# REMOTE SENSING OF VEGETATION 3-D STRUCTURE

## Quantifying Patterns
## &
## Understanding Processes

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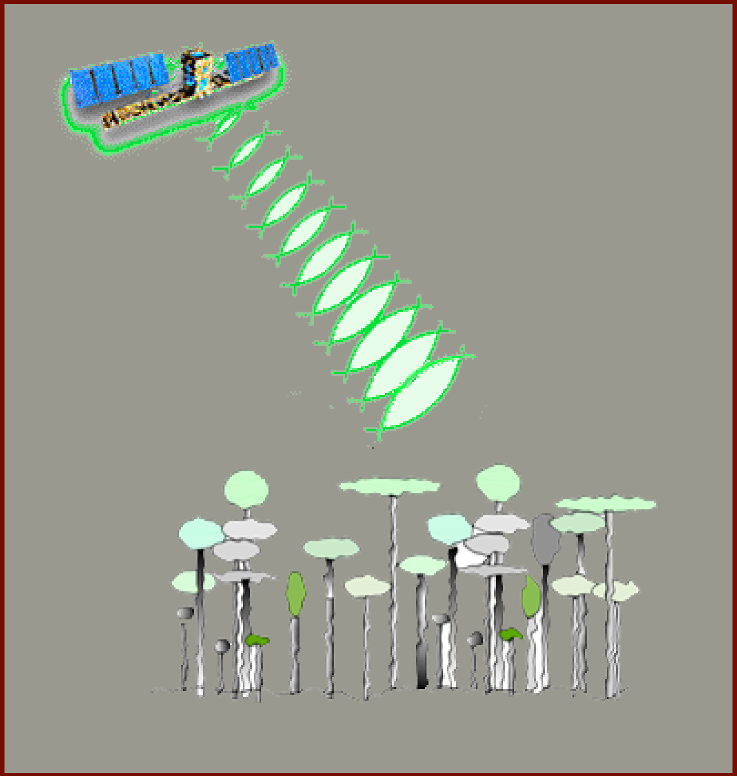
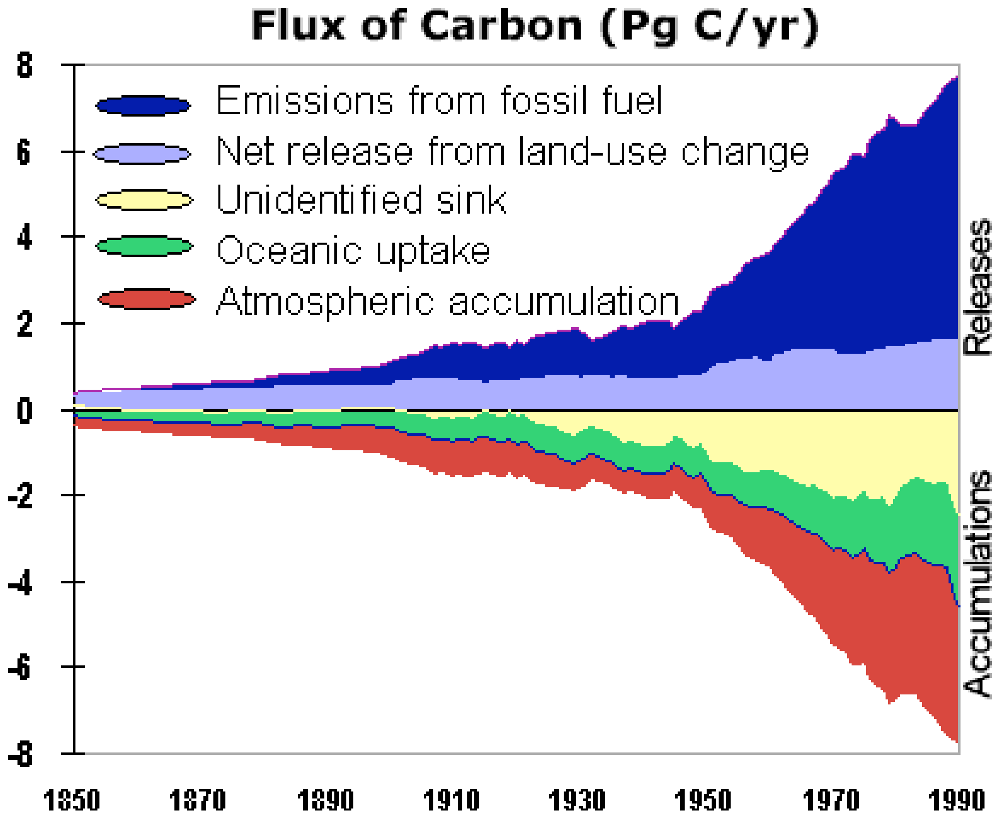


2006 NASA WORKSHOP
August 21-25, 2006, UMD

Global distribution of vegetation biomass to quantify terrestrial carbon stock

Vegetation structure and biomass to model and understand ecosystem function and disturbance and recovery processes

Spatial patterns of vegetation structure to characterize habitats and to understand underlying processes of biological diversity

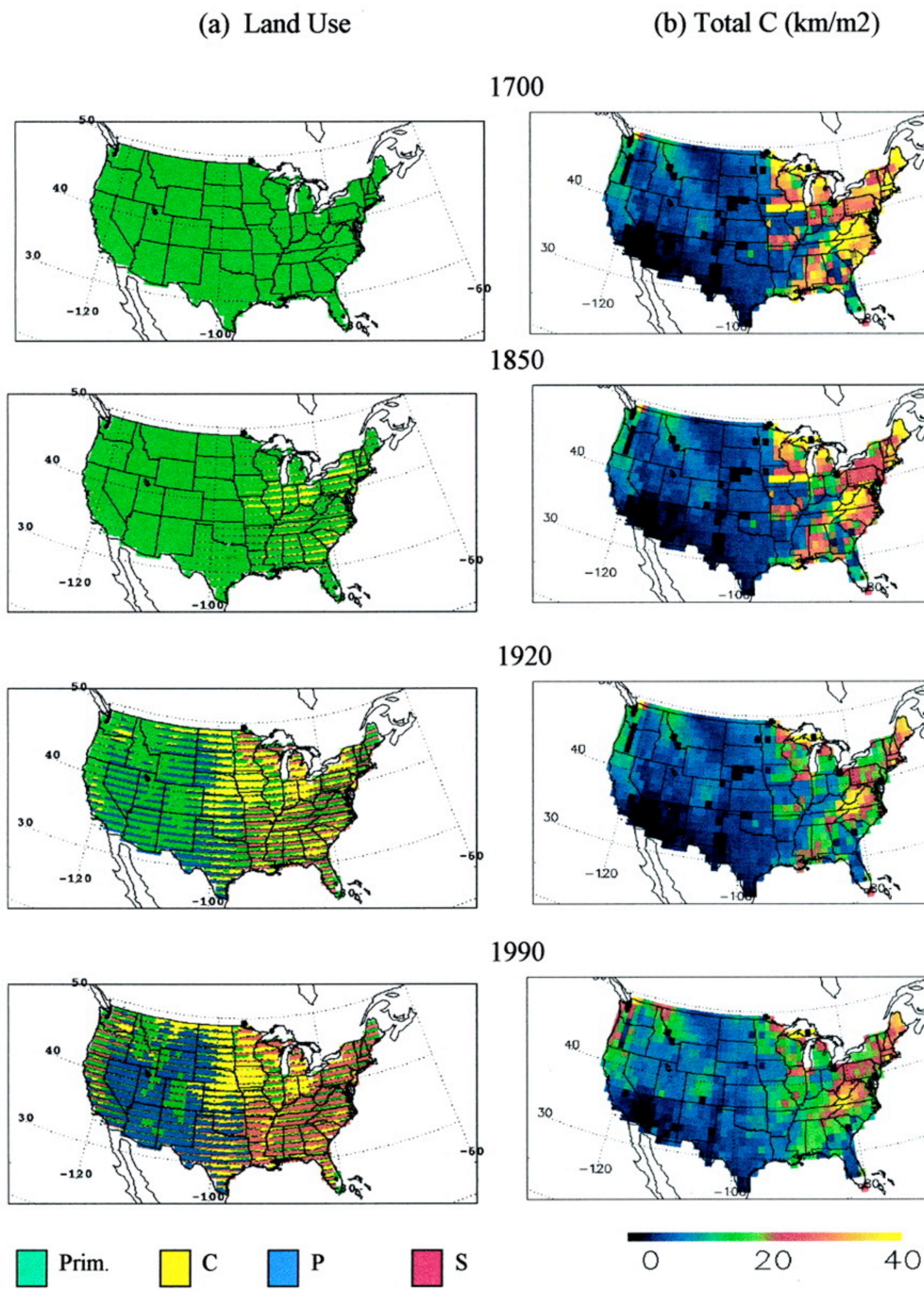


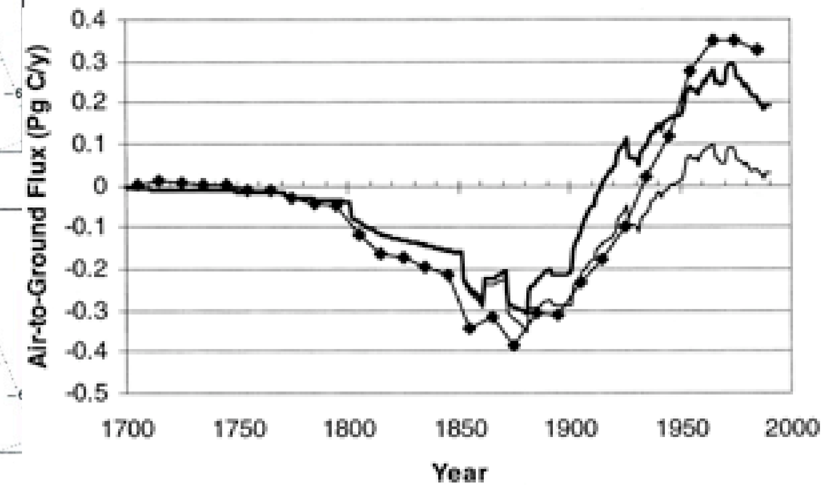

# Carbon Balance of the World's Terrestrial Ecosystem is Uncertain!

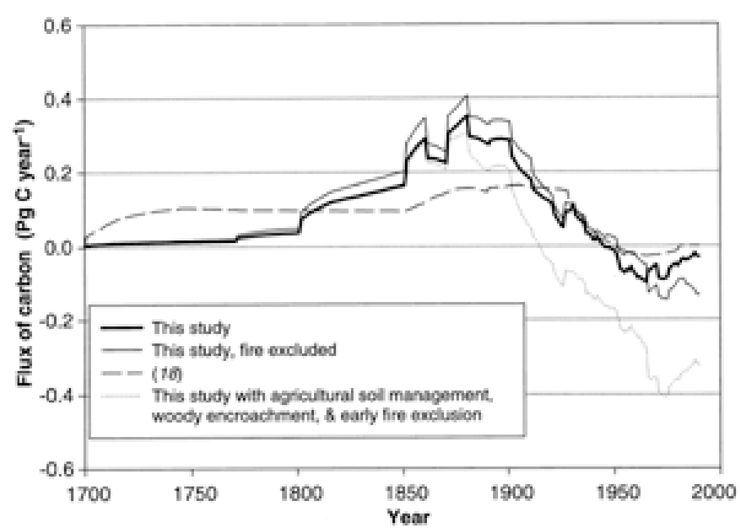
Houghton, 2003

*Annual terrestrial flux of carbon in the 1990s (PgC $yr^{-1}$)*

| | $O_2$ and $CO_2$ | Inverse calculations $CO_2$, $^{13}CO_2$, $O_2$ | Forest inventories | Land-use change |
|---|---|---|---|---|
| Globe | -0.7 | -0.8 | - | 2.2 |
| Northern mid-latitudes | - | -1.8 | -0.65 | -0.03 |
| Tropics | - | 0.6 to 1.2 Source | ?? | 0.5 to 3.0 Source |



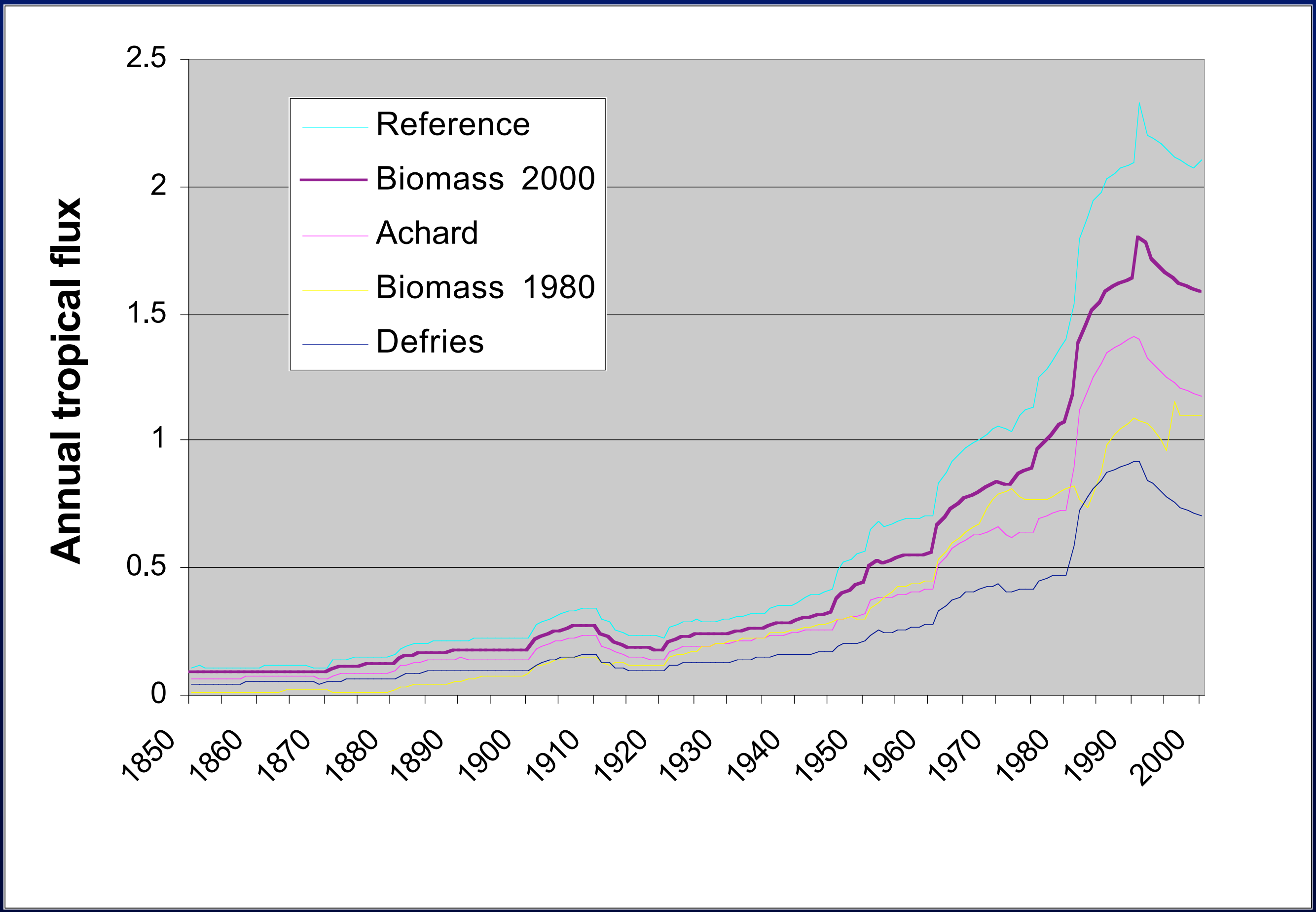



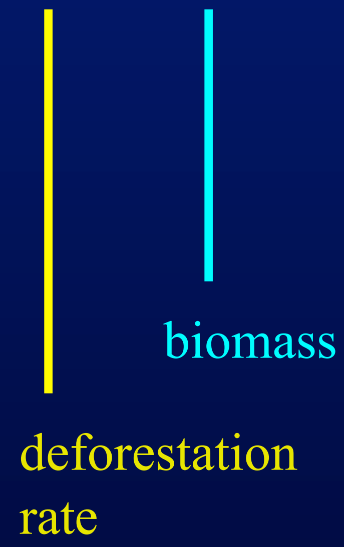

Houghton, et al. 2001)

G. C. Hurtt et al., *Proc. Natl. Acad. Sci.* (2002)

*Five scenarios:*

1. Houghton (2003) (Reference)
2. Achard et al. (2004)
3. DeFries et al. (2002)
4. Adjust starting biomass to yield FAO 2000 biomass
5. Adjust starting biomass to yield FAO 1980 biomass, and try to obtain 1990 and 2000 biomass by shifting the forest types deforested

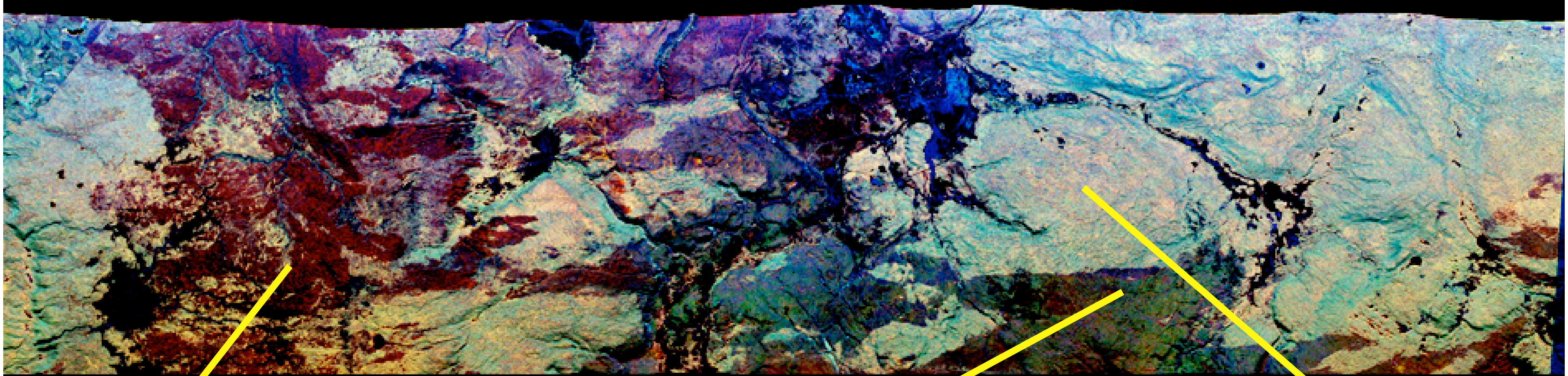



Houghton, 2004

# Mapping Disturbance and Recovery

## Yellowstone National Park



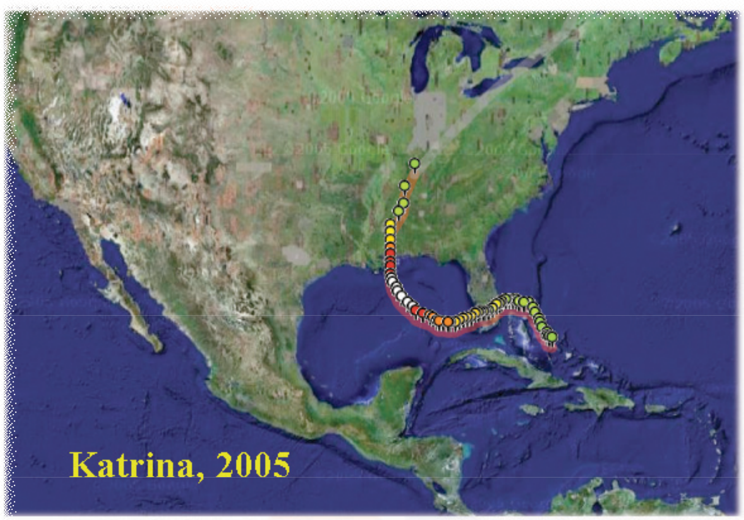
2003 Burn

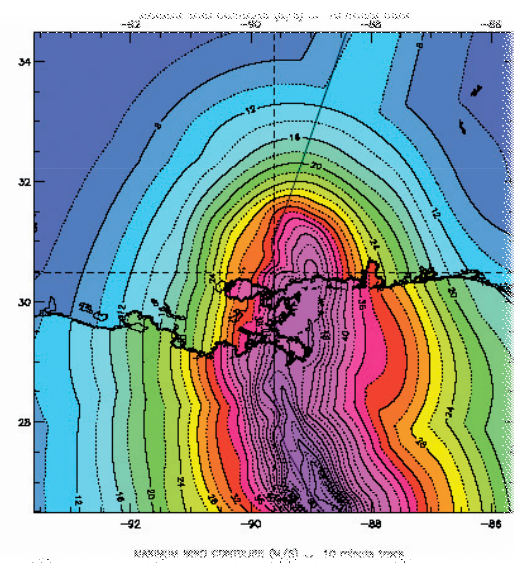
1988 Burn

Pine Beatle Disease

# Impact of Disturbance on US Carbon Sequestration Pool


Early estimates from forest inventories indicate potential
timber losses from Hurricane Katrina alone amount to
roughly 4.2 billion cubic feet of timber (15-19 billion board feet),
spread over 5 million acres of light to heavily damaged forest land in Mississippi,
Alabama, and Louisiana.



Blowdowns in the Amazon Basin

Chambers et al.

**Images taken ~1.5 years after the event, whereas satellite imagery in the previous slide were taken ~6 months after the event. The edge of blowdowns can be readily identified, with vegetation rapidly filling up the disturbed area, revealing a rapid loss of the woody signal associated with downed trees. Ongoing field investigations at INPA with Niro Higuchi are quantifying mortality rates along the mapped disturbance gradient.**

# Sources of Uncertainties

1. Land cover and land use change
   (deforestation, reforestation, cultivation, logging)
2. Wood debris, forest floor, soils
3. $CO_2$ fertilization, changes in climate
   (regrowth, enhanced regrowth)
4. Woody Encroachment, Woodland thickening
5. Wood products
6. Sediments and river transports
7. Biomass stock
   Volume-to-biomass, age-to-biomass
8. Disturbances
   (fire, insects)

Estimated rate of carbon accumulation in the US ($PgCyr^{-1}$ in 1990)

| | Pacala *et al.* (2001)* | | | | |
|---|---|---|---|---|---|
| | Low | High | Houghton *et al.* (1999)† | Houghton (in press)† | Goodale *et al.* (2002) |
| Forest trees | −0.11 | −0.15 | −0.072‡ | −0.046§ | −0.11 |
| Other forest organic matter | −0.03 | −0.15 | 0.010 | 0.010 | −0.11 |
| Cropland soils | 0.00 | −0.04 | −0.138 | 0.00 | NE |
| Woody encroachment | −0.12 | −0.13 | −0.122 | −0.061 | NE |
| Wood products | −0.03 | −0.07 | −0.027 | −0.027 | −0.06 |
| Sediments | −0.01 | −0.04 | NE | NE | NE |
| Total sink | −0.30 | −0.58 | −0.35 | −0.11 | −0.28 |
| % of total sink neither in forests nor wood products | 43% | 36% | 74% | 55% | NE |

# Canopy Process Models

**Plant communities are heterogeneous in their structure & function**

Structure is important for:

predicting current and future biophysical and biogeochemical functioning.

predicting the resilience of ecosystems to climatological perturbation

# Big Leaf Models

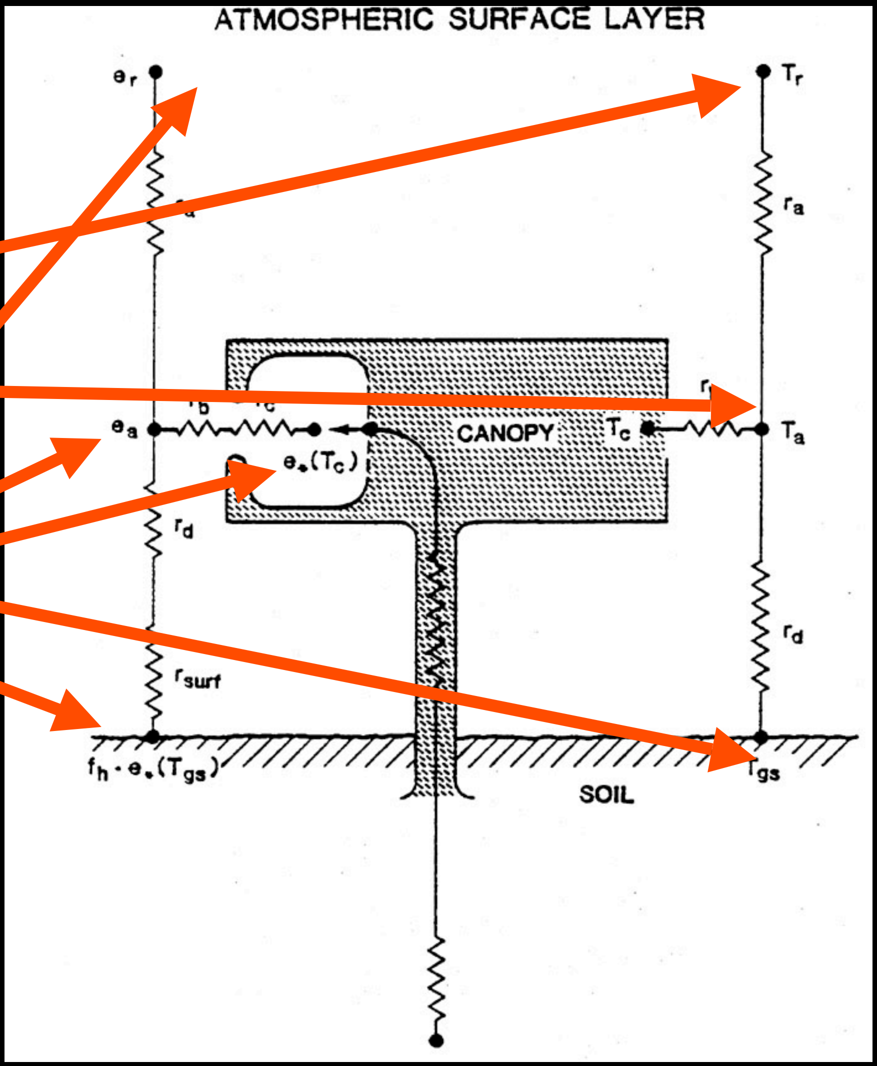
Examples of Variables Considered:

$T_r$ = Air Temperature

$T_a$ =Air Temperature in Canopy Air Space

$T_s$ = Soil Temperature

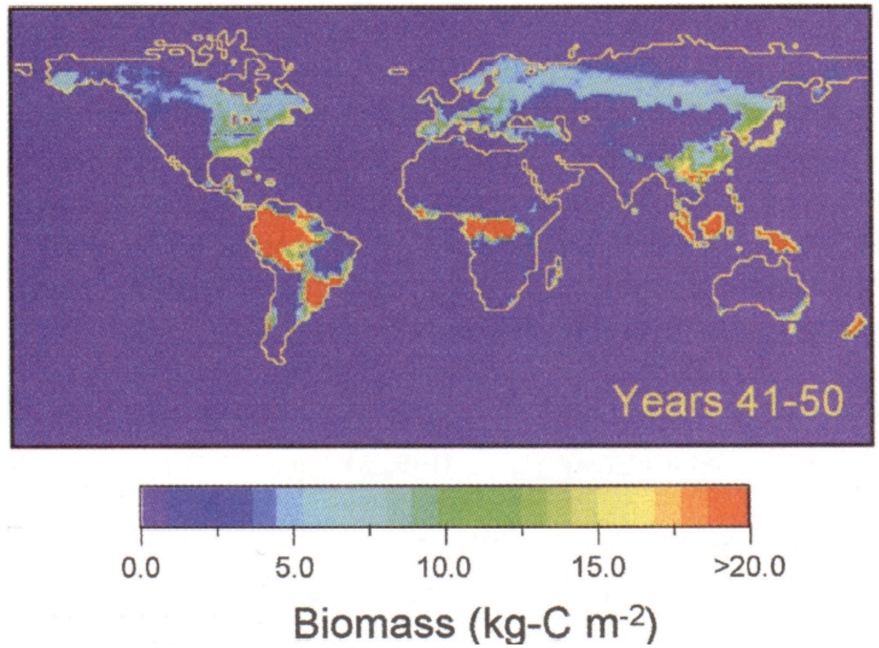
$e_i$ = Vapor Pressure Deficits



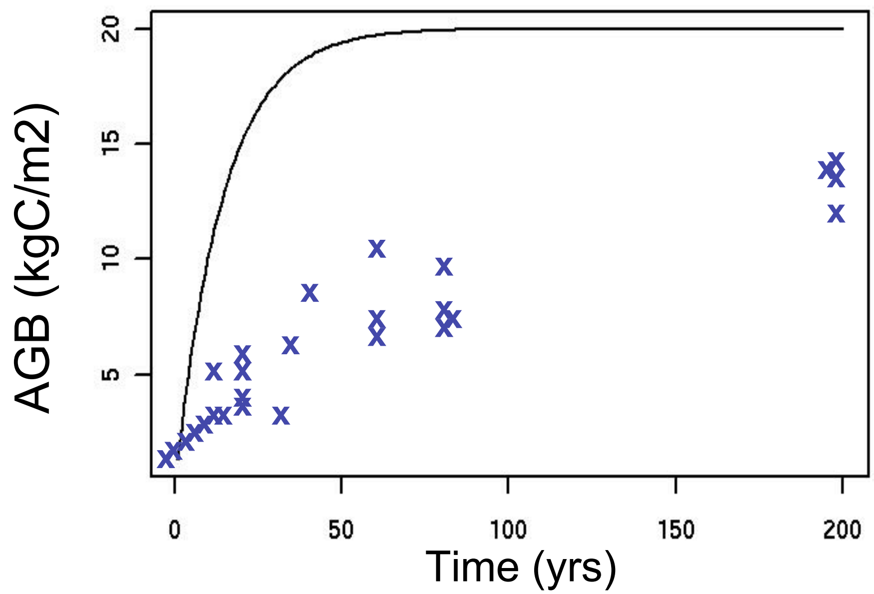

H. Shugart

Big-leaf models tend to predict unrealistic long-term ecosystem dynamics

e.g.: IBiS evergreen PFT above-ground biomass dynamics




Comparison of above-ground biomass dynamics to observations at San Carlos (tropical forest) 2°N,68°W:




P. Moorcroft

Material Flow Models

Canopy Process Models

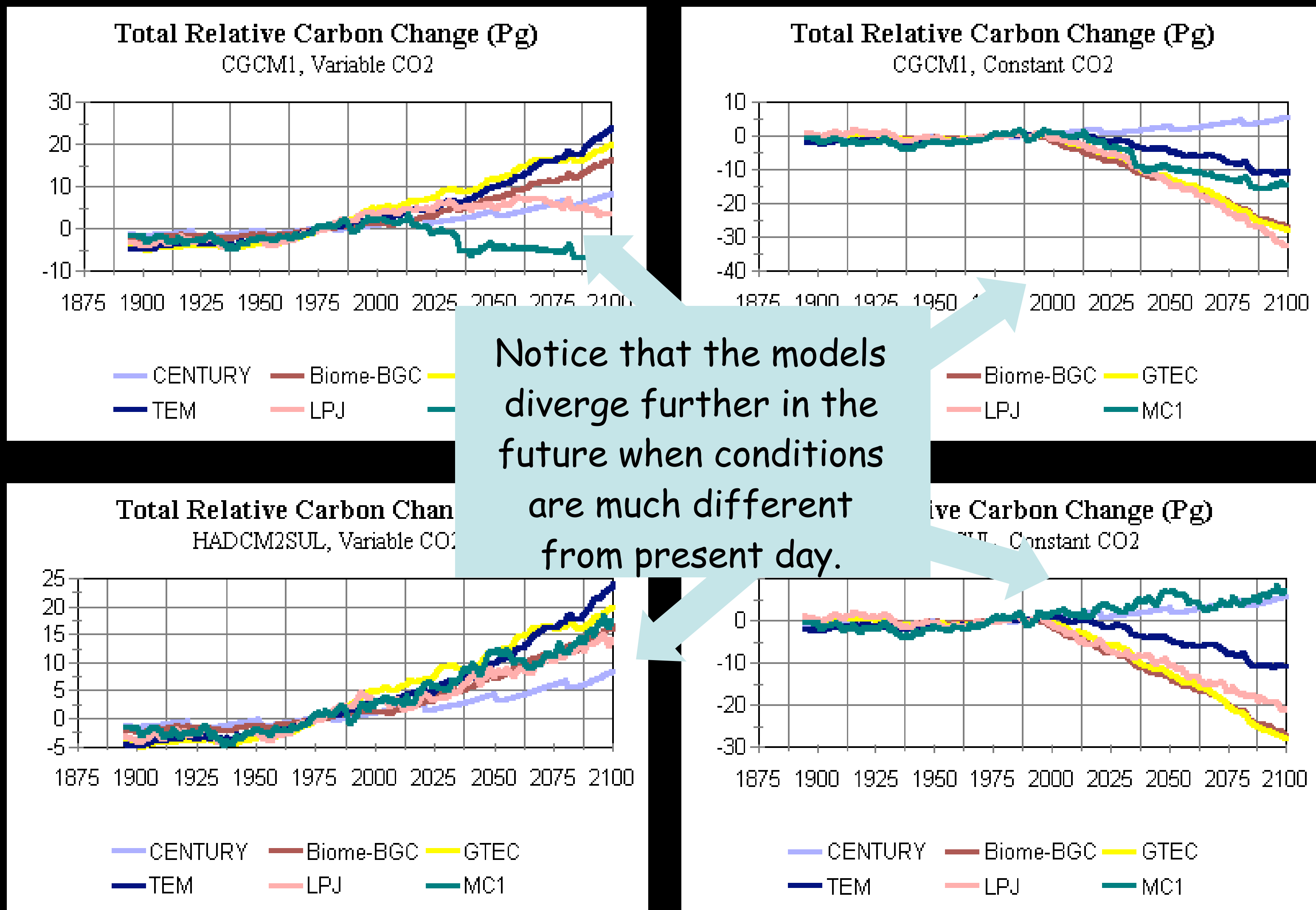
Dynamic Global Vegetation Models or

# DGVM's


Biogeographic Approaches

H. Shugart

# Changes in Carbon under different cases
## 2 Climate Scenarios x 2 $CO_2$ cases x 6 DGVM's

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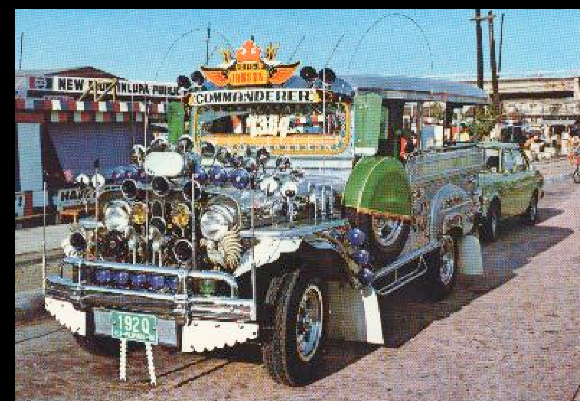
Dynamic Global Vegetation Models or

# DGVM's

**The Ideal**

**The Prototype**



**One important step in improving our models of global ecosystem dynamics is to incorporate the effects of structure.**

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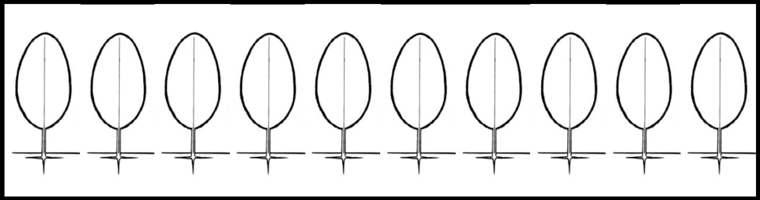
# Equivalent Structures with Respect to One Variable Can Be Different with Respect to Other Variables



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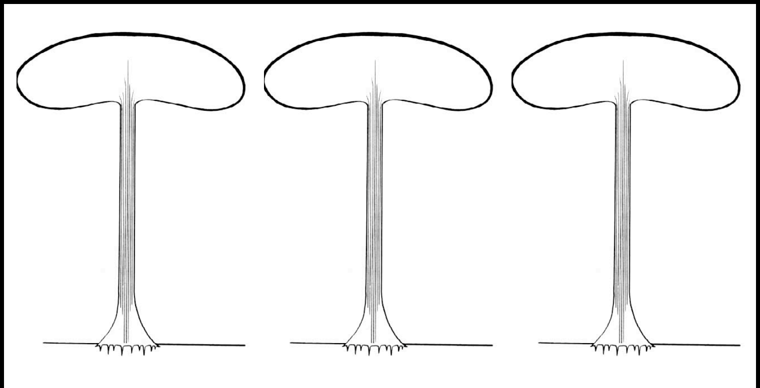
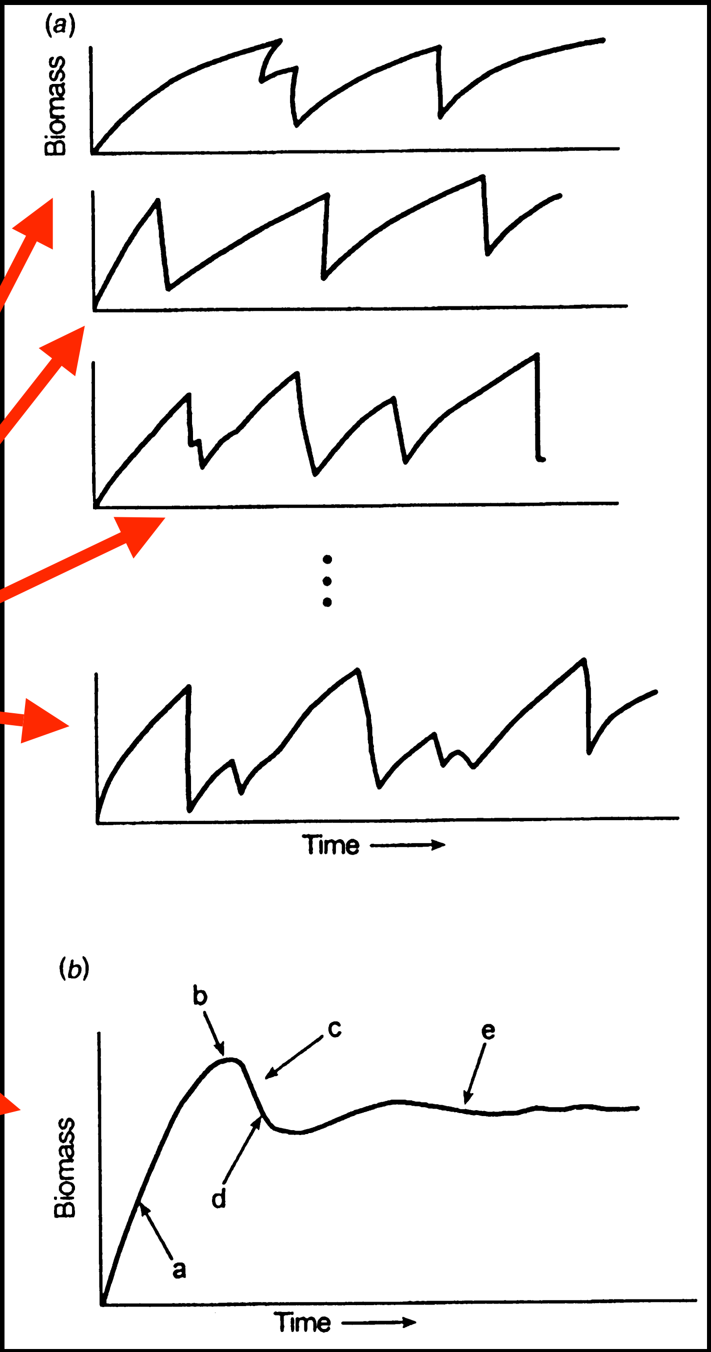


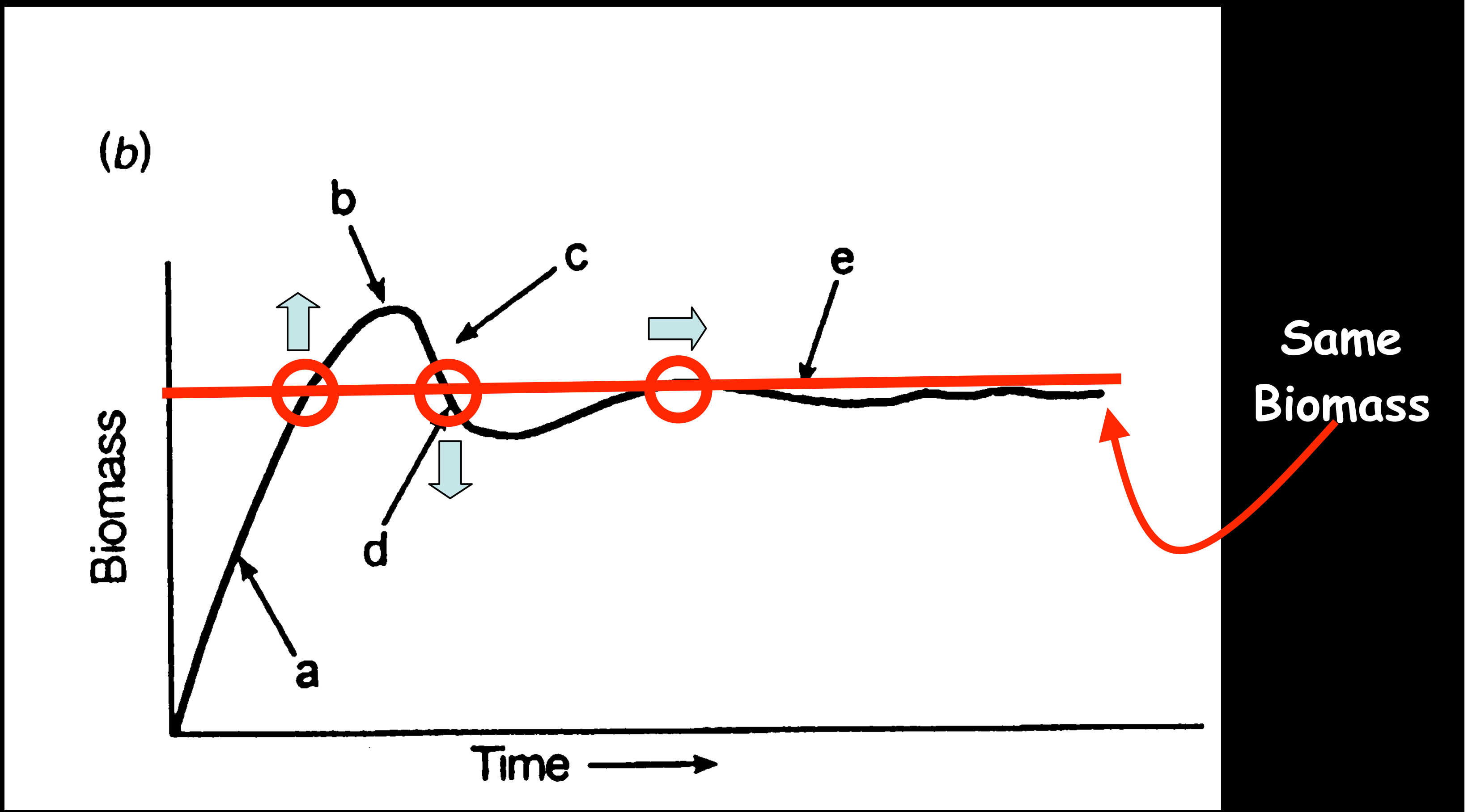
# Large and Small Scale Dynamics are Different and Influenced by Structure

Small-Scale Dynamics

≠

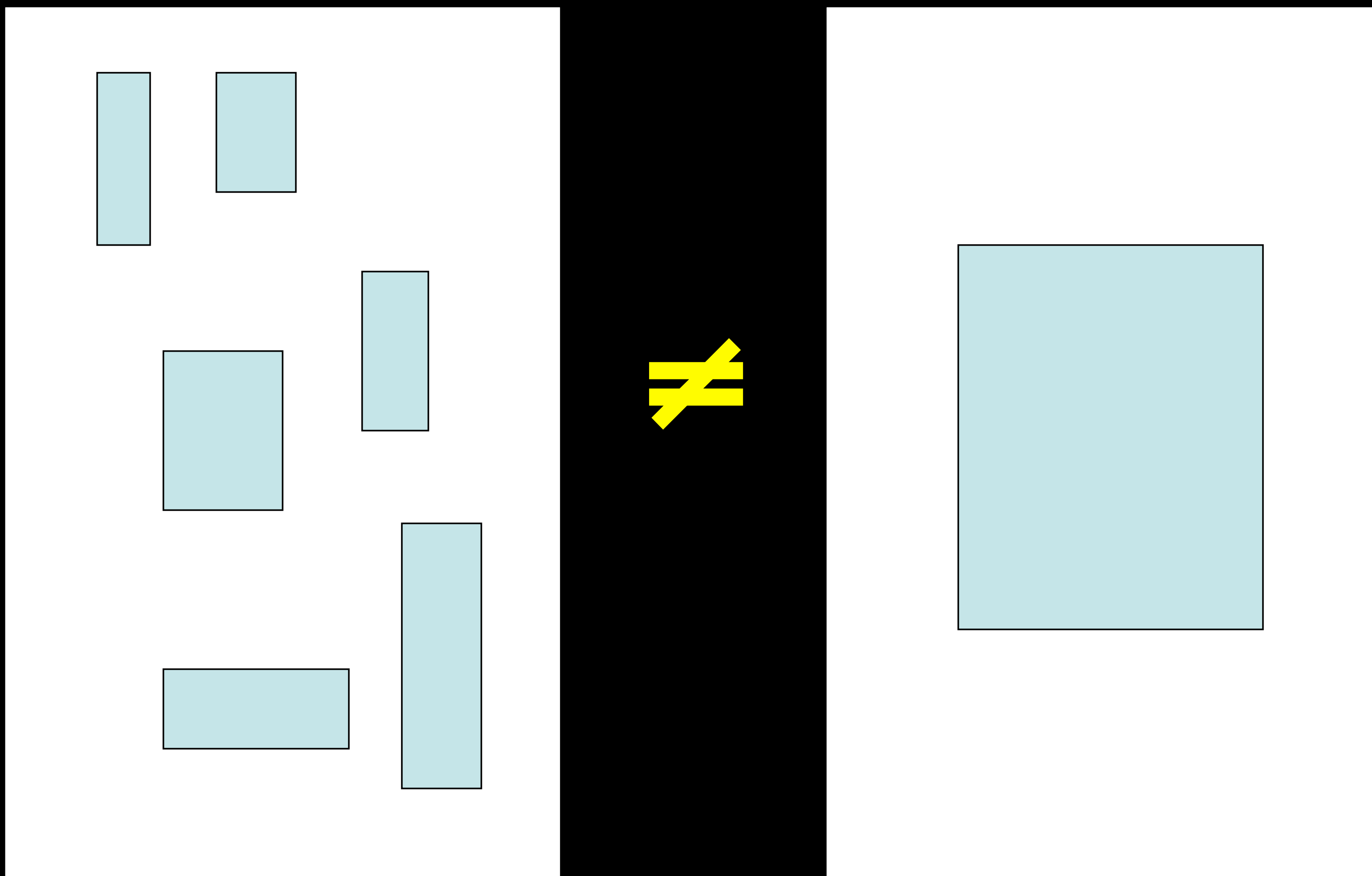
Large-Scale Dynamics





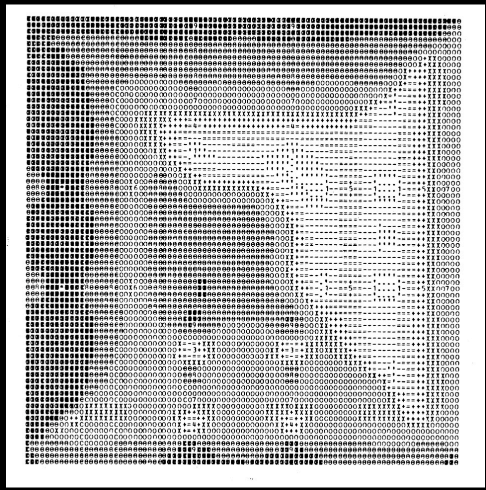
(b)
b
c
e
Biomass
d
a
Time
Same Biomass

# Different Landscape Configurations vary in Structure, Composition and Performance

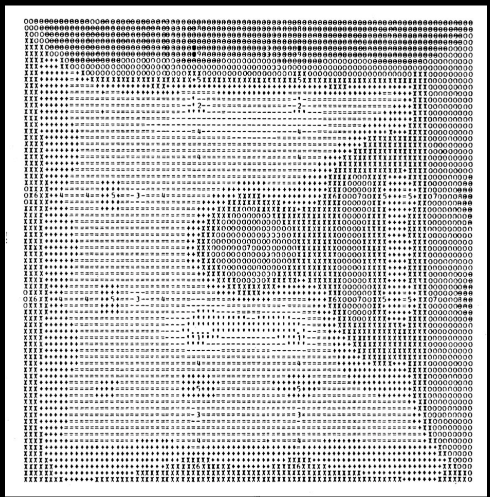


# Differences in Distributions of Species of Trees on Wisconsin Woodlots

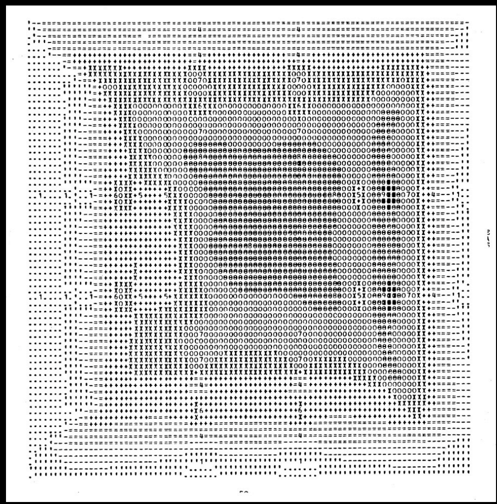
*Tilia americana*

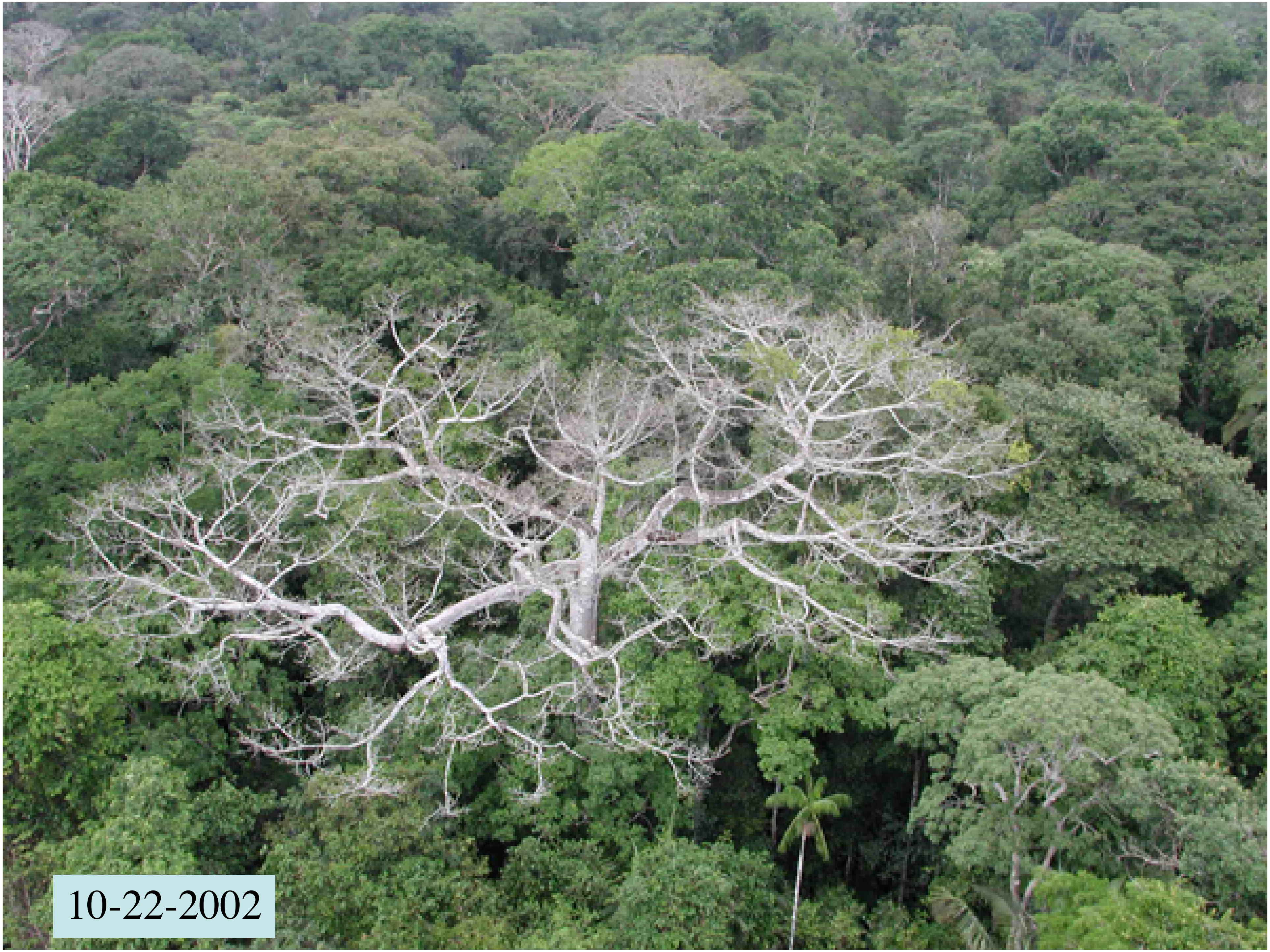


*Fraxinus* sp.



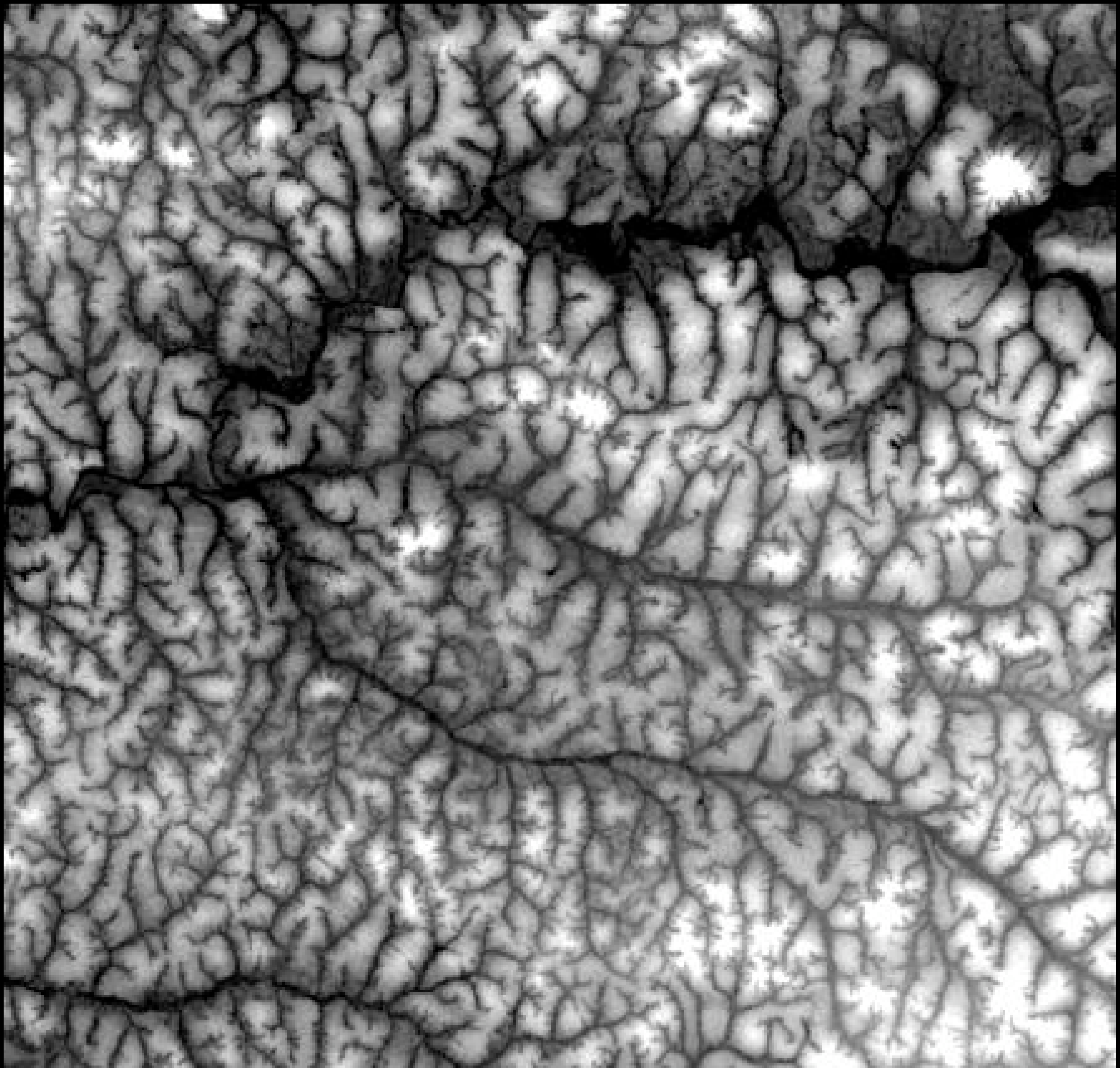
*Fagus grandifolia*

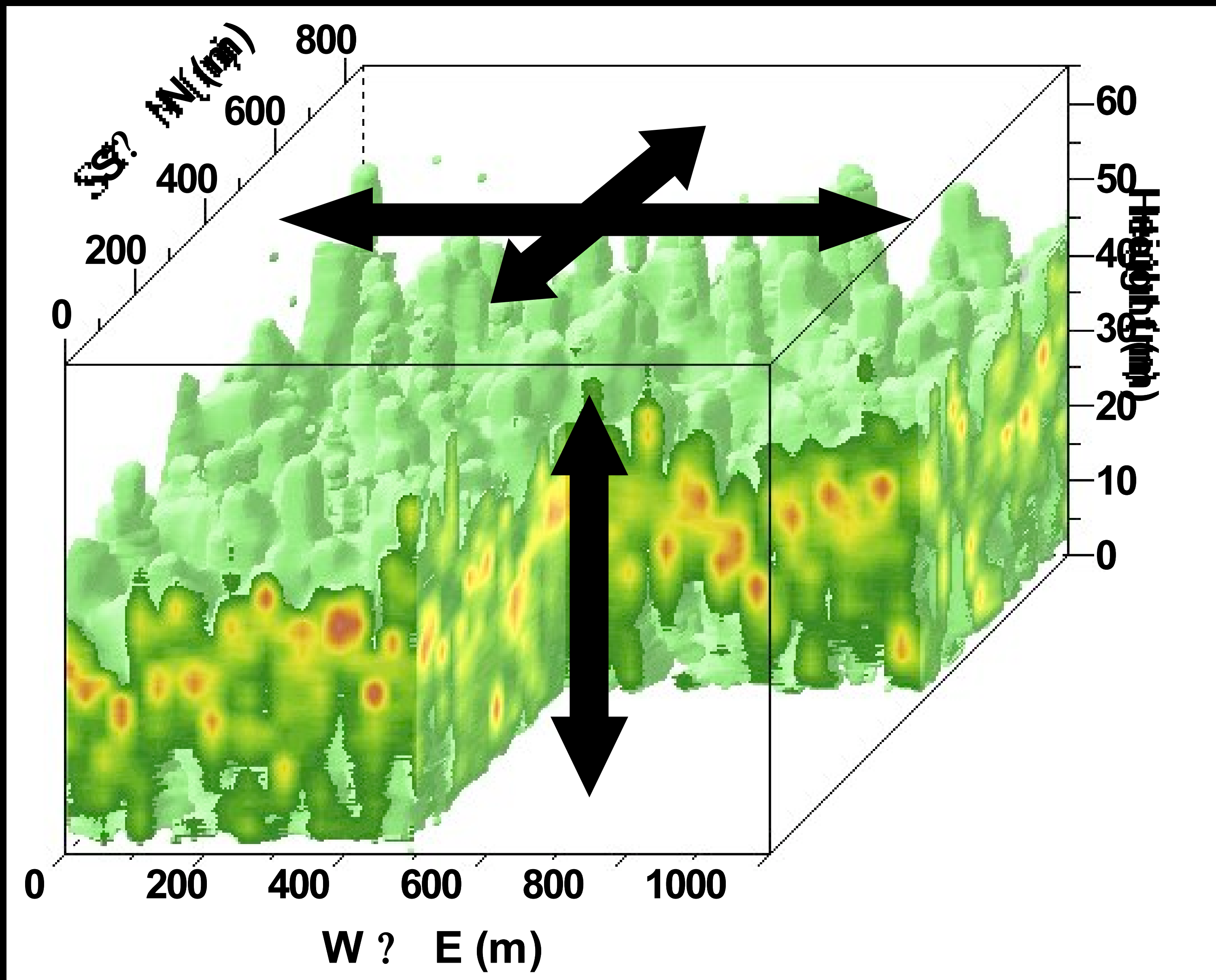



10-22-2002

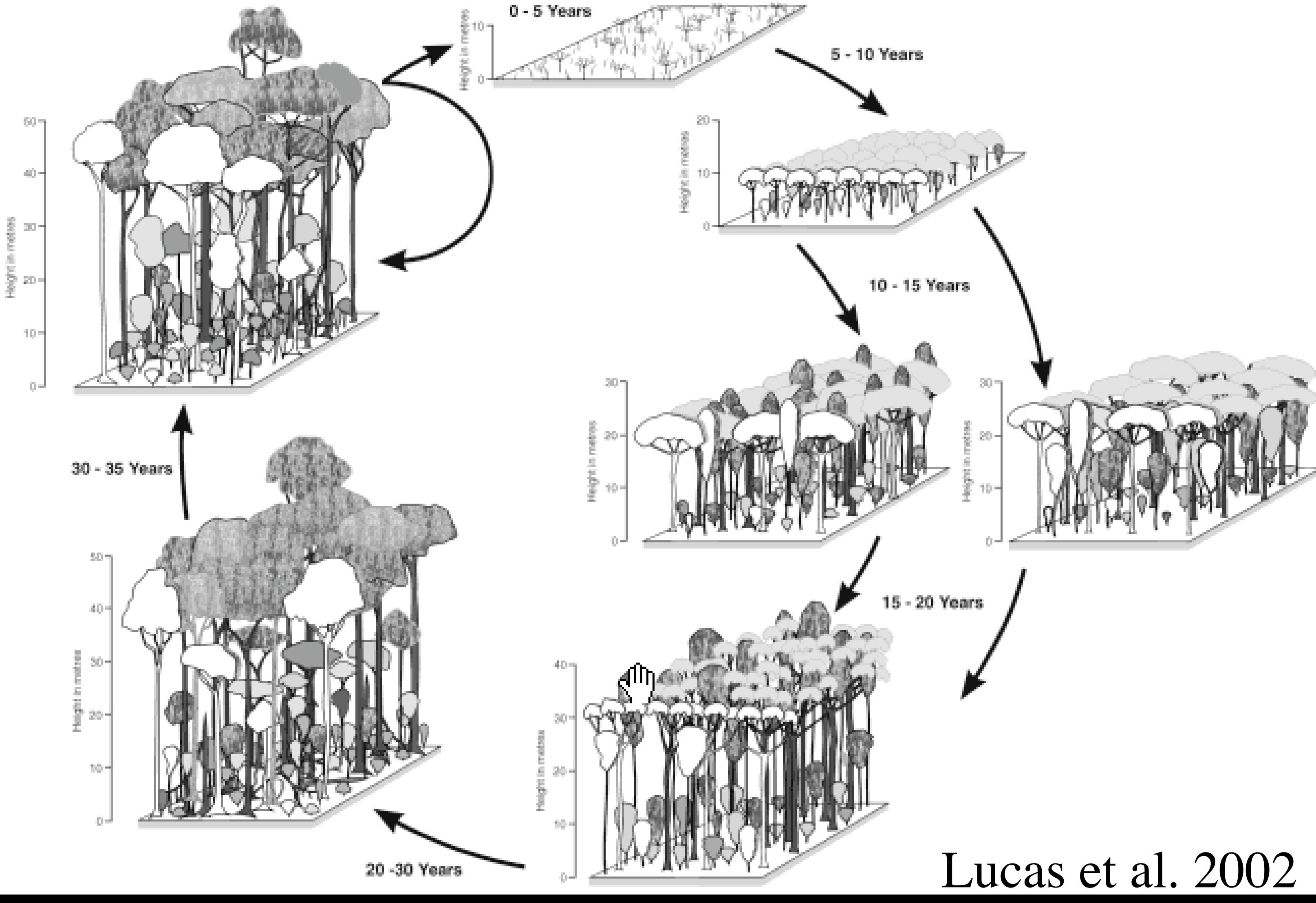

11-01-2002

# Landscape Patterns and Geomorphology in Central Amazon





0
200
400
600
800
1000
W ? E (m)
60
50
40
30
20
10
0




Lucas et al. 2002

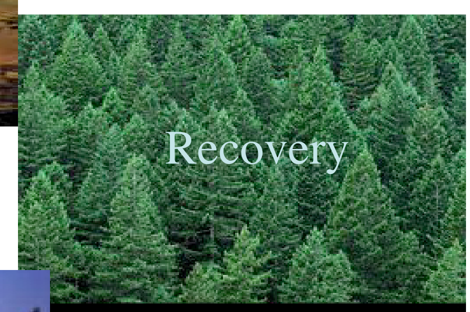
# Global Measurements of Vegetation Structure and Biomass

**Global measurement of above ground biomass in forested ecosystems to estimate the terrestrial carbon stock.**

**Global measurement of changes of carbon stock of forested ecosystems as a result of processes of disturbance and recovery to accurately model terrestrial carbon dynamics**

**Measurements of 3-dimensional forest structure to define and model forest Ecosystem dynamics and habitat biodiversity of forested ecosystems.**

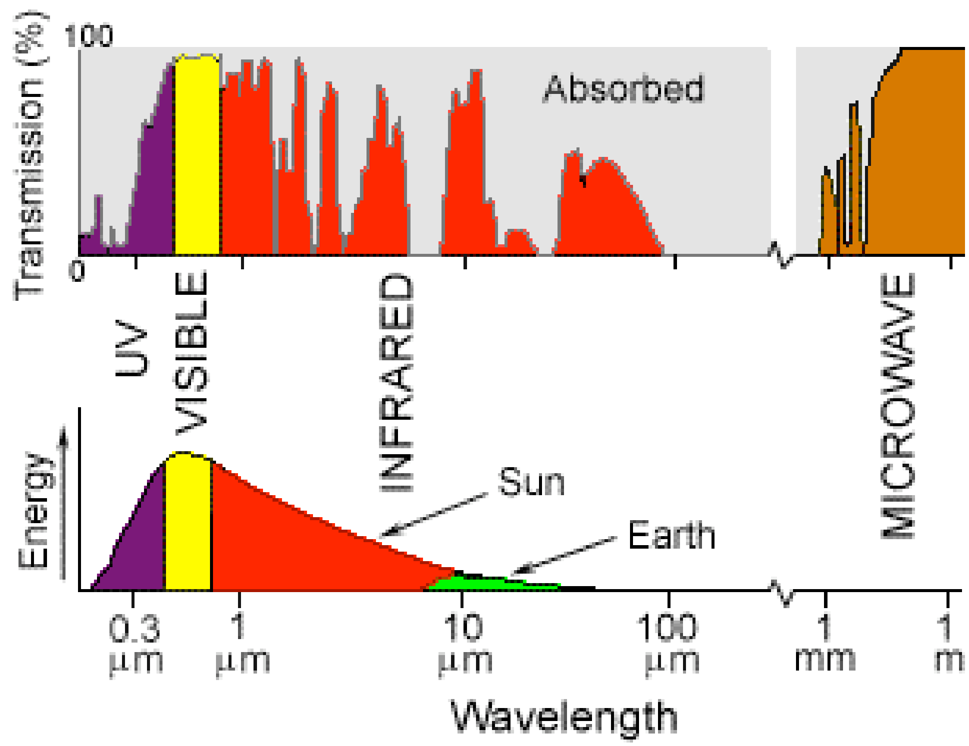


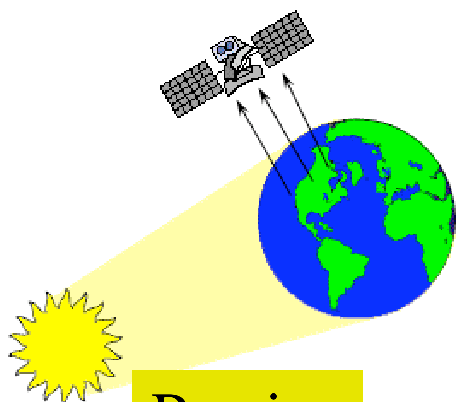




# Remote Sensing Observation

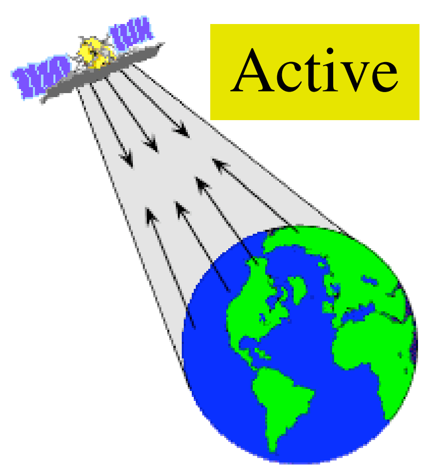
Techniques

Bands

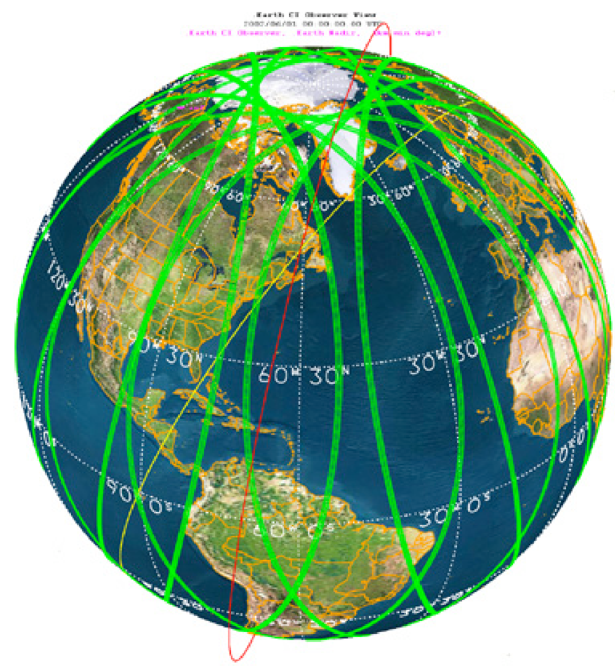


Passive



Active

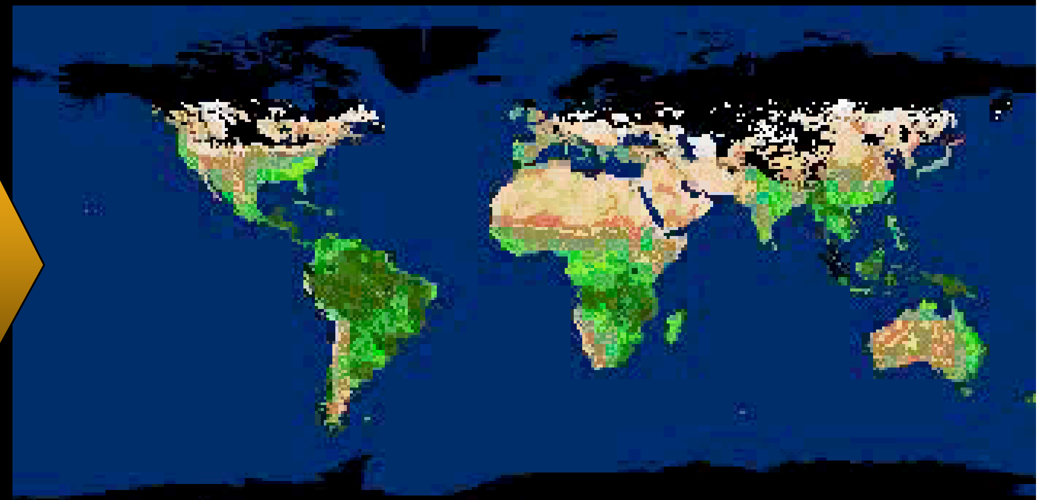


$$\int f(s,t)\,ds\,dt$$

| S | T |
|---|---|
| H | L |
| L | H |
| H | H |
| L | L |

Space

Time



Temporal Capability

Spatial Capability

# Sensors Measuring Vegetation Structure and Biomass

**Active Sensors**

- **LIDAR**
- **RADAR**

**Passive Sensors**

- Multi-angle optical Spectrometers
- Hyperspectral
- Multispectral
- Microwave Radiometers

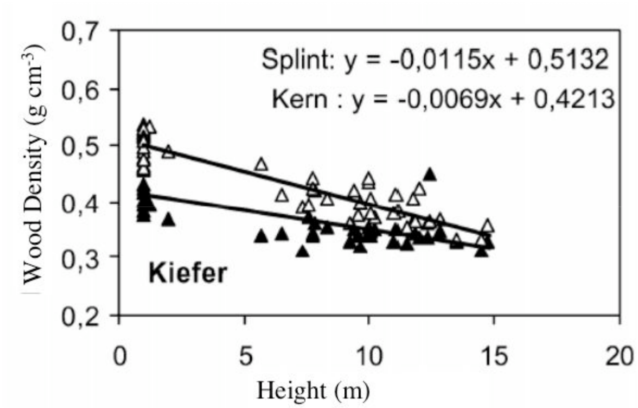
Above Ground Biomass Density(AGBD)

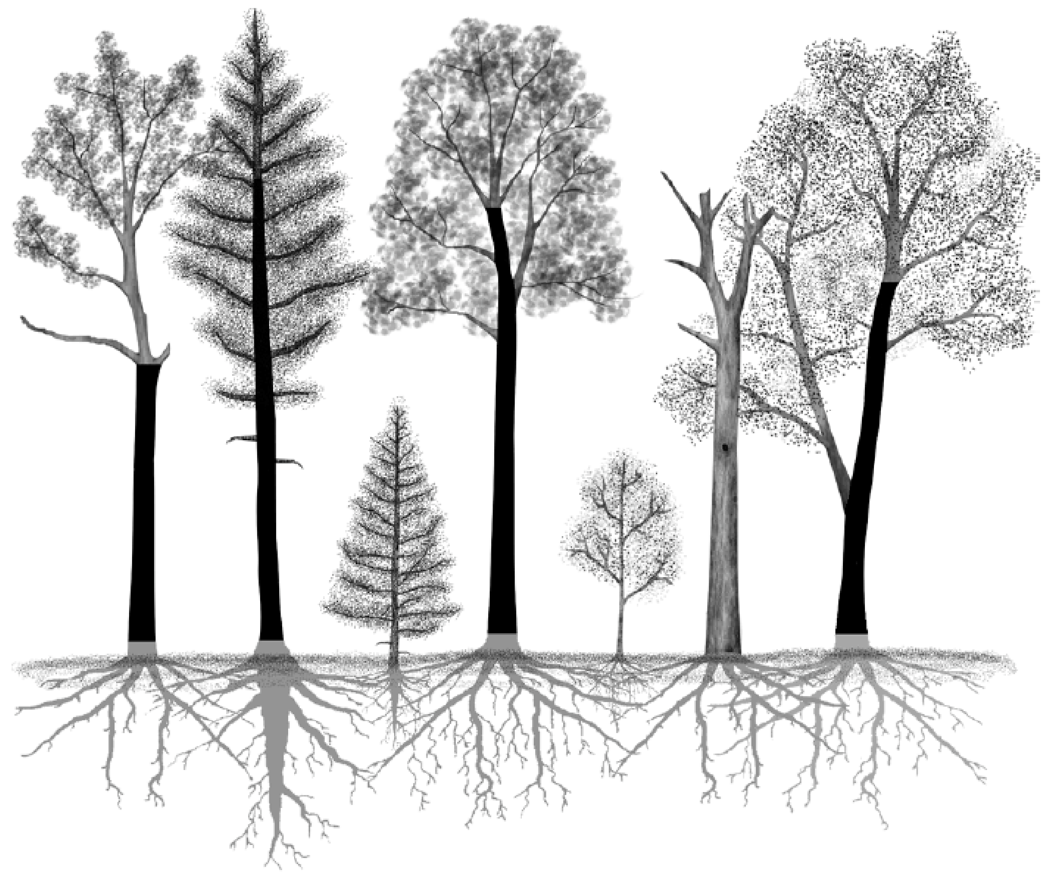
$$AGBD = \frac{1}{A}\sum_i \frac{\pi D_i^2}{4} H_i T_i W_i$$

$$Vol = \frac{1}{A}\sum_i \frac{\pi D_i^2}{4} H_i$$

$$BA = \frac{1}{A}\sum_i \frac{\pi D_i^2}{4}$$

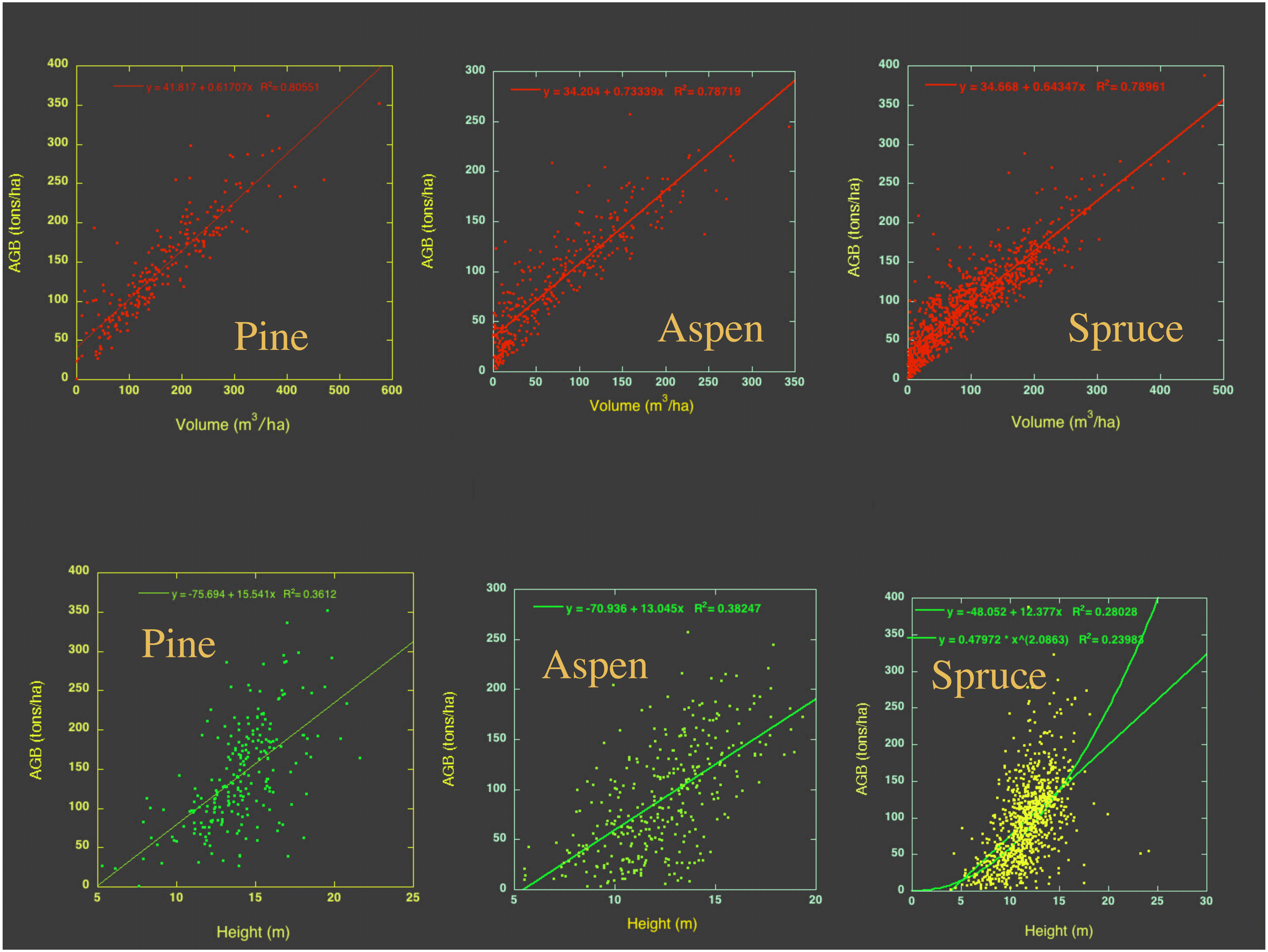
A: Area sampled
D: Diameter at Breast Height, DBH
H: Tree Height
T: Tapering Factor (species dependent)
W: Wood Density (species dependent)

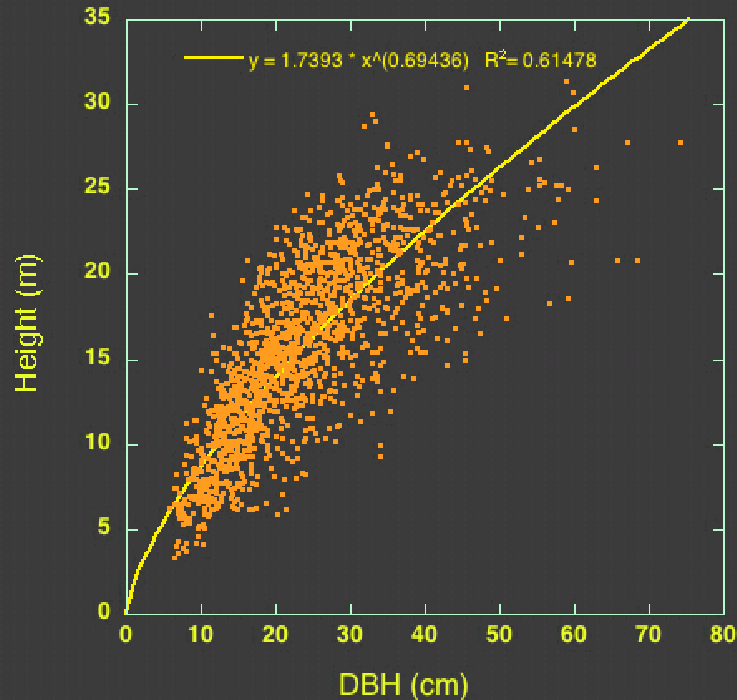


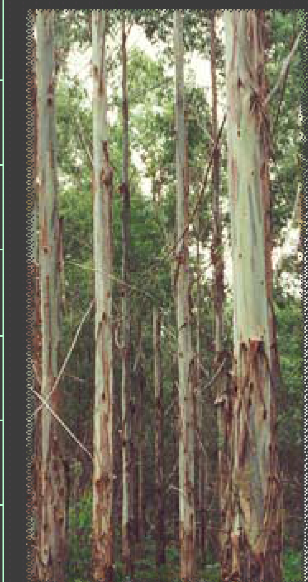



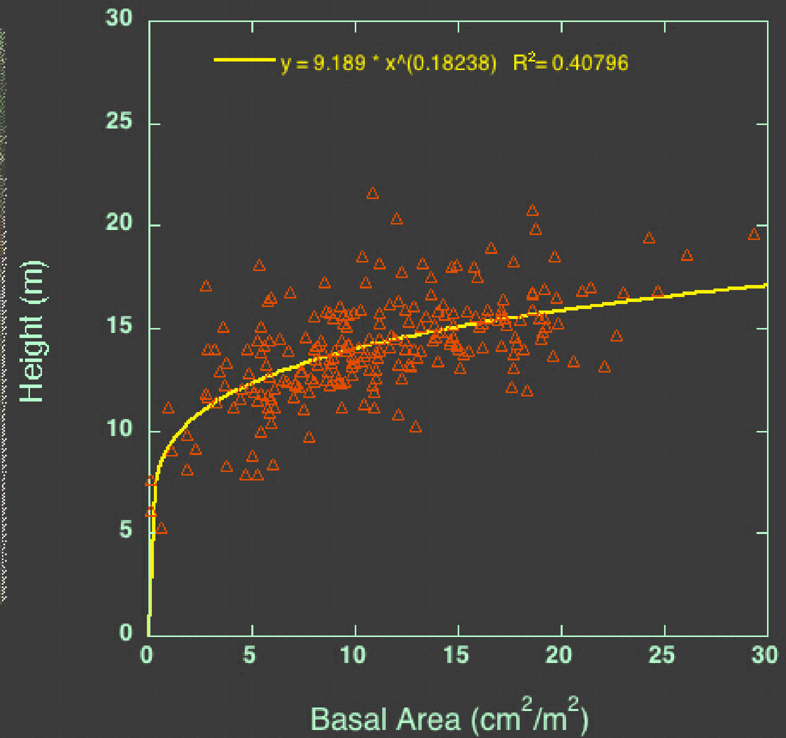
Wood density decreases as a function of tree height

Water content(dielectric constant) increases as a function of tree height


y = 41.817 + 0.61707x R²= 0.80551
Pine
AGB (tons/ha)
Volume (m³/ha)
y = 34.204 + 0.73339x R²= 0.78719
Aspen
AGB (tons/ha)
Volume (m³/ha)
y = 34.668 + 0.64347x R²= 0.78961
Spruce
AGB (tons/ha)
Volume (m³/ha)
y = -75.694 + 15.541x R²= 0.3612
Pine
AGB (tons/ha)
Height (m)
y = -70.936 + 13.045x R²= 0.38247
Aspen
AGB (tons/ha)
Height (m)
y = -48.052 + 12.377x R²= 0.28028
y = 0.47972 * x^(2.0863) R²= 0.23983
Spruce
AGB (tons/ha)
Height (m)



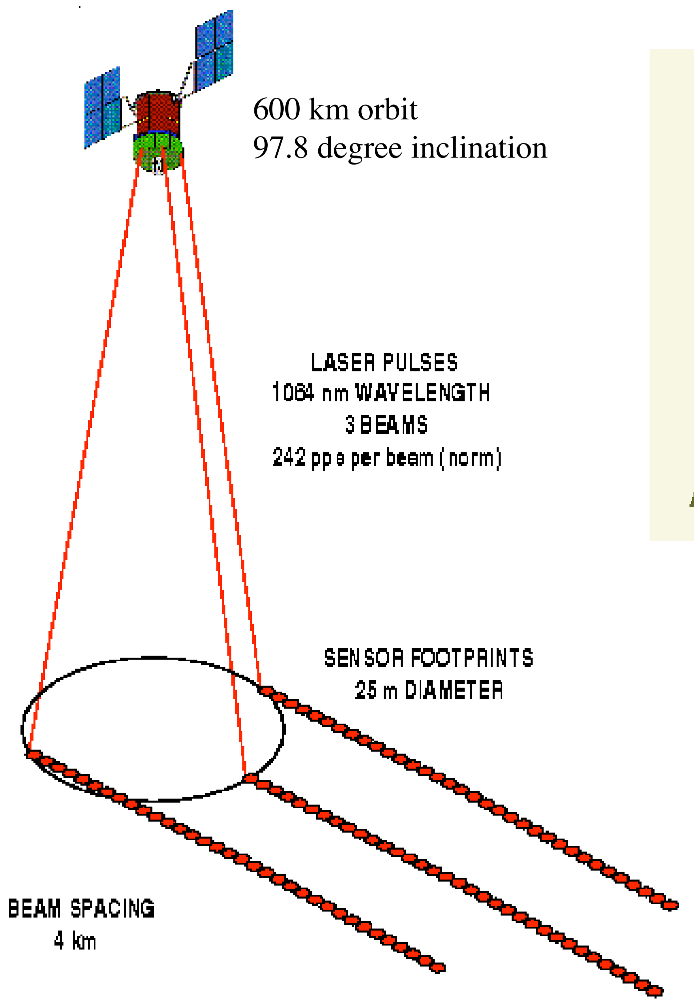



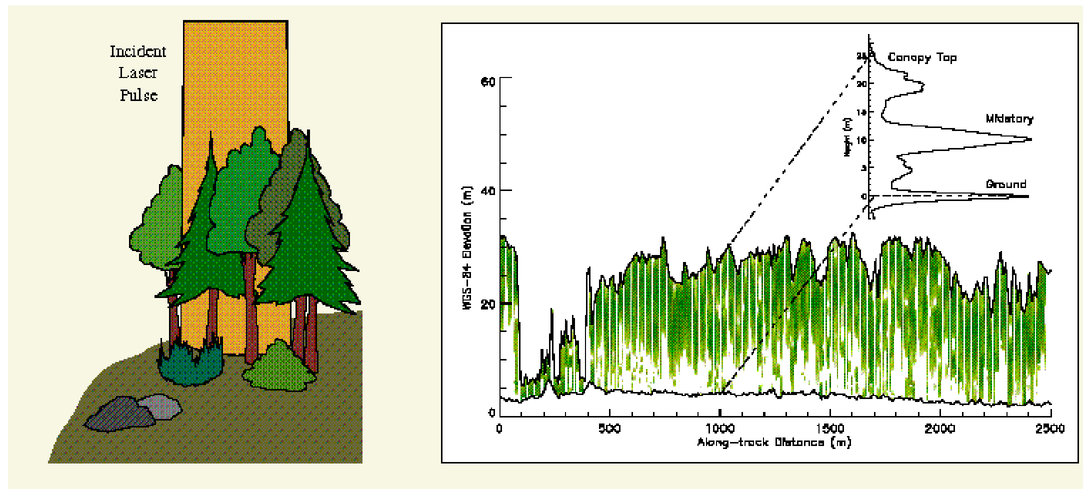


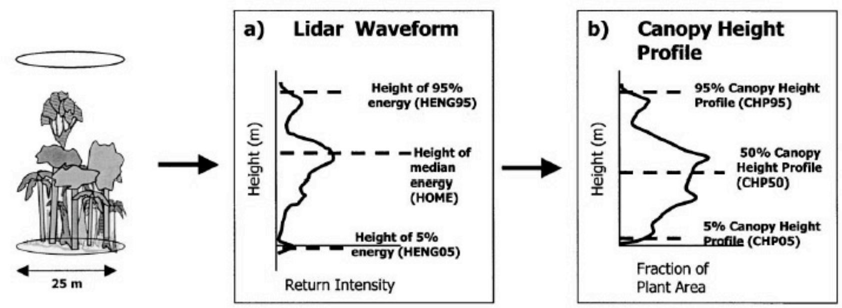

Basal Area and height are independent parameters

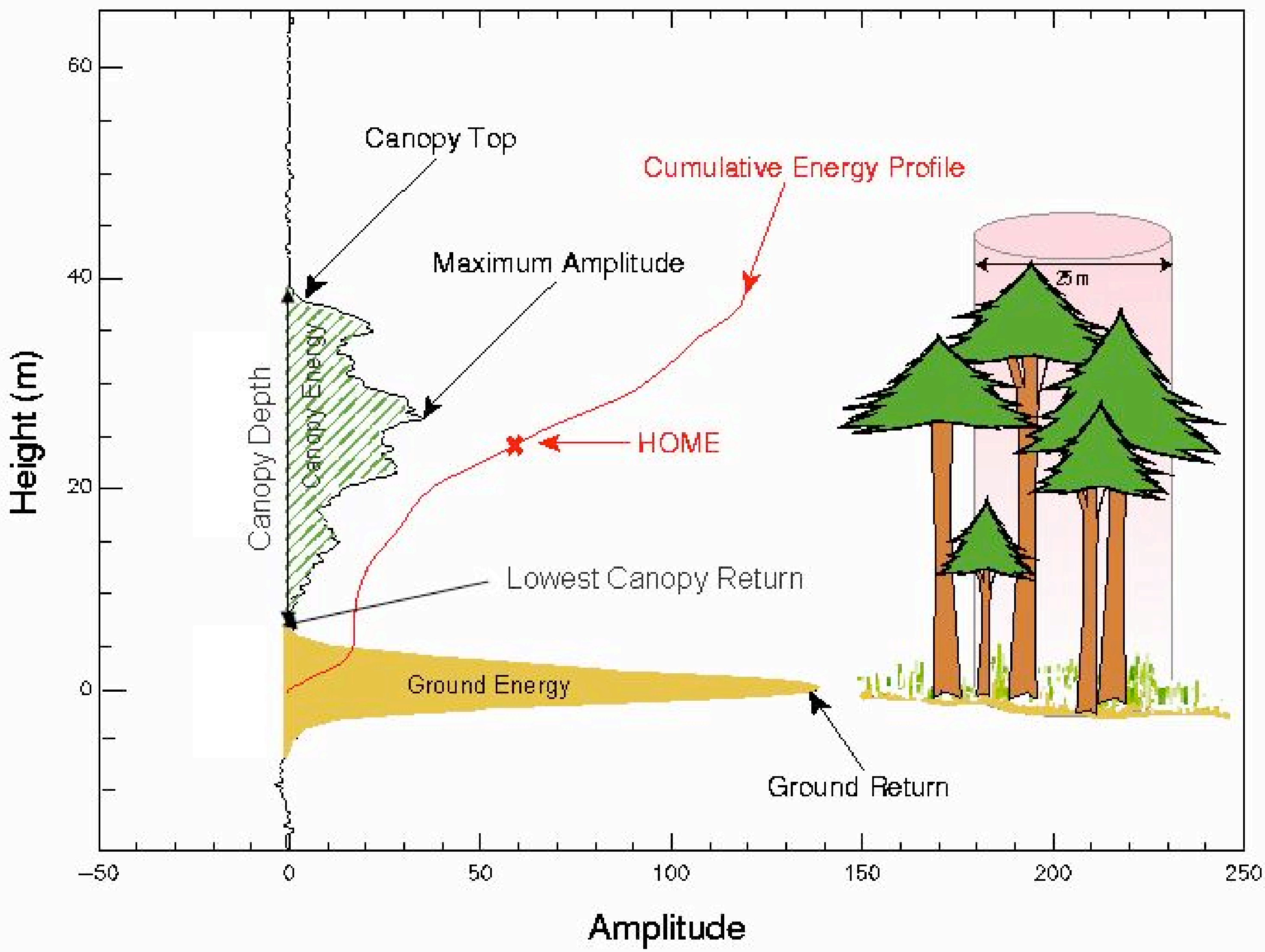
Estimation of height from dbh or basal area results in large errors

# Forest Canopy Laser Altimetry



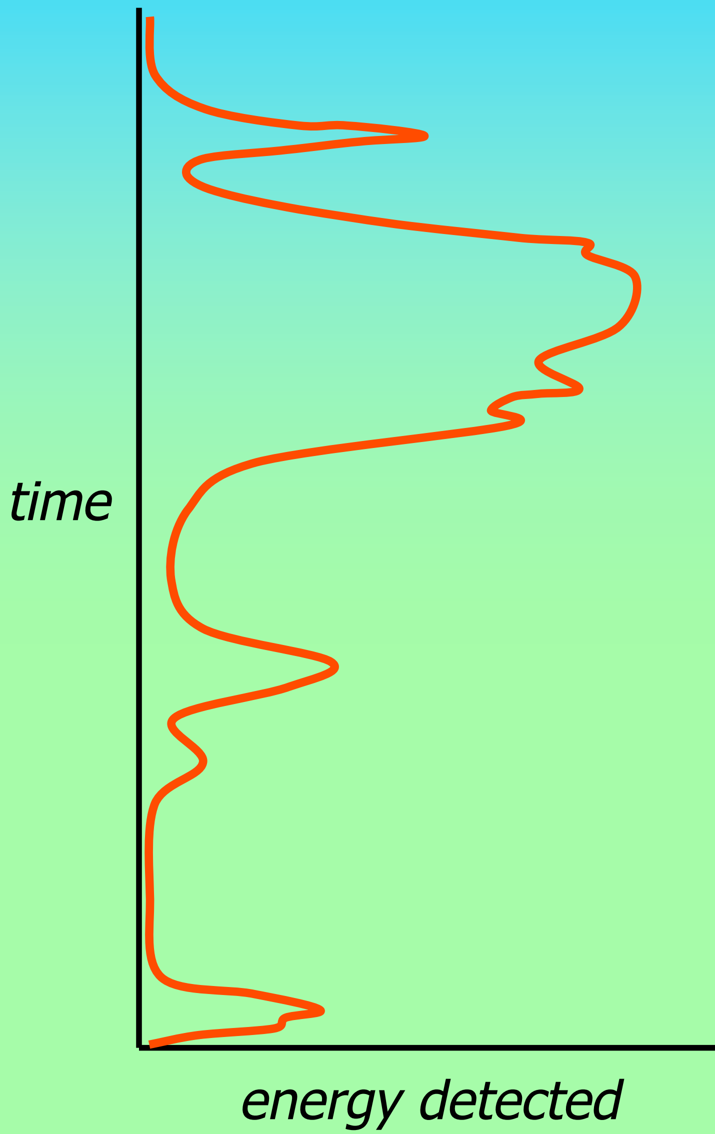



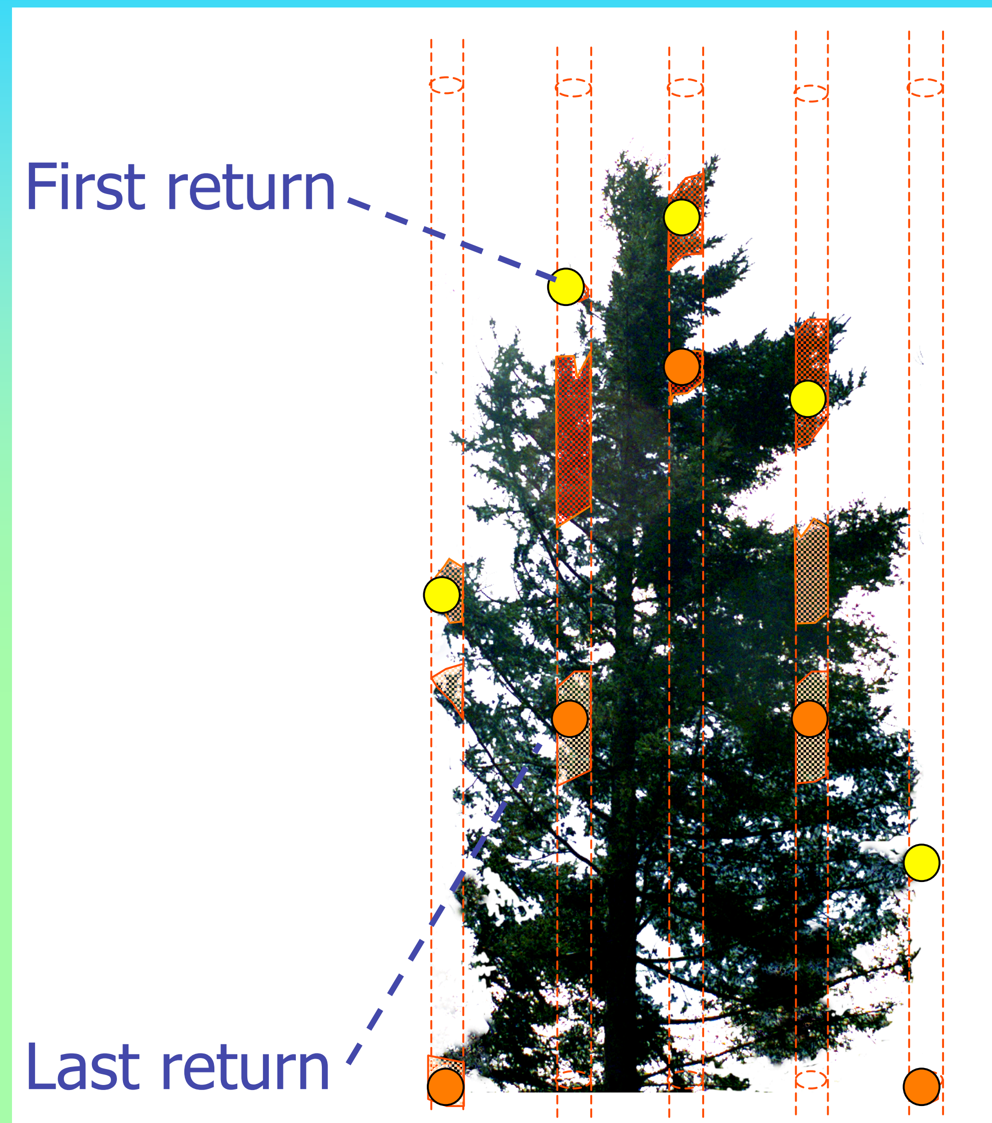





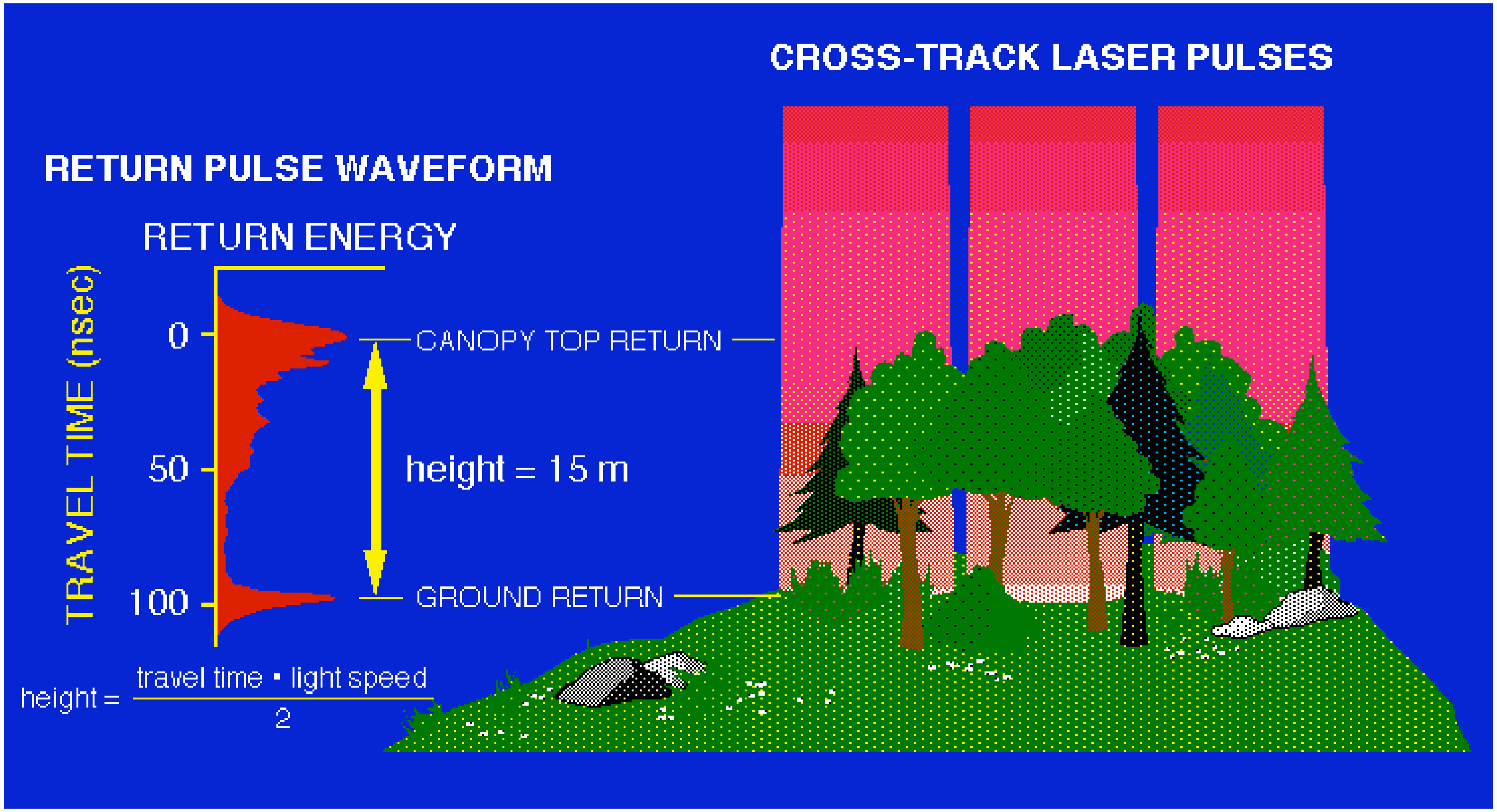
Canopy Top
Cumulative Energy Profile
Maximum Amplitude
25 m
Canopy Depth
Canopy Energy
HOME
Lowest Canopy Return
Ground Energy
Ground Return
Height (m)
60
40
20
0
-50
0
50
100
150
200
250
Amplitude

# Small footprint scanning LIDAR    Single Return



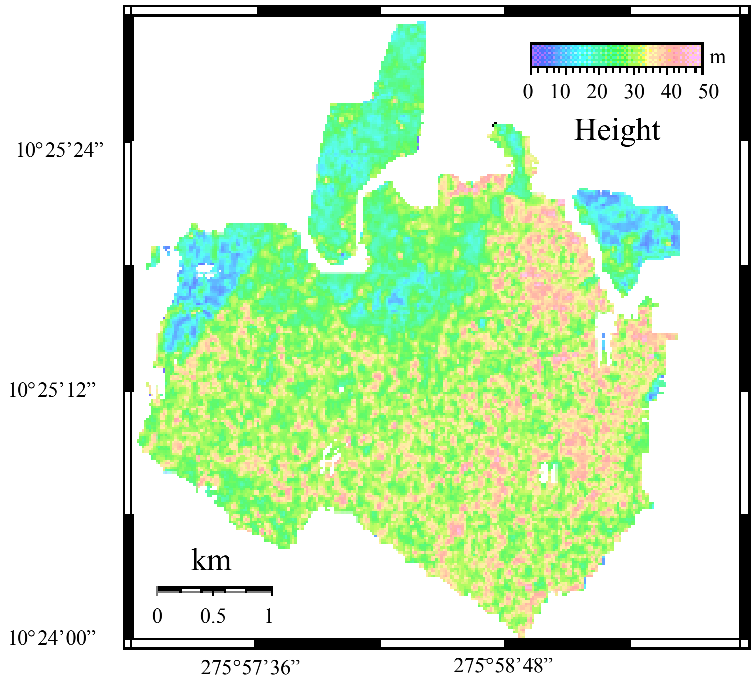



# Large Footprint/Waveform Lidar

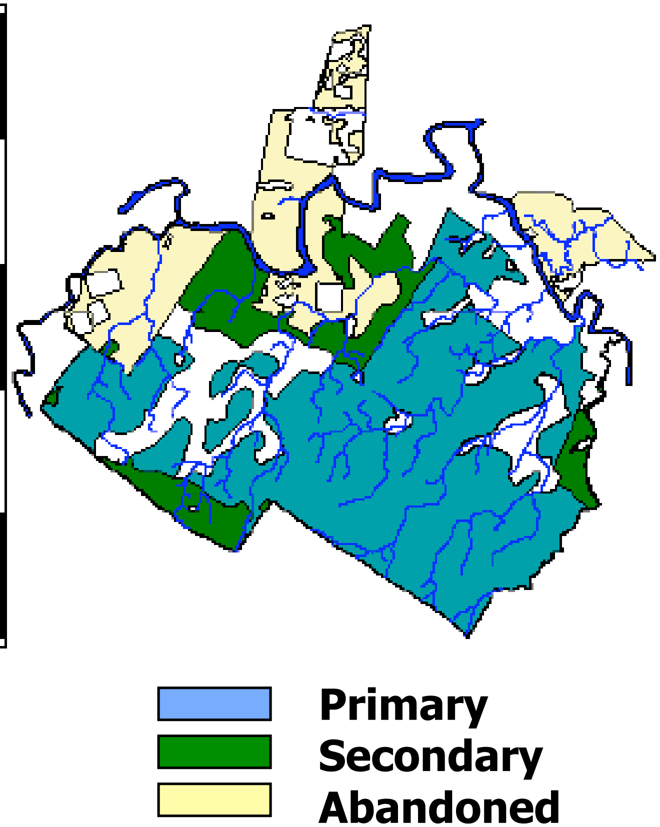


# Lidar (LVIS) Derived Successional State

**La Selva Height**

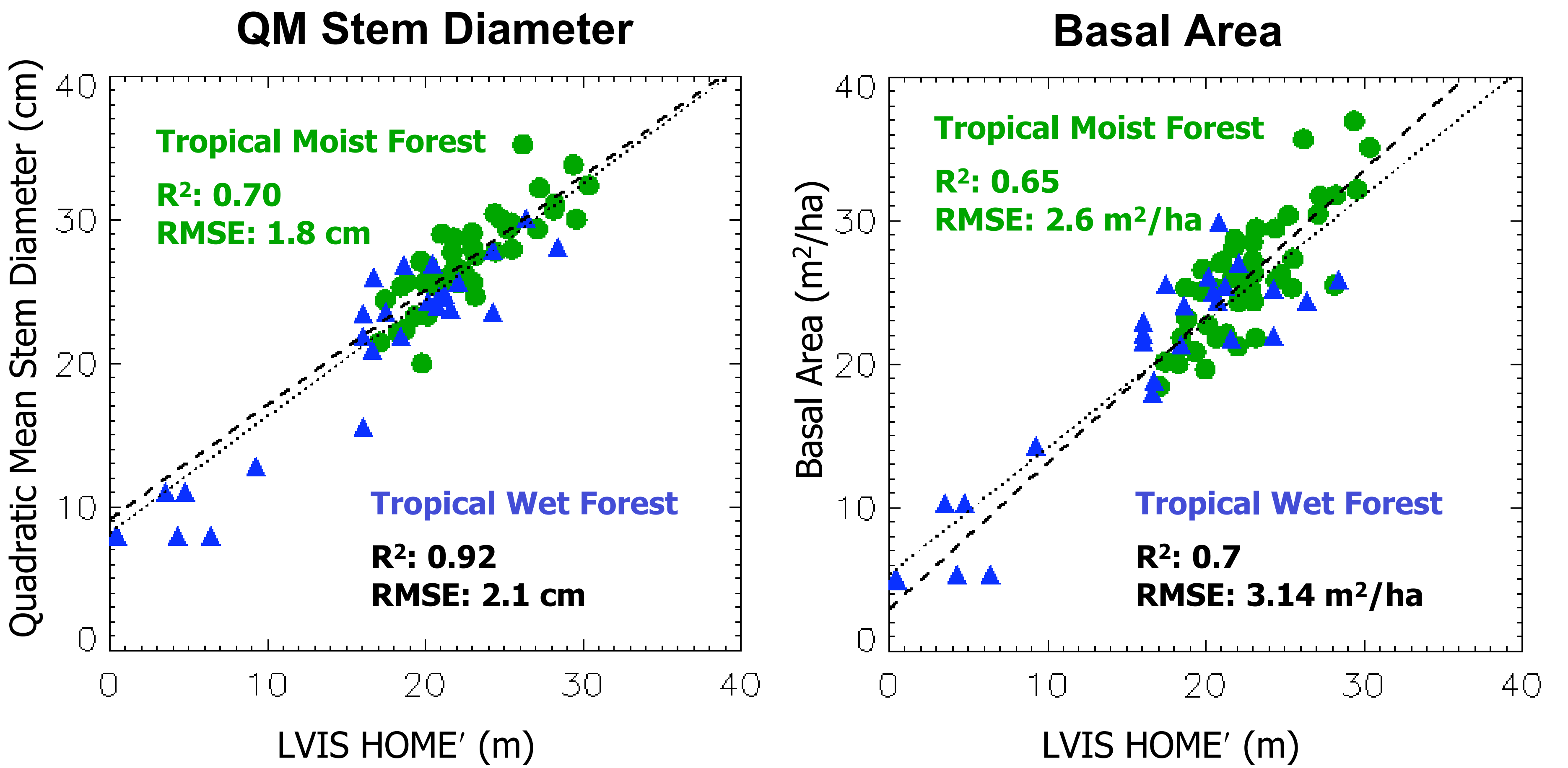



**La Selva Landuse**




From: B. Peterson, 2000, *Recovery of Forest Canopy Heights Using Large-footprint Lidar*, M.A. Thesis, University of Maryland College Park, 58 pp.

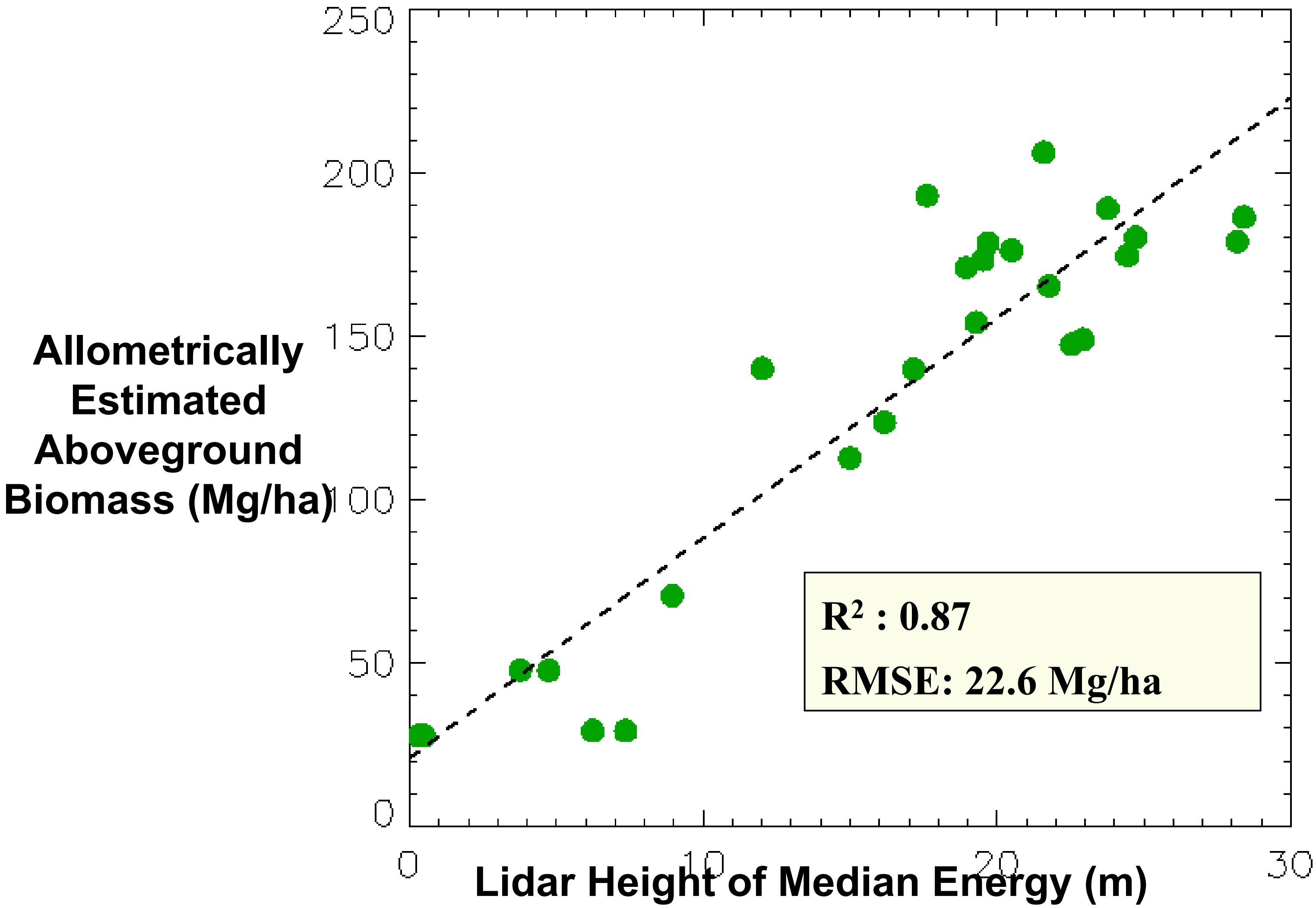
# Lidar-estimated Vegetation Structure Characteristics, La Selva




From: J. Drake, R. Dubayah, D. Clark, R. Knox, J. Blair, M. Hofton, R. Chazdon, J. Weishampel, and S. Prince, Estimation of forest structural characteristics using large footprint lidar, *Remote Sensing of the Environment*, 79, 305-319, 2002.

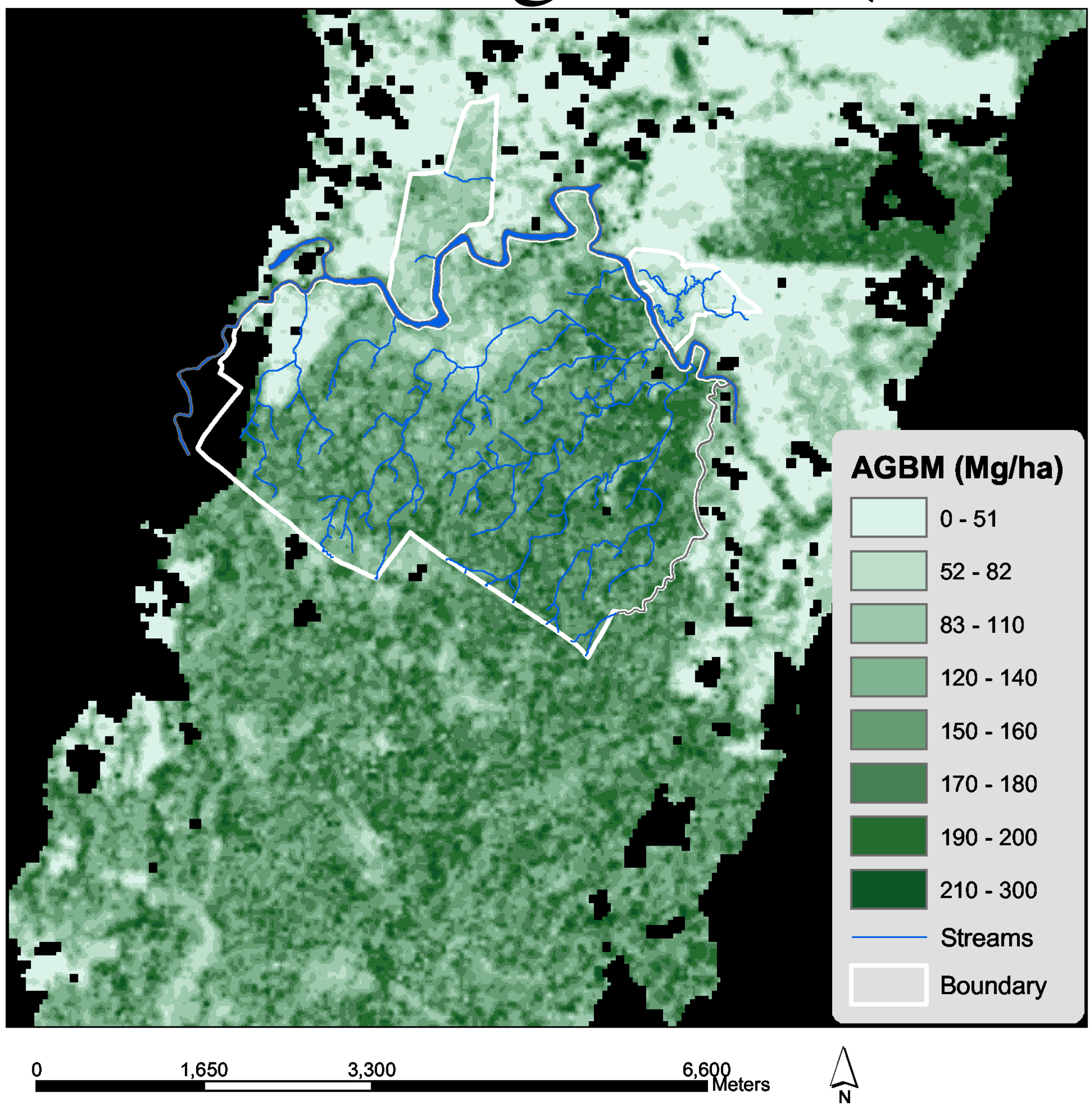
**Estimating Aboveground Biomass at La Selva Using Lidar (LVIS)**

# Aboveground Biomass Estimation using Lidar

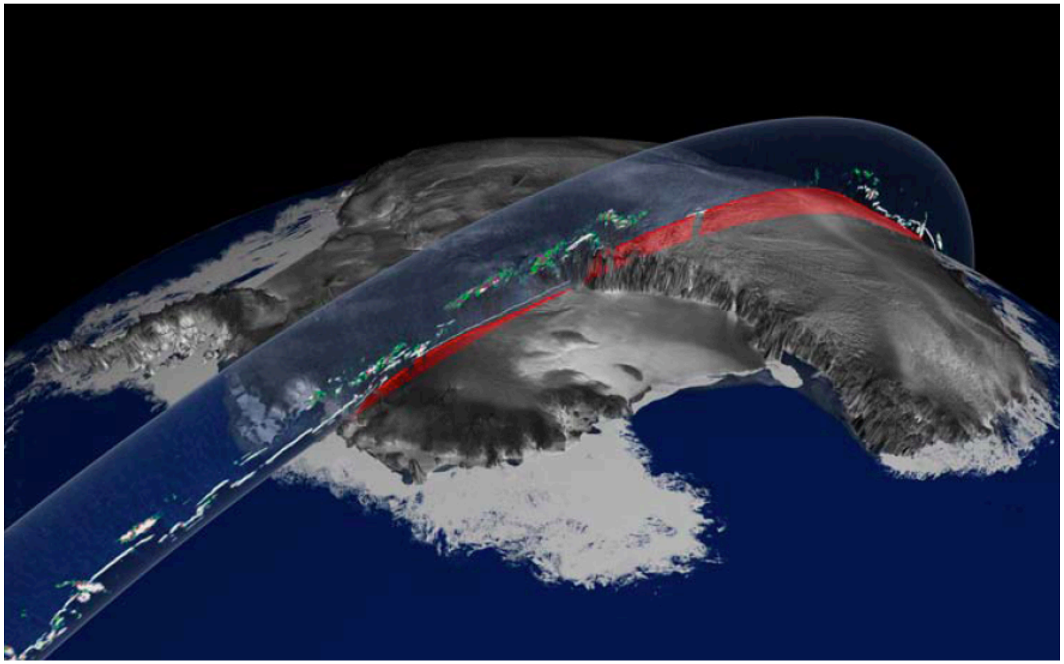



From: J. Drake, R. Dubayah, D. Clark, R. Knox, J. Blair, M. Hofton, R. Chazdon, J. Weishampel, and S. Prince, Estimation of forest structural characteristics using large footprint lidar, *Remote Sensing of the Environment*, 79, 305-319, 2002.

# Estimating Aboveground Biomass at La Selva Using Lidar (LVIS)




From: J. Drake, R. Dubayah, D. Clark, R. Knox, J. Blair, M. Hofton, R. Chazdon, J. Weishampel, and S. Prince, Estimation of forest structural characteristics using large footprint lidar, *Remote Sensing of the Environment*, 79, 305-319, 2002.

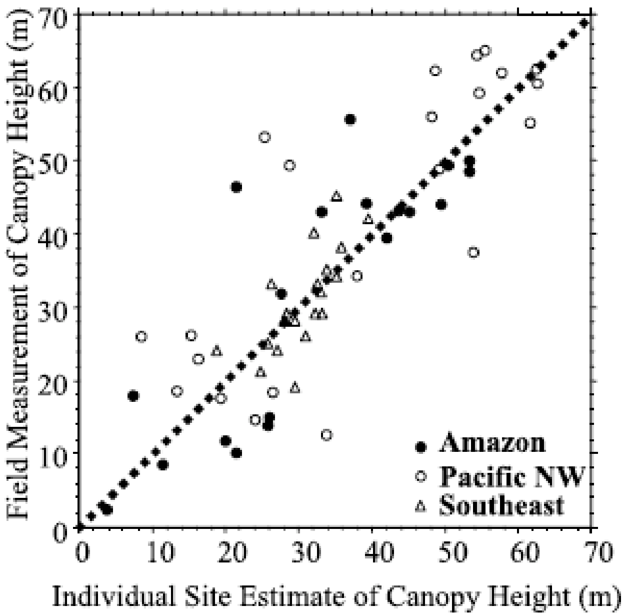



Equations relating Waveform Width, Change in Elevation, and Forest Height

$$\text{Forest height} = B_0 * \text{Width} + B_1 * \text{Change in Elevation}$$

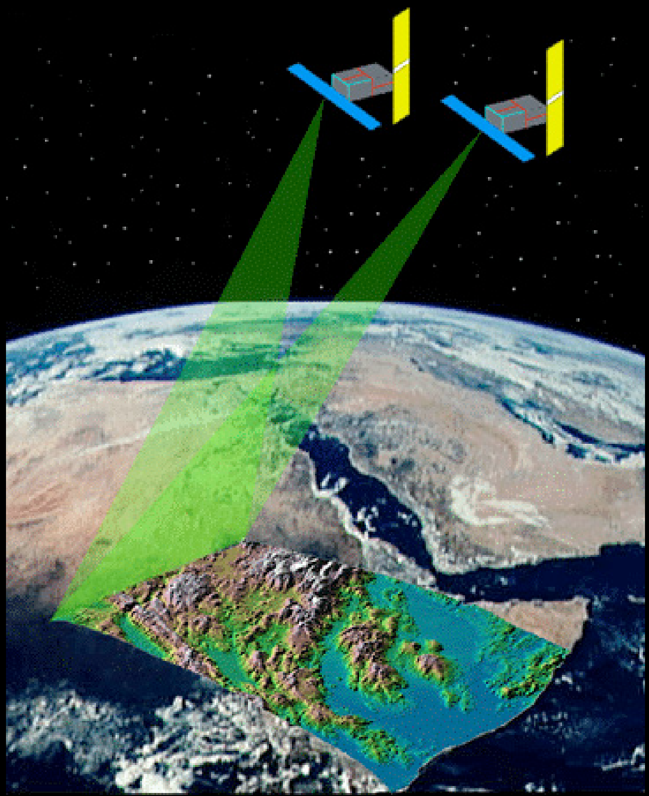
| | $R^2$ | $B_0$ | $B_1$ | Bias (m) | Standard Error (m) | Count |
|---|---|---|---|---|---|---|
| Amazon | 68% | 1.08249 | 0.22874 | -0.48 | 9.90 | 19 |
| Pacific NW | 64% | 0.96599 | 0.05953 | -1.71 | 12.66 | 24 |
| Southeast | 59% | 0.68778 | 0.14517 | 0.01 | 4.85 | 23 |
| Combined | 67% | --- | --- | -0.76 | 9.61 | 66 |
| All | 48% | 0.88896 | 0.15427 | -0.84 | 12.14 | 66 |

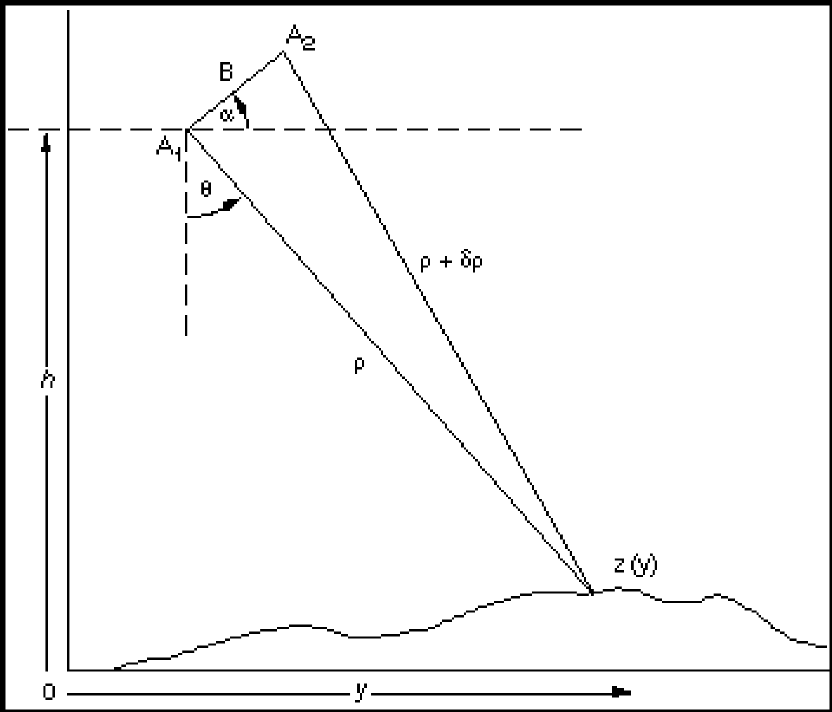
Harding et al. 2004

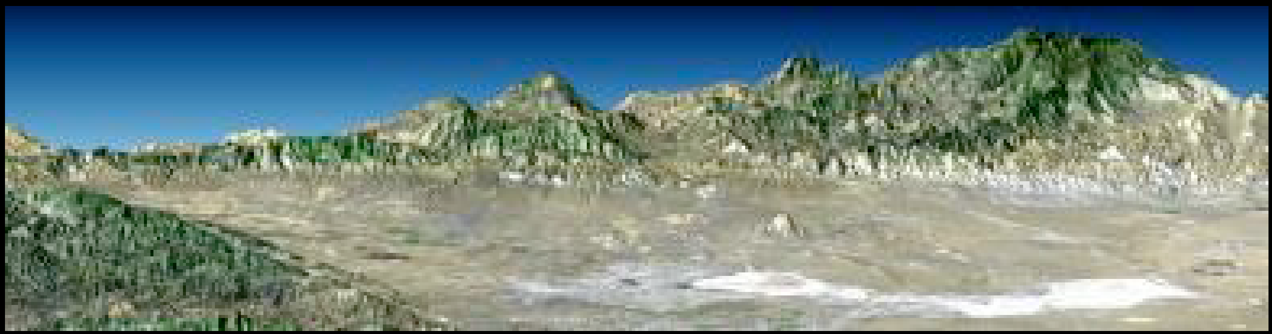


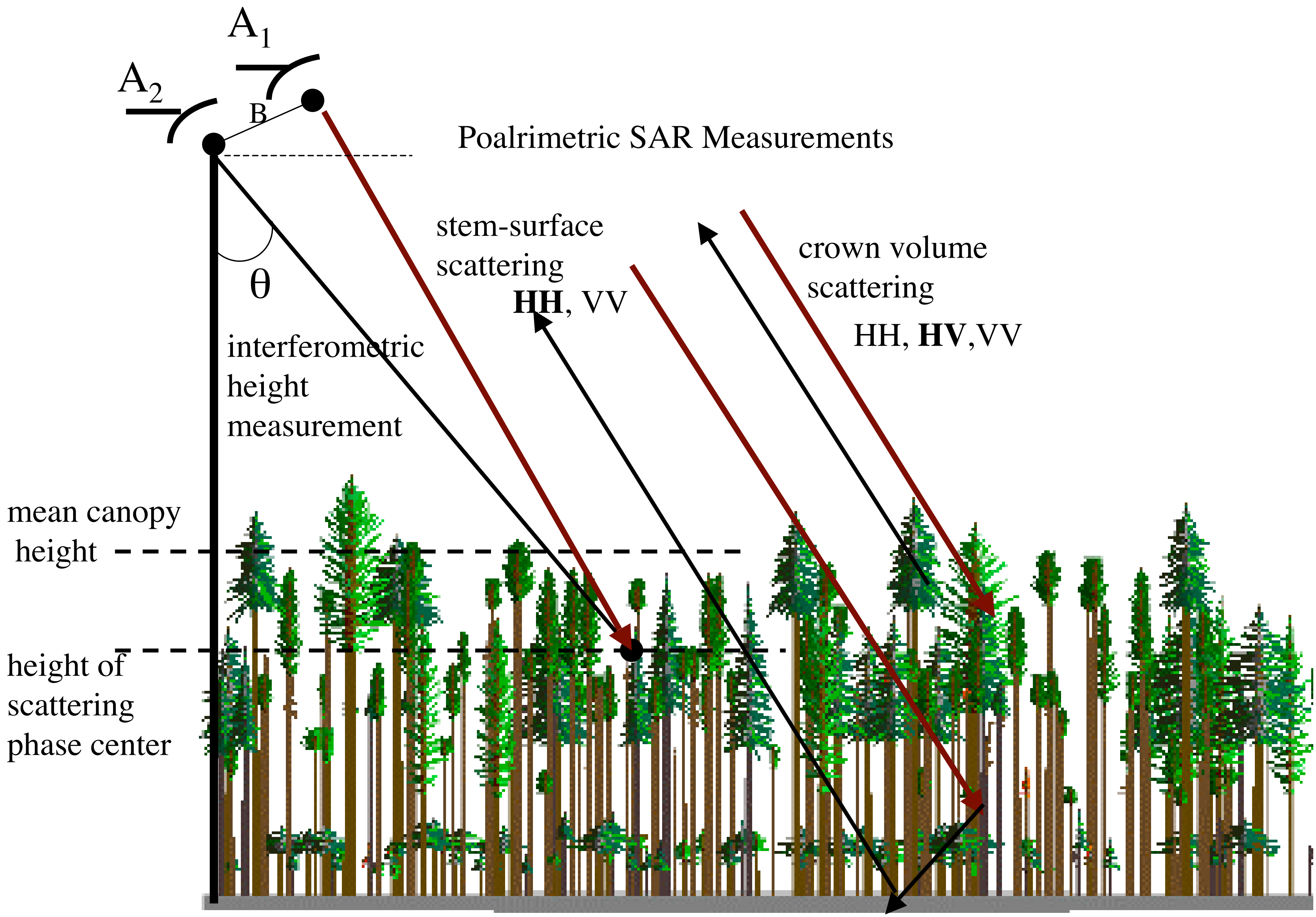

Lefsky et al. 2005

# SAR Polarimetry & Interferometry

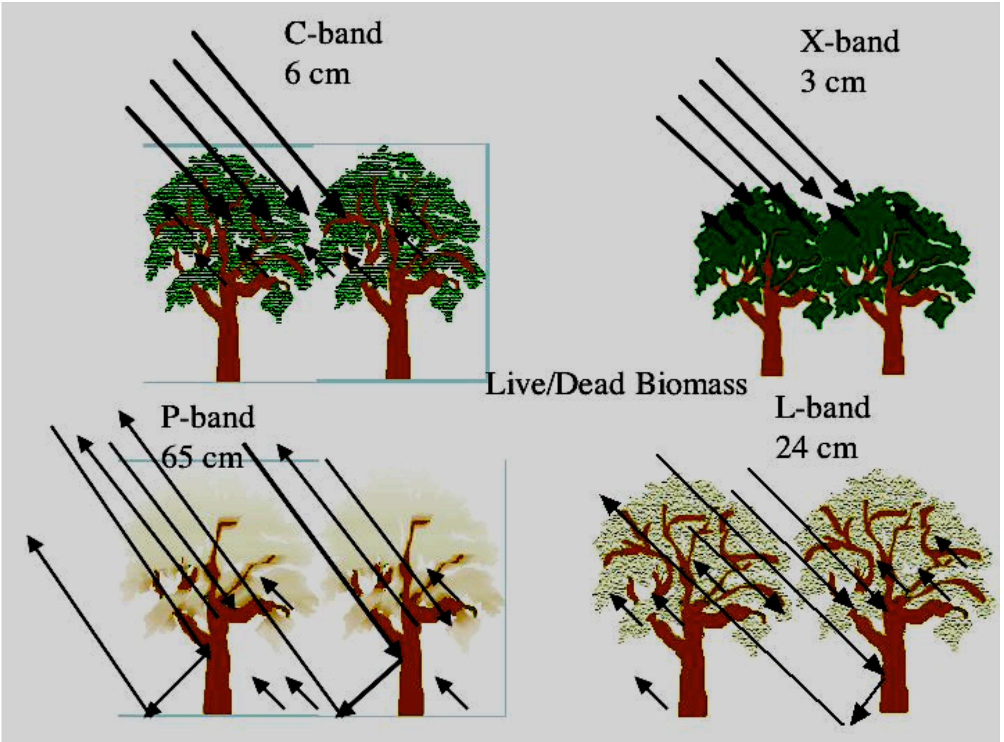




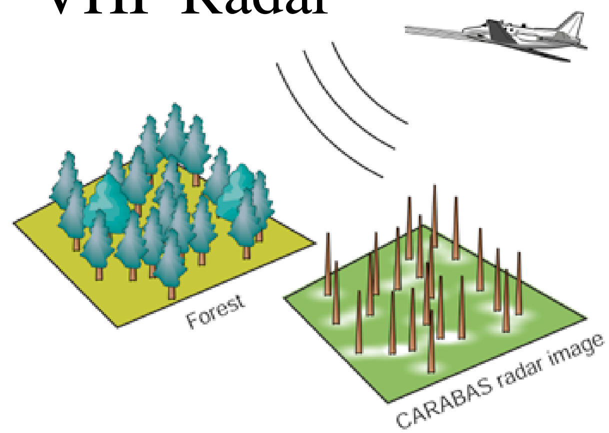



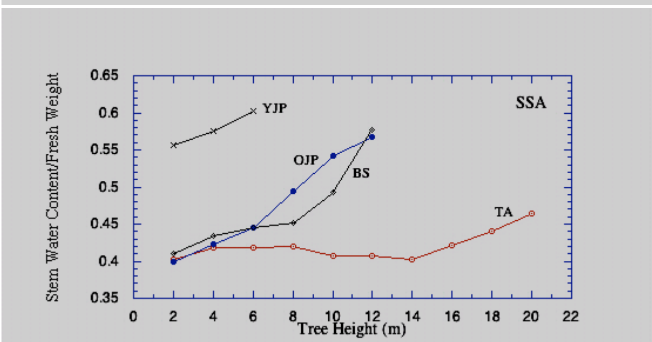


$A_1$
$A_2$
B
Poalrimetric SAR Measurements
stem-surface
scattering
**HH**, VV
crown volume
scattering
HH, **HV**,VV
θ
interferometric
height
measurement
mean canopy
height
height of
scattering
phase center




VHF Radar



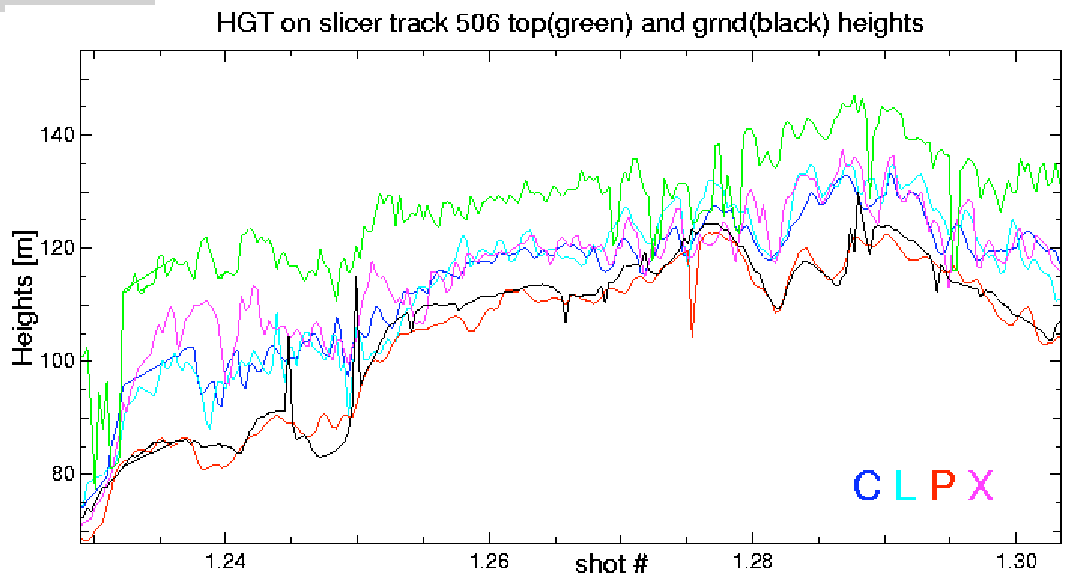




$$\sigma^0 = f(\frac{1}{A}\sum Vol_i, \varepsilon)$$

$$\varepsilon = g(W)$$

$\varepsilon$ : dielectric constant

$W$ : wood density (1 - water content)

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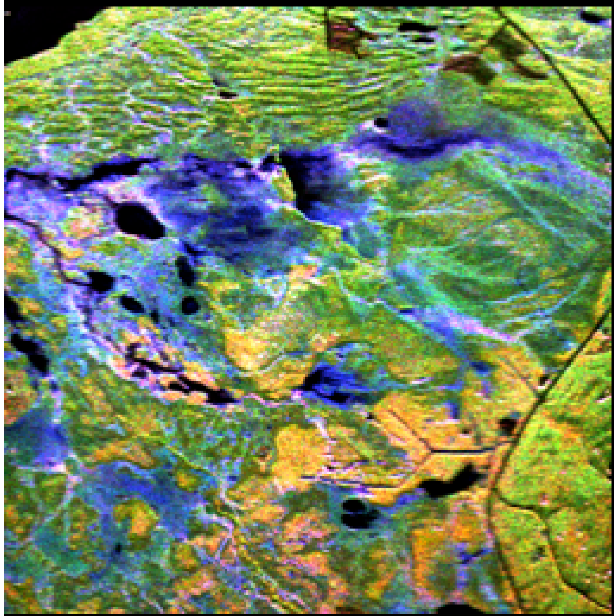
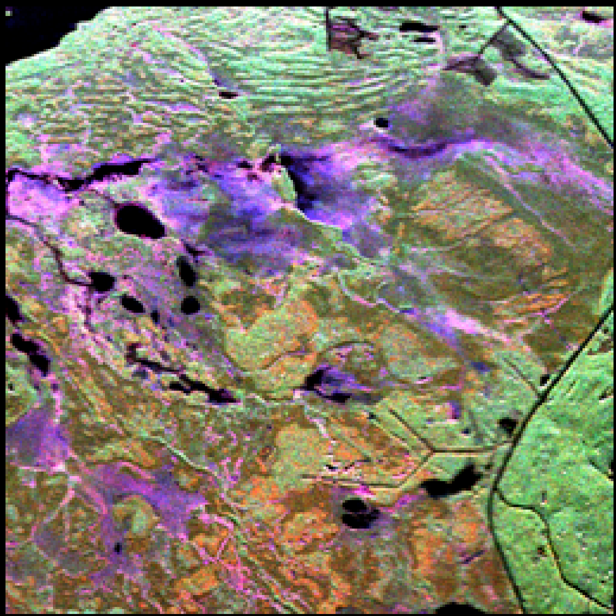
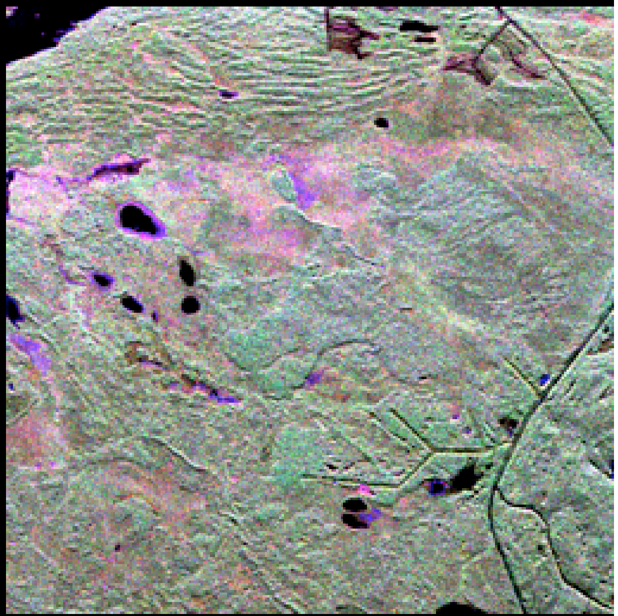
# Radar Observation of Forest Stands
# Impact of Polarization & Wavelength



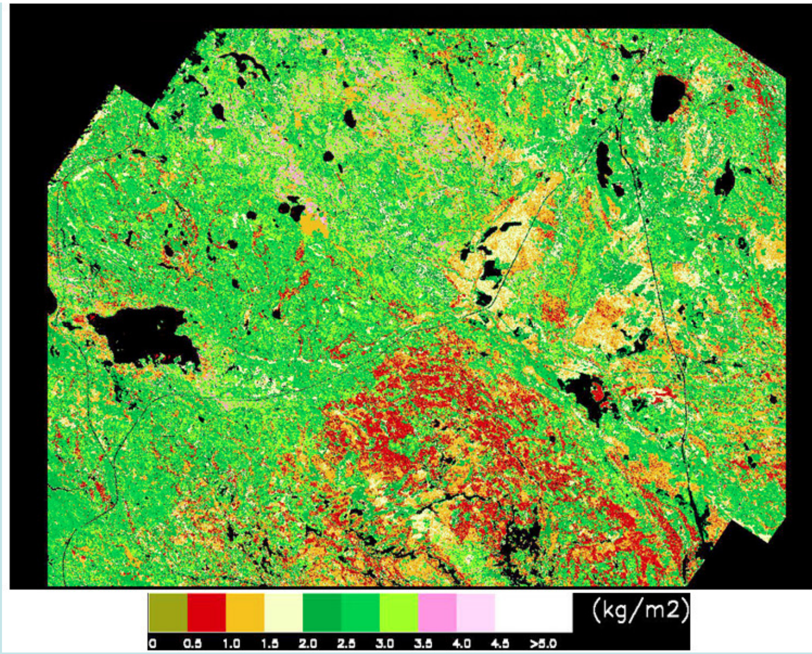
P-band (HH,HV,VV)

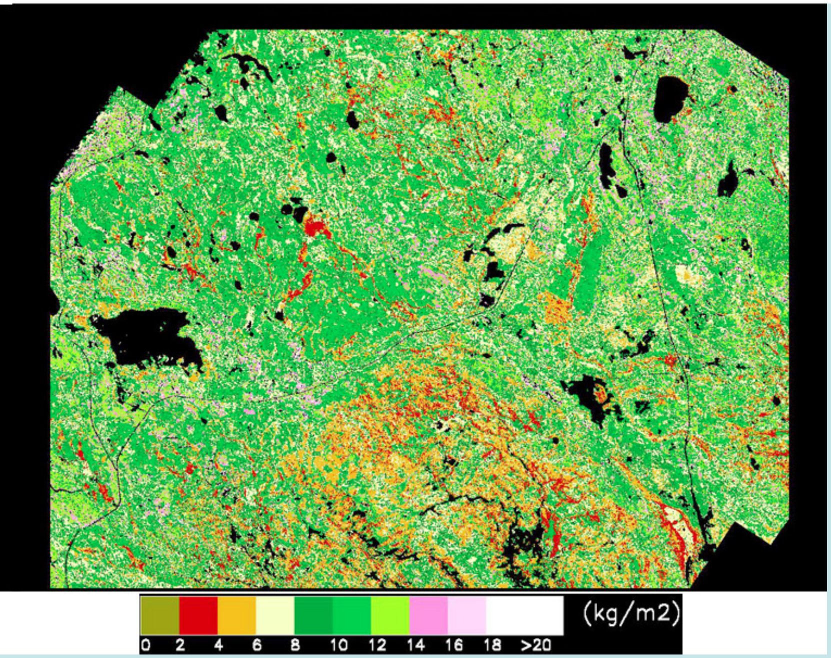


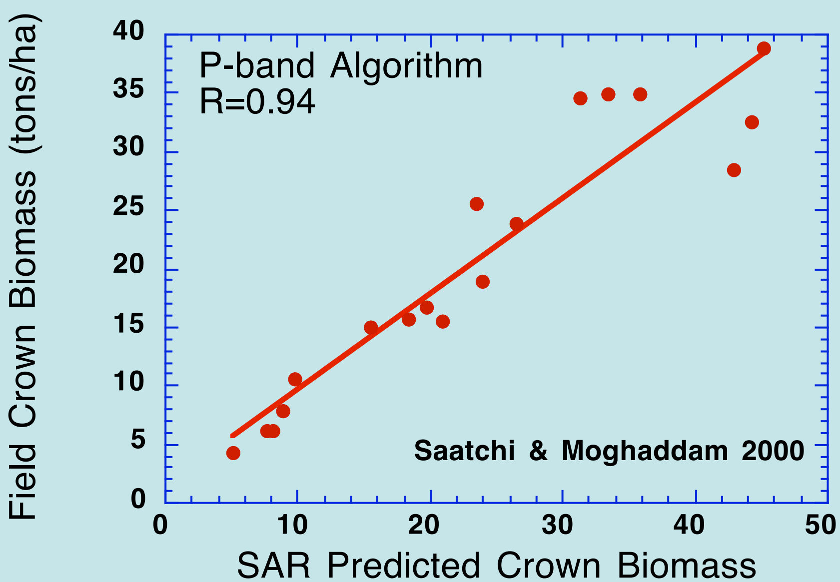
L-band(HH,HV,VV)

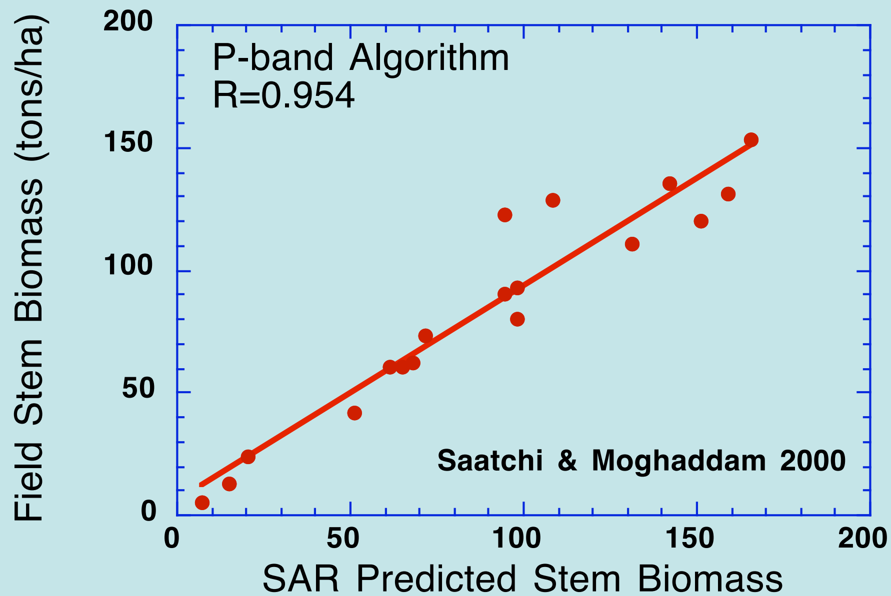


C-band (HH,HV,VV)

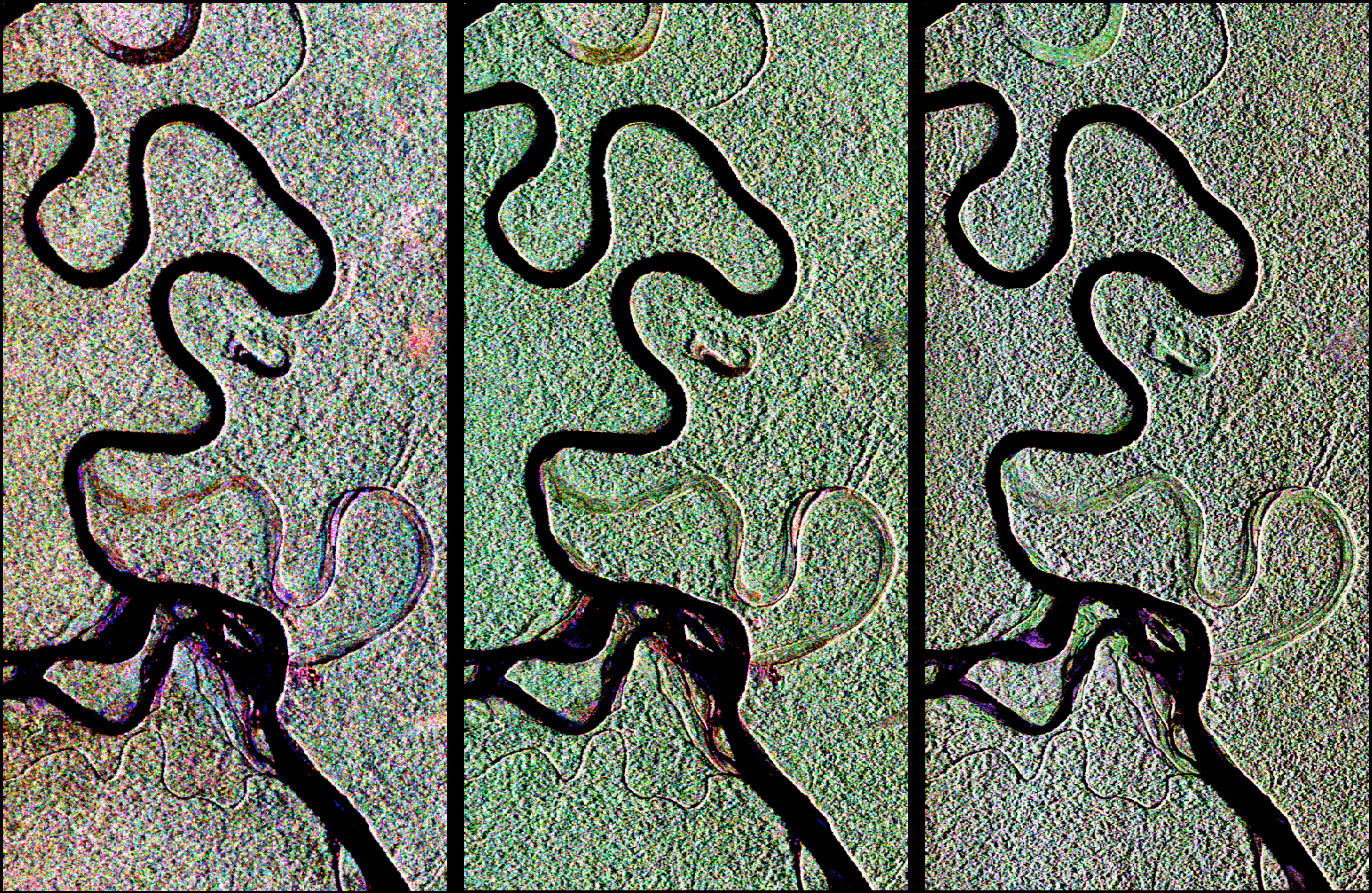

(kg/m2)
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 >5.0


(kg/m2)
0 2 4 6 8 10 12 14 16 18 >20

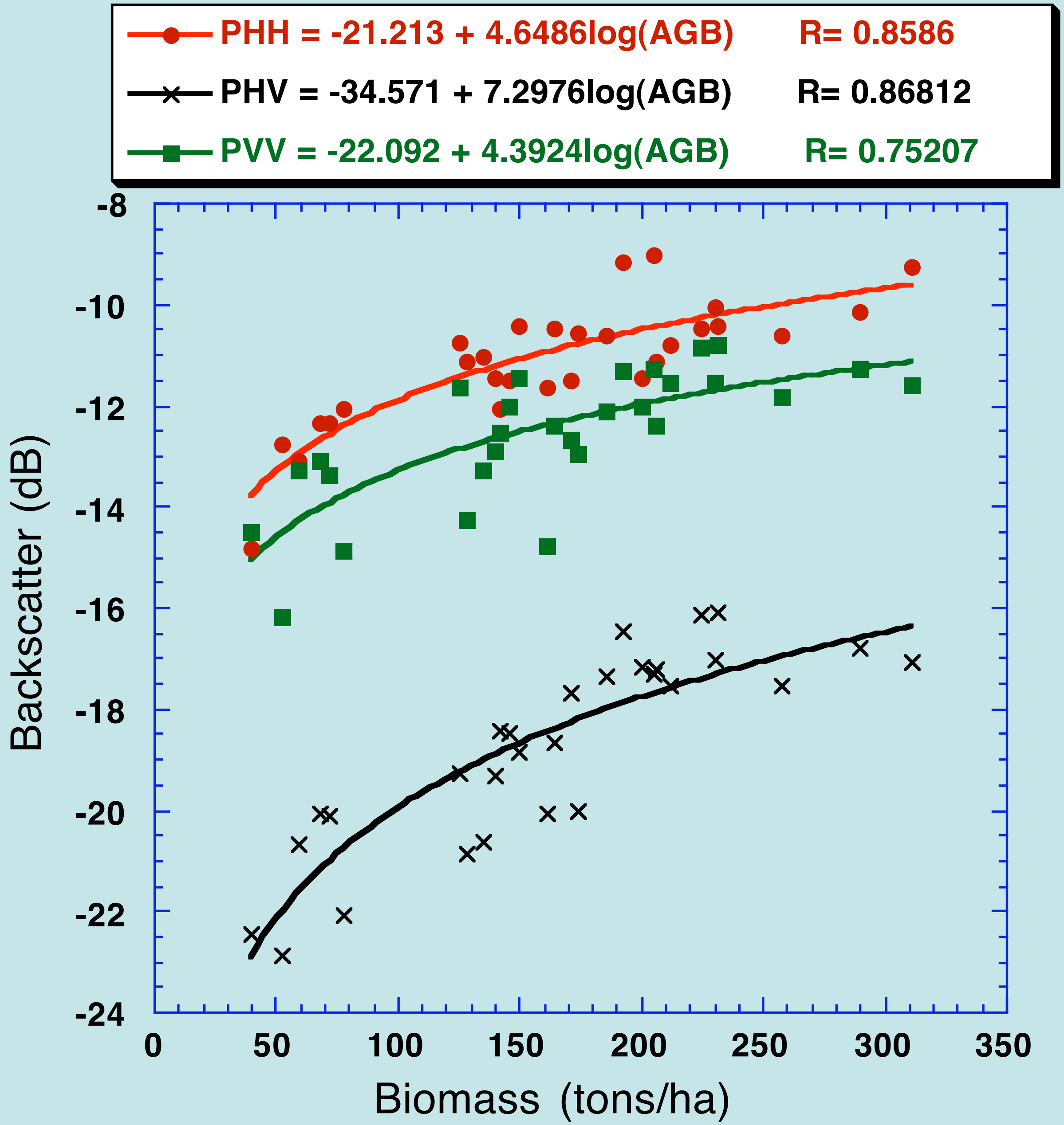

P-band Algorithm
R=0.94
Saatchi & Moghaddam 2000
Field Crown Biomass (tons/ha)
SAR Predicted Crown Biomass
0 5 10 15 20 25 30 35 40
0 10 20 30 40 50


P-band Algorithm
R=0.954
Saatchi & Moghaddam 2000
Field Stem Biomass (tons/ha)
SAR Predicted Stem Biomass
0 50 100 150 200
0 50 100 150 200

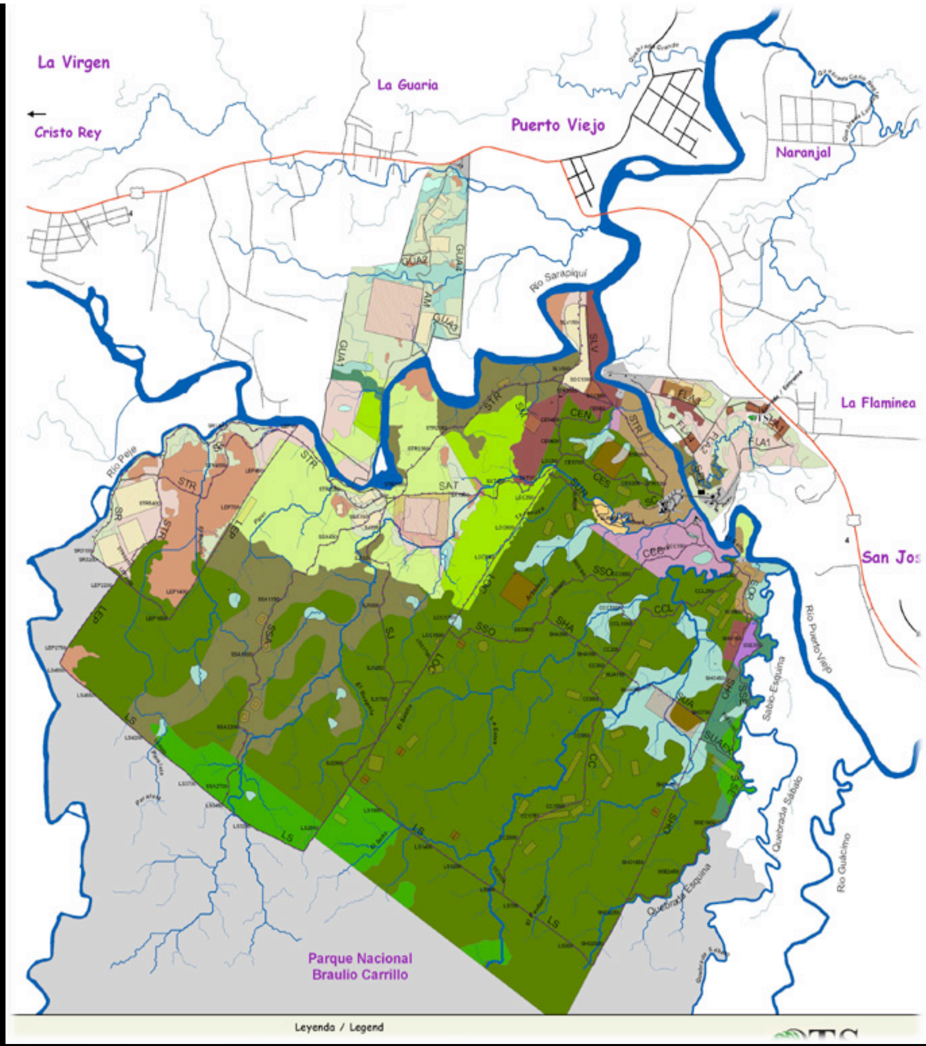
# AIRSAR Polarimetric Data Over Manu National Park, Peru



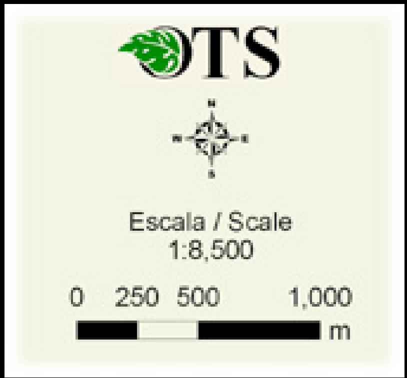
(PHH, PHV, PVV) (LHH, LHV, LVV) (CHH, CHV, CVV)

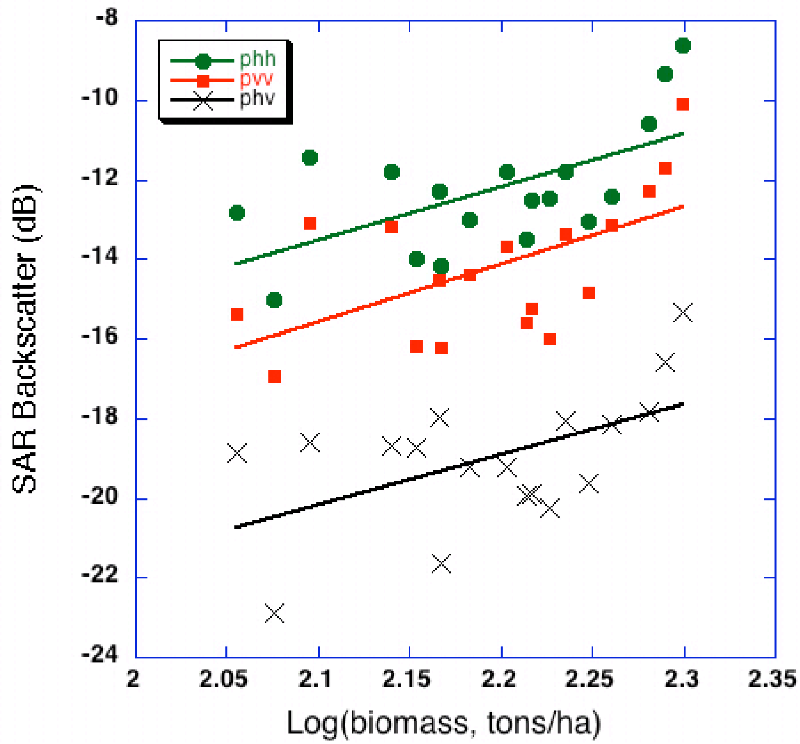


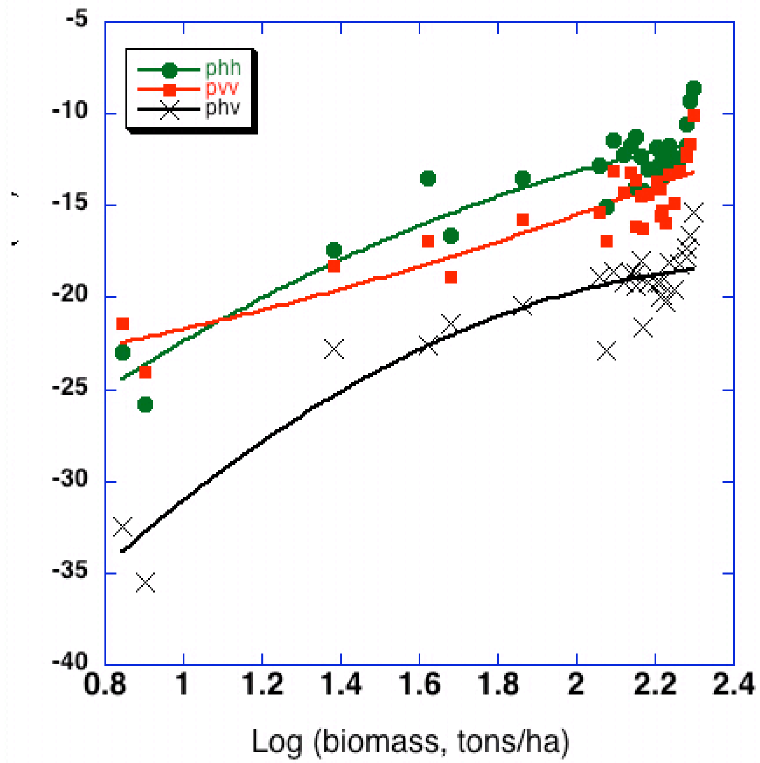
PHH = -21.213 + 4.6486log(AGB) R= 0.8586
PHV = -34.571 + 7.2976log(AGB) R= 0.86812
PVV = -22.092 + 4.3924log(AGB) R= 0.75207
-8
-10
-12
-14
-16
-18
-20
-22
-24
Backscatter (dB)
0
50
100
150
200
250
300
350
Biomass (tons/ha)




RED: PHH GRN: PHV BLU:PVV





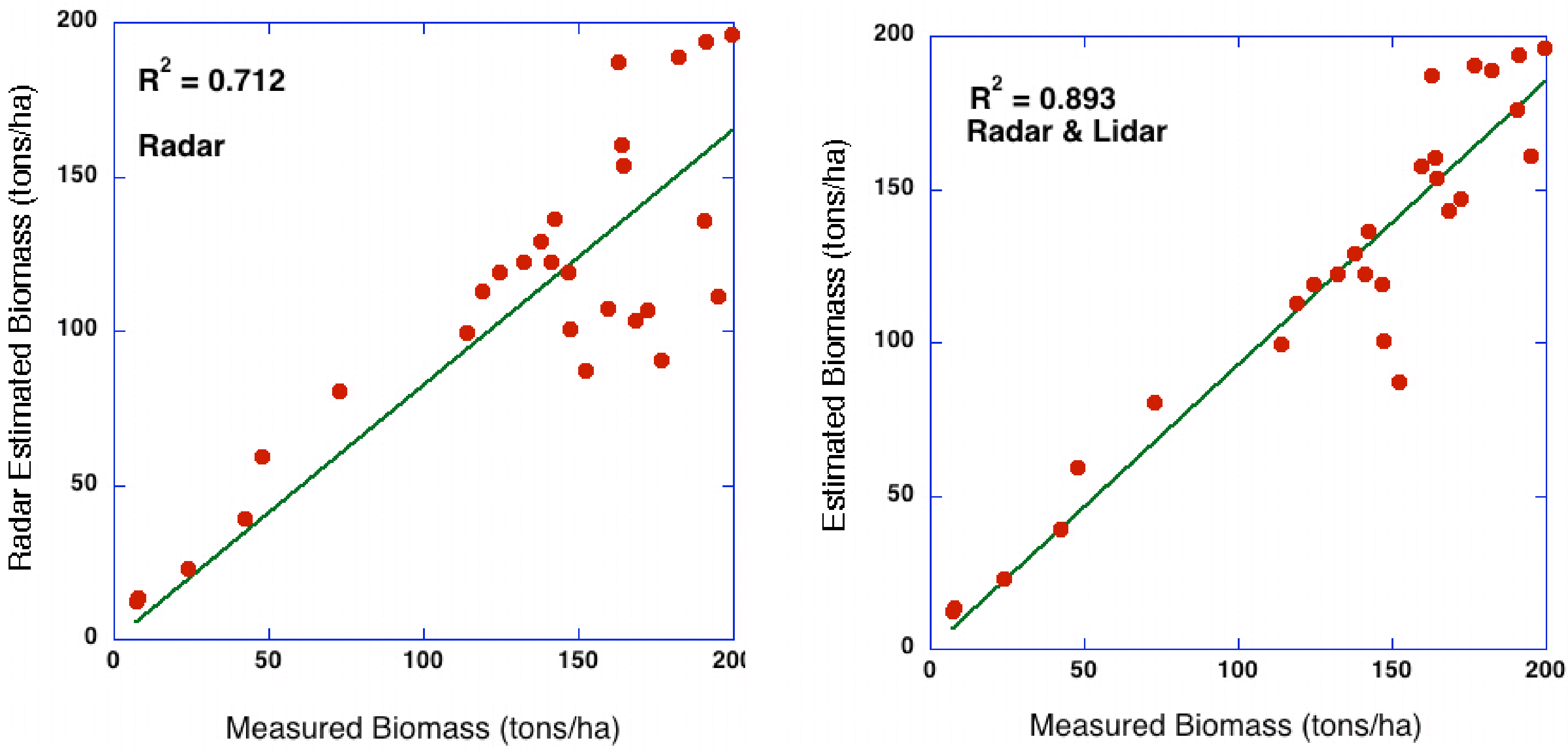




$$\sigma hh = -53.91 + 28.54 \log(BM) - 5.72 \log^2(BM) \quad R^2 = 0.87$$

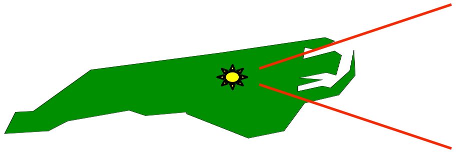
$$\sigma vv = -25.33 + 2.27 \log(BM) - 1.31 \log^2(BM) \quad R^2 = 0.87$$

$$\sigma hv = -37.96 + 18.69 \log(BM) - 3.15 \log^2(BM) \quad R^2 = 0.85$$

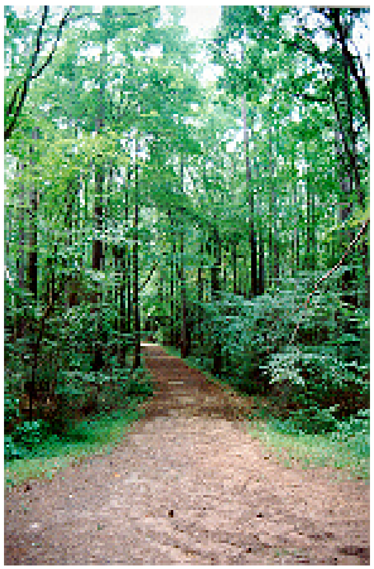
# Fusion of Radar and Lidar Data



## Duke Forest Study Site



mixed connifer and deciduous near Durham, NC

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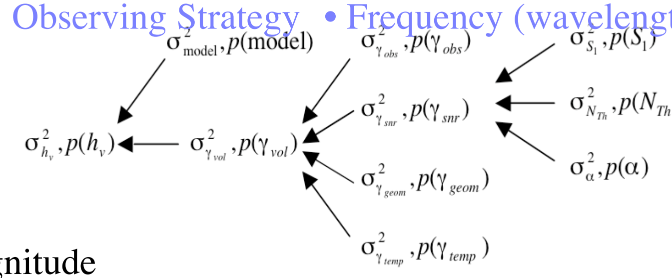
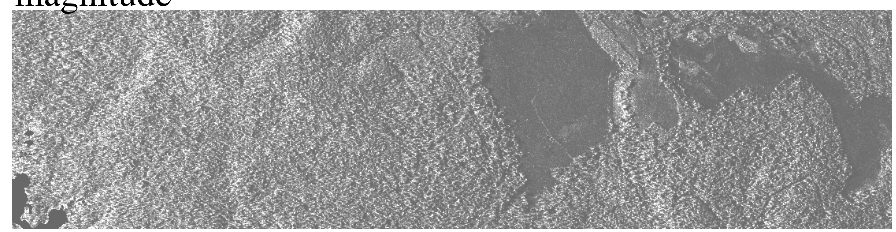
## Volumetric Height Error Estimates

mapping of measurement errors into volumetric height estimate errors

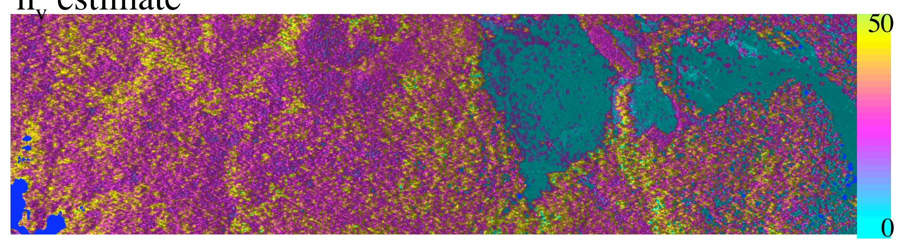
- Look Angle Errors
- Baseline Length
- Observing Strategy
- Management of Measurement
- Altitude or Range
- Frequency (wavelength)



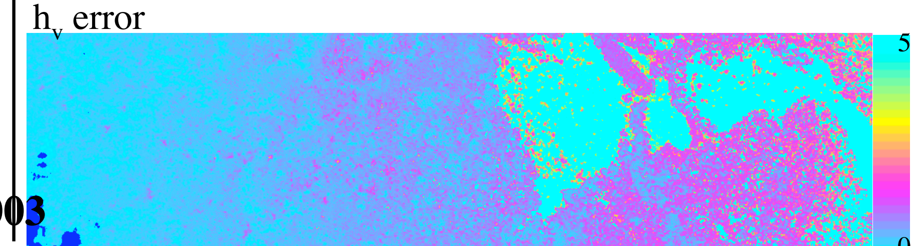

magnitude



$h_v$ estimate



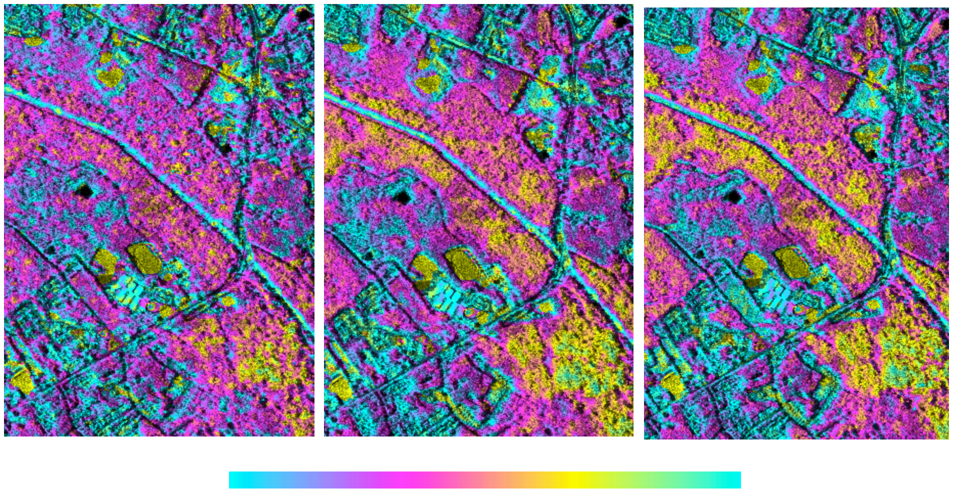

$h_v$ error



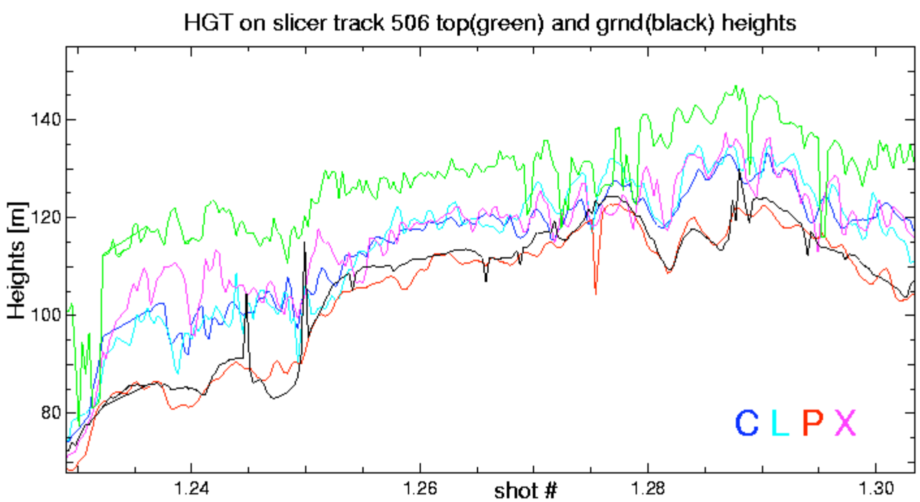

θ=25 deg θ=55 deg

## Height Maps as a Function of Frequency

L-band Minus P-band | C-band Minus P-band | X-band Minus P-band



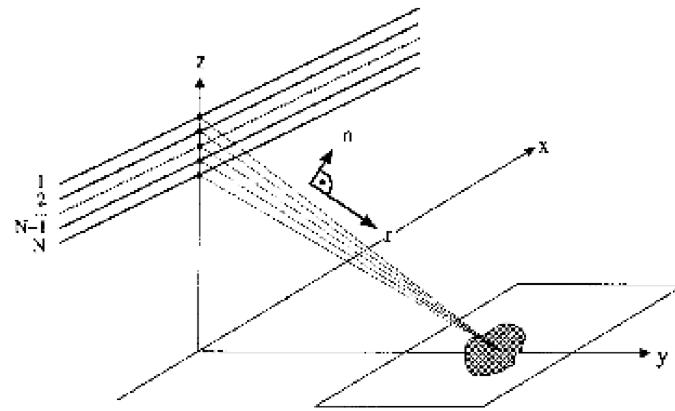

L-, C-, and X-band all penetrate into the canopy about the same distance. P-band phase center is at the canopy base

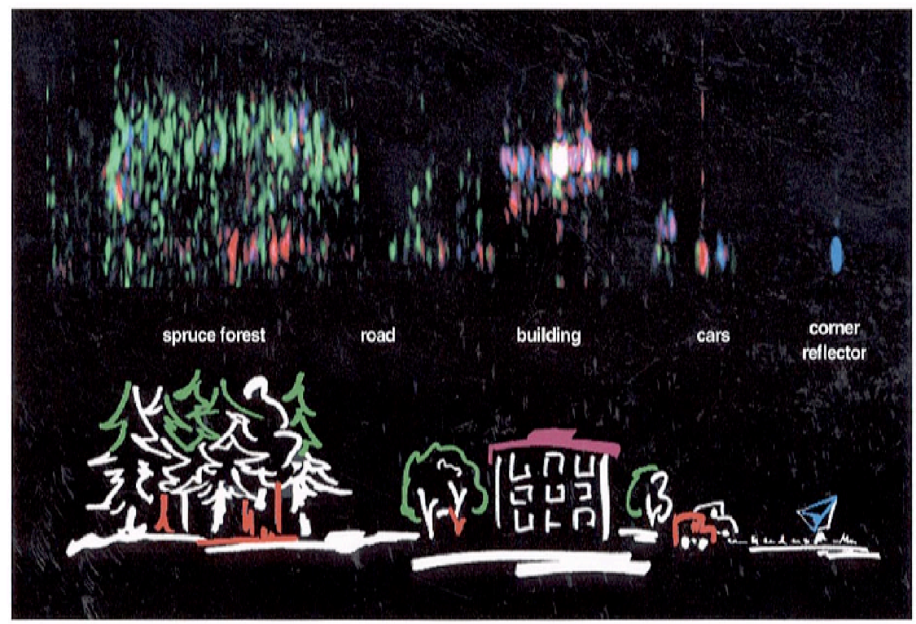



**S. Hensley, P. Siqueira, E. Rodriguez, T. Michel, 2003**

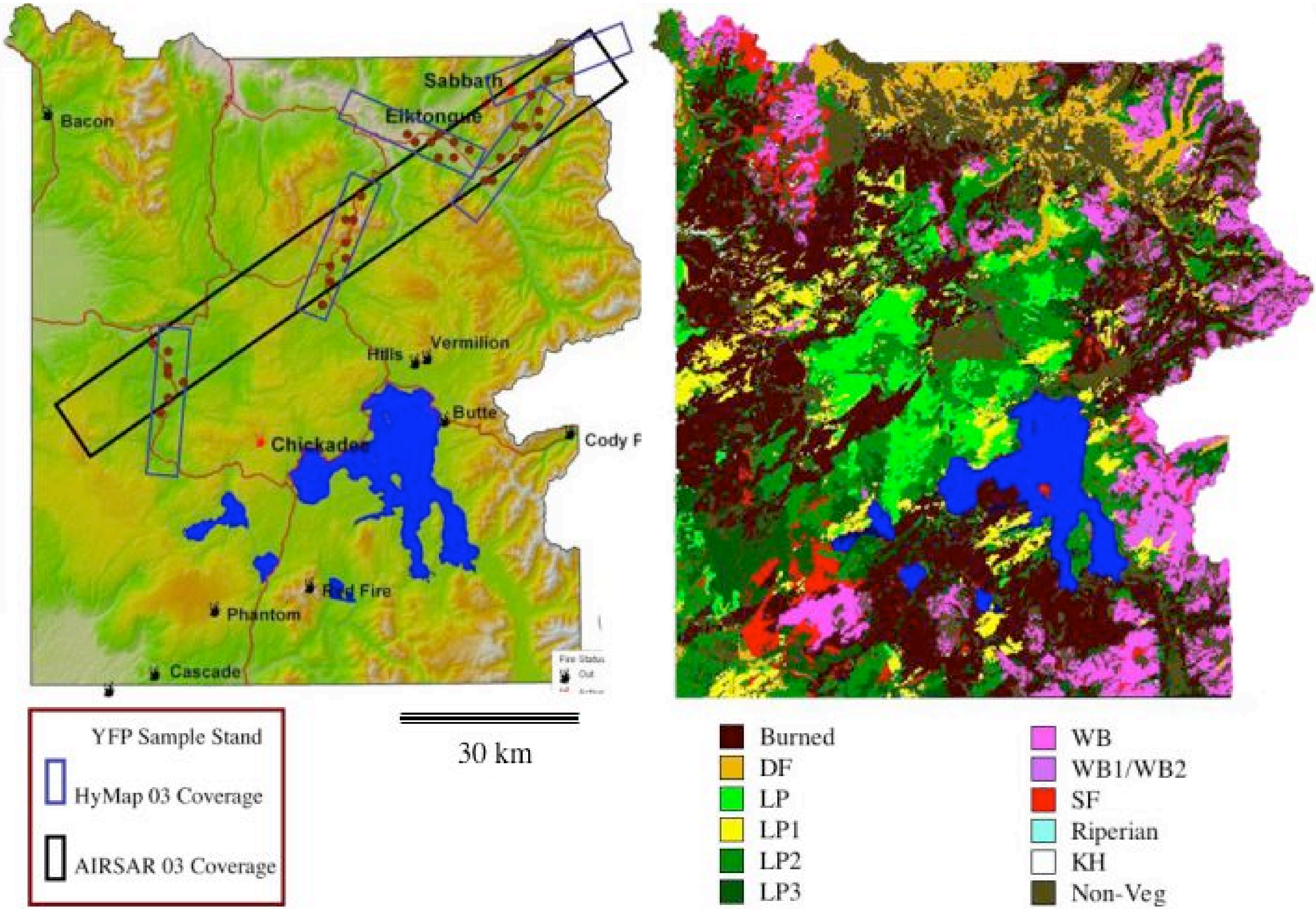
## Multi-Baseline Interferometry for Forest Structure

L-band multibaseline (multi-pass) experiment conducted by the DLR, Germany

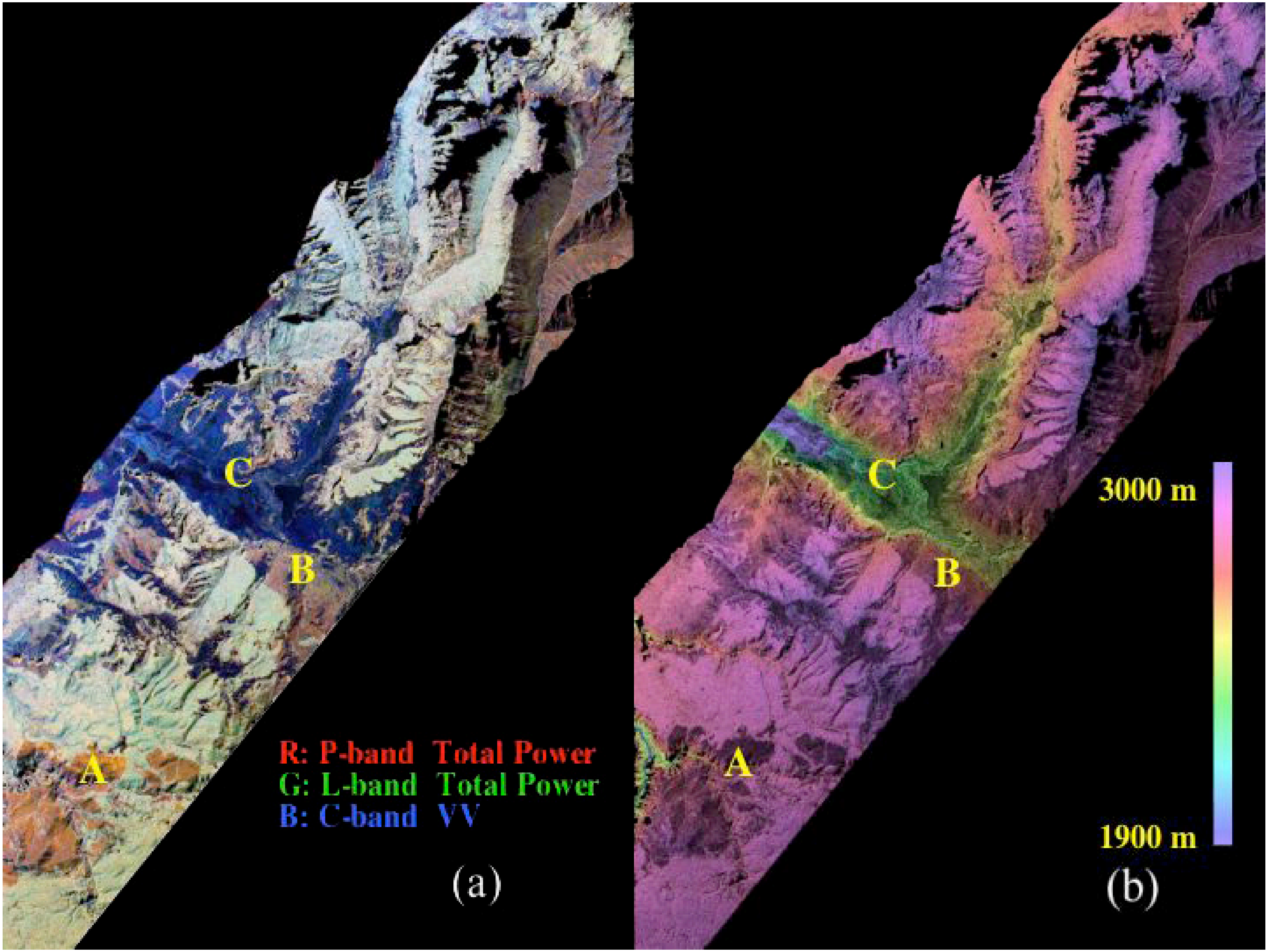


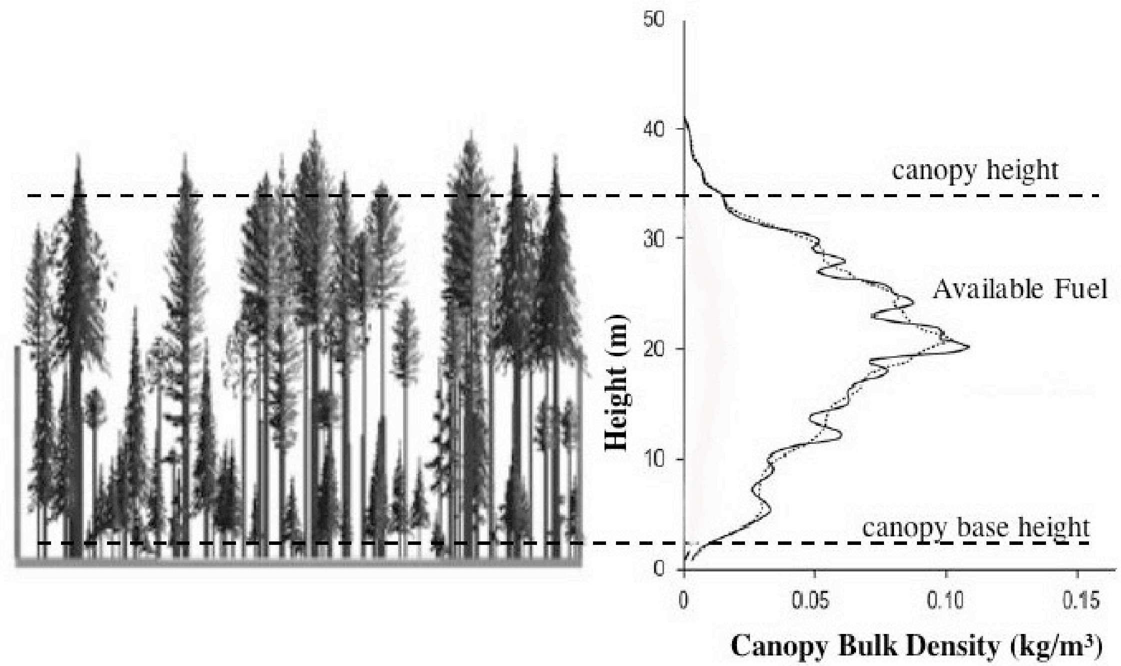



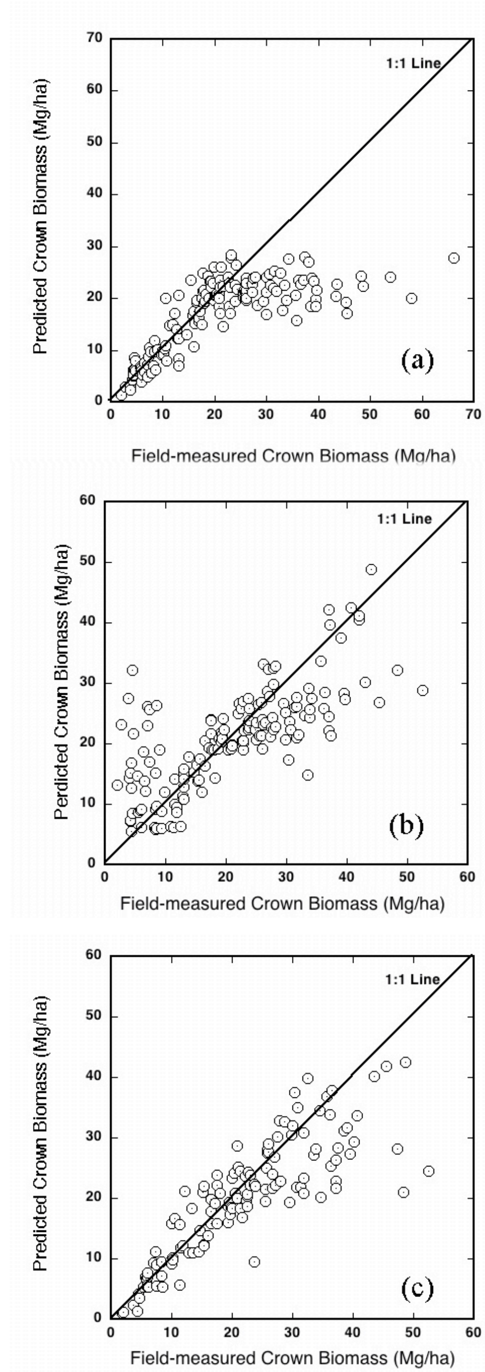

Reigber, A., Moreira, A., “First Demonstration of Airborne SAR Tomography Using Multibaseline L-Band Data,” IEEE Trans. Geosci. Rem. Sens., 38(5), 2000.

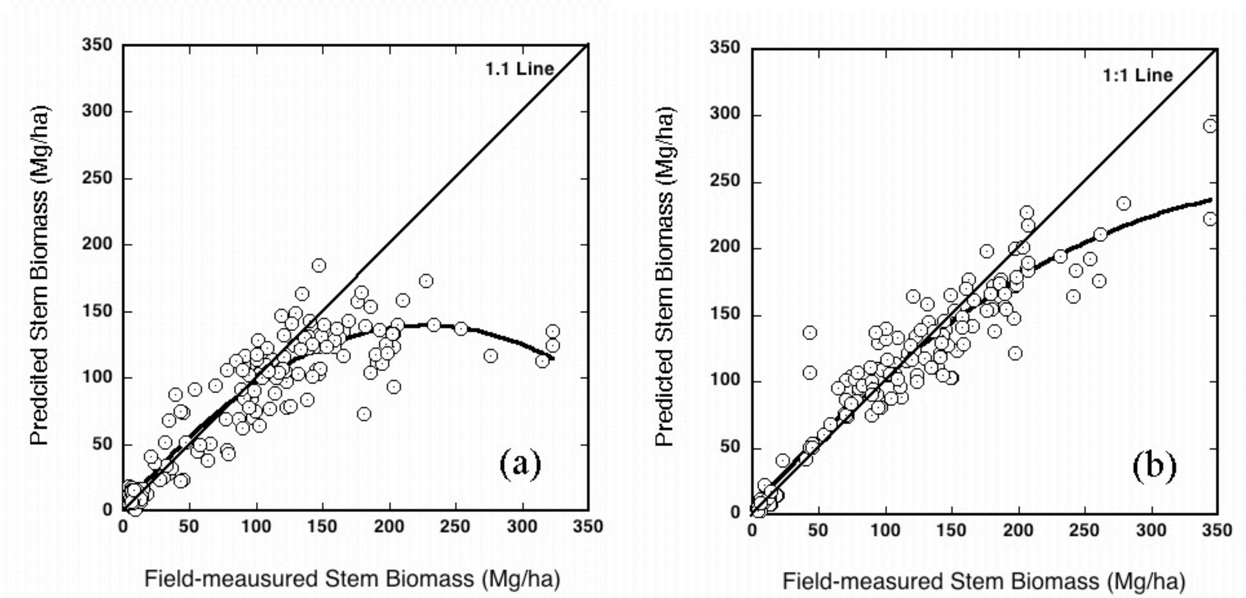


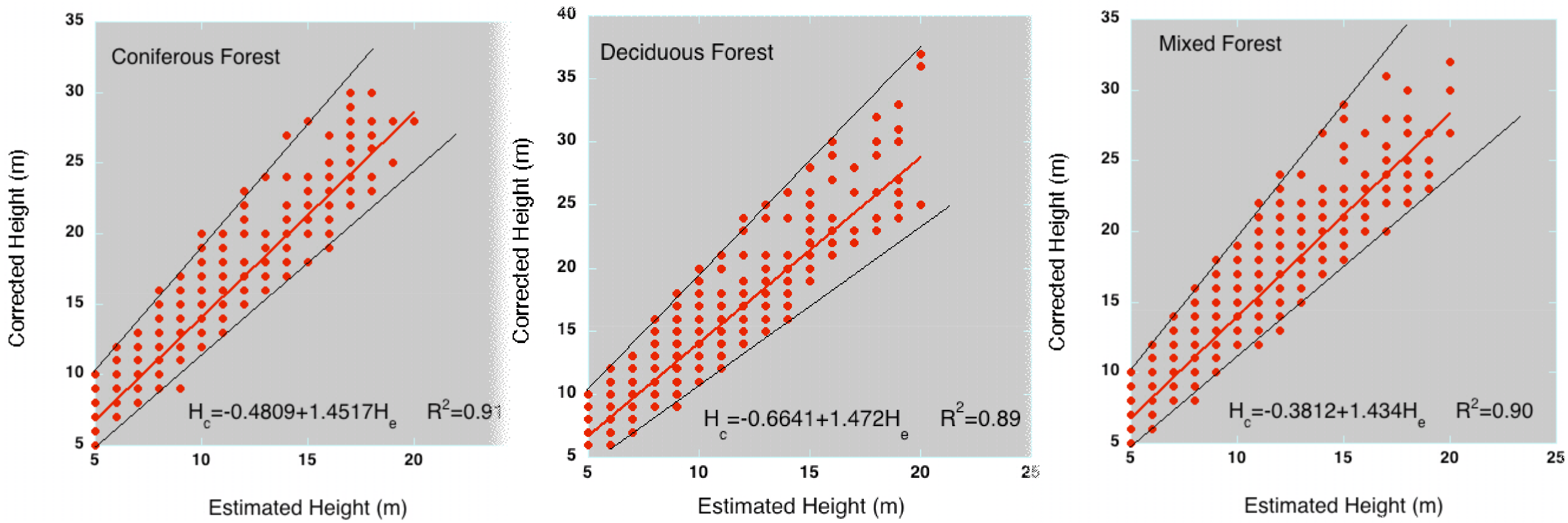
Sabbath
Elktongue
Bacon
Hills
Vermilion
Butte
Chickadee
Cody F
Red Fire
Phantom
Cascade
Fire Status
Out
YFP Sample Stand
HyMap 03 Coverage
AIRSAR 03 Coverage
30 km
Burned
DF
LP
LP1
LP2
LP3
WB
WB1/WB2
SF
Riperian
KH
Non-Veg


C
B
A
R: P-band Total Power
G: L-band Total Power
B: C-band VV
(a)
C
B
A
3000 m
1900 m
(b)


canopy height
Available Fuel
canopy base height
Height (m)
Canopy Bulk Density (kg/m³)
0
10
20
30
40
50
0
0.05
0.10
0.15


1:1 Line
(a)
Predicted Crown Biomass (Mg/ha)
Field-measured Crown Biomass (Mg/ha)
1:1 Line
(b)
Perdicted Crown Biomass (Mg/ha)
Field-measured Crown Biomass (Mg/ha)
1:1 Line
(c)
Predicted Crown Biomass (Mg/ha)
Field-measured Crown Biomass (Mg/ha)

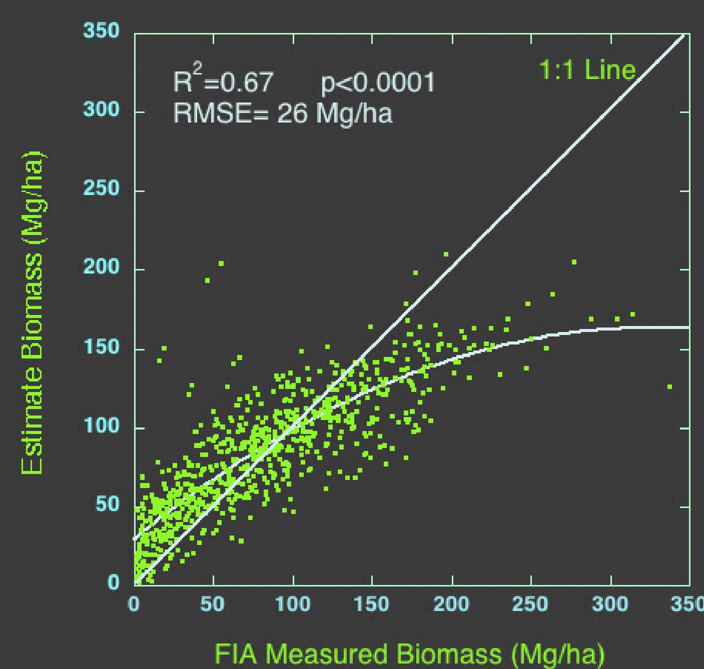

1.1 Line
(a)
Predcited Stem Biomass (Mg/ha)
Field-meausured Stem Biomass (Mg/ha)
1:1 Line
(b)
Predicted Stem Biomass (Mg/ha)
Field-measured Stem Biomass (Mg/ha)

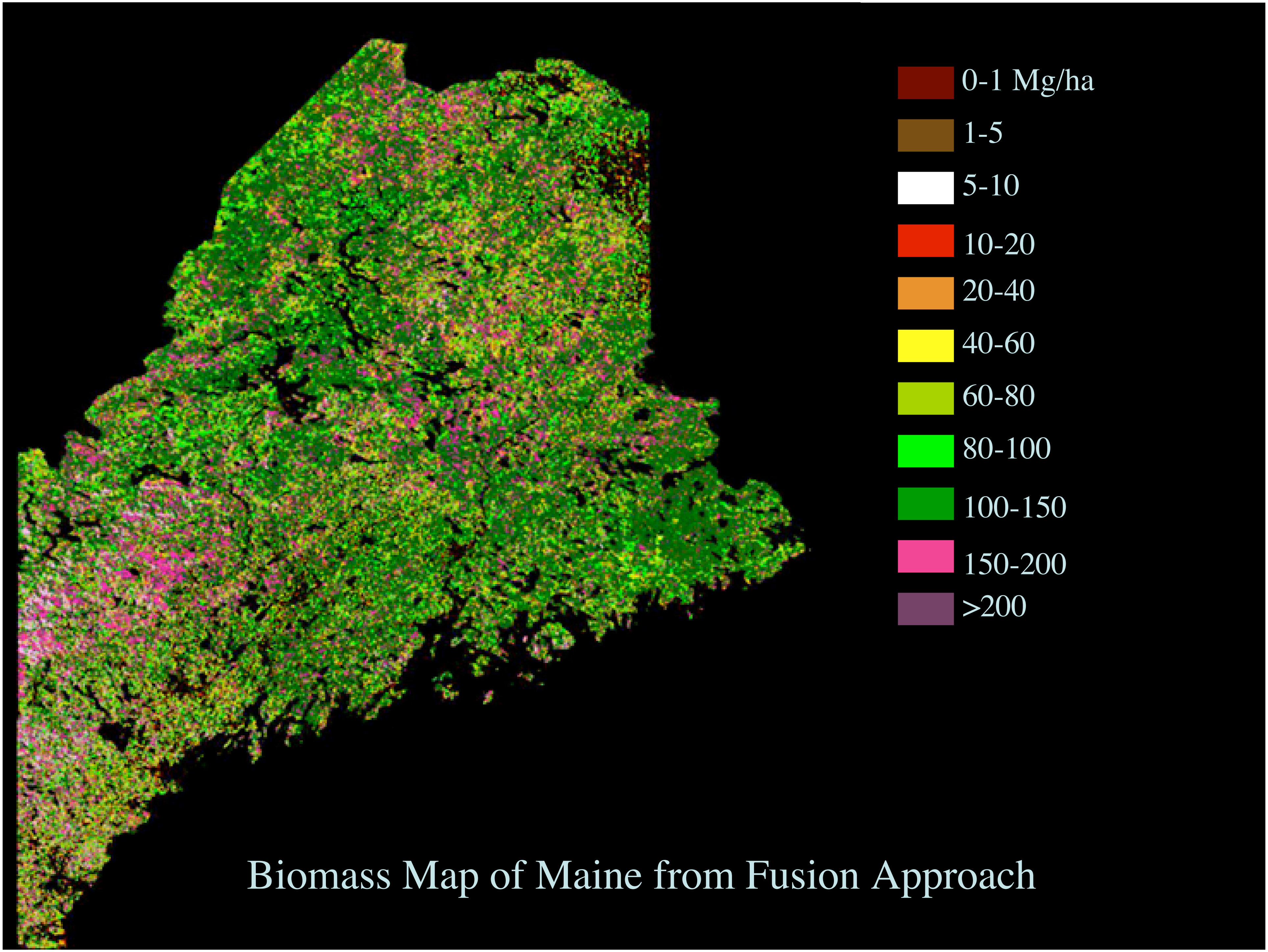



# Approach:

Develop Three relations for Deciduous, Coniferous, and Mixed Forests:

$$AGLB = f(H_{srtm}, LAI, VCF)$$

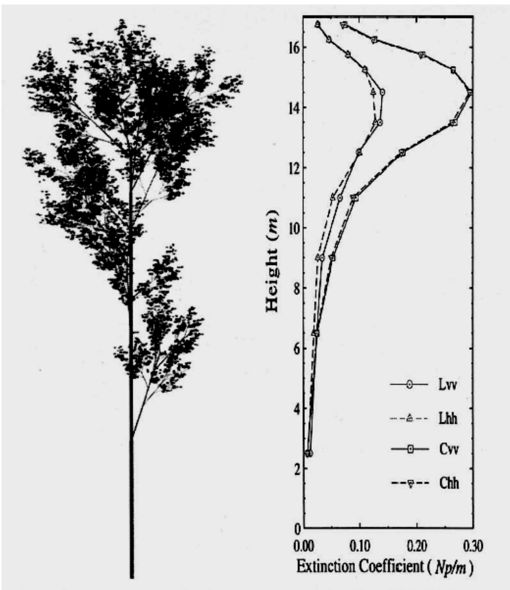


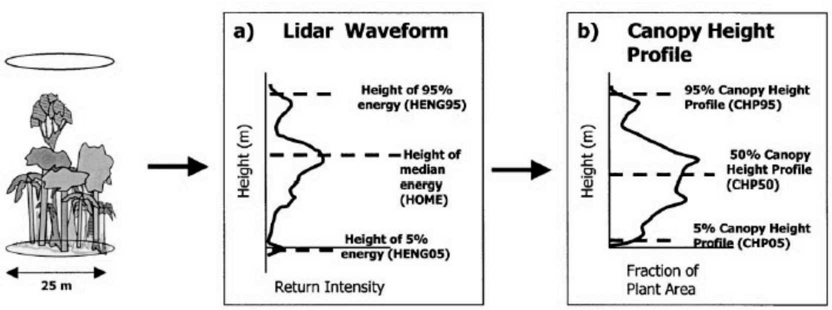



Biomass Map of Maine from Fusion Approach

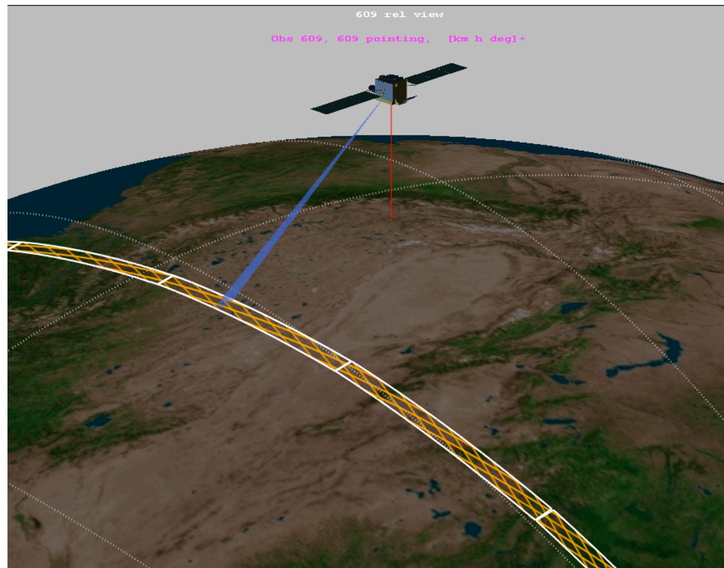
# Fusion of Radar and Lidar Measurements

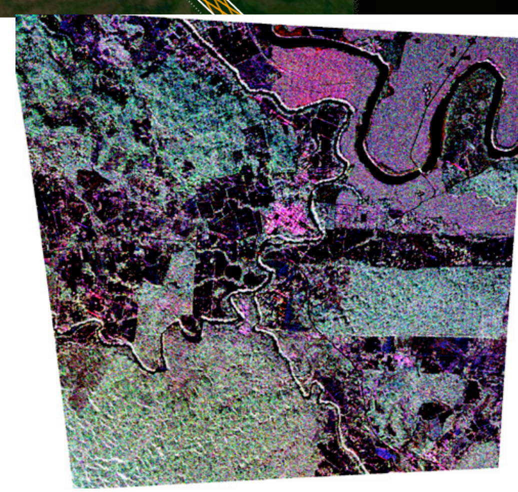
## Modeling Approach




## Geostatistical Approach



1-2% of
Area has
Lidar samples

# Science & Measurement Requirements
# Vegetation Structure and Biomass

| Science Objectives | Scientific Measurement requirements | Instrument Functional Requirements | Mission Functional Requirements |
|---|---|---|---|
| Develop globally consistent and spatially resolved estimates of above-ground forest biomass and terrestrial carbon stocks.<br><br>Develop globally consistent and spatially resolved estimates of forest age-state and vegetation structure to understand the trajectory of terrestrial ecosystems and their relationship to carbon cycle.<br><br>Monitor and Quantify changes in terrestrial carbon sources and sinks resulting from disturbance and recovery.<br><br>Improve habitat quality determination for biodiversity estimates.<br><br>Enable improved management of forestry and the global carbon cycle<br><br>Develop globally consistent and spatially resolved measures of wetland extent, inundation state and estimate the methane emission | Above Ground Live Woody Biomass (greater of +/- 10 tons or 20% of total) at 1 ha spatial resolution (specify accuracy for large areas)<br><br>forest height samples<br>at 25 m resolution and 1-2 m accuracy<br><br>biomass change from disturbance (greater of +/- 10 tons or 20%) at 1 ha resolution.<br><br>biomass change from accumulation or degradation at scale of 1 km(?) and precision of 2-4 tons/ha/year<br><br>interannual change of forested area at 1 ha resolution | P-Band Radar(435 Mhz):<br>Polarimetric<br>Resolution: 100 m<br>Absolute accuracy: 1 dB<br>Relative Accuracy: 0.5 dB<br>Constant Incidence angle between 20-30°<br><br>Repeat Pass Interferometry<br><br>3 beam Full Wave<br>Lidar( 1064 nanometer<br>Resolution: 20 m<br>Accuracy: 1-5 m<br><br>Minimum three-year mission life. | DAAC data archiving and distribution.<br><br>Field validation program.<br><br>Global Forest Above Ground Live Biomass<br>Product<br><br>Global Forest Height<br>Integration of data products into multisource land data assimilation.<br><br>Orbit: 600 km, circular, polar, sun-synchronous,<br>~6 am/pm equator crossing<br><br>30-45 day repeat cycle<br><br>3-5 years baseline mission |