Inventory Essentials
and
Best Practices
for
Forest Inventory Management

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Introduction to Inventory Essentials

Forest inventory methods have evolved and improved significantly over the past sixty years. However, not all forest management organizations have kept up with this evolution. Part of the reason for the wide variance in current practices has been a significant decline in the published information regarding this evolution. Applied forestry research and development essentially ended with the close of the 20th century (National Science Council, 2002; U.S. Endowment, 2017). This report will attempt to clarify the current status of forest inventory methods.

Much good effort and research in the 1952 to 1985 time period went into various methods of cruising timber stands. This past development was especially focused on field methods for achieving reliable and efficient estimates of “standing volume”. The emphasis was on “volume”.

Background on Fifty years of Inventory

Beginning in the 1970s was a rapidly expanding field of forestry research into computerized growth models and forest planning systems. Traditional yield tables based on per acre statistics of stand averages (trees, basal area and volume per acre) gave way to tree-list growth models. These growth models provided the ability to characterize variation within each stand, such as species composition, stand structure and spatial pattern. Expanding computer-based storage capacities allowed forest inventory to shift from per acre averages for each stratum to complete tree lists for every stand within each stratum. This created a pivotal change in inventory.

Meanwhile, in 1994 the Clinton Administration adopted the Northwest Forest Plan for protection of habitat for the Northern Spotted Owl. This plan was overlaid on all US Forest Service and Bureau of Land Management lands throughout the West. It quickly became a guiding principle for State, County and Tribal forest management. State agencies adopted rules and restrictions to be applied to all forest ownerships regarding silvicultural harvesting systems. This resulted in a silvicultural shift from even-aged, clearcut harvest regimes to a wide variety of partial cutting, selection thinning and over-story retention regimes. This created a pivotal change in silviculture.

Since 1990, working forests under a wide variety of ownerships in the West have evolved into mixed species composition, irregular stand structures, and varying degrees of non-uniform spatial tree distributions. The inventory, growth, silviculture and planning on these forests has become much more complex and interdependent than assumed in the traditional single-species, even-aged, harvest planning of the 1950 – 1990 time period. This shift to alternative silvicultural systems away from clearcutting has been made mostly due to imposed restrictions and/or public
sentiment regarding forest management. Not one example may be found where this shift was made by the forest owner to improve sustained yield or cash flow.

Overview of the Principle Changes in Inventory Methods

1) The 1950 – 1960s Inventory Objective was standing volume. Sample designs were based on strip cruises typically covering five percent of the forest land base. Only commercial tree species greater than 11-inches Dbh were tallied. Western hemlock and Grand fir were considered weed species and therefore, not tallied. Height measurements were in numbers of logs, not total height. Forest maps were hand-colored strata of volume classes. Growth estimates were made by hand calculations, based on published yield tables and charts.

2) In the 1970 – 1980s Forest inventory separated into two basic approaches – Un-stratified and stratified sampling methods.

   a. The un-stratified approach became known at the Continuous Forest Inventory (CFI) method. A grid of permanent plots was established across the forest at a pre-determined level of intensity mostly based on cost to install and maintain some targeted number of plots. Volumes and species composition could be obtained from each plot and then expanded to the whole forest based on the number of acres which each plot represented. CFI grids were established at levels from 1 plot per 40 acres (corporate timberlands) to 1 plot per 2,176 acres (USDA National Forest Survey later known at Forest Inventory & Assessment (FIA)). By re-measuring these permanent plots on a 5 or 10-year cycle, the land owner could estimate the rate of forest growth and decline occurring across the landscape.

   b. Strata-based inventory sampling started with a complete coverage of aerial photography (typically at a resolution of 1:12,000 or slightly higher on 9-inch square photos resulting in about 1 square mile visibility per photo). The photo interpreter typically traveled across the ownership to pre-calibrate his/her ocular estimates of species, size and density from the photos by what could be directly observed from the ground. The interpreter then created a stratification of about 3 to 5 dozen levels for species, size and density without making another field tour. This was a purposeful decision to force a level of consistency into the ocular classifications applied across the entire forest. A grease pencil was used on the photos to create individual stand polygons in the range of 10 to 100 acres in size. Sometimes the polygons were defined as small as five acres for clearly unique circumstances. Experience demonstrated that attempts to create more than 4 dozen strata levels only resulted in lower levels of confidence that real differences between strata actually existed. A sample of temporary plots was then installed across a number of stands within each stratum. These plots were compiled and grouped by stratum to create forest-wide strata-averages of species composition and volume. These strata averages were then assigned to every stand polygon within each stratum.

With the advent of computer processing in this period, the inventory forester began to consider moving beyond published yield table look up for future growth by invoking
newly developing growth models driven by the inventory initial strata-average conditions.

3) 1990s Shift to Stand-level volume with Strata-level growth capacity. Cruise plots began to be compiled by stand rather than by stratum. The species composition and volume of each stand was stored stand by stand. The average of all cruised stands was extrapolated to the un-cruised stands of the same stratum. Each cruised stand was grown forward with a computer growth model and a local site index value. Un-cruised stands were extrapolated at each growth update from the grown cruised stands of that stratum.

Computer processing and storage provided the opportunity to store and track all parameters for each stand through time. This became essential with the inclusion of spatial constraints on silviculture due to wildlife buffers. Harvest planning by stand became critical to mitigate spatial constraints around wildlife buffers. The previous standard practice of harvest planning by strata classes was no longer adequate.

Those ownerships which had evolved to CFI-based inventories found that the whole permanent plot approach was now inadequate to address silviculture or harvest planning with the inclusion of stand-specific spatial constraints for wildlife buffers. The CFI approach had a run of less than twenty years from start-up to close due to the other advances in forest management which were occurring in the same time frame. Some forest management organizations still hang onto the CFI approach only due to existing regulation or policy. A grid of permanent plots is no longer adequate as an inventory for managing a working forest. Even using the CFI plots weighted by strata acres instead of traditional equal acreages per plot caused the entire forest inventory to shift.

4) In the 2000 – 2020s decades the stand structure, species composition and spatial patterns by stand (between and within) for long-term planning became the essential components for silvicultural and harvest planning. The standing volume in each stand became secondary. Primary was the ability to make decisions using species composition, log values, harvest and access costs, spatial habitat restrictions, mixed-species stands with differential growth by species and localized site growth capacity. These all became active parameters available for harvest planning due to the every improving computer speed and storage capacities.

Looking back at this history, inventory methods on some ownerships have evolved rapidly while others have barely evolved at all. This is partly due to a lack of strong R&D guidance through these past forty years. Some forest management organizations have actually shifted backward in the kind and quality of forest inventory being applied.

It should become quite clear in regard to what level each ownership inventory has evolved as this report unfolds and discusses the fundamental components of forest inventory – strata, stands, plots and trees. These shifts in methods are summarized in Table 1.

As noted initially, part of the reason for the direction in forestry practice has been a significant decline in forestry research. This was reported in detail by the National Research Council 2002 Report, “National Capacity in Forestry Research”. This report identifies critical needs and made suggestions for significant improvements. To quote, “...forestry research capacity is at a
crossroads, if not a precipice.” The U.S. Endowment for Forestry and Communities calls for … a sector-wide commitment to implement their 2017 Report recommendations... “The paucity of (forestry research) innovation stems from a decline in research and development funding and a subsequent drop in R&D capacity.” “Re-building the research and development capacity of the U.S. forest sector requires fundamental changes.” “The sector needs new models and a new culture of enterprise.”

Little has been accomplished or published since 1990 regarding the objective and methods associated with achieving a reliable forest inventory. Forestry articles and publications on inventory cruising over the past 30 years have not evolved beyond methods associated with “harvest” cruising. There have been a large number of articles and presentations produced about the “mechanics” of sampling a forest. However, very little has been produced about the “objectives” for sampling a forest.

A specific distinction is being made here by separating “harvest” cruising from “inventory” cruising. Harvest cruising is about defining the volume available for cutting a specific stand. Inventory cruising is about defining the species composition, stand structure and spatial distribution of the trees within a given stand. Stand volume is no longer an important or critical parameter in defining the reliability of an inventory cruise. It appears that some forestry practitioners and researchers have not evolved past the belief that forestry is un-changed since 1990. In fact, the demands on forestry have changed significantly. All of the assumptions and beliefs of traditional forest management and forestry research must be questioned and re-evaluated. In this regard, what is the objective of an inventory cruise?

Understanding the Difference between Inventory Cruising and Harvest Cruising

This distinction is important and it is based on how soon the cruise information is to be applied. For a pre-harvest cruise, it most often will be used in the next 1 month to 3 years. However, an inventory cruise may be maintained and grown for 10-20 years or longer. The important considerations for a pre-harvest cruise are:

- Tally of merchantable trees by species and size class
- Volume and tree size for logging engineering planning
- Access and restrictions for scheduling and harvest setting designs
- Grade / Sorts / Products for marketing planning
- Value / Profitability for business planning

The important considerations for an inventory cruise are:

- Tally of all trees by species and size class regardless of current merchantability
- Classification of tree status for future growth due to past competitive stress effects
- Determination of site index for stratification of growth potential
- Spatial distribution of trees within the “Stand” polygon for clumpiness impact on growth
- Damage and vigor assessment for future expectation of defect and growth constraints
Table 1. Summary chart of the trends in forest inventory, silviculture and planning over the past sixty years.

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Cruise Objective</th>
<th>Cruise Target</th>
<th>Site Index</th>
<th>Growth Method</th>
<th>Growth Model</th>
<th>Silvicultural Planning</th>
<th>Harvest Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950 - 1960s</td>
<td>Harvest Volume</td>
<td>Strata Average</td>
<td>Strata Site Class</td>
<td>Hand Look up</td>
<td>Yield Table</td>
<td>Clearcut &amp; Plant</td>
<td>Strata Harvest Age</td>
</tr>
<tr>
<td>1970 - 1980s</td>
<td>Strata Volume</td>
<td>Strata Average</td>
<td>Strata Average</td>
<td>Computer Look-up</td>
<td>Stand Average</td>
<td>Strata Average</td>
<td>Strata Acres &amp; Age</td>
</tr>
<tr>
<td>1990s</td>
<td>Stand Volume</td>
<td>Stand Average</td>
<td>Stand Average</td>
<td>Growth model</td>
<td>Tree List / DI</td>
<td>Site Class Average</td>
<td>Non-Spatial LP</td>
</tr>
<tr>
<td>2000 - 2020s</td>
<td>Stand Structure</td>
<td>Stand Specific</td>
<td>Macro-Site</td>
<td>Growth model</td>
<td>Tree List / DD</td>
<td>Stand Specific</td>
<td>Stand Specific</td>
</tr>
</tbody>
</table>

Definitions of Time Frame Sequence in each column:

**Cruise Objective** = The level of resolution desired at the time the sample plots were established.

**Cruise Target** = Definition of how the sample plots were aggregated before compiling to a per acre summary of attributes.

**Site Index** = Initially defined in 3 to 5 classes, then site index averages per stratum, then traditional height/age basis, finally by growth capacity.

**Growth Method** = Originally a printed yield table, then look-up from computer model averages, and finally stand-specific tree list input / output

**Growth Model** = Published yield table, then computer stand-average model output, followed by stand, tree-list output with higher resolution.

**Silvicultural Planning** = Default to even-age harvests, then targeted levels by strata, shifting to site levels within strata, finally by stand capacity.

**Harvest Planning** = Simple allocation of acres by stratum, then refined by strata site, adjusted to stand site capacity, finally by spatial capacity.
Further definitions for Table 1 – Growth model types:

*Normal Yield Tables* – local forest manager makes professional judgement on amount of adjustment.

*Stand Average growth models* – project only stand average parameters of strata averages (e.g., DFSIM, PPSIM)

*Tree List – Distant Independent growth models* (Tree List / DI) – project stand tree lists assuming only evenly-spaced trees across the stand with one average density for all trees. Thinning treatment assumes all residual trees get equal increase in growing space (e.g., ORGANON, FVS). These architectures (Monro, 1974) are adequate for single species, even-aged stands where very little spatial irregularity (clumpiness) or vertical stand structure (all-aged) exists. Some limited species mixtures are possible if these mixtures are part of the same canopy height.

*Tree List – Distant Dependent growth models* (Tree List / DD) – project stand tree lists utilizing cruised measurement of stand clumpiness and spatial patterns. Trees may be in any combination and mixtures of species, size and spatial distributions. Simulated thinning response occurs only on residual trees near locations of removals (e.g., FPS). This architecture is required for mixed species, mixed stand structure silvicultural history or future expectation. These stand types typically express wide ranges in spatial patterns (clumpiness) and structure which the Individual Tree – Distant Independent growth models were not designed or calibrated to forecast.
Sample Designs – Strata

1) Initially Stratify the whole forest – Once only, do not repeat
   a. Create not more than 48 – 60 forest strata (plus non-forest)
   b. Species classes (4 – 6), Size classes (4), and Density classes (3)

2) Break these strata into uniquely identified (and numbered) stand polygons
   a. Individual stands should be within a 10 – 80 acre range only
      i. Larger polygons cross site, silviculture and operational bounds
      ii. Smaller polygons result in edge bias effects on growth forecast. The stand growth may actually be influenced by shading and moisture demands from other neighboring stands. This becomes more significant where the surrounding stands are larger. Nearby stands with average diameters greater than 20-inches (yellow – red trends) have in excess of a 10% influence on growth dynamics for stands less than 10 acres in size.

   In other words, growth projection of a 5-acre stand where some silvicultural treatment is expected to yield a 15% gain may not actually be observed if that small stand is heavily shaded by large neighbors.

3) Select at least a 20% sample of acres (stands) within each stratum to cruise
   a. Select stands based on probability proportional to size by stratum
Sample Designs – Stands

1) Grow every stand (cruised and un-cruised) forward annually (not by plot).
   a. Each stand contains unique site index, silviculture and operability
   b. Each stand contains unique riparian and wildlife constraints
   c. Each stand contains unique history – silviculture and access
2) Annual and long-term forest planning must be based on stands
   a. Forest planning should be in 5-year periods over a 100-year horizon
   b. Near-term planning may re-structure stands into harvest units
3) GIS Lump/Split utilities are key elements of a working forest

Sample Designs – Plots

1) Plots within stands should be distributed systematically across entire stand
2) Small tree frequencies define density across shade tolerance classes
3) Large tree frequencies define silvicultural options and asset values
4) Systematic spatial pattern of plots provides ability to classify clumpiness
   a. A single plot design is used throughout the entire stand
   b. The Cruiser decides when a plot falls inside or outside of stand boundary
   c. Use the un-biased walk-through method for plots along stand edges
5) Plots are distributed by stand without regard to non-vegetative bounds
   a. Within stand riparian and wildlife buffers are ignored
   b. Within stand administrative boundaries are ignored
6) Plots are compiled by stand to create a within-stand species/size structure
   a. Plots are not re-assigned or copy-pasted to other stands
   b. Subsets of plots are not used or assigned to Lump/Split stand portions
   c. All plot data is archived at the end of each year’s annual report
   d. Only new cruises are compiled each year which provide fresh input
7) Plot frequency within each stand should be in the range of 3 to 16 plots
   a. Fewer than 3 plots disallows variance and clumpiness parameters
   b. Installing more than 16 plots begins to absorb excess cost without associated improvements in reliability or stand structure characterization.

Sample Designs - Trees

1) Sample all trees of all species and sizes within each stand
2) Use a combination of prism-sweep and fixed-area plot designs for sampling
   a. Tally frequencies between 1 and 10 trees per species/size class only. Do not count more than 10 trees per class
   b. Sample small trees on a fixed-area basis – frequency is primary
      i. Tally by species and size class
         1. Height class = 2-feet for 1 to 3-foot tall trees, Dbh = 0
         2. Height class = 5-feet for 3 to 6-foot tall trees, Dbh = 0
         3. Height class = nearest 2-feet for 6 to 20-foot tall trees
         4. Dbh class = nearest 1-inch for trees above 20-feet tall
ii. Small trees are those below 5-inches Dbh

iii. Fixed-area basis works well at $\frac{1}{100}$th acre circle (11.8-foot)

iv. Record tree condition and vigor class

   1. Default condition is a healthy, natural-origin tree
   2. Group code “.P” for planted tree
   3. Group code “.S” for stump-sprout tree
   4. Default vigor class assumes 3-year needle retention
      a. Vigor = 1 for highly stressed trees
      b. Vigor = 2 for moderately stressed trees
      c. Vigor = 4 for robust, vigorous trees
      d. Vigor = 5 for exceptional growth characteristics

   c. Sample large trees on a prism-sweep basis – size is primary
      i. Tally by species and 1-inch Dbh class
      ii. Measure total heights by sub-sampling within species
         1. Height sample every $3^{rd}$ tree (or plot) in plantation rows of single-species stands
         2. Height sample every $2^{nd}$ tree (or plot) in even-aged, uniformly-stocked stands (natural or planted)
         3. Height sample every tree in mixed-species, mixed-age class stands with selection harvesting history
      iii. Estimate % live crown length on all height-sampled trees
      iv. Estimate % defect by $\frac{1}{3^{rd}}$ total tree height classes. Only sample defect by log position if the cruise objective is current harvest volume, not current inventory stand structure.
         1. Sample defect on all height-sampled trees
         2. Sample defect on all trees for species with defect exceeding 15% average on height-sampled trees
      v. Measure taper only in stands with erratic silvicultural history
         1. Use a separate felled-tree taper sample to localize volume estimation for cruised Dbh and Height pairs
         2. Use only taper height method to $80\%$ of Dbh
         3. Never use taper diameter method at 17-foot height, field optical tools have too little precision for this method
      vi. Tree age and increment measurements do not provide sufficiently significant information to warrant the time needed
      vii. Record vigor class 1 – 5 (as in small tree sample) for trees (and stands) where health, disease, insects or mechanical damage may affect future growth and survival. Averages are not extrapolated to un-sampled trees. Default for un-sampled, healthy trees is vigor class = 3.

   d. Record recent dead trees (less than 5 years) by species and 2-inch Dbh class.
      i. Record Group code = “.D”
      ii. Record height to nearest 10-feet
      iii. Record % defect by $\frac{1}{3^{rd}}$ tree heights as with live trees

3) Use a $\frac{1}{20}$th acre fixed-area circular plot for standing dead trees (snags) without conventional log valuation potential (e.g., dead more than 5 years). Sample design warranted due to expected rare occurrence of this class of standing trees.
a. Record only trees larger than typical minimum merchantable tree criteria
b. Record species and Dbh to nearest 2-inch class, Group code = “SN”
c. Record height to nearest 10-feet
d. Record defect condition where:
   i. Condition = 1 for sound wood, bark in place; 2 for hard snag; and, 3 for soft snag
4) Use a minimum 100-foot line transect for down woody material
   a. Start the line transect from each plot center oriented to the line of travel. In stands with topographic differentiation, split the transect length equally with one segment perpendicular to the line of travel.
   b. Record each crossing of the line segment of a tree segment as an independent sample. A crossing is defined as the point where the pith crosses the line. Record the segment diameter at the point of crossing the transect.
   c. Record species, segment diameter, and defect class for each transect sample. A segment must meet the minimum merchantable log length and diameter previously defined for live trees in the stand.

Cruise Compilation Methods

1) Compile each stand cruise independently. Plots are unique to each stand and are always compiled as a complete set.
2) Un-measured heights are estimated based on the set of measured heights within each species of each stand. The most abundant species by basal area per acre may be used for default height estimation for species without any height measurements in that specific stand.
3) Height estimation methods should allow for variation in observed heights within a species and dbh class.
4) Each compiled stand should provide an index of spatial variation within the stand. Mixed-species, mixed-size class stands with selection harvesting history tend to have a high degree of spatial clumpiness. Clumpy stands have a significant departure in growth dynamics from uniform, even-aged stands. This results in a necessity to capture an index of this spatial variation as it may exist in each stand.

Cruise Expansion to Un-sampled Stands

1) Building a new inventory database usually results in only a portion of stands within each stratum with field-sampled species, size, density structures.
2) Un-sampled stands may be assigned a stand structure from the weighted-by-acres average tree list generated from sampled stands within the same stratum class.
3) Each expanded (estimated) tree list in each stand may be grown independently of all other stands. This allows for unique inputs of site capacity, silvicultural options and operational constraints to have an impact on forest-wide dynamics of wood and value flows.
4) Once 20 to 30 percent of acres in each stratum have been field sampled, then further cruise expansion to un-sampled stands should be curtailed. The inventory forester should be constantly aware of the forest-wide impact of
running a cruise expansion. Expansions may cause a forest-wide shift in species abundance, log distributions, standing volume and value assessments.

5) Shifts in forest-wide standing inventory parameters, where more than 30 percent of strata acres have been field-sampled, should only be the result of stand-specific new field samples. This provides for a much more consistent and robust trend in forest-wide statistics from one year to the next.

Year-end Updates and Reporting

1) Each year-end inventory update should begin with a copy of the previous year-end GIS stand polygon layer edited to incorporate all new harvest units, acquisitions, deletions and boundary adjustments occurring during the current year. Only the spatial parameters are updated in this step, which are numbers and sizes of vegetative polygons (the inventory stand layer). The only requirement is that each stand polygon is uniquely identified and numbered, both within the previous and current year-end layers. It is not necessary for the previous year-end numbering method to match the current year-end numbering method.
   a. The previous year-end stand polygon layer is then overlaid (intersected) by the new current year-end polygon layer. This temporary intersect layer provides all of the acreage adjustments and weighting necessary to dis-assemble previous polygons (old number) and then re-assemble these spatial segments into the new year-end polygons (new number).
   b. These polygon segment weights are then used to compute a new stand species/size/density structure (tree list) from the previous intersected polygons per acre tree lists (weighted by the number of acres in each contributing segment). The sum of the acres in contributing segments equals the total acres in the new year-end stand polygon.
   c. All continuous parameters are populated from weighted averages of previous stand parameters. All discrete parameters (text and numeric labels) are populated from the values in the largest previous contributing polygon segment. These default parameter values may be updated in a later step. The new year-end stand polygon layers are now fully populated, both for spatial and vegetation database components (acres, species, stocking and volumes).

2) Update the GIS road network and road class buffer widths. Update the stand polygon acreage parameters to compute net forest acres (net of roads).
3) Update the GIS stream courses and riparian buffer widths. Update the stand polygon acreage parameters to compute net working acres (net of riparian).
4) Review and update all administrative costs, silvicultural costs and operating costs appropriate for the current year-end reporting. Review and update all species-specific log specifications, log rules and log values appropriate for the current year-end reporting. Re-merchandize all stands in the new forest inventory database incorporating all cost and value parameters.
5) Select (flag) all stand polygons in the current year-end database which were harvested in the current year.
a. Run reports on these selected stands for year-end harvest volume and value reports. This is the book reported harvest depletion for the current year. It may not match truck scales accumulated from across the forest.
b. Deplete the species tree lists from these selected stands, but keep these polygons with their acreages (gross, net and riparian), site and topographic parameters.

6) De-select harvested polygons and then select all other stand polygons.
   a. Save the stand volume, value and acreage listings of these stands to a background table.
   b. Link the tree list growth model to the inventory. Grow all stands for one year from the previous year-end to the current year-end.
   c. Report the changes in volume and value due to growth over the past year. These reports may include all combinations of forest-wide and stand-based summaries.

7) Select all stand polygons in the current forest inventory (both harvested and grown).
   a. Update the inventory database with all new cruises from all sampled stands in the current year. Select only those cruised stands. Some cruises may be post-harvest cruises after a previous thinning.
   b. Compile all cruises using the current merchantability and value assignments.
   c. Select all inventory stands to produce forest-wide reports of the new current standing forest inventory. These reports may include all combinations of forest-wide and stand-based summaries.
   d. The changes in standing inventory from the previous forest-wide summaries are due to new information obtained in the current set of cruised stands.

8) This is now the point in inventory database management where any other changes in methods, parameters or classifications should be made. These may include standard merchandizing parameters, values, ownership or database software utilities.

9) Archive the full suite of databases (spatial and attribute) to begin a new year of inventory management.

10) Prepare a copy of the new forest-wide inventory database for long-term forest planning. Forest planning should occur on an annual basis.

This completes all inventory essentials for a robust working forest inventory.

Congratulations... You have just completed your sophomore year in forestry...!!!

Silvicultural Essentials are completed in the Junior year.

Planning Essentials are completed in the Senior year.
**Impact of using Diameter Limit Thresholds in Sampling and Reporting**

Attempting to apply a “Pre-harvest cruise” to an “In-place forest inventory” may have severe consequences. A true example was a tree farm where all polygons were cruised with tree tallies down to 9-inches at diameter breast high (Dbh). This cruise gave a very good assessment of the currently merchantable timber volume. The forest manager could summarize the current market value by species and log size for any stand in the inventory.

However, this tree farm is in a region of California where only selection harvest silvicultural practices are being applied. Therefore, the residual tree stocking by species and size after selection harvest would determine the number of years and volumes that might be grown on each stand in future. Since no trees were tallied in the pre-harvest cruise under 9-inches Dbh, there was no merchantable volume in-growth projected to occur over the next thirty years! To develop a sustained yield assessment from this database would be worse than useless. It would be totally in error. (Unless, by chance, there actually were no existing trees less than 9-inches on the entire forest) The message is, “Tally all species and size classes if you expect to use this cruise for inventory and long-term planning.”

**Impact of Relying on Volume Statistics as an Assessment of Inventory Confidence**

To use sampling errors and confidence statements around standing volume per acre as a criterion for a reliable cruise has no useful meaning for inventory assessments. The major problem with basal area per acre, cubic volume per acre and board volume per acre is that these are all “censored” parameters. Inventory cruising must provide a complete tree list of all species, tree sizes and spatial distributions. If the inventory cruising has been censored (such as a 9-inch minimum Dbh), then these statistics have very limited usefulness for assessing confidence.

**Recognizing the Silvicultural Impact on Traditional Stand Statistics**

To demonstrate the consequences of focusing all inventory statistics only on the variation in censored parameters, a series of eight large forest inventories were compiled (Table 2). These inventories were from all regions of the United States representing the full range of silviculture from single-species plantations to mixed-species, mixed stand structure selection harvested stands. Each dataset was from a single ownership where the cruise design was consistently applied across that ownership. All stands from all regions were compiled using the Forest Biometrics Research Institute (FBRI), Forest Projection and Planning System (FPS Version 7.53). A total of 28,199 stands were compiled based on 446,869 plots across 1,297,267 acres.

Table 2 provides averages by ownership for the primary stand parameters for each inventory. All stands from all regions were compiled with a minimum 7-inch Dbh limit for volume.

<table>
<thead>
<tr>
<th>Trees = number of trees per acre</th>
<th>QDbh = quadratic mean diameter at breast height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal = basal area per acre</td>
<td>Top Ht = average height of largest 40 trees per acre</td>
</tr>
<tr>
<td>CCF = Crown Competition Factor</td>
<td>Clump = clumpiness index (explained later)</td>
</tr>
<tr>
<td>CubicGrs = gross cubic volume per acre</td>
<td>BoardGrs = gross board volume per acre</td>
</tr>
</tbody>
</table>
Table 2. Statistics for eight forest inventories selected from across the United States.

<table>
<thead>
<tr>
<th>Region</th>
<th>Stands</th>
<th>Trees</th>
<th>QDbh</th>
<th>Basal</th>
<th>Top_Ht</th>
<th>CCF</th>
<th>Clump</th>
<th>CubicGrs</th>
<th>BoardGrs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Count</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
</tr>
<tr>
<td>Southeast US</td>
<td>3,006</td>
<td>196</td>
<td>7.8</td>
<td>64</td>
<td>34</td>
<td>96</td>
<td>0.82</td>
<td>864</td>
<td>3,208</td>
</tr>
<tr>
<td>California Coast</td>
<td>1,741</td>
<td>769</td>
<td>6.6</td>
<td>184</td>
<td>68</td>
<td>266</td>
<td>0.79</td>
<td>2,758</td>
<td>14,140</td>
</tr>
<tr>
<td>Western Oregon</td>
<td>2,842</td>
<td>419</td>
<td>6.5</td>
<td>92</td>
<td>59</td>
<td>141</td>
<td>0.78</td>
<td>1,703</td>
<td>6,524</td>
</tr>
<tr>
<td>Northern Idaho</td>
<td>7,441</td>
<td>804</td>
<td>4.8</td>
<td>92</td>
<td>58</td>
<td>157</td>
<td>0.76</td>
<td>1,880</td>
<td>9,851</td>
</tr>
<tr>
<td>California Sierras</td>
<td>489</td>
<td>946</td>
<td>6.1</td>
<td>144</td>
<td>77</td>
<td>202</td>
<td>0.75</td>
<td>3,273</td>
<td>12,694</td>
</tr>
<tr>
<td>NE Washington</td>
<td>1,395</td>
<td>942</td>
<td>5.2</td>
<td>106</td>
<td>72</td>
<td>180</td>
<td>0.74</td>
<td>2,244</td>
<td>11,340</td>
</tr>
<tr>
<td>Central Oregon</td>
<td>5,717</td>
<td>844</td>
<td>6.1</td>
<td>122</td>
<td>51</td>
<td>182</td>
<td>0.73</td>
<td>2,897</td>
<td>15,236</td>
</tr>
<tr>
<td>Lake States</td>
<td>5,568</td>
<td>1,059</td>
<td>6.0</td>
<td>75</td>
<td>44</td>
<td>153</td>
<td>0.61</td>
<td>1,197</td>
<td>4,405</td>
</tr>
<tr>
<td>Summaries</td>
<td>28,199</td>
<td>747</td>
<td>6.1</td>
<td>110</td>
<td>58</td>
<td>172</td>
<td>0.75</td>
<td>2,102</td>
<td>9,675</td>
</tr>
</tbody>
</table>

Using standard statistical methods, the mean, standard deviation, and coefficient of variation were compiled for each set of sample plots within each stand. Table 3 provides the average coefficient of variation (CV) observed across all stands for each of the primary stand parameters in each region.

Plots = total number of plots in inventory  
Tpa_Err = CV for numbers of trees per acre  
BA_Err = CV for basal area per acre  
CCF_Err = CV for Crown Competition Factor  
Cub_Err = CV for cubic volume per acre  
Brd_Err = CV for board volume per acre  
Acres (Avg) = average stand size in acres  
Acres (Sum) = total acres in inventory  
Acres/Plot = average number of acres per plot

Table 3. Average coefficients of variation for primary parameters from inventories in Table 1.

<table>
<thead>
<tr>
<th>Region</th>
<th>Plots</th>
<th>Tph_Err</th>
<th>BA_Err</th>
<th>CCF_Err</th>
<th>Cub_Err</th>
<th>Brd_Err</th>
<th>Acres</th>
<th>Acres</th>
<th>Acres/Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sum</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Avg</td>
<td>Sum</td>
<td>Sum</td>
<td>Avg</td>
</tr>
<tr>
<td>Southeast US</td>
<td>65612</td>
<td>19</td>
<td>9</td>
<td>13</td>
<td>9</td>
<td>11</td>
<td>87.3</td>
<td>262,354</td>
<td>4.1</td>
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<td>33,347</td>
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<td>13</td>
<td>17</td>
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<td>45.7</td>
<td>79,590</td>
<td>2.4</td>
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<td>15</td>
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<td>22</td>
<td>36.0</td>
<td>102,241</td>
<td>1.9</td>
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<tr>
<td>Northern Idaho</td>
<td>129,047</td>
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<td>16</td>
<td>27</td>
<td>22</td>
<td>59.7</td>
<td>444,046</td>
<td>3.4</td>
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<tr>
<td>California Sierras</td>
<td>6,893</td>
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<td>18</td>
<td>18</td>
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<td>89.9</td>
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<td>36.6</td>
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<td>52</td>
<td>53</td>
<td>23.3</td>
<td>129,971</td>
<td>3.2</td>
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<tr>
<td>Summaries</td>
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<td>17</td>
<td>23</td>
<td>24</td>
<td>53</td>
<td>1,338,158</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Stand Clumpiness – Table 2 displays a parameter defined as “Clump”. This parameter provides an estimate of the variation in stand density across each stand based on Crown Competition Factor (CCF) (Krajicek et al, 1961). The CCF is computed for each field sample plot. The unique advantage of CCF is that it includes the contribution to density of trees with Dbh equal to
zero. Basal area, Stand density index (Reineke, 1933) and Relative density index (Curtis, 1982) are censored indices in that they only include trees from the stand which have a non-zero Dbh.

If a stand demonstrated an average Dbh of 20 inches and final harvest was a clear-cut removal, then one could argue that zero-inch Dbh trees contribute little to stand density. However, if a stand demonstrates an average Dbh of 2 inches, then one could argue that ignoring zero-inch Dbh trees is a serious error. In inventory cruising, it is essential to measure all trees regardless of size. In other words, inventory cruise statistics should be based on un-censored parameters to understand the full scope of species mix, stand structure and spatial distribution.

These CCF observations from each plot are used to compute an estimate of clumpiness. The average CCF among all plots is commonly reported in a number of cruise compilers. However, the variance of CCF provides a very efficient additional piece of information. This variance estimate is most robust for clumpiness if the series of plots from each stand were distributed uniformly across the entire stand polygon. A low estimate of variance indicates a very uniform stand density and structure, such as a plantation. A high estimate of variance indicates a very irregular stand density and structure, such as an all-aged, mixed-species natural-origin stand.

Figures 1, 2 and 3 display the coefficient of variation for numbers of trees per acre, basal area per acre and cubic volume per acre, respectively. Each Figure displays results from three types of forest inventories. These are a) plantations; b) even-aged, natural stands; and, c) all-aged, natural stands.

In Figures 1 and 2, note how the variation increases when observing basal area versus numbers of trees per acre. This increase is due to the censored characteristics of basal area, which does not consider trees with a Dbh less than 1-inch.

In Figures 2 and 3, note how the variation increases when observing volume versus basal area. This increase is due to the censored characteristics of volume, which does not consider trees with a Dbh less than 7-inches (in these datasets).

Figure 4 introduces observed variation in stand clumpiness between cruised stands. Uniform stand spatial patterns have a clumpiness value near 1.0. Very clumpy stands exhibit a clumpiness value approaching a value near 0.0. Uniform plantations with few, small openings result in clumpiness values near 0.95 while highly variable stands spatial patterns result in values near 0.45. A stand with a clumpiness value near 0.35 may be visualized as a few thickets of trees scattered across a broad talus rock slope. Stands with clumpiness values lower than 0.35 cease to be identified as a forest stand with strata labels typically changing to meadow, rock, grass, water or ice. More definitive descriptions and discussion of clumpiness indices may be found in Lefkovitch (1966), Pielou (1959) and Ripley (1981).
Any Individual Tree – Distant-dependent growth model (Monro, 1974) may use this clumpiness information to replicate the observed spatial variation in inventory growth projections. Whole Stand and Individual Tree – Distant-independent growth models do not have the capacity to use this additional information from an inventory cruise. As a result all trees from the inventory cruise are assumed (by default) to be uniformly distributed in these last two model types.

The inventory forester relies on and requires a fully integrated working forest inventory set of methods and tools. The inventory is made up of stands representing every age, size, structure and species composition. These stands must be projected into the future while attempting and evaluating an array of alternative silvicultural regimes. Only a well-designed and integrated inventory and growth model architecture will achieve these goals with confidence.

Combining cruise methods using censored sampling designs with growth models without the capacity to correct for clumpiness may lead to very biased expectations of future silvicultural growth response, inventory species composition, stand structure and value.

There are some very basic considerations when determining how to design, sample and manage for a working forest inventory. For example, consider the final expected tree diameters at the time stands will be selected for harvest. If this forest is a working forest as part of a long-term harvest plan, then the average diameters of all trees across the forest will be one-half the diameter of the final harvest. Look back at Table 2 to observe the average diameters of all stands across the country used in this analysis. There is not one average above 8-inches in diameter. If the inventory forester had used a 7-inch minimum merchantable diameter, the variance in volume becomes the last parameter which should be used to determine confidence in sample size.

Conclusions

Reviewing the variation in inventory cruise statistics displayed in Figures 5, 6 and 7 should provide ample evidence that using volume metrics as indications of confidence should be set aside. These volume metrics may have been useful when the cruise objective was immediate harvest removal of standing volume. However, when the cruise objective is to build or strengthen a working forest inventory, then using volume metrics as measures of confidence should be discontinued.

Note the trend in Figure 5 where variance in number of trees per acre increases as stand types shift from plantations to all-aged stand structures. Also note that clumpiness in plantations is distinguished from variance in tree count per plot. However, as stand structure becomes more complex, the variance in tree count by plot overwhelms the ability to distinguish clumpiness.
Observations of basal area and volume in Figures 6 and 7 expose the impact of censored parameters when computing variance. Variance computations default to zero for cruised stands where tree dimensions are below the minimum threshold for those parameters.

The inventory forester should begin to recognize that variation in these parameters is to be expected. The more complex the existing stand structure, then it should become obvious that increased intensity in numbers of plots per stand does not imply reduction in variance.

Most working forests are anything but perfectly uniform in species composition, size structure or spatial pattern. In spite of these observations, many current university courses, continuing-education workshops and forestry professionals still hang on to traditional methods. They simply have not thought through the consequences of assuming the methods of the 20th century are adequate for the 21st century. It is the responsibility of each inventory forester to question, review and determine the most robust approaches for managing a working forest. The methods and tools are available if one takes the time to investigate.
Figure 1. Differences in coefficient of variation for #trees/acre by stand type (a, b, c) and sampling density.
Figure 2. Differences in coefficient of variation for basal area/acre by stand type (a, b, c) and sampling density.
Figure 3. Differences in coefficient of variation for volume/acre by stand type (a, b, c) and sampling density.
Figure 4. Variation in stand clumpiness by stand type (a, b, c) and sampling density.
Figure 5. Differences in coefficient of variation for #trees/acre by stand type (a, b, c) and stand clumpiness.
Figure 6. Differences in coefficient of variation for basal area/acre by stand type (a, b, c) and stand clumpiness.
Figure 7. Differences in coefficient of variation for volume/acre by stand type (a, b, c) and stand clumpiness.
Appendix – Approaches to Tree Height Estimation

The Evolution of the FPS Cruise Compiler

Traditionally, the inventory forester has laid out a string of temporary plots across a stand to obtain a sample of the characteristics of that stand. These characteristics include species composition, diameter class distributions and associated volume assessments. Depending on the level of resolution desired, these characteristics may include tree list details of vigor, defect, taper, crown, age and log values. If the objective of this cruise (field sample) is for harvest volume and value, then volume per acre and value per acre are of interest. If the objective of this cruise is for standing inventory reporting and silvicultural planning, then tree list structure, dimension and spatial pattern is predominant.

In any regard, various cruise designs have evolved (over decades) to facilitate field efficiency while not compromising overall precision and reliability of outputs. To this end, it has been demonstrated across many forest types and regions that 100 percent tallies of tree species and diameter breast height (Dbh) classes are essential and consistent requirements. It has also been documented that tallies of trees to 1-inch Dbh classes is sufficient. Diameter measurements to higher levels of precision on all or a sample of the cruise plots only reduces field efficiency without an associated improvement in overall accuracy. However, sub-sampling of trees within plots across a stand has been found to be useful in improving field efficiency without an associated loss in overall accuracy. The parameters most often included in sub-sampling lists include height, age, taper, defect, vigor, crown and log-position grading.

The intensity of sub-sampling for tree parameters in a stand varies greatly depending on the stand structure and the objective of the cruise. If the stand is a machine-planted, single-species plantation, then the intensity of sub-sampling may be very light. However, if the stand is mixed species of natural origin with past repeated thinning entries, then the intensity of sub-sampling may be much more demanding.

Much of the decision about the intensity of sub-sampling revolves around the frequency of tree height measurements. If a tree is measured (sub-sampled) for height, then many of the other sub-sampled parameters are included on these same trees. Examples are defect, taper, crown, vigor and log grading.

This brings us to the objective of this analysis and report. Most of the documented history and evaluation of forest sampling has been based on single-species, even-aged forest stands. Additionally, almost all of this past history was based on parametric regression approaches. The nature of parametric regression is to focus on the average trends rather than the associated distributions of tree parameters behind these trends.

The perfect example of past approaches is the estimation of tree heights from a field sample of plots where only a portion of the trees were measured for height.

In 1973, Drs. Robert O. Curtis (USFS) and James D. Arney (Weyerhaeuser) were contracted to build a Douglas-fir, region-wide growth model to replace US Forest Service Bulletin 201 (McArdle and Meyer, 1949) for Douglas-fir growth and yield. Field data were gathered from fourteen organizations across British Columbia, Washington and Oregon. In almost all cases and ownerships, the measurement of tree heights had been conducted on only a portion of the trees in
each sample plot. In order to select the most robust basis for estimating tree heights for unsampled trees, Dr. Curtis spent one full year evaluating alternative parametric regression approaches (Arney, 1985b). The final height-Dbh model selected was

\[
\text{Height} = 4.5 + b_1 \times \text{Exp}(b_2 \times \text{Dbh}^{b_3}) \quad \text{Curtis (1967)}
\]

The \(b_i\) parameters are estimated by parametric regression from the sub-sampled tree heights across the plots in each stand.

This parametric Height-Dbh regression model was incorporated into the Stand Projection System (SPS) and Forest Projection and Planning System (FPS) by James D. Arney in 1985a and 1996, respectively. Regression estimated heights for all trees in both cruise compilers were automatically produced for each species in each stand. Trees sub-sampled for height retained their individually observed heights while un-sampled trees used the estimated heights based on the Dbh of each sample tree. This was the approach used in FPS for all versions 4.0 to 6.99

The shortcomings of this parametric regression model approach began to be apparent when cruising and compiling mixed-species stands with a history of past thinning entries. In March 2011, the FPS software package was upgraded and released as Version 7.00. All cruise compilations from this version forward are compiled using nonparametric regression methods.

This report provides an assessment of the differences in methodology between FPS Versions 4 to 6 and FPS Version 7 cruise compilation results. Every other cruise compiler (from all sources known to this author) use parametric regression methods comparable to this Version 6 cruise compiler (Hulshof, Swenson and Weiser, 2015).

Datasets

Eleven stands in a mixed-age Ponderosa Pine forest of central Oregon were selected to demonstrate the differences in estimating tree height distributions using parametric and nonparametric regression methods. Each stand was sampled with 25 plots where every tree was measured for both Dbh and total height on every plot. This resulted in 3,130 individually measured Ponderosa Pine trees across all eleven stands. This is an average of 284 sample trees per stand and 11 trees per plot. This is a purposely very robust sample to minimize any concern that sub-sample intensities per plot may contribute to poor population estimates when considered independently.

Each sampled stand of 25 plots was then separated into three sets:

- Set A contains all measured heights for all trees on all 25 plots
- Set B contains measured heights for only the odd-numbered plots in each stand
- Set C contains measured heights for only the even-numbered plots in each stand

This assessment is being conducted with the view that the inventory cruise sampling objective is to provide stand structure characteristics for forest silvicultural planning and growth projection. In this regard, the FPS Growth Model analyses (Arney, 2016) have demonstrated that tree growth capacity is highly correlated with past history of stand density and suppression. This is characterized by observing the Dbh / Height ratio of individual trees in a stand. Trees with a past history of high stand density have short crowns, cylindrical taper profiles and small Dbh relative
to total height (0.33 – 1.00 centimeters Dbh per meter of height). Trees with a past history of low stand density have long crowns, conical taper profiles and large Dbh relative to total height (1.67 – 4.00 centimeters Dbh per meter of height).

Figures 1 and 2 display Stand #101 tree height measurements both as total height over Dbh, and as Dbh/Height ratio over Dbh, respectively. It is easily observed that the small trees have a wide range of tree forms (Dbh/Height ratios) while larger trees have a much narrower range (Figure 2).

Figures 3 and 4 display Stand #101 trees measured for height on odd-numbered plots only (blue dots). The estimated heights from the FPS Version 6 Cruise Compiler (V6) for even-numbered plots are displayed as red dots. Since this is a parametric regression equation the outputs result in a single trend line as a function of observed Dbh. *Any variation in Dbh/Height ratios due to past density effects are removed in the parametric regression fitting process.*

Figures 5 and 6 also display Stand #101 trees measured for height on odd-numbered plots as blue dots. However, in this case, the FPS Version 7 (V7) Cruise Compiler is using a nonparametric regression process which results in estimated heights for even-numbered plots distributed in proportion to the variation in heights observed on odd-numbered plots. *Any variation in Dbh/Height ratios due to past density effects are retained in the nonparametric regression fitting process.*

If the only objective for the field sample is to obtain an estimate of current total stand volume, then either the parametric or the nonparametric approach may be acceptable. However, if the objective is to use this sampled tree list to characterize the growth and yield dynamics for current and future silvicultural projections, then the nonparametric approach provides a more definitive result. The nonparametric approach will also produce a broader variation in taper profiles and log size distributions. If value differentials by log dimension are important, then the nonparametric approach may be more definitive.

Not addressed in this analysis and discussion is the effect of the proportion of trees being measured versus estimated. This analysis only considered the effects of a 50/50 percent split between measured and estimated. This could have been by alternate plots or trees. Other field designs have measured heights on only every third plot or only the first 2 or 3 trees per plot. Other designs have measured heights only on trees selected by a more restrictive BAF (basal area factor) than used for species and tree tallies.

In every case, the forester should be considering the inventory objective and kind of stand structure to be sampled prior to deciding on the method and intensity of sub-sampling tree heights.

With the evolution of expanded wildlife, watershed and social restrictions on forest management practices, the FPS Cruise Compiler, Growth Model and Harvest Scheduling components were all upgraded to fully nonparametric regression approaches in Version 7. This is a much more robust and resilient biometric approach than the traditional averaging and smoothing regression techniques of the 1970 to 1990 era.
Figure 1. Measured heights over Dbh.

Figure 2. Measured Dbh/Height ratios (cm/m) over Dbh.
Figure 3. Height measured on odd-numbered plots only.

Figure 4. Dbh/Height ratios of measured and estimated heights.
Figure 5. Nonparametric estimated heights as red observations.

Figure 6. Nonparametric distribution of estimated tree forms.
This dataset, containing eleven cruised stands of 25 plots each, was field sampled to include a measured height on every tree in every plot. This provided the ability to consider differences in results if even-numbered plots had been selected for height-measured sub-sampling instead of odd-numbered plots. Figures 1 through 6 display the results of sub-sampling measured heights on the odd-numbered plots and regression estimating heights on the even-numbered plots.

Tables 1 to 3 and Figure 7 display the combined results of all estimated heights when odd-numbered plots were used to estimate even-numbered plots and vice versa (even-numbered plots used to estimate odd-numbered plots). There are a total of 3,130 Ponderosa Pine trees on the plots from all eleven stands. These Tables and Figure display the distributions of trees by estimated Dbh/Height ratios from each stand compiled independently, both ways, and finally accumulated for this analysis.

The FPS Version 7 Cruise Compiler uses a nonparametric Pascal smoothing approach across both the range in 4-inch Dbh classes and in Dbh/Height ratio classes. These are displayed vertically and horizontally, respectively, in Tables 1 to 3. The Dbh/Height ratio values are in centimeters of Dbh per meter of height. The transformation from inches and feet to centimeters and meters is shown below.

$$\text{Dbh/Height ratio} = 8.333 \times \frac{\text{Dbh}}{(\text{Height} - 4.5)} \text{ in cm/m}$$

It is important in this methodology to subtract height to the Dbh position so that both Dbh and (Height – 4.5) trend toward a value of zero at the same rate. To do otherwise creates a bias.
Table 1. All height-measured Ponderosa Pine trees across eleven cruised stands.

<table>
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<th>DbhCls</th>
<th>Totals</th>
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<th>1.00</th>
<th>1.33</th>
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</tr>
<tr>
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Table 2. Accumulated height-estimated trees across all cruised stands compiled using FPS Version 7.

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<th>3.00</th>
<th>3.33</th>
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</table>

Table 3. Accumulated height-estimated trees across all cruised stands compiled using FPS Version 6.

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<th>2.67</th>
<th>3.00</th>
<th>3.33</th>
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</tr>
<tr>
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<td>3</td>
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<td></td>
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</tr>
</tbody>
</table>
Appendix – Field Measurement Precision

There are an increasing number of operational field cruises being designed where the precision of measurements have been specified at levels either not achievable or not efficient.

Two recent examples are:

1) Measurement of individual tree Dbh (diameter at breast height) to the nearest 0.1-inch precision rather than the more traditional 1-inch precision;
2) Measurement of individual tree form class using a handheld Spiegel Relaskop (or similar optical device). The attempt is to determine a tree diameter at some fixed height on the sample tree (such as 17-feet above ground). This diameter is then divided by the Dbh at breast where both diameters are assumed to be precise to 0.1-inch. The expected result is Girard 16-foot Form Class.

An actual field inventory of approximately 60,000 acres with 1,500 stands was used to evaluate these alternative field methods. This inventory was sampled over a three-year period using variable plot cruising designs to accommodate the full range of tree sizes found in the various stands.

The plots were systematically spread through each stand at a rate of approximately one plot for every 2.5 acres. This resulted in a total of 23,342 plots over 1,500 stands.

Only a single basal area factor (Baf) was used in each stand where the cruiser attempted to use a factor which would result in 3 – 9 trees per plot. The actual result was an average of 5.8 trees per plot over all plots in all three years.

This forest was predominately Douglas-fir (62%) and Western Hemlock (20%) with 19 other associated species.

Total heights were measured on approximately every third tree with care to obtain some heights for every species in each stand. This resulted in measured heights for 36 percent of the 135,585 trees sampled by species and Dbh across all plots.

All sample trees were recorded to the nearest 0.1-inch Dbh. Since the use of diameter tapes will always have a tendency to be biased high due to moss, branches and loose debris, the diameter measurements were not rounded to the nearest 0.1-inch. Instead, the diameter measurements were truncated to the 0.1-inch Dbh. This means that a diameter tape showing 12.47 inches (to the nearest 1/100th inch) is truncated to 12.4 rather than rounded up to 12.5 inches.

<table>
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<tr>
<th>Baf</th>
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</tr>
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<tr>
<td>10.00</td>
<td>64</td>
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<tr>
<td>13.61</td>
<td>9</td>
</tr>
<tr>
<td>15.69</td>
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<td>17.78</td>
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<td>20.00</td>
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</tr>
<tr>
<td>22.50</td>
<td>120</td>
</tr>
<tr>
<td>25.15</td>
<td>348</td>
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<tr>
<td>27.78</td>
<td>3,908</td>
</tr>
<tr>
<td>33.61</td>
<td>8,418</td>
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<tr>
<td>46.95</td>
<td>540</td>
</tr>
<tr>
<td>54.40</td>
<td>11</td>
</tr>
<tr>
<td>54.45</td>
<td>393</td>
</tr>
</tbody>
</table>

#Plots 23,342
Four copies of the inventory database were built:

1) **Dbh = 0.1 Inch.** All plots were compiled by stand using a nominal log length of 32-feet to a minimum top diameter inside bark of 5.0 inches. The FBRI Forest Projection and Planning System (FPS Version 7.51) forest management software suite was used to compile and report all volume and value statistics. The compiled results are displayed by site class (Table 1).

Table 1. Compiled using Dbh observations to the 0.1-inch precision.

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Area</th>
<th>Trees</th>
<th>Basal</th>
<th>TopHt</th>
<th>NetCF</th>
<th>NetBF</th>
<th>NetVal</th>
<th>Total Stand in 1,000s</th>
<th>Net Cubic</th>
<th>Net Board</th>
<th>Net Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>126.9</td>
<td>11.1</td>
<td>341</td>
<td>227</td>
<td>87</td>
<td>4,638</td>
<td>17,673</td>
<td>2,344</td>
<td>589</td>
<td>2,243</td>
<td>297</td>
</tr>
<tr>
<td>3</td>
<td>1,985.3</td>
<td>10.7</td>
<td>236</td>
<td>148</td>
<td>76</td>
<td>2,693</td>
<td>9,690</td>
<td>1,181</td>
<td>5,346</td>
<td>19,236</td>
<td>2,346</td>
</tr>
<tr>
<td>4</td>
<td>7,483.7</td>
<td>11.6</td>
<td>253</td>
<td>187</td>
<td>88</td>
<td>4,144</td>
<td>16,004</td>
<td>2,219</td>
<td>31,013</td>
<td>119,772</td>
<td>16,607</td>
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<tr>
<td>5</td>
<td>26,513.5</td>
<td>13.2</td>
<td>214</td>
<td>204</td>
<td>102</td>
<td>5,537</td>
<td>23,108</td>
<td>3,805</td>
<td>148,803</td>
<td>612,879</td>
<td>100,880</td>
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<tr>
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<td>20,297.0</td>
<td>14.0</td>
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<td>205</td>
<td>111</td>
<td>6,198</td>
<td>26,771</td>
<td>4,789</td>
<td>125,801</td>
<td>543,366</td>
<td>97,198</td>
</tr>
<tr>
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<td>56,406.5</td>
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<td>213</td>
<td>200</td>
<td>102</td>
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<td>3,853</td>
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</tbody>
</table>

2) **Dbh = 1.0 Inch.** A copy of the full inventory database was then made. In this copy of the database, all trees in the sample plots were rounded to the nearest 1-inch class (from the 0.1-inch precision Dbh measurements). For example, all trees between 11.6 and 12.5 inches were adjusted to 12.0 inches. Everything else remained intact from the original database (Table 2).

Table 2. Compiled using Dbh observations to the 1-inch precision.

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Area</th>
<th>Trees</th>
<th>Basal</th>
<th>TopHt</th>
<th>NetCF</th>
<th>NetBF</th>
<th>NetVal</th>
<th>Total Stand in 1,000s</th>
<th>Net Cubic</th>
<th>Net Board</th>
<th>Net Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>126.9</td>
<td>11.1</td>
<td>336</td>
<td>227</td>
<td>87</td>
<td>4,771</td>
<td>19,294</td>
<td>2,368</td>
<td>605</td>
<td>2,321</td>
<td>300</td>
</tr>
<tr>
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<td>1,985.3</td>
<td>10.7</td>
<td>237</td>
<td>149</td>
<td>78</td>
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<td>1,265</td>
<td>5,518</td>
<td>19,981</td>
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<td>188</td>
<td>88</td>
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<td>16,313</td>
<td>2,225</td>
<td>31,571</td>
<td>122,081</td>
<td>16,726</td>
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<tr>
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<td>205</td>
<td>102</td>
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<td>3,832</td>
<td>148,515</td>
<td>620,605</td>
<td>101,595</td>
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<td>191</td>
<td>205</td>
<td>111</td>
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<td>28,998</td>
<td>4,815</td>
<td>126,785</td>
<td>547,974</td>
<td>97,735</td>
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<td>1,312,962</td>
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</tr>
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</table>
3) **Dbh = Highest.** A third copy of the inventory database was made. In this copy, all trees had their observed Dbh increased by 0.4 inches. The trees in the previous database which were 12 inches became 12.4 inches. The objective is to observe the impact of a cruise which still results in the same diameters to a precision of 1-inch being compiled at the upper limits of the diameter classes (Table 3).

Table 3. Compiled using Dbh observations to the 1-inch precision at upper class limits.

<table>
<thead>
<tr>
<th>Site Class</th>
<th>#Stands</th>
<th>Area</th>
<th>Dbh</th>
<th>Trees Basal</th>
<th>TopHt</th>
<th>NetCF</th>
<th>NetBF</th>
<th>NetVal</th>
<th>Total Stand in 1,000s</th>
<th>Net Cubic</th>
<th>Net Board</th>
<th>Net Value</th>
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<td>2</td>
<td>4</td>
<td>126.9</td>
<td>11.6</td>
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<td>120333</td>
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<td>13.8</td>
<td>197 205</td>
<td>102</td>
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<td>23178</td>
<td>3879</td>
<td>148202</td>
<td>614523</td>
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<td>528</td>
<td>20297.0</td>
<td>14.5</td>
<td>178 205</td>
<td>111</td>
<td>6229</td>
<td>26743</td>
<td>4860</td>
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<tr>
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<td>196 201</td>
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<td>5536</td>
<td>23036</td>
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<td>312255</td>
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</tbody>
</table>

4) **Dbh = Lowest.** A forth copy of the inventory database was made. In this copy, all trees had their observed Dbh decreased by 0.4 inches. The trees in the second database which were 12 inches became 11.6 inches. The objective is to observe the impact of a cruise which still results in the same diameters to a precision of 1-inch being compiled at the lower limits of the diameter classes (Table 4).

Table 4. Compiled using Dbh observations to the 1-inch precision at lower class limits.

<table>
<thead>
<tr>
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<th>Area</th>
<th>Dbh</th>
<th>Trees Basal</th>
<th>TopHt</th>
<th>NetCF</th>
<th>NetBF</th>
<th>NetVal</th>
<th>Total Stand in 1,000s</th>
<th>Net Cubic</th>
<th>Net Board</th>
<th>Net Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4</td>
<td>126.9</td>
<td>10.8</td>
<td>357 226</td>
<td>87</td>
<td>4564</td>
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<td>579</td>
<td>2180</td>
<td>283</td>
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<tr>
<td>3</td>
<td>58</td>
<td>1985.3</td>
<td>10.5</td>
<td>247 148</td>
<td>76</td>
<td>2647</td>
<td>9550</td>
<td>1173</td>
<td>5255</td>
<td>18959</td>
<td>2330</td>
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<tr>
<td>4</td>
<td>213</td>
<td>7483.7</td>
<td>11.4</td>
<td>264 186</td>
<td>88</td>
<td>4097</td>
<td>15630</td>
<td>2178</td>
<td>30660</td>
<td>118468</td>
<td>16301</td>
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<tr>
<td>5</td>
<td>741</td>
<td>26513.5</td>
<td>13.0</td>
<td>222 204</td>
<td>102</td>
<td>5504</td>
<td>22933</td>
<td>3759</td>
<td>145928</td>
<td>608576</td>
<td>99653</td>
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</tr>
<tr>
<td>6</td>
<td>528</td>
<td>20297.0</td>
<td>13.7</td>
<td>201 205</td>
<td>111</td>
<td>6176</td>
<td>26641</td>
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</tr>
</tbody>
</table>

The results from these four compilations of the same inventory were then compared to one another to observe if the difference in precision of Dbh measurements has an impact on the total standing inventory report (Table 5).
As may be observed in the lower portion of Table 5, the percentage differences of the various ways of handling Dbh precision have essentially a one percent or less impact on any of the inventory statistics. This comparison is the same magnitude for both the “per acre” and “Total” inventory statistics.

Table 5. Comparison of the four variations of compiling the same cruise.

<table>
<thead>
<tr>
<th>Cruise Method</th>
<th>Summaries per Acre</th>
<th>Total Inventory (in 1,000s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dbh</td>
<td>Trees</td>
</tr>
<tr>
<td>Dbh = Highest in Class</td>
<td>13.7</td>
<td>196</td>
</tr>
<tr>
<td>Dbh = 0.1-inch Precision</td>
<td>13.1</td>
<td>213</td>
</tr>
<tr>
<td>Dbh = 1.0-inch Precision</td>
<td>13.2</td>
<td>211</td>
</tr>
<tr>
<td>Dbh = Lowest in Class</td>
<td>12.9</td>
<td>221</td>
</tr>
</tbody>
</table>

As may be observed in Table 5, the small shift in recorded Dbh may cause the Baf expansion of numbers of trees by size to shift accordingly. However, the height statistics are un-affected by this variation in diameter measurement precision. Significantly more variation would be anticipated by sending a second team of cruisers out to re-sample this inventory. Subsequent samples are observed to vary the total inventory by five percent or more. Due to this expectation and experience, differences of one percent are not considered significant enough to report.

Cost of Precision

These results demonstrate an important factor when designing a field inventory. That factor is field precision of equipment and staff. From the office it would appear that greater precision of inventory statistics would be available if the cruisers measured trees to a higher resolution. While individual trees being sampled may be recorded to a higher precision, it may be a false expectation to assume that results in the forest-wide results have a higher precision.

This cruise established plots at a density of one plot per 2.5 acres. A subsequent field sample will most likely result in plot centers occurring at other points in each stand. Resulting variance has been commonly observed to be much greater than 1 percent. Therefore, the added precision of Dbh measurements has not improved the resulting standing inventory statistics.

Let us assume that a knowledgeable and experienced team of cruisers could provide a production rate of about 20 plots per day per cruiser on this inventory. They would sample about one-third of tree heights and record Dbh to the nearest 1-inch diameter class.
These 23,342 plots would require 1,167 cruiser days to complete the project. Now, experience shows that measuring each tree to 0.1-inch will add approximately 45 seconds to the time spent measuring and recording each tree. Since there were 135,585 sample trees in this field inventory, this additional time accumulates to 212 cruiser days. This is an 18 percent addition to the time required to complete the project for no additional information or precision.

If we assume an average cost of field inventory to be $7.00 per acre, the expected cost of the inventory would be approximately $420,000. An additional 18 percent in field time due to tree measurements to 0.1-inch would result in an added expense of about $75,000.

*This additional cost would be much better spent on cruising more stands in a given year than spending more time on each plot for no additional gain in knowledge.*
Appendix – Measuring Individual Tree Taper in an Inventory Sample

The goal is to obtain a more precise estimate of tree volume than may be achieved with only Dbh and total height. A measurement of the shape of the tree is desired as a third parameter for volume estimation.

Girard "Form Class" versus FPS “Taper Class”

The traditional practice for estimating tree form has been to select a sample height on the tree and then measure an associated upper stem diameter at that height. The most common example of this approach is the Girard 16-foot Form Class measurement. The cruiser determines a point on the tree which appears to be 17 feet from ground level (including a 1-foot stump height). Then, most commonly, a Spiegel Relaskop is used to estimate the diameter of the tree at that height. Girard Form Class is then computed as the diameter inside bark at 17-feet divided by the diameter outside bark at breast height. Resulting values typically range from 0.66 to 0.86 as dib/Dbh ratios.

An alternative approach is to select a sample diameter on the tree and then measure the associated height to that diameter using the same Spiegel Relaskop identified previously. Since the Relaskop is designed to easily adjust for slope, backing away from the tree until the tree is ‘boader line’ at breast height is well understood. Then the cruiser shifts up the tree profile until a height is achieved which is 80 percent of the view bars width at breast height. That height is recorded. Taper Class is then that intermediate height (-4.5) divided by total tree height (-4.5). Values typically range from 0.10 to 0.50 as height ratios.

The Spiegel Relaskop is designed to be relatively precise for measurements of height while removing the effects of topographic slope and terrain. It is only precise for tree diameter at fixed edges of black and white horizontal bars. This is not effective for a precise measurement of a tree diameter at a specific height, as is required for Girard Form Class. The cruiser must interpolate within the Relaskop bars visible in the view of the tree bole. However, it is efficient for a precise measurement of height at a specific relative diameter, as is required for FPS Taper Class.

As discussed in the FPS Forester’s Guidebook and FPS Mathematics of Trees, quality control and review of field precision should begin before going to the field.

Tree form changes due to crown recession when a tree experiences high densities. Intermediate and suppressed trees have a more cylindrical form than open-grown trees. This is demonstrated in Figure 1 where 5,656 felled and measured Douglas-fir trees were grouped by FPS Taper Class. Diameters and heights along the bole were simply converted to relative diameters and heights as portions of Dbh and total height, respectively. The trees were then simply grouped into five taper classes based on the relative height values of each tree at the point where the
upper diameter is 80 percent of the Dbh. Look closely at Figure 1 and notice that the greatest height differences between curves occur at approximately 80 percent of Dbh. The highest curve represents suppressed tree forms (Taper Class = 50%). The lowest curve represents open-grown tree forms (Taper Class = 10%). Note the vertical reference bar to highlight this index point.

Also notice that an 80-foot tall tree would have a 17-foot form class measurement at \((17-4.5)/(80-4.5) = 0.166\) height level in Figure 1. This is approximately the greatest horizontal difference between taper class curves anywhere in the Figure. To distinguish between these five taper curves in the field would require the precision in measurements as outlined in Table 6.

Table 6. Comparison of measurement precision required to determine “taper” versus “form” classes.

<table>
<thead>
<tr>
<th>Taper Class</th>
<th>ht80 (ft)</th>
<th>ht80 diff.</th>
<th>dob17</th>
<th>dib17</th>
<th>dib diff.</th>
<th>Form Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>12.1</td>
<td>7.5</td>
<td>9.2</td>
<td>8.2</td>
<td>0.8</td>
<td>.68</td>
</tr>
<tr>
<td>20%</td>
<td>19.6</td>
<td>7.5</td>
<td>10.1</td>
<td>9.0</td>
<td>0.5</td>
<td>.75</td>
</tr>
<tr>
<td>30%</td>
<td>27.1</td>
<td>7.5</td>
<td>10.6</td>
<td>9.5</td>
<td>0.4</td>
<td>.79</td>
</tr>
<tr>
<td>40%</td>
<td>34.6</td>
<td>7.5</td>
<td>11.0</td>
<td>9.9</td>
<td>0.2</td>
<td>.82</td>
</tr>
<tr>
<td>50%</td>
<td>42.1</td>
<td>7.5</td>
<td>11.3</td>
<td>10.1</td>
<td></td>
<td>.84</td>
</tr>
</tbody>
</table>

As you can readily observe, to distinguish a taper difference in a 12-inch, 80-foot tree using the taper class method requires observing a 7.5-foot difference in height between each class. This is feasible using a standard handheld Spiegel Relaskop. However, to distinguish the same differences using the form class method requires observing a 0.2 to 0.8-inch difference in *inside bark* diameter at 17 feet up the tree bole. Each 0.02 step in Form Class (i.e., 78% to 80%) requires a 0.2-inch precision in diameter inside bark at 17 feet in Table 6 (a 12-inch tree which is 80 feet tall).

*Measuring Girard Form Class on a per tree basis is not feasible using any standard field instrumentation available to the forester unless it includes a ladder and bark gauge.*

The observation of relative height, (intermediate height - 4.5ft) / (total height - 4.5ft), where outside bark diameter is eighty percent of the diameter at breast height is the most consistent method for obtaining a third parameter in the field given the limitations of the measuring instruments available to the forester. This is a strong statement since most foresters, who were traditionally estimating taper in the Northwest, have relied on Girard Form Class methods.

No regressions had been attempted on these 5,656 trees prior to display in Figure 1. The point being made here is that the scaling to a relative basis takes away the need to account for large trees versus small trees. Only the difference in taper profile is left to be disclosed. Taper Classes are the relative height values (10%, 20%, 30%, 40% and 50%) at 80% of Dbh (vertical bar).
**Taper Equations**

Traditional developments of taper equations have relied on the use of a diameter measurement at a fixed height to distinguish differences in taper profiles, such as Girard Form Class. When a large dataset is obtained containing trees across a broad range of Dbh and total height, the traditional least squares regressions tend to default to the trend in average profile from a small tree to a large tree. The variation in observed form is mostly absorbed due to the least squares parametric statistical approach. This shortcoming is evident when overlaying typical taper equations on the Figure 1 display of raw tree averages grouped by Taper Class.

**Figure 1.** Raw averages of felled-trees by Taper Class.
Examples are the tree taper and volume functions used in the FVS and ORGANON growth models. These are based on parametric models and are displayed in Figures 2 and 3, respectively.

![Flewelling Parametric Taper Model Comparison to 5,656 Felled-Tree Non-Parametric](image)

Figure 2. Douglas-fir taper model (dashed lines) used in FVS relative to actual data.

Without fault to the author, the range in absolute tree dimensions among trees is far greater than the range in differences due to taper. As a result the regression analysis collapses to the basic equation form selected by the author, rather than discover the underlying taper. The taper regression approach selected by the author tends to be more sensitive to the butt of the tree than the top.
Again, without fault to the author, the range in absolute tree dimensions among trees is far greater than the range in differences due to taper. As a result the taper regression analysis collapses to the basic equation form selected by the author. In this case this equation form is more sensitive to upper stem profiles than lower stem profiles.

Results from these parametric taper approaches – Two parametric equation forms, one species, are creating two very different results in two different growth models even if the growth dynamics were modeled identically. Even the starting cruise compilation results in different volumes!

The FPS Taper Class approach provides a clear separation of tree profile differences regardless of tree size. The nonparametric lookup table for taper by Dbh and height provides a robust basis for volume without having to spend time measuring taper in field inventories.
References


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