  43  33   0 LP  --  0   2.1  16  26   2   2   1 DF  LP  0 1  65  5=OS
```

Figure 3—Example of a Structural Statistics report.

canopy cover, major species, and a code indicating if the stratum is invalid, valid, or the uppermost valid stratum. For the stand, the number of valid strata, percent canopy cover, and structural class are reported. These statistics are output for the stand before simulated harvests and are repeated for post harvest conditions when a harvest is simulated. Table 1 provides a summary of the data displayed in the report, and table 2 defines the structural classes.

The canopy strata are initially defined by naturally occurring gaps in the distribution of tree heights. The gaps are found when the heights of two trees in a list sorted by height differ by more than 30 percent of the height of the taller and at least 10 feet. The two largest gaps define three potential strata. If there is only one gap, two potential strata are defined and if there are no gaps, one potential stratum is defined. Trees in the sorted list that have very small sampling probability are skipped until the sum of the skipped trees' sampling probability accounts for over two trees per acre.

Initially defined strata must have over 5 percent canopy cover or they are rejected. Nominal stratum d.b.h. and height are computed by averaging the nine sample trees centered on the 70th percentile tree. Once the strata are defined, the stand is classified as *bare ground*, *stand initiation*, *stem exclusion*, *understory reinitiation*, *young forest multistrata*, *old forest single stratum*, or *old forest multistrata* as a function of the number of strata, the nominal d.b.h. of trees in the strata, and stocking (table 2).

Appendix 2 contains a more detailed explanation of the method used to produce the report. The classification logic can be tuned to achieve specific goals using an FVS keyword that is described in the next section titled "FVS User Information."

Latham and others (1998) have presented a procedure for defining strata based on the crown length of the single tallest tree in each succesive "stratum." Our search for naturally occurring gaps in the height distribution attempts to focus on the outcome of disturbance-triggered pulses of regeneration—a concept fundamental to the O'Hara classification.

O'Hara and others (1996) described two stem exclusion classes, open and closed canopy. In the method presented in this report, this distinction is not made. To capture O'Hara's distinction, we classify stands that meet the d.b.h. criteria for stem exclusion and have low stocking as *stand initiation*. Stands with low stocking are those with a stand density index (Reineke 1933) below 30 percent of the site-specific maximum for the stand. Site-specific maximum stand density indices are part of FVS.

Stands that would be *old forest single stratum* using Stage and other's (1995) rules are classified *old forest multistrata* when the d.b.h. of the smallest tree in the stratum is less than 3 inches. This rule is designed to

Table 1—Description of the data displayed in the Structural Statistics report.

Heading	Description
Year	FVS cycle year. Data reported are for the beginning of each cycle.
Rm Cd	0 = row reports the conditions prior to any simulated tree removals. 1 = row reports the conditions after any simulated tree removals. If there are no removals in a cycle, then there is no row with a “Rm Cd” of 1.
DBH	Nominal d.b.h. attributed to the stratum is computed as follows: a list of trees in the stratum is constructed by accumulating trees in descending order of height until the sum of the cover is 95 percent (a percentage that does not account for crown overlap). Percentiles in the distribution of crown areas are computed for all trees in this list and the 70th percentile tree is found. The four trees larger and the four trees smaller than this 70th percentile tree are selected. An average d.b.h. is computed for those 9 sample trees, weighting each tree record by the number of trees per unit area represented by the record. When less than four larger or four smaller trees are found, just those within the range are included in the average. This rule was devised in an attempt to mimic the selection of trees seen in an aerial photograph under the assumption that the observers estimates would be more strongly influenced by the larger trees.
Height, Nom	*Nominal* height of the stratum. It is the weighted average heights of the same trees used to compute nominal d.b.h.
Height, Lg	Height of the *tallest* tree in the stratum.
Height, Sm	Height of the *shortest* tree in the stratum.
Crown Bas	Weighted average height to crown base of all trees in the stratum.
Crown Cov	Percent canopy cover, accounting for overlap, of trees in the stratum.
Major Sp1	Code for the tree species that accounts for the most crown cover of all trees in the stratum.
Major Sp2	Code for the tree species that accounts for the second most crown cover of all trees in the stratum.
CD	Stratum status code, where 0 = the stratum is invalid, 1 = the stratum is valid, and 2 = the stratum is the uppermost valid stratum.
NS	The number of valid strata.
Tot Cov	Percent canopy cover, accounting for overlap, of trees in the stand.
Struc Class	Stand structural class (table 2).

Table 2—Definition of structural classes for the forest stand or patch (several parameters values can be set by the user, see the StrClass keyword presented below).

Code	Name	Description of stand
0 = BG	*bare ground*	Less than 5 percent crown cover (StrClass field 2) and fewer than 200 trees per acre (StrClass field 6).
1 = SI	*stand initiation*	Less than 5 percent crown cover (StrClass field 2) and greater than or equal to 200 trees per acre (StrClass field 6), or one stratum with an nominal d.b.h. less than 5 inches (StrClass field 3; a stratum must have more than 5 percent crown cover to be considered a valid stratum).
2 = SE	*stem exclusion*	One stratum with an nominal d.b.h. between 5 and 25 inches (StrClass fields 3 and 4). This classification is changed to *stand initiation* if the stand density index is below 30 percent (StrClass field 7) of the maximum allowed for the stand.
3 = UR	*understory reinitiation*	Two strata with the uppermost having a d.b.h. between 5 and 25 inches (StrClass fields 3 and 4).
4 = YM	*young forest, multistrata*	Three or more strata with the uppermost having a d.b.h. between 5 and 25 inches (StrClass fields 3 and 4).
5 = OS	*old forest, single stratum*	One stratum, over 25 inches d.b.h. (StrClass field 4), and smallest tree is greater than 3 inches d.b.h.
6 = OM	*old forest, multistrata*	Two or more strata, d.b.h. of uppermost stratum is over 25 inches d.b.h.; or one stratum, over 25 inches d.b.h., and smallest tree is less than or equal to 3 inches d.b.h. (this could alternatively be called an *old forest, continuous stratum* stand).

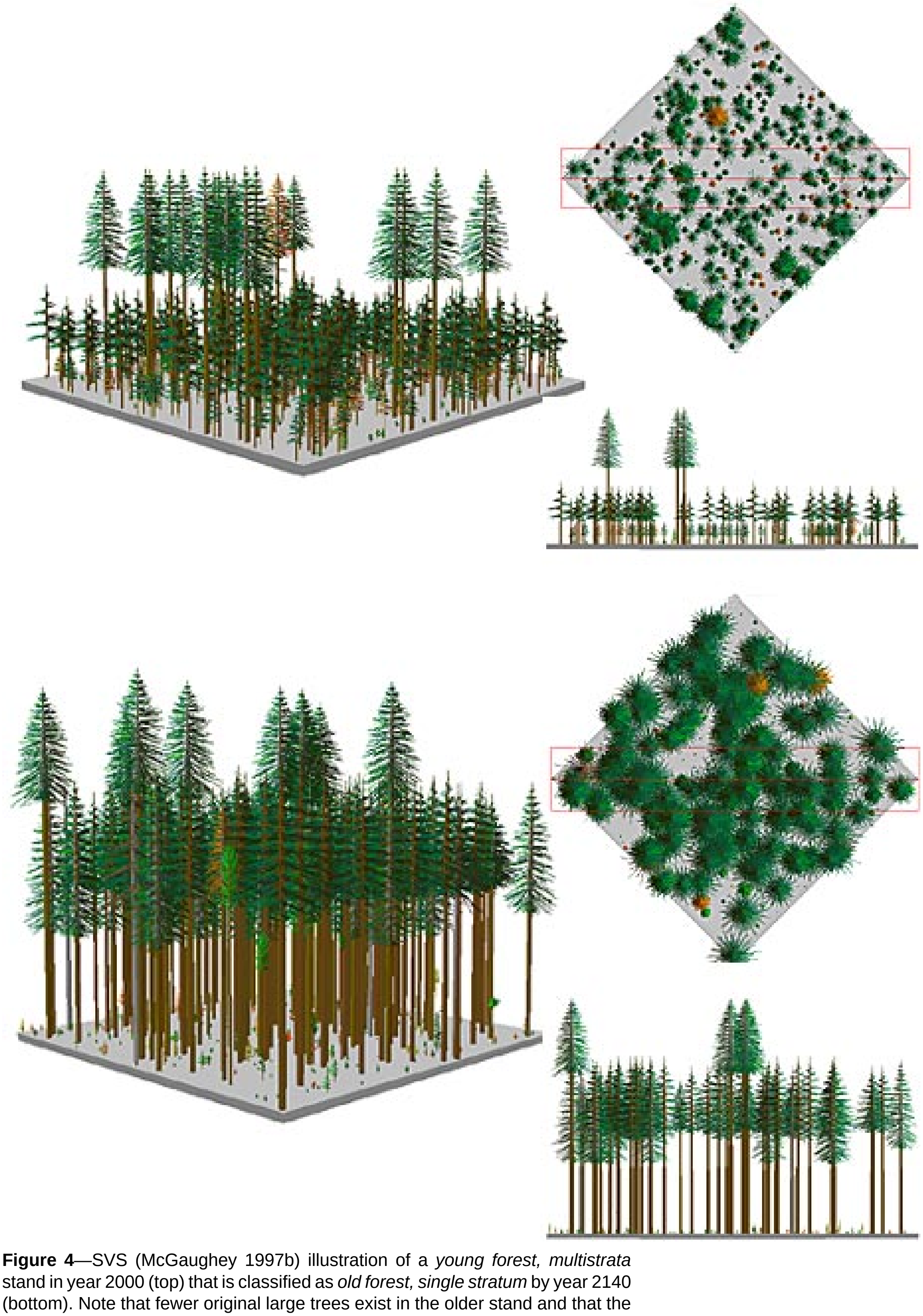

Figure 4—SVS (McGaughey 1997b) illustration of a *young forest, multistrata* stand in year 2000 (top) that is classified as *old forest, single stratum* by year 2140 (bottom). Note that fewer original large trees exist in the older stand and that the distinct valid strata that existed earlier in the stand's life have merged by year 2140.

better capture the situation where there are no breaks in the canopy but where a wide range of diameters indicates substantial continuing regeneration.

Figure 4 portrays a *young forest, multistrata* stand using the Stand Visualization System (McGaughey 1997b) for the end of the first simulation cycle (year = 2000). Later, the stand is classified as *old forest, single stratum* in the year 2140 because the initially distinct strata have merged.

A comprehensive analysis of the classification logic is beyond the scope of this report, but early experience indicates that the procedure provides an informative characterization of structural variation in an extensive inventory data set (Stage and others 1995). However, incorrect interpretations can occur if the other structural statistics are ignored. User's are encouraged to experiment with the parameters of the rules to serve their particular needs.

Note that the classification can vary between runs of FVS with different starting values of the random number generator. This behavior is inherent in any classification system based on statistics sensitive to random variation such as average d.b.h. of a subset of trees. When the stratum d.b.h. is near the class boundary, the classification of the stand in one class versus another is sensitive to the interaction between the arbitrary rules and the variation inherent in the sample data and in the processes of growth and regeneration.

FVS User Information

StrClass Keyword

Use the StrClass Keyword to cause the table of stand structural class statistics to be printed, to set some of the parameters of the structural classification, or both. This keyword conforms to the standard FVS usage rules.

StrClass Request calculation of structural classification by FVS and that the results be made available to the Event Monitor (Crookston 1990).

- Field 1: A nonzero entry causes FVS to print the table of structural statistics; default is 1.
- Field 2: The minimum percent cover that must be exceeded for a potential stratum to qualify as a valid stratum; default is 5 percent.
- Field 3: The d.b.h. boundary separating seedling/sapling-sized trees from pole-sized trees, default is 5 inches.
- Field 4: The d.b.h. boundary separating pole-sized trees from large trees that may be considered *old*, default is 25 inches.
- Field 5: The percentage of a tree's height that is used to define the minimum gap size, default is 30 percent.
- Field 6: Minimum trees per acre that must be exceeded for a stand that has less than 5 percent cover to be classified *stand initiation* rather than *bare ground* (default is 200 trees per acre, which implies an average spacing of about 15 feet).
- Field 7: The percentage of the maximum stand density index that must be exceeded for a stand to be classified *stem exclusion* rather than *stand initiation*, default is 30 percent.

Event Monitor Use

When the StrClass keyword is used, thereby triggering the classification logic, the following Event Monitor variables are automatically defined by FVS:

- BSClass The before-thinning structural class code, see table 1.
- ASClass The after-thinning structural class code, see table 1.
- BStrDbh The before-thinning nominal d.b.h. of the uppermost stratum.
- AStrDbh The after-thinning nominal d.b.h. of the uppermost stratum.
- BCanCov The before-thinning percent canopy cover for the stand.
- ACanCov The after-thinning percent canopy cover for the stand.

The Event Monitor contains an often used function called SpMcDBH (Crookston 1990, p. 19). Since the introduction of this function, it has been enhanced to include more arguments. With the introduction of the new percent canopy cover, this function has been enhanced further to compute the cover for any subset of the trees in the stand, including the subset of all trees. The subset is defined by the arguments to the function. The current definition of this function is as follows:

SpMcDBH (arg1,...,arg8) Returns one of seven attributes for a subset of the trees. The attribute depends on the value of the first argument:

1 = trees per acre
2 = basal area per acre
3 = total cubic volume/acre
4 = total board foot volume/acre
5 = quadratic mean diameter
6 = average height
7 = percent canopy cover

The subset of trees is defined by the remaining seven arguments:

arg2 = the numeric species code for the trees in the subset. A zero indicates all species are included.

arg3 = the tree-value class for trees included in the subset. A zero indicates trees of all tree-value classes are included (codes 1, 2, and 3 are defined).

arg4 = to be included in the subset, the tree's d.b.h. must be greater than or equal to this value.

arg5 = to be included in the subset, the tree's d.b.h. must be less than this value.

arg6 = to be included in the subset, the tree's height must be greater than or equal to this value.

arg7 = to be included in the subset, the tree's height must be less than this value.

arg8 = code 0 for live trees, code 1 for recent mortality, or code 2 for harvested trees.

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Appendix A: Computing Percent Canopy Cover

The simplified grid method used to compute canopy cover percent while accounting for overlap follows the procedure outlined here. After running the algorithm, the fundamental underlying mathematical relationship described in equation 2 was found to represent the logic of the algorithm. The algorithm is presented as evidence that the equation is appropriate.

Accept the following definitions:

percentCover is the percent canopy cover,
$crarea_i$ is crown area per acre of sample tree record *i*
grid is a vector of 1000 real values indexed with the letter *k*,
full is the number of square units of crown area to fill one member of *grid* (when the units are feet and acres, the value of *full* is 43560/1000 = 43.560 ft^2),
ix is a random integer between 1 and 1000.

Follow this procedure.

```
For each tree i {
  remain = crarea_i / full
  while (remain > 0) {
    define a new ix
    k = ix
    if (remain > 1) {
      remain = remain – 1
      grid_k = 1 }
    else if (grid_k < 1) {
      grid_k = grid_k + (( 1 – grid_k ) * remain)
      remain = 0}}}
percentCover = 0.1 Σ grid_k
```

Note that grid cells are represented by real numbers rather than binary bits that have the value 1 when the cell contains some projected canopy cover and the value 0 when the cell contains no canopy cover. In this case, the proportion of a grid cell covered by canopy is stored. If a sample tree projects less than *full* cover, the proportion is accumulated. This is often the case in FVS when a tree has a very small sampling probability or after several years of simulated mortality reduced the sampling probability. In a bit map approach, such trees are either lost because they project less canopy than represented by the bit, they are over accounted for because the bit is turned on regardless of the amount of cover represented by the bit, or another random number is needed to see if the bit should be turned on or not.

Overlap is accounted for by not letting a grid cell contain more than *full* units of canopy cover. If a single grid cell is selected twice, the crowns, or some portion thereof, are defined to be overlapping. When *remain* and $grid_k$ are both less than 1, a tree record's canopy, or some portion thereof, is not sufficient to fill a cell. The method used for this case is the same used by Moeur (1986) except that Sutterland's rule applied to the total canopy rather than one thousandth.

The simplified grid method assumes that the distribution of trees in space is random, but only to the resolution of the grid cell. When two trees are in the same grid cell, the assumption of some overlap implies that they must be near each other. The smaller the trees are, the closer they must be if their crowns overlap even a fractional amount. However, the actual spatial arrangement of the trees is never actually inferred as is the case with a bit map approach, thereby avoiding complications arising from tree stems occupying the same point.

The simplified grid method accounts for all the crown area of each tree in the sample. In a bit map approach, part of the crown area for a boundary tree may be lost by extending outside the grid, causing underestimates of percent canopy cover. Bit map approaches can make up for this lost crown by placing that portion that falls outside of the map somewhere inside the map's edge. Corners of the map present complications that can lead to inaccurate results if ignored. Our method avoids this issue and accounts for the complete crown area.

Appendix B: Structural Classification Logic

Five parameters, which can be changed by using the StrClass keyword in FVS, are used in the classification rules. They are defined as follows:

Parameter name	Role of parameter	Field on StrClass keyword
cmin	Minimum percent crown cover that must be exceeded for a potential stratum to be considered a significant stratum; default = 5 percent crown cover	2
dpole	Nominal d.b.h. that defines the break point between seedling/sapling-sized trees and pole-sized trees; default is 5 inches.	3
dlarge	Nominal d.b.h. that defines the break point between pole- and large-sized trees; default is 25 inches.	4
pht	Percentage of a sample tree's height that defines the minimum size of a gap between the top of sample tree and the top of the next shorter sample tree. That is, a gap must be equal to or larger than this gap size to be considered true gap; default is 30 percent.	5
tmin	Minimum number of trees per acre that must be exceeded for a stand that has less than *cmin* cover to be classified *stand initiation* rather than *bare ground*; default is 200 trees.	6
pSDImax	Percentage of the maximum stand density index that must be exceeded for a stand to be classified *stem exclusion* rather than *bare ground*.	7

Classification proceeds through the following steps:

1. If there are no sample trees, then the stand is *bare ground*.

2. A list of sample tree records, each of which represent over 0.00001 trees per acre, is constructed.

3. If there is only one sample tree record in the list (a rare event), then the following rules apply:

a) If the sample tree's canopy covers less than *cmin* of the ground, then the stand is classified *bare ground* if the sample tree represents less than *tmin* trees, and otherwise the stand is classified as *stand initiation*.

b) If the sample tree's canopy covers over *cmin* of the ground (this can happen if the sample tree represents many trees per acre, if it is a large tree, or both), and its diameter is less than *dpole*, then the stand is classified *stand initiation*.

c) If the sample tree's canopy covers over *cmin* of the ground and its diameter is greater than or equal to *dpole* and less than *dlarge*, then the stand is classified *stem exclusion*. This classification is changed to *stand initiation* if the stand density index is below *pSDImax* of the maximum SDI allowed for the stand.

d) If the sample tree's canopy covers over *cmin* of the ground and its diameter is greater than or equal *to dlarge*, then the stand is classified *old forest single stratum*.

4. Find the two largest gaps in the distribution of tree heights to define boundaries of potential strata. In the list of trees sorted by descending order of heights, the two largest gaps are located using these rules:

a) A gap between a tree and the next smaller tree must be larger than a minimum gap size. The minimum gap size is a percentage (*pht*) of the height of the taller tree or 10 feet, whichever is greater. For example, if *pht* is 30 percent, and the larger tree is 100 foot tall, then the gap size must be at least 30 feet. Consider another example where the larger tree is 20 foot tall. Because the 30 percent rule gives 6 feet, the minimum gap size between a 20 foot tall tree and the next smaller tree would be set to 10 feet because 10 feet is greater than 6 feet. The indices of the two largest gaps are recorded.

b) An additional rule is used during the search for gaps. If the next smaller sample tree represents less than two trees per acre, the program skips it and looks to the tree that is smaller than it, and so on, until the sum of the number of trees per acre represented by the smaller sample trees passed over exceeds two trees per acre. For example, say the larger tree is 100 feet tall and the next smaller tree is 75 feet tall (the gap is 25 feet, which is less than 30 feet, and therefore does not qualify). Furthermore, say that the 75 foot tall tree represents only 0.5 trees per acre and that the next smaller tree below it is 65 feet tall and represents 1.6 trees per acre. In this case, the 75 foot tree would be considered an "insignificant ladder" tree, one that would not be seen as forming a continuous canopy because it is so rare. But it is not entirely ignored because it, in combination with the 65 foot tall tree, represents over two trees per acre. In this case the gap is defined to be 35 feet (100 foot tall tree minus the 65 foot tree), which is larger than the minimum required for a valid gap.

c) If no valid gaps are found, the stand is considered to have only one potential stratum. If one valid gap is found, the stand has two potential strata, and if two gaps are found, the stand has three potential strata.

5. Canopy cover is computed for each potential stratum. A stratum is considered valid if the cover exceeds *cmin*.

6. Compute the nominal d.b.h. of the uppermost stratum by averaging the d.b.h.'s of the nine trees centered on the 70th percentile sample tree in the distribution of crown widths. (Fewer than four trees above or four below may be used if the sample is sparse).

7. Using the number of valid strata computed in steps 2 through 5, the nominal d.b.h. of the uppermost stratum from step 6, the site's maximum SDI, and the number of trees (when there is less than 5 percent crown cover), the structural class for the stand is assigned using the definitions in table 2.

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