Understanding the Effects of Cruise Design on Volume and Defect Estimation

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The forest industry has used reasonably "standardized" cruising methods over the past forty years. Central components of these cruising methods have been: 1) a string of plots in a stand; and 2) varying degrees of sub-sampling of tree species, diameters, heights and defect within each plot.

The shortcoming in the execution of this field method is how the data are handled in the cruise compiler to obtain volume and defect distributions. The primary sample is the size and number of plots installed in the stand. It is common practice to sub-sample individual tree attributes within these plots including species, diameter, height, taper, defect, log grade, age, crown and damage. This paper attempts to clarify the implications of various methods of compiling these sub-samples to obtain a robust estimate of total stand volume, size and defect distributions.

The emphasis in this analysis is on the accuracy of the "distribution" of the estimated stand volume across species, tree sizes, and log distributions. The objective of this analysis is to clarify the implications of alternative methods of expanding the sub-sampled attributes to estimates of total stand volume.

Stand Volume Estimation

Traditionally, only limited information was desired on distributions of trees by size. Therefore, it has been common to apply a variable-radius plot design for tree selection on each plot, but to only measure the size characteristics of these trees on a subset of the plots. This saves time in the field while providing a good estimate of total stand volume. Trees from the "count-only" plots are used to expand the more detailed tree attribute samples from the "measure" plots. Tree tallies on each plot using a variable-radius plot design convert easily to individual estimates of basal area per acre. The average basal area per acre from these count-only plots is used to expand the measured-plot tree volumes to total stand estimates. The measured tree volume over tree basal area is multiplied by the count-only plots average basal area per acre to obtain total volume per acre in the stand.

Many cruise compiler software routines have been built to conduct the simple series of calculations necessary to obtain total stand volume from this cruise design methodology. Most forestry students have learned to conduct these calculations by hand as part of their college coursework. Most professional cruisers have recognized that using a sub-sampling method within plots for various tree attributes saves significant time in the field. It has become common practice to only measure tree attributes on one of every three plots established in each stand. This has been commonly referred to as cruise designs with "count" and "measure" plots. The one-in-three combination has been found to be adequate for volume estimation in most existing natural stands in the West.

Volume Distributions

Over the past twenty years, this cruise method has been applied in circumstances required increasing levels of definition on the "distribution" of stand volume estimates. The primary distributions of interest have been species, size and defect. Providers of cruise compiler software programs have modified and updated their compilers to produce these more detailed and expanded reports on volume distributions by various tree-level attributes. Typically, these updated cruise compiler routines have not updated the range of statistics associated with providing estimates of the distribution of volume by species, size or defect. The standard statistics presented refer to the total stand volume only. No statistical statement is provided for the detailed reports on log size distributions, log sort distributions and net-of-defect distributions common to most cruise compilers today.

The analyses presented here attempt to clarify the biometric methods behind these cruise compilers and their impact on reliability of the "distributions" of volume characteristics commonly reported.

Sample Dataset

The essence of biometric principals behind cruise compilation may be most easily presented using a very simple dataset. Every cruiser has experienced that "measure" plots which sample the "range" of tree attributes provide more robust and repeatable reports of log size distributions and value distributions. Confidence is usually higher in reported distributions (as compared to the cruiser's field observations) when the cruiser has sampled "measure" trees across the range of species, size and defect distributions.

This dataset is made up of ten trees in which essentially every third tree has "measure" plot characteristics included in the sample. The trees are sorted by size with the smallest being the first "measure" tree followed by two "count" trees. This results in four "measure" trees and six "count" trees with measurements across the range of size. All trees are the same species for simplicity and the diameter at breast height is recorded for all trees. Only the "measure" trees have observations of tree height and defect. The defect is recorded by 16-foot log segment (an often used field procedure). Defect is the cruiser's "experienced eye" estimation of the percentage of volume loss in the segment. These observations are displayed in Table 1 with percent defect by log position.

Table 1. Field data for volume computations (M = Measure, C = Count).

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11	13	15	17	19	21	23	25	27	29
Height	60			104			144			166
Log#1	100%			100%			100%			100%
Log#2	0			0			0			0
Log#3				0			0			0
Log#4				0			0			0
Log#5				0			0			0
Log#6							0			0
Log#7							0			0
Log#8										0
Log#9										0

Additionally for simplicity, only the butt log has defect and it was always 100 percent. This basic dataset provides all that is necessary to demonstrate the differences in biometric methods among cruise compilation approaches currently applied in the forest industry. Other distributions of tree size and defect could have been used; but the principals applied in this analysis would remain the same.

The Forest Biometrics Research Institute (FBRI) cruise compiler is used in this analysis to develop all tree volumes and log breakdowns within each tree. This cruise compiler is part of the Forest Projection and Planning System (FPS) software package provided by FBRI. This analysis is about cruise designs and the analytical approaches to estimating stand volume distribution characteristics. It is not about differences among tree volume and taper equations applied in various cruise compilers. Therefore, the FPS tree volumes are used throughout these analyses as a common reference basis. This simplification has no impact on the objective, results or conclusions from these analyses.

Three methods of cruise compilation are compared in this analysis:

1) Cruise compilation using count and measure trees where count trees are only tallied by species;
2) Cruise compilation using count and measure trees where count trees are recorded by 1-inch dbh (diameter at breast height) class and species.
3) Cruise compilation using count and measure trees where regressions of tree height and defect are applied to count trees by 1-inch dbh class and species.

The third method requires the most computational steps within the cruise compiler. The other two methods are easily extracted from some of the steps in developing results from method number three (3).

Method #1 – Cruise compilation using V/BAR tree tallies

The FBRI cruise compiler was used to merchandize each of the measured trees into 16-foot log segments to estimate gross board foot volume to a 5-inch minimum small-end log diameter inside bark. Standard U.S. Forest Log Scaling rules were applied which results in Scribner board foot volumes being assigned to logs based on the small-end log diameter, rounded to the nearest 1-inch class.

Table 2. Scribner board-foot **gross** volumes for measured trees by log position.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11			17			23			29
Height	60			104			144			166
Log#1	30			110			240			400
Log#2	20			80			180			300
Log#3				60			140			240
Log#4				30			100			180
Log#5				20			70			140
Log#6							40			100
Log#7							20			70
Log#8										30
Log#9										20
Totals:	**50**			**300**			**790**			**1480**

The computations to compute total stand net Scribner board-foot volume are quite simple as presented in Table 3 and the following notes:

Table 3. Scribner board-foot **net** volumes for measured trees by log position.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11			17			23			29
Height	60			104			144			166
Log#1	0			0			0			0
Log#2	20			80			180			300
Log#3				60			140			240
Log#4				30			100			180
Log#5				20			70			140
Log#6							40			100
Log#7							20			70
Log#8										30
Log#9										20
Totals:	**20**			**190**			**550**			**1080**
Basal:	**0.7**			**1.6**			**2.9**			**4.6**
Gross V/Bar	**75.8**			**190.3**			**273.8**			**322.7**
Net V/Bar	**30.3**			**120.5**			**190.6**			**235.5**

Average Gross Volume / Basal Area ratio per tree = (75.8 + 190.3 + 273.8 + 322.7) / 4
= 215.6 board feet per square foot of basal area
Average Net V/Bar = (30.3 + 120.5 + 190.6 + 235.5) / 4 = 144.2 bdft/sqft of basal area
Average basal area per tree = (0.7 + 1.6 + 2.9 + 4.6) / 4 = 2.43 sqft per tree
Therefore:

Total stand gross volume = (215.6 * 2.43 * 6) + (50 + 300 + 790 + 1480) = 5,760 bdft
Total stand net volume = (144.2 * 2.43 * 6) + (20 + 190 + 550 + 1080) = 3,940 bdft

Using the sum of measured tree volumes, the proportion of stand volume may be determined for each sampled tree. Each tree may then be assigned a portion of the total stand volume to generate an estimate of the distribution of volume by tree and log size classes. Table 4 displays these computations using the %Net columns:

Table 4. Scribner board-foot net volumes expanded to the total stand.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11			17			23			29
Height	60			104			144			166
%Net	1.09%			10.33%			29.89%			58.70%
Log#1	0.0			0.0			0.0			0.0
Log#2	42.8			171.3			385.5			642.4
Log#3				128.5			299.8			514.0
Log#4				64.2			214.1			385.5
Log#5				42.8			149.9			299.8
Log#6							85.7			214.2
Log#7							42.8			149.9
Log#8										64.2
Log#9										42.8
Totals:	**42.8**			**406.9**			**1,177.8**			**2,312.8**

The total stand Scribner net volume is 3,940 board feet from a gross volume of 5,760 board feet. Net volume is 68% of total volume in this sample dataset. The best estimate of the distribution of volume by Dbh class is displayed in the following chart.

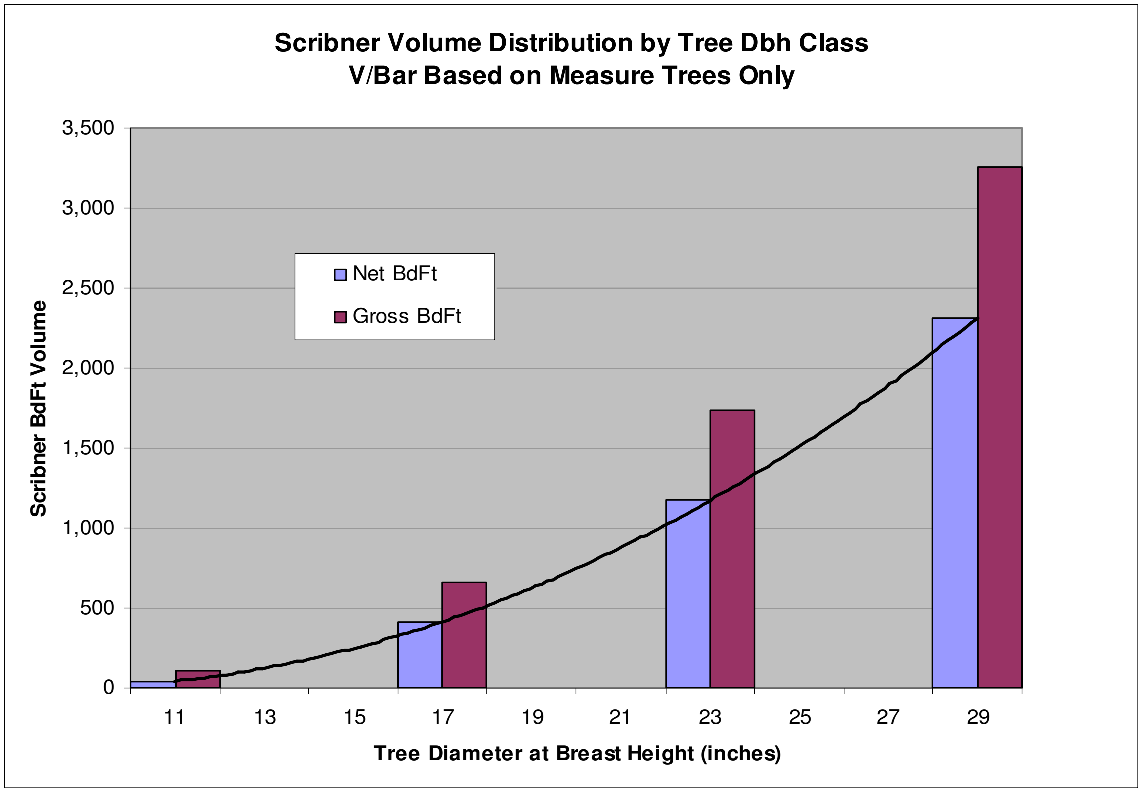


Figure 1. Scribner board volume by Dbh class.

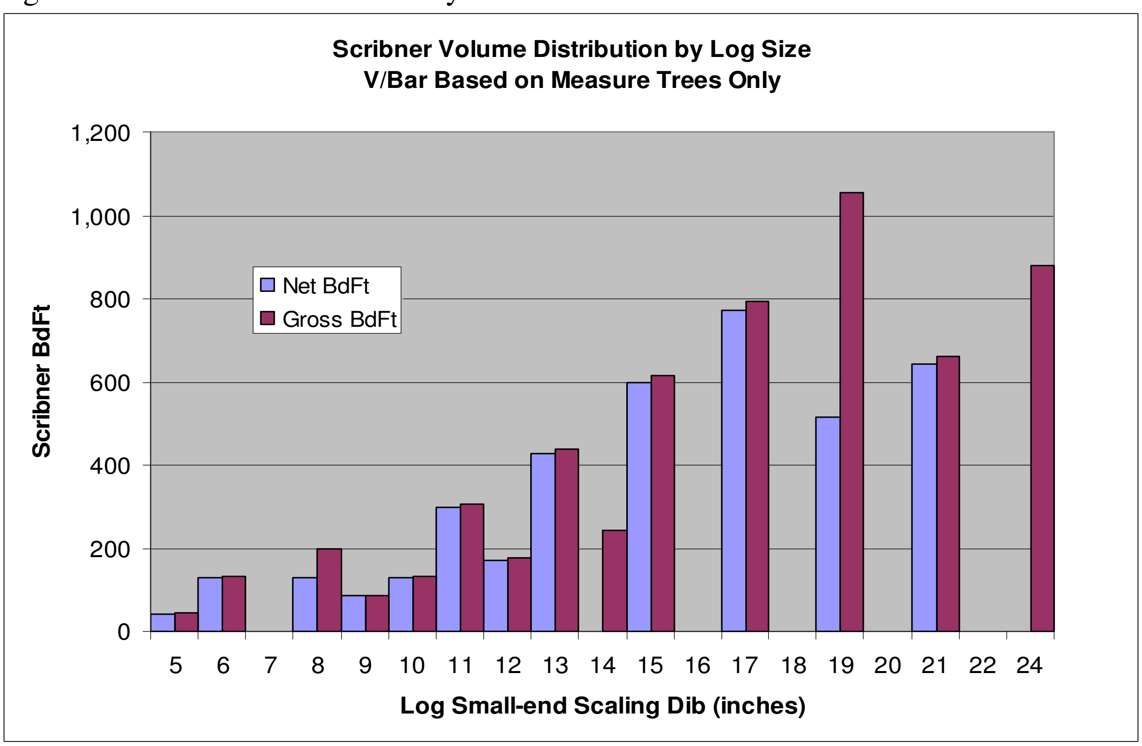


Figure 2. Scribner volume by 1-inch small-end log diameter class.

Method #2 – Cruise compilation using V/BAR and Count-only Dbh Classes

This is an identical field procedure to Method #1 with the addition of tallying the count-only trees by dbh class. In this dataset there are four measure trees and six count-only trees. The diameters of the count trees contribute to the size distribution information used in the cruise compiler. The basic computations are the same as previously with the addition of a few additional steps.

As previously:

Average Gross Volume / Basal Area ratio per tree = (75.8 + 190.3 + 273.8 + 322.7) / 4
= 215.6 board feet per square foot of basal area
Average Net V/Bar = (30.3 + 120.5 + 190.6 + 235.5) / 4 = 144.2 bdft/sqft of basal area
Average basal area per tree = (0.7 + 1.6 + 2.9 + 4.6) / 4 = 2.43 sqft per tree
Therefore:
Total stand gross volume = (215.6 * 2.43 * 6) + (50 + 300 + 790 + 1480) = 5,760 bdft
Total stand net volume = (144.2 * 2.43 * 6) + (20 + 190 + 550 + 1080) = 3,940 bdft

Additional computations:

An individual tree basal area may be computed for every tree when count-only trees are tallied by dbh class. This is then available to multiply the average measure-tree V/Bar ratio to estimate both gross and net volumes for every tree in the sample.

Table 5. Using the Count-only trees to expand the distribution of volumes.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11	13	15	17	19	21	23	25	27	29
Height	60			104			144			166
Basal	0.7	0.9	1.2	1.6	2.0	2.4	2.9	3.4	4.0	4.6
GrsV/B	75.8	215.6	215.6	190.3	215.6	215.6	273.8	215.6	215.6	322.7
NetV/B	30.3	144.2	144.2	120.5	144.2	144.2	190.6	144.2	144.2	235.5
GrsVol	50	199	265	300	425	519	790	735	857	1480
NetVol	20	133	177	190	284	347	550	492	573	1080

As before, the total stand Scribner net volume is 3,940 board feet from a gross volume of 5,760 board feet. Net volume is 68% of total volume in this sample dataset. Due to the addition of count-only trees with recorded dbh classes, the updated distribution of volume by Dbh class is displayed in Figure 3.

However, since no other detail about the count-only trees is available regarding height or numbers of logs, the distribution of volume by log diameter class is not improved over the results from Method #1. The volume by log diameter class is still represented by Figure 2.

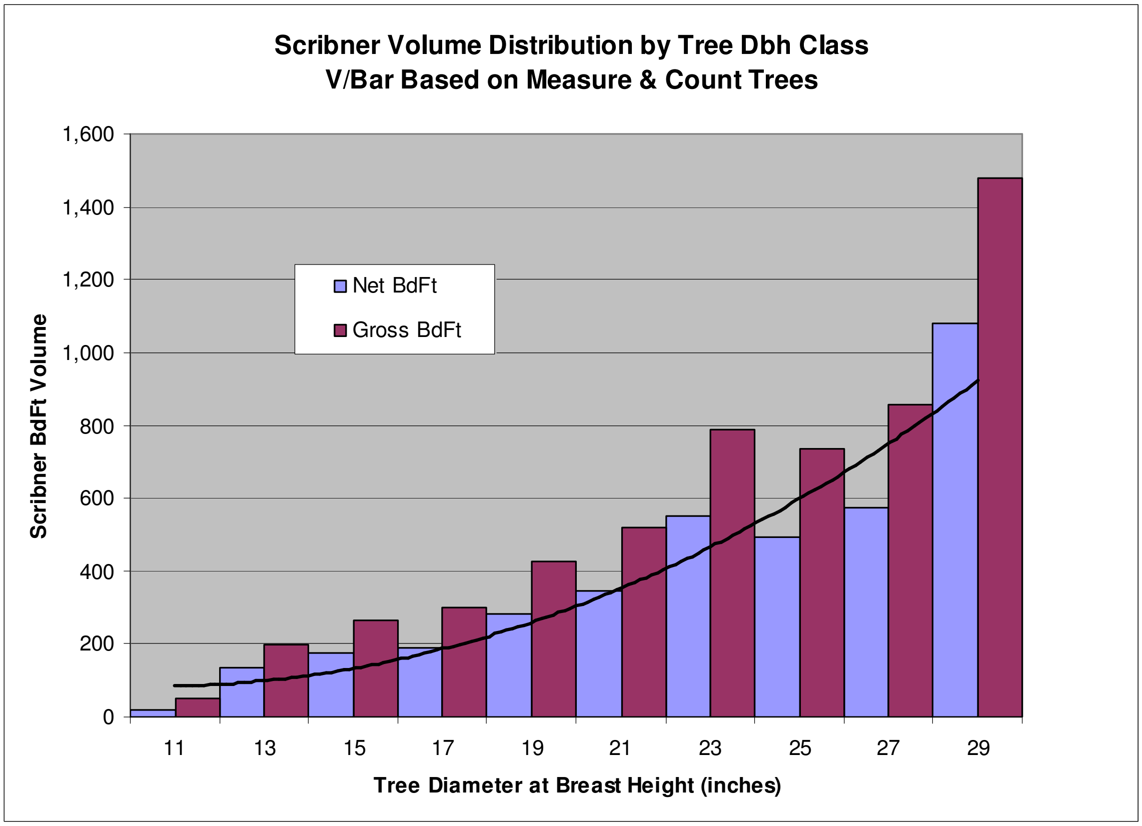


Figure 3. Scribner volume by Dbh class with count-only trees by 1-inch dbh class.

Note the improvement in definition of volume by dbh class compared to Method #1 (Figure 1 versus Figure 3). The cost of the cruiser putting in the plots is no different and the time required to tally trees by 1-inch dbh class is insignificant. However, if tree size distributions are important, then this simple addition to the data collection and cruise compilation is an obvious benefit.

Method #3 – Cruise compilation using Height / Dbh regressions

While Method #2 provides much better definition of tree dbh distributions of volume compared to Method #1, it does nothing to improve information about the log size distribution of volume. If value is differential among species and log sizes, then a definitive log size distribution is important to assign value distributions. This may be accomplished by increasing the proportion of measure trees to count-only trees in the cruise sample design. However, this has the potential of significantly increasing the cost of obtaining this additional sample detail.

An alternative cruise compilation technique is available that significantly improves the range of details computed from a cruise without additional field measurements. This approach uses a preliminary and separate analysis to estimate total heights for each count-only tree if a diameter at breast height had been recorded. As a result, every sample tree, measure and count, has either a measured or estimated total height matched to a dbh for that tree. This pair of statistics (dbh and height) provides the cruise compiler with sufficient information to merchandize each tree into logs. Once the expansion factors for the measured trees are computed, the log distributions of the count-only trees may also be expanded. The result is a highly definitive log size distribution by species, size, and volume. This regression model was recommended by Robert O. Curtis (1967).

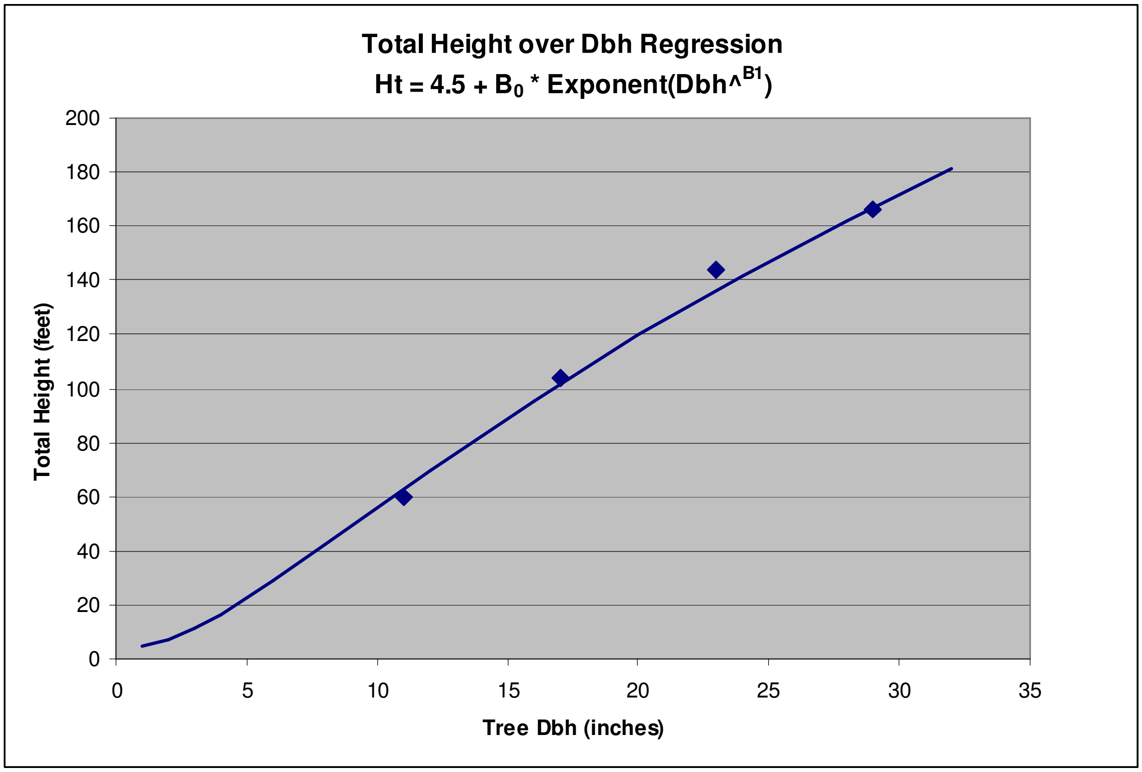


Figure 4. Regression of measured tree heights over diameters at breast height.

The cruise compiler fits a non-linear regression line to the measured tree heights over the measured tree diameters at breast height. If the measured trees have been sampled across the range of diameters, then this usually provides a very robust estimate of the count-only tree heights given their diameters were recorded. The cruise compiler provides volume estimates for every log in every tree along with estimated heights for count trees.

Table 6. Scribner board-foot **gross** volumes for all trees by log position.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11	13	15	17	19	21	23	25	27	29
Height	60	76.4	89.3	104	113.7	125.2	144	146.9	157.1	166
Log#1	30	60	80	110	140	180	240	280	330	400
Log#2	20	30	60	80	100	140	180	210	280	300
Log#3		20	30	60	70	100	140	160	210	240
Log#4			20	30	40	70	100	110	160	180
Log#5				20	30	40	70	80	110	140
Log#6						20	40	60	70	100
Log#7							20	30	40	70
Log#8									20	30
Log#9										20
Totals:	**50**	**110**	**190**	**300**	**380**	**550**	**790**	**930**	**1220**	**1480**

The Scribner gross volume is then simply the summation of all of the individual trees (both measured and count-only). The total Scribner gross volume is 6,000 board feet.

The next step is to obtain a robust estimate of the defect distribution to count-only trees. This is important to derive net volumes by log size and position. These details provide direct input into log value determinations for each tree and log. This level of detail is not available in either Method #1 or Method #2.

Rather than chase specific log dimensions (which will vary from cruise to cruise, species to species and region to region), it is much more consistent and robust to assign defect by position in the tree. In this way, when merchandizing specifications change, the distribution of defect remains constant. Defect is an attribute of the tree and not of a log. The definition of a log may change from cruise to cruise, day to day, or cruiser to cruiser.

Defect assignment by log segment

If defect is recorded by log segment, then the cruise compiler assigns each log to height positions on the tree. The tree is divided into three vertical segments of equal height. These are referred to as the butt one-third, middle one-third and top one-third of height. The top one-third may include or totally contain the non-merchantable stem.

The percent of defect by log position is weighted by the gross cubic volume of that log segment. Then the weighted average defect in each one-third segment is determined from all logs within that segment. A linear regression of defect by tree dbh is then developed for each species in the cruise.

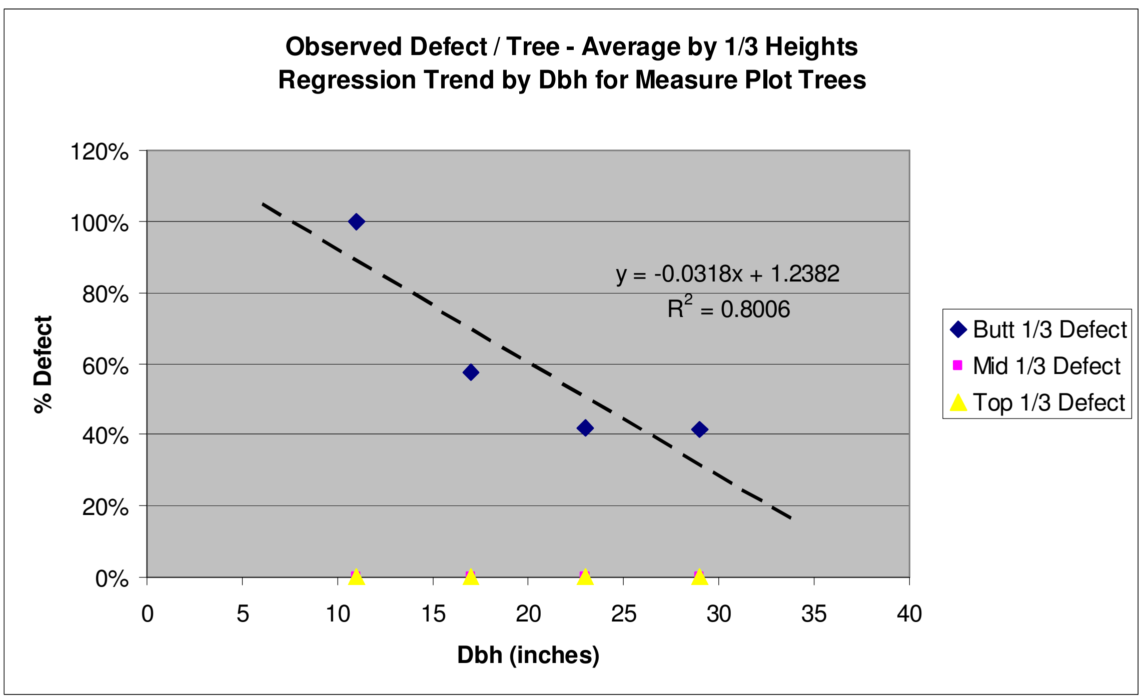


Figure 5. Regression of Defect by one-third tree heights from measured trees.

Table 7. Observed defect on measure trees and estimated defect on count-only trees.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11	13	15	17	19	21	23	25	27	29
Height	60	76.4	89.3	104	113.7	125.2	144	146.9	157.1	166
Butt 1/3	100%	82%	76%	57%	63%	57%	42%	44%	38%	42%
Mid 1/3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Top 1/3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
GrsVol	50	110	190	300	380	550	790	930	1220	1480
NetVol	20	36	83	190	183	310	550	642	909	1080

The total stand Scribner net volume is 4,004 board feet from a gross volume of 6,000 board feet. Net volume is 67% of total volume in this sample dataset. The best estimate of the distribution of volume by Dbh class is displayed in the following chart.

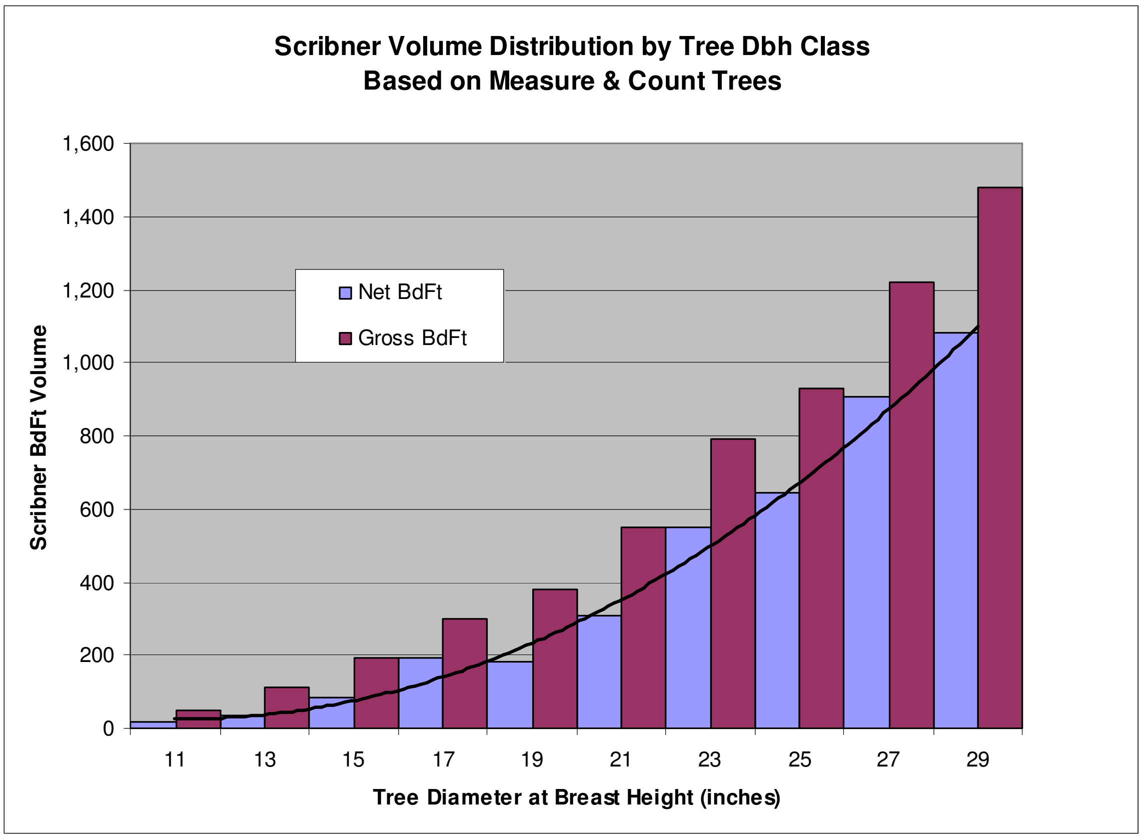


Figure 6. Distribution of Scribner volume for all trees using Method #3.

Since defect is either observed or estimated for every segment of every tree, the defect by log position may be determined to compute net volume by log segment. This procedure provides the ability to adjust the merchandizing specifications in the cruise compiler to evaluate alternative size and value combinations of species and log mixes.

Table 6 displays both the field observed defect by log position and the cruise compiler estimated defect from the regression analyses by one-third total height positions.

Table 6. Scribner board-foot **net** volumes for all trees by log position.

Field	**M**	**C**	**C**	**M**	**C**	**C**	**M**	**C**	**C**	**M**
Tree#	1	2	3	4	5	6	7	8	9	10
Dbh	11	13	15	17	19	21	23	25	27	29
Height	60	76.4	89.3	104	113.7	125.2	144	146.9	157.1	166
Log#1	0	11	19	0	51	77	0	156	205	0
Log#2	20	5	14	80	37	60	180	117	174	300
Log#3		20	30	60	26	43	140	89	130	240
Log#4			20	30	40	70	100	110	160	180
Log#5				20	30	40	70	80	110	140
Log#6						20	40	60	70	100
Log#7							20	30	40	70
Log#8									20	30
Log#9										20
Totals:	**20**	**36**	**83**	**190**	**183**	**310**	**550**	**642**	**909**	**1080**

These log segments are defined by the cruise compiler for small-end diameter, large-end diameter, cubic volume and board volume. All of these parameters may be used to produce distribution reports of volume and value in the stand. The log distribution is well defined from this approach with out any additional field work required.

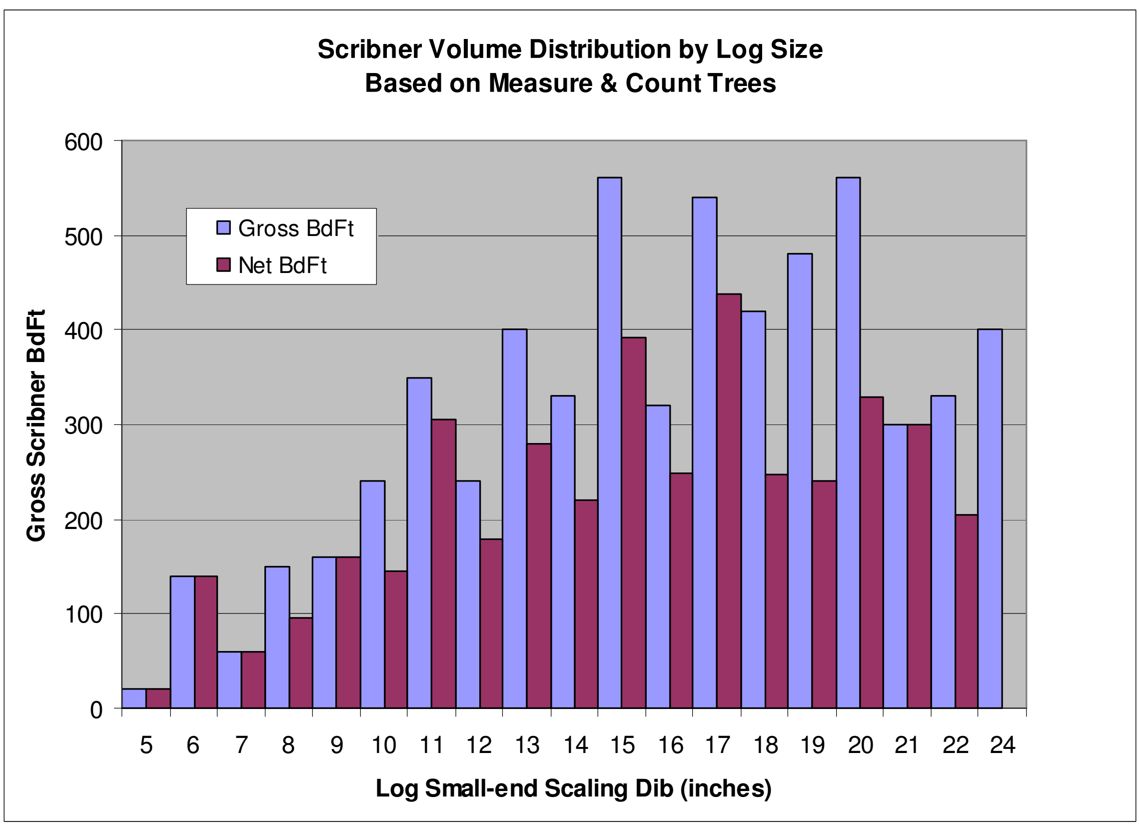


Figure 7. Distribution of Scribner volume by log size for all trees in the cruise.

Conclusions

It should be apparent from the computations in this series of analyses for Methods #1, #2 and #3 that significantly more information may be obtained from the same field sample if the cruise compiler is designed to extract it.

It should also be apparent that sub-samples of total height are very useful in providing sufficient additional tree detail, along with diameter, to merchandize every tree into log segments, whether measured or tallied by diameter class. This additional information relies on gathering a diameter class estimate for every count-only tree. This single additional attribute has almost a zero increase in cost or time to collect. In summary, when designing a cruise, it should be obvious from these analyses that count-only trees should always be recorded by species and dbh, at least.

Almost all growth models currently in use in the forest industry are classified as tree-list models. This means that they actually grow each tree in the inventory list of a stand, rather than projecting just the average statistics of the stand. It should be apparent from the comparisons of Figure 1 and Figure 6 that growth projection results are much more robust where the input tree list is well defined rather than aggregated. The accuracy of the growth projection will only be as good as the input resolution.

Comparing the volume results from the three methods also displays significant differences in total volume results depending on the proportions of measure to count trees in the cruise. The following table displays the percent difference in gross (net) volumes for Methods #1 and #2 as compared to Method #3.

	Method #1	Method #2	Method #3
Gross Volume	5,760.2	5,760.2	6,000.0
Net Volume	3,940.4	3,940.4	4,003.7
%Net Volume	68.4%	68.4%	66.7%
%Diff from #3	-4% (-1.6%)	-4% (-1.6%)	0% (0%)

It would be hoped that all three methods would provide identical total volume estimates even though size distributions are of limited availability from the first two methods. This is not the result. The shortcoming is due to a constant V/Bar ratio being applied to all count-only trees. The actual impact of variations in tree size cannot be adequately addressed by these first two methods. These differences in total yield are observed to expand as the ratio of measure to count-only trees declines. The ratio was one in three in this analysis.

The inclusion of the height/dbh regressions is the pivotal benefit of Method #3.

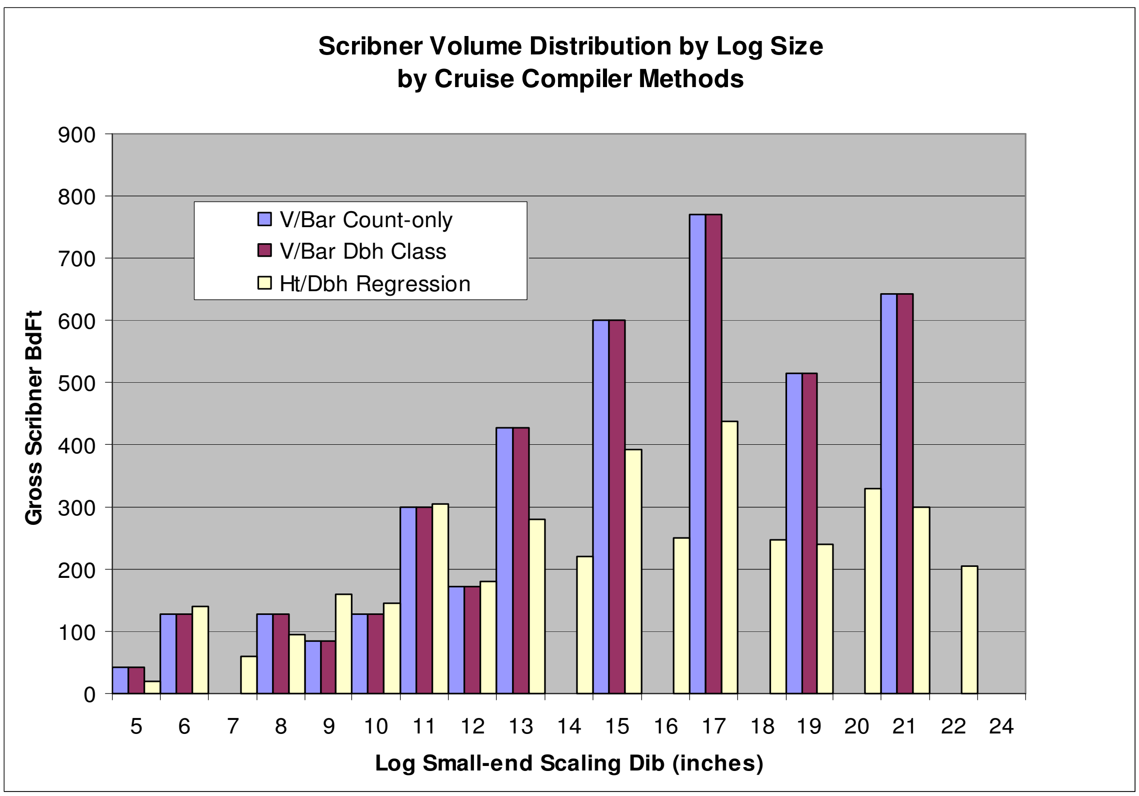
Even though the measured heights were only on the sub-sample of measured trees, this additional information was extremely valuable in providing estimates of total height on the count-only trees. This is the leading factor in the third method providing much more robust estimates of total volume, volume by dbh class and volume by log diameter class.

Assignment of Defect Distributions

This analysis provided estimates of both gross and net volumes using three methods. Most of the discussions in the conclusions have been about robust estimates of the distributions of volume in general. It should be pointed out, however, that the second most robust conclusion from these comparisons is the ability to define the distribution of defect.

Note that the factor providing the greatest improvement in definition of the volume distribution was using the regression analysis to estimate heights for the count-only trees. Once this factor was introduced into the cruise compilations, the ability to define log size distributions of all trees was significantly improved. In fact, log dimensions for count-only trees were not possible in Methods #1 and #2.

Method #3 also uses regression analyses of defect over dbh class from the measured trees to estimate defect for the count-only trees. There are three separate regressions – the butt one-third height class; the mid one-third height class; and the top one-third height class. In a typical cruise of one measure plot to two count plots, the impact of the size and species of the count-plot trees is pivotal to the amount and distribution of estimated defect in the stand. Regression estimates of defect for count-only trees plays as great a role in final net yields as does the regression estimates of height.



If the distribution if defect is so variable that the defect regressions find a non-significant trend, then the defect sample should be extended to a much larger fraction of the stand. In older natural stands, this may be the preferred default cruise design. In fact, the most robust design would be for the cruiser to call defect directly by one-third tree heights.

Recommendations

These analyses have identified a number of obvious recommendations for designing, executing and compiling a cruise. These recommendations are listed here as a six step review list prior to the execution of any sample cruise.

1) Lay out a systematic grid across the entire forested stand of interest so that plot locations are positioned to sample all topographic and vegetative differences within the stand boundaries.
2) Any combination of measure and count plots may be used. The ratio of measure to count should not be less than one measure plot per three plots in a string (one measure – two count).
3) Always include both the species and 1-inch class diameter at breast height (dbh) on all count-only trees.
4) Care should be exercised to include every species in the list of measured trees to characterize the differences among species in this stand. The FBRI cruise compiler was designed to facilitate this objective by allowing measured trees to occur on any plot. This is not necessarily the case with all cruise compilers.
5) Care should be exercised to include sub-sampled heights across the range of diameters of each species found in the stand. This provides a much more robust height / diameter regression when projecting heights on count-only trees. Again, the FBRI cruise compiler was designed to facilitate this objective by incorporating a very robust height / dbh regression methodology. This capability is not common among most other cruise compilers, which should be a major concern if they are used.
6) Anticipate the importance of defect in the stand prior to designing the sample cruise. Sampling defect is similar to sampling mortality. Defect is highly variable and poorly correlated with most commonly collected tree attributes (dbh, height).
    a. If the stand is young and vigorous, then defect should be minor with logging breakage being a primary component. As a rule of thumb, defect should total less than eight percent for both existing and logging deductions. In this case, sampling for defect may be limited to the height sample (measured) trees only.
    b. If the stand is of natural origin, older, mixed age and/or has a history of previous harvesting, then defect may be more significant. As a rule of thumb when defect is expected to be significant; then defect sampling should be included on every tree, both measured and counted. Defect may only be included on count-only trees if the cruise compiler uses a regression fitting method for defect by diameter. The FBRI cruise compiler is the only known compiler with this capacity. This approach is only possible by using the one-third of height stratification methods discussed earlier in this report. In any case, if defect is significant in the stand, then every tree in the cruise must be included in the defect sample for the cruise compiler to provide a reliable report of net-of-defect volume. See Iles (2003) for defect sampling rules.

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