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Monitoring stand structure in mature coastal Douglas-fir forests: effect of plot size

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Abstract

National and regional interest in the distribution and trends of forest habitat structure and diversity have placed demands on forest inventories for accurate stand-level data. A primary need in the coastal Pacific Northwest of the United States is information on the extent and rate of development of mature forest structure. The objective of this study was to evaluate alternative sampling schemes within a standard national cluster plot design able to efficiently determine density of large live trees and snags, tree mortality, and tree species richness. A simulation approach used stem maps from 19 permanent forest plots dominated by mature *Pseudotsuga menziesii* (Douglas-fir) of at least 1 ha in size that had been sampled for up to 23 years. Clustered subplots sampling between 0.5 and 81% of the stand area were randomly located in stands to select mapped trees. Estimation error analysis compared the percent difference between sample data and full-stand values by subplot size for 30 iterations per subplot size per stand. Comparison with analyses of regional inventory plots allowed greater inference concerning results.

Samples of at least 40% of a stand (four 18 m radius subplots) were required to reduce errors for estimated density of large trees ($\geq$122 cm DBH) below 25% of true density at least 66% of the time. For mortality, subplots sampling at least 50% of a stand were needed to reach errors below 50% of true mortality at least 66% of the time. However, for trees <75 cm DBH, the standard inventory sample of 0.07 ha with four 7.3 m radius subplots did meet these accuracy levels for density and mortality. Relatively large plots were required to estimate species richness within one species of true richness, particularly for the relatively diverse smaller tree size classes. Efficient sampling of species richness could use species lists, instead of measuring many small trees on large plots. Reducing sample errors to acceptable levels will increase the utility of inventory plot data to evaluate stand structure, successional development, carbon sequestration, species diversity, and ground-truth for remote sensing.

Keywords: Plot size; Inventory; Old-growth; Stand structure; *Pseudotsuga menziesii*

1. Introduction

Forest managers and policy makers have given increased attention in recent years to assessing and monitoring ecosystem sustainability at the national level (Santiago Declaration, 1995; Gillespie, 1999). Similar attention has been focused on achievement of ecological objectives concerning wildlife habitat, native and exotic species, and disturbance effects at the regional level (Hemstrom et al., 1998; Mulder et al., 1999). National and regional inventory programs are being asked to provide this information (Blue Ribbon Panel on Forest Inventory and Analysis,

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1992). However, monitoring ecological attributes often requires more measurements and greater site-level precision than are typically needed for regional assessments of timber value. For example, knowing how many standing dead trees (i.e. ‘‘snags’’) are present for wildlife use on a landscape is useful, but knowing how the abundance of snags varies with forest seral stage provides information about their potential habitat value.

Managing for mature and old-growth forest attributes has become an important emphasis for many federal and state forest managers in the Pacific Northwest of the United States (FEMAT, 1993; Max et al., 1996). But the criteria for classifying forests into these types require detection of forest attributes at relatively low densities. For example, commonly used criteria for old-growth *Pseudotsuga menziesii* (Douglas-fir) stands include at least 20 live trees/ha ≥100 cm DBH (diameter at breast height) or >200 years in age, and 10 snags/ha ≥50 cm DBH (Old-Growth Definition Task Group, 1986). Monitoring stand-level ecological objectives in the region often requires determining the size distribution of live and dead trees, species composition, and the abundance of coarse woody debris (Ohmann and Cohen, 1993; Hemstrom et al., 1998). Thus many of the inventory and monitoring needs in the region extend beyond the traditional objectives of regional, aggregate estimates of forest attributes. Instead, relatively precise data are needed from individual plots in order to classify them into habitat types (Williams et al., 2001), to serve as ground-truth for remote-sensing classifications, and to monitor development of stand structure in response to alternative management approaches.

The Forest Inventory and Analysis program (FIA) of the USDA Forest Service Research Stations is responsible for the inventory of all forest lands across the country. Recent changes have been made to the program to improve national consistency and timeliness, including the use of a standard plot design and standard data collection protocols (Reams et al., 1999; Gillespie, 1999). The FIA field plots are systematically located at a density of one plot per 2430 ha (6000 acres). Each sample plot consists of four points spaced 36.3 m (120 ft) apart, with two nested subplot sizes at each point. Trees less than 12.7 cm (5 in.) DBH are sampled with 2.07 m (6.8 ft) radius ‘‘microplots’’, while larger trees are sampled with 7.32 m (24 ft) radius ‘‘subplots’’. Protocols are designed to accommodate optional 18 m (59 ft) radius ‘‘annular plots’’ to sample elements that occur at low density, at the discretion of regional FIA programs.

The ability of this or other potential sampling designs to provide the information desired in the Pacific Northwest in the most efficient manner possible is unknown. The national FIA plot design was based on a detailed study of cost-efficiency for estimating tree density, basal area, and volume in the forests of Maine and New Jersey (Scott, 1993). However, large trees, which occur at low densities, are more common, and forests are generally more structurally complex in the Pacific Northwest than in the eastern US (Waring and Franklin, 1979).

The objective of this study was to assess the effect of different plot sizes on the accuracy of measuring important attributes of individual mature forest stands: density of large trees and snags, species richness, and mortality. Alternative plot sizes were constrained to evaluate potential modifications to the standard FIA four-point cluster plot.

2. Methods

2.1. Stem-mapped reference stands

Data for 19 homogeneous permanent plots at least 1 ha in size were provided by the H.J. Andrews LTER Permanent Sample Plot group (Acker et al., 1998). Plots had been subjectively placed to characterize and monitor mature and old-growth stands in a variety of forested plant communities. The stands used for this study were dominated by *P. menziesii* (Douglas-fir) and represented a range of west-slope Cascade Mountain plant communities, from warm and dry *Pseudotsuga* associations to cool, wet *Abies amabilis* (Pacific silver fir) associations (Hemstrom et al., 1987). Most of the plots were located in central Oregon, and the rest were in southern Washington. The age range for five of the stands was 90–150 years, and are referred to as the ‘‘mature’’ age class (Table 1). The remaining stands were >400 years old and are referred to as the ‘‘old-growth’’ age class. All live trees ≥15 cm had been stem-mapped, tagged, measured, and periodically remeasured during 10–23-year periods on each plot. Stem-mapped plots are hereafter referred to as ‘‘reference stands’’.

Table 1
Characteristics of stem-mapped reference stands used for simulated sampling[a]

Stand	Type	Area (ha)	Age (years)	QMDdom (cm)	Species (*N*)	Dominant species	Large trees, (*n*/ha)	Mortality, (*n*/ha/yr)
AX15	None	1.0	150	47	5	Psme, Tshe	0	3.5
RS24	Mature	1.0	90	57	6	Psme, Tshe	0	6.2
RS35	Mature	2.0	130	62	7	Psme, Alru	1	3.0
RS37	Mature	1.0	130	71	7	Psme, Acma	1	1.8
RS26	Mature	1.0	150	62	6	Psme, Tshe	0	3.4
RS22	Old-growth	1.0	450	88	5	Abpr, Psme	5	4.1
RS23	Old-growth	1.0	450	93	7	Tshe, Psme	7	1.0
TO04	Old-growth	1.0	750	101	7	Tshe, Psme	13	2.9
RS01	Old-growth	1.0	460	77	7	Psme, Acma	14	2.0
RS02	Old-growth	1.0	460	107	5	Psme, Tshe	22	7.2
RS03	Old-growth	1.0	460	104	7	Psme, Thpl	23	1.2
RS38	Old-growth	1.0	450	141	8	Psme, Thpl	24	2.5
RS34	Old-growth	2.0	450	125	5	Thpl, Psme	25	0.9
RS31	Old-growth	1.0	450	97	5	Psme, Tshe	28	1.1
RS27	Old-growth	1.0	450	109	7	Psme, Tshe	34	2.0
RS30	Old-growth	1.0	450	115	5	Psme, Thpl	35	0.5
RS28	Old-growth	1.0	450	136	6	Psme, Tshe	39	1.2
RS29	Old-growth	1.0	450	130	5	Psme, Thpl	42	1.0
GMNF	Old-growth	4.0	325	133	4	Abpr, Psme	46	1.7

[a] Type indicates how stand was used for grouped analyses. QMDdom: quadratic mean diameter of dominant and codominant trees. Species codes are: Psme: *P. menziesii*, Tshe: *Tsuga heterophylla*, Alru: *Alnus rubra*, Acma: *Acer macrophyllum*, Abpr: *Abies procera*, Thpl: *Thuja plicata*. Large trees refers to trees ≥122 cm DBH.

The analysis of the reference stands consisted of repeated simulated "sampling" of the stands with randomly placed plots of different sizes. Toroidal edge correction was used to ensure equal sample probability of all trees while correcting for edge effects (Griffith, 1983; Boots and Getis, 1988). This adjustment in effect "joins" the opposite edges of a mapped stand, creating a continuous surface for random plot placement. A common statistical approach to adjust for plot boundary effects is to increase the weights of border trees to compensate for reduced sample probabilities (O'Regan and Palley, 1965). This approach was not used for this study because it assumes a uniform increase in the response variable with sample area, and cannot account for different spatial point patterns. Toroidal edge correction requires fewer assumptions, but can give unrealistic results when the spatial scale of point patterns is large relative to the area of the mapped plot.

Trees were sampled using the FIA cluster plot design, with the centers of three subplots spaced 36.6 m from the central subplot on azimuths of 0°, 120°, and 240°. The center of the central subplot ("plot center") was randomly placed for each of 30 iterations. Subplot sizes ranged from 2 to 50 m in plot radius. Sizes increased in 2 m increments up to 18, except that 7.32 m was used instead of 8 to match the standard FIA subplot size. Larger sample areas were simulated by increasing the radius of the central subplot incrementally to 50 m while keeping the other three subplots at 18 m radius. The reference stands that covered more than 2 or 4 ha were sampled with two or four cluster plots, respectively, with plot centers kept 100 m apart. These subplot sizes sampled between 0.5 and 81.2% of the area of the reference stands (Table 2). Trees included within the four subplots (eight or 16 subplots for the larger stands) were then used to calculate the response variables of interest (e.g. tree density). This simulated sampling was repeated for each subplot size 30 times in each stand.

The response variables of interest for the reference stand analysis were live tree density, species richness, and mortality by size class (dead trees—snags—were not digitized in the reference stand data, so their density could not be evaluated). Mortality was determined from remeasurement data of individual tagged

Table 2
Sizes of circular sample subplots used, and proportion of a 1 ha stand sampled by four plots[a]

Radius (m)	Sampled (%)
2.0	0.5
4.0	2.0
6.0	4.5
7.32	6.7
10.0	12.6
12.0	18.1
14.0	24.6
16.0	32.2
18.0	40.7
28C	49.8
38C	60.6
44C	69.4
50C	81.2

[a] Sizes greater than 18 m are distinguished with letter C, to reflect that only the center subplot increased in size, while the other three subplots remained at 18 m radius.

trees over the 10–23-year periods (depending on the stand) for which data were available. The four diameter size classes used were: 15.0–32.9, 33.0–74.9, 75.0–121.9, and ≥122.0 cm DBH (5.9–12.9, 13.0–29.4, 29.5–47.9 and ≥48.0 in., respectively). The 33 and 122 cm DBH cutoff points correspond with those used by the CVS inventory for forests west of the Cascade crest (Max et al., 1996). The 75 cm cutoff was chosen to divide the intermediate size class into two classes of approximately equal range. The mature stands had few, or no, trees in the largest size class (Table 1). The estimation error for density and mortality was calculated as the "relative difference" between the sample estimate and the "true" value of the reference stand area used for analysis:

$$\text{rel\_dev}_{jk} = \frac{\text{abs}(x_{ijk} - \mu_{jk})}{\mu_{jk}}$$

where x_{ijk} is the value (e.g. density) from subplot size i for tree size j in stand k, and μ_{jk} the true value for tree size j in stand k. The estimation error used for species richness was absolute, not relative, because absolute difference is more interpretable (i.e. error is in terms of number of species rather than the percentage of the number of species).

The focus of this study was on the magnitude of the error for each individual sample using a particular subplot size, in a specific stand. However, to simplify display of the results, mean estimation errors were calculated for the 30 iterations of each response variable, for each combination of tree size class by subplot size by stand age class (stand AX15 was not included in the means because its size structure was unique, with a high density of slow-growing, relatively small trees). To facilitate interpretation of these means, the distribution of estimation errors, relative to the mean, were then examined to determine the proportion of the 30 estimation errors which were lower in magnitude than the mean. Plot size had a greater effect on the estimation errors than size class or stand, so errors were averaged by plot size and distributions reported.

Alternative approaches to the analysis of plot size often have different objectives. For example, some evaluate the effect of plot size and number of plots on among-plot variation (Johnson and Hixon, 1952; Reich and Arvanitis, 1992), in order to assess the accuracy of population totals, but not the error of individual estimates. Another commonly used approach for statistical testing of sample errors is the Chi-square test of accuracy (Freese, 1960). This test compares the variance between sampled and expected values with a desired sample accuracy (often expressed as a percentage of the true value). However, the test behaves erratically for low numbers, and it does not describe the magnitude or distribution of the sampling error.

Another common approach for simulating spatial count and density data is the Poisson distribution (Diggle, 1983). It was not used for the primary analysis of plot size because it simulates sample probabilities for simulated populations with random spatial distributions. However, it was used for comparison with the estimated densities generated from simulated sampling of the mapped reference stands. The Poisson distribution function was used to calculate the probabilities of estimating different densities with a given true density and plot size. The relative differences between estimated and true densities were calculated, then averaged using the Poisson probabilities as weights.

Additional analyses were done to address the question: if sampling of large trees in mature and old-growth stands were to occur using the 18 m radius optional "annular" subplots on FIA plots, what should the lower limit for DBH be for defining "large"? In other words, for trees greater than DBH = x, what is the gain in accuracy from using an 18 m radius sample plot instead of the standard 7.32 m radius sample plot? This was answered using the same approach described above, with random placement of sample plots within the stands, and relative difference of density estimates for trees over a specified diameter limit (ranging from 35 to 125 cm) calculated for each plot size.

2.2. CVS data

In order to expand the scope of inference of the plot size analysis, plot data from inventories of Bureau of Land Management (BLM) in western Oregon and National Forest System (NFS) lands in Oregon and Washington were used to evaluate plot size effects on tree density estimates. These plots provided a broader, presumably more representative, sample of forest conditions than those represented by the stem-mapped reference stands. These inventories used the Current Vegetation Survey (CVS) plot design (Max et al., 1996). Each sample plot consisted of four points spaced 40.8 m from a central point in each cardinal direction. Trees $\geq$33 cm were sampled with 15.6 m radius plots around each point, and "large trees" (defined as trees >81 cm DBH east of the Cascade crest and trees >122 cm DBH west of the crest) were sampled on a circular 1 ha plot surrounding the points. The data from NFS lands were used to calculate frequency distributions for densities of large trees from large-diameter stands, for comparison with the reference stands.

More detailed analyses were possible for CVS plots on BLM lands, because the distance from the subplot center was recorded for all sampled trees. This made it possible to use the BLM sample as the "best" estimate of stand density and examine the effect of sampling the data with smaller plot sizes for each size class. One analysis with the BLM data compared density estimates of trees greater than 75 cm DBH using the FIA 7.32 and 18 m radius plots with the CVS sample. This analysis used the 303 inventory plots for which four or more subplots fell in the same forest type and stand size class, based on categories described in the field. Where all five subplots fell in the same stand type, subplot number 5 was dropped. Another analysis compared sampling of trees over 122 cm DBH using four 18 m radius plots to the full hectare BLM sample. This evaluation used the first four points in a plot and the full hectare sample, limited to the 237 plots which had all five points in the same stand type.

3. Results

3.1. Density

Relative difference declined exponentially with increasing subplot size for all tree diameter classes in all stands (Fig. 1). The curves tended to level off after a subplot radius of about 12 m, where mean relative differences ranged from 20 to 40%. The exception to this was the largest tree size in mature stands, where two of the stands had only one tree per hectare and the other two had none. Relative differences usually increased with tree size class, although mean differences in mature stands were higher for the 13–33 cm DBH class than for the 33–17 cm DBH class. The proportion of relative differences that were less than the mean relative difference were quite consistent at about 56% for subplot sizes above 4 m radius (Table 3). Applying this information to Fig. 1, it appears that a 4-subplot cluster of 10 m radius subplots is sufficient to meet an accuracy criteria of relative differences $\leq$25%, approximately 66% of the time, for trees <75 cm DBH in old-growth stands. However, meeting the same criteria for trees $\geq$122 cm DBH in old-growth stands would require subplots at least 18 m in radius.

For a given subplot size, the magnitude of mean relative differences in tree density was primarily related to the magnitude of true stand density (Fig. 2). Mean relative differences for the standard FIA 7.32 m radius subplot were greater than 25% for most stands for tree size class densities less than 100 trees/ha. The same level of accuracy was reached with the optional FIA 18 m radius subplots for most stands for stand densities of 20 trees/ha and higher. The relative differences simulated from the reference stands were lower than those simulated for the same plot size using the Poisson process model. This was expected, given that the Poisson model simulates a random spatial distribution and large trees are often regularly distributed at larger spatial scales. The disparities in mean relative difference from these two approaches for the same plot size were generally between 5 and 10% for most stand densities. If the

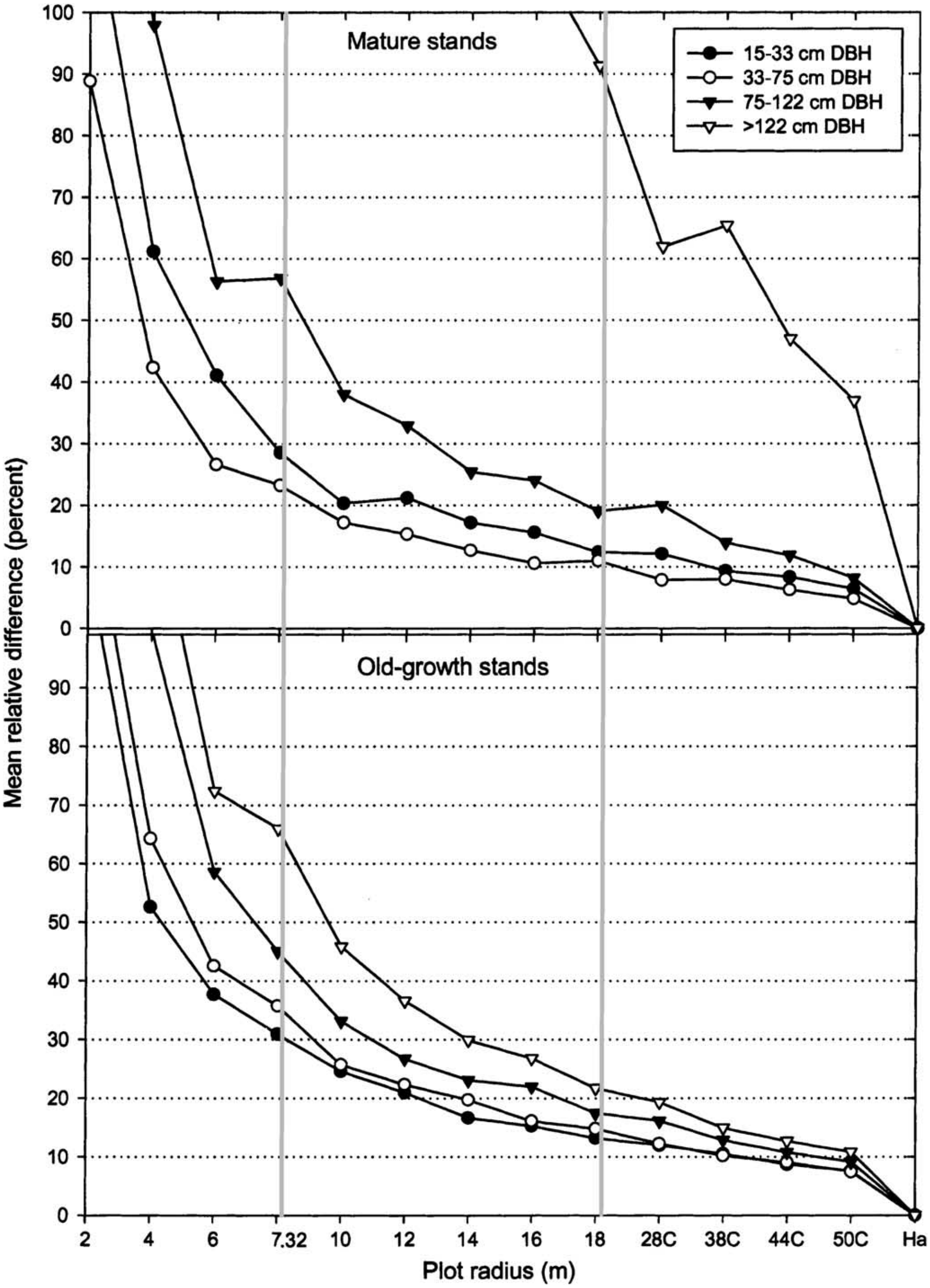

Fig. 1. Effect of plot size on mean relative difference between estimated and actual tree density by stand type, subplot size, and tree diameter classes. Sample size is four mature stands and 14 old-growth stands times 30 iterations per stand.

Table 3
The proportion of estimation errors for each response variable that were less than the mean estimation error by subplot size[a]

Radius (m)	Density (%)	Mortality (%)	Richness (%)
2.0	75	94	37
4.0	60	80	48
6.0	57	72	51
7.32	57	68	51
10.0	58	62	56
12.0	56	58	59
14.0	57	58	64
16.0	56	53	65
18.0	56	51	68
28C	55	54	71
38C	54	54	76
44C	55	58	84
50C	56	59	88

[a] The values shown are averaged across tree size class and stand ($n = 76$). Subplot sizes are described in Table 2.

same relationship held for hectare-size sample plots, one might expect mean relative differences below 25% for tree densities greater than 5 trees/ha on hectare plots.

3.2. Mortality

The mean relative differences for measuring annual tree mortality were substantially greater than those for tree density. Relative differences for mortality dropped exponentially with increasing subplot size but showed little tendency to level off (Fig. 3). Annual mortality was a rare event in most stands, with actual density of mortality trees by stand and tree size class ranging from 0 to 3.6 trees/ha per year. The magnitude of relative differences was proportional to the true stand mortality rate for each size class. The proportion of relative differences that were less than the mean relative difference were below 70% for subplot sizes above 6 m radius (Table 3). Applying this information to Fig. 3, it appears that a 4-subplot cluster of 10 m radius subplots are sufficient to meet an accuracy criteria of relative differences ≤50% at least 66% of the time for trees <75 cm DBH in mature stands. However, meeting the same criteria in old-growth stands would require at least 16 m radius subplots for trees <75 cm DBH, and subplots >18 m radius for trees ≥122 cm DBH.

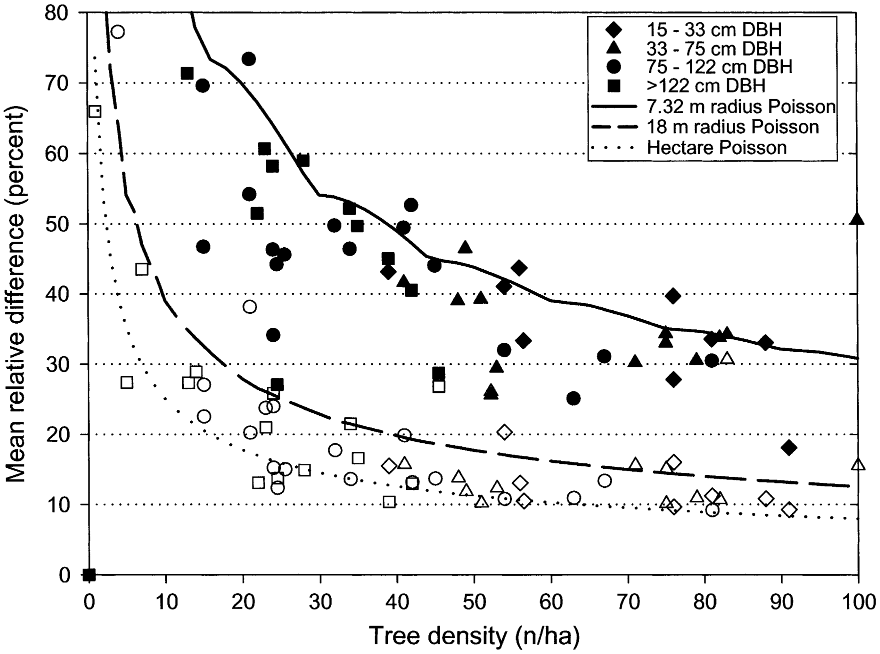

Fig. 2. Mean relative differences for the 7.32 and 18 m radius subplot sizes plotted against actual density by tree size for each stand ($n = 30$). Symbol shape designates tree size; the shaded and open fills are for the smaller and larger subplot sizes, respectively. Differences estimated using a Poisson process model for those plot sizes and a hectare plot are shown for comparison.

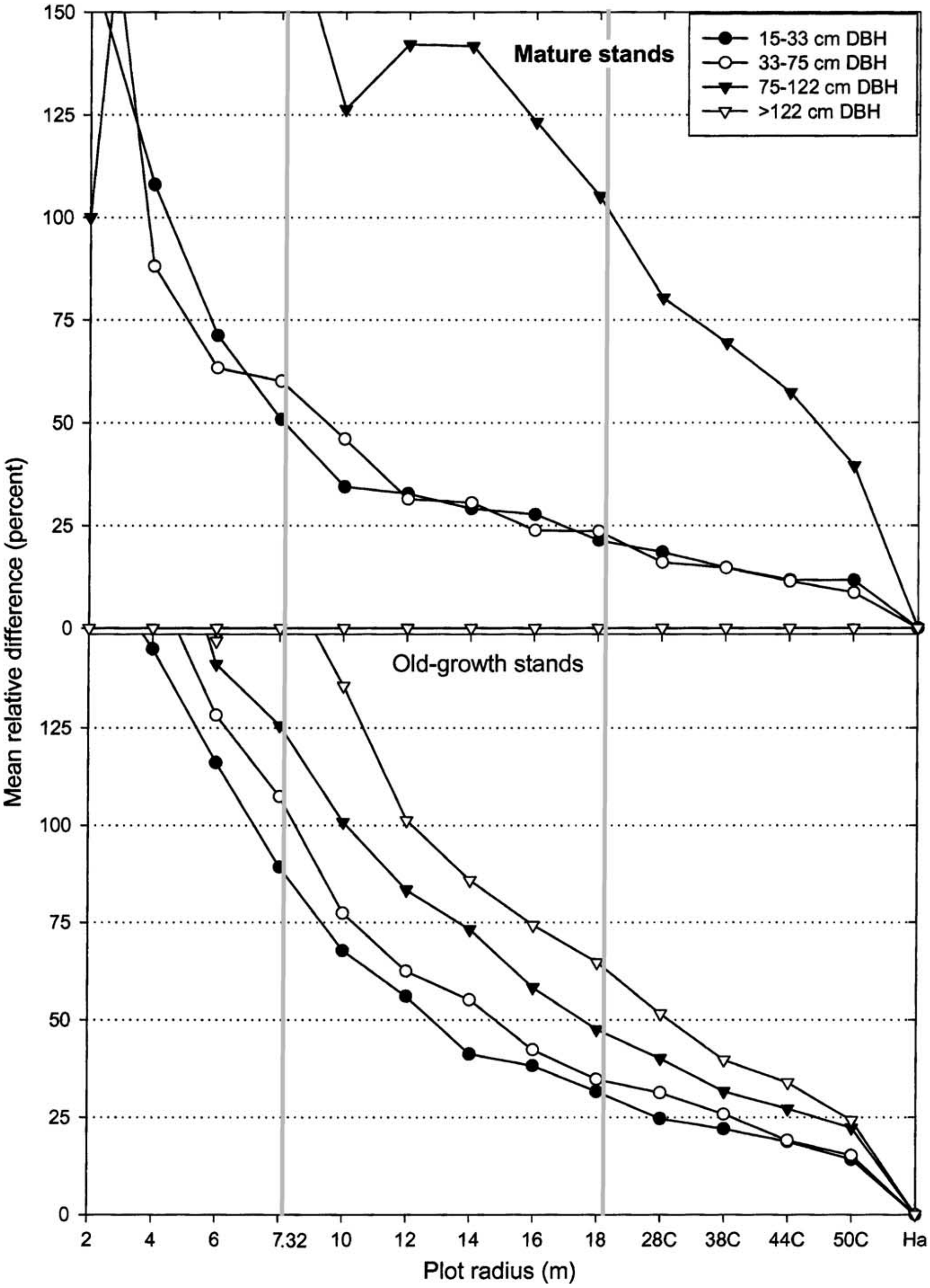

Fig. 3. Mean relative difference of density of annual tree mortality by stand type, subplot size, and tree diameter classes. Sample size is four mature stands and 14 old-growth stands times 30 iterations per stand.

3.3. Species richness

Tree species richness in the different reference stands varied from five to eight species (Table 1). Most stands had at least one species that was relatively rare (i.e. was represented in less than 10% of the stems present), and one had six. The mean difference in species richness decreased with increasing tree size class, reflecting trends in actual richness (Fig. 4). Mean species richness was higher in the old-growth stands than in the mature, except for the smallest tree size class. The proportion of relative differences that were less than the mean relative difference increased steadily with increasing subplot size (Table 3). Applying this information to Fig. 4, it appears that a 4-subplot cluster of 7.32 m radius subplots is sufficient to meet an accuracy criteria of differences ≤1 species about 50% of the time for trees ≥33 cm DBH in mature stands, and trees ≥122 cm DBH in old-growth stands. Meeting the same criteria for the smaller tree sizes, however, would require subplots at least 16 m in radius in the old-growth stands, and more than 18 m in radius in the mature stands.

3.4. Diameter limits for large trees

Mean relative differences of large tree density increased with increasing diameter limit, reflecting greater proportional error from sampling populations with lower and lower densities (Fig. 5). This was particularly true for mature stands at the higher limits, where population densities were quite low (i.e. <10 trees/ha). For the 7.32 m radius plot size in the old-growth stands, mean relative difference was 25% for trees ≥35 cm DBH, and began to increase at a faster rate for diameter limits above 85 cm DBH, exceeding 40%. In contrast, mean relative differences were below 25% for all diameter limits for 18 m radius plots in old-growth stands. This suggests that meeting a 25% accuracy criteria might require using the 18 m radius optional FIA subplot for sampling trees ≥45 cm DBH. Applying a less stringent criteria of avoiding the rapidly increasing error levels for large trees might suggest setting the cutoff at 85 cm DBH.

The distribution of estimated densities of large-diameter trees in large-diameter stands on NFS CVS plots provided useful information about the effort required to sample different tree sizes (Table 4). Large-diameter stands were defined as those with a quadratic mean diameter of dominant and codominant trees ≥65 cm. For increasing diameter limits from 65 to 125 cm DBH, the median estimated density of trees in these stands ranged from 53.4 to 3.0 and 12.6 to 0 for west-side and east-side stands, respectively ("sides" are relative to the Cascade crest). Thus the median number of trees ≥75 cm DBH sampled by a cluster plot of four 18 m radius subplots in large-diameter stands, with a sample area of 0.4 ha, might be 15 trees on the west-side (39.3 trees/ha × 0.4 ha), and three trees on the east-side (8.6 trees/ha × 0.4 ha). In contrast, the old-growth (west-side) reference stands had a mean density of 63 dominant and codominant trees per hectare ≥75 cm DBH, which might only be encountered on about 10% of the large-diameter CVS plots. One of the reasons for the difference is that the set of "large-diameter" CVS plots includes many mature stands. In addition, the systematic placement of CVS plots means that many plots have multiple stand types, streams, roads, or non-forest patches within them (note the large proportion of east-side stands with few dominant and codominant trees comprising the "stand"), while the reference stands were subjectively placed in homogenous forested stands. Although land type and boundary information was recorded for the NFS CVS plots, it was sketched on hard copy maps and cannot be readily linked to plot data or incorporated into analyses of a large number of stands. In contrast, databases for BLM CVS plots (and national FIA plots) identified the land type of each data item.

3.5. BLM hectare analysis

Simulated sampling of live trees and snags from the BLM CVS plots (of the 285 plots where four subplots occurred in the same land type) for trees ≥75 cm DBH confirms that use of the standard FIA 7.32 m radius subplots results in substantial differences (on the order of 100% or more) in estimates of stand density compared to that estimated with the CVS sample (Fig. 6). The estimated densities for the 18 m radius subplots are quite similar to the CVS results, because the sample is identical for trees between 75 and 122 cm DBH, which make up most of the density on these plots. For trees and snags >122 cm DBH on CVS plots (of the 237 plots where the entire hectare was in the same land type), the sample of four 18 m radius

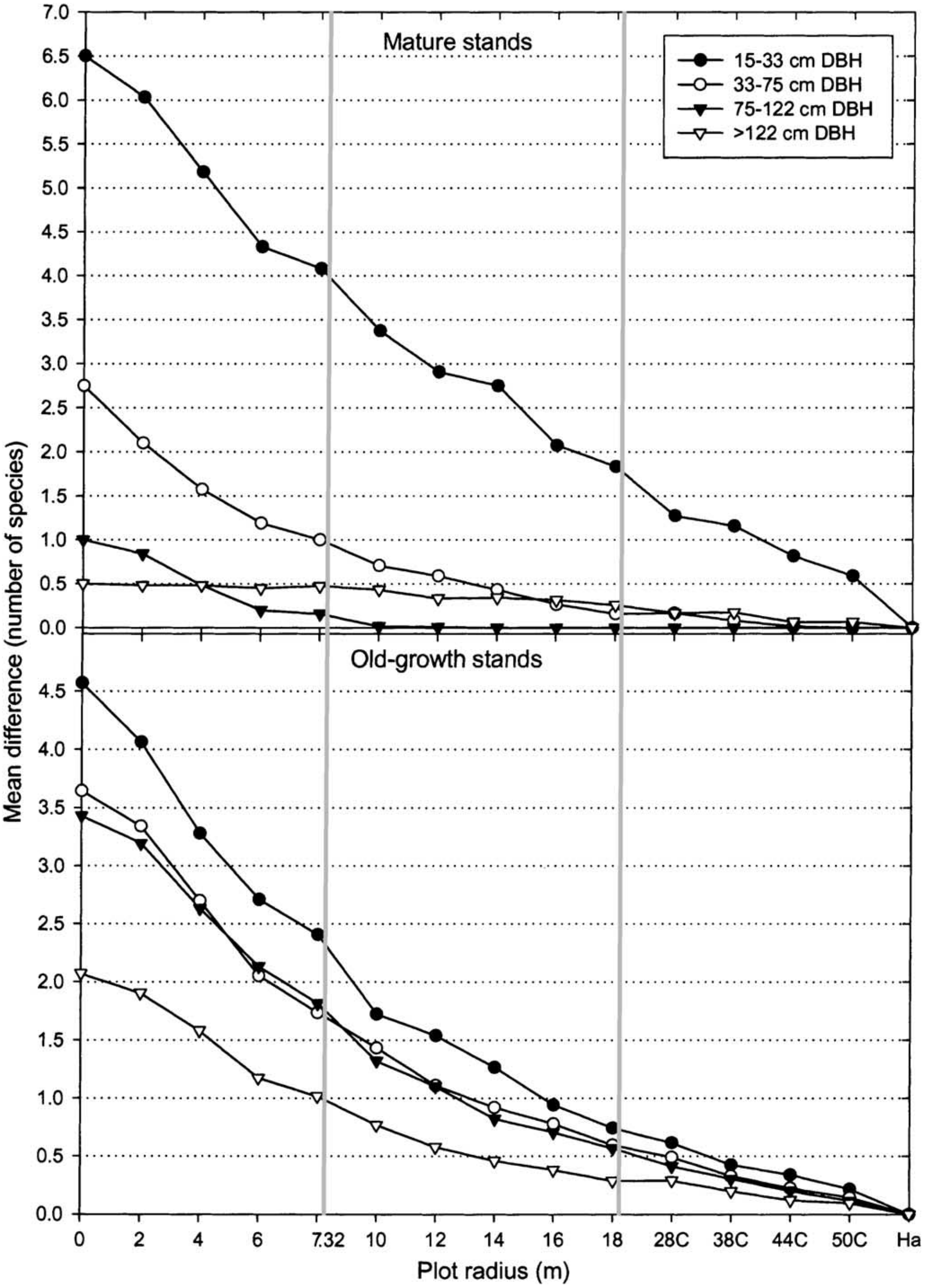

Fig. 4. Mean difference of tree species richness by stand type, subplot size, and tree diameter classes. Actual mean richness is shown at plot size of 0. Sample size is four mature stands and 14 old-growth stands times 30 iterations per stand.

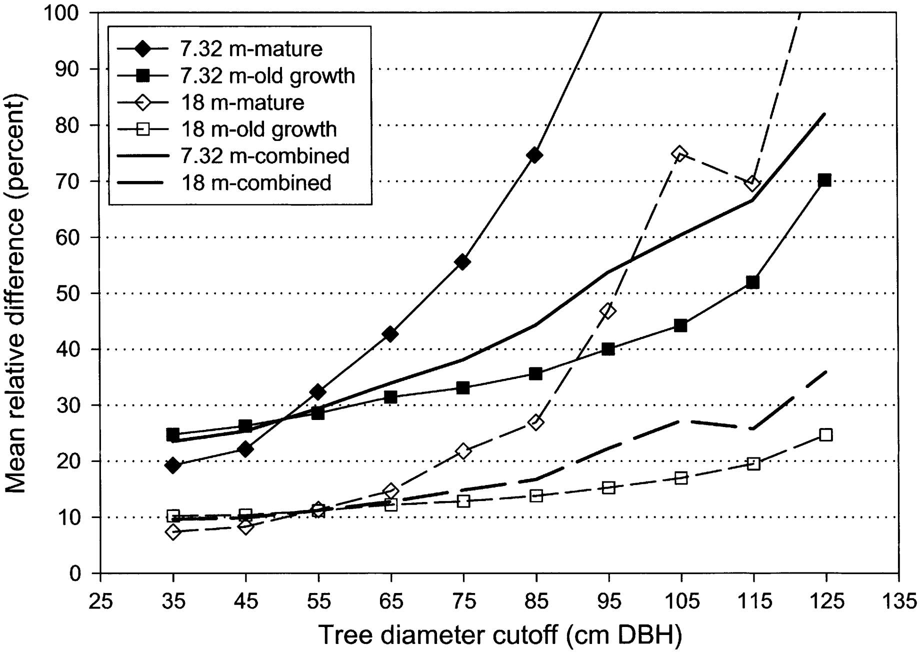

Fig. 5. Mean relative difference for density of trees greater than a specified diameter limit for 7.32 m radius and 18 m radius plot sizes and stand types. Sample size is four mature stands and 14 old-growth stands times 30 iterations per stand.

Table 4
Distributions of estimated quadratic mean diameters (QMD in cm) and density of trees greater than a given diameter limit (trees per hectare), from CVS plots on NFS lands[a]

Distribution	QMD	≥65	≥75	≥85	≥95	≥105	≥115	≥125
West-side plots ($N = 992$)								
Minimum	65.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0
5%	66.0	15.6	10.5	5.6	2.6	0.0	0.0	0.0
10%	67.2	23.0	16.7	10.5	5.0	2.0	0.0	0.0
25%	70.8	36.7	26.3	17.6	9.2	4.6	2.0	1.0
Median	77.9	53.4	39.3	26.2	16.7	10.2	5.6	3.0
75%	86.9	72.5	53.0	37.7	26.3	17.7	11.1	7.0
90%	98.4	90.0	65.6	49.3	36.1	27.0	17.5	12.0
95%	108.2	102.5	77.6	58.9	42.8	32.7	23.5	16.0
Maximum	166.3	157.2	130.8	122.9	104.6	60.4	45.2	37.0
East-side plots ($N = 125$)								
Minimum	65.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0
5%	65.4	1.0	1.0	0.0	0.0	0.0	0.0	0.0
10%	65.7	2.0	1.0	0.0	0.0	0.0	0.0	0.0
25%	66.9	3.6	2.6	1.0	0.0	0.0	0.0	0.0
Median	72.1	12.6	8.6	4.0	2.0	1.0	0.0	0.0
75%	79.8	33.1	24.5	15.0	7.0	5.0	1.0	0.0
90%	89.0	57.6	37.2	21.0	15.0	8.6	4.0	3.0
95%	96.1	73.5	47.4	33.6	24.6	15.0	11.0	6.0
Maximum	114.7	106.8	75.3	59.0	48.0	35.0	26.0	19.0

[a] This only includes plots with a quadratic mean diameter of dominant and codominant tree(s) ≥65 cm DBH. Plots are divided into "west-side" and "east-side" in reference to the crest of the Cascade Mountains.

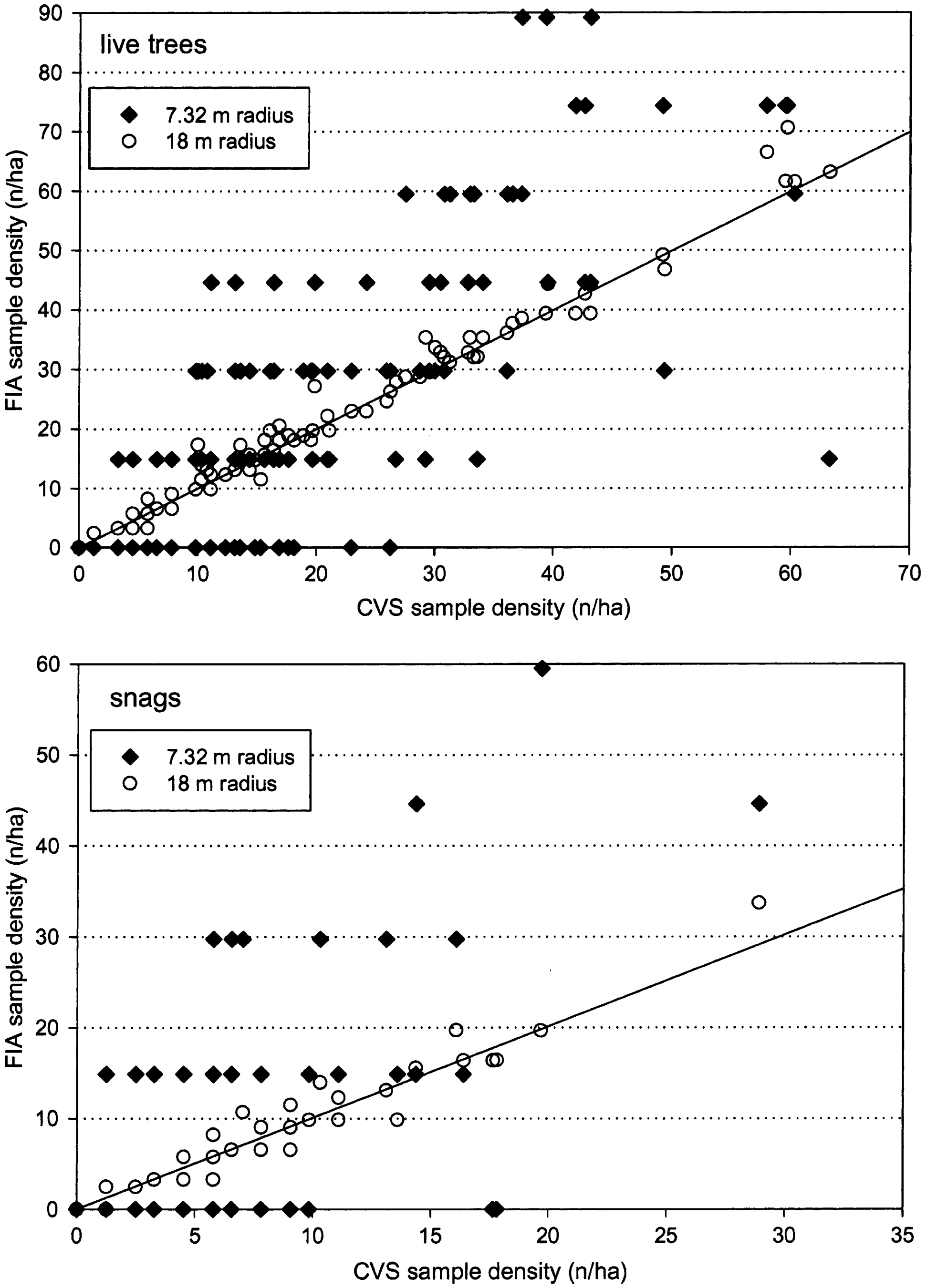

Fig. 6. Density of live trees and snags ≥75 cm DBH sampled on BLM CVS plots, compared to simulated subsamples using the FIA 7.32 m radius or 18 m radius subplots. Straight line is a 1:1 line. Data are from 285 plots in western Oregon which had four subplots in the same stand type.

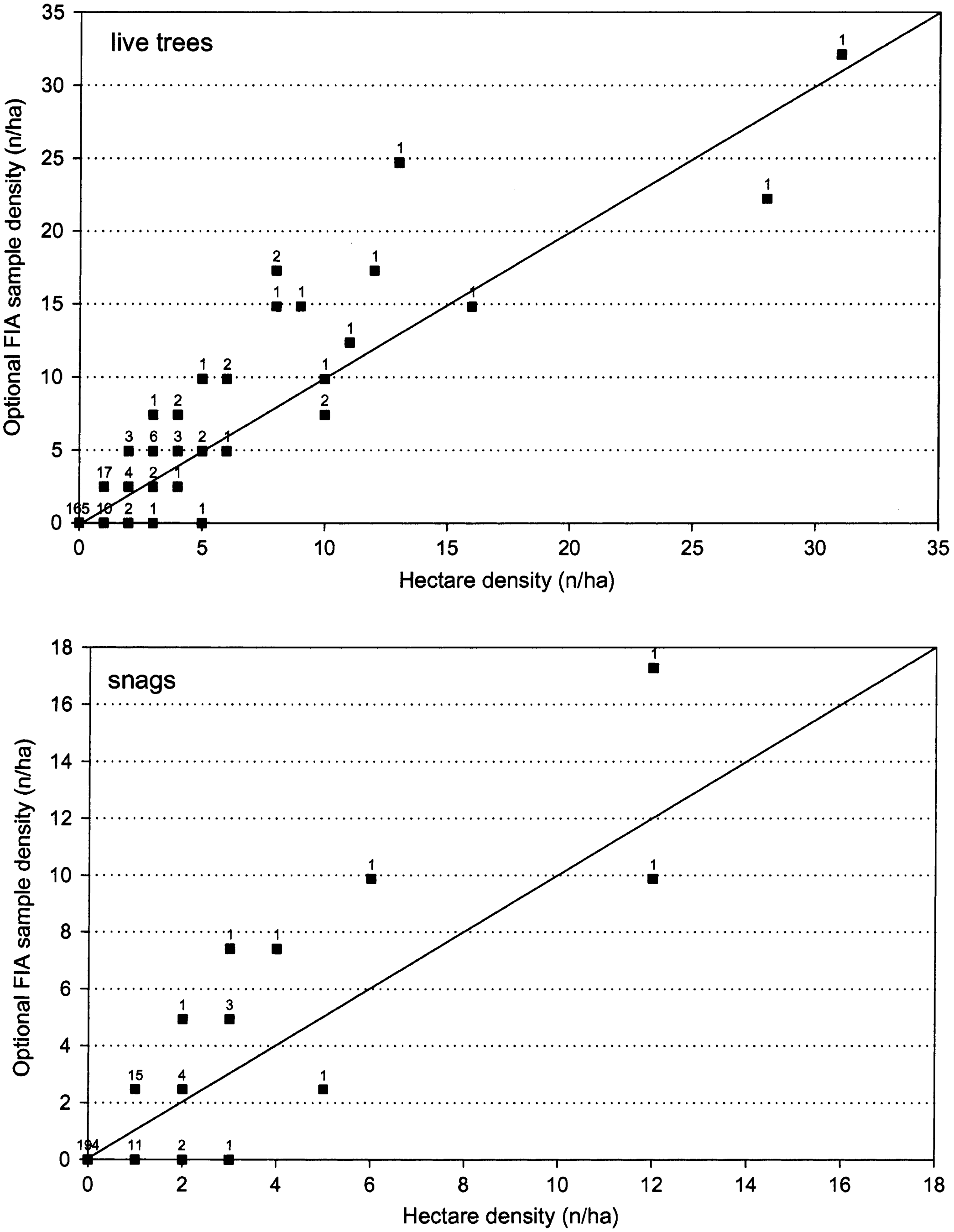

Fig. 7. Density of live trees and snags ≥122 cm DBH sampled on BLM CVS hectare plots compared to a subsample using the four optional FIA 18 m radius subplots. Straight line is a 1:1 line, and numbers above points are number of plots. Data are from 237 plots in western Oregon which had the full hectare in the same stand type.

subplots indicates errors approaching 100% for densities of 10 trees/ha or less (Fig. 7).

4. Discussion

This study evaluated the individual plot-level estimation error for different sizes of inventory plots in mature and old-growth coastal Douglas-fir forests. While it is well known that accuracy increases with plot size (Johnson and Hixon, 1952; Freese, 1960), the spatial scale of non-random point patterns does affect the relationship (Reich and Arvanitis, 1992). The analyses in this paper were able to provide information about the level of accuracy provided by a range of plot sizes, and an indication of the amount of effort involved for implementing different designs in a regional inventory. The comparison with a readily calculated statistical approach suggests ways in which the information could be applied to other forest types.

Sample plot estimates of tree density met the criteria for error less than or equal to 25% at least 66% of the time for the smaller tree size classes (<75 cm DBH) when plots sampled about 13% of a hectare stand (i.e. four-point clusters of 10 m radius subplots). Meeting the same criteria for the largest tree size class (≥122 cm DBH) in old-growth stands required sampling at least 40% of a hectare stand (18 m radius plots). In contrast, sampling for volume or biomass appears to require less sample intensity than sampling for density by tree size class. Estimation errors for stand volume in a 16 ha old-growth *P. menziesii* stand were less than 15% with plots sampling 10% of the area (Johnson and Hixon, 1952). Estimating total biomass of a 20 ha midwestern old-growth stand within 10% required sampling 25% of the stand, while getting within 5% required sampling 48% of the stand (Spetich and Parker, 1998). The density errors using inventory cluster samples from the reference stands were lower than those from the Poisson process model (Fig. 2), suggesting the large trees in these stands were regularly distributed at those scales (Moeur, 1993). The difference could provide a basis for estimating sample errors using the Poisson process model for rare attributes in other forest types (e.g. other than mature *Pseudotsuga* stands), provided tree spatial patterns are not too dissimilar (e.g. Schreuder et al., 1992; Williams et al., 2001).

The criteria for accuracy of tree mortality estimates used in this study was less stringent than that used for density, given that tree mortality is generally a rare event. Thus for the smaller tree size classes (<75 cm DBH), the same plot size (four 10 m radius subplots) met the criteria for mortality (error less than or equal to 50% at least 66% of the time) and for tree density. For the largest tree size class (≥122 cm DBH) in old-growth stands, however, plots needed to sample at least 50% of a hectare stand. A study of augmented inventory plots in California indicated that mortality estimates for trees ≥28 cm DBH from the standard FIA plot design were significantly different than those from a full hectare (Busing et al., 1996). Adding the optional 18 m radius annular plots provided much better mortality estimates, but the authors felt that the full hectare sample was preferable. Sample errors for tree mortality probably depend on the sample period used, since mortality is often episodic (Franklin et al., 1987).

Species richness of several tree size classes in the reference stands was greatly underestimated by sampling with the standard FIA subplot size. Samples of 70 and 40% of the hectare stands was needed to meet the one-species error criteria for trees <33 cm DBH in the mature and old-growth stands, respectively. However, it would be impractical to measure small trees, which tend to occur at relatively high densities, with large plots. Although providing less information, species richness could instead be recorded (perhaps by pre-established size classes) on the larger plots using a simple species list. These results suggest that using inventory sample plots to examine factors affecting stand-level species richness (e.g. Stapanian et al., 1997) be done with caution. Even estimates of tree species richness at the regional level appear to be sensitive to plot size (Schreuder et al., 2000).

Some of the limitations of this study grew out of their strengths. The stem-mapped permanent plots were subjectively placed in homogeneous stands, which allowed in-depth examination of a population of interest. However, subjective placement raises the possibility that stands were exemplary rather than typical (i.e. particularly large trees or high species richness). In addition, systematically placed inventory plots probably contain greater within-plot variability because of topographic variation or presence of stand boundaries. Accounting for these possibilities would suggest using larger plot sizes than those indicated by the analyses. The CVS sample data provided a useful real-world context for the reference stand analysis, even though they were not complete enumerations of the trees in a stand. Because most of the reference stands were one hectare in size, the errors for given sample plot sizes apply to 1 ha "stands". It was not possible to evaluate the sample error of hectare plots (except with the Poisson process model). However, this problem is somewhat intractable, because the area and degree of internal heterogeneity (both patch level and due to gradients) included in a stand is fundamentally a subjective decision.

Given the accuracy criteria adopted for this study, augmentation to the standard FIA plot design in coastal forests would improve the ability to detect and monitor the structure and composition of mature and old-growth Douglas-fir forests, and meet regional managers' stand-level information needs (Mulder et al., 1999; Hemstrom et al., 1998). Anecdotal support for the need for larger plots in the region comes from the systematic placement of a standard FIA plot in a grove of old-growth redwoods (*Sequoia sempervirens*), where no redwoods were sampled by the four 7.32 m radius subplots (Richard Busing, personal communication). In this study, the standard plot design appeared to be adequate for estimating density and mortality of trees <75 cm DBH, while adding the optional 18 m radius annular subplots to the FIA cluster plot appeared to be adequate for trees ≥75 cm DBH. Based on the reference stand analysis, this augmented sampling in a stand meeting the minimum criteria for old-growth of 20 trees/ha ≥100 cm DBH would yield estimated densities between 16 and 24 trees/ha approximately 66% of the time. For managers needing to monitor increases in density of large trees as young stands develop (Hemstrom et al., 1998), or monitor particularly rare elements like large snags, even larger sample plots may be advisable. There is considerable interest on the part of federal land managers to maintain the CVS hectare sample for large trees and snags as the inventory transitions to the standard FIA design. For rare attributes with relatively large estimation errors (for a given plot size), a relatively large number of sample plots (e.g. ≥30 plots) should be used to characterize a population of interest (e.g. mature Douglas-fir stands).

It was beyond the scope of this study to include a cost-benefit analysis of the effort required to sample different plot sizes (Zeide, 1980; Scott, 1993). This would have required estimates of the time required to locate, monument, and measure different tree sizes on different subplot sizes in a range of stand conditions. The actual cost of using larger plot sizes would depend on the proportion of field work represented by additional trees, the proportion of field plots that have large trees, and the density of large trees on those plots. In the Pacific Northwest, the majority of stands with trees ≥75 cm DBH are found on publicly managed lands. This study suggests that out of the ∼12,000 plots on NFS lands in Oregon and Washington, sampling that tree size with the four 18 m radius subplots (0.4 ha total area) would require measuring an additional 14–42 trees on the 500 large-diameter stands with the greatest density.

Standardized, systematically placed inventory plots provide a wealth of valuable information concerning forest structure, composition, and development. Plot-level data are being used to evaluate habitat characteristics, disturbance effects, disease outbreaks, fuel loadings, and accuracy of remote-sensing classifications. Monitoring the abundance of large trees and snags, and the development of old-growth characteristics, is vital to support the management activities of public agencies in the Pacific Northwest. The development of Habitat Conservation Plans, watershed plans, and riparian protection guidelines governing forest industry indicates they have become important on private lands as well. Knowledge of the stand-scale sampling error for important attributes will help characterize existing conditions and evaluate management policies.

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