

# Evaluating uncertainty in mapping forest carbon with airborne LiDAR

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and Conservation Group



UNIVERSITY OF  
CAMBRIDGE

Cambridge  
Conservation  
Initiative

Forests hold globally significant reserves of carbon, but high uncertainty associated with estimates



# Topics

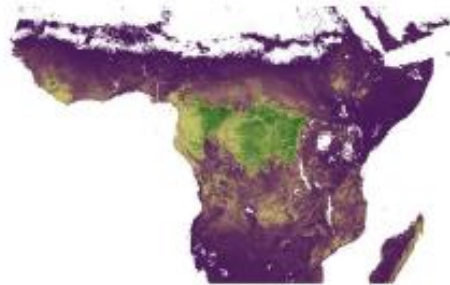
- **The essentiality of inventory plots**
- **Do we even need LiDAR to get accurate and precise carbon stock and flux estimates?**
- **Improving plot-level estimates**
- **The benefits of using LiDAR**
- **Choice of estimation equation**
- **Measuring carbon fluxes by repeat-LiDAR surveying**

# Topics

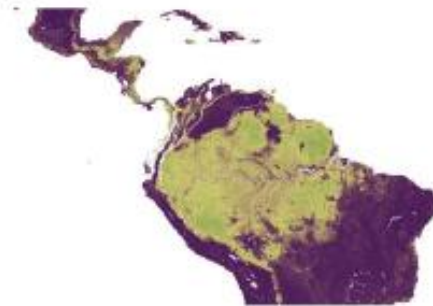
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- **From LiDAR strips to landscapes**

# Comparison, same scale, 5km res

Baccini et al. (2012)



Saatchi et al. (2011)

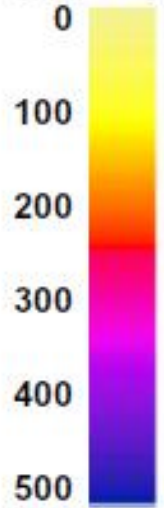


0 100 200 300 400 500 Mg ha<sup>-1</sup>

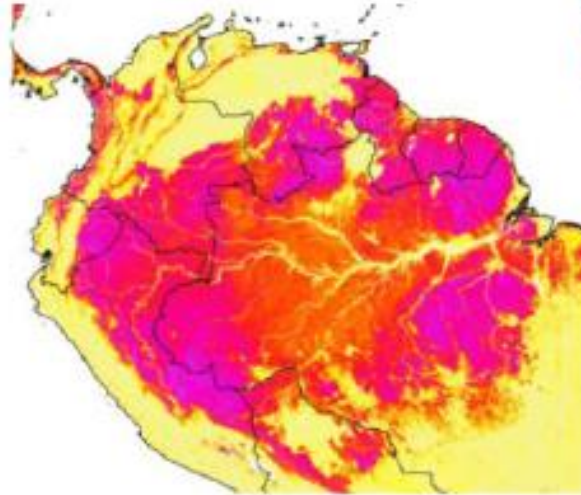


Mitchard ETA, Saatchi SS, Baccini A, Asner GP, Goetz SJ, Harris NL, Brown S. 2013. Uncertainty in the spatial distribution of tropical forest biomass: a comparison of pan-tropical maps. *Carbon Balance & Management*

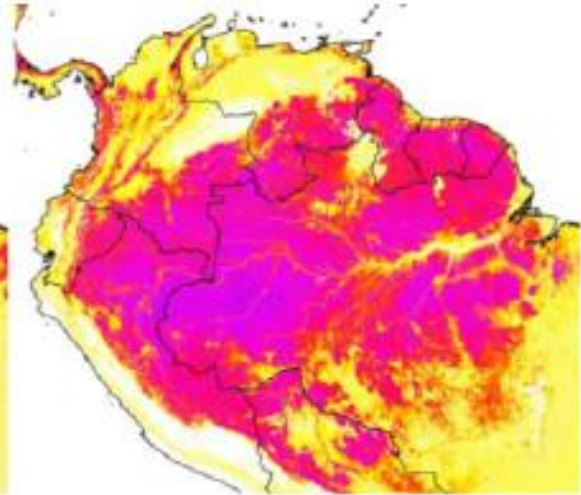
AGB  
(Mg ha<sup>-1</sup>)



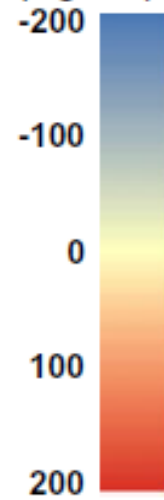
A: *RS1* Saatchi



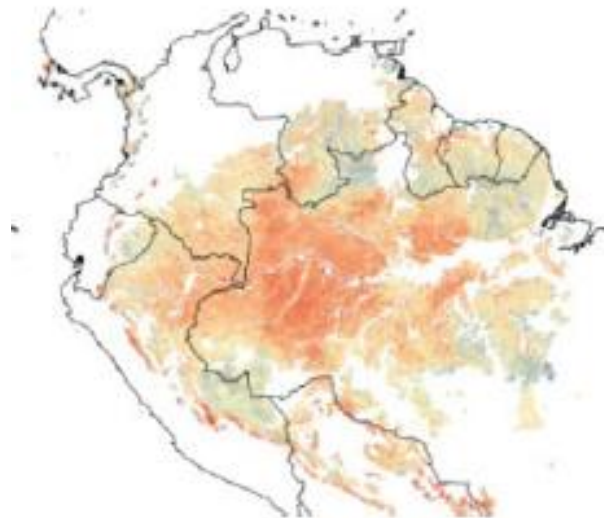
B: *RS2* Bacchini



AGB difference  
(Mg ha<sup>-1</sup>)

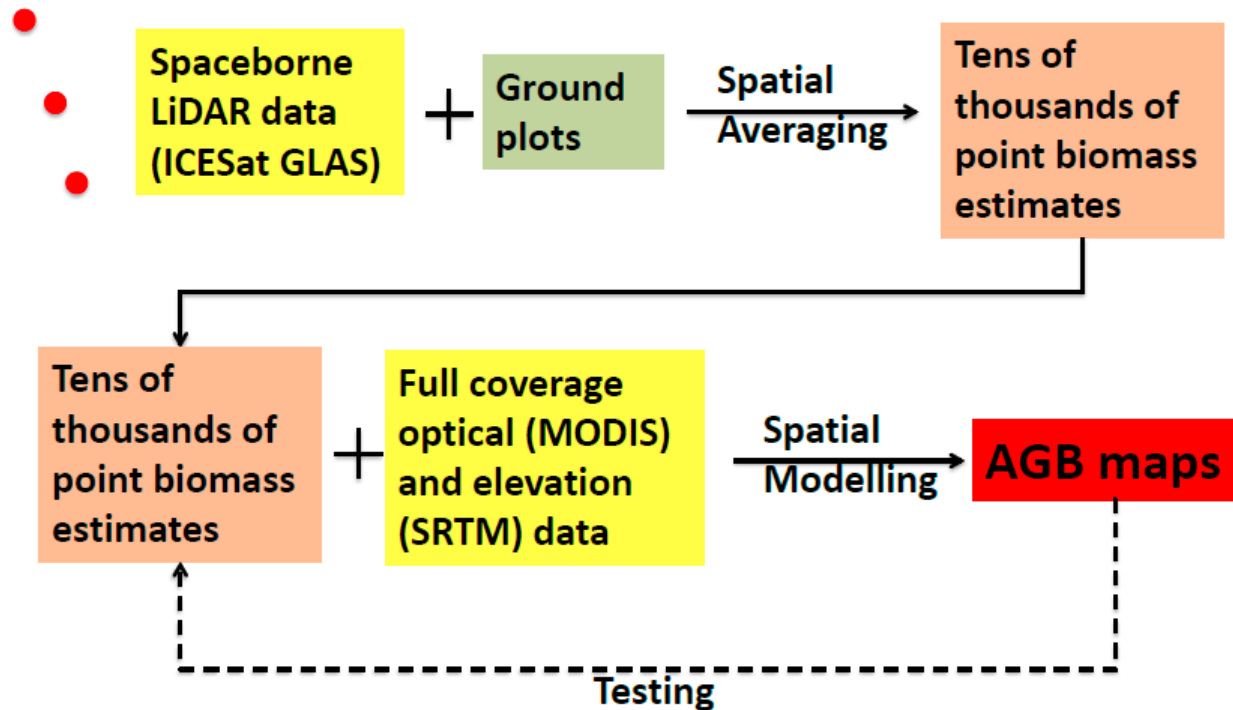


F: *RS1-RS2*



# Informative to explore why they are so different?

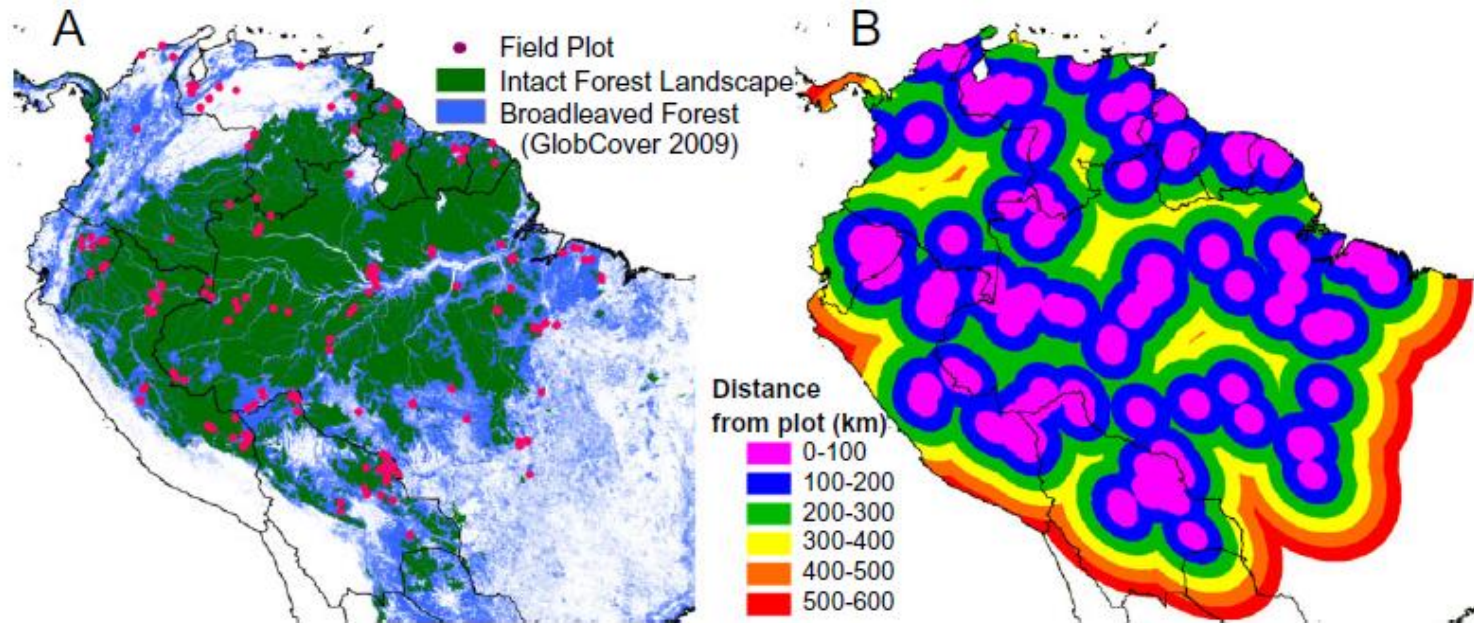
## Common elements



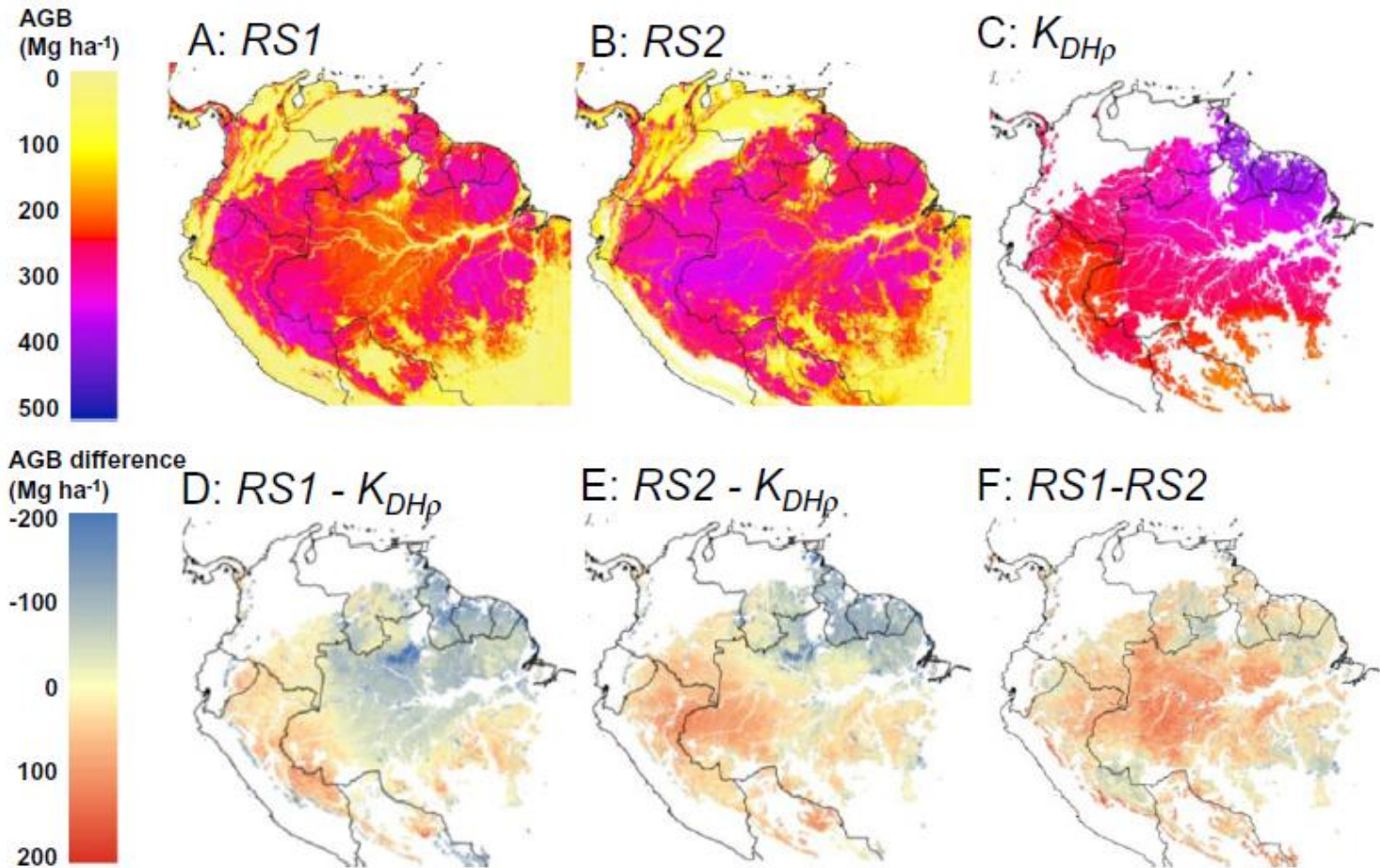
# Differences

- Method for converting GLAS footprints to AGB
- Allometric equations – same source (Chave et al. 2005) but with/without height
- RS data – different MODIS products; Saatchi has Ku-band radar (QuikSCAT)
- Modelling method – Maxent (Saatchi), RandomForest (Baccini)
- Resolution – 1km (Saatchi), 500 m (Baccini)
- Year: ‘early 2000’s’ (Saatchi), 2007-8 (Baccini)

How do the remotely sensed maps compare with those based on forest inventory plots?



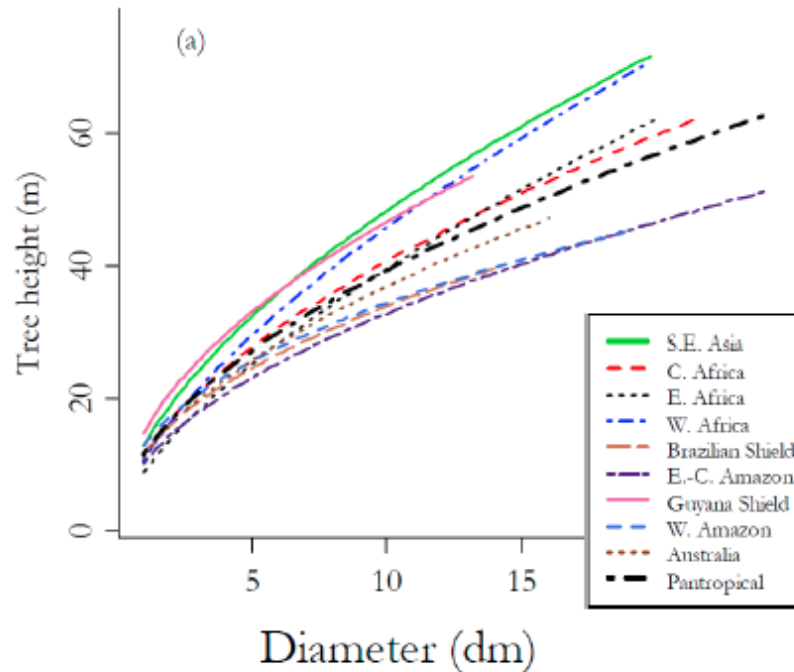
**Figure 1** Location of forest field plots in South America. (a) The location of all plots used in the analysis, overlaid on the intact forest landscape (IFL) and GlobCover broad-leaved forests layers. (b) Map showing the distance from the nearest plot in kilometres.



**Figure 3** Above-ground biomass (AGB) maps of South America and maps of their differences. (a) AGB map *RS1* (Saatchi *et al.*, 2011); (b) AGB map *RS2* (Baccini *et al.*, 2012); (c) kriged map of AGB from field plots, with AGB calculated using diameter, species-specific wood density, and a regional height model ( $K_{DHP}$ ), showing only areas identified as intact forest landscapes (IFL); (d) difference between *RS1* and  $K_{DHP}$ ; (e) difference between *RS2* and  $K_{DHP}$ ; (f) difference between *RS1* and *RS2*. Difference maps have non-IFL areas masked out. The projection is sinusoidal, an equal-area projection.

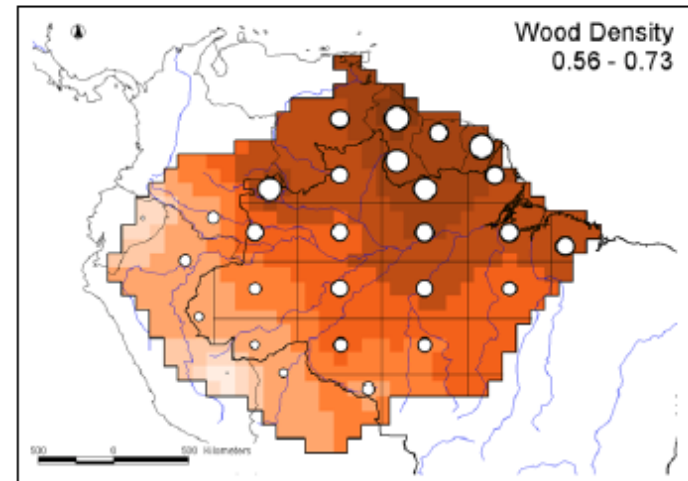
# IMPORTANT DRIVERS OF CARBON DENSITY NOT MEASURED BY LIDAR

## Diameter-height relationships



Feldpausch *et al.* 2011  
*Biogeosciences*

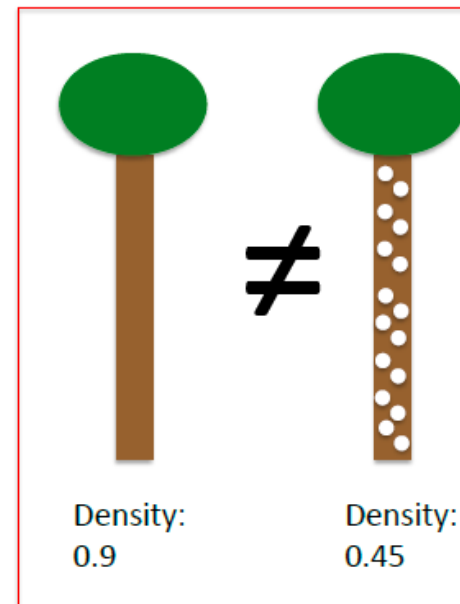
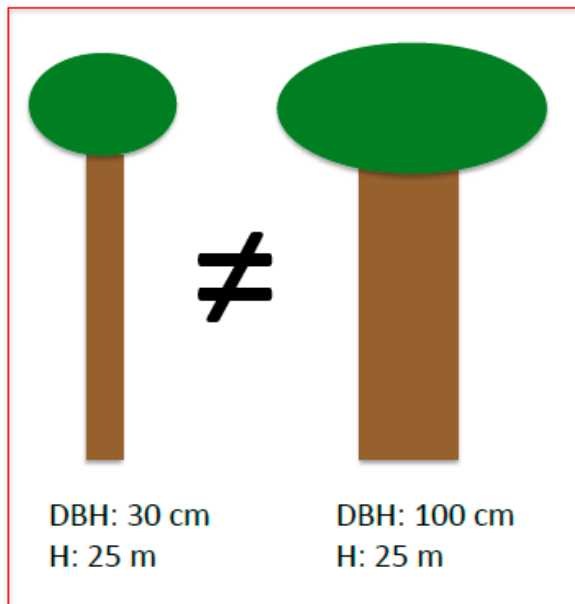
## Wood density



Ter Steege *et al.* 2006  
*Nature*

# Conclusions

- Must consider spatial variation in wood density and forest structure



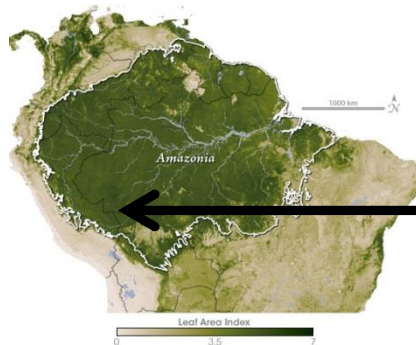
**And this requires plots on the ground!**

# *species impact on AGB at the tree-scale*

*Whole trees measured directly - cut, dried, weighed:*

| Species                       | D (cm) | H (m) | $\rho$ (g/cm <sup>3</sup> ) | AGB (t, dry mass) |
|-------------------------------|--------|-------|-----------------------------|-------------------|
| <i>Apuleia leiocarpa</i>      | 108    | 30    | 0.855                       | 12.2              |
| <i>Cavanillesia umbellata</i> | 115    | 28    | 0.132                       | 2.3               |

*Whole trees measured directly - cut, dried, weighed*



R. C. Goodman, O. L. Phillips, T. R. Baker,  
2012, *Nature* 491: 527

Taken from Phillips's talk at the European Space Agency, Jan 2015

# The heaviest tropical tree!

*Dipteryx micrantha*, AGB = 76 t



Taken from Phillips's talk at the European Space Agency, Jan 2015

# On the value of permanent plots

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NATURE | LETTER

日本語要約

Long-term decline of the Amazon carbon sink

R. J. W. Brienen, O. L. Phillips, T. R. Feldpausch, E. Gloor, T. R. Baker, J. Lloyd, G. Lopez-Gonzalez, A. Monteagudo-Mendoza, Y. Malhi, S. L. Lewis, R. Vásquez Martínez, M. Alexiades, E. Álvarez Dávila, P. Alvarez-Loayza, A. Andrade, L. E. O. C. Aragão, A. Araujo-Murakami, E. J. M. M. Arets, L. Arroyo, G. A. Aymard C., O. S. Bánki, C. Baraloto, J. Barroso, D. Bonal, R. G. A. Boot, J. L. C. Camargo, C. V. Castilho, V. Chama, K. J. Chao, J. Chave, J. A. Comiskey, F. Cornejo Valverde, L. da Costa, E. A. de Oliveira, A. Di Fiore, T. L. Erwin, S. Fauset, M. Forsthofer, D. R. Galbraith, E. S. Grahame, N. Groot, B. Hérault, N. Higuchi, E. N. Honorio Coronado, H. Keeling, T. J. Killeen, W. F. Laurance, S. Laurance, J. Licona, W. E. Magnussen, B. S. Marimon, B. H. Marimon-Junior, C. Mendoza, D. A. Neill, E. M. Nogueira, P. Núñez, N. C. Pallqui Camacho, A. Parada, G. Pardo-Molina, J. Peacock, M. Peña-Claros, G. C. Pickavance, N. C. A. Pitman, L. Poorter, A. Prieto, C. A. Quesada, F. Ramírez, H. Ramírez-Angulo, Z. Restrepo, A. Roopsind, A. Rudas, R. P. Salomão, M. Schwarz, N. Silva, J. E. Silva-Espejo, M. Silveira, J. Stropp, J. Talbot, H. ter Steege, J. Teran-Aguilar, J. Terborgh, R. Thomas-Caesar, M. Toledo, M. Torello-Raventos, R. K. Umetsu, G. M. F. van der Heijden, P. van der Hout, I. C. Guimarães Vieira, S. A. Vieira, E. Vilanova, V. A. Vos & R. J. Zagt

Editor's summary

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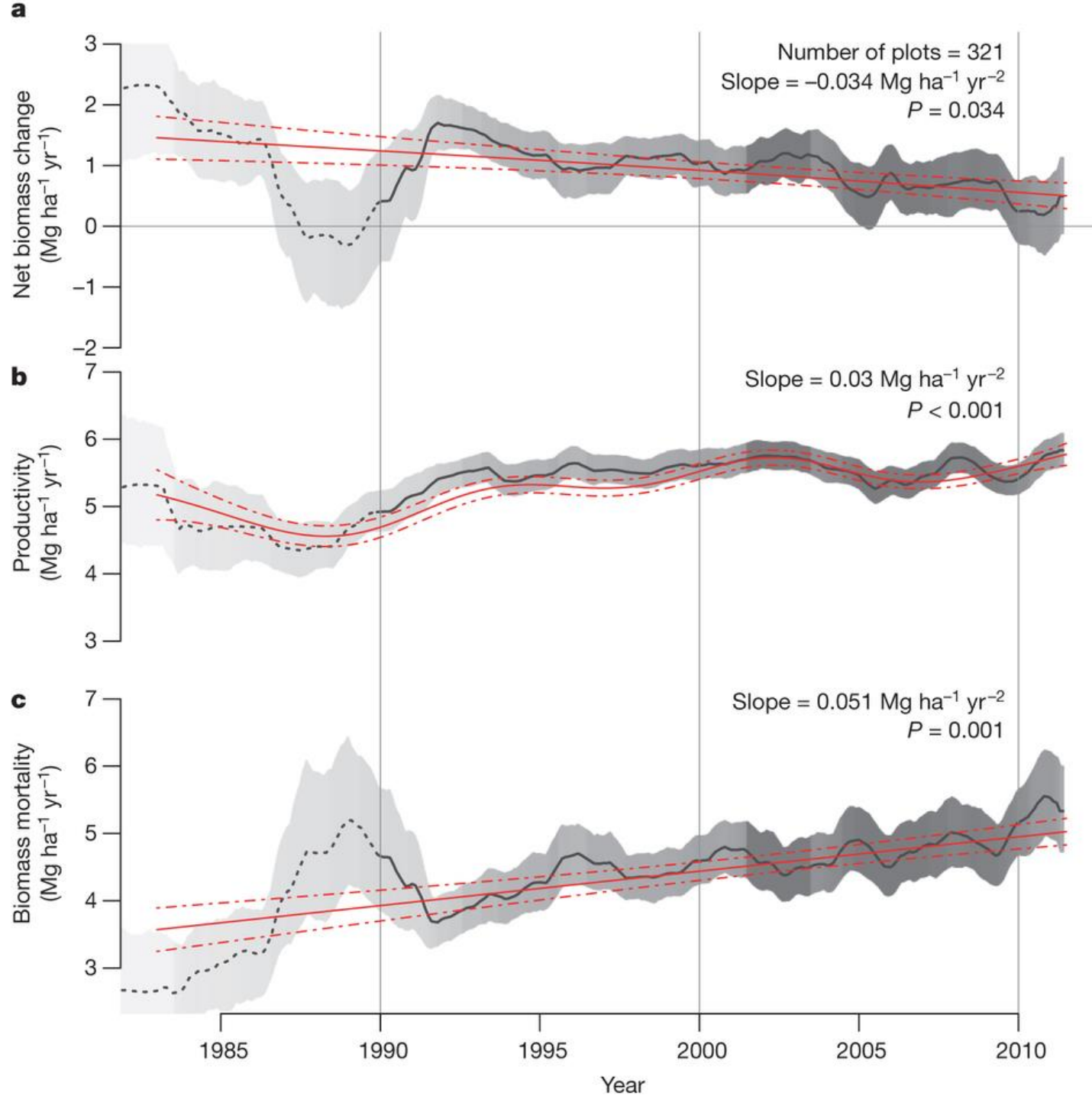
Biogeochemistry: Signs of saturation in the tropical carbon sink

by Hedin

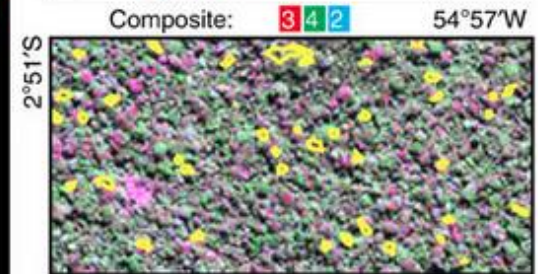
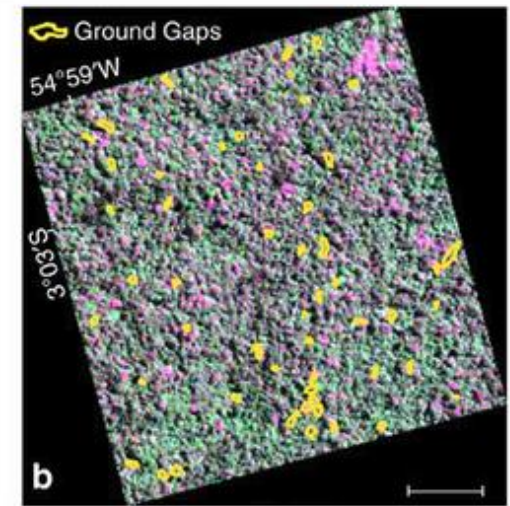
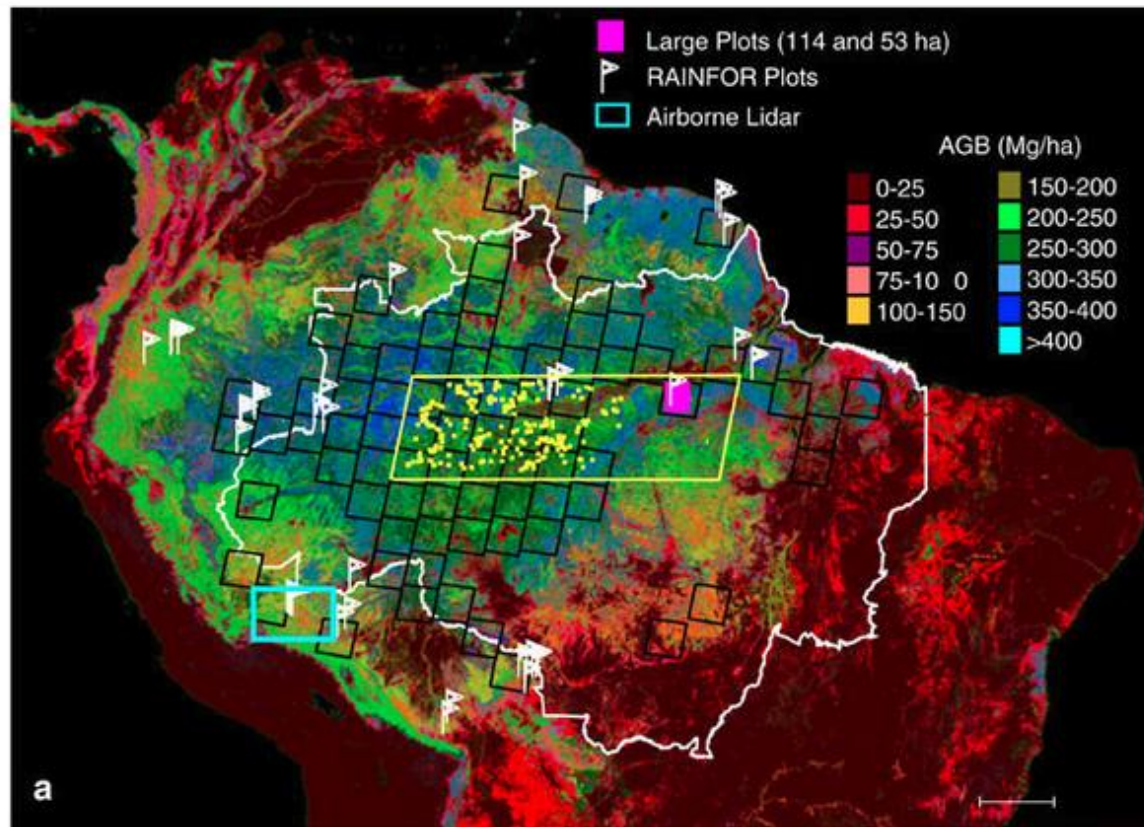
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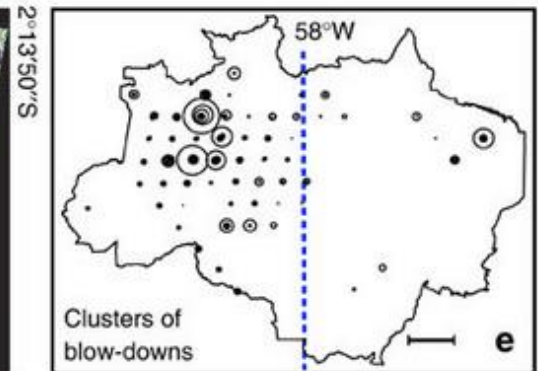
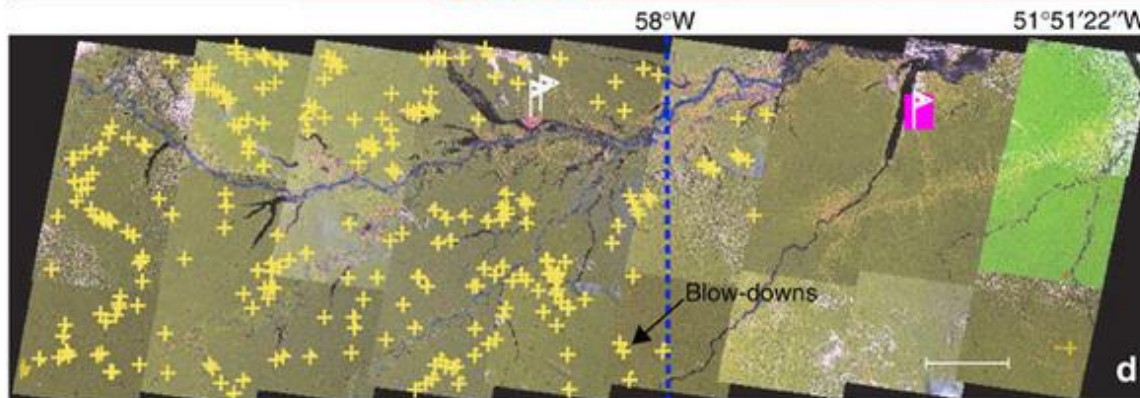
ASSESSING SCIENCE



# Rainfor plots not currently well aligned with RS products – more plots needed



Composite: 3 4 2



Clusters of blow-downs

# How can ground data help for calibration and validation ?

- ground data are also estimates, but they are independent and *always based on individual organisms* (trees), not canopy structural features
- requires *(1) matching to RS in time, (2) accurate tree dimensions, and (3) accurate species identification*



Taken from Phillips's talk at the European Space Agency, Jan 2015



**2. Accurate Dimensions: Foresters' skills**



### **3. Accurate Identification: Botanists' skills**

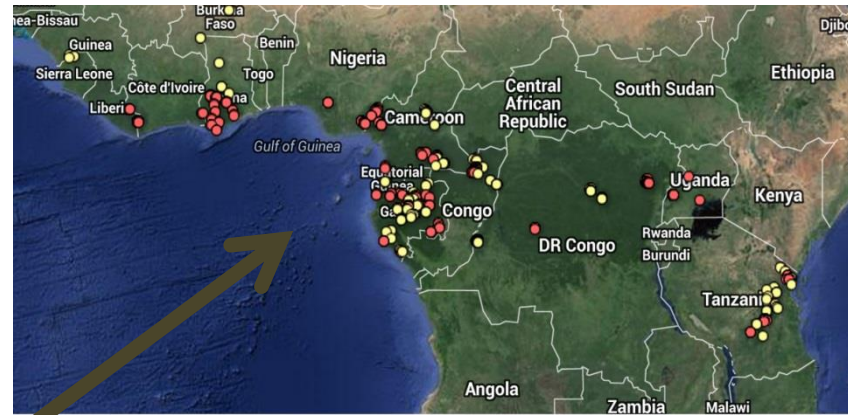
# Pan-tropical teamwork

(standardised protocols: many people, plots, institutions)

**RAINFOR** (Red Amazonica de Inventarios Forestales), 500 biomass & dynamics plots

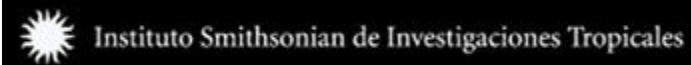


**AfriTRON**  
(African Tropical Forest Observation Network) >250 biomass plots



**CTFS-ForestGEO**, 61 large dynamics plots, ca. 30 tropical

# RAINFOR: Partners



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## Designing systems to monitor carbon stocks in forests and shrublands

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Received 2 September 2000; accepted 14 May 2001

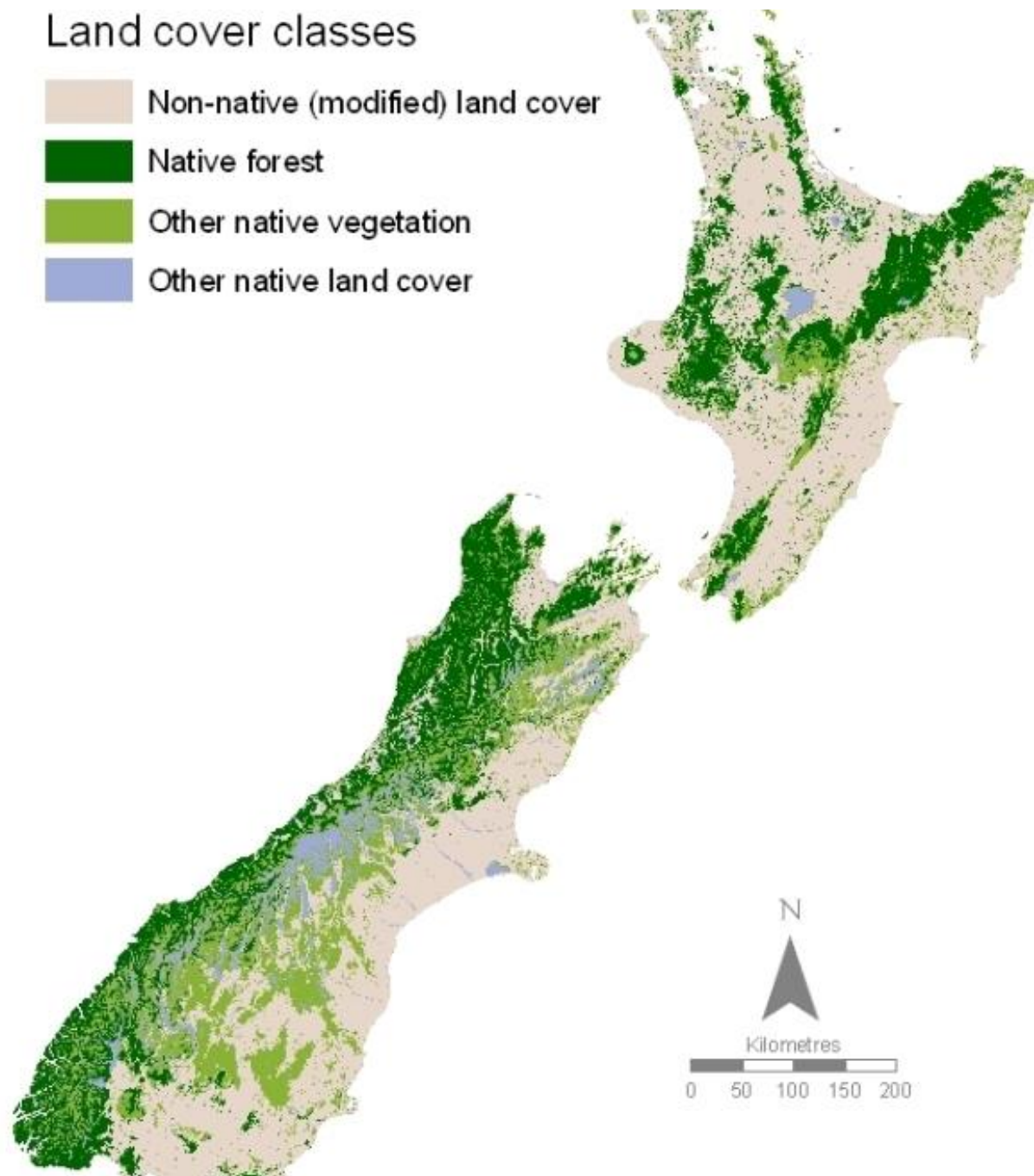
### Abstract

The United Nations framework convention on climate change (FCCC) commits signatory nations to monitor changes in all fluxes and sinks of carbon, including those related to vegetation and soil. This paper describes a system for monitoring carbon in New Zealand's forests and shrublands (6.3 and 2.6 million ha, respectively), which was tested on a 60 km-wide transect across the South Island. A 9 km<sup>2</sup> grid was superimposed onto a land-cover map (SPOT imagery) to obtain 62 ground-sampling points. New permanent plots were established at 43 of these points and 18 existing plots were revisited (one site was inaccessible). On each plot, the dimensions of all trees, shrubs and coarse woody debris (CWD) were measured, and these measurements converted to per-hectare C-stocks using regression relationships. C-stocks in fine litter and mineral soil were quantified using data from New Zealand's national soil-C monitoring system that quantifies national-scale soil-C stocks using a soil-C database stratified by soil type, climate, and land-cover; we used these data to derive values for the transect.

The total C-stock in all pools was 290 t/ha in forests and 163 t/ha in shrublands, 58 and 30% of which was living biomass (respectively). The living biomass components had the greatest variances, so precision could be improved by increasing the sample size of trees, particularly large trees. The C-stock of CWD was highly variable among plots, but was a relatively small component of the total C-stock (10% forest and 3% shrubland). For the moment, we know little about the uncertainty associated with measuring C-sequestration (i.e. change in C-stocks over time), but this information will become available

## Land cover classes

- Non-native (modified) land cover
- Native forest
- Other native vegetation
- Other native land cover



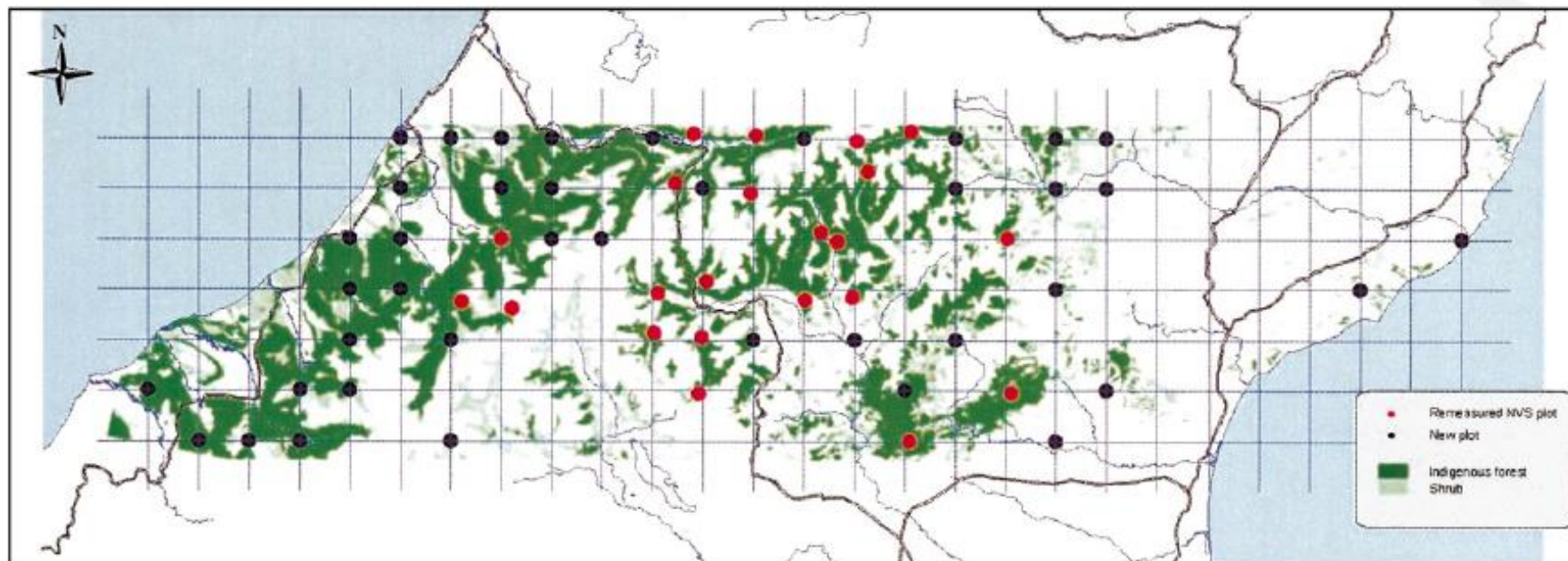


Fig. 2. A satellite-based vegetation map (LCDB) of a transect across South Island, New Zealand, onto which a 9 km<sup>2</sup> grid is superimposed. New permanent plots were established at the grid intersections wherever forest or shrubland was identified on the LCDB (black dots), unless a existing permanent plots was located within the vicinity, which was selected for remeasurement (red dots).



$$AGB_{TREE} = \alpha * WD^{\beta} * DBH^{\gamma} * H^{\delta}$$

AGB = Biomass of individual tree

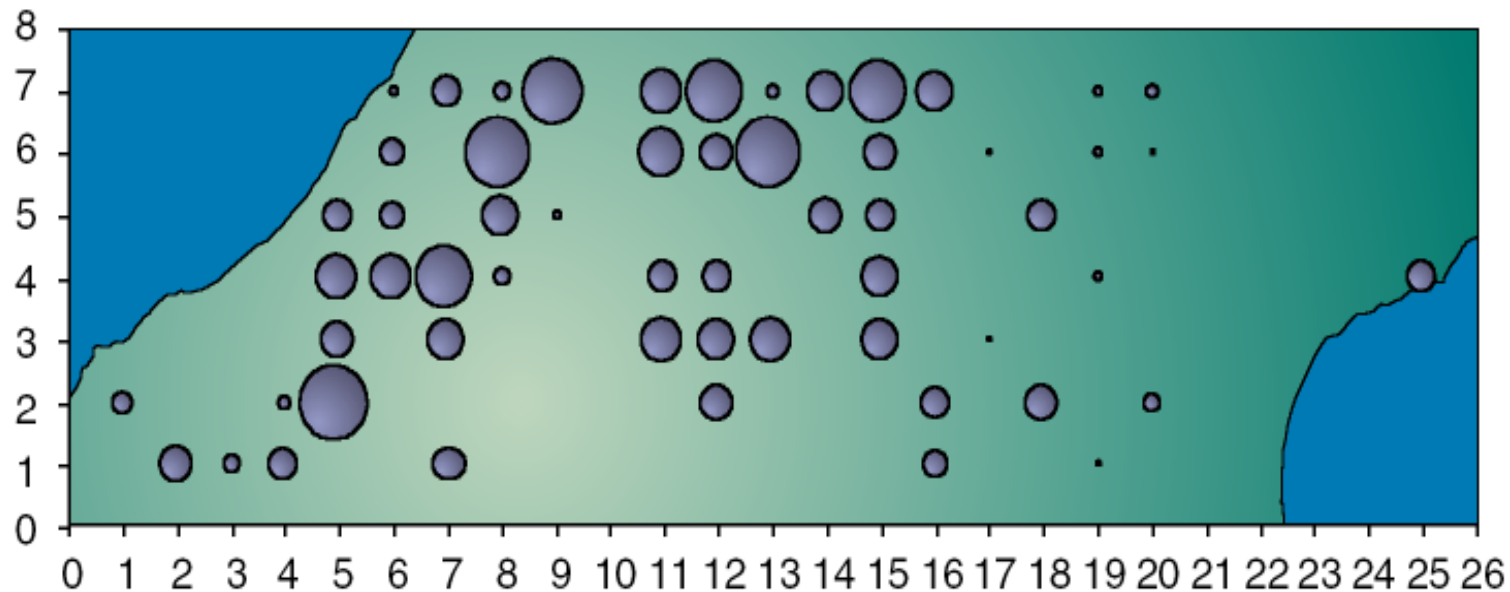
WD = wood density of species

DBH = Diameter at chest height

H = height (estimated from DBH)

# Carbon storage in New Zealand woodlands

Carbon stock in trees, shrubs, and dead wood



Vegetation type

Per-hectare C-stocks (t/ha)

Living biomass

Coarse woody  
debris

Indigenous forest

$169.1 \pm 18.4$  (38)

$29.6 \pm 9.5$  (38)

Shrubland

$48.6 \pm 13.5$  (23)

$5.2 \pm 3.2$  (23)

Forest + shrubland

$123.6 \pm 14.8$  (61)

$20.5 \pm 7.8$  (61)

# Soils and litter

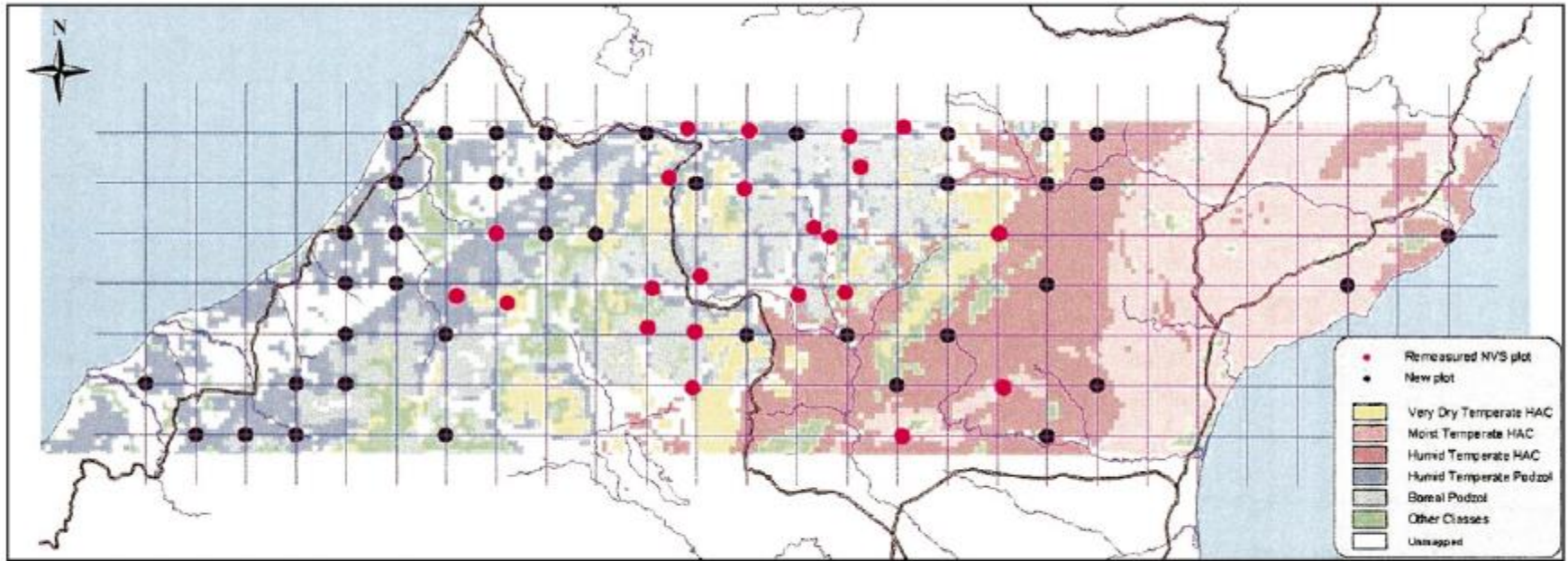


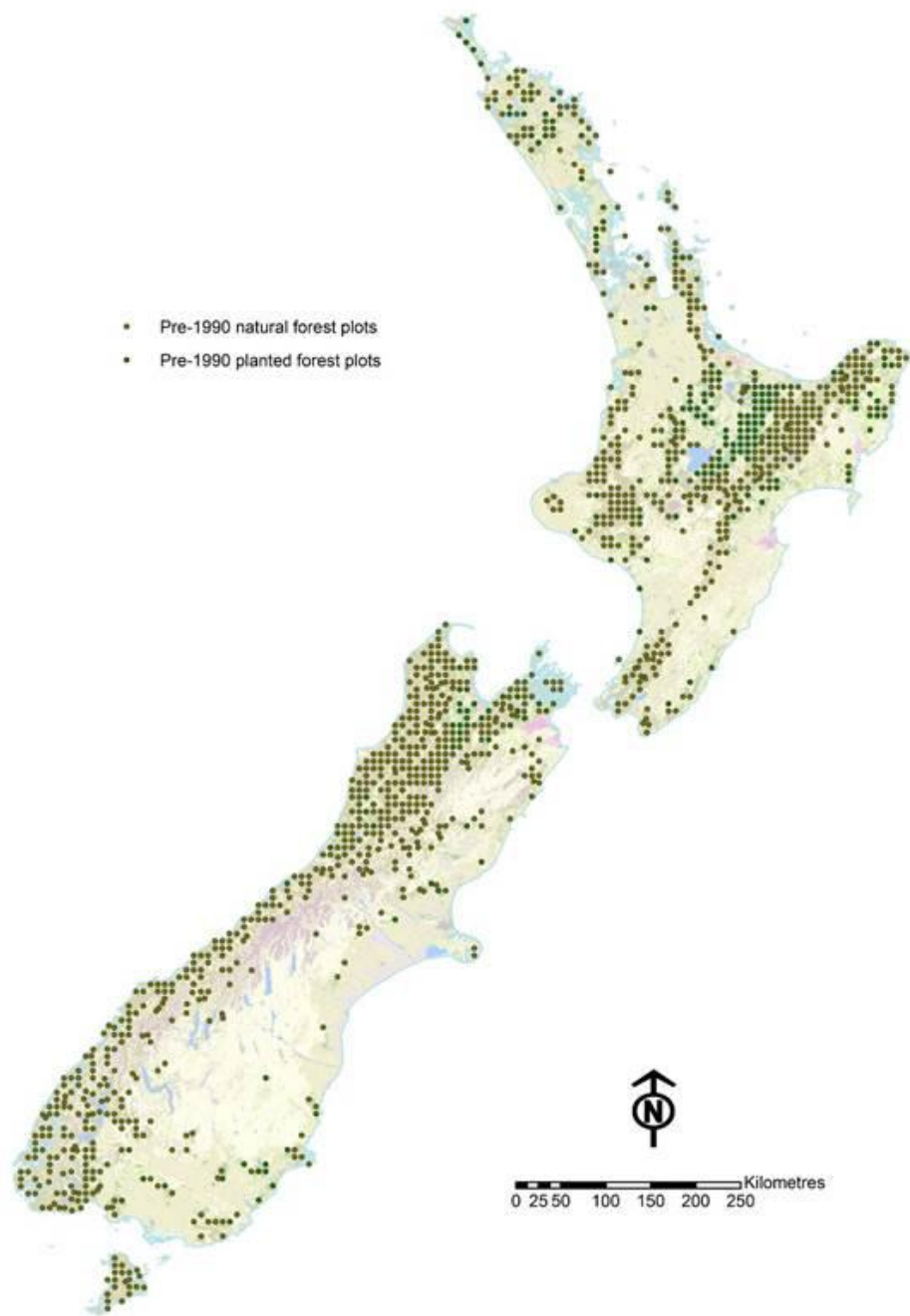
Fig. 3. Map showing major soil types along the transect, with the 9 km grid and plot locations superimposed.

Table 5  
Aerial extent and per-hectare C-stocks (t/ha) of litter (diameter <10 cm) and mineral soils in five major soil classes on the transect<sup>a</sup>

|                        | Indigenous forests |                         |                           | Shrublands |                        |                           |
|------------------------|--------------------|-------------------------|---------------------------|------------|------------------------|---------------------------|
|                        | Area (kha)         | Litter                  | Mineral soil<br>(0–30 cm) | Area (kha) | Litter                 | Mineral soil<br>(0–30 cm) |
| Humid temperate podzol | 120                | 14.8 ± 5.7 (14)         | 64.7 ± 6.7 (17)           | 34         | 6.6 ± 5.7 (6)          | 129.5 ± 26.0 (6)          |
| Boreal podzol          | 45                 | 14.5 ± 3.7 (7)          | 90.8 ± 12.4 (9)           | 22         | 7.5 ± 3.6 <sup>b</sup> | 103.0 ± 11.4 <sup>b</sup> |
| Humid temperate HCA    | 30                 | 20.1 ± 4.6 (4)          | 96.1 ± 8.0 (4)            | 51         | 15.3 ± 9.9 (8)         | 80.5 ± 13.5 (8)           |
| Moist temperate HCA    | 13                 | 15.5 ± 3.3 <sup>b</sup> | 79.9 ± 26.2 (2)           | 18         | 1.0 ± 0.8 (7)          | 89.0 ± 10.6 (6)           |
| Other soils            | 87                 | 15.5 ± 3.3 <sup>b</sup> | 76.6 ± 5.2 <sup>b</sup>   | 50         | 7.5 ± 3.6 <sup>b</sup> | 103.0 ± 11.4 <sup>b</sup> |
| Total <sup>c</sup>     | 295                | 15.5 ± 2.0              | 76.1 ± 2.7                | 175        | 8.9 ± 2.2              | 100.2 ± 5.1               |

Stocks ( $\pm$ S.E.M.) of all major carbon components in indigenous forests and shrublands along the South Island transect, with sample sizes taken in brackets<sup>a</sup>

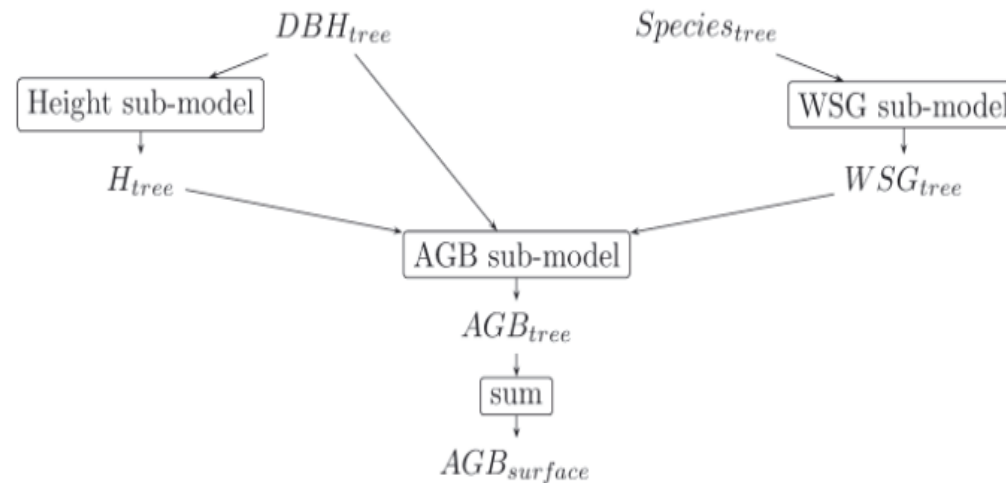
| Vegetation type    | Per-hectare C-stocks (t/ha) |                     |                          |                           |                       | Area | Total C<br>(million tonnes) |
|--------------------|-----------------------------|---------------------|--------------------------|---------------------------|-----------------------|------|-----------------------------|
|                    | Living biomass              | Coarse woody debris | Fine litter <sup>b</sup> | Mineral soil <sup>b</sup> | All pools             |      |                             |
| Indigenous forest  | 169.1 $\pm$ 18.4 (38)       | 29.6 $\pm$ 9.5 (38) | 15.5 $\pm$ 2.0 (25)      | 76.1 $\pm$ 2.6 (32)       | 290.3 $\pm$ 21.0 (38) | 295  | 85.6 $\pm$ 6.2              |
| Shrubland          | 48.6 $\pm$ 13.5 (23)        | 5.2 $\pm$ 3.2 (23)  | 8.9 $\pm$ 1.1 (21)       | 100.2 $\pm$ 5.2 (20)      | 162.9 $\pm$ 14.8 (23) | 175  | 28.5 $\pm$ 2.6              |
| Forest + shrubland | 123.6 $\pm$ 14.8 (61)       | 20.5 $\pm$ 7.8 (61) | 12.5 $\pm$ 1.7 (46)      | 85.3 $\pm$ 3.8 (52)       | 241.9 $\pm$ 17.2 (61) | 470  | 114.5 $\pm$ 8.1             |



# Topics

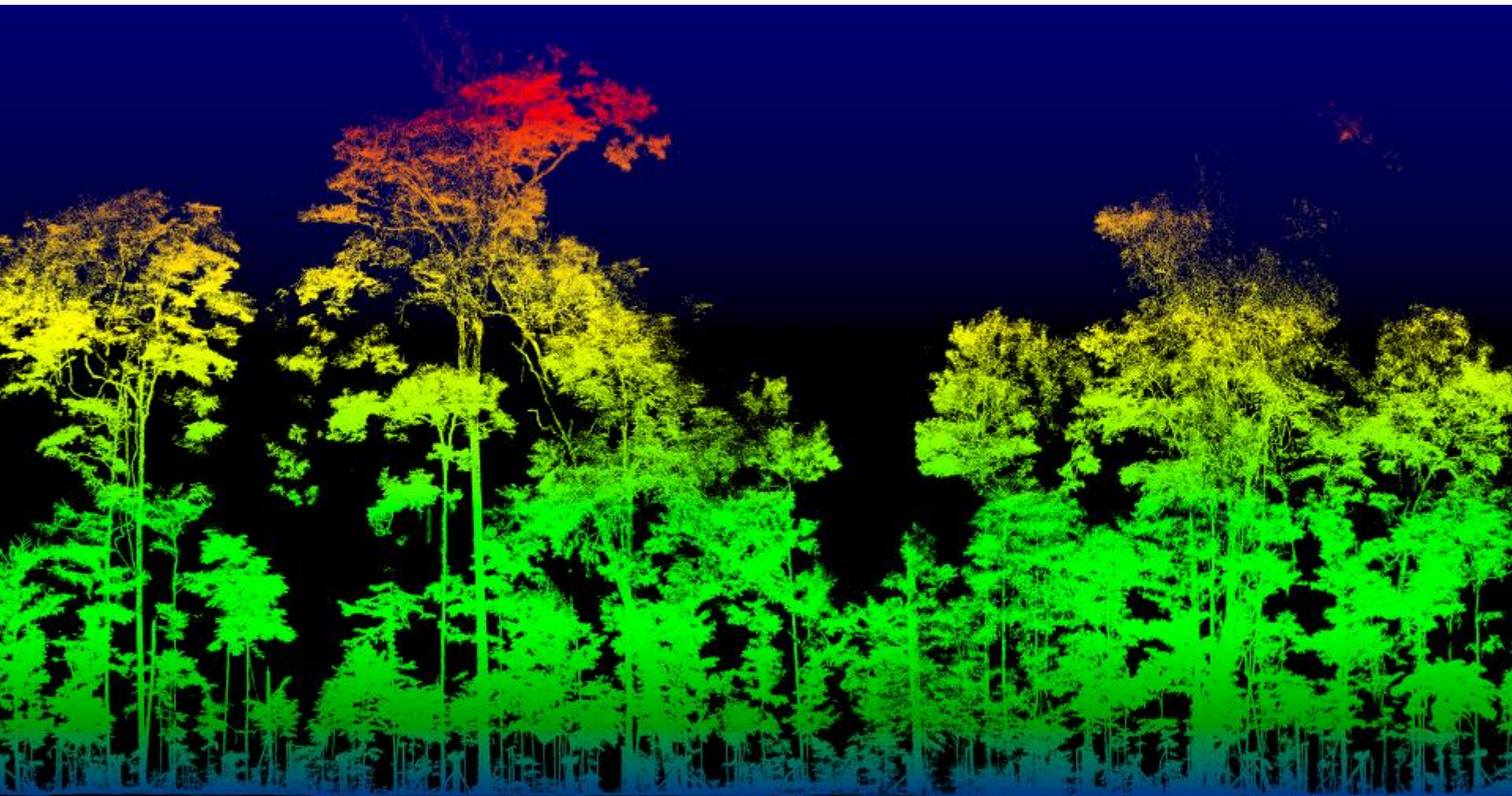
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- There are several papers looking at error propagation



**Fig. 1.** Biomass estimation process at the forest plot scale.

# Using tLidar to improve allometry



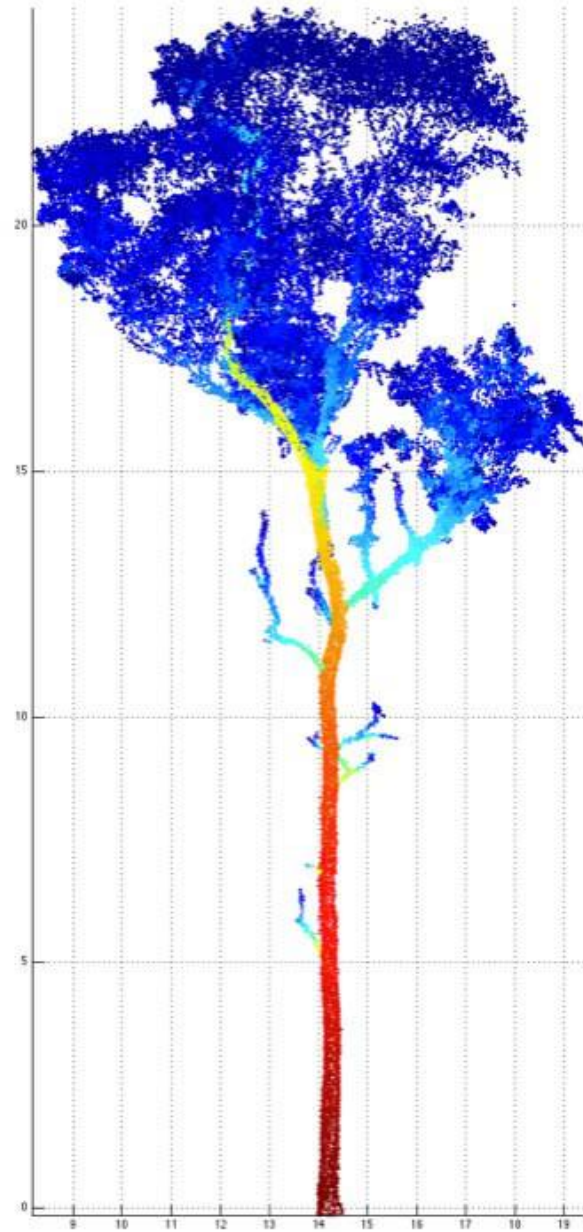
Thanks to Mat Disney, UCL

# Caxiuana drought experiment



<https://www.youtube.com/watch?v=C4-xBCQ291M&feature=youtu.be>

# Segmenting trunks to get accurate volumes



Thanks to Mat Disney, UCL

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# The benefits of using LiDAR

- You can get wall-to-wall maps of carbon density.
- Good for calibrating / validating satellite imagery
- Although carbon density in any one pixel will be estimated with lower precision than from an inventory plot, you estimate carbon density in millions of pixels vs a few hundred plots, so the precision of regional estimate should be much better.
- Better than plots for measuring disturbance (e.g. Espirito Santo et al 2014).
- Great for detecting subtle differences in forest structure indicative of recovering secondary forests vs old-growth forest
- Saves money, once properly calibrated.

## Example from the Mediterranean of SD of ground plots vs LiDAR

**Table 2.** Comparison of the lidar modelling of above-ground biomass (AGB) and biomass change (AGB change) with forest inventory and tree-ring data: values given are mean (and standard deviation in parentheses).

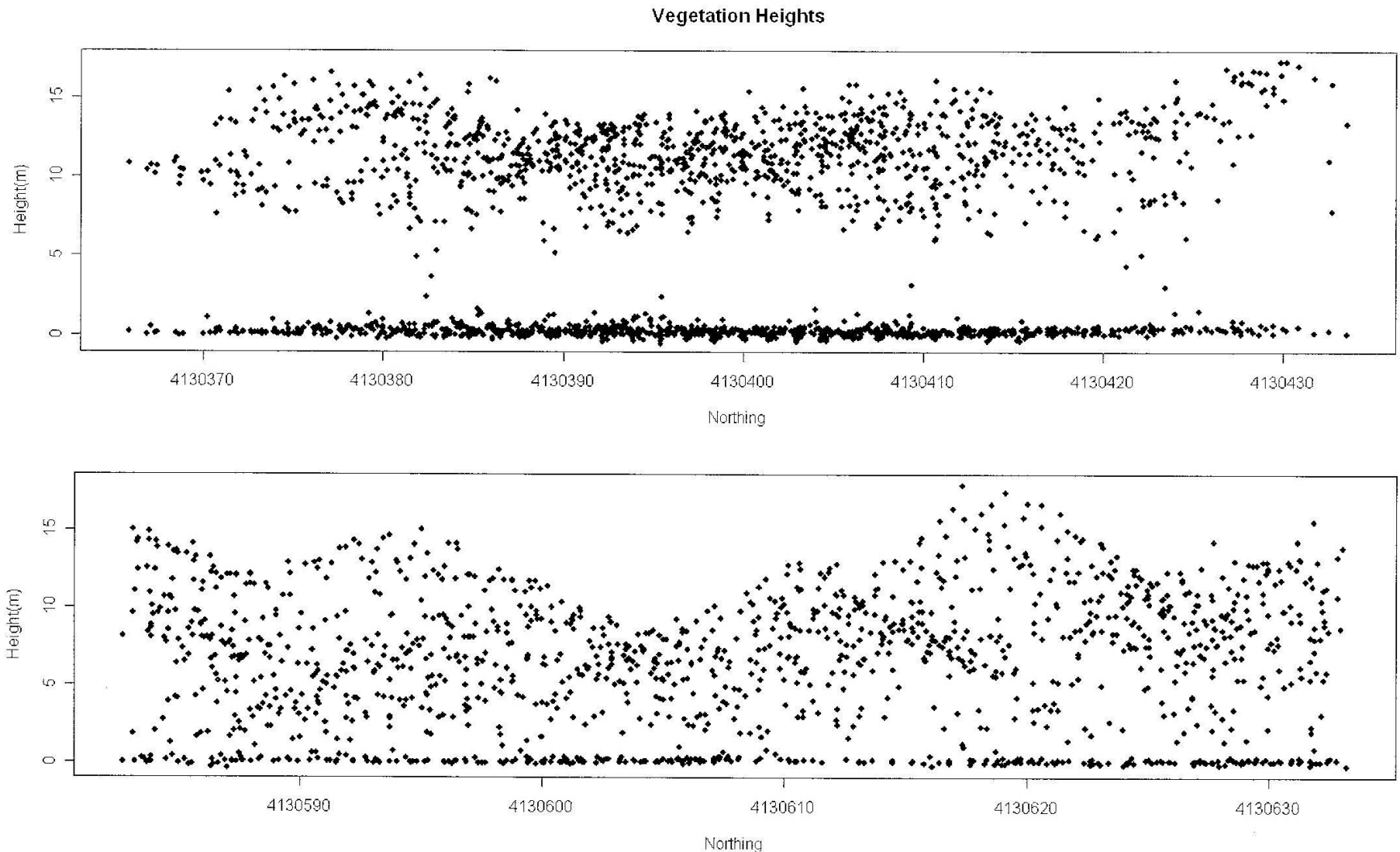
|                                                      | Lidar data            | Forest inventory data | Tree-ring data      |
|------------------------------------------------------|-----------------------|-----------------------|---------------------|
| AGB ( $\text{Mg ha}^{-1}$ )                          | 41.80 ( $\pm 25.68$ ) | 42.8 ( $\pm 52.7$ )   | –                   |
| AGB change ( $\text{Mg ha}^{-1} \text{ year}^{-1}$ ) | 1.22 ( $\pm 1.92$ )   | 1.19 ( $\pm 1.17$ )   | 1.13 ( $\pm 0.54$ ) |
| Sample size                                          | 9136 grid cells       | 66 plots              | 13 plots            |

SD similar, but RMSE goes as  $1/\sqrt{N}$  so very low for landscape

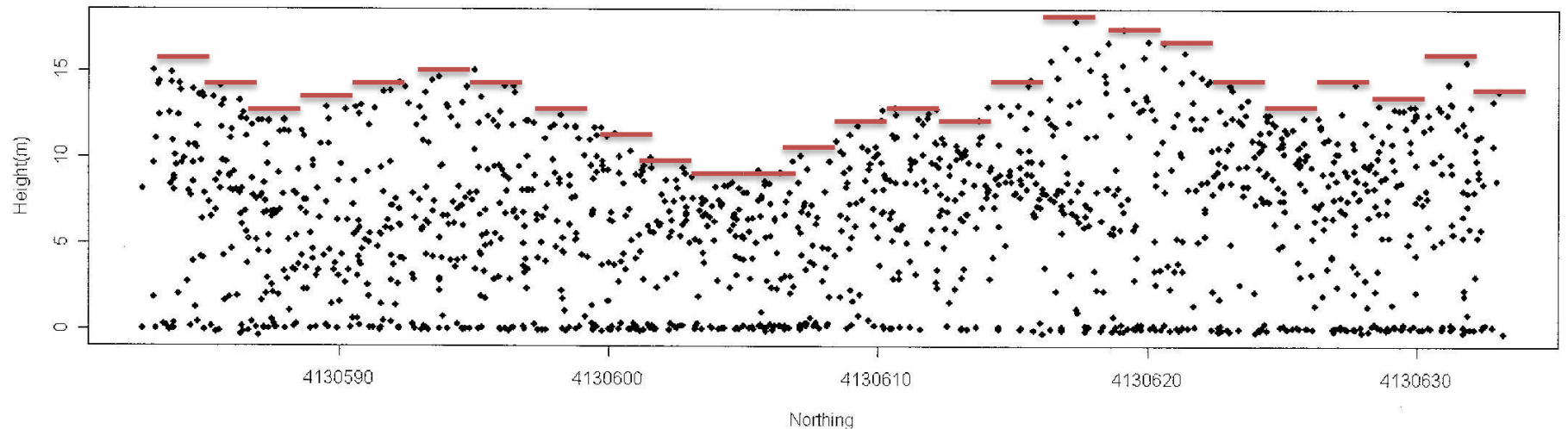
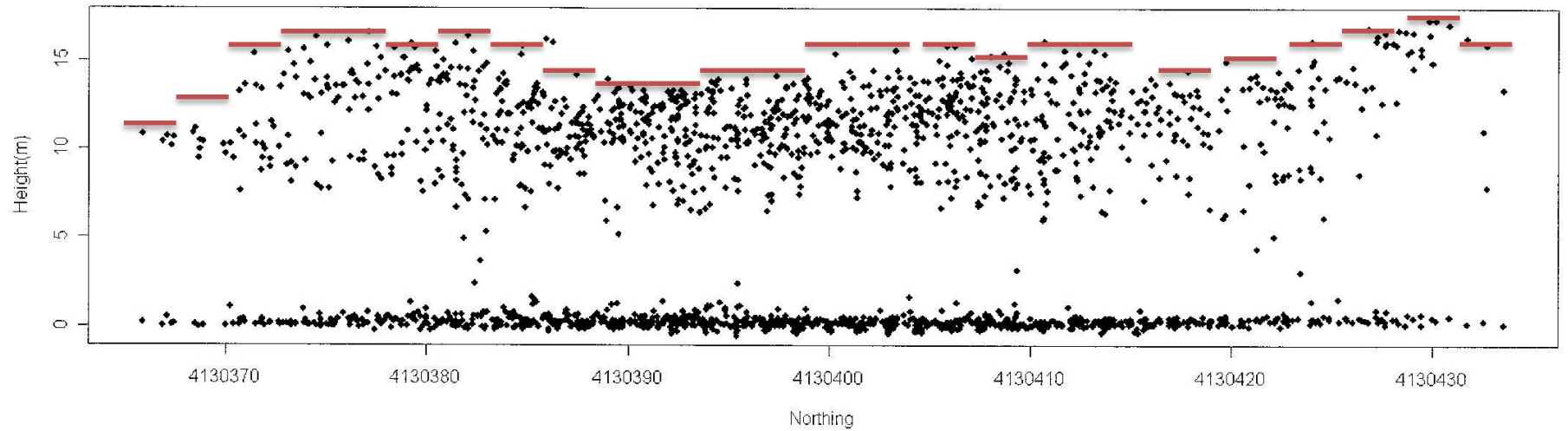
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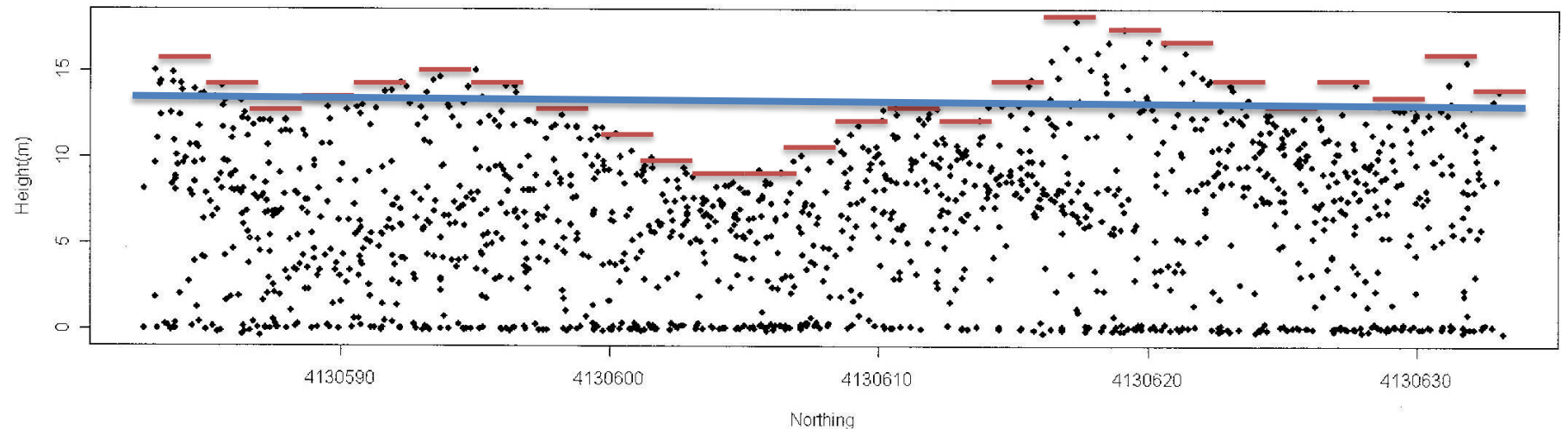
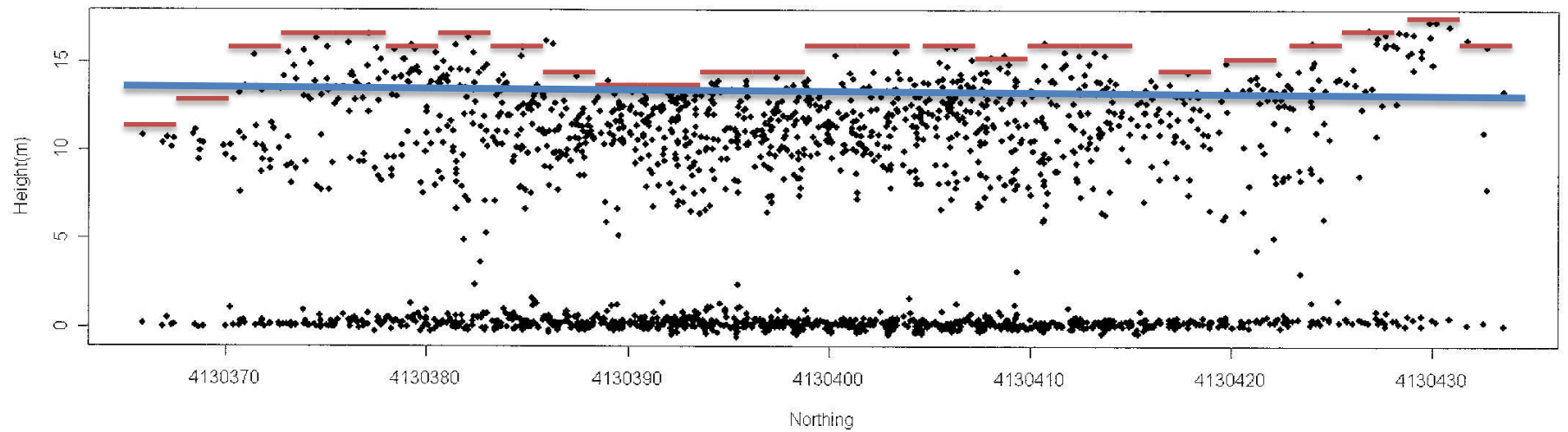
# Asner and Mascaro's Universal model

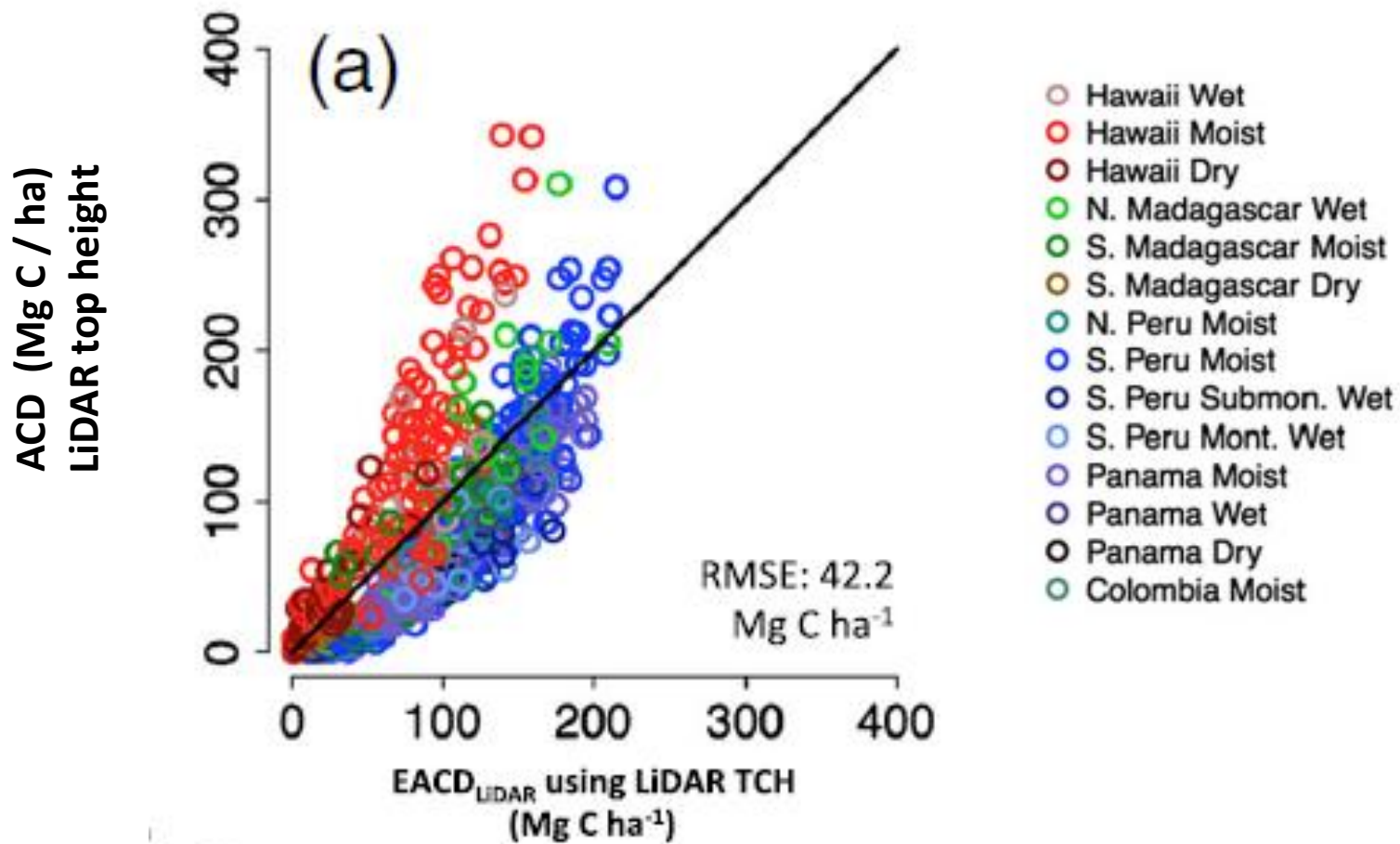


Vegetation Heights



Vegetation Heights

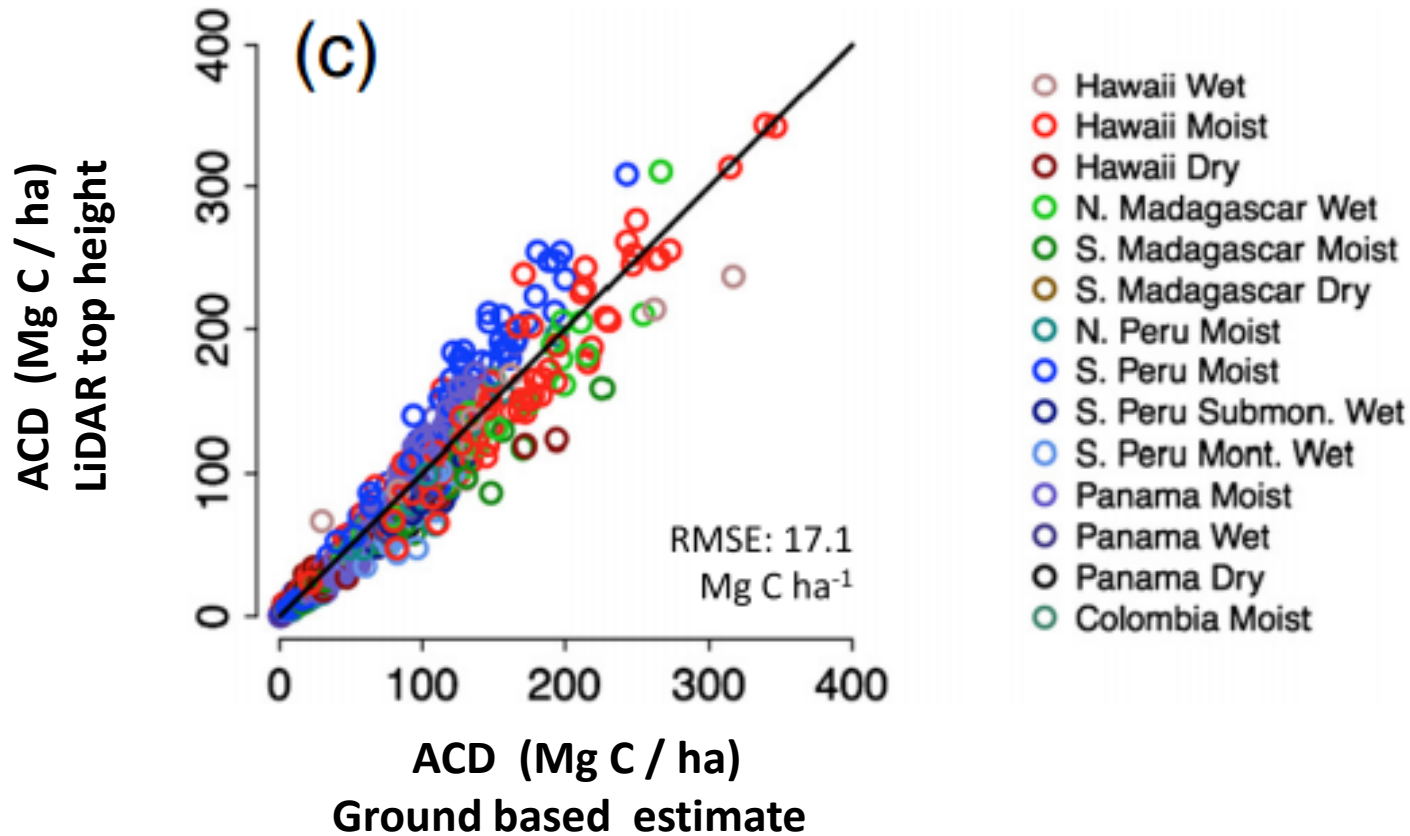




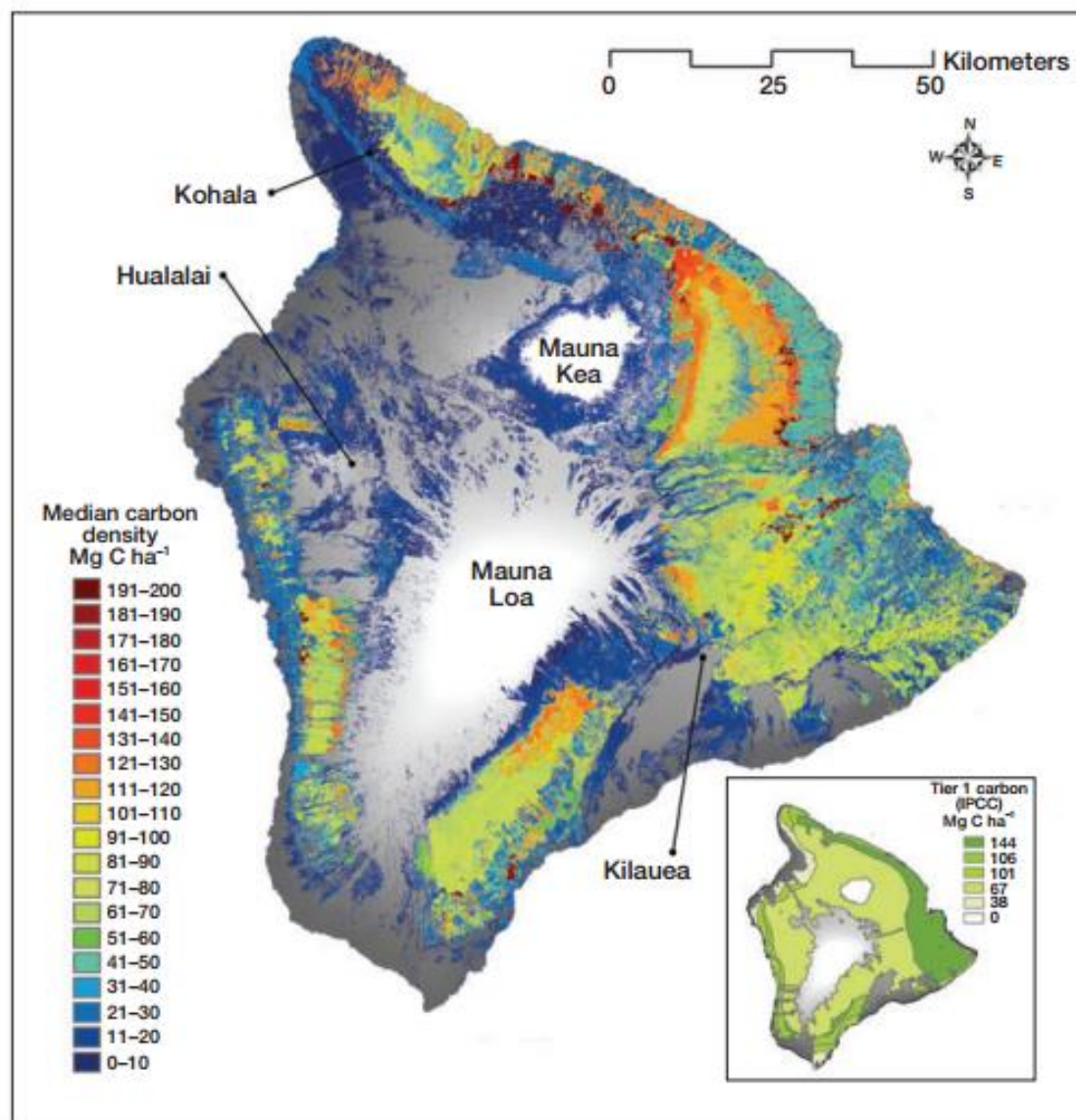
Drawing from the form of Chave et al. (2005; model 2), Asner, Mascaro, et al. (2012) proposed the following general plot-aggregate allometry:

$$EACD_{field} = aTCH^{b1}BA^{b2}\rho_{BA}^{b3} \quad (6)$$

where  $TCH$  is LiDAR-derived top-of-canopy height (m; replacing MCH as discussed above),  $BA$  is plot-averaged basal area ( $\text{m}^2 \text{ha}^{-1}$ ),  $\rho_{BA}$  is basal-area weighted wood density.



But not so convincing in several temperate studies!



**Figure 4.** Median values of aboveground C density throughout Hawaii Island, in units of  $\text{Mg C ha}^{-1}$ , mapped at 30-m spatial resolution through a combination of airborne LiDAR and satellite vegetation mapping. Inset shows aboveground C density estimated via IPCC Tier 1 data and methods (see WebPanel 5).

Other studies confirm the effectiveness of this approach

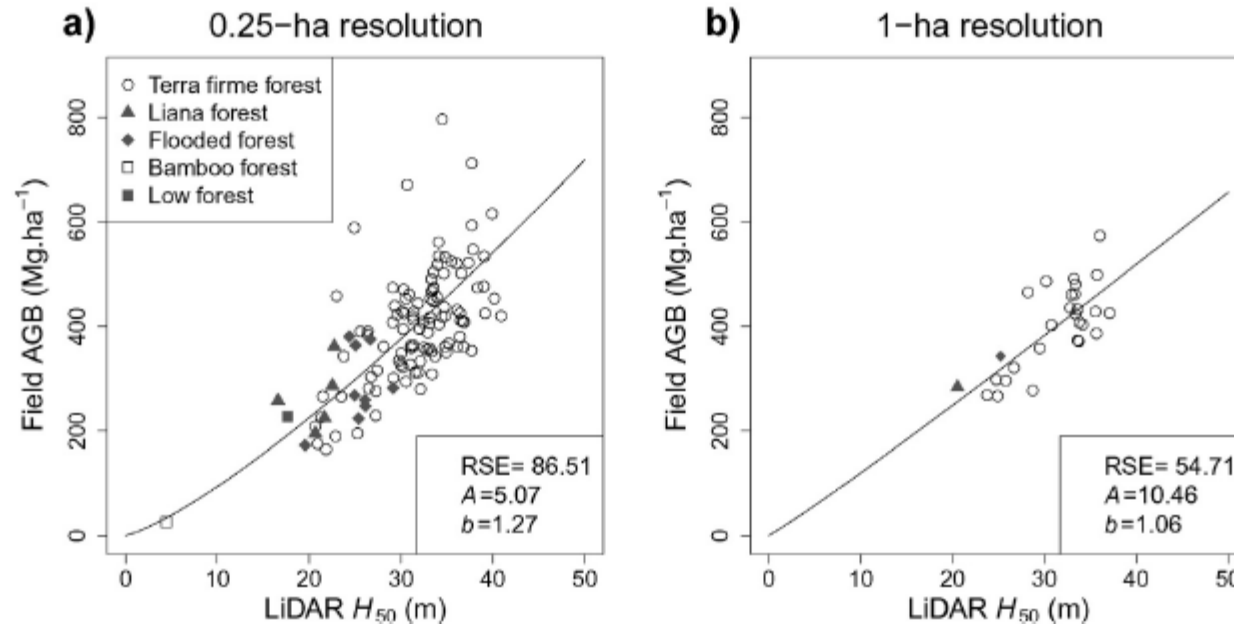


Fig. 3. Relationship between the aboveground biomass density (AGB) and LiDAR  $H_{50}$  for (a) 119 plots of 0.25-ha and 1 plot of 0.125 ha (bamboo forest), and (b) 29 plots of 1 ha. The residual standard error (RSE) and the coefficients of the power-law model of Eq. (8) (see methods) are provided in the bottom-right insets.

Best to have calibration plots of 1 hectare in size. 0.25 hectares isn't bad though

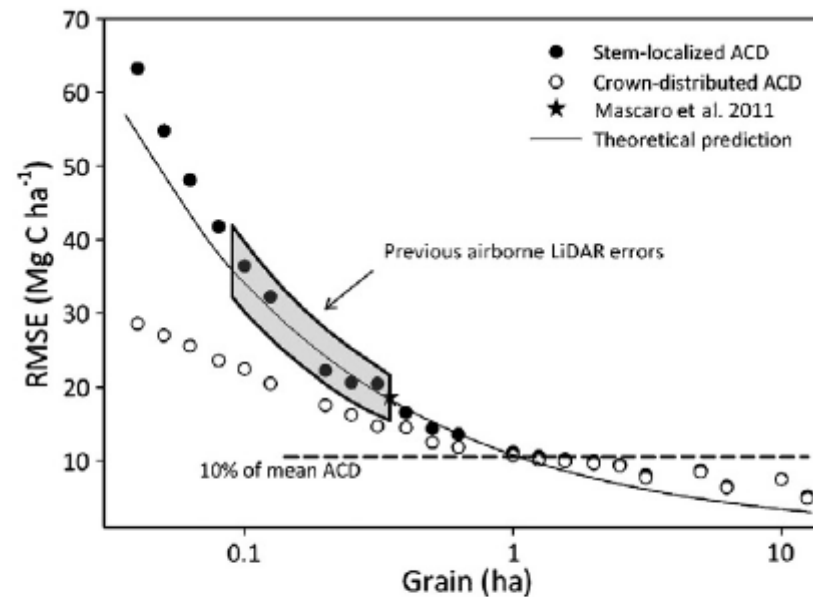


Fig. 3. Observed decline in LiDAR-based carbon density prediction error with decreasing spatial resolution in the 50-ha forest dynamics plot on Barro Colorado Island, Panama, using stem-localized and crown-distributed aboveground carbon density estimates (ACD), compared with the theoretical expectation that errors should decline with  $(\text{grain size})^{-1/2}$  (Asner et al., 2010). The calibration grain size is 0.36 ha (Mascaro et al., 2011).

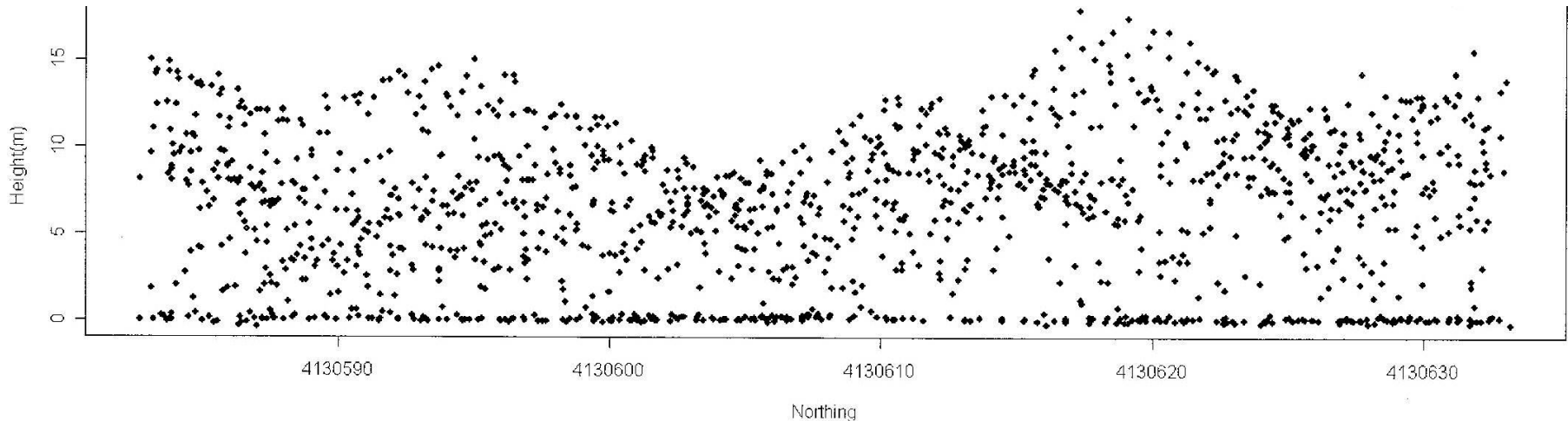
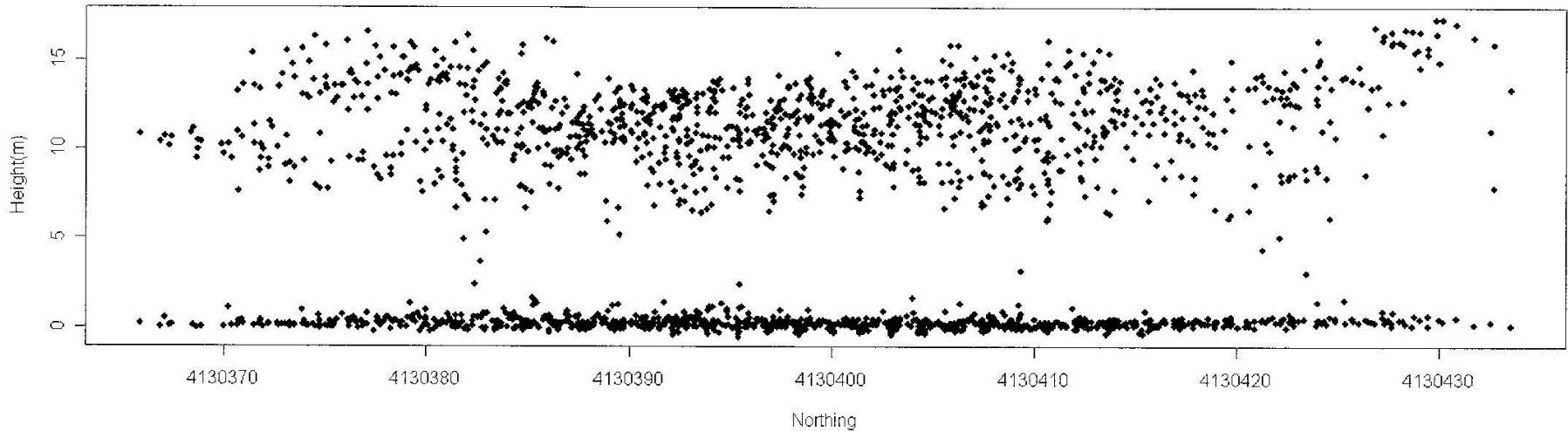
Mascaro et al. (2011)

See also Chen and Laurin (2014)

# What do we really want ARS to tell us?

## A tree centric approach

Vegetation Heights

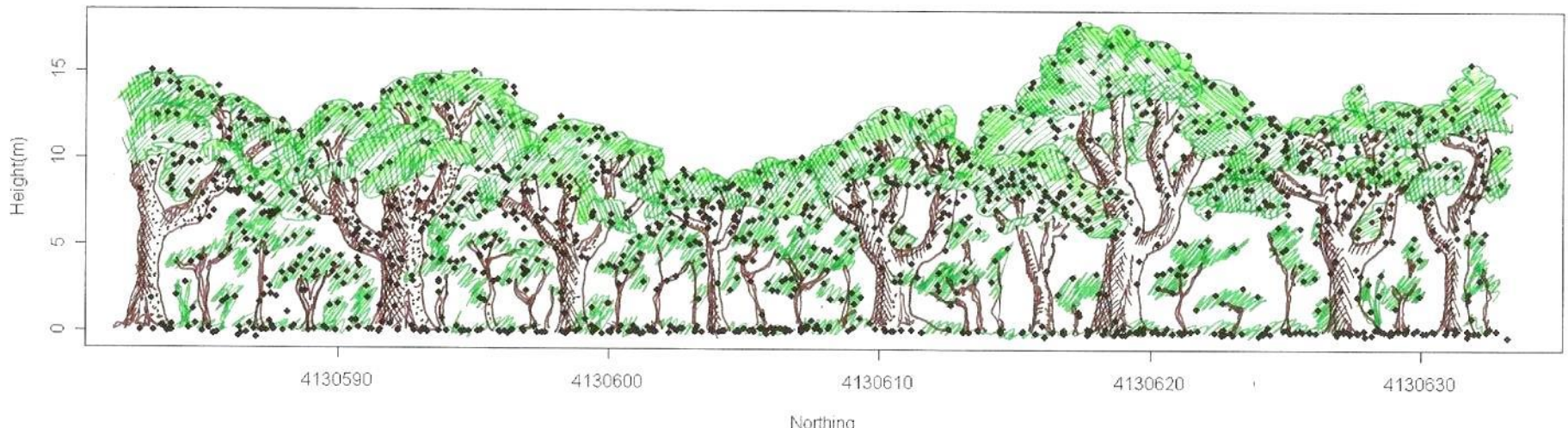
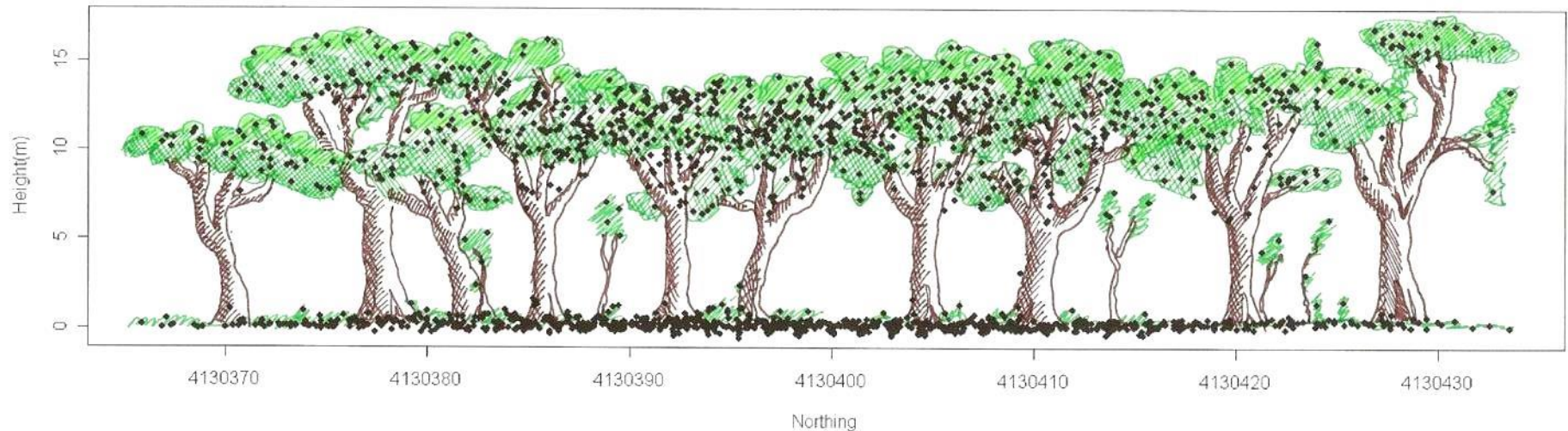


# What do we really want ARS to tell us?

A tree centric approach !

+ identify species

Vegetation Heights



# Tree Centric Mapping of Forest Carbon

Traditional field analyses of AGB are based on ground measurements of DBH

$$AGB_{TREE} = \alpha * WD^{\beta} * DBH^{\gamma} * H^{\delta}$$

Instead of measuring diameter on ground, we can estimate it from LiDAR-derived height and crown area of each tree

$$DBH = \varepsilon * H^{\rho} * (1 + \vartheta * CA)$$

We also identify tree species by machine learning, using the hyperspectral dataset

And estimate WD from this species information.

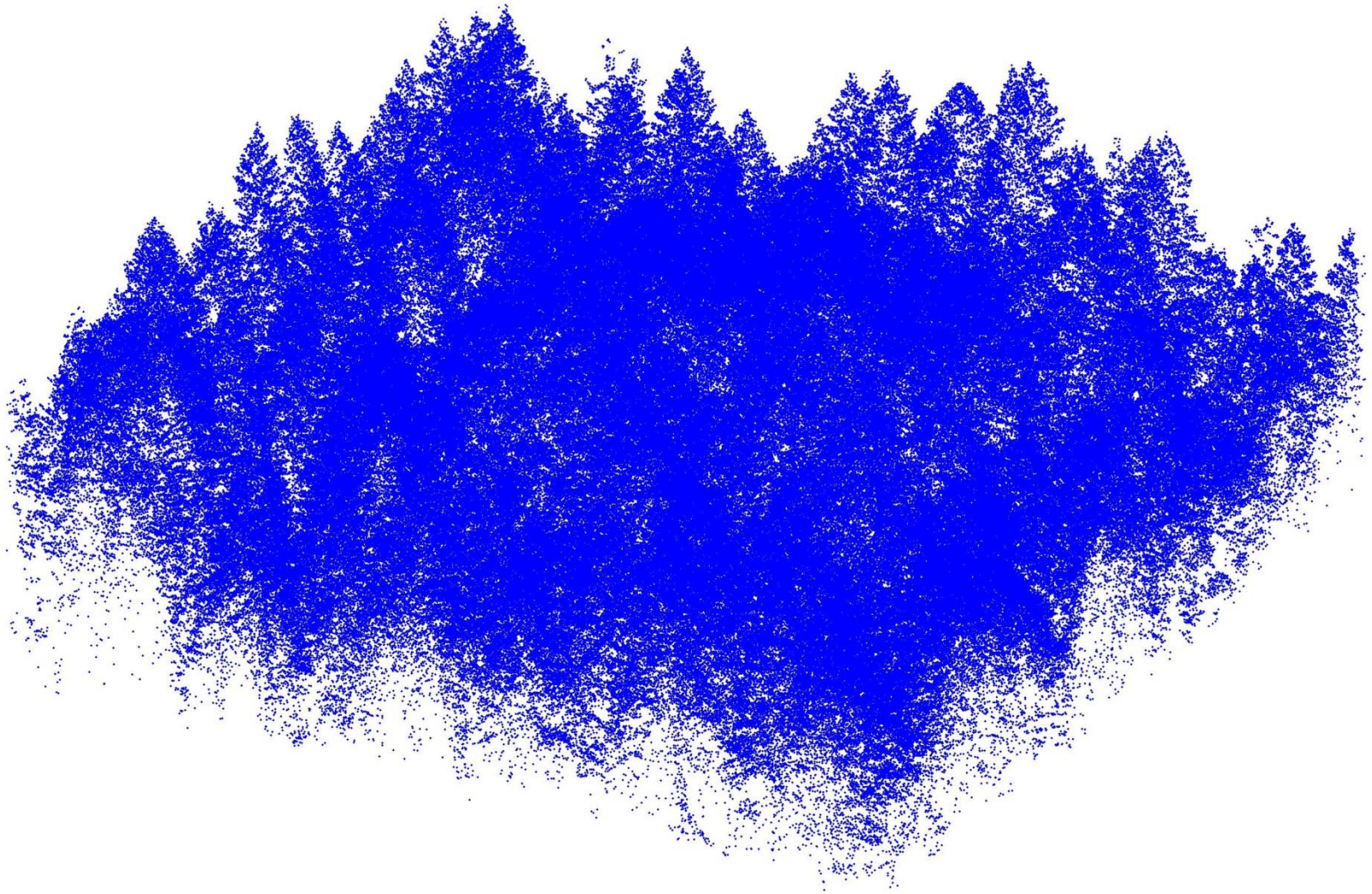
# 3-D Individual Tree Segmentation Based on Normalised Cut from Fully Integrated LiDAR and Optical Imagery

Juheon Lee<sup>a,b</sup>, Xiaohao Cai<sup>a,b</sup>, Jan Lellmann<sup>b</sup>, Carola-Bibiane Schönlieb<sup>b</sup>, and David Coomes<sup>a</sup>

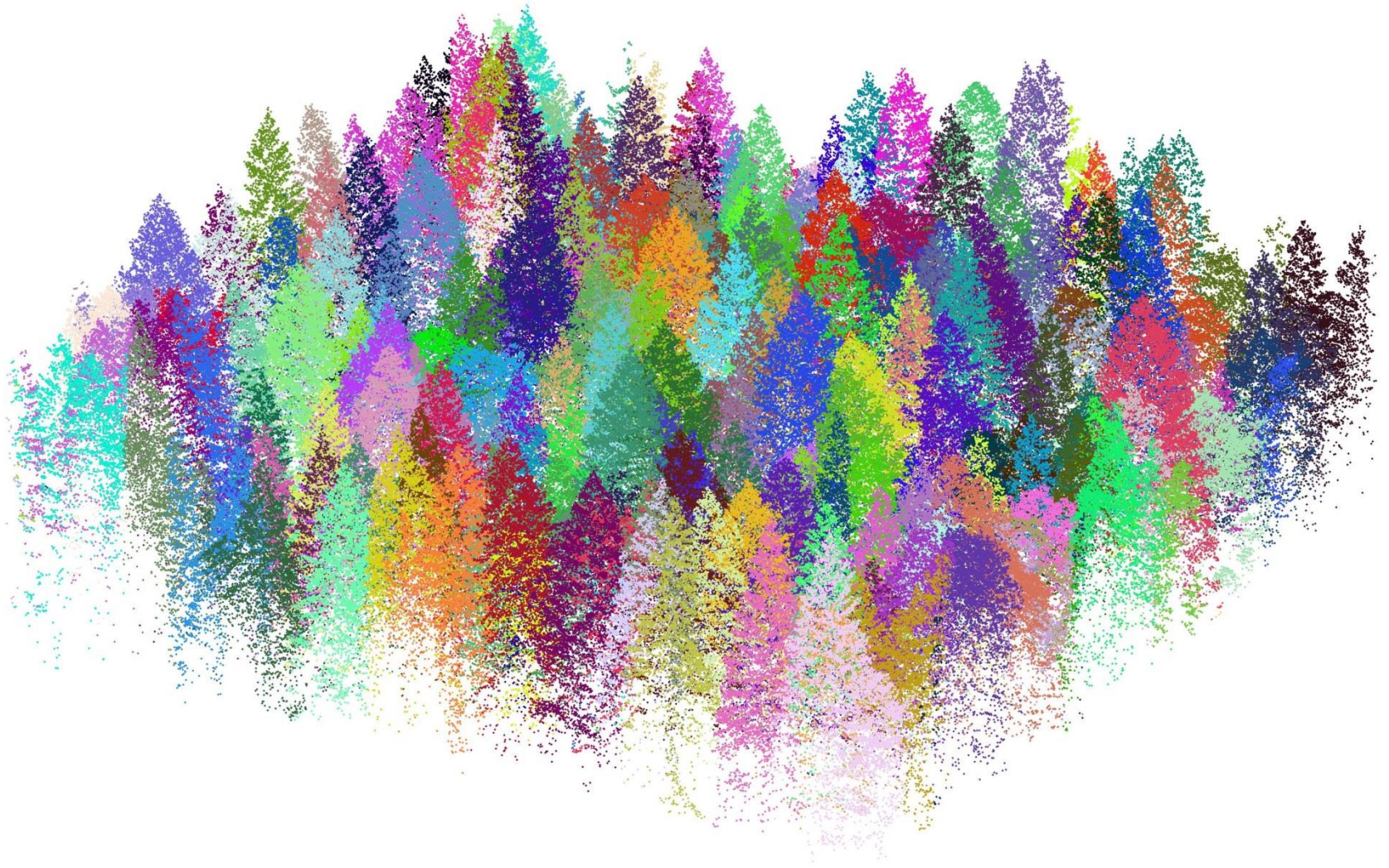
<sup>a</sup>Forest Ecology and Conservation Group, Department of Plant Sciences,  
University of Cambridge, CB2 3EA.

<sup>b</sup>Image Analysis Group, Department of Applied Mathematics and Theoretical Physics (DAMTP),  
University of Cambridge, CB3 0WA.

# Airborne laser scanning point cloud – Italian Alps



# Tree recognition from laser scanning point cloud – Italian Alps



# Tree Centric Mapping of Forest Carbon in Italy



# Tree Centric Mapping of Forest Carbon in Italy

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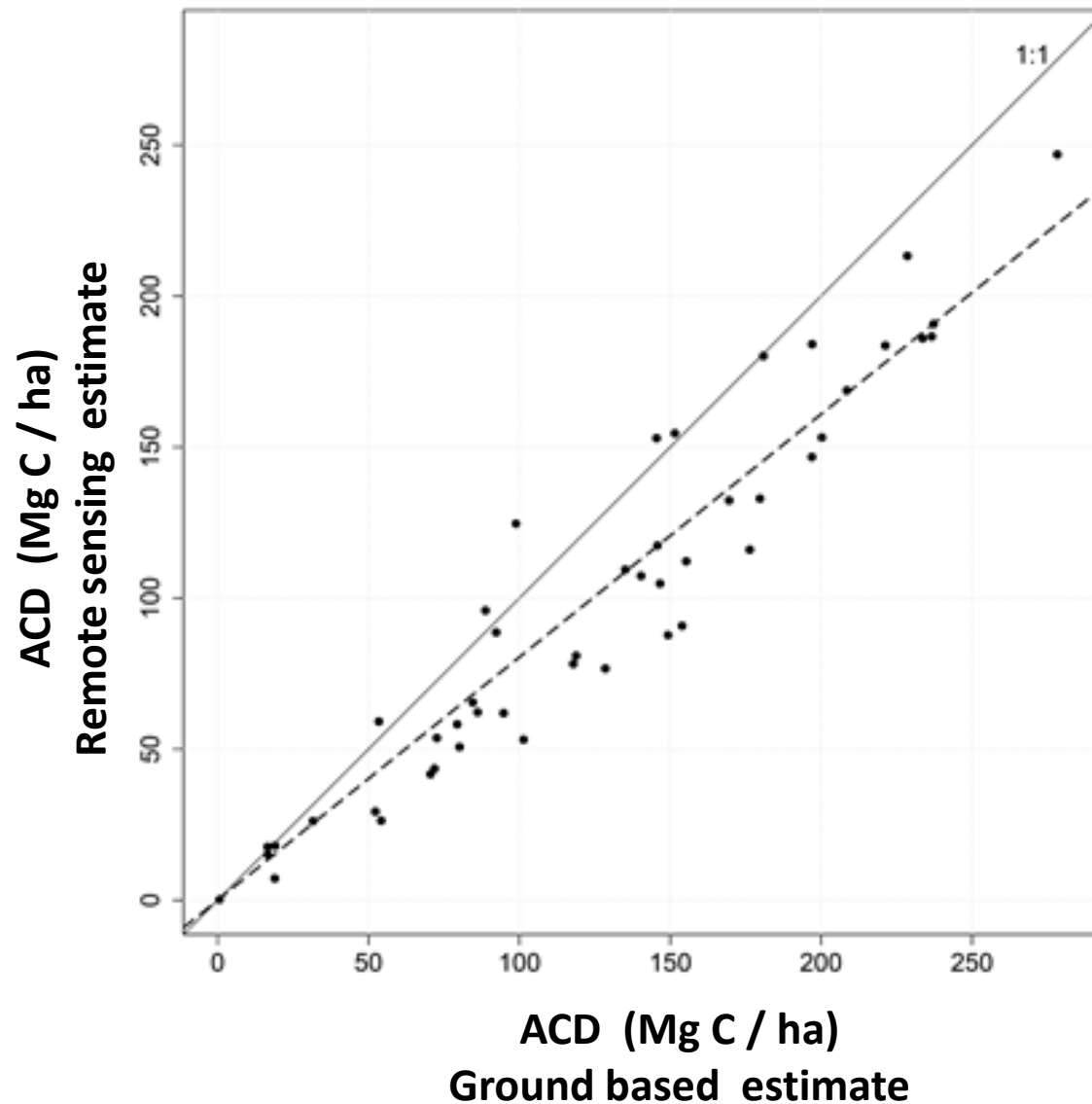
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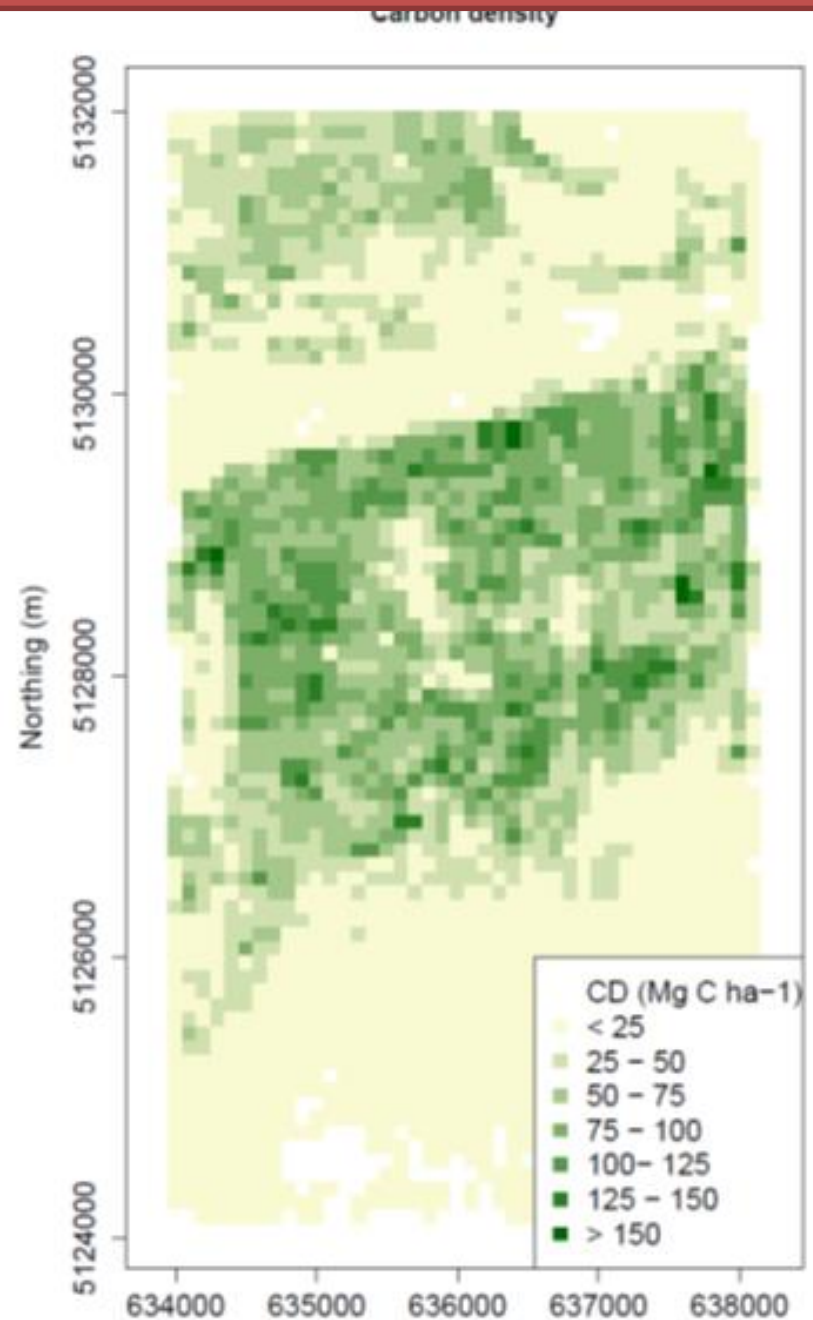
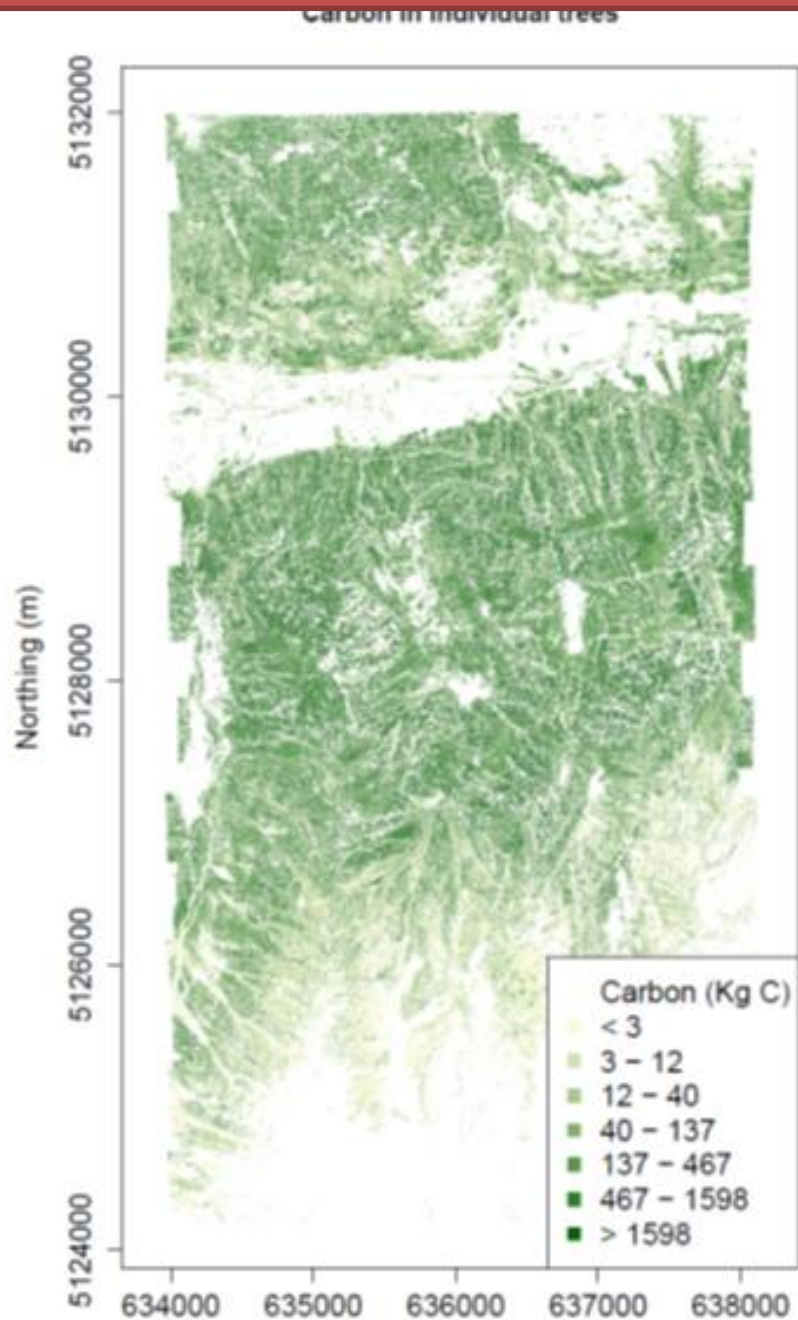
We also identify tree species by machine learning, using the hyperspectral dataset

And estimate WD from this species information.

Excellent correlation between LiDAR and ground estimates of forest biomass (validation plots), with slight bias evident



# Allows individual tree carbon or carbon density to be mapped



A tree-centric approach to carbon density mapping is appealing because it is based on the fundamental principles of individual tree allometres



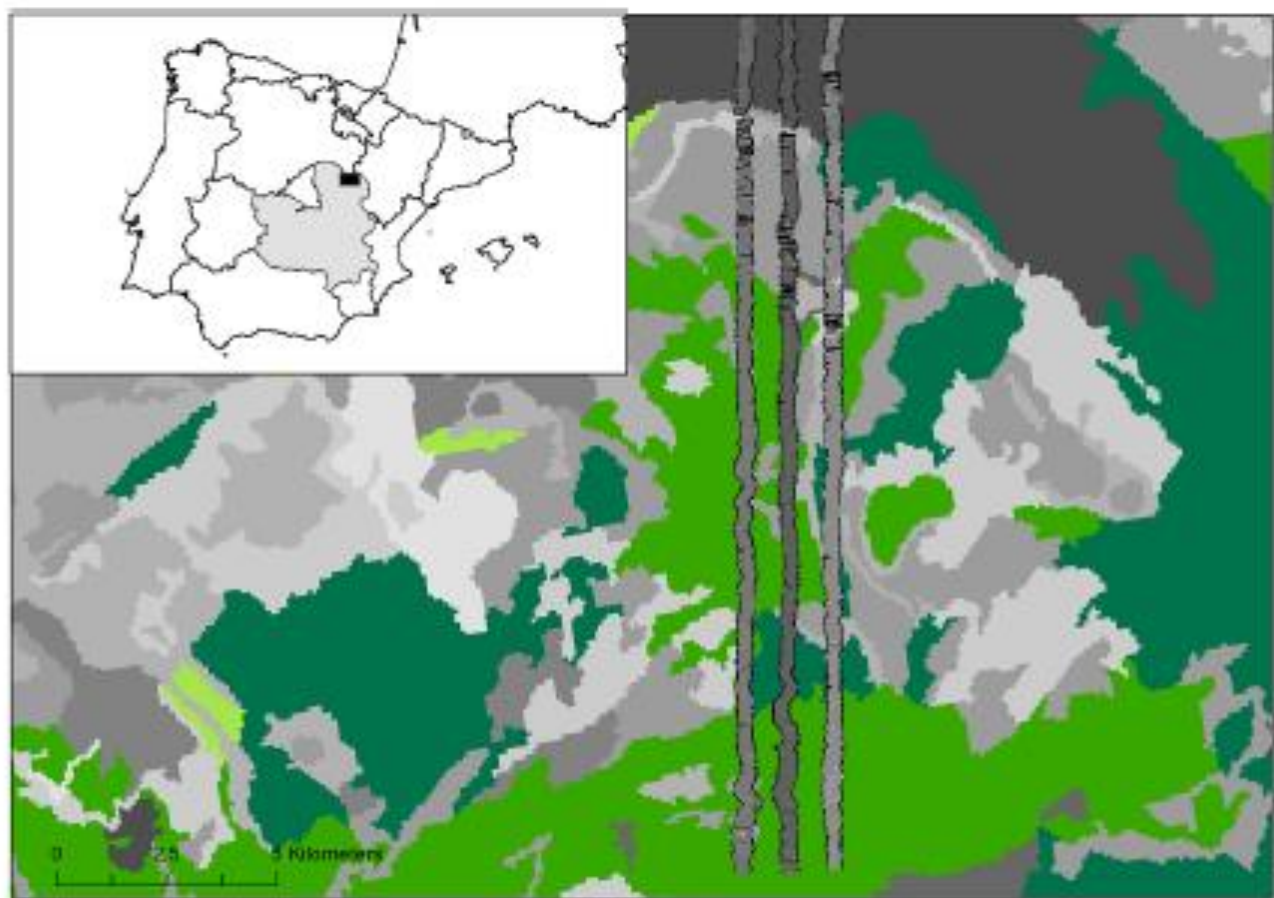
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Cambridge  
Conservation  
Initiative

# Topics

- The essentiality of inventory plots
- Do we even need LiDAR to get accurate and precise carbon stock and flux estimates?
- Improving plot-level estimates
- The benefits of using LiDAR
- Choice of estimation equation
- **Measuring carbon fluxes by repeat-LiDAR surveying**
- From LiDAR strips to landscapes





**Figure 2.** Study area. Shown in lighter green, mixed forest, and darker green, coniferous forest. Other land covers (including agricultural) in shades of grey, with darkest grey indicating an area burned by forest fire in 2005 and excluded from these analyses. The three north–south parallel strips show the lidar survey coverage.

**Table 1.** Specifications for the lidar surveys undertaken at Alto Tajo (Spain) in 2006 and 2011.

|                                   | 2006            | 2011             |
|-----------------------------------|-----------------|------------------|
| Lidar sensor                      | Optech-ALTM3033 | Leica ALS050     |
| Wavelength (nm)                   | 1064            | 1064             |
| Beam divergence (mrad)            | 0.20            | 0.22             |
| Vertical discrimination (m)       |                 | 2.8              |
| Detection system                  | Two return      | Four return      |
| Date of deployment                | 16 May 2006     | 21 May 2011      |
| Pulse rate frequency (MHz)        | 33.33           | 67.2–74.4        |
| FoV (degrees)                     | 12              | 40               |
| Scan frequency (Hz)               | 42.4            | 35.8–40.0        |
| Point density ( $\text{m}^{-2}$ ) | 0.5             | 2                |
| Number of flight lines            | 3(N–W)          | 4 (E–W) + 3(N–W) |
| Altitude (m)                      | 2063–2073       | 2097–2140        |

**Table 2.** Comparison of the lidar modelling of above-ground biomass (AGB) and biomass change (AGB change) with forest inventory and tree-ring data: values given are mean (and standard deviation in parentheses).

|                                                      | Lidar data            | Forest inventory data | Tree-ring data      |
|------------------------------------------------------|-----------------------|-----------------------|---------------------|
| AGB ( $\text{Mg ha}^{-1}$ )                          | 41.80 ( $\pm 25.68$ ) | 42.8 ( $\pm 52.7$ )   | –                   |
| AGB change ( $\text{Mg ha}^{-1} \text{ year}^{-1}$ ) | 1.22 ( $\pm 1.92$ )   | 1.19 ( $\pm 1.17$ )   | 1.13 ( $\pm 0.54$ ) |
| Sample size                                          | 9136 grid cells       | 66 plots              | 13 plots            |

## Careful study of how to measure change in French Guiana

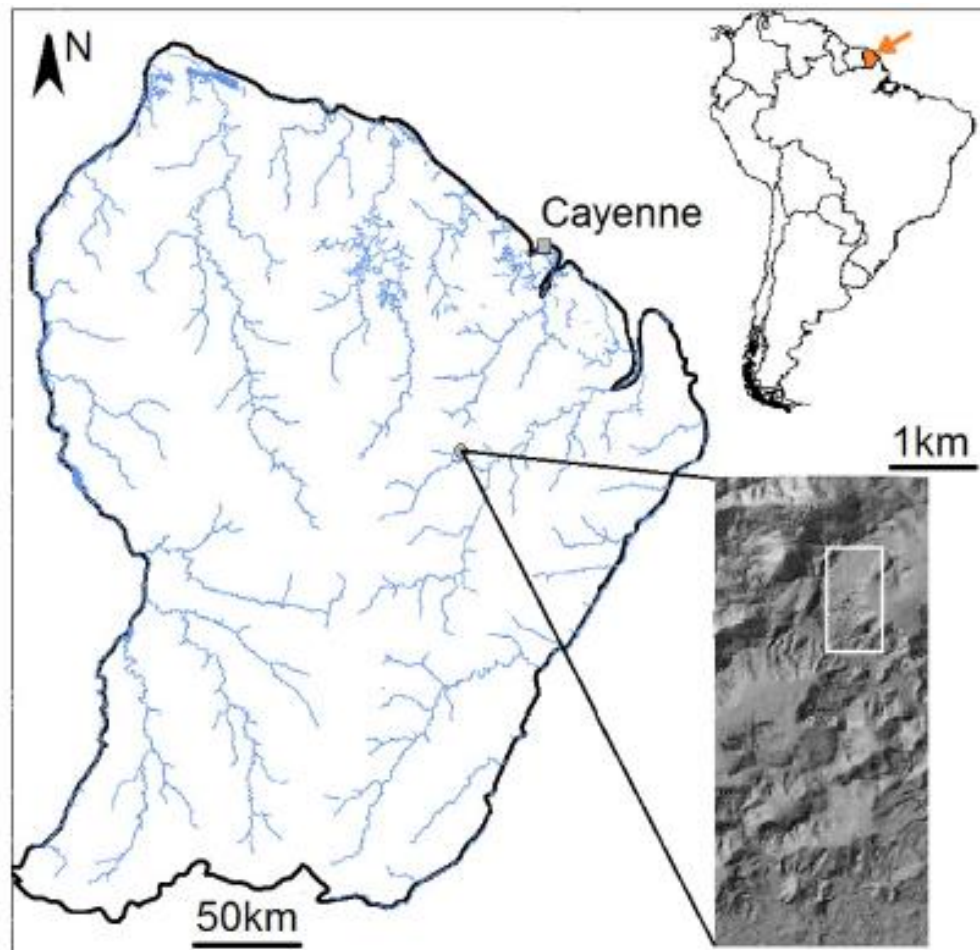
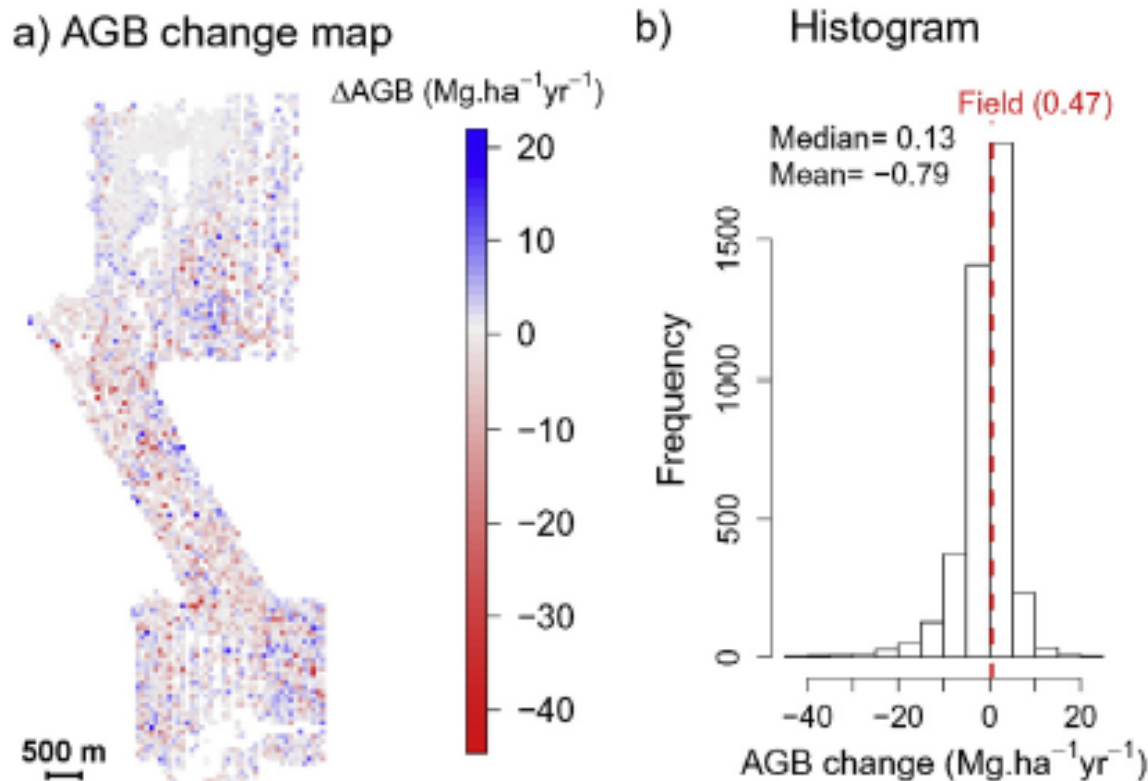


Fig. 1. Geographic location of the study area in South America (top right) and in French Guiana (left). The study area of 2400 ha (bottom right) is illustrated by a hillshade model.

# Careful study of how to measure change in French Guiana



**Fig. 6.** AGB change inferred from the LiDAR model at 50-m resolution. (a) Map over the study area, and (b) histogram of the AGB changes with the mean field based estimates ( $\pm 0.47 \text{ Mg ha}^{-1} \text{ year}^{-1}$ ; red slashed line). LiDAR AGB change was calculated as the difference between the AGB estimated from the two LiDAR datasets (2012 minus 2007 or 2008). Grid units containing more than 15% of 1-m<sup>2</sup> pixels with less than 2 LiDAR points/m<sup>2</sup> in the 2007/8 dataset were discarded. Similar results were obtained at 100 m resolution (not shown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

# Topics

- The essentiality of inventory plots
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- Choice of estimation equation
- Measuring carbon fluxes by repeat-LiDAR surveying
- From LiDAR strips to landscapes

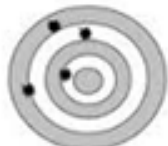
# From LiDAR strips to landscapes

- A. Fuse LiDAR heights with GLAS estimate. Or with 2018 GEDI estimates.
- B. Fuse with radar data collected by satellites (e.g. Japanese space agency JAXA has annual calls for using its L-band radar data, ALOS-2).
- C. Major environmental layers that Brazilian already has mapped (e.g. disturbance, fires, soils)
- D. Topographic and elevational indices

# Concluding thoughts

- You need plot data to get information on wood density and tree packing density
- Sources of uncertainty and imprecision really well understood at the plot levels
- LiDAR is an excellent tool for measuring canopy height, and when combined with wood density and basal area estimates from the ground, can deliver accurate biomass map

We'd like our estimates of carbon to be accurate and precise - that's the scientist in all of us!



Not Accurate  
Not Precise



Accurate  
Not Precise



Not Accurate  
Precise



Accurate  
and Precise

**Accuracy:** this requires us to think through every step of the process to ensure we're not introducing biases along the way!

**Precision:** Do we wish to design a system that gives maps of carbon with known precision at, say, a one-hectare scale? Or do we wish to estimate the entire carbon stock at a regional scale with known accuracy? The distinction is an important one!