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Predictive mapping for tree sizes and densities in southeast Alaska

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Abstract

The Forest Service has relied on a single forest measure, timber volume, to meet many management and planning information needs in southeast Alaska. This economic-based categorization of forest types tends to mask critical information relevant to other contemporary forest-management issues, such as modeling forest structure, ecosystem diversity, or wildlife habitat. We propose the joint distribution of tree density and mean tree diameter as a more comprehensive set of forest measures. Focusing on those measures, we build a predictive-mapping model by using existing geographic information system data resources and existing ground-sampled inventory data. The utility of our predictive-mapping model will need to be tested with additional intensive ground-sampled data and in applications that involve forest managers, planners, and biologists. Such tests will reveal the model's utility in addressing contemporary forest-management problems and information needs.
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Keywords: Old-growth forests; Forest structure; Forest measurement; Predictive mapping; Stand density index; Southeast Alaska; Tongass National Forest

1. Introduction

A basic challenge in forest inventory and management is distilling complex, multidimensional, multiscaled, forest ecosystems into a small number of attributes that are easily measurable in the field and have practical value for planners, scientists, and the public. For decades, the USDA Forest Service (F.S.) has relied on a single economic measure (timber volume or net-board-foot-volume per acre) for most information needs and decision making in the Tongass National Forest (NF)[1]. Although volume measures may meet certain management information needs, such as resource inventories, timber-sale layouts, and economic modeling, they do not provide adequate information on forest structure, ecosystem diversity, or wildlife habitat.

Contemporary forest management can no longer rely exclusively on measures of timber volume. The problem is that forested stands measuring the same timber volume tend to include a wide range of structures, tree sizes, tree densities, tree ages,

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[1] The Tongass NF comprises 80% of the land area of southeast Alaska.

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and site conditions. Timber volume alone is not well suited for today's broader forest-management missions that require consideration of diverse values and ecological relationships. Unfortunately, decades of timber-volume inventorying and mapping have left the Tongass forest managers and biologists highly dependent on timber-volume measures. The history of Tongass timber-volume inventory maps reveals the limitations of this approach.

1.1. History of timber-volume maps on the Tongass NF

In the early 1980s, photo-interpreters used stereo aerial photographs to delineate the Tongass NF into roughly 300,000 polygonal units of relatively homogenous land and forest character (ESCA-Tech, 1979). Roughly two-thirds of the Tongass NF was photo-classified as non-forested or unproductive forest. The remaining one-third, classified as productive forest, was delineated further based on visible differences in the forest canopy including texture, crown sizes, species, heights, density, and dead trees. These polygons were labeled according to age (greater than or less than 150 years), species composition, crown density, and timber-volume class (VC), VC4 = 8000–20,000 net board-foot per acre (nbf/a), VC5 = 20,000–30,000 nbf/a, VC6 = 30,000–50,000 nbf/a, and VC7 > 50,000 nbf/a).

All photo-delineated polygons were digitally transferred into computerized geographic information system (GIS) databases and made available for mapping. Most maps highlighted differences among timber-volume classes (VC4-7). These maps were used in several management and planning applications, including (1) forest stratification for ground-sampling inventory programs; (2) site-specific information for critical forest-management issues, such as wildlife-habitat modeling and timber-sale planning; and (3) administering the federal proportionality law (Tongass Timber Reform Act, 1990), designed to protect forest diversity by limiting the amount of logging in higher timber-volume classes.

In 1989, inventory specialist Jim Brickell conducted a statistical analysis of the photointerpreted (mapped) timber-volume classes by using ground-sampled inventory data (Brickell, 1989). Finding that the differences in timber-volume classes were not statistically different

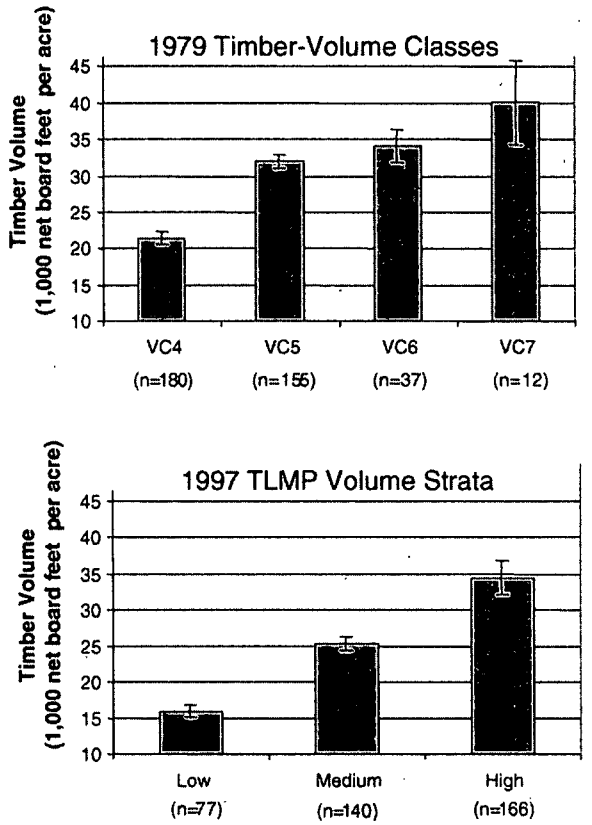

Fig. 1. Forest-wide timber-volume means and one standard error from 1980s inventory.

on the ground (Fig. 1), Brickell concluded that continued use of mapped timber-volume classes to represent distinct volume categories could not be justified statistically, and the three highest timber-volume classes (5, 6, and 7) could be lumped together without any appreciable loss of precision in the overall volume estimate. Brickell's conclusions, along with corroborating evidence from a timber sale in Kelp Bay, AK, provided the basis for a lawsuit that challenged the use of mapped timber-volume classes. A U.S. District Court judge ruled that the Forest Service's timber-volume classes represented arbitrary and capricious information for meeting the requirements of the proportionality law (U.S. District Court for the District of Alaska, 1994).

In preparing for the 1997 revision of the Tongass Land Management Plan (TLMP), FS staff found itself with a legacy of forest-management issues and federal regulations related to timber volume, but no

defensible means of mapping timber volume. At that time, managers, planners, and biologists agreed that at a minimum, there needed to be a statistically defensible means of portraying timber-volume distributions across the forest. Julin and Caouette (1997) provided several options for mapping timber volume. The selected option used Brickell's recommendations (specifically to collapse volume classes 5, 6, and 7 into one class and supplement with ancillary GIS information) to create a revised timber-volume map. The new map, hereafter referred to as the 1997 TLMP timber-volume map, was perceived as an improvement because, unlike the old mapping system, its mapping groups (low, medium, and high) provided statistical differences among forest-wide means (Fig. 1). The revised timber-volume map was used extensively in the 1997 TLMP as a tool for modeling timber economics, wildlife habitat, resource inventories, and forest diversity.

Although the 1997 TLMP timber-volume map adequately portrays timber-volume information, the revised map does not adequately portray or model forest structure, ecosystem diversity, or wildlife habitat. As a result, there have been many challenges and appeals to the 1997 TLMP (USDA, 1997b). A common complaint is that over 40% of the mapped productive old-growth forest is lumped into a high-volume category. Writing in *Defenders* magazine (Schoen, 1998), Alaska wildlife biologist John Schoen described Tongass NF planning as "fatally flawed" because the FS was unable to identify and map the biggest and best old-growth stands. In Schoen's words, "To maintain forest diversity and protect key management indicator species (e.g., brown bears and black-tailed deer), the FS must identify and protect these habitats [biggest and best old-growth stands]."

The FS has suggested that the problem is not necessarily timber volume mapping, but the continued reliance on timber-volume as the primary means for measuring, inventorying, mapping, and managing the forest (Caouette et al., 2000). Timber volume alone cannot adequately model or communicate the rich diversity in forest structures, ages, and underlying ecosystems in southeast Alaska temperate rainforest. Forest Service managers, planners, and biologists need to move beyond timber volume toward a more comprehensive system of forest measures, models, and maps that better represent the diversity of the forest.

1.2. Alternative measures

We propose the joint distribution of tree density and mean tree diameter as a more comprehensive system for measuring and modeling forest diversity in southeast Alaska. Caouette et al. (2000) found that these measures are more directly related to forest structure and the aerial photo-interpretation of forest canopies than is timber-volume.

The joint distribution of tree density and mean tree diameter is widely reported in the literature for applications in silviculture, forest ecology, and wildlife biology. Reineke (1933) first used the combination of trees per acre and mean tree diameter to develop a system classifying forested stands relative to their expected maximum level of stocking. This system of classification, called stand density index or SDI, has been used extensively in multiple forest-related disciplines. Silviculturists manipulate SDI to influence species composition, stand structure, stem quality, rate of diameter growth, and stand volume (Daniel et al., 1979). Ecologists and wildlife biologists recognize that stands with similar SDI, regardless of differences in age or site quality, exhibit similar levels of competition, site occupancy, crown closure, self-pruning, and differentiation of crown classes (Lilieholm et al., 1994). Plant ecologists later redefined concepts of SDI as the negative 3/2 self-thinning law, which is now a central unifying concept in vegetation biology (Harper, 1977; Barnes et al., 1998).

There appears to be more utility in the joint distribution of tree density and mean diameter than SDI alone. Lilieholm et al. (1994) used tree density and mean diameter to model forest structures optimal for goshawk nesting in the Douglas-fir forests of southeastern Idaho, and Hansen et al. (1995) used tree density and mean diameter to discriminate among forest age classes in Oregon's Western Cascade Mountains.

Spies and Franklin (1991) reported tree density and mean diameter as key discriminating variables in their study of 22 quantifiable forest attributes relating to wildlife habitat, ecosystem function, and successional development in Douglas-fir forests of the Pacific Northwest. They concluded, "Tree sizes and densities might be reasonably successful in identifying old-growth habitat from aerial photographs. These measures can be used advantageously when simple indicators of forest habitat conditions are sought, such

as when aerial-photo inventories of habitat conditions over large areas are needed."

1.3. Predictive mapping

Predictive mapping rests on the premise that forest vegetation patterns can be predicted and mapped by combining two types of GIS remotely sensed information: that obtained from the aerial photo-interpretation of the forest canopy and that obtained from the aerial photo-interpretation of the surrounding environment (Franklin, 1995; Ohmann and Gregory, 2002). This type of modeling is well suited for southeast Alaska, where environmental conditions such as soil type, slope, elevation, aspect, and geology all tend to play important roles in controlling forest composition and structure.

1.4. Objective

Assuming that tree density and mean diameter provide a more comprehensive forest measurement system than timber volume, we decided to build a predictive-mapping model based on these measures. Such a model should help planners, managers, and biologists move beyond the limits of timber volume and begin to address a wider range of forest-management challenges and information needs, including those related to forest structures, forest ecosystems, and wildlife habitat.

2. Methods

Our approach to creating a predictive-mapping model began with examination of a small but relevant set of attributes from existing FS GIS layers. We started with aerial-photo-interpreted timber-volume classes (VC4-7) and then added mapped environmental data from other GIS layers. Although some relevant environmental data are easily mapped and incorporated into spatial models, others are not. For example, landforms and land types are not easily mapped across the Tongass NF owing to inconsistencies in mapping protocols previously used for Tongass NF administrative areas. Some environmental factors are difficult to use in spatial models because their role in controlling forest vegetation patterns depends on other environmental factors. For example, the role of elevation in controlling forest composition and structure can differ substantially at different latitudes, longitudes, or aspects. We selected soil type, slope, and aspect as the most relevant, readily available mapped environmental factors. The selection of these environmental factors was based on previous studies in southeast Alaska, including DeMeo and Loggy (1989) and Harris (1989).

In a series of exploratory analyses, we looked for statistically meaningful differences in tree densities and sizes as related to mapped timber-volume classes and mapped environmental attributes (e.g., soil type, slope, and aspect). Our final proposed predictive-mapping model resulted from patterns observed in the exploratory analyses. Our proposed predictive-mapping model is compared to the 1997 TLMP timber-volume map.

2.1. Materials

The 1980s forest inventory was designed and carried out separately in the three former Tongass NF administrative areas (Chatham, Ketchikan, and Stikine) (USDA, 1982). In the Stikine and Ketchikan Areas the sampling was conducted on five-plot clusters covering roughly 12 ha, whereas in the Chatham Area the sampling was conducted on plot transects in a few dozen large (600 ha) study areas. Sampling in all three administrative areas used variable-radius sampling techniques (USDA, 1986) and did not include wilderness areas. Ground-sampled data included tree species, tree diameter, tree height, defect, disease, slope, aspect, elevation, soil type, and understory composition.

The 1990s forest inventory was conducted by the Pacific Northwest Research Station, Forest Inventory and Analysis (FIA) Program based in Anchorage, AK. This inventory was designed to use an extensive grid system with point locations evenly spaced 4.8 km apart. Four-plot clusters covering roughly 1 acre (2.5 ha) were used to sample site and forest conditions in the non-wilderness portions of southeast Alaska (USDA, 1995; Max et al., 1996). Grid points landing on rock, snow, or ice were surveyed remotely using aerial photographs or aircraft flyovers. All other grid points were sampled on the ground using fixed-radius plots. Trees were recorded by species and measured for diameter, height, crown height, crown area, defect, and disease. Site measures included slope, elevation, aspect, soils, and understory vegetation.

The timber type (TIMTYP) layer provided mapped information on land and forest types (ESCA-Tech, 1979). Photo-interpreters used color stereo aerial photographs (1:15,840) to delineate approximately 300,000 polygons across the Tongass NF. Minimum polygon size was 12 ha and averaged roughly 150 ha. Polygon attributes for productive forest lands included age, timber volume, species composition, crown closure, and health.

The common land unit (CLU) layer provided mapped information on site and soil conditions, including soil composition, slope, and aspect (USDA, 1989, 1990). The CLU layer was available only for the non-wilderness portions of the Tongass NF. Polygons were delineated using color aerial stereo photographs (1:15,840). Polygons with similar land characteristics were grouped and labeled with soil management unit codes (SMUs). Minimum polygon size was 48 ha and averaged roughly 240 ha. Polygons attributed as hydric soils greater than or equal to 50% and slope class ≤ 2 (0–55%) were designated as hydric soils (DeMeo and Loggy, 1989). These soil designations were consistent with those used for the 1997 Tongass NF land management plan (Julin and Caouette, 1997; USDA, 1997a).

A digital elevation model (DEM) provided aerial-photo-interpreted information on elevation (U.S. Department of the Interior, 1990). We used DEM to develop an aspect-based polygonal cover by using the LATTICEPOLY command in the ARCINFO[2] software (minimum polygon size = 12 ha). Aspects between 67.5° and 292.5° were classified as south (wind exposed), and all other aspects plus flat terrain were classified as north (wind protected). These classification boundaries matched wind-disturbance patterns observed by Harris (1989) on Prince of Wales Island in southeast Alaska.

The land status (LANDSTAT) layer provided information on land ownership, including FS land, private land, and land belonging to boroughs and municipalities and other government agencies. Information on FS land included wilderness and recreation, research natural areas, wild and scenic rivers, and other special land use designations (USDA, 1997b). The managed stands (MS) layer provided information on FS timber harvest, including year of harvest and management status (USDA, 1989).

Locations of all inventory plots were mapped in GIS, polygons surrounding each plot were identified, and polygon attributes were added to plot data records. Those plots not mapped as productive old-growth (VC4-7) were deleted from the database, as were plots associated with non-Forest Service lands or the Yakutat Foreland. Plots in which some portion was on a road, within a harvest area, was inaccessible, or had fewer than four subplots were also deleted from the database. An additional 55 plots in the 1990s inventory were deleted because plot centers were within 7.6 m (25 ft) of a polygon boundary (the theoretical minimum distance needed to ensure that the centermost subplot did not straddle a polygon boundary). Plots associated with polygons having incomplete GIS data were deleted. Ground-measured inventory data were summarized, using all live trees greater than 23 cm (9 in.) in diameter (two plots were deleted because there were no trees greater than 23 cm). The final database included 372 plots for the 1980s inventory and 513 plots for the 1990s inventory.

2.2. Exploratory analyses

Plot data were sorted by inventory type (1980s and 1990s), timber-volume class (4, 5, 6 and 7), and selected environmental classes (hydric soils and aspect). Forest-wide means and 90% confidence intervals for measures of stand density index (SDI) and quadratic mean tree diameter (QMD) were calculated for specified mapped attributes. We used the quadratic mean diameter (diameter of tree with average basal area) in lieu of the arithmetic mean because of its implicit weighting toward the larger trees in the stand (large-diameter trees are often considered indicators of structural diversity, stand age, site condition, or wildlife habitat value). We used the stand density index (SDI) in lieu of trees per unit area because stands with similar SDI exhibit similar levels of competition and site occupancy. Mean SDI and QMD, and their confidence ellipses, were calculated twice using the 1980s and 1990s inventory, respectively. Means and confidence ellipses were calculated only in cases where there were five or more sample plots. The joint distribution of SDI and QMD was assumed to be bivariate normal for both inventories.

[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Our aim was to test for statistical differences in the joint distribution of SDI and QMD means among TIMTYP timber-volume classes and other mapped environmental attributes. Traditional univariate statistical tests, such as the t- or F-test, do not work for multidimensional response variables. There are multivariate statistical tests that use multiple analysis of variance (MANOVA) such as Wilks' Lambda (Johnson and Wichern, 1992), but these tests are little more than additive results of individual univariate models. Non-overlapping ellipses were considered indicators of significant differences or statistical signals, and, conversely, overlapping confidence ellipses were indicators of no significant differences. Confidence intervals of 90% were used in lieu of more traditional 95% intervals. Although far from perfect, this method was considered an objective method for comparing simultaneous differences among SDI and QMD means. The strength in our approach is not the robustness of a single statistical test, but the corroboration of results between two independent forest inventories. The results of our exploratory analysis were used to build a proposed mapping model that will eventually require more rigorous statistical testing with more suitable data. No statistical inferences are made from these results.

The process described above, sorting and grouping inventory plots according to GIS polygon attributes, calculating SDI and QMD means and confidence ellipses, visually examining confidence ellipses for overlap, and comparing the direction and magnitude of differences across inventories, was repeated several times in this study. The following GIS attributes were examined:

- TIMTYP timber-volume classes (4, 5, 6, 7).
- CLU hydric soil classes.
- DEM aspect classes (non-hydric soils).
- TIMTYP timber-volume classes intersected with CLU hydric soils classes.
- TIMTYP timber-volume classes (non-hydric soils) intersected with DEM aspect classes.

2.3. Predictive mapping for tree sizes and densities

Results of the exploratory analyses were used to develop a new mapping model for the non-wilderness portions of the Tongass NF. The goal was to create a limited number of mapping groups that would in turn provide a wider range of options for predicting tree sizes and densities on the ground. The model was developed hierarchically beginning with the TIMTYP volume classes and adding hydric soil designations and aspect classes. Mapping groups were kept in the final model when they corresponded to non-overlapping confidence ellipses and consistent directional differences in the exploratory analyses. Mapping groups chosen for the final model were assigned labels that help identify the GIS attributes used to create them.

2.4. Model evaluation

The predictive-mapping model developed in this paper was evaluated by comparing it to the 1997 TLMP timber-volume map (currently used in Tongass NF forest-management and planning). The distribution of means and confidence ellipses in SDI and QMD space were compared visually. A visual comparison appears to be the only option for comparing models as there are no known statistical tests for such comparisons. One model was considered superior when the group means occupied more regions in the two-dimensional SDI and QMD space, providing a wider range of options for predicting tree size and density patterns on the ground. This assumes that the number of mapping groups in each model was kept to a reasonable minimum, and the costs or penalties for additional mapping groups in one model are negligible.

3. Results

3.1. Exploratory analyses

We plotted means and confidence ellipses for SDI and QMD for a specific set of GIS attributes. Means and 90% confidence ellipses were examined visually for statistical differences (i.e., non-overlapping confidence ellipses) and consistency between inventories (1980s and 1990s).

Both inventories had non-overlapping confidence ellipses for TIMTYP volume classes 4, 5, and 6, and overlapping confidence ellipses for volume class 7 (Fig. 2, row 1). The direction and magnitude of differences among the means were consistent between the two inventories: higher timber-volume classes generally had lower tree densities and larger tree diameters.

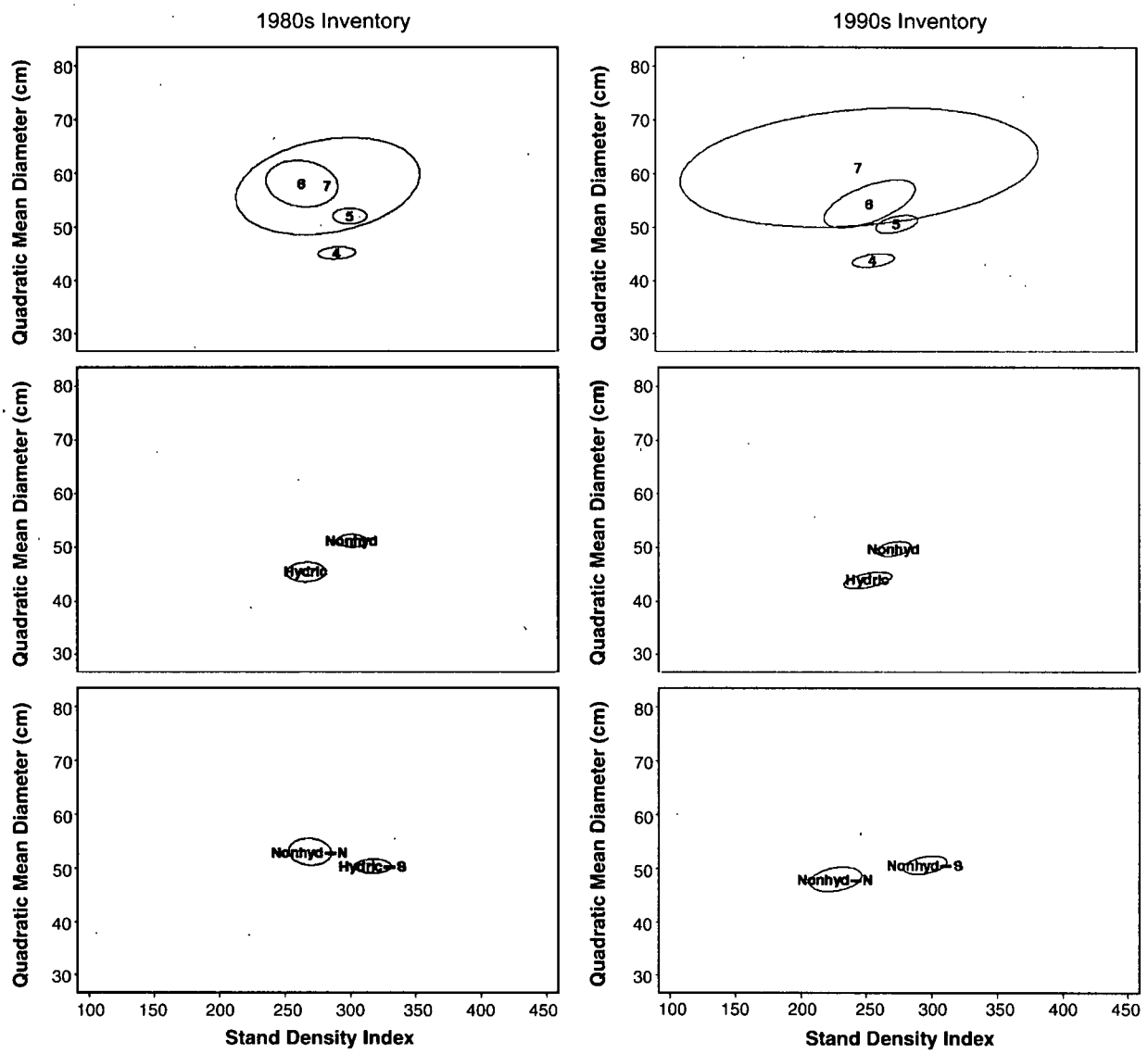

Fig. 2. Forest-wide means and 90% confidence ellipses for timber-volume classes (row 1), hydric-soil classes (row 2), and aspect classes (row 3). See Fig. 7 for sample sizes.

Both inventories had non-overlapping confidence ellipses for CLU hydric-soil classes (Fig. 2, row 2). The direction and magnitude of differences among the means were consistent between the two inventories: hydric soils generally had smaller tree diameters and lower tree densities than did non-hydric soils.

Both inventories had non-overlapping confidence ellipses for DEM aspect classes within the non-hydric soil classes (Fig. 2, row 3). The direction and magnitude of differences among the means were consistent between the two inventories: south aspects generally had higher tree densities than did north aspects.

Both inventories had non-overlapping confidence ellipses for TIMTYP volume classes 4 and 5 sorted by CLU hydric-soil classes (Fig. 3, rows 1 and 2). The direction and magnitude of differences among the means were consistent between the two inventories: hydric

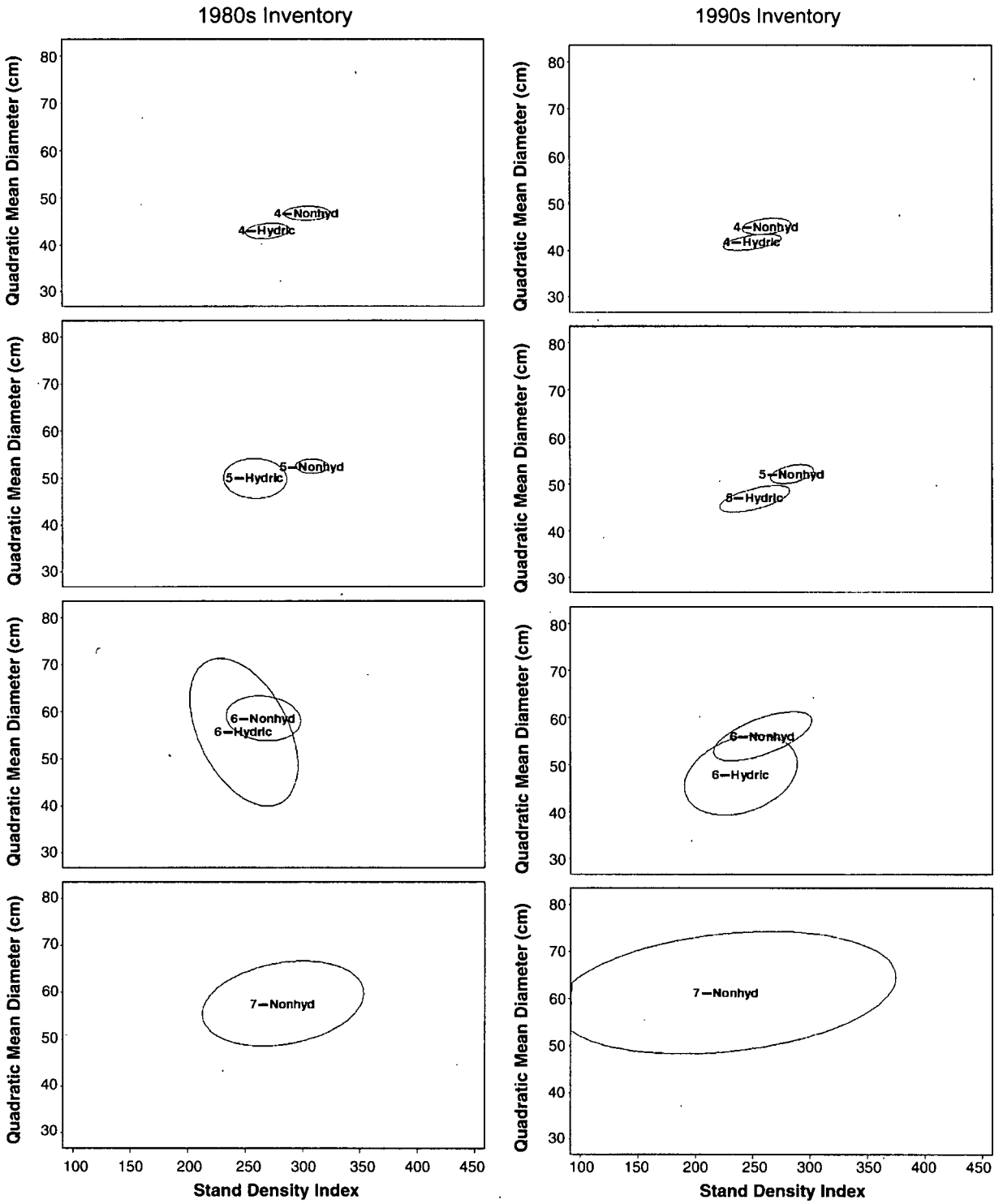

Fig. 3. Forest-wide means and 90% confidence ellipses for timber-volume classes interacted with hydric-soil classes. See Fig. 7 for sample sizes.

soils generally had smaller tree diameters and lower tree densities than did non-hydric soils. There were overlapping confidence ellipses for TIMTYP volume class 6 divided by CLU hydric-soil classes (Fig. 3, row 3). Sample sizes for TIMTYP volume class 7 sorted by hydric soils were too small ($n < 5$) for a meaningful comparison (Fig. 3, row 4).

Both inventories had non-overlapping confidence ellipses for non-hydric TIMTYP volume classes 4 and 5 divided by DEM aspect classes (Fig. 4, rows 1 and 2). The direction and magnitude of differences between the means were consistent for the two inventories: south aspects generally had higher tree densities than did north aspects.

There was overlap in the confidence ellipses for non-hydric TIMTYP volume class 6 sorted by DEM aspect classes for the 1980s inventory, and no overlap for the 1990s inventory (Fig. 4, row 3). However, there were substantial inconsistencies in the direction and magnitude of the differences between means. Non-hydric TIMTYP volume class 7 divided by DEM aspect classes had overlapping confidence ellipses for the 1980s inventory and insufficient data ($n < 5$) for the 1990s inventory (Fig. 4, row 4).

3.2. Predictive mapping for tree sizes and densities

Results of the exploratory analyses were used to develop a new hierarchical mapping model for predicting trees sizes and densities in the Tongass NF. Results of the exploratory analysis supported the retention of TIMTYP volume classes 4, 5, and 6 as separate mapping entities, and supported lumping volume classes 6 and 7 into one group (because their means occupied roughly the same region in the two-dimensional SDI and QMD space). This first level of modeling resulted in three tree size and density (SD) mapping groups: SD-4, SD-5, SD-67 (Fig. 5).

Results of the exploratory analyses supported splitting SD-4 and SD-5 into separate hydric-soil classes. This second level of modeling resulted in five mapping groups: SD-4H, SD-4, SD-5H, SD-5, SD-67. Results of the exploratory analyses supported the splitting of SD-4 and SD-5 by DEM aspect classes. This third, and last, level of modeling resulted in seven mapping groups: SD-4H, SD-4N, SD-4S, SD-5H, SD-5N, SD-5S, SD-67 (Fig. 5).

3.3. Model evaluation

Means and 90% confidence ellipses for SDI and QMD were plotted for each level of the hierarchical mapping model (Fig. 6, rows 1–3), and plotted again for the 1997 TLMP timber-volume map (Fig. 6, row 4). Although there are no statistical tests for comparing our proposed mapping model to the 1997 TLMP timber-volume model, a visual comparison indicates that our proposed mapping model provides more options for modeling and predicting tree size and density distributions across the Tongass NF.

4. Discussion

Forest mapping is a powerful tool for communicating ideas. We believe our predictive-mapping model, based on tree sizes and densities, can help planners, managers, and scientists move beyond the limitations of timber volume and address a wider range of forest-management issues and information needs. Our proposed predictive-mapping model reflects basic relationships between tree sizes and densities and the aerial-photo-interpretation of forest canopies. For example, forests associated with higher timber-volume classes tend to have lower densities and larger-diameter trees than do lower timber-volume classes. Our proposed predictive-mapping model also reflects basic relationships between tree sizes and densities and environmental conditions. For example, forests associated with hydric soils generally have smaller trees and lower tree densities than do forest associated with non-hydric soils, and south-facing non-hydric forests tend to have higher tree densities than do north-facing non-hydric forests. Although there are many exceptions to these generalizations, we believe that our mapping model, used at any of the three hierarchical levels, will be more responsive to key forest-management issues than are current mapping models based solely on timber volume.

We suggest that the most appropriate uses for our proposed predictive-mapping model are in forest- or landscape-level planning and analyses. Our model can be used for site-specific purposes only with a clear understanding that it is a probability model; it is a tool that can be used to increase the probability of locating certain tree size and density patterns on the ground. The

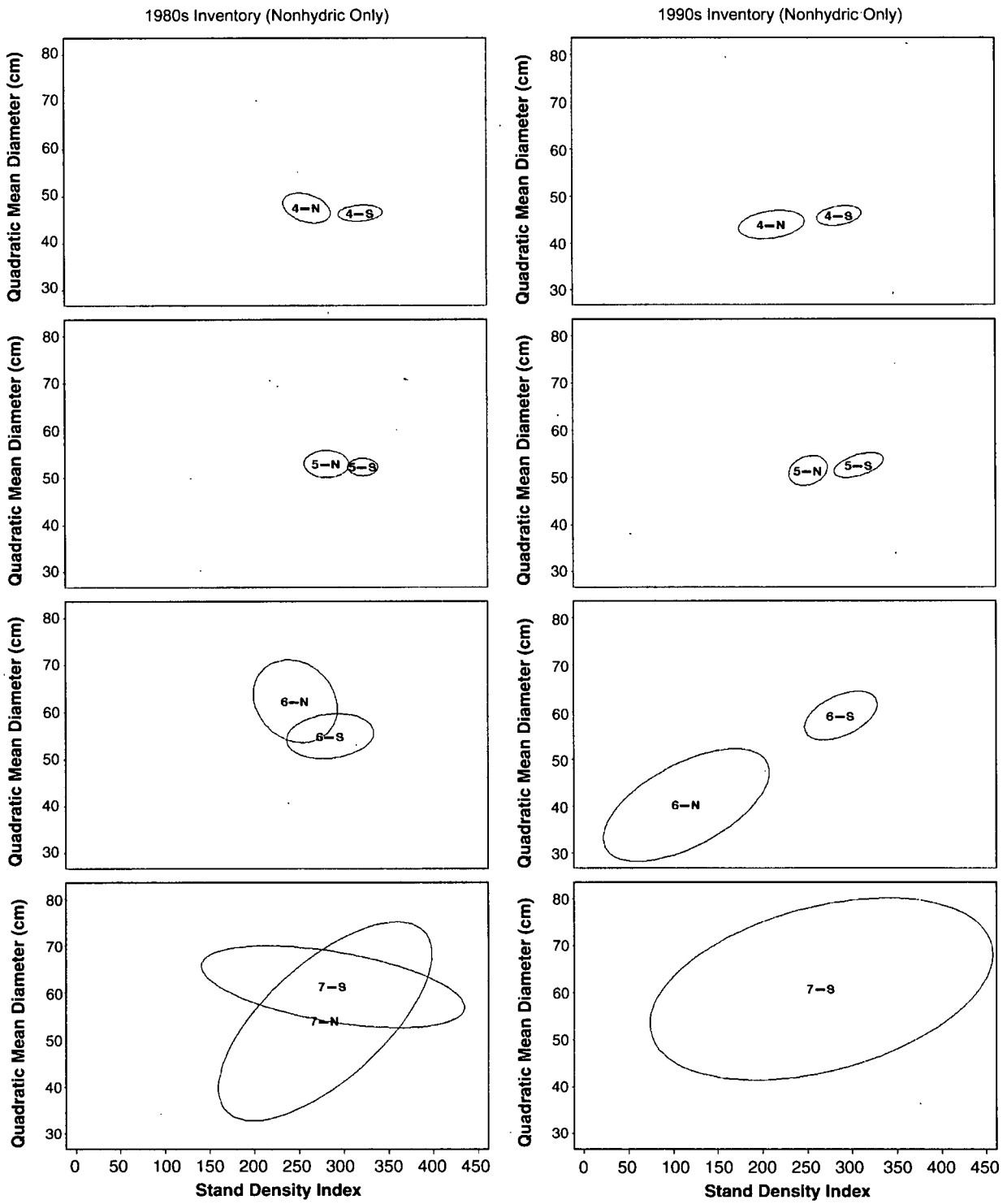

Fig. 4. Forest-wide means and 90% confidence ellipses for timber-volume classes interacted with hydric-soil classes and aspect classes. See Fig. 7 for sample sizes.

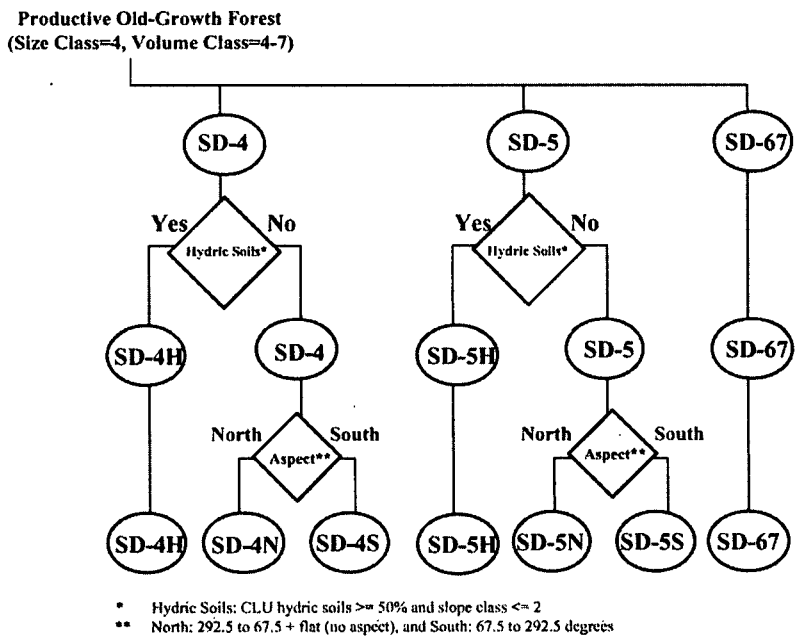

Fig. 5. Diagram showing development of tree size and density mapping groups.

effectiveness of this tool has yet to be tested. We need more ground-sampled data and closer work with biologists, ecologists, silviculturists, planners, and managers to see if our model can help with their particular needs, interests, or applications.

Although our proposed mapping model may help to identify and locate relevant forest types, it does not yet represent a forest classification. There is a long-standing need to classify forest types into simple consistent descriptive and quantitative terms. Devising such a classification could be a long-term goal for mapping on the Tongass NF. National protocols for vegetation classification and mapping are currently being developed. Preliminary reports indicate a mean tree size (QMD) and tree density (crown closure) framework for classifying and mapping forest structure.

We recommend measuring SDI and QMD and other forest attributes in at least 20 randomly selected polygons from each of seven mapping groups in the final model, with at least 20 ground-sampled plots per polygon. Such sample sizes would provide enough statistical power (80%) to detect differences between mapping groups that are considered grossly perceptible to an observer (80% of one standard deviation, with alpha equal to 0.10) (Cohen, 1988). Such data would allow for the following analyses: (1) test for statistical differences among mapping groups; (2) estimate probabilities for finding specific forest attributes within a randomly selected polygon from any particular mapping group; (3) test for correlations between forest overstory and understory conditions; and (4) quantitatively analyze specific polygons that represent forest types or stands of interest (e.g., big-tree forests, hydric forests, or south-facing wind-exposed forests).

We caution that there is a substantial amount of variation and noise in any forest-mapping exercise. Although most variation comes from the microscale diversity of the forest structures in southeast Alaska, other sources of variation are errors in the mapping and map assessment process, such as distortion in aerial photographs, geo-referencing errors, errors in locating mapped units on the ground, measurement errors, and errors resulting from the time lag between aerial-photo-interpretation and ground sampling. With so much variation, error, and noise in the data, it is highly unlikely that any mapping model will lead to conclusive, definitive, and totally acceptable results (Spies and Cohen, 1999). The best we may be able to do is to evaluate maps based on their ability to detect statistical signals among relevant measurable forest attributes, then

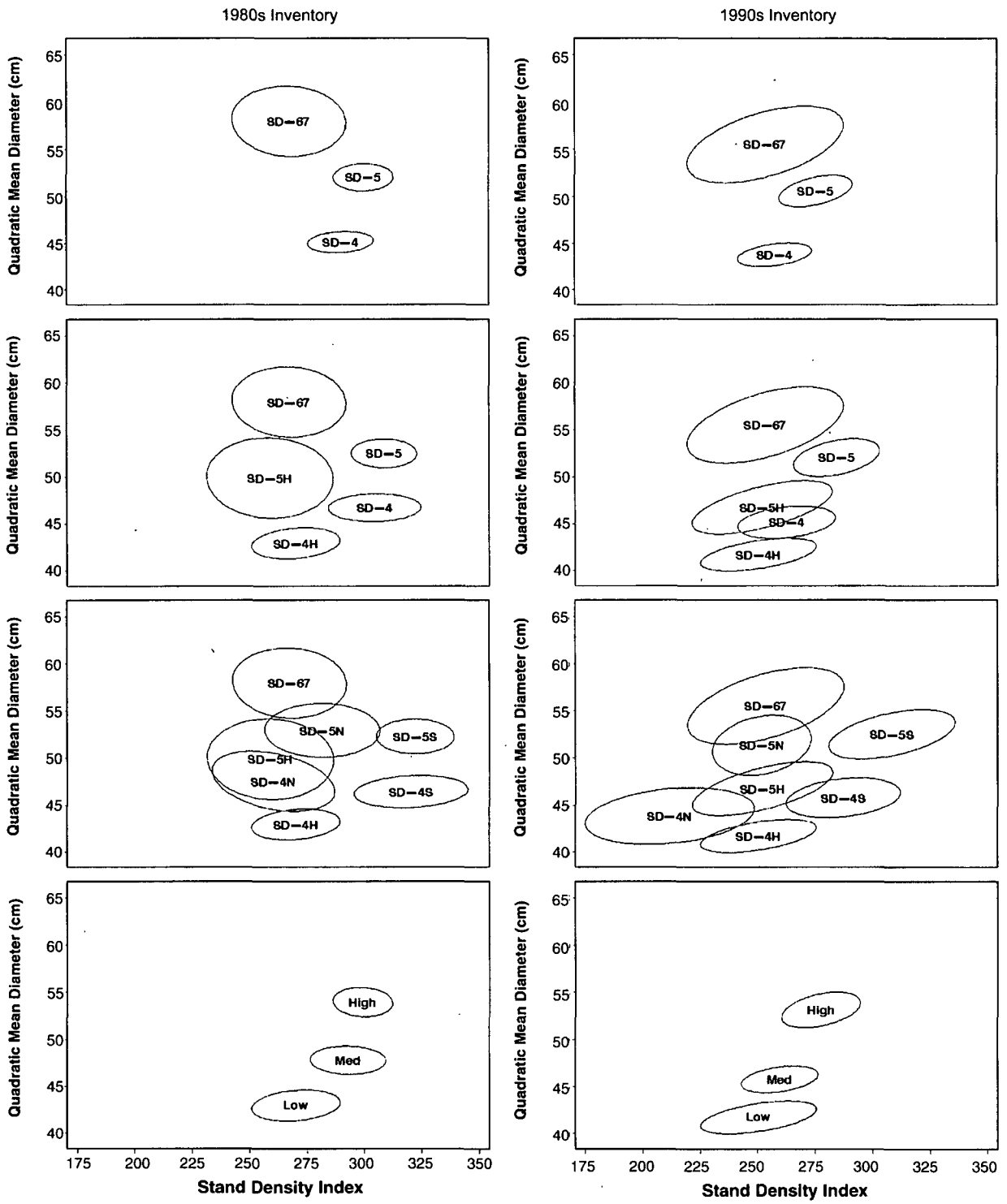

Fig. 6. Forest-wide means and 90% confidence ellipses for three nested (hierarchical) levels of the final predictive-mapping model and for the 1997 TLMP timber-volume map. See Fig. 7 for sample sizes.

Figure 2		1980s	1990s
1st row	Volume Class 4	174	249
	Volume Class 5	151	210
	Volume Class 6	37	45
	Volume Class 7	10	9
2nd row	Hydric	107	169
	Nonhydric	265	344
3rd row	Nonhydric - N	87	120
	Nonhydric - S	178	224

Figure 3		1980s	1990s
1st row	VC4 - Hydric	74	101
	VC4 - Nonhydric	100	148
2nd row	VC5 - Hydric	27	58
	VC5 - Nonhydric	124	152
3rd row	VC6 - Hydric	6	9
	VC6 - Nonhydric	31	36
4th row	VC7 - Hydric	0	1
	VC7 - Nonhydric	10	8

Figure 4		1980s	1990s
1st row	VC4 (Nonhydric) - S	74	100
	VC4 (Nonhydric) - N	26	48
2nd row	VC5 (Nonhydric) - S	83	88
	VC5 (Nonhydric) - N	41	64
3rd row	VC6 (Nonhydric) - S	16	30
	VC6 (Nonhydric) - N	15	6
4th	VC7 (Nonhydric) - S	5	6
	VC7 (Nonhydric) - N	5	0

Figure 6		1980s	1990s
1st row	SD-4	174	249
	SD-5	151	210
	SD-67	47	54
2nd row	SD-4H	74	101
	SD-4	100	148
	SD-5H	27	58
	SD-5	124	152
	SD-67	47	54
3rd row	SD-4H	74	101
	SD-4S	74	100
	SD-4N	26	48
	SD-5H	27	58
	SD-5S	83	88
	SD-5N	41	64
	SD-67	47	54
4TH row	Low	74	101
	Medium	133	216
	High	165	196

Fig. 7. Sample sizes for means and confidence ellipses reported in Figs. 2–4 and Fig. 6.

use those signals to support claims that some mapping models provide more relevant information on forest conditions than do others, as we have demonstrated in this paper.

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