## Topic Series 13
# Resource Inventory Methods

## AERIAL IMAGERY FOR TIMBER VOLUME ESTIMATION

Timber volume cannot be estimated from aerial photographic measurements with the precision that can be obtained from ground measurements. The high standard of error associated with pure aerial estimates of stand volume is the result of:

1. inaccuracies of aerial volume tables that relate photo identifiable tree characteristics (crown width, tree height, etc.) to individual or stand-level tree volumes.

2. inability to identify and measure individual sample tree characteristics (merchantable height, cull, etc.) because of photo scale and crown closure.

3. inability to see/count all sample trees under the primary canopy layer.

4. inability to relate photo identifiable tree characteristics to actual stem measurements and merchantability characteristics.

## I. Estimation of Tree and Stand Characteristics on Aerial Photographs

### Tree Diameter

Stem diameter (dbh) is related with crown diameter (r=+0.82).
Height is related with dbh (r=+0.51).
Number of trees is related with dbh (r=-0.358).

Crown diameter is measured with either crown wedges or dot-type scales in thousandth of inches. For example, at a scale of 1:20,000, a crown measurement of 0.01 inch would equate to a crown diameter of 17 feet.

With crown diameter, height, and number of trees, past studies have estimated dbh'es within 0.74 inches at the 95% level.

Rules of Thumb:

Southern pines (Minor); dbh,in. = 0.5(crown dia,ft.)+5

Eastern U.S.; dbh,in = 0.75(crown dia, ft.)

Western U.S.; dbh,in = crown diameter, ft.

**Tree Height**

Parallax bar - dominant heights are visible

$$\frac{\delta h}{(H-h)} = \frac{dp}{AP_b + dp}$$

$$\frac{\delta h}{(H-h)} = \frac{dp}{AP_b + dp}$$

$$\delta h = \frac{(H-h)(dp)}{AP_b + dp}$$

$$\delta h \text{ per } 0.01mm = \frac{(H-h)0.01}{AP_b + 0.01}$$

Example: For $AP_B$=3.1 inches and (H-h)= 8,000, $\Delta h$ = 1.02 ft per 0.01 mm

Estimation - comparison with known heights

**Stand Density**

Percent crown closure = proportion of forest canopy occupied by trees

Used in lieu of trees or basal area per acre as density measure.

Trees per acre; not all trees are visible in or below primary canopy.

## II. Measurement of Volume on Aerial Photographs

### Individual Tree Volumes

Aerial volume table is the relationship between the independent variables tree height and crown diameter and the dependent variable tree volume.

*Volumes of individual second-growth southern pines* [1]

| Crown diameter class (feet) | Total tree height, in feet | | | | | | |
|---|---|---|---|---|---|---|---|
| | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
| | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* |
| 10 | 9. 5 | 11. 5 | 12. 5 | 15. 0 | 17. 5 | 19. 5 | ----- |
| 12 | 12. 5 | 14. 5 | 16.. 5 | 18. 0 | 20. 5 | 22. 5 | ----- |
| 14 | 15. 0 | 17. 0 | 19. 0 | 23. 5 | 25. 0 | 27. 5 | 30. 5 |
| 16 | 17. 5 | 20. 5 | 24. 0 | 27. 5 | 30. 5 | 33. 0 | 36. 0 |
| 18 | ------ | 23. 5 | 27. 0 | 30. 5 | 34. 5 | 38. 0 | 42. 5 |
| 20 | ------ | 28. 0 | 33. 5 | 36. 0 | 40. 0 | 45. 5 | 49. 0 |
| 22 | ------ | 32. 5 | 37. 0 | 42. 5 | 46. 5 | 52. 0 | 57. 5 |
| 24 | ------ | 37. 0 | 42. 5 | 48. 5 | 54. 5 | 60. 0 | 66. 0 |
| 26 | ------ | 42. 5 | 47. 5 | 54. 0 | 61. 0 | 67. 5 | 75. 5 |
| 28 | ------ | ------ | 53. 0 | 60. 5 | 70. 5 | 76. 0 | 83. 0 |
| 30 | ------ | ------ | 60. 5 | 68. 0 | 78. 0 | 85. 5 | 94. 5 |

[1] Based on 342 trees in Arkansas, Lousiana, and Mississippi. Gross volumes are inside bark and include the merchantable stem to a variable top averaging 6 inches i.b. Reprinted from (*4*).

Use of aerial volume table is limited by ability to develop suitable table for local area and by the difficulty in accurately counting tree crowns on aerial photos.

## Stand Volumes

Tree height, crown diameter, and percent crown closure are strongly related to stand volume. Avery (1958) published a three-variable stand-volume table for both pines and hardwoods in Mississippi.

Minor's (1993) equation for cord volume in pine stands for trees 4.6 inches DBH and larger is:

Volume (cords) = [0.62 (Height in feet) - 0.48] [%crown closure as decimal]
$r^2$ = 90%; standard error of mean estimate = +/- 0.2 cords

## Problems and Limitations

1. Can't get cull, form, and dbh.
2. Merchantable height is related strongly to total height.
3. Inability to get current photography when needed.
4. Expensive to develop local aerial volume tables and to do photo-interpretation for small areas.

*Composite aerial volume per acre for northeast Mississippi* [1]

10-FOOT AVERAGE CROWN DIAMETER

| Average stand height (feet) | Crown closure percent | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15 | 25 | 35 | 45 | 55 | 65 | 75 | 85 | 95 |
| | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* | *Cu. ft.* |
| 30 | 190 | 310 | 430 | 560 | 690 | 810 | 940 | 1,060 | 1,180 |
| 40 | 230 | 380 | 530 | 690 | 840 | 990 | 1,140 | 1,300 | 1,450 |
| 50 | 260 | 440 | 620 | 800 | 980 | 1,150 | 1,330 | 1,510 | 1,680 |
| 60 | 300 | 500 | 690 | 890 | 1,090 | 1,290 | 1,490 | 1,680 | 1,880 |
| 70 | 340 | 570 | 800 | 1,030 | 1,260 | 1,490 | 1,720 | 1,950 | 2,180 |
| 80 | 380 | 640 | 890 | 1,140 | 1,400 | 1,650 | 1,910 | 2,160 | 2,420 |

15-FOOT AVERAGE CROWN DIAMETER

| Average stand height (feet) | 15 | 25 | 35 | 45 | 55 | 65 | 75 | 85 | 95 |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 210 | 350 | 500 | 640 | 780 | 930 | 1,070 | 1,220 | 1,360 |
| 40 | 260 | 430 | 610 | 780 | 950 | 1,130 | 1,300 | 1,480 | 1,650 |
| 50 | 310 | 510 | 730 | 930 | 1,140 | 1,350 | 1,550 | 1,770 | 1,970 |
| 60 | 360 | 590 | 830 | 1,070 | 1,300 | 1,550 | 1,780 | 2,030 | 2,260 |
| 70 | 400 | 660 | 940 | 1,200 | 1,460 | 1,740 | 2,000 | 2,280 | 2,540 |
| 80 | 440 | 740 | 1,040 | 1,330 | 1,620 | 1,930 | 2,220 | 2,530 | 2,820 |
| 90 | 480 | 800 | 1,140 | 1,450 | 1,770 | 2,100 | 2,420 | 2,760 | 3,070 |

20-FOOT AVERAGE CROWN DIAMETER

| Average stand height (feet) | 15 | 25 | 35 | 45 | 55 | 65 | 75 | 85 | 95 |
|---|---|---|---|---|---|---|---|---|---|
| 40 | 270 | 450 | 630 | 820 | 1,000 | 1,190 | 1,370 | 1,550 | 1,720 |
| 50 | 320 | 540 | 750 | 970 | 1,190 | 1,410 | 1,630 | 1,840 | 2,040 |
| 60 | 360 | 610 | 860 | 1,110 | 1,360 | 1,600 | 1,850 | 2,100 | 2,330 |
| 70 | 410 | 680 | 960 | 1,240 | 1,520 | 1,800 | 2,080 | 2,360 | 2,610 |
| 80 | 450 | 760 | 1,070 | 1,380 | 1,690 | 2,000 | 2,310 | 2,620 | 2,900 |
| 90 | 500 | 840 | 1,190 | 1,530 | 1,870 | 2,220 | 2,560 | 2,900 | 3,220 |
| 100 | 540 | 920 | 1,290 | 1,670 | 2,040 | 2,410 | 2,790 | 3,160 | 3,500 |

25-FOOT AVERAGE CROWN DIAMETER

| Average stand height (feet) | 15 | 25 | 35 | 45 | 55 | 65 | 75 | 85 | 95 |
|---|---|---|---|---|---|---|---|---|---|
| 50 | 320 | 550 | 770 | 1,000 | 1,220 | 1,450 | 1,670 | 1,900 | 2,120 |
| 60 | 370 | 620 | 880 | 1,130 | 1,390 | 1,650 | 1,900 | 2,160 | 2,410 |
| 70 | 410 | 700 | 980 | 1,270 | 1,550 | 1,840 | 2,130 | 2,410 | 2,700 |
| 80 | 460 | 780 | 1,100 | 1,420 | 1,740 | 2,060 | 2,380 | 2,700 | 3,020 |
| 90 | 510 | 860 | 1,220 | 1,570 | 1,930 | 2,280 | 2,640 | 2,990 | 3,350 |
| 100 | 550 | 940 | 1,320 | 1,710 | 2,090 | 2,480 | 2,860 | 3,250 | 3,630 |

[1] Gross volumes are inside bark and include the merchantable stem to a variable top not smaller than 3 inches i.b. Reprinted from (*3*).

## III. Using Aerial Photos with Conventional Ground Inventories

Volume estimates from aerial photographs are of limited usefulness in cruises of small or accessible forest stands, but aerial photos can be used with conventional ground inventory procedures in a number of ways. Photos are used to:

1. segregate forest stands and classify (i.e delineate) them into type, size, and density classes.

2. develop planimetric maps of inventory areas with ground control points and transfer of detail with sketch master or GIS digitizing procedures.

3. determine acreage of stands, types, tracts, and forests either directly from photos (i.e with no ground control points) or from planimetric maps prepared from photos (i.e. with control points and/or with GIS).

4. locate sample points/plots according to desired stratification method and navigate to points/plots during field inventory phase.

## IV. Area Determination from Aerial Photos

**<u>Media of area measurement</u>**

1. Directly on Photos
   Problems - topographic displacement and scale variation

2. On planimetric maps made from photos

**<u>Methods of area measurement</u>**

1. Dot grid
2. Planimeter
3. Computer assisted methods (CADD, GIS)

## V. Types of Photo-Ground Cruises

**<u>Single Phase, Photo-Controlled Ground Cruise</u>**

Is the most common use of aerial photos in forest inventory for small accessible tracts where cost of developing photo volume data is not warranted.

Acres, types, etc. are determined from photos or maps prepared from photos. Per acre and stand volumes are obtained from conventional ground inventory methods.

**Two Phase (Double Sample) Photo-Ground Cruise**

Used for large, perhaps inaccessible, tracts where the cost of conventional ground inventory is prohibitive.

In double sampling scheme, a large number of photo plots are interpreted/measured for volume and a smaller number of ground plots are measured for volume. A regression estimator can be used to obtain the adjusted volume per acre from the double sample equation:

$$\bar{Y}_{lr} = \bar{y} + \beta(\bar{X} - \bar{x})$$

where $\bar{Y}_{lr}$ = adjusted volume per acre (linear regression)

$\bar{y}$ = ground volume per acre (2st phase)

$\bar{X}$ = photo volume per acre (1st phase)

$\bar{x}$ = photo volume per acre (2nd phase)

$\beta$ = regression coefficient for ground volume over photo volume

$y_i$ = ground volume per acre (2nd phase)

$x_i$ = photo volume per acre (2nd phase)

$X_i$ = photo volume per acre (1st phase)

$n_1$ = sample size 1st phase

$n_2$ = sample size 2nd phase

$c_1$ = cost per 1st phase plot

$c_2$ = cost per 2nd phase plot

$$Var(\bar{Y}_{lr}) = \frac{s_{y.x}^2}{n_2} + \frac{s_y^2 - s_{y.x}^2}{n_1}$$

$$\sum y^2 = \sum Y_i^2 - \frac{(\sum Y_i)^2}{n_2}$$

$$\sum x^2 = \sum X_i^2 - \frac{(\sum X_i)^2}{n_2}$$

$$\sum xy = \sum X_i Y_i - \frac{\sum X_i \sum Y_i}{n_2}$$

$$\beta = \frac{\sum xy}{\sum x^2}$$

$$s_y^2 = \frac{\sum y^2}{n_2 - 1}$$

$$s_{y.x}^2 = \frac{\sum y^2 - \frac{(\sum xy)^2}{\sum x^2}}{n_2 - 2}$$

$$s_{\bar{y}\,lr} = \sqrt{\frac{s_{y.x}^2}{n_2} + \frac{(s_y^2 - s_{y.x}^2)}{n_1}}$$

$$s_{\bar{y}\,lr} = \sqrt{s_{y.x}^2 [\frac{1}{n_2} + \frac{(\bar{x}_1 - \bar{x}_2)}{\sum x^2}] (1 - \frac{n_2}{n_1}) + \frac{s_y^2}{n_1} (1 - \frac{n_1}{N})}$$

$$p = \frac{\sum xy}{\sqrt{\sum x^2 \sum y^2}}$$

$$If\ p^2 > \frac{4c_2c_1}{(c_2 + c_1)^2} \quad then\ D.S.\ efficiency > S.R.S.$$

$$var_1 = p^2 S_y^2 \qquad var_2 = (1 - p^2) S_y^2$$

$$ratio(\frac{n_2}{n_1}) = \sqrt{\frac{var_2\, c_1}{var_1\ c_2}}$$

$$n_1 = \frac{C}{c_1 + (ratio)\, c_2} \qquad since\ C = n_1c_1 + n_2c_2$$

$$n_2 = (ratio)\, n_1$$

**Table 11-1: Example of Two Phase, Photo-Ground Cruise: Cubic foot volume from ground plots and (low altitude 70mm camera) photo plots**

| | PHASE 1 | .....PHASE 2..... | | SUMS OF SQUARES/PRODUCTS | | |
|---|---|---|---|---|---|---|
| | Photo-X | Photo-x | Grnd-y | $x^2$ | $y^2$ | x*y |
| | 1400 | 1400 | 1584 | 1960000 | 2509056 | 2217600 |
| | 1500 | | | 0 | 0 | 0 |
| | 1900 | | | 0 | 0 | 0 |
| | 1500 | | | 0 | 0 | 0 |
| | 1600 | | | 0 | 0 | 0 |
| | 1500 | | | 0 | 0 | 0 |
| | 900 | | | 0 | 0 | 0 |
| | 1700 | | | 0 | 0 | 0 |
| | 1500 | | | 0 | 0 | 0 |
| | 1300 | | | 0 | 0 | 0 |
| | 1700 | | | 0 | 0 | 0 |
| | 1500 | | | 0 | 0 | 0 |
| | 1200 | | | 0 | 0 | 0 |
| | 1600 | | | 0 | 0 | 0 |
| | 1200 | 1200 | 1344 | 1440000 | 1806336 | 1612800 |
| | 1300 | | | 0 | 0 | 0 |
| | 2100 | | | 0 | 0 | 0 |
| | 1600 | | | 0 | 0 | 0 |
| | 1900 | | | 0 | 0 | 0 |
| | 1100 | | | 0 | 0 | 0 |
| | 1700 | 1700 | 2083 | 2890000 | 4338889 | 3541100 |
| | 1400 | 1400 | 1584 | 1960000 | 2509056 | 2217600 |
| | 1700 | 1700 | 1968 | 2890000 | 3873024 | 3345600 |
| | 1600 | | | 0 | 0 | 0 |
| | 1900 | | | 0 | 0 | 0 |
| | 2000 | | | 0 | 0 | 0 |
| | 800 | | | 0 | 0 | 0 |
| | 1100 | | | 0 | 0 | 0 |
| | 1900 | 1900 | 1919 | 3610000 | 3682561 | 3646100 |
| | 1500 | | | 0 | 0 | 0 |
| | 1700 | 1700 | 2042 | 2890000 | 4169764 | 3471400 |
| | 1200 | 1200 | 1247 | 1440000 | 1555009 | 1496400 |
| | 1200 | 1200 | 1277 | 1440000 | 1630729 | 1532400 |
| | 1700 | | | 0 | 0 | 0 |
| | 1300 | | | 0 | 0 | 0 |
| | 1300 | 1300 | 2083 | 1690000 | 4338889 | 2707900 |
| | 1400 | | | 0 | 0 | 0 |
| | 1800 | | | 0 | 0 | 0 |
| | 1400 | | | 0 | 0 | 0 |
| | 800 | | | 0 | 0 | 0 |
| $n_1$ | 40 | | | | | |
| $n_2$ | | 10 | 10 | | | |
| Sums | 59400 | 14700 | 17131 | 22210000 | 30413313 | 25788900 |
| Means | 1485.0 | 1470.0 | 1713.1 | | | |
| SScorrected | | | | 601000 | 1066197 | 606330 |
| B-slope | | | | | | 1.0089 |
| $Ybar_{lr}$ | | | 1728.23 = 1713.1 +1.0089(1485 - 1470) | | | |
| cost $c_1$ | | | 5.00 | | | |
| cost $c_2$ | | | 10.00 | | | |
| $s_y^2$ | | | 133275 | | | |
| $s_{y.x}^2$ | | | 56811 | | | |
| $s_{ybar\ lr}$ | | | 87.14 | | | |
| p | | | 0.76 | | | |
| $p^2$ | | | 0.57 | | | |
| $4c_1c_2/(c_2+c_1)^2$ | | | 0.89 if $p^2$ > this value then DS more efficient than SRS | | | |
| Best: DS vs SRS | | | SRS best since $p^2 < 0.89$ | | | |

## VI. Sample Size Determination and Distribution

**Sample Size Determination**

1. Simple Random Sampling
   a. Infinite population

$$n = \frac{t^2 cv^2}{ae^2}$$

$$\text{where } cv = \text{coefficient of variation}(\%)$$

$$ae = \text{allowable error}(\%)$$

$$t = \text{Student's } t \text{ at } \alpha, n \text{ d.f.}$$

   b. Finite population

$$n = \frac{N t^2 (cv\%)^2}{N(ae\%)^2 + t^2 (cv\%)^2}$$

$$\text{where } N = \text{max samples} = \frac{\text{acres}}{\text{plot size}}$$

2. Double Sampling - (see previous section)

**Sample Distribution**

1. Random

2. Systematic - emphasize possible bias

## VII. Timber Inventory with LiDAR

See paper by Parker and Evans, "An application of LiDAR in a double-sample forest inventory"

**Allocation of Phase 1 and Phase 2 Plots in Double Sample**

Phase 1 sample size[1]:

$$n_1 = N_{rs}\left[(1 - \rho^2)\sqrt{\left(\frac{c_2}{c_1}\right)\left(\frac{\rho^2}{1 - \rho^2}\right)} + \rho^2\right]$$

Phase 2 sample size[1]:

$$n_2 = N_{rs}\left[(1 - \rho^2) + \rho^2\sqrt{\left(\frac{c_1}{c_2}\right)\left(\frac{1 - \rho^2}{\rho^2}\right)}\right]$$

where $\rho^2$ is coefficient of determination, $c_1$ and $c_2$ are costs of Phase 1 and Phase 2 samples.

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[1] Adapted from Johnson, E.W. 2000. **Forest Sampling Desk Reference**. CRC Press, Boca Raton, FL. 985 pp.

Table 13-1. Phase 1 and 2 estimates of basal area (ft$^2$)and volume per acre (ft$^3$) and regression estimates from LiDAR double sample (with composite species) in southern Idaho research area.

| Sample Phase: | Basal Area (ft$^2$) | Volume (ft$^3$) |
|---|---|---|
| Phase 1 LiDAR $(\bar{X})$ | 44.67 | 1,119 |
| Phase 2 Ground $(\bar{y})$ | | 1,272 |
| Phase 2 LiDAR $(\bar{x})$ | 45.43 | 1,096 |
| Regression Estimates: | | |
| $\beta$ | 34.070[1] | 1.137[2] |
| $\bar{Y}_{lr}$ (Adjusted ft$^3$) | 1,246 | 1,297 |
| $S_{\bar{Y}_{lr}}$ | 72.98 | 74.42 |
| $\rho^2$ | 0.6343 | 0.6191 |
| 95% CI Sampling Error | 11.7% | 11.5% |

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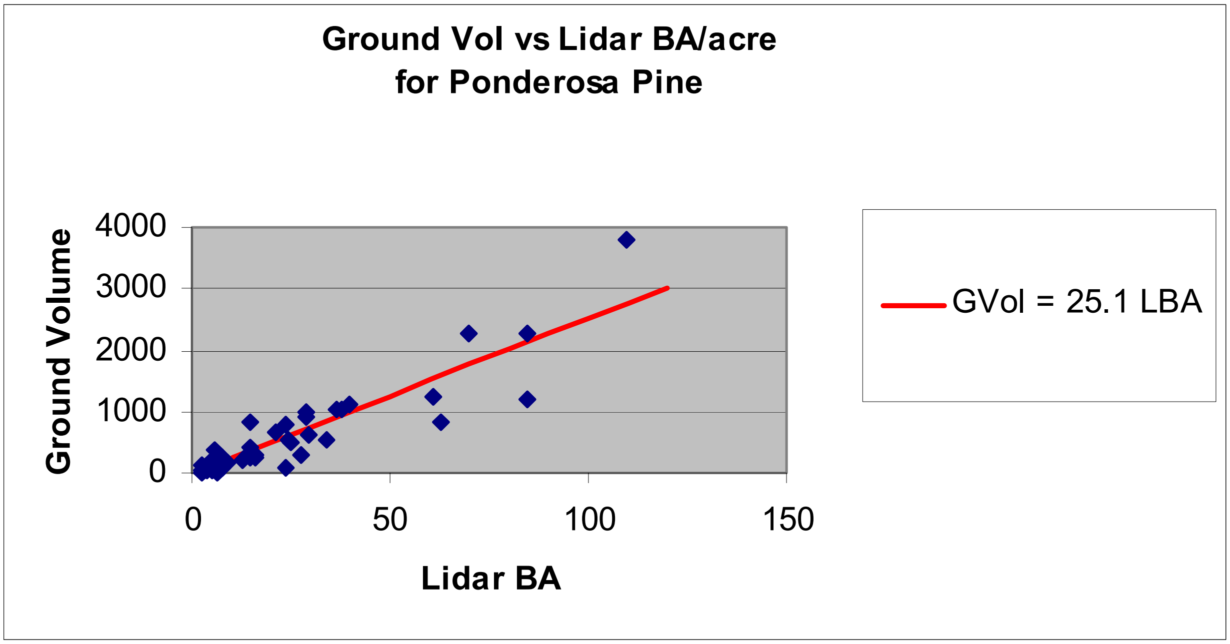
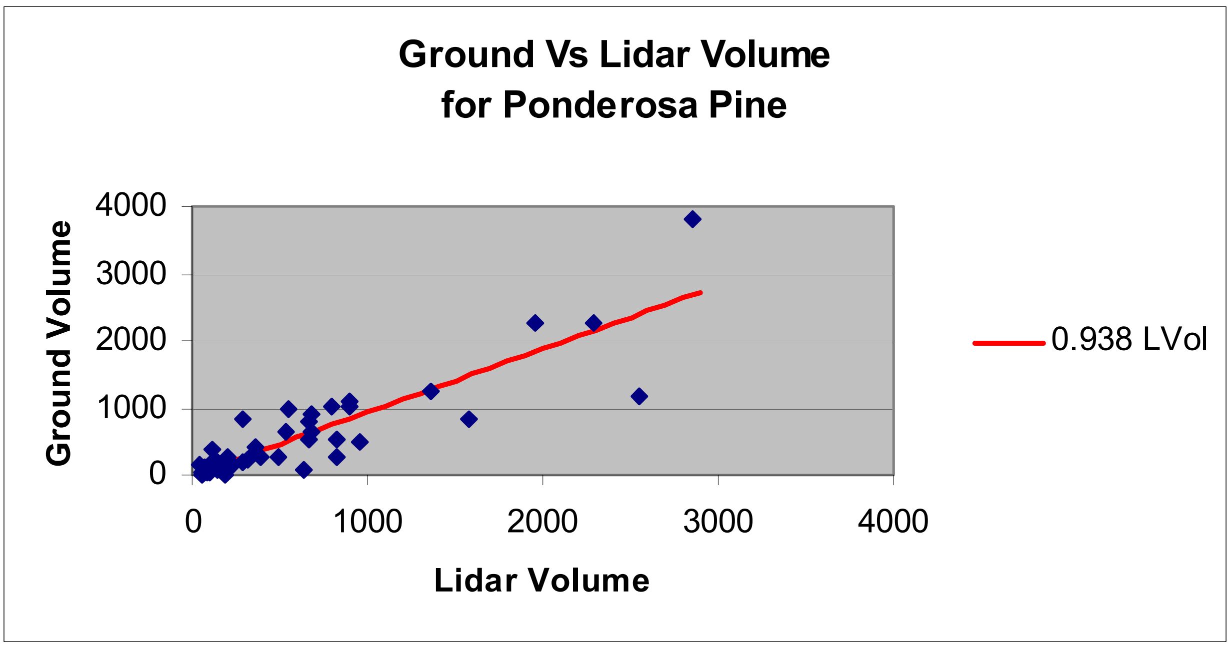
[1] Cubic feet of ground volume per one square foot of LiDAR basal area from model:

$$\bar{Y}_{lr} = \bar{y} + \beta(LiBA - liba)$$

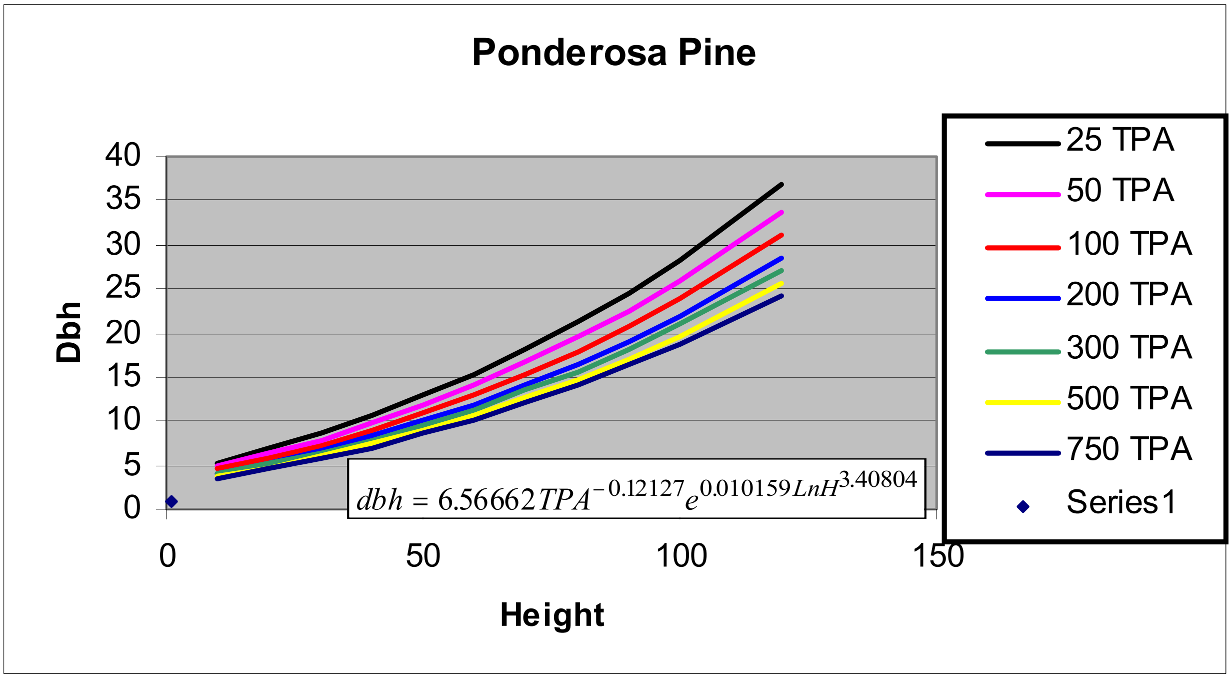
[2] Cubic feet of ground volume per one cubic foot of LiDAR volume from model:

$$\bar{Y}_{lr} = \bar{y} + \beta(LiVOL - livol)$$

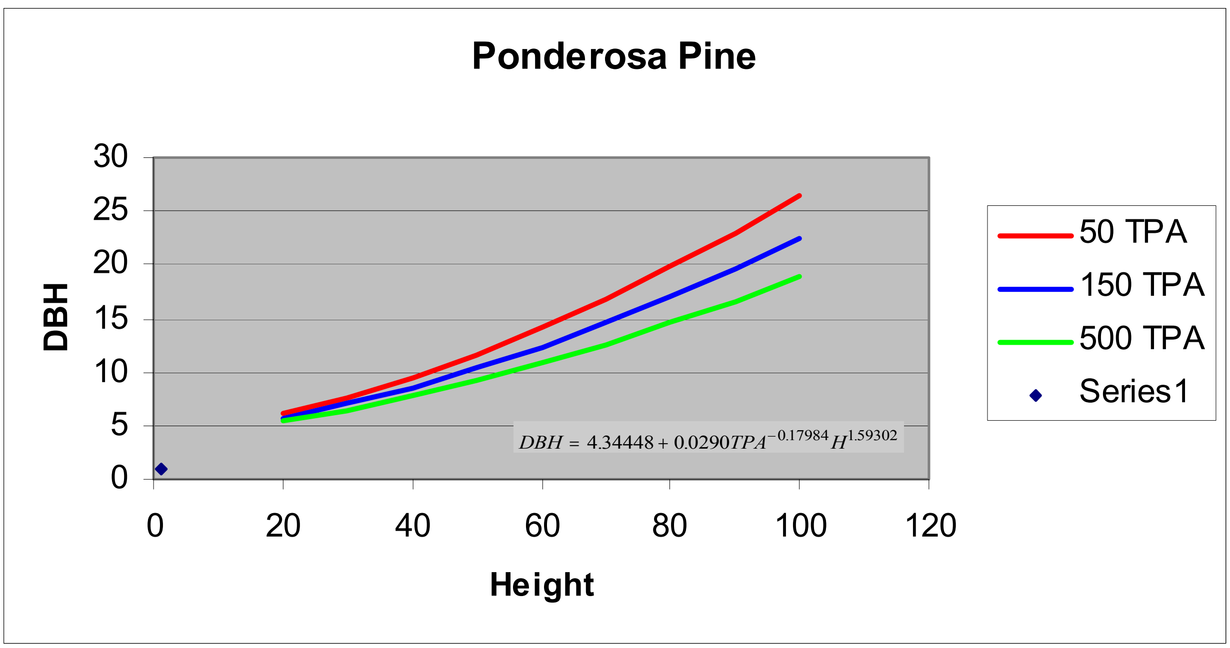

Ground Vol vs Lidar BA/acre
for Ponderosa Pine
Ground Volume
4000
3000
2000
1000
0
0
50
100
150
Lidar BA
GVol = 25.1 LBA



Ground Vs Lidar Volume
for Ponderosa Pine
Ground Volume
4000
3000
2000
1000
0
0
1000
2000
3000
4000
Lidar Volume
0.938 LVol



Ponderosa Pine
40
35
30
25
20
15
10
5
0
Dbh
0
50
100
150
Height
25 TPA
50 TPA
100 TPA
200 TPA
300 TPA
500 TPA
750 TPA
Series1
$dbh = 6.56662 TPA^{-0.12127} e^{0.010159 LnH^{3.40804}}$

Ponderosa Pine
30
25
20
15
10
5
0
DBH
0
20
40
60
80
100
120
Height
50 TPA
150 TPA
500 TPA
Series1
$DBH = 4.34448 + 0.0290 TPA^{-0.17984} H^{1.59302}$

## VIII. Large-area Resource Inventory with Satellite Data

**Use of LandSat Imagery for Stratification**

Strata

Change detection

**Use of GPS for Plot Location**

Real-time, Differential GPS

Coordinate system

**Demonstration of Ms Forest Inventory System**