

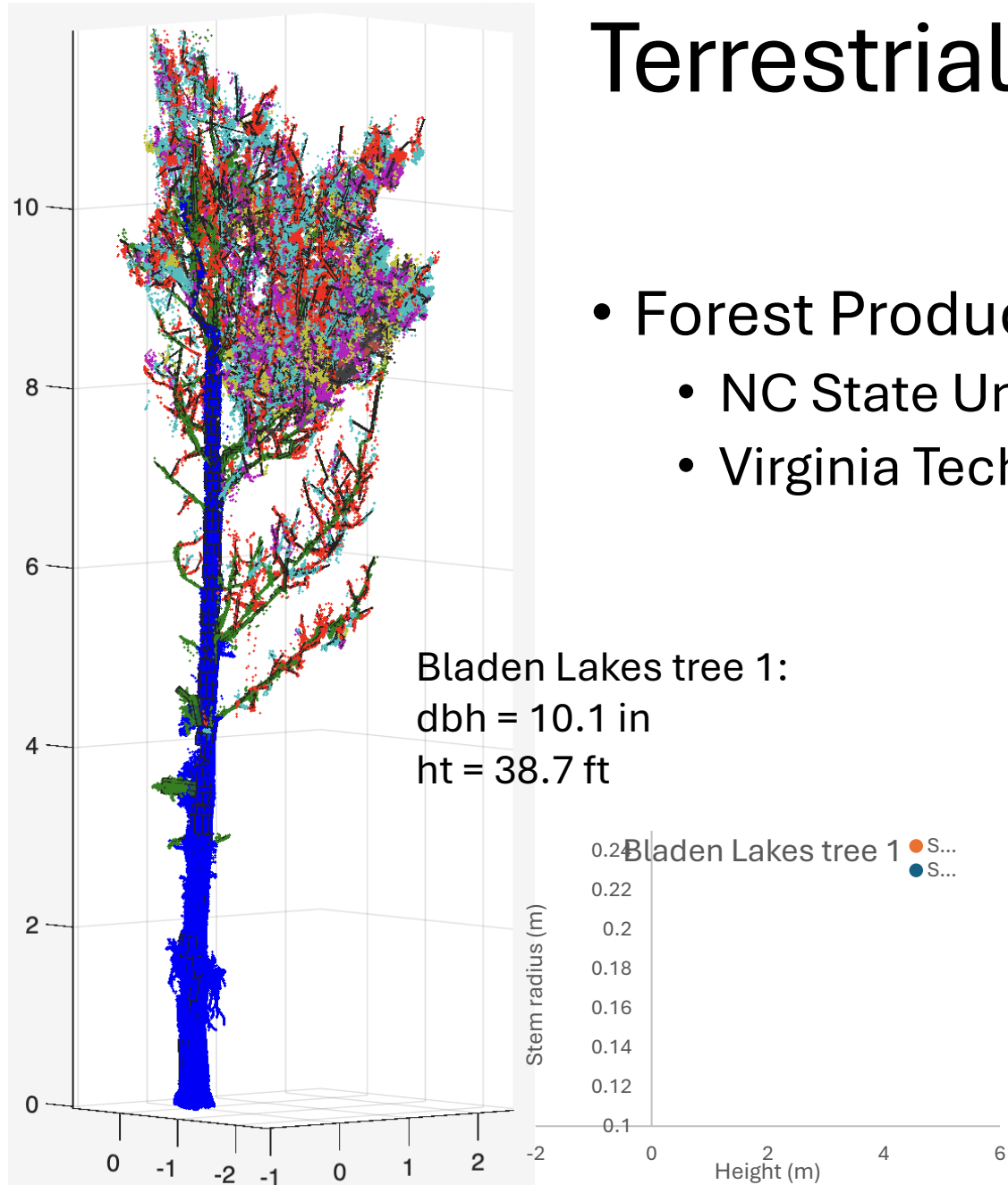
Terrestrial and Airborne Laser Scanning: Applications in Research and Inventory

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Industry partners: Chad Lincoln (FIA), Nate Herring (AFM), Scott Hillard (AFM)



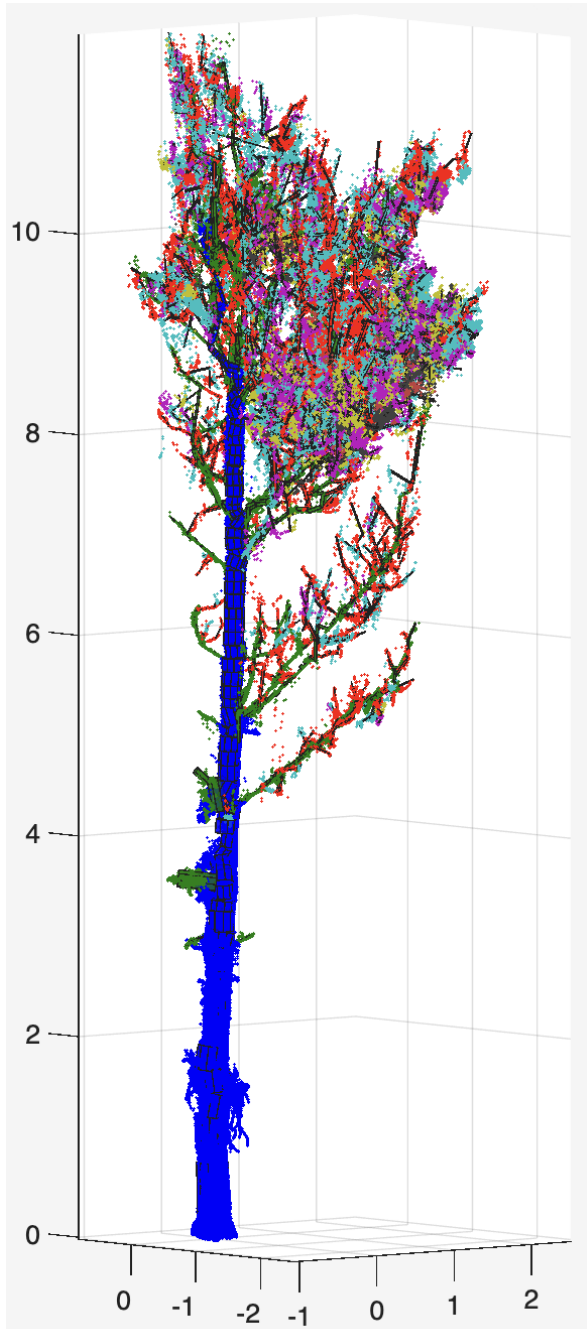
Terrestrial Laser Scanning



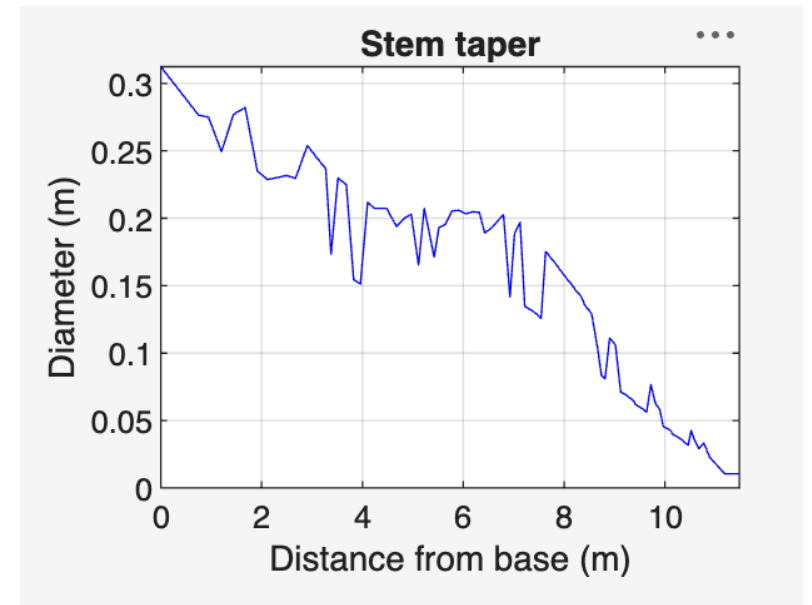
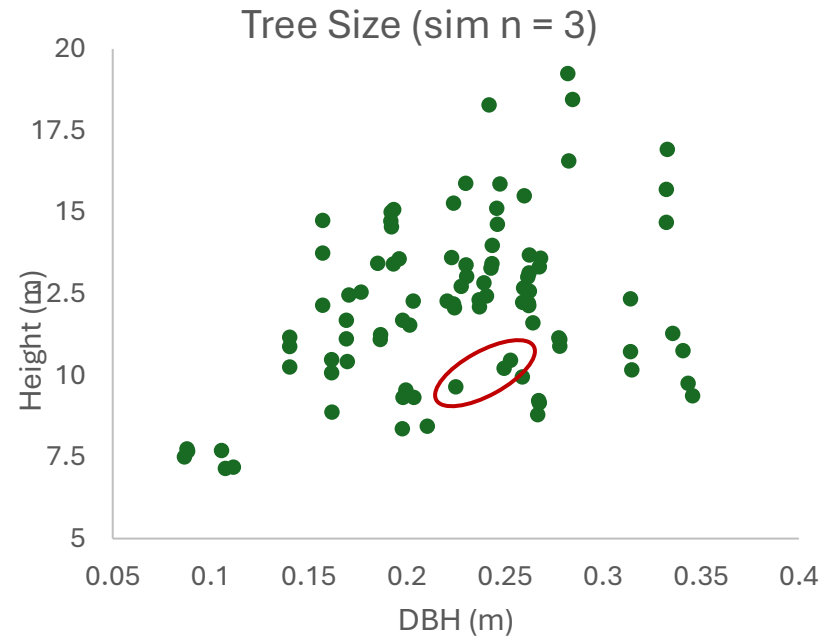
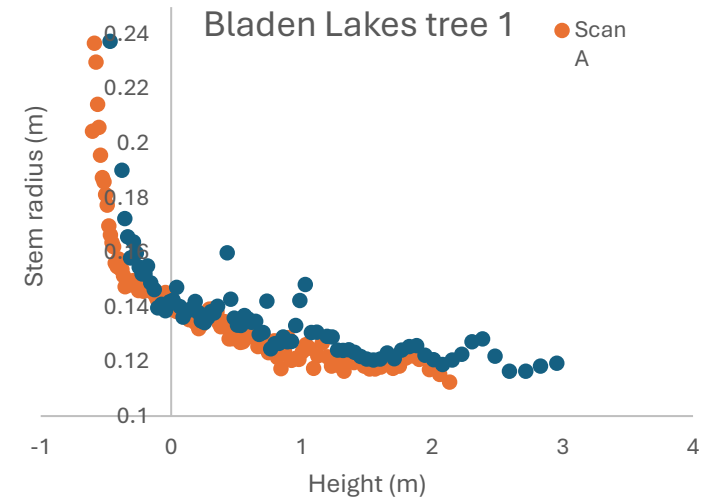
- Forest Productivity Co-op
 - NC State Univ.
 - Virginia Tech co-op

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- Clonal nutrition trials
 - Bladen Lakes, NC
 - Critz, VA

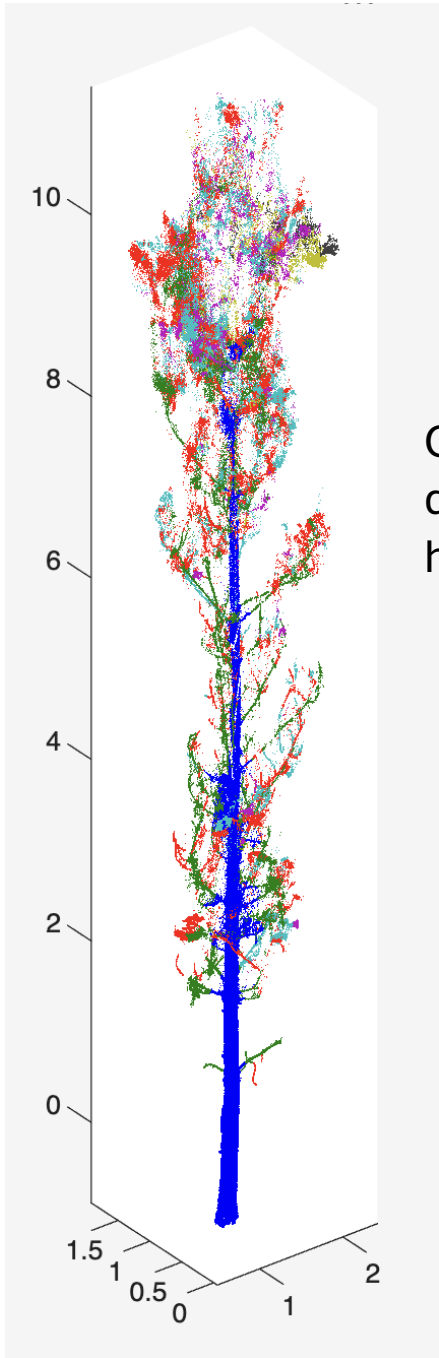
Terrestrial Laser Scanning



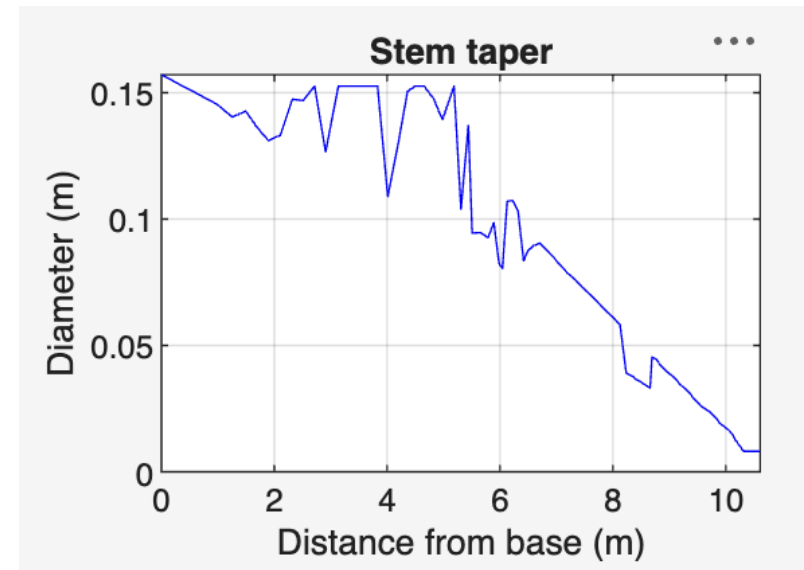
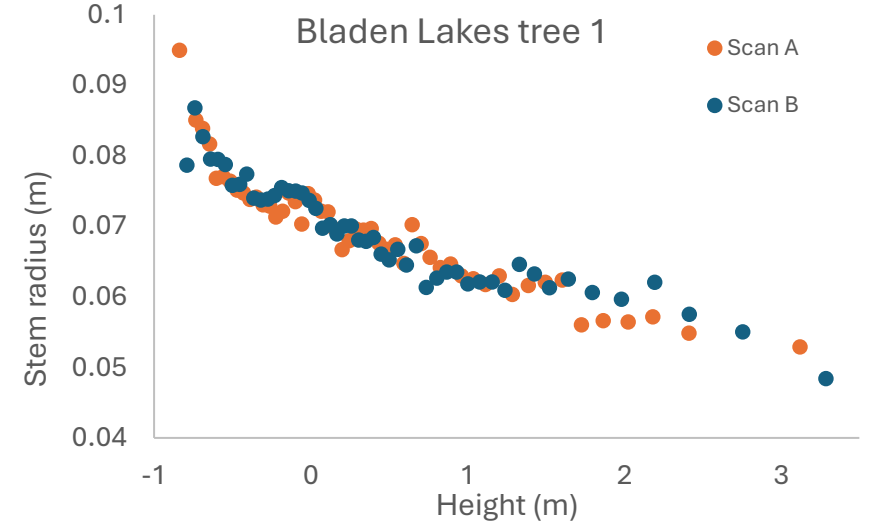
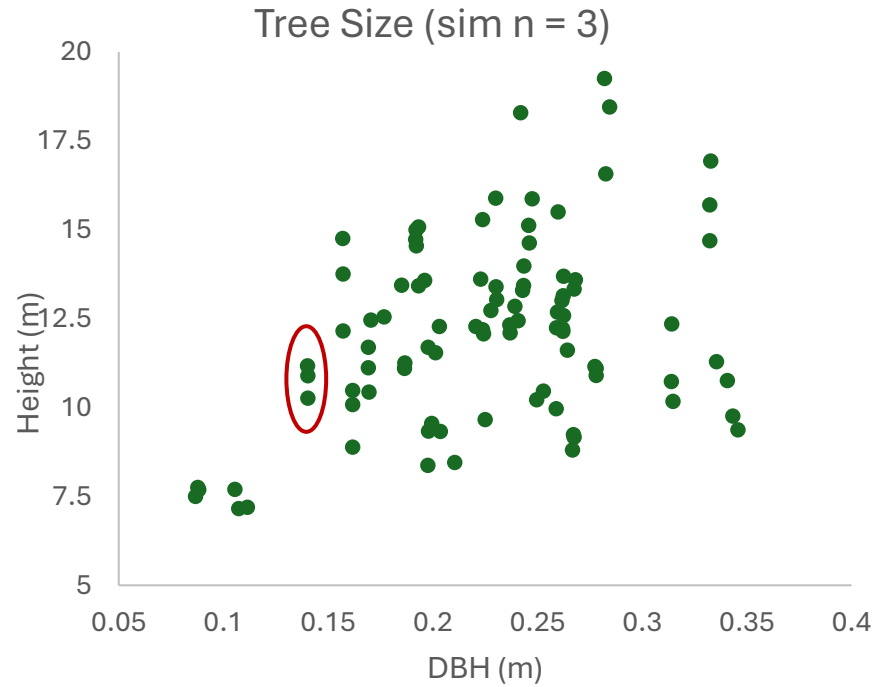
Bladen Lakes tree 1:
dbh = 25 cm
ht = 10.7 m
TLS scans = 2



Terrestrial Laser Scanning



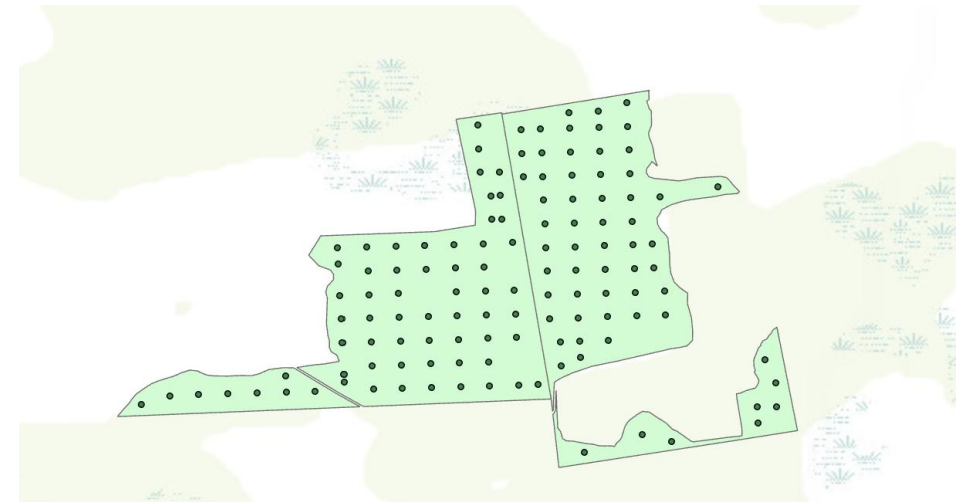
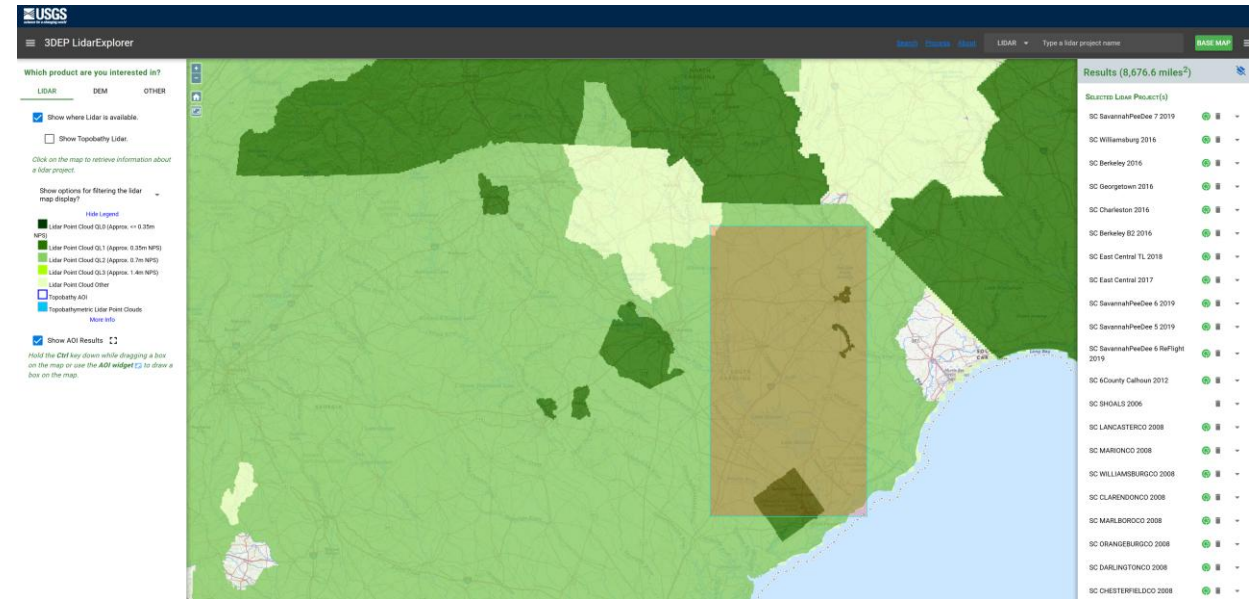
Critz tree 5:
dbh = 14 cm
ht = 10.7 m



Case study – Wateree, SC

Provided by Forest Investment Associates (FIA)
and American Forest Management (AFM)

1. Ground inventory data in **2023: 539**, 1/10th-acre circular plots. Plot location is recorded with a typical below canopy GPS accuracies of 3-5 meters.
2. Lidar data: **2019** Lidar acquisition in SC downloaded from 3DEP LidarExplorer (SC SavannahPeeDee 2019).



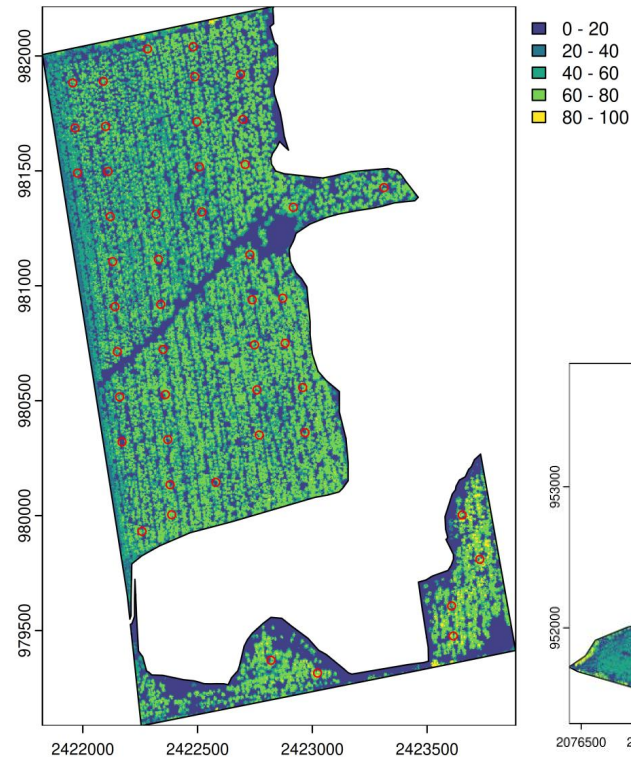
Direct estimates of forest attributes

1. Ground inventory data in 2023

- 1) 1132, 1/10th-acre circular plots (v1: 1314 plot)
- 2) 24 stands
- 3) Plot number: 22 ~ 92 per stand
- 4) Tree species: Loblolly pine (82%)
- 5) Direct estimates: e.g. Volume (cubic

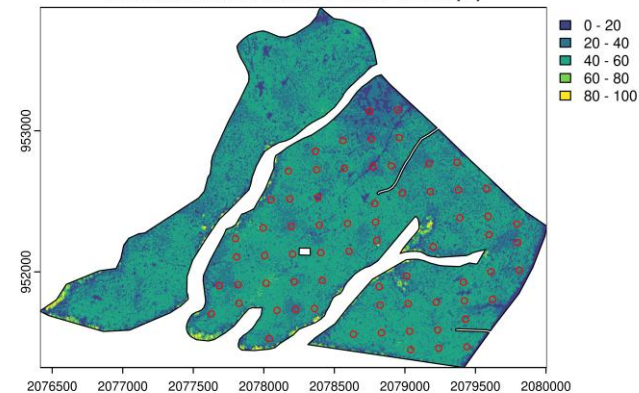
| Name | Mean | Min | Max |
|------------|----------|----------|----------|
| volume | 2,379.37 | 1,005.41 | 3,938.66 |
| n_plots | 47 | 22 | 92 |
| pct_stderr | 5.33 | 2.39 | 10.88 |

CHM in stand GRN110-0001-0002 (ft)



Maximum stand

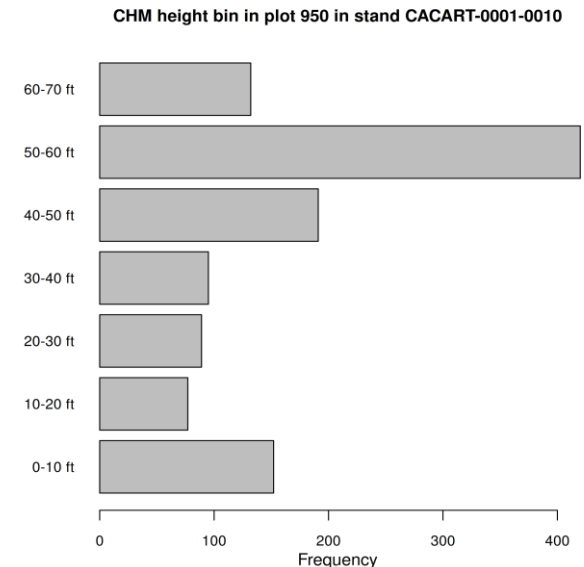
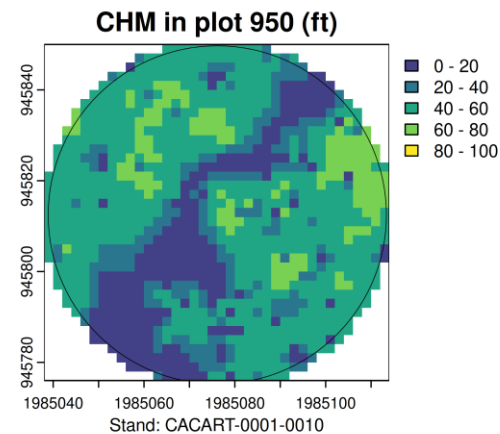
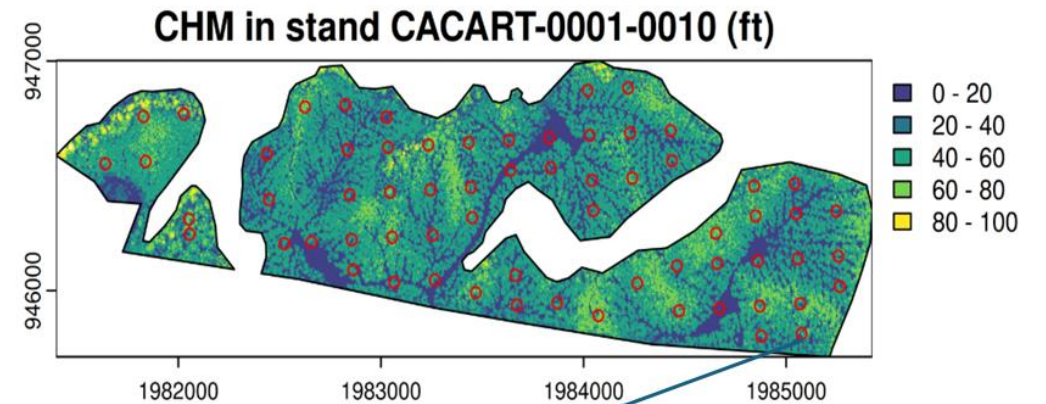
CHM in stand KIRKLD-0001-0001 (ft)



Minimum stand

Canopy height model (CHM) construction

1. Wall-to-wall CHM derived from Lidar point cloud with the resolution of 2 feet.
2. Number of pixels per plot
Total 24 stands
Pixels \approx 1089 per plot
3. CHM bins: proportion of ground area covered by 10-foot height class (0-10], (10-20],..., (80-90], (90-100], which will be used as X in the SAE models



SAE model building

- Property of unit-level SAE: Battese, Harter & Fuller model (BHF)

$$y_{dj} = x'_{dj}\beta + u_d + e_{dj}, \quad j = 1, \dots, N_d, \quad d = 1, \dots, D,$$
$$e_{dj} \sim N(0, \sigma_e^2), \quad u_d \sim N(0, \sigma_u^2)$$

The EBLUP:
$$\hat{Y}_d = f_d \bar{y}_d + (\bar{X}_d - f_d \bar{x}_d)' \hat{\beta} + (1 - f_d) \hat{u}_d$$

$$\hat{u}_d = \hat{\gamma}_d (\bar{y}_d - \bar{x}'_d \hat{\beta}) \quad \hat{\gamma}_d = \hat{\sigma}_u^2 / (\hat{\sigma}_u^2 + \hat{\sigma}_e^2 / n_d) \quad f_d = n_d / N_d$$

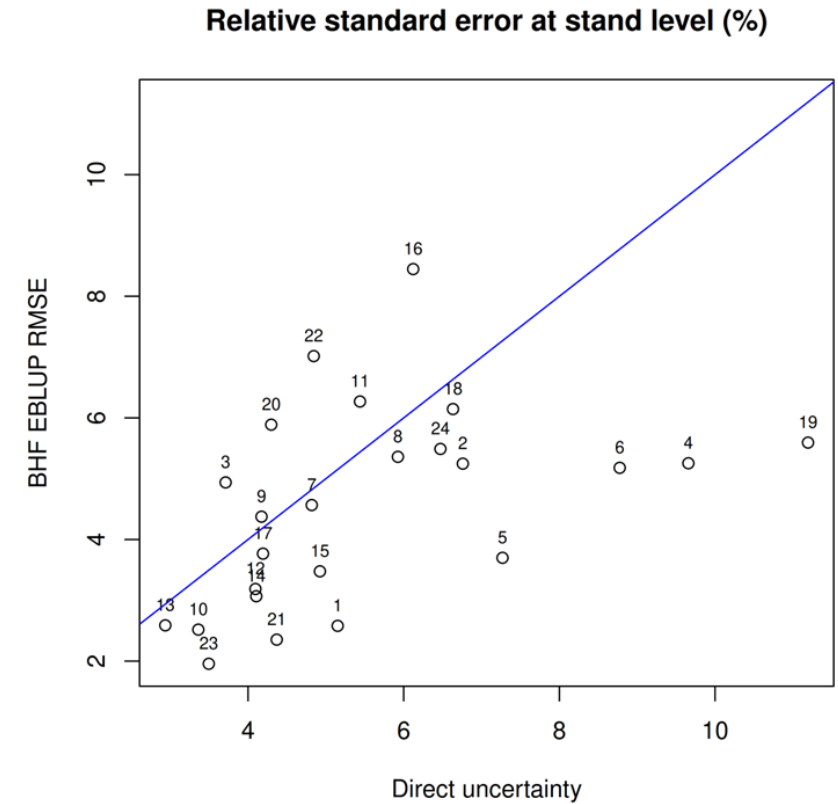
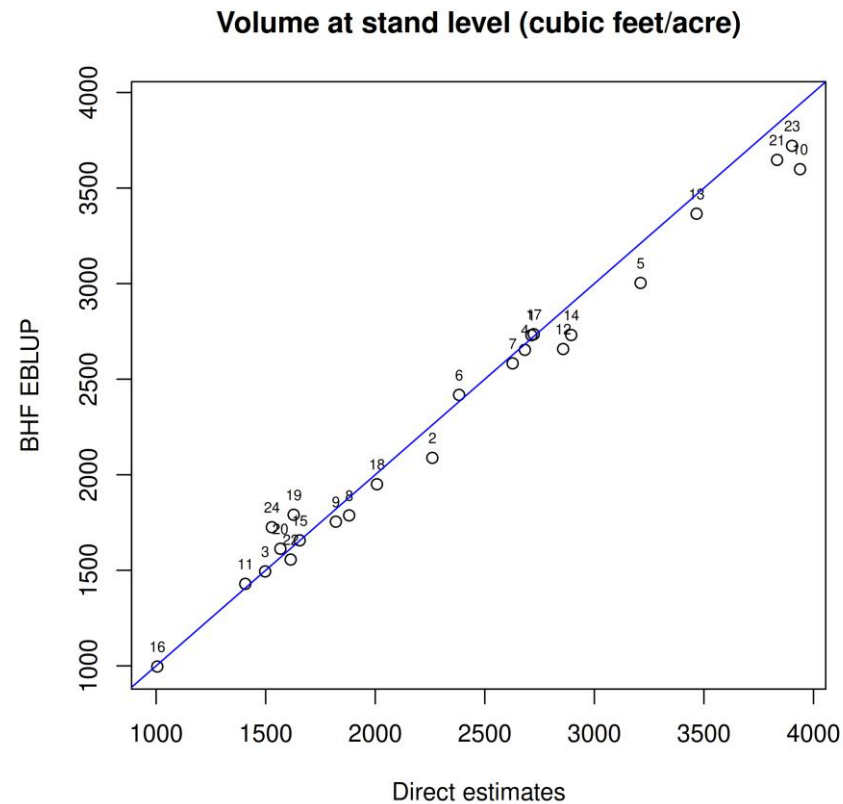
- 1) Direct observations of volume/acre (y_{dj})
- 2) Auxiliary data (x'_{dj}): CHM bins; Domain population (X'_d)
- 3) R “sae” package:
 - eblupBHF, select the best BHF models with
 - (a) minimum AIC
 - (b) predictors significant at 0.01 level
 - pbmseBHF, get corresponding BHF RMSE

Results

1. BHF models: EBLUPs and EBLUP RMSEs

- Significant fixed effect and estimates (24 stands as 1 population)
 - Random-effect (area) variance $\sigma_u^2 = 243,591$
 - Residual variance $\sigma_e^2 = 406,360$

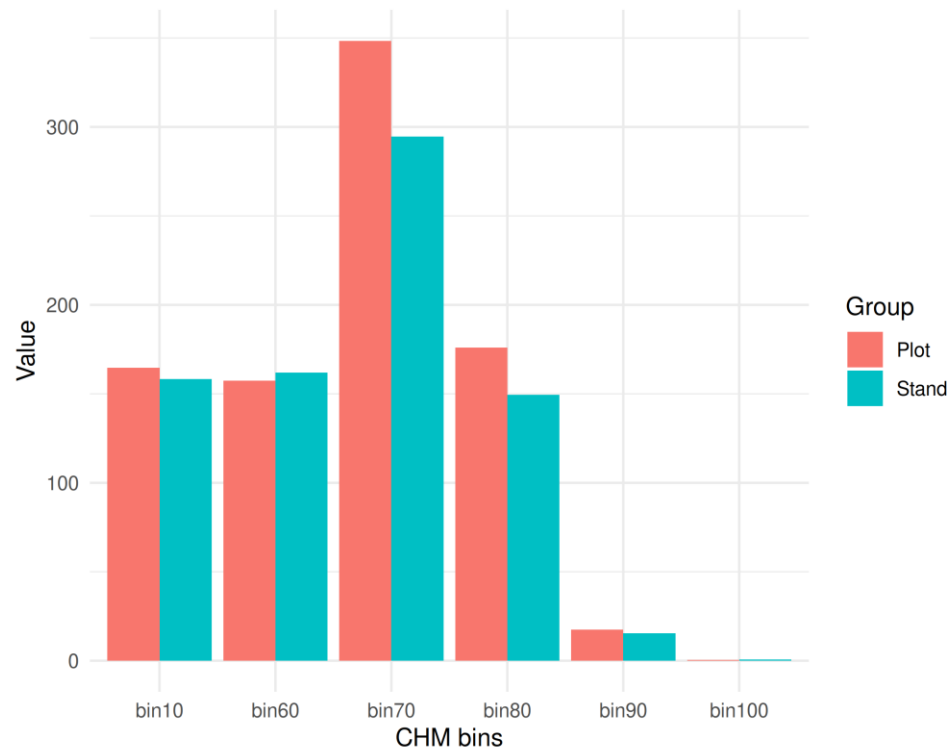
| Fixed effect | Estimate |
|--------------|----------|
| Intercept | 1731.80 |
| bin 10 | -1.19 |
| bin 60 | 1.74 |
| bin 70 | 1.88 |
| bin 80 | 3.72 |
| bin 90 | 6.73 |
| bin 100 | -37.95 |



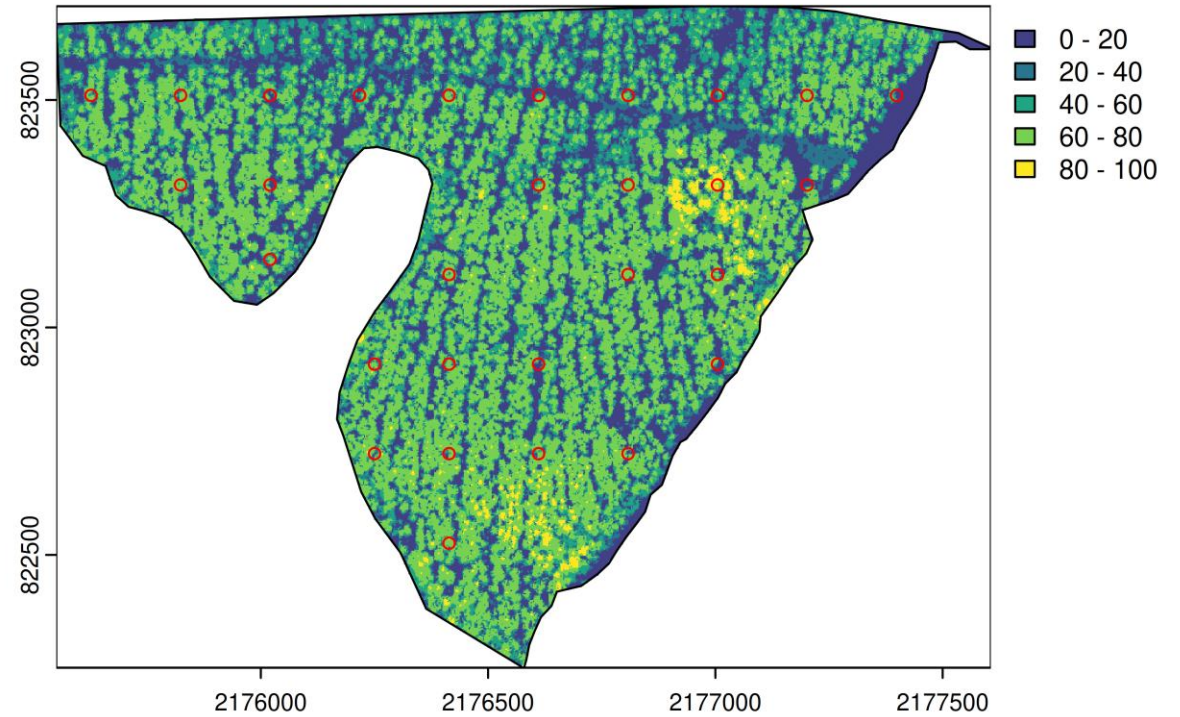
Results

- BHF EBLUPs < direct estimates
 - Stands #5: CEINES-0002-0025

Stand 5 Mean CHM bins at plot/stand level



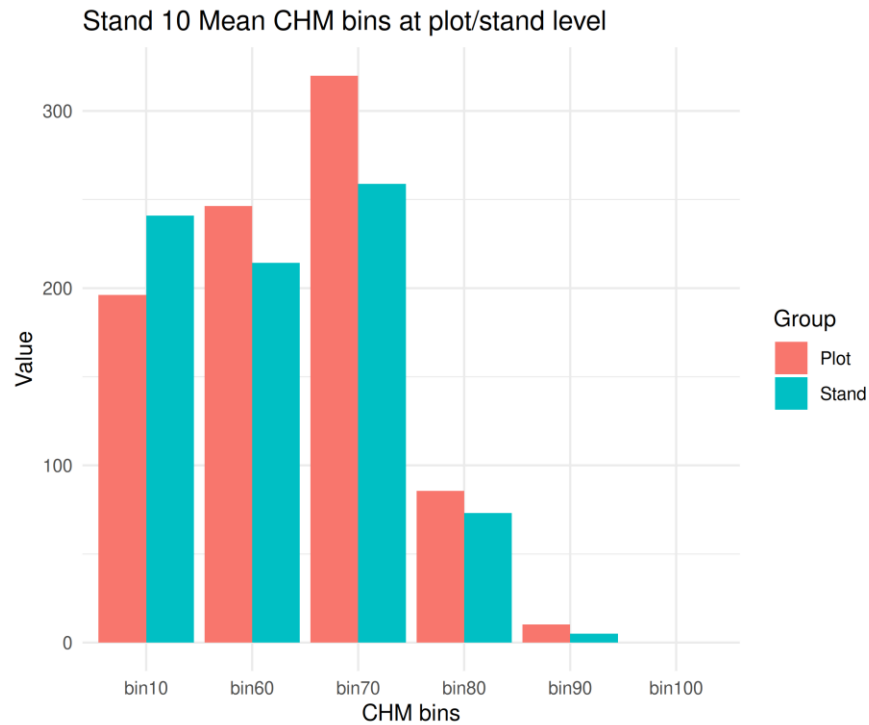
CHM in stand CEINES-0002-0025 (ft)



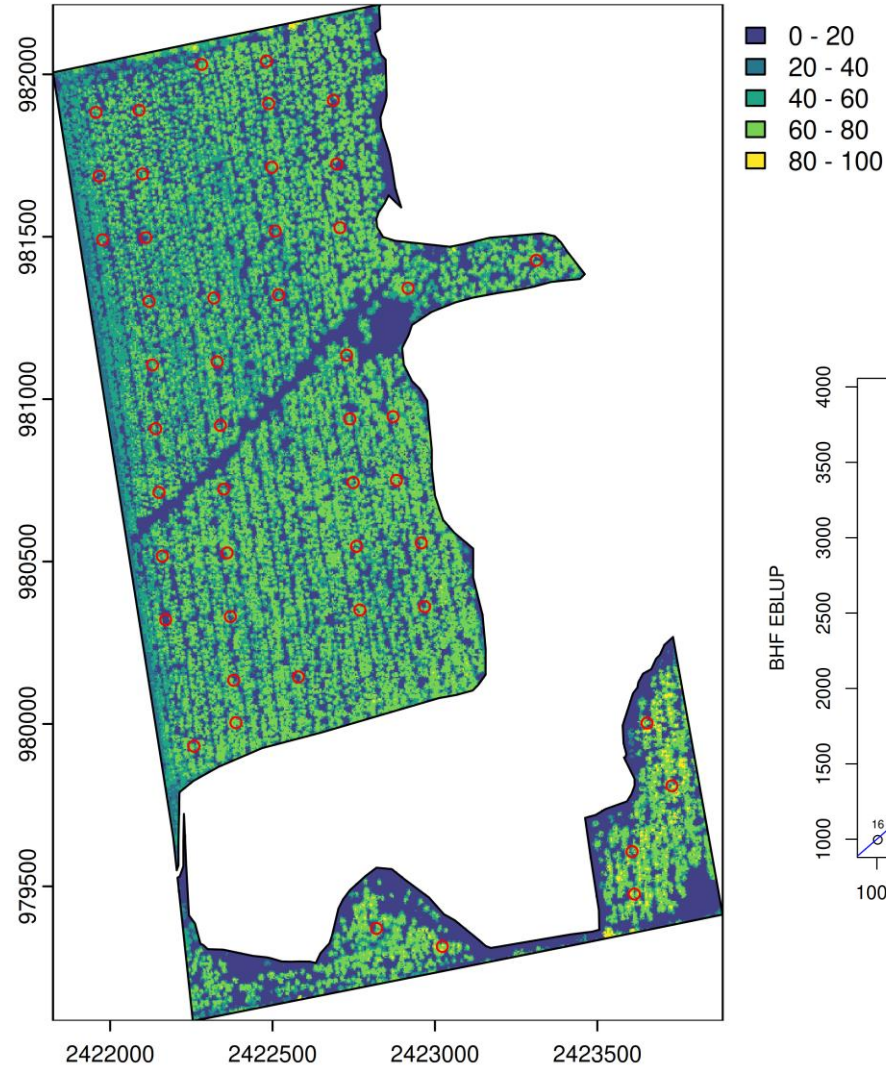
- Base map in Arc GIS pro, NAIP image updated February 2025

Results

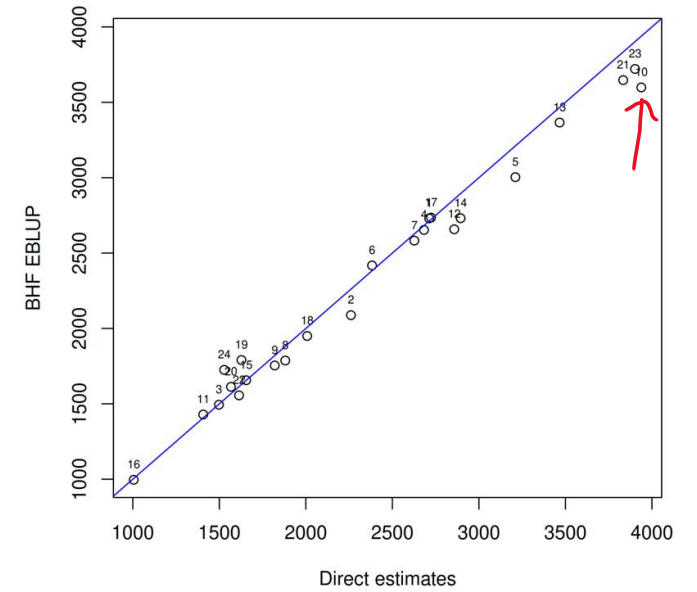
- BHF EBLUPs < direct estimate
 - Stands #10: GRN110-0001-00



CHM in stand GRN110-0001-0002 (ft)

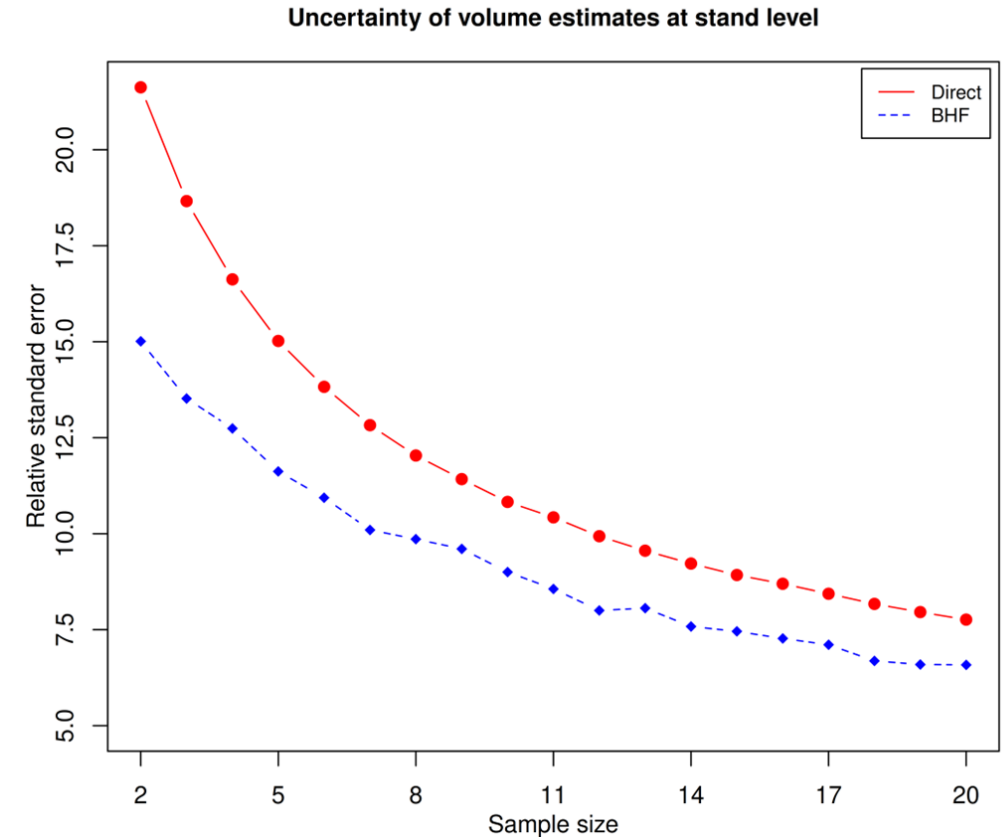


Volume at stand level (cubic feet/acre)



Discussion

- Sample size in every stand vs. BHF EBLUP MSE
 - Simulation
 - random sampling in every stand
 - Select sample size, plot $n=2,3,\dots,20$
 - For every n , repeat BHF models 200 time
 - Calculate mean of BHF EBLUP MSE
 - Results
 - 1) EBLUP MSE < direct stderr
 - 2) $n=2$, BHF improves the most precision gain
 - 3) As n increases, precision gain is small, but still help



Estimation of domain without sample

- Unit-level EBLUP estimator (Breidenbach et al, 2018)

1. EBLUP collapse to Synthetic estimator: $\hat{Y}_d = X'_d \hat{\beta}$
2. Uncertainty (MSE) of unit-level Synthetic estimator:

$$MSE(\hat{Y}_d) = g_{1d} + g_{2d} + g_{4d}$$

$$g_{1d} = \hat{\sigma}_u^2, \quad g_{2d} = X'_d \widehat{cov}(\hat{\beta}) X_d, \quad g_{4d} = \frac{\hat{\sigma}_e^2}{N_d}$$

where g_{1d} is the random effect variance estimate, g_{2d} is the uncertainty in the model parameter estimates, and g_{4d} is the error domain means

- Reference

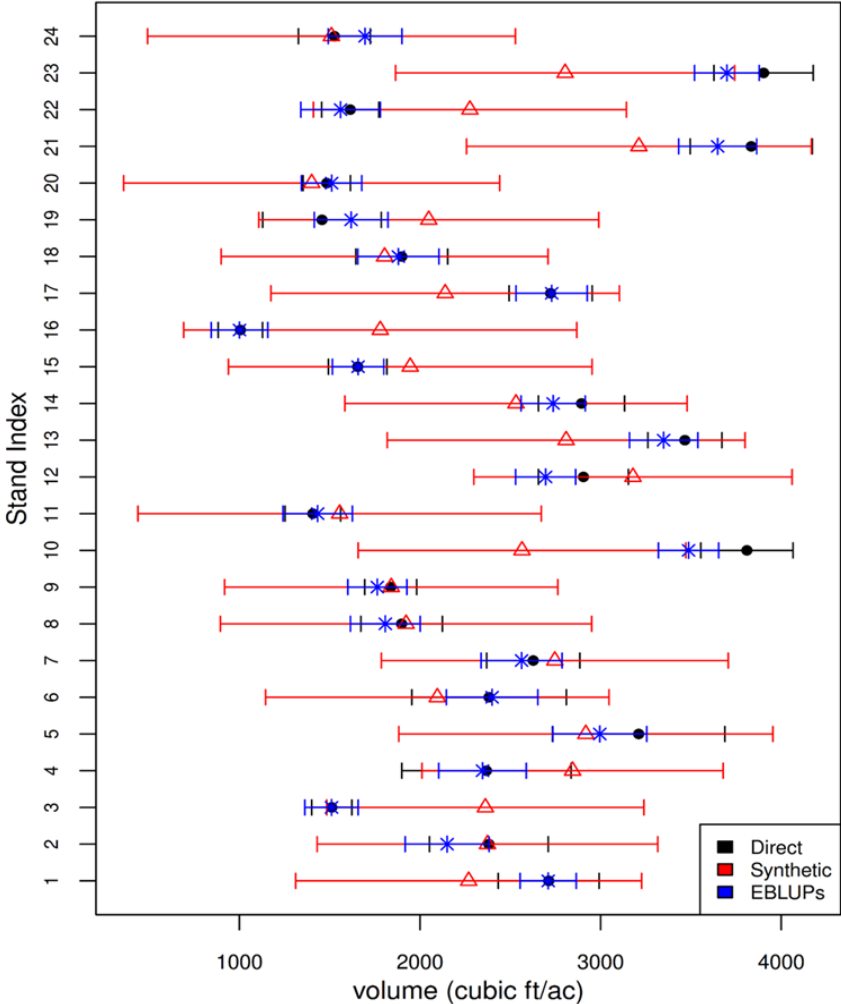
Breidenbach, J., Rahlf, J., Magnussen, S., Astrup, R. (2018) Unit-level and area-level small area estimation under heteroscedasticity using digital aerial photogrammetry data.

Remote Sensing of Environment, 212, 199-211. <https://doi.org/10.1016/j.rse.2018.04.028>

Estimation of domain without sample

- Predict volume of 1 stand without plot: BHF model from remaining 23 stands with

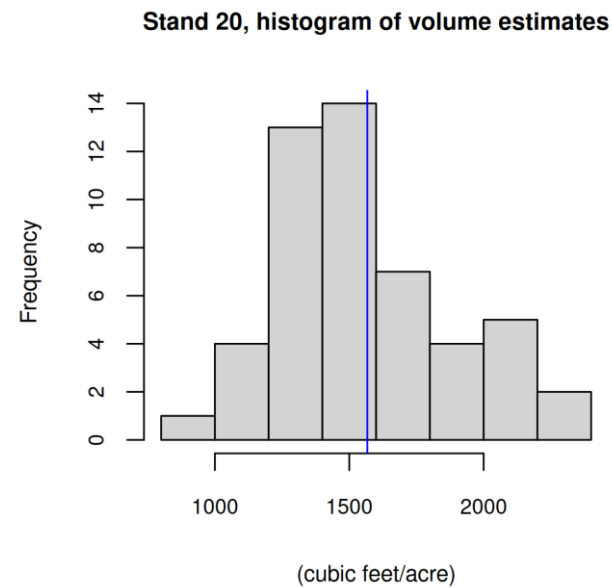
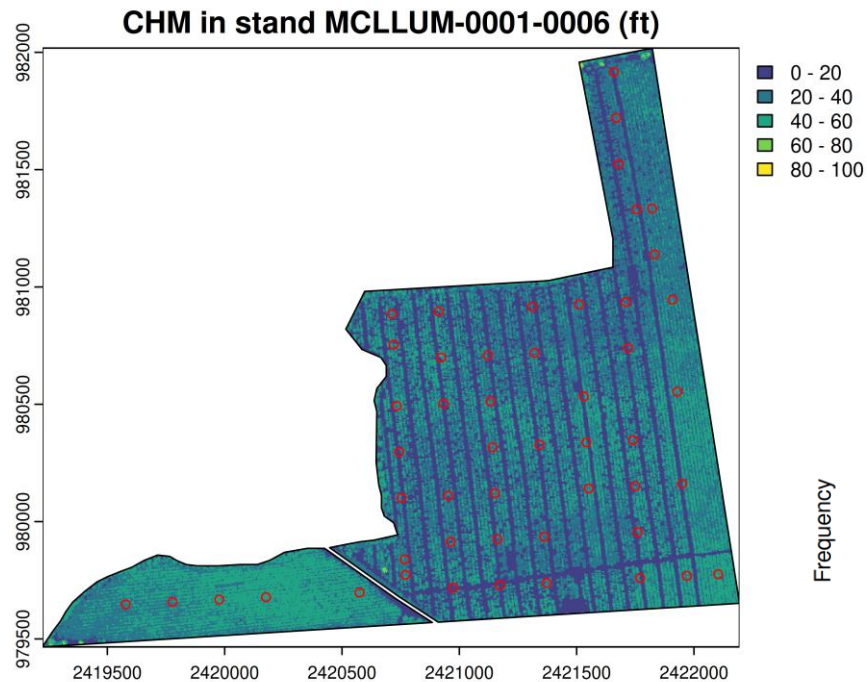
Volume estimates with confidence Intervals (24 stands)



| Stand Index | Sample size | Direct stderr % | Synthetic RMSE % | Ratio RMSE : SE |
|-------------|-------------|-----------------|------------------|-----------------|
| 24 | 44 | 6.48 | 34.04 | 5.26 |
| 23 | 44 | 3.50 | 12.27 | 3.51 |
| 22 | 40 | 4.84 | 27.39 | 5.65 |
| 21 | 42 | 4.37 | 12.70 | 2.91 |
| 20 | 63 | 4.41 | 35.78 | 8.11 |
| 19 | 46 | 11.19 | 32.94 | 2.94 |
| 18 | 41 | 6.63 | 24.30 | 3.66 |
| 17 | 47 | 4.19 | 18.07 | 4.31 |
| 16 | 68 | 6.12 | 55.21 | 9.02 |
| 15 | 92 | 4.92 | 31.02 | 6.30 |
| 14 | 53 | 4.11 | 16.70 | 4.07 |
| 13 | 45 | 2.94 | 14.58 | 4.96 |
| 12 | 50 | 4.26 | 15.47 | 3.63 |
| 11 | 47 | 5.44 | 40.49 | 7.45 |
| 10 | 61 | 3.35 | 12.14 | 3.63 |
| 9 | 65 | 3.92 | 25.60 | 6.53 |
| 8 | 53 | 5.93 | 27.63 | 4.66 |
| 7 | 31 | 4.82 | 18.65 | 3.87 |
| 6 | 29 | 8.78 | 20.36 | 2.32 |
| 5 | 29 | 7.27 | 16.45 | 2.26 |
| 4 | 28 | 9.66 | 17.96 | 1.86 |
| 3 | 74 | 3.68 | 29.63 | 8.05 |
| 2 | 30 | 6.76 | 20.20 | 2.99 |
| 1 | 65 | 5.15 | 18.01 | 3.50 |

Discussion

- BHF models: EBLUP RMSE > direct stderr
 - Time: plot measurement (2023) ≠ lidar point cloud collection (2019)



- Stand #20 MCLLUM-0001-0006
 - EBLUP RMSE%: 5.05
 - Direct stderr%: 2.83



Conclusion

1. Auxiliary data, CHM bins works well for BHF models
 1. Possible temporal misalignment
 2. High sampling intensity limits gains from BHF small area estimation
2. BHF EBLUPs can provide more precise volume estimates at stand-level

$$\hat{Y}_d = f_d \bar{y}_d + (\bar{X}_d - f_d \bar{x}_d)' \hat{\beta} + (1 - f_d) \hat{u}_d$$

- 1) Mixed model, area/stand effect (\hat{u}_d)
- 2) Both sample (\bar{x}_d) and population levels (\bar{X}_d)
- 3) Adjust sample estimates to whole stand