Multibeam Lidar Measurements for DESDynI

Michael Lefsky & **Ralph Dubayah**
Colorado State University **University of Maryland**

J. Bryan Blair, Robert Knox, Ross Nelson, Gouqing Sun
NASA/GSFC

The Importance of Vegetation Science

- **Decadal Survey Science Priorities**
  - **Carbon, nitrogen & water cycles**
  - **Changes in land use**
  - **Changes in disturbance**
- **Satellite data products**
  - **Disturbance patterns**
  - **Primary productivity**
  - **Vegetation cover**
  - **Standing biomass**
  - **Vegetation height and canopy structure**
  - **Habitat structure**
- **Research exploring efficacy of lidar**
  - **Biodiversity and habitat structure**
  - **Carbon stocks and fluxes**
  - **Disturbance**
  - **Highly relevant to DESDynI mission goals**
  - **Airborne work provides only real opportunity to assess DESDynI-like spatial resolutions**

Power of Lidar Remote Sensing

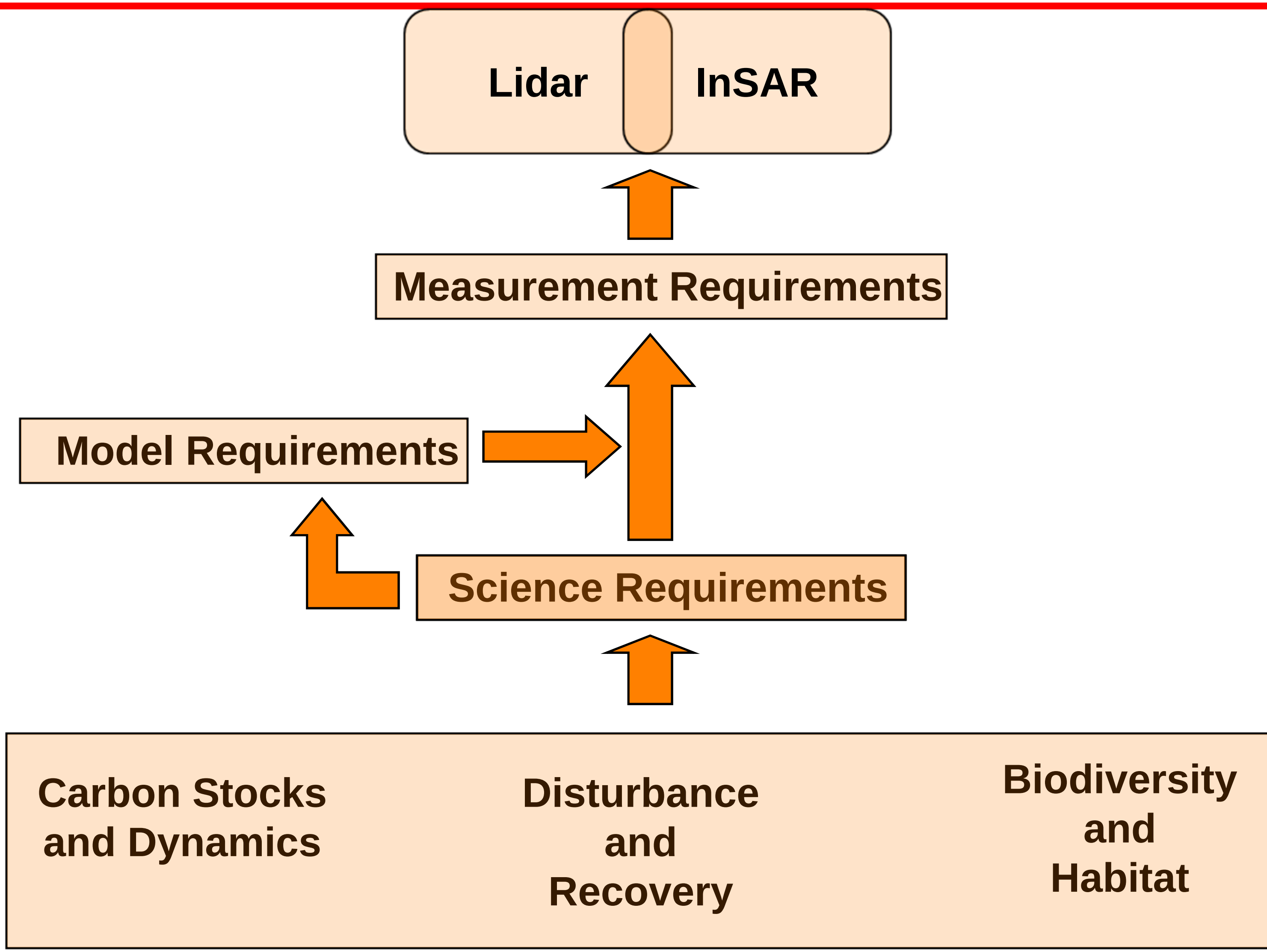
- **Lidar has unique ability to measure vertical and spatial heterogeneity across multiple scales**
  - **Good understanding of what lidar measures and why it works**
- **Derives key structure important for vegetation science**
  - **Tree height**
  - **Crown volume**
  - **Vertical foliage profile**
  - **Canopy cover profile**
  - **Biomass**
  - **Tree density**
  - **Growth dynamics and successional state**
- **Substantial gaps in knowledge**
  - **Limited work on fusion with other sensors**
  - **No forest-centric space missions**
    - **ICESAT not withstanding**
  - **Measurement accuracies achievable from space in sampling-type mission**
    - **Beam spacing, look angle, gridding**
  - **Few researchers working on large-footprint lidar**

Outline

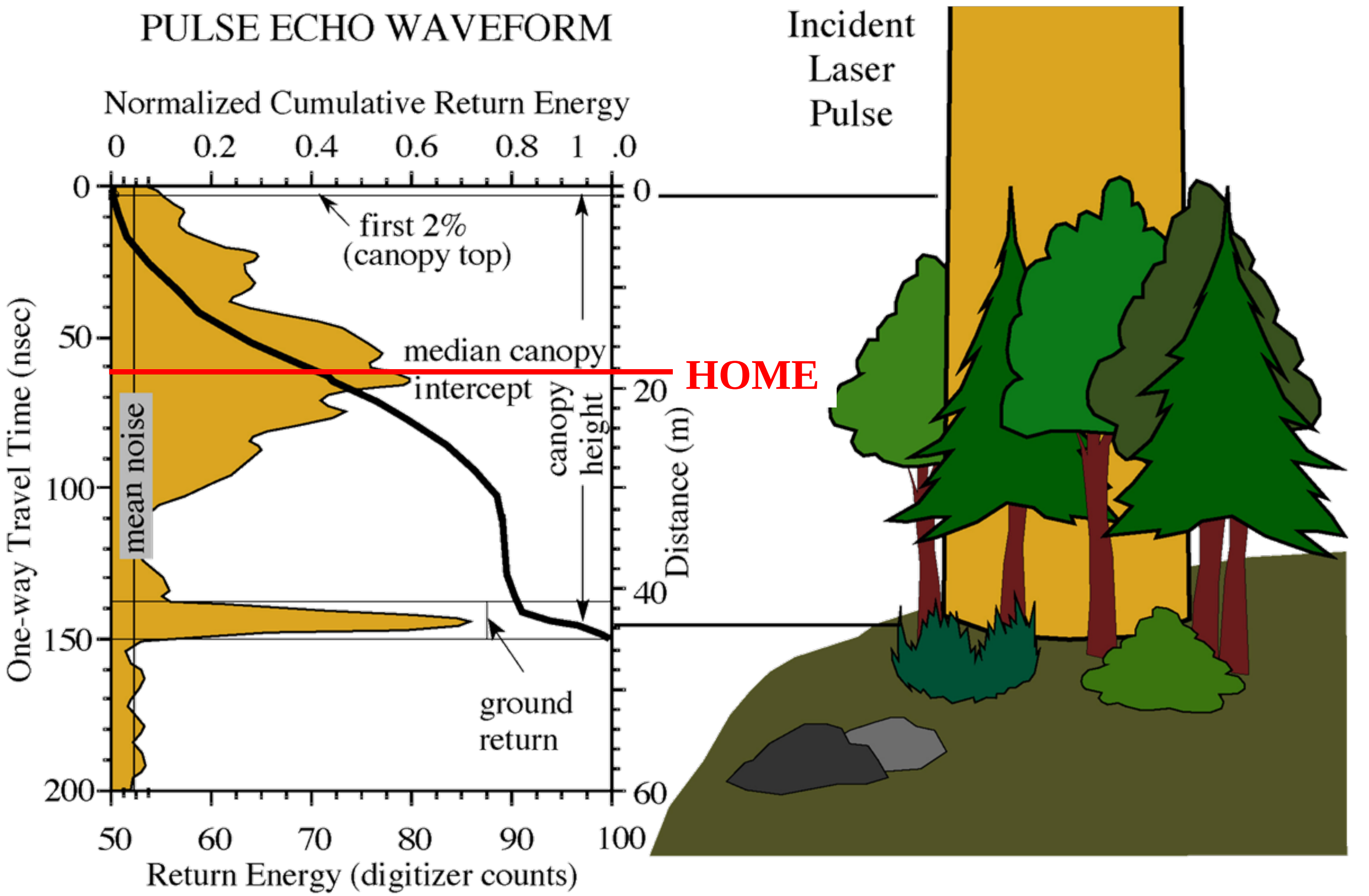
Overview of lidar remote sensing to help inform discussions of measurement requirements for DESDynI

- **Basics of Lidar Remote Sensing**
- **Waveform Metrics and Accuracies**
- **Biomass Estimation and Accuracies**
- **Sampling Issues**
- **Modeling Requirements**
- **Limitations of Lidar**
- **Summary**

From Science to Measurement Requirements



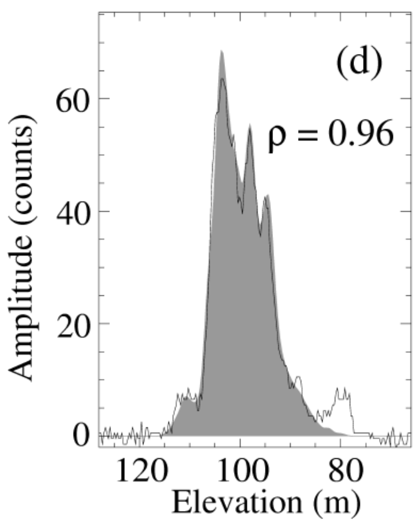
What Does Lidar Measure?

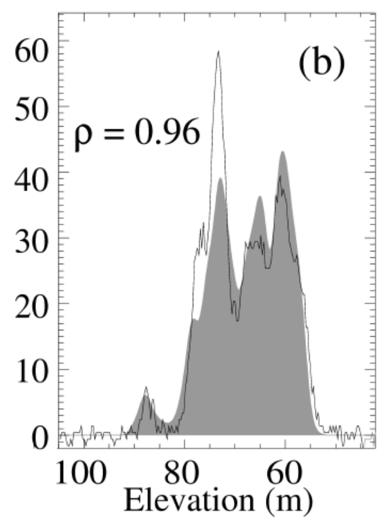


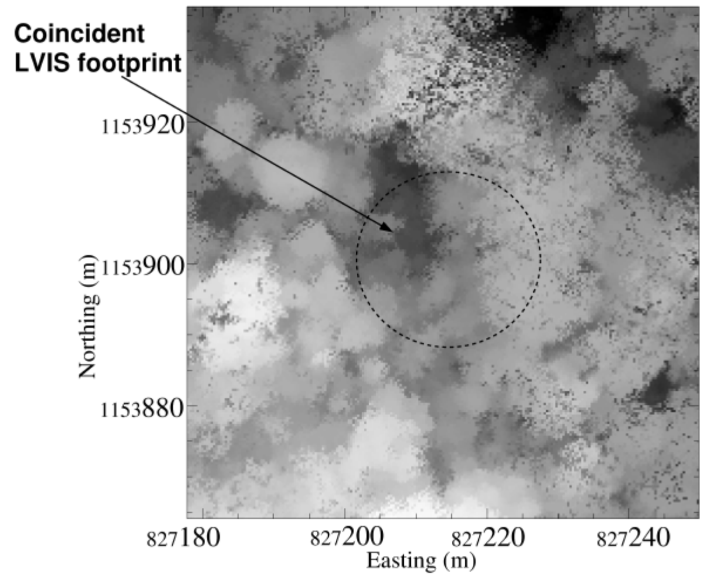
HOME: Height of median energy

What Does Lidar Measure?

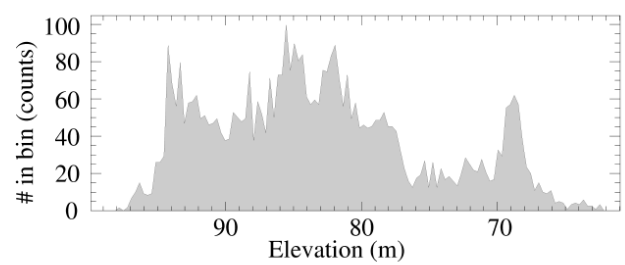
- **Data collected by waveform recording and discrete return lidar shown to be equivalent**







Histogram of FLIMAP-Measured Elevations within the Coincident LVIS Footprint



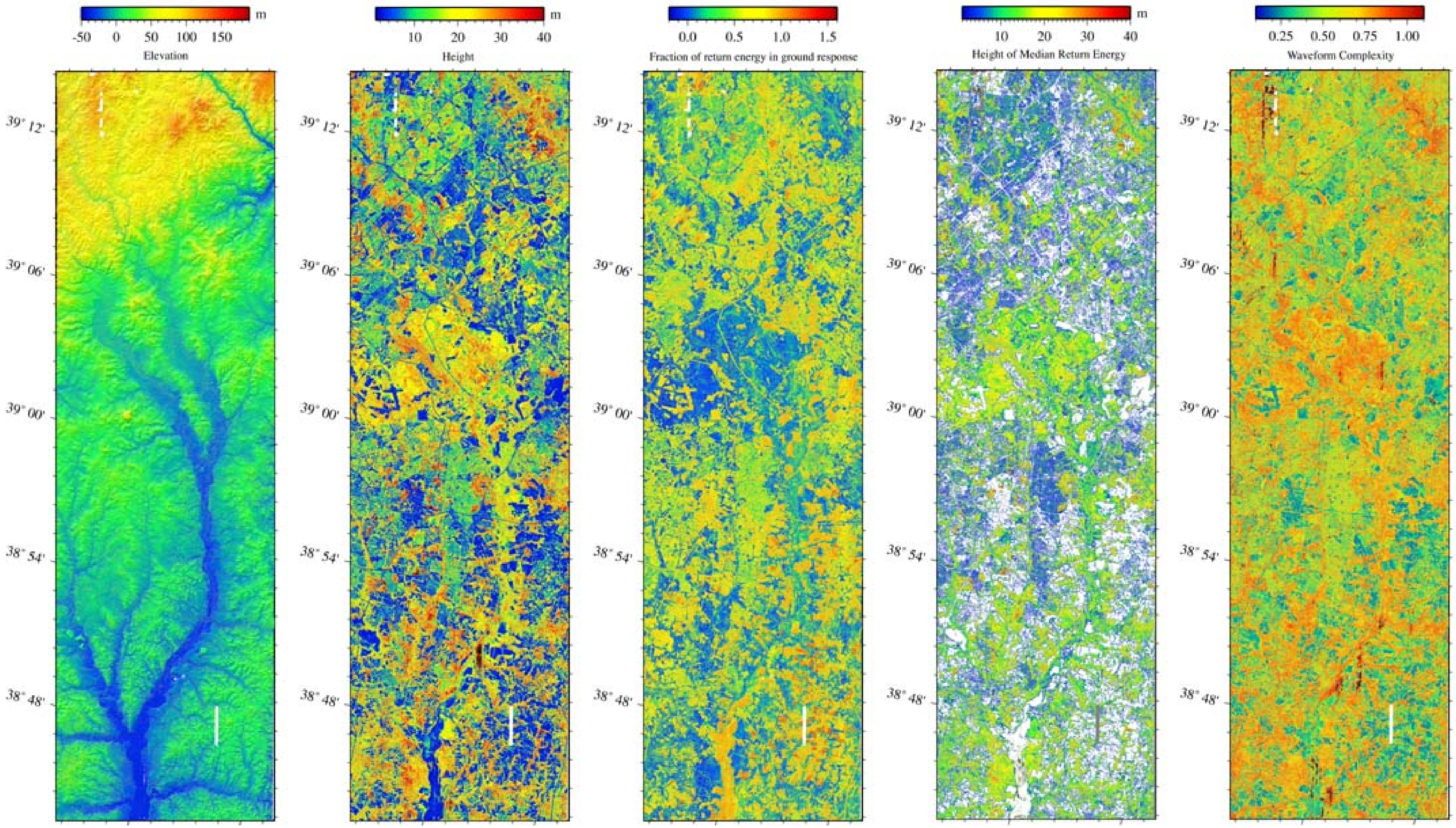
From: Blair and Hofton, Modeling laser altimeter return waveforms over complex vegetation using high-resolution elevation data, *Geophysical Research Letters*, 26, 2,509-2,512, 1999.

UNIVERSITY OF MARYLAND 1856

Energy & Entropy Metrics

- **Energy metrics should be considered "new" surface state variables**
  - **No fundamental difference between canopy cover and energy metrics as a flavor of surface variable**
  - **Energy as a function of height (RH25, RH50 (HOME), RH75, RH100)**
  - **Direct measurement**
  - **RH50 often better predictor of biomass than RH100**
  - **Accuracies function of digitization resolution (e.g. 30 cm)**
- **Entropy metrics**
  - **Similar to foliar height diversity**
  - **Seen limited application**

Direct Retrievals from Return Waveforms



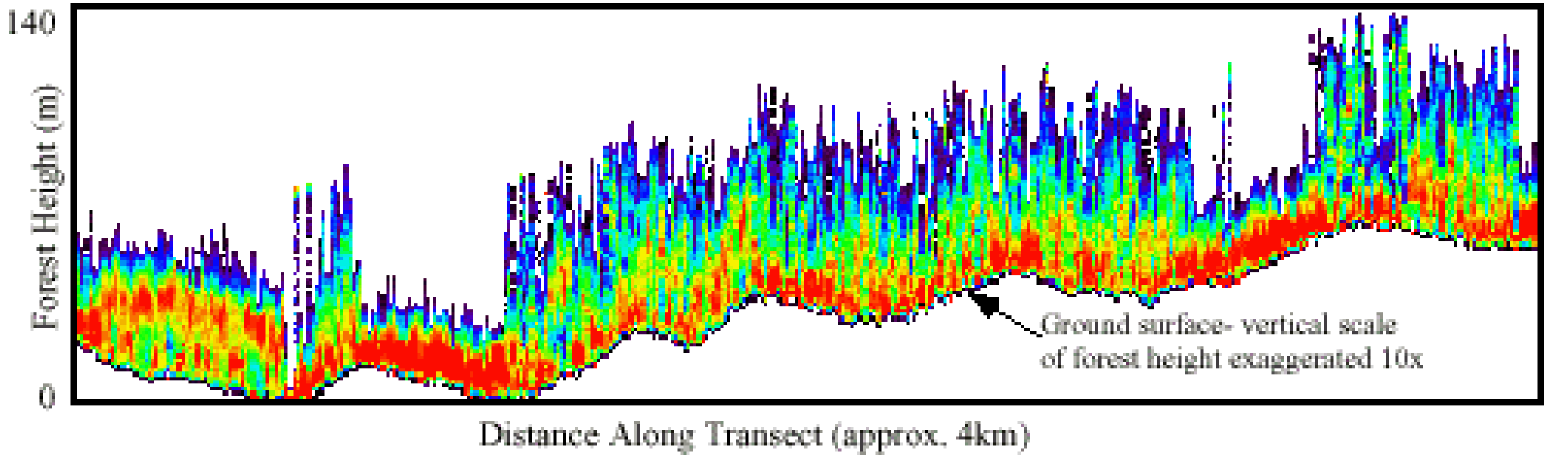
Elevatio n | **Height** | **Ground Energy** | **HOME** | **Complexit y**

km
0 5 10

Canopy Profiles

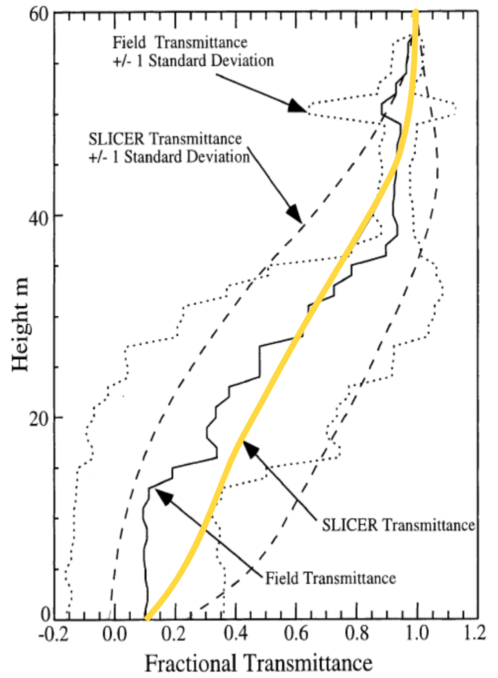
- **Canopy Height Profile**
  - **Vertical distribution of foliage and non-photosynthetic vegetation**
    - **Direct measurement of vertical distribution of intercepeted surfaces, must be corrected for attenuation lower in the canopy (e.g. MacArthur-Horn log transforms)**
  - **Good agreement with field studies**
- **Light Transmittance Profile**
  - **Similar to canopy height profile above**
  - **Assumptions about scattering**
- **Foliar Profile**
  - **Vertical distribution of leaf material**
  - **Assumptions about leaf amount, clumping, reflectance make this a modeled retrieval**

Canopy Profiles



- **Canopy Height Profile**
  - **Vertical distribution of foliage and non-photosynthetic vegetation**
    - **Direct measurement of vertical distribution of intercepeted surfaces, must be corrected for attenuation lower in the canopy (e.g. MacArthur-Horn log transforms)**
  - **Good agreement with field studies**

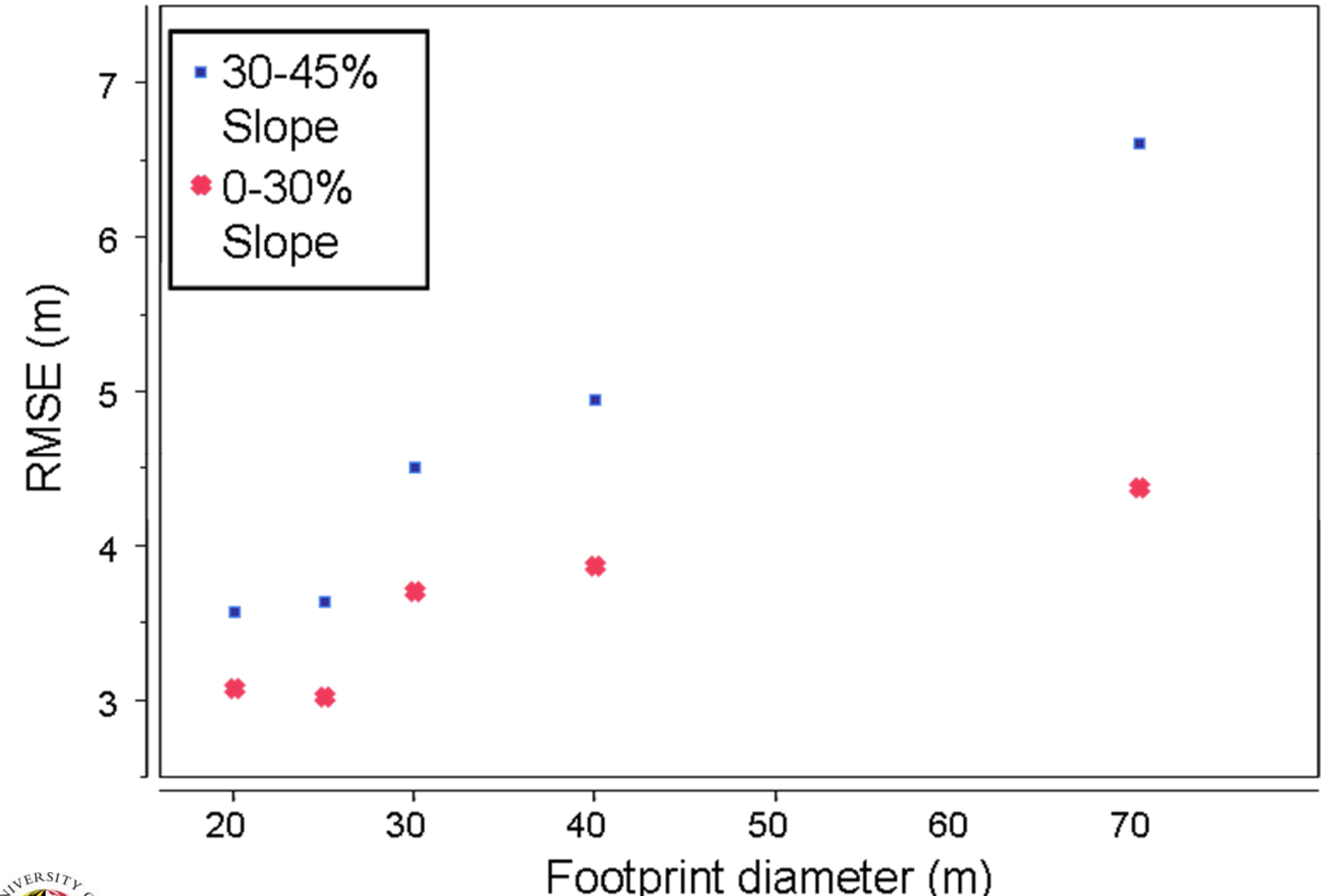
- **Light Transmittance Profile**
  - **Similar to canopy height profile**
  - **Assumptions about scattering**



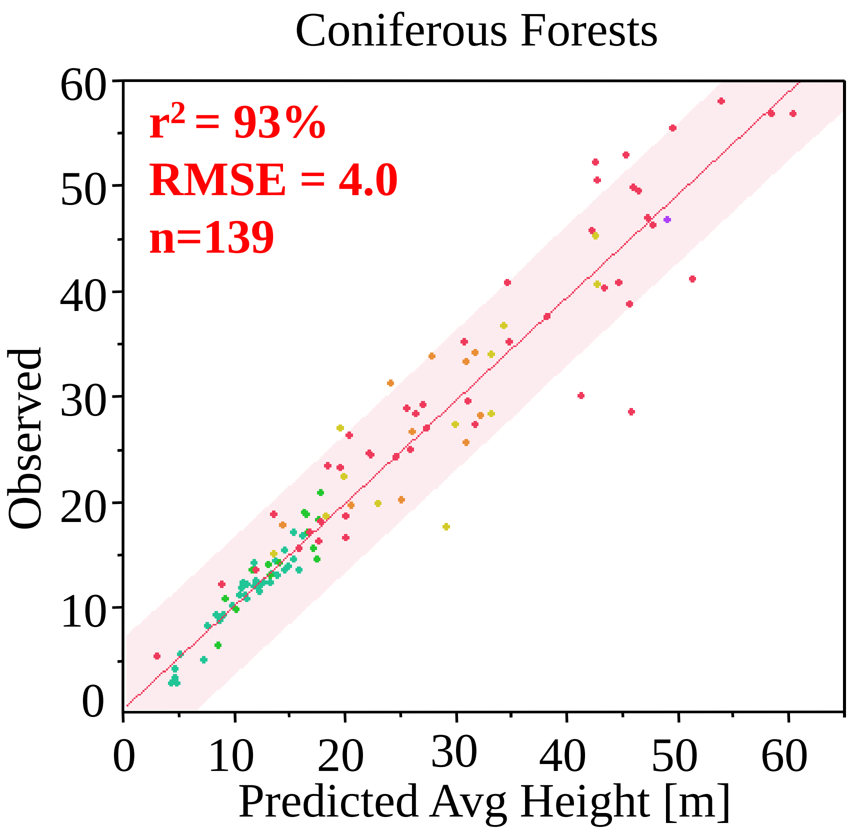
What height accuracies have been observed?

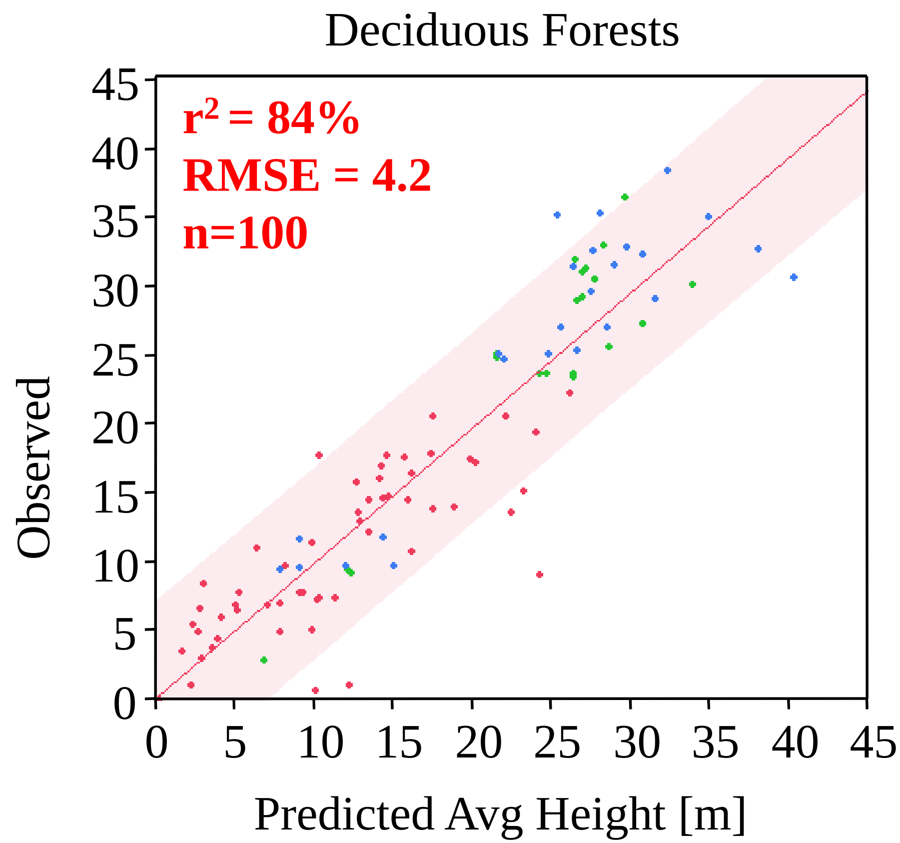
- **Canopy height is a direct measurement**
- **Current studies show RMSE ~ 2 - 5 meters**
  - **Footprint scale**
  - **Footprint radii of 10-15 m, canopy heights from 5 - 100 m**
  - **RMSE magnitude mostly due to difficulties with field observation**
- **Sources of error**
  - **Canopy shape (flat vs. pointy canopies)**
  - **Phenology (leaf-off)**
  - **Slope (confounds ground and canopy top returns)**
  - **Canopy cover (insufficient penetration to ground)**
  - **Footprint size**
    - **Too large (>25 m) causes slope problems, sensitivity issues**
  - **Placement of tallest stem (closer to middle is better)**
  - **Look angle**

Effects of Slope & Footprint Size



What height accuracies have been observed?





- **Reduction to 1 m error require ~ 16 samples**

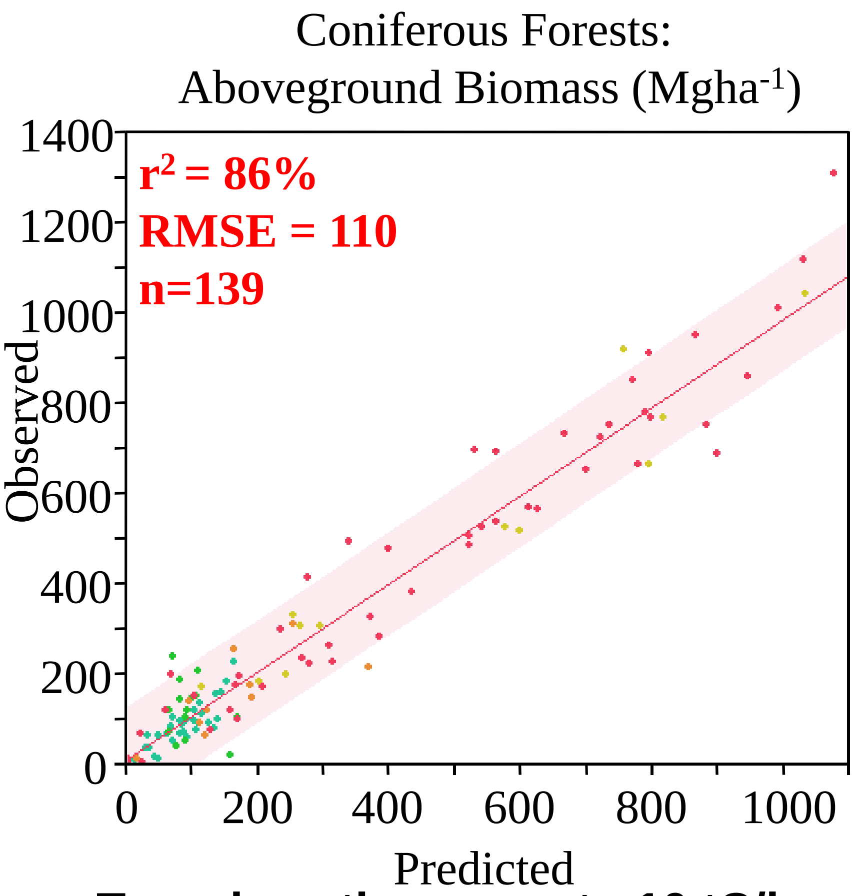
Douglas-Fir, Lefsky et al. 2002
Jack Pine, Sherrill et al. In review
Ponderosa Pine, Lefsky et al. 2002
Lodgepole Pine, Sherrill et al. In review
True Fir, Lefsky et al. 2002

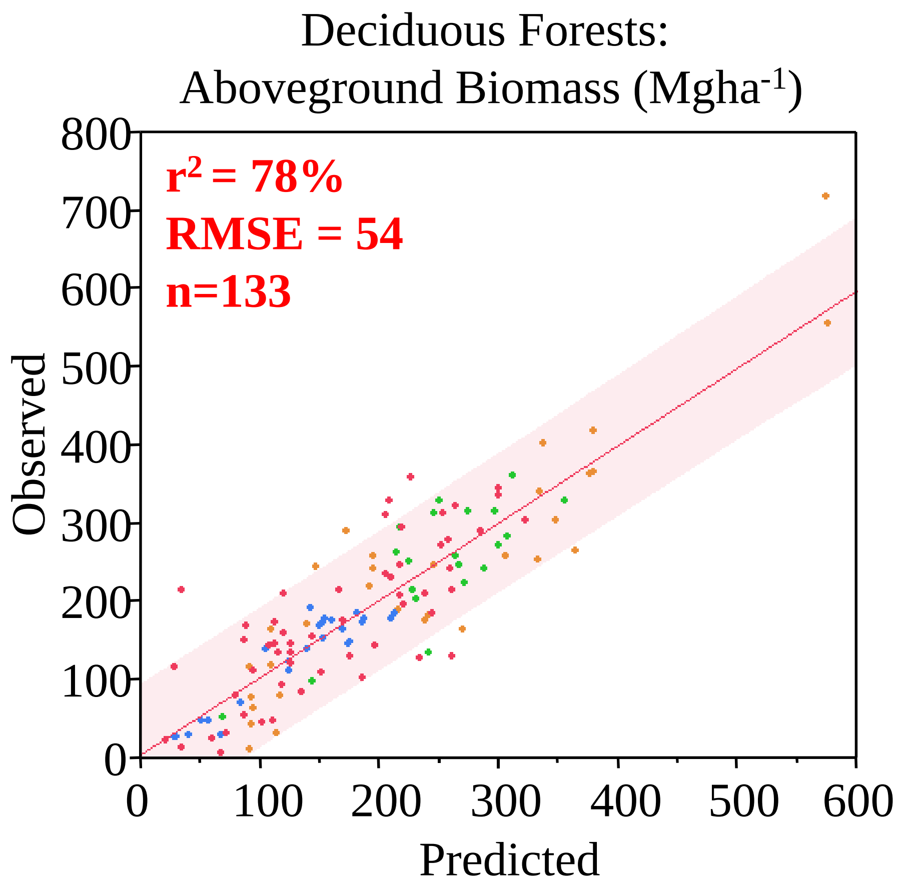
Brazil (GLAS), Lefsky et al. 2007
New Hampshire, Andersen et al. 2006
Costa Rico, Drake et al. 2002
Maryland, Lefsky et al. 1999

Estimating Biomass

- **Modeled Retrieval (Biomass)**
  - **Statistical regression between height, height^2,energy metrics and ground data**
  - **Generally efficacious**
- **Ecosystem Model Initialization (Biomass and Flux)**
  - **Initialized with lidar height distributions**
  - **Model calculates biomass and carbon flux**
- **Limitations**
  - **Statistical approaches**
    - **Requires ground data over range of biomass**
    - **Assumes allometric equations are accurate**
    - **Issues of non-stationarity**
  - **Ecosystem modeling approaches**
    - **Requires information/ assumptions on successional state**
    - **Other data rarely at resolution of lidar**

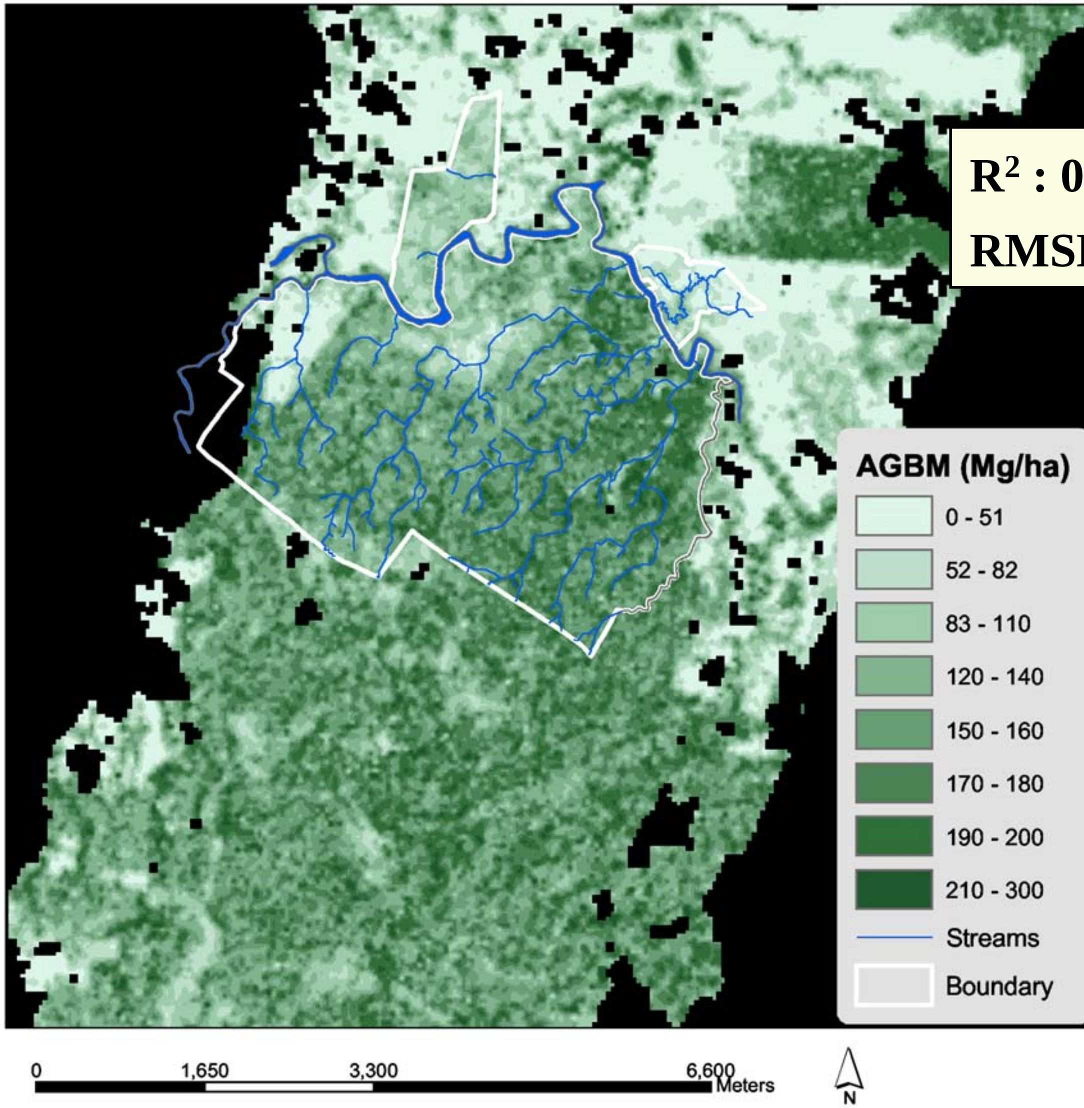
What biomass accuracies have been observed?





- **To reduce the errors to 10 tC/ha requires ~ 7 - 25 samples**

La Selva Biomass



R^2 : 0.87

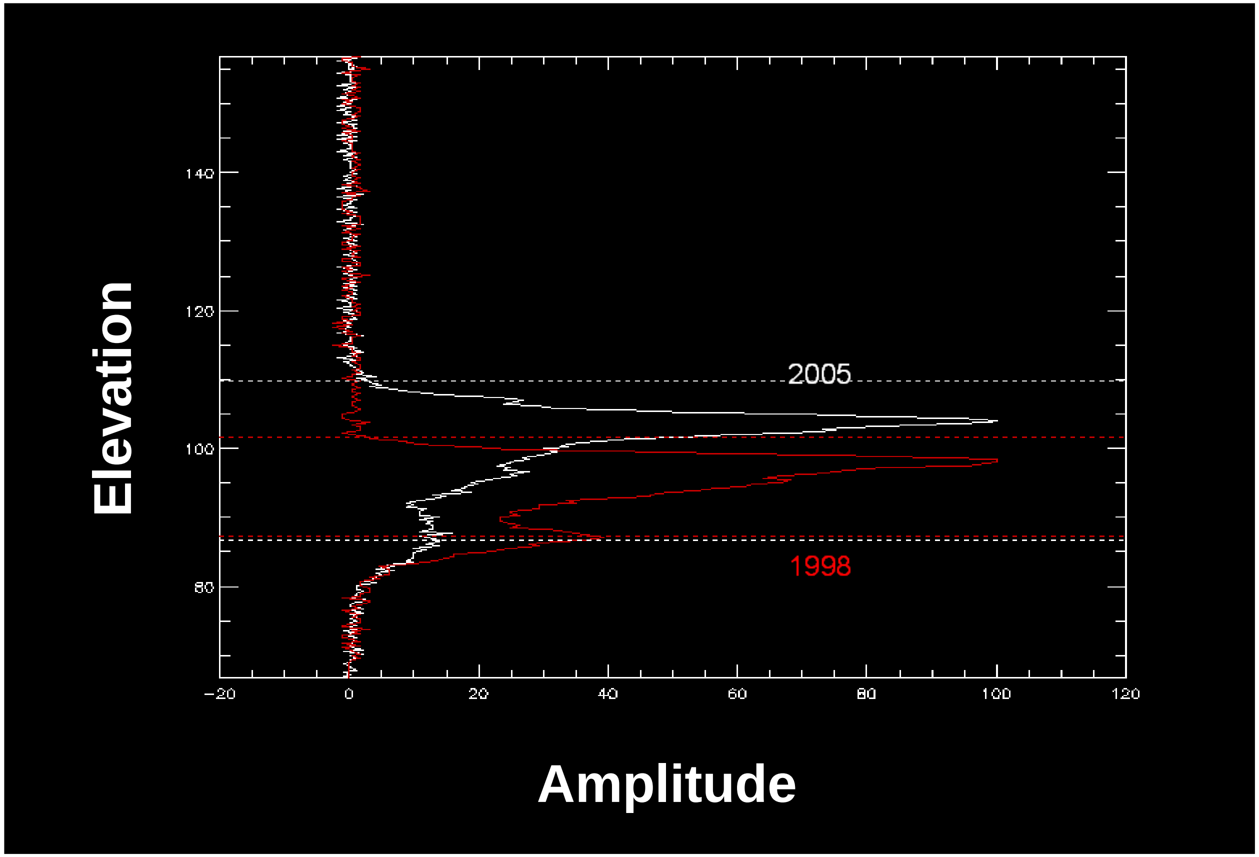
RMSE: 22.6 Mg/ha

Observing Growth Dynamics

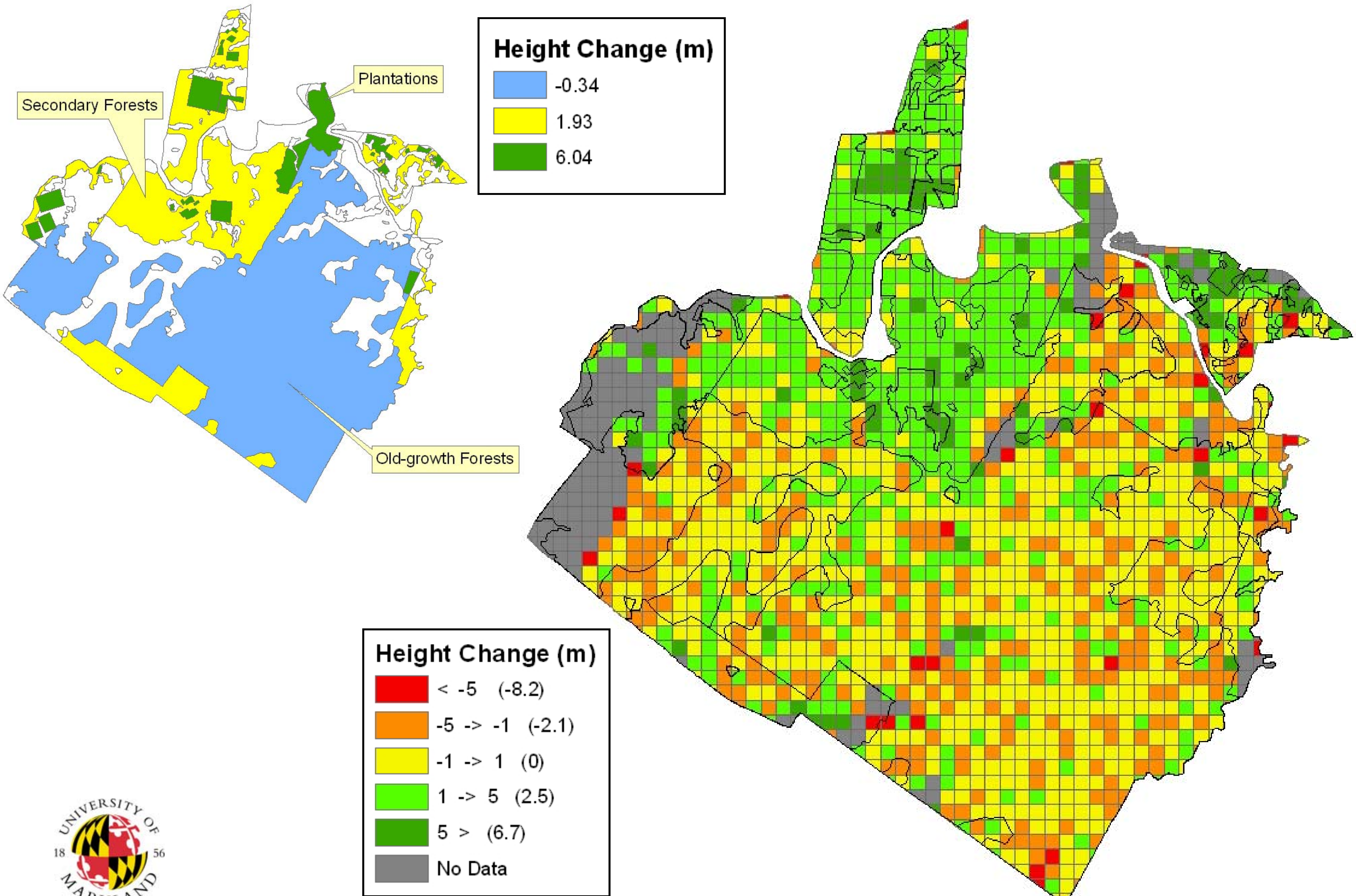
- Direct measurement
  - Requires two successive observations
  - Time must be great enough to observe growth relative to RMSE errors (measurement + potential sampling error)
- 3-5 years minimum period based on LVIS studies
  - Unlikely to measure growth change < 2 m from space
    - Slope effects, geolocation, canopy phenology
  - Potentially easier to get growth change at stand level (vs. footprint)
- Disturbance & Mortality
  - Direct, simple, no time period requirement
  - Easy at orbital crossovers
  - Inferred over larger areas

Growth Dynamics From Lidar

- **Sampling lidar can be used to observe dynamics**
  - **Not efficient for forest loss mapping (compared to radar or TM)**
  - **Can directly measure growth/loss in canopy at footprint or grid scale**
    - **Orbital cross-overs could provide millions of direct observations**

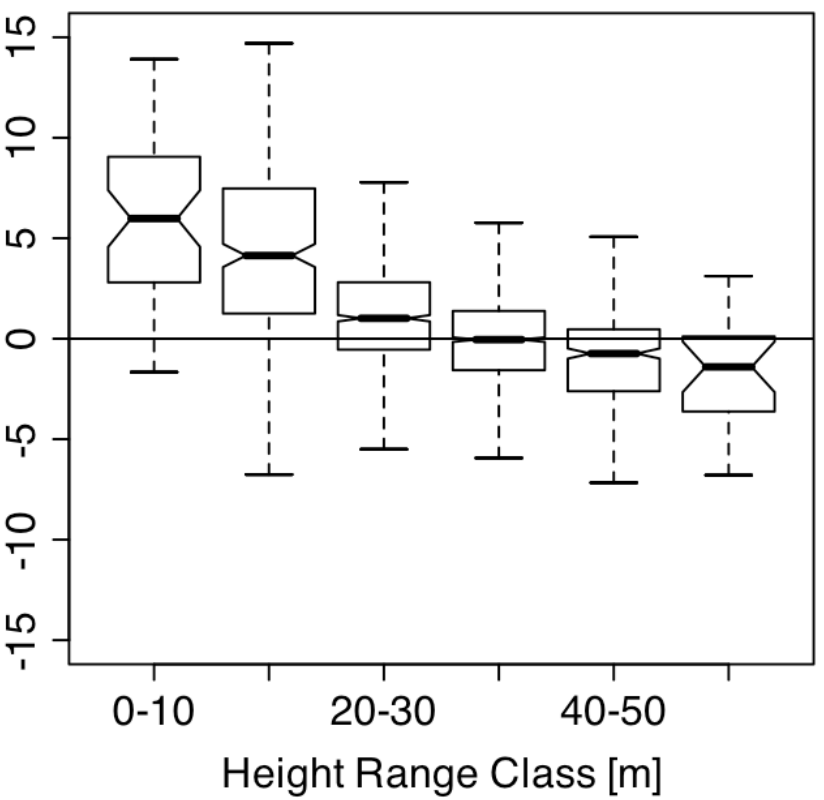


La Selva Forest Dynamics (2005-1998)

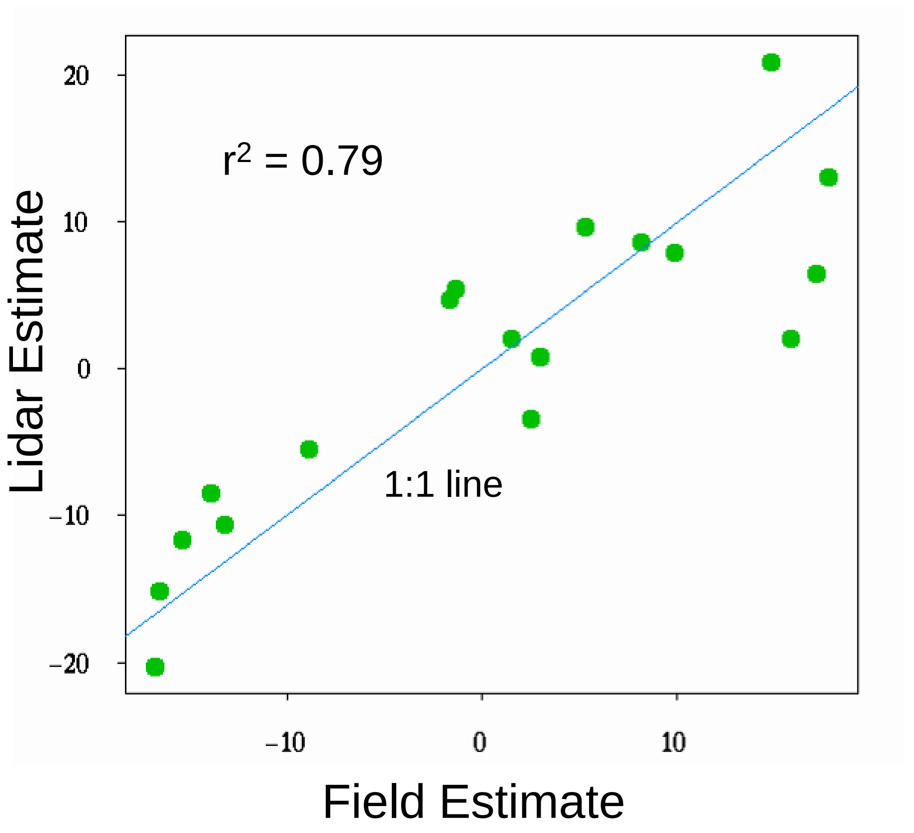


La Selva Forest Dynamics (2005-1998)

Height Change [m]



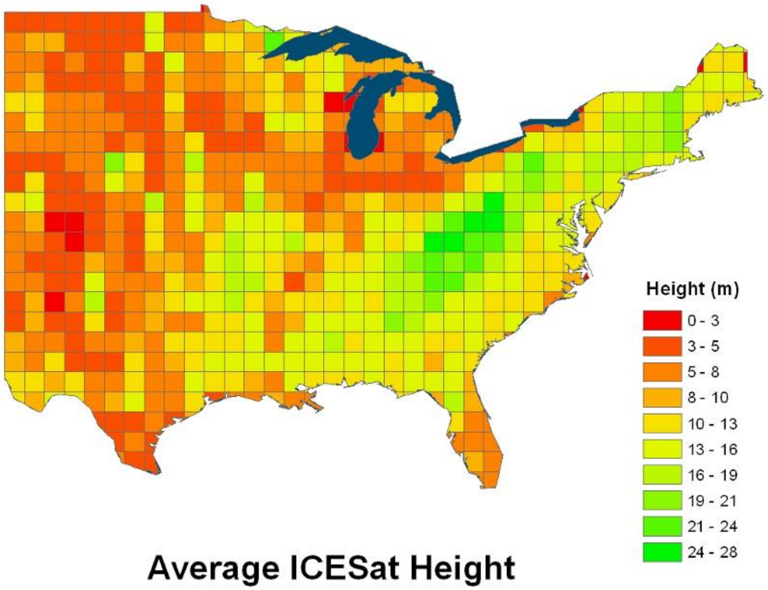
Biomass Change [Mg/ha]
0.5 ha Old Growth Plots



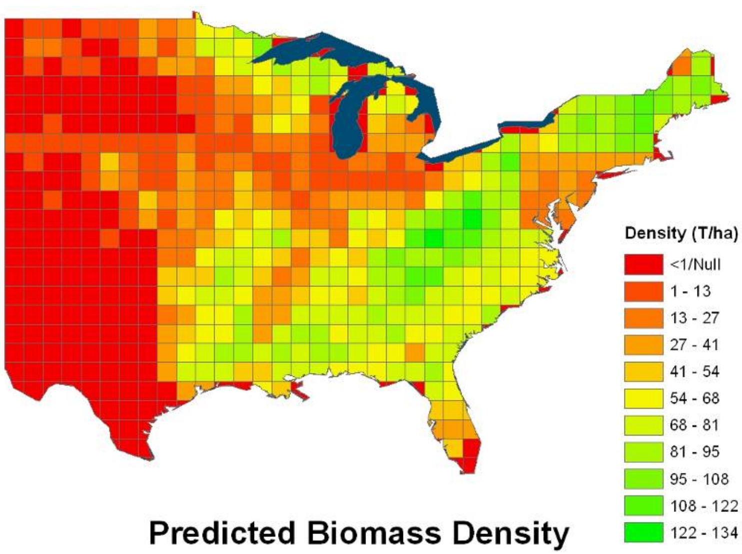
How will spatial sampling influence these errors?

- **Science requirements dictate model and measurement requirements**
- **Useful to explore possible mission scenarios**
  - **Number of lasers, length of mission, orbit -> grid spacing**
  - **Provide assessment of lidar capability per se to frame discussions**
- **Optimal sampling strategy difficult to formulate**
  - **Function of spatial variability of forest structure, temporal phenology, orbital constraints, energy constraints, etc.**
    - **Theoretically possible but not worth the effort**
    - **Conditioned by science requirements**
  - **Pragmatic approach**
    - **Pick 10 - 20 test areas**
    - **Range of stand-level variability**
      - **Height, slope, canopy shape, canopy closure, phenology**
    - **Stratification scenarios**
    - **Priority funding area**

Example: Biomass From ICESAT



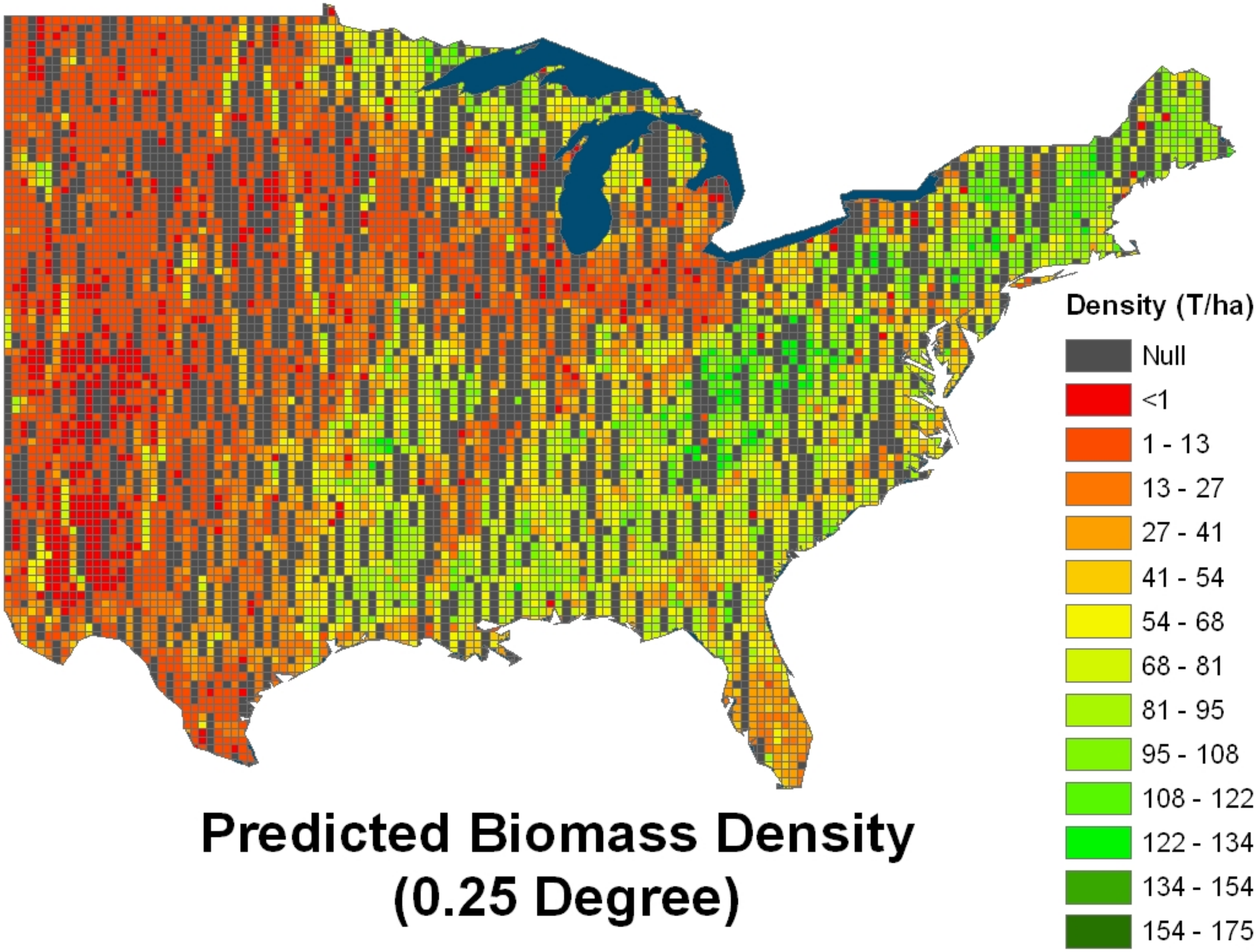
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Example: Biomass from ICESAT

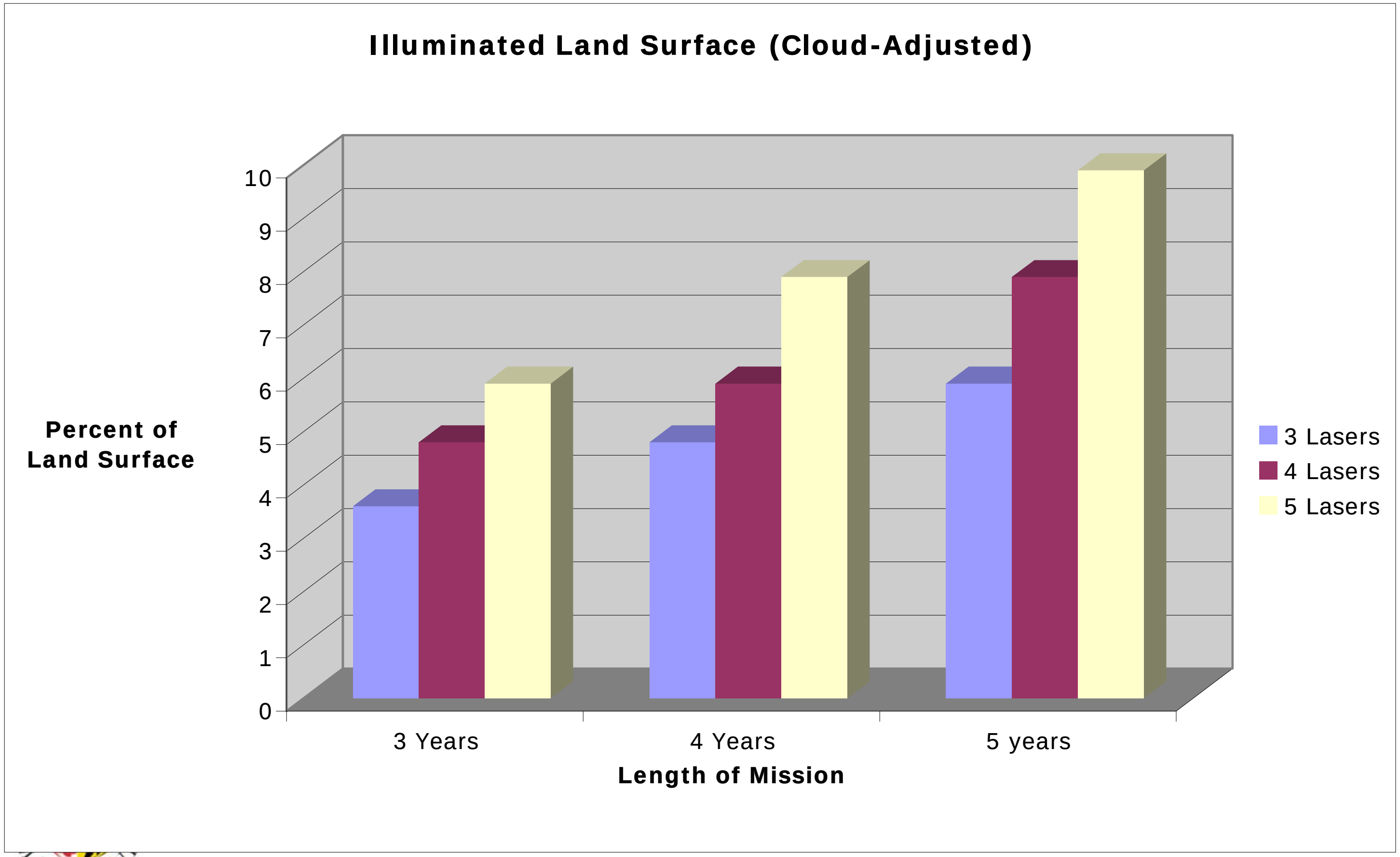
- **What size grid will DESDynI lidar create?**



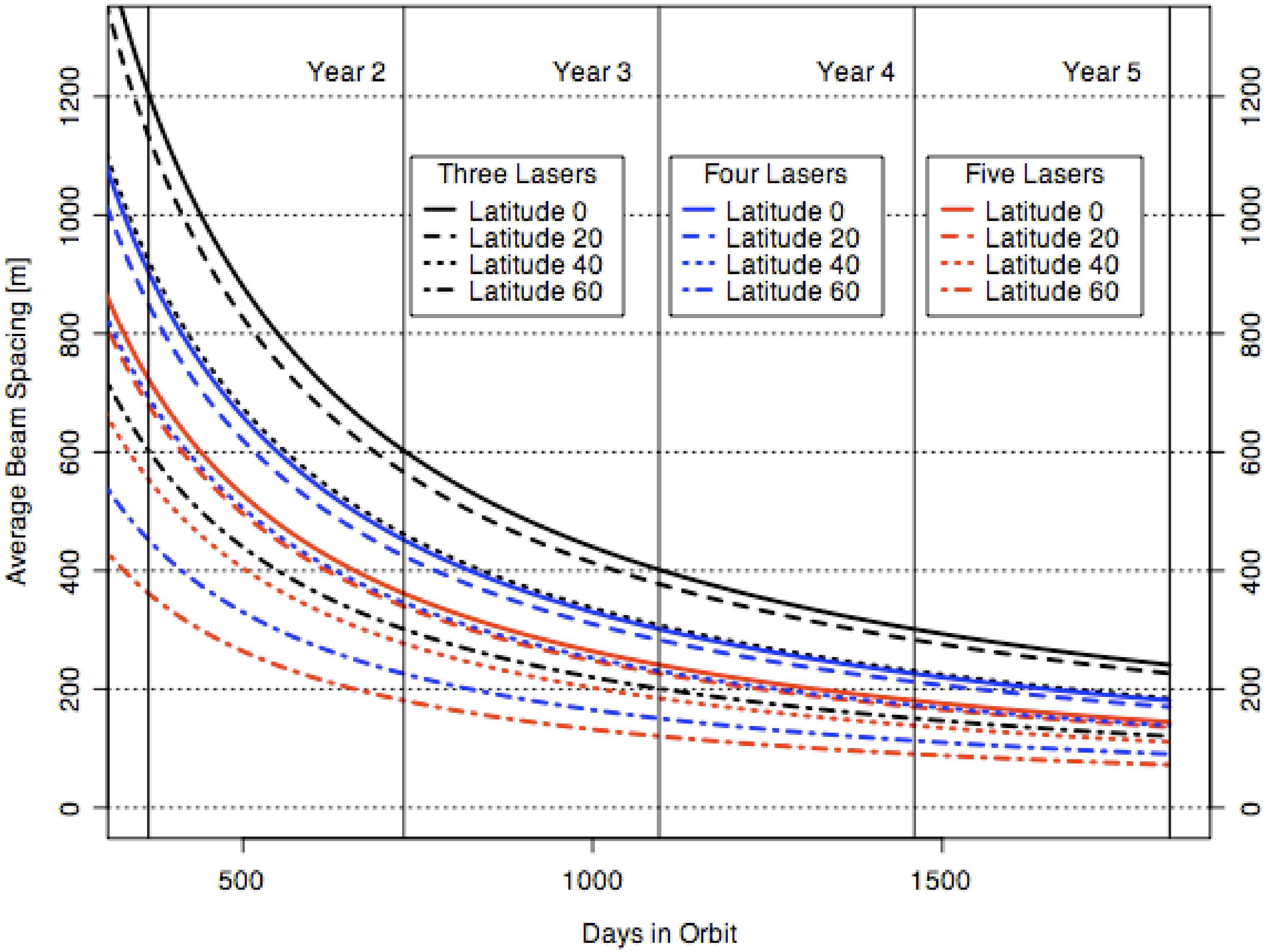
Predicted Biomass Density (0.25 Degree)

Quick and Dirty Orbit Sims

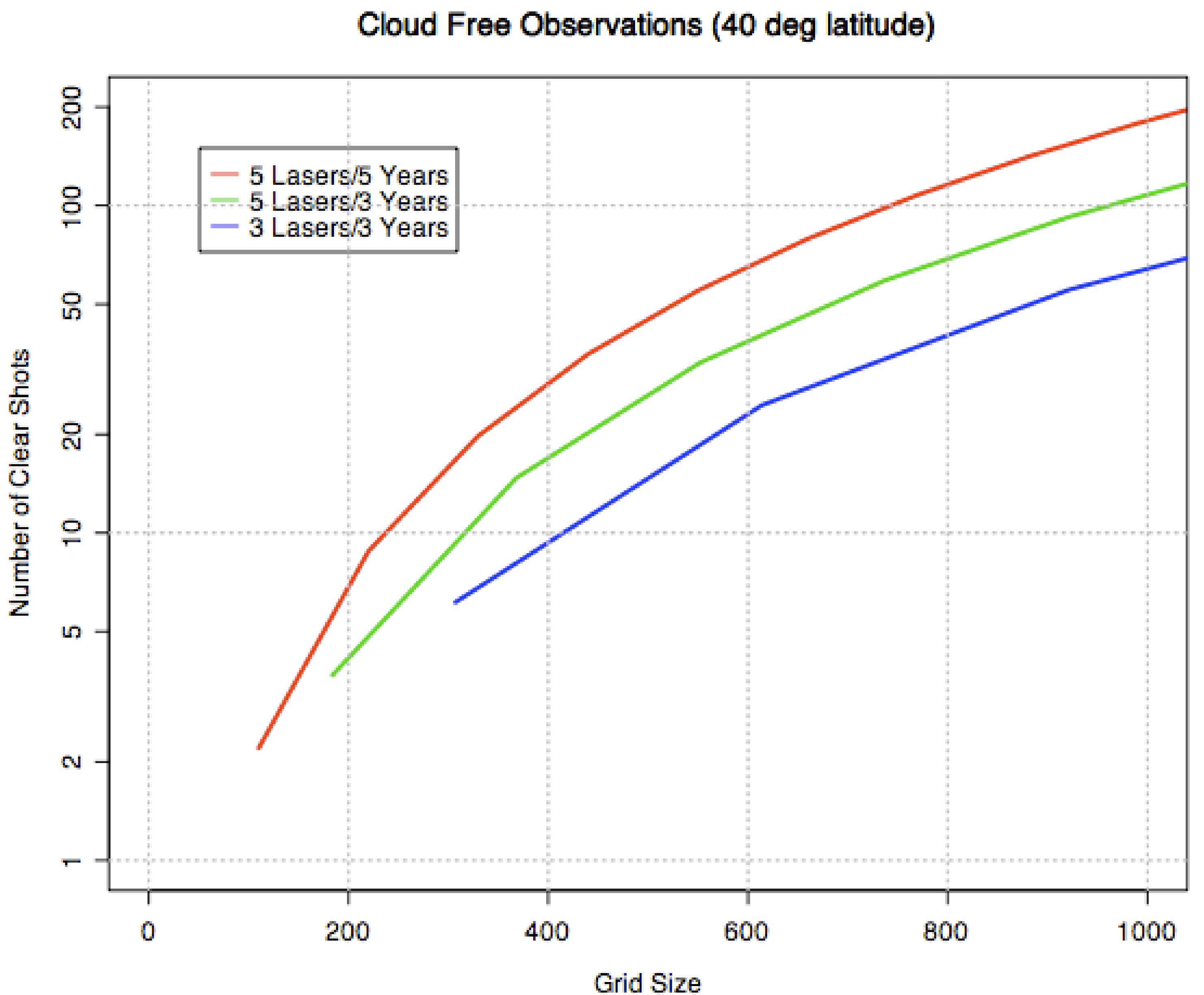
- **Assume**
  - **Near-polar orbit (97 deg inclination)**
  - **500 km orbit**
  - **25 m footprint, 30 m spacing**



Laser Coverage

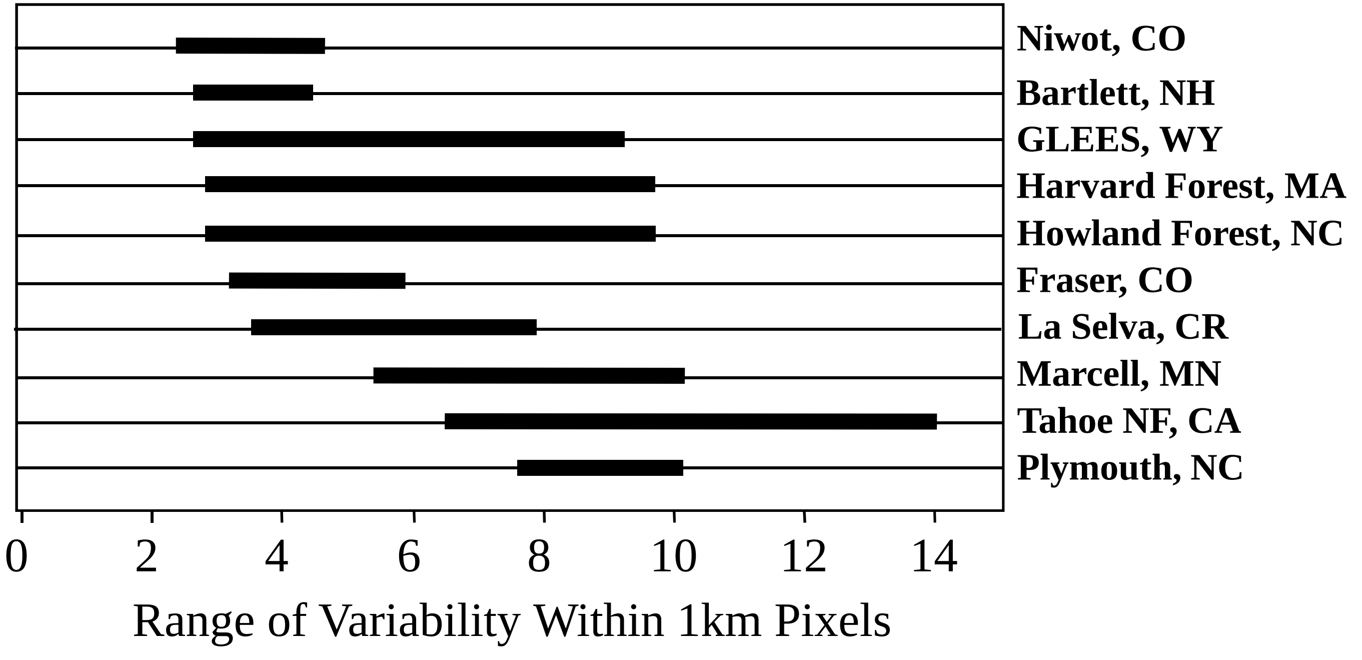


Anticipated Observations



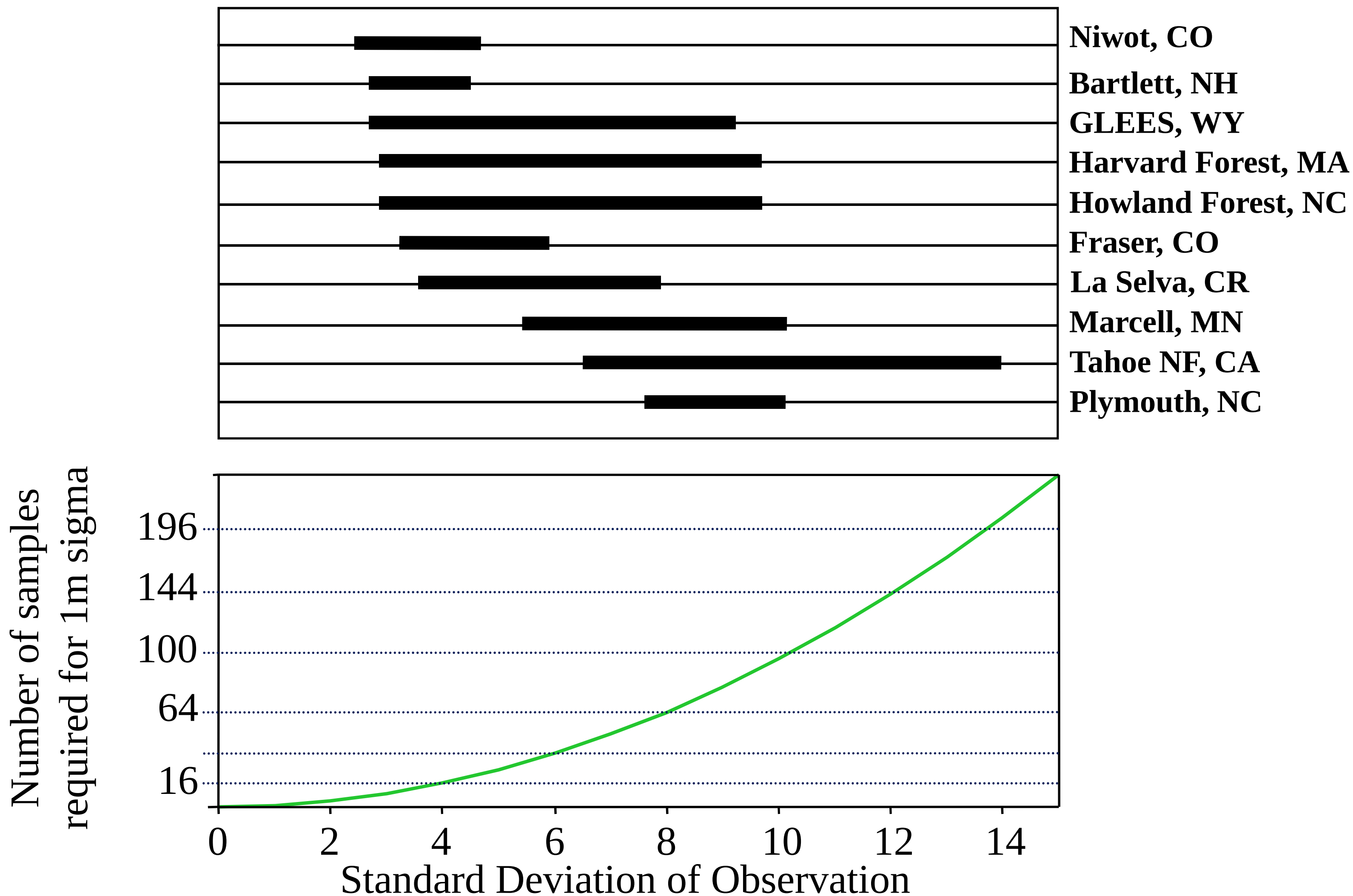
Spatial variability of canopy height

- **Sparse spaceborne lidar collected from spatially variable landscapes.**
  - **Confidence in estimates of mean characteristics of the landscape function of:**
    - **The spatial density of observations**
    - **The spatial resolution of the sampling grid**
    - **The statistical power of any stratifying layers**



Spatial variability of canopy height

Increasing the spatial density of observation…..



Landscape variability and measurement errors

Total standard deviation represents the sum of the uncertainty due to variability within a grid-cell and measurement error

Total standard deviation (m)

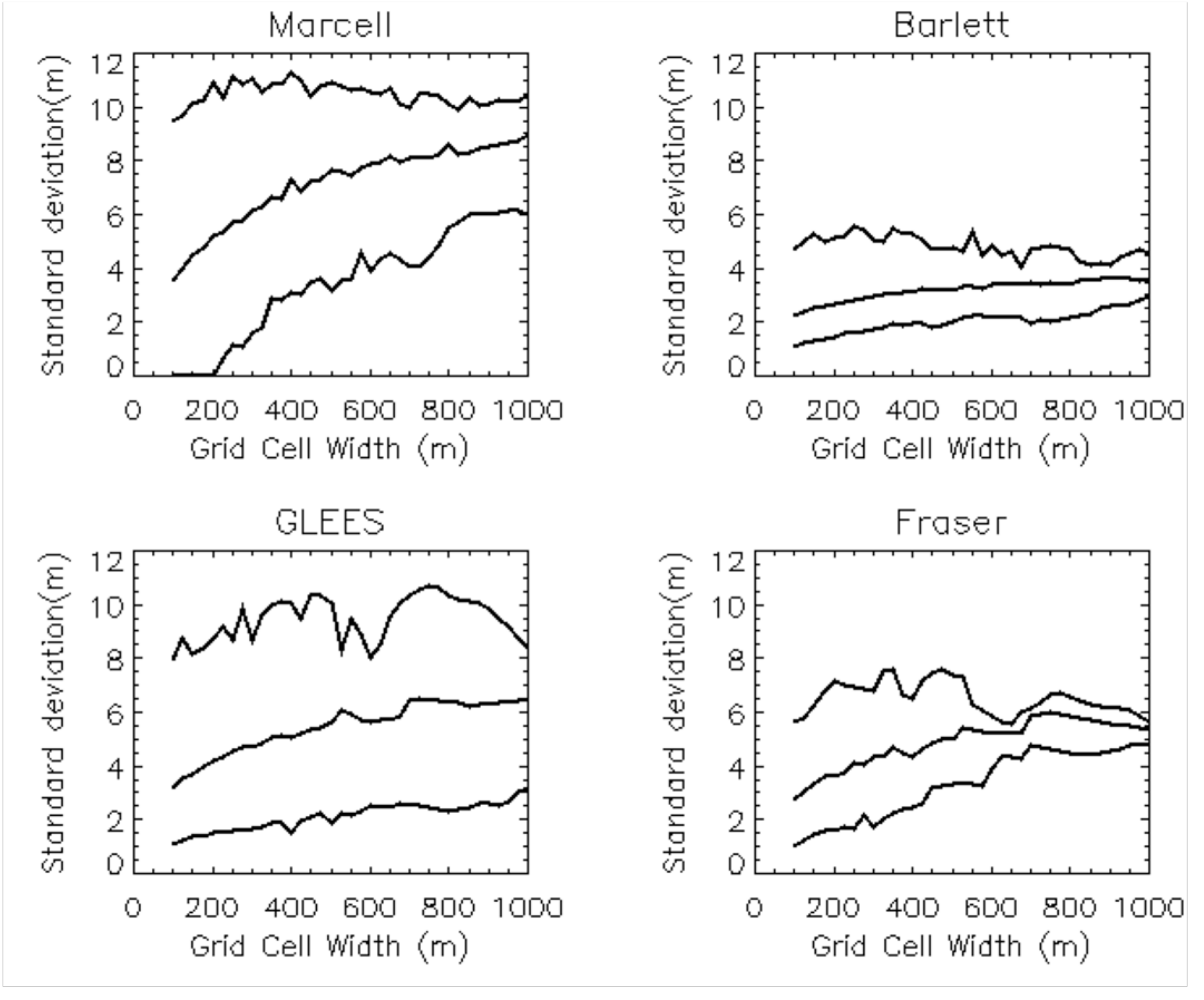
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Standard deviation of height (m) within a grid-cell
(Uncertainty due to variability within a grid-cell)

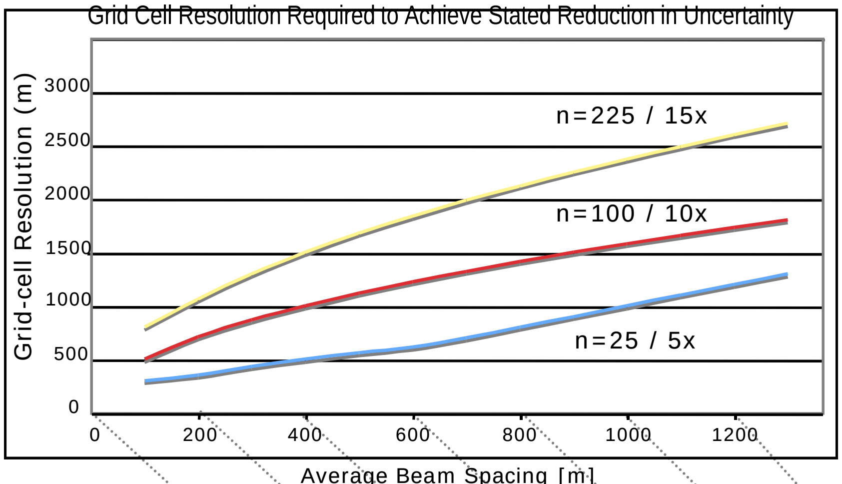
UNIVERSITY OF MARYLAND 1856

Spatial variability of canopy height at four conifer sites

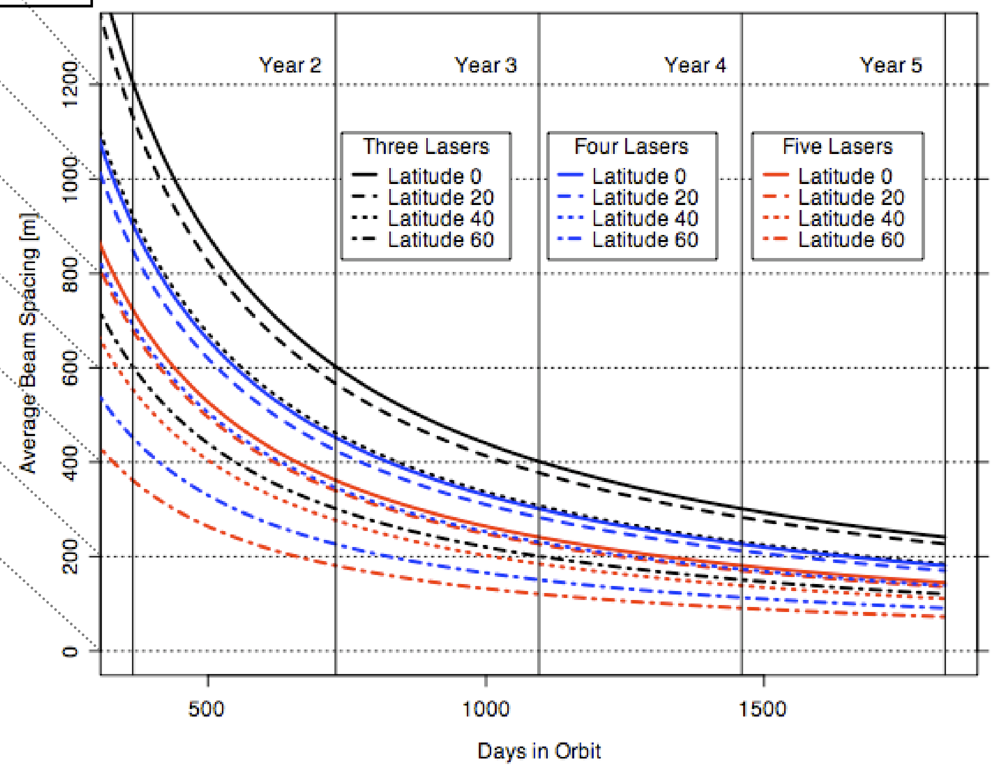
Increasing the grid cell size of the sampling grid…..



Laser Coverage to Reduce Uncertainty



- **For 50 - 100 tC/ha RMSE reduction > 10 tC/ha**
  - **3 lasers/3 years**
    - **300 - 600 m grid resolution**
  - **5 lasers/5 years**
    - **200 - 400 m grid resolution**



- **For 4 - 8 m height RMSE need**
  - **3 lasers/3 years**
    - **500 -1000 m grid resolution**
  - **5 lasers/5 years**
    - **300 - 600 m grid resolution**

Marriage of Ecosystem Models and Lidar Data

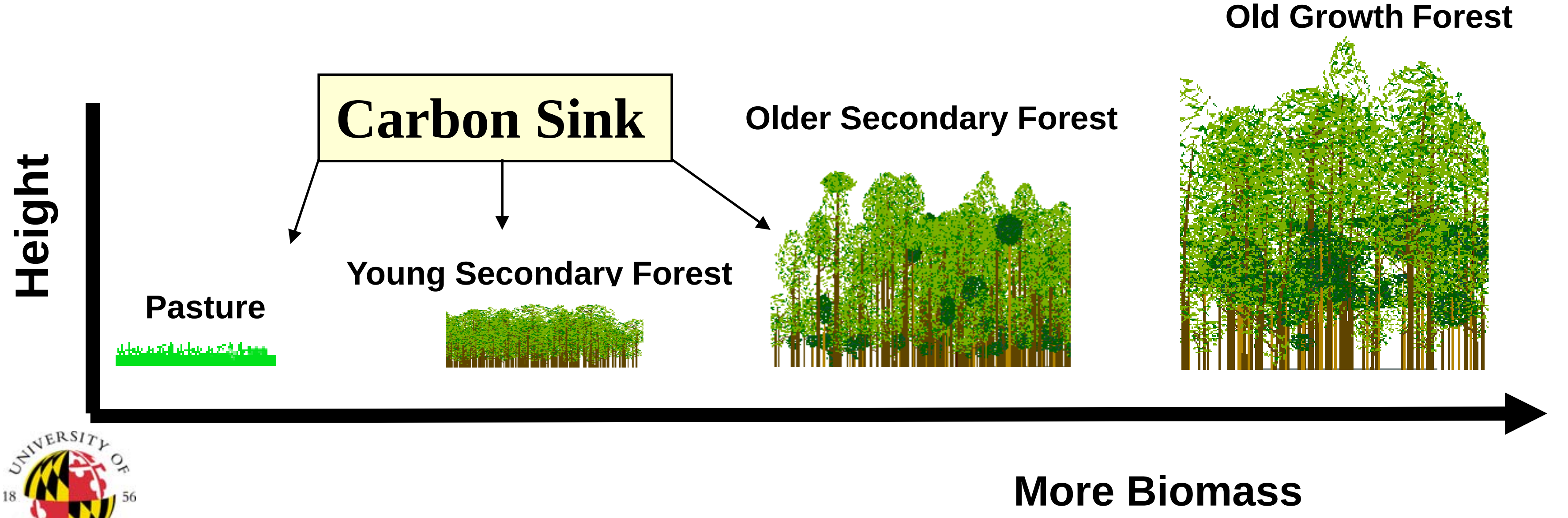
- **Combined use of ecosystem models and forest structure data powerful**
  - **Experience with height-structured Ecosystem Demography Model**
  - **Essential for initialization of stocks -> fluxes**
- **A primary purpose of space-based vegetation structure data to drive ecosystem models**

Model data requirements should inform mission measurement requirements

UNIVERSITY OF MARYLAND 1856

Ecosystem Demography Model Linkage

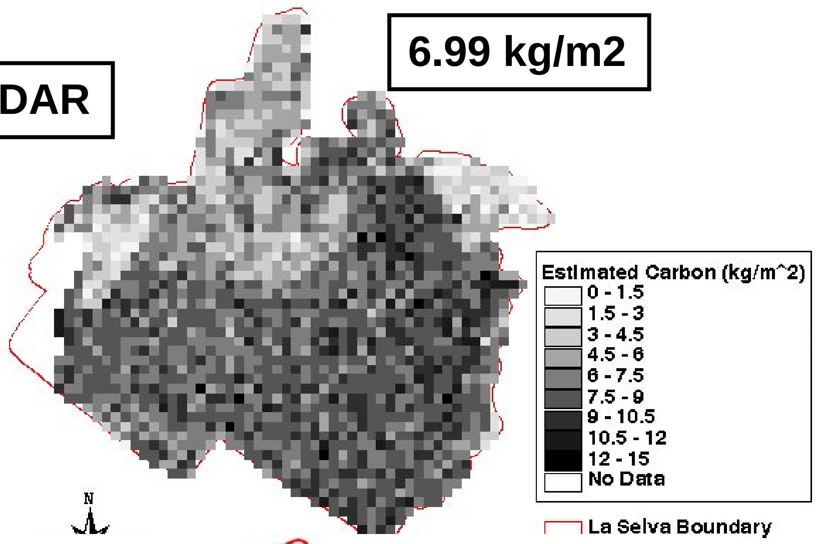
- **ED height-structured ecosystem model**
  - **Must be initialized for non-equilibrium conditions**
  - **Stocks and fluxes vary strongly with successional state**
- **Lidar data products**
  - **Initialize height and biomass distributions**
  - **Provide estimate of successional status**
  - **Validate model carbon and vegetation structure**



Aboveground Carbon Comparison

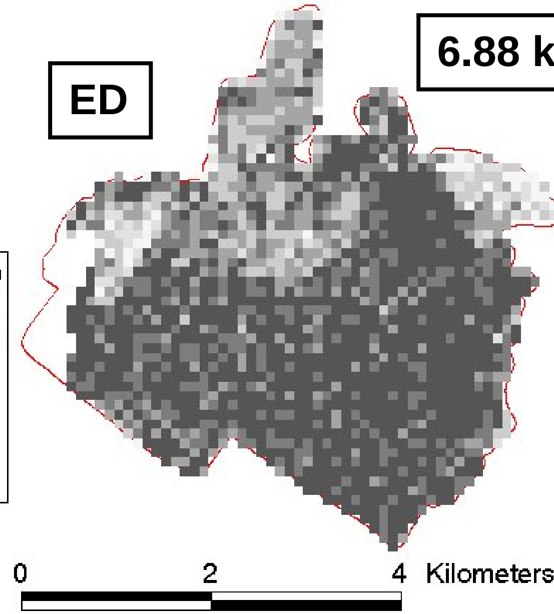
LIDAR

6.99 kg/m2

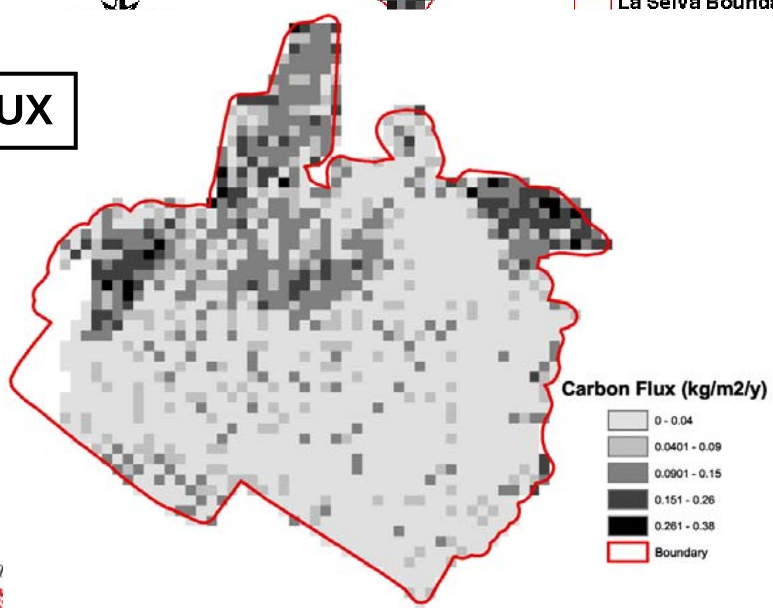


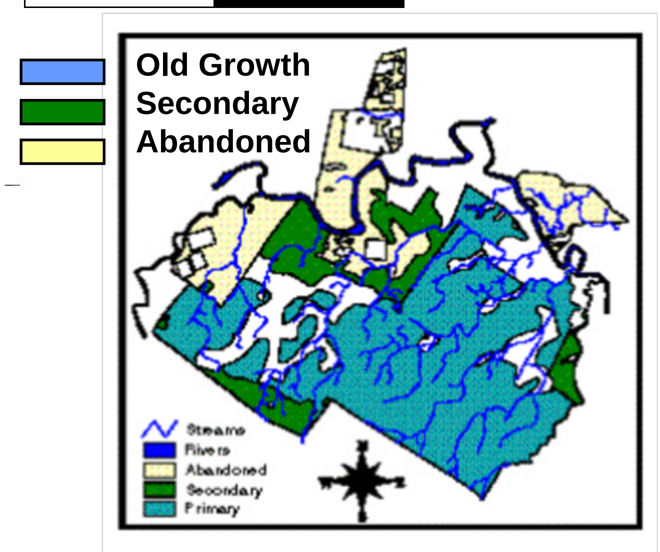
ED

6.88 kg/m2

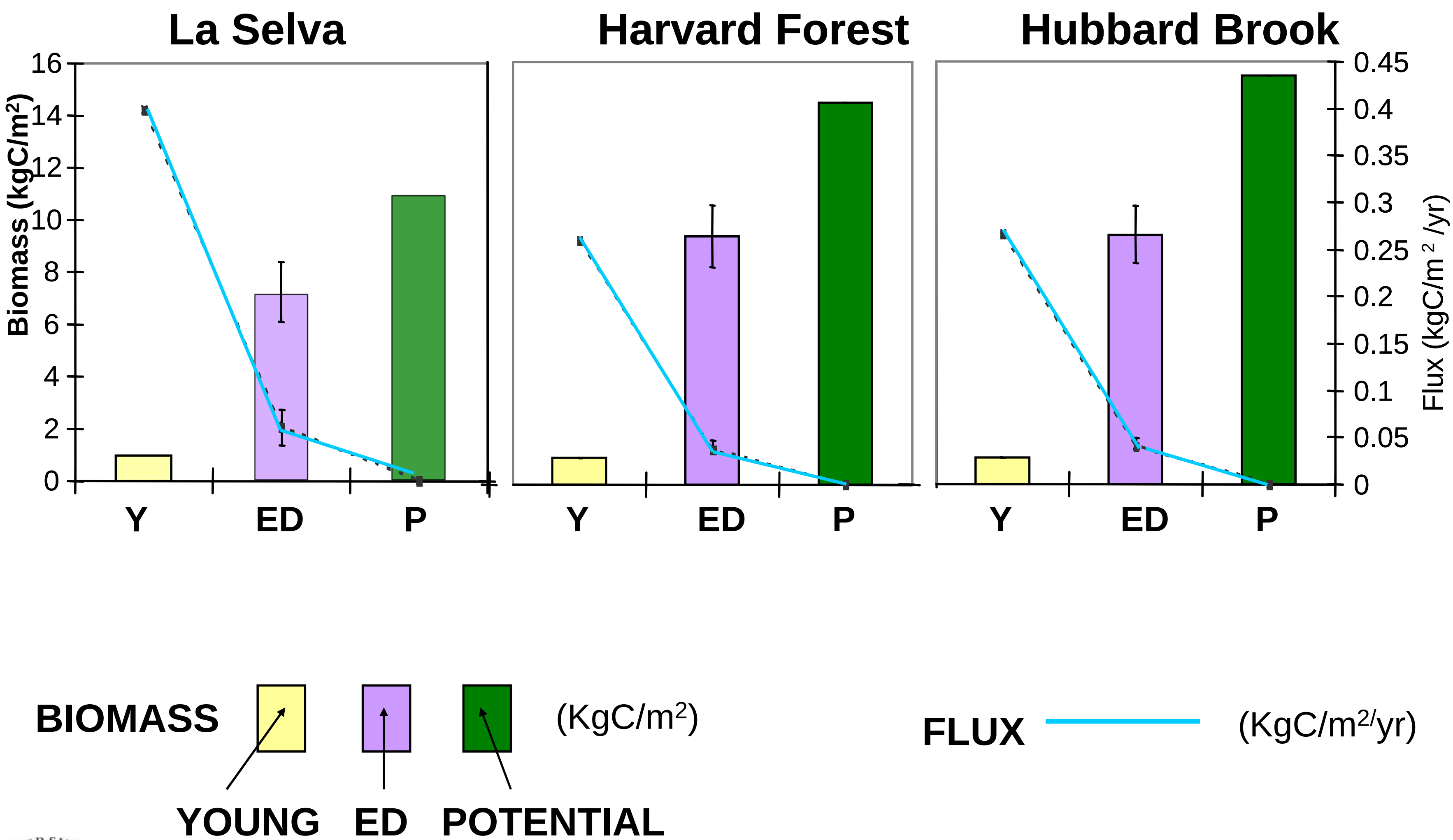


FLUX





Power of Lidar Initialization



Model Requirements

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- **Slope of biomass/height line provides error estimates**
  - **Tropical/temperate forests (Costa Rica/ US)**
- **2.6 tC/ha/m -> 5.1 tC/ha/m**
  - **Relative to mean canopy height for 1 ha grid cell**
- **Desired accuracy: 10 tC/ha**
  - **Implies < 2 m height errors**
- **Other Requirements?**
  - **Height distributions**
  - **Light/canopy profiles**

Summary

- **Footprint level height accuracies across biomes**
  - **~ 2 - 5 [m] RMSE**
  - **Pooled sites show ~ 4 [m] RMSE**
  - **RMSE decreases as a function of lidar sample size**
- **Footprint level biomass accuracies**
  - **Pooled coniferous sites: ~ 50 Mg/ha RMSE**
  - **Pooled deciduous sites: ~ 100 Mg/ha RMSE**
  - **Smaller errors reported at individual sites**
  - **RMSE decreases as a function of lidar sample size**
- **Modeling requirements**
  - **Average 1 ha height < 2 m to achieve AGBM < 10 tC/ha**
  - **Model biomass accuracy closely matches 1 ha biomass maps derived from lidar-field data**
- **Observing dynamics**
  - **Primary forest dynamics (growth/loss) detected if repeat period from 3 - 5 years (at footprint and 1 ha scales)**

UNIVERSITY OF MARYLAND 18 56

Summary (cont.)

- **Grid size and height error**
  - Function of beam spacing, height variability, length of mission
  - Assuming RMSE of ~ 4 and 8 [m] -> meet 1 m requirement
    - 3 lasers/3 years: 500 - 1000 m grid cell resolution
    - 5 lasers/5 years: 300 - 600 m grid cell resolution
- **Grid size and biomass error**
  - Function of beam spacing, biomass variability, length of mission
  - Assuming biomass RMSE of ~ 50 and 100 Mg/ha -> meet 10tC/ha requirement
    - 3 lasers/3 years: 200 - 400 m grid cell resolution
    - 5 lasers/5 years: 300 - 600 m grid cell resolution
    - Grid size can (should?) be spatially variable
- **Slope/footprint size interactions**
  - Slope can add 3-4 m of error as footprint size increases
  - Limitations on ICESAT-size footprints

Conclusions

- **Space-based lidar as envisioned for DESDynI**
  - **Provide accurate estimates of canopy height, energy metrics and distributions at relatively fine grid resolutions**
  - **Provide accurate estimates of biomass and distribution**
  - **Provide data for driving ecosystem models at policy relevant spatial and temporal scales**

- **Needed studies**
  - **Quantitative analysis of height, biomass accuracies achievable across many sites for development of sampling and stratification schemes <- Science Requirements**
  - **Model requirements**
    - **Height, height distribution, light profiles, other metric accuracies**
    - **Large scale ecosystem model implementation using lidar**
  - **Fusion, fusion, fusion…**
    - **Lidar derives structure well, needs spatial coverage**