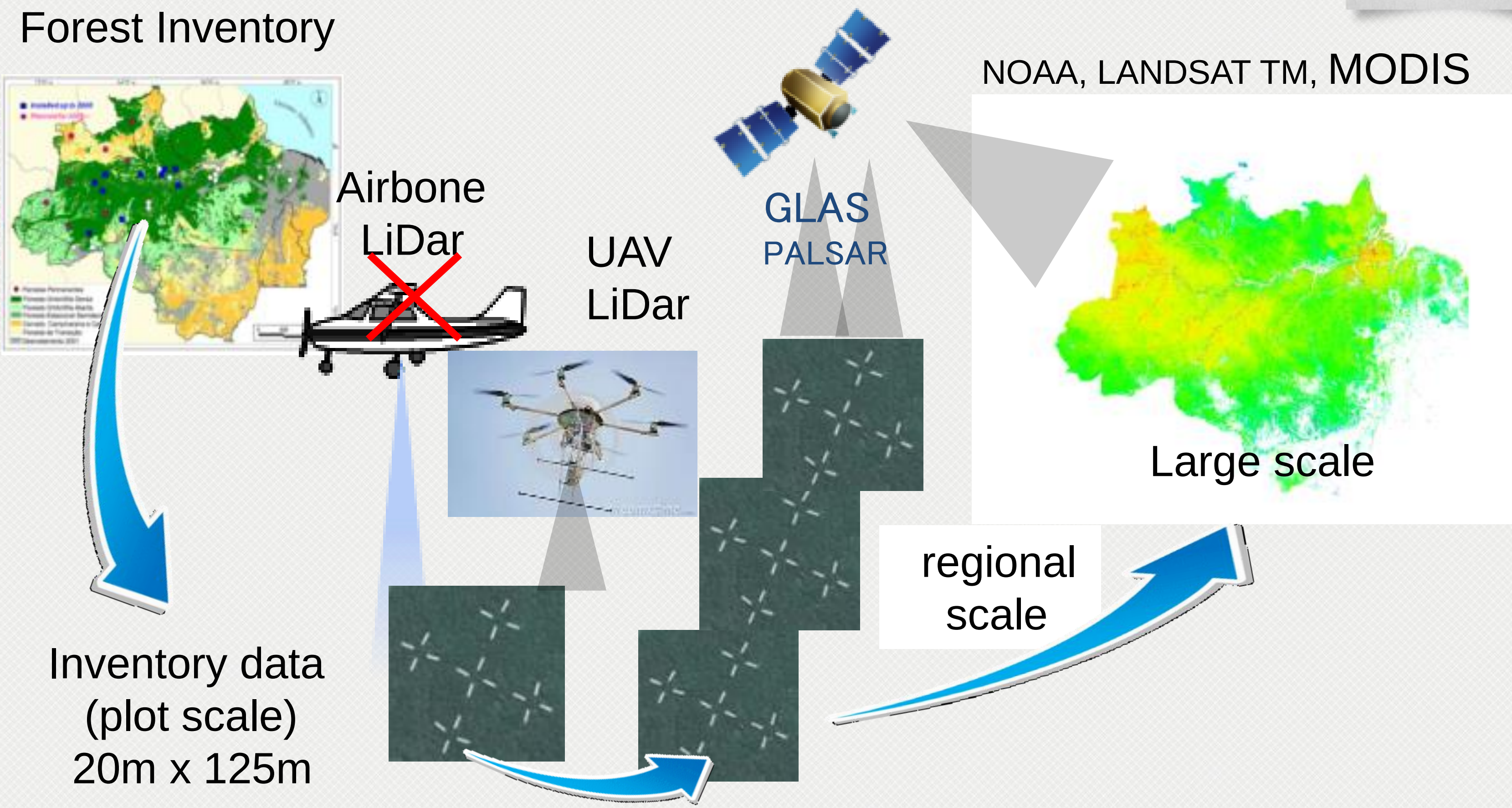
Carbon dynamics maps for Brazilian Amazon using the ground data including CFI system and remote sensing



REDD+ MRV requires a combination of remote sensing and ground-based forest carbon inventory

Objective of the RS Study

To estimate the parameters to <u>upscale plot data to regional-scale</u> for evaluating <u>forest carbon</u> dynamics in central Amazon using remote sensing and GIS.

- **Haruo Sawada, Yoshito Sawada, Keiji Jindo, Kanya Tokunaga (IIS/UT)**

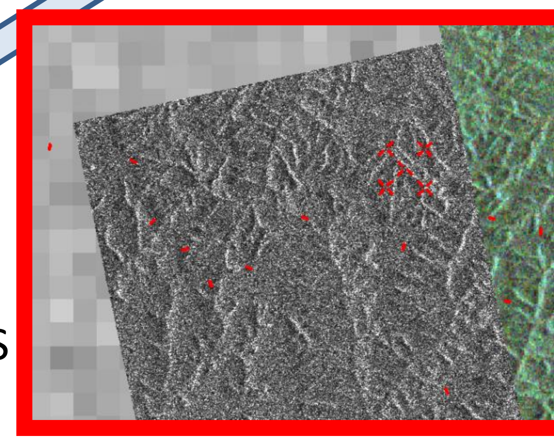
Takahiro Endo(UT/RESTEC),

- **Moacir Campos, Carlos H. Celes (INPA)**
- **Dalton Valeriano, Yosio Shimabukuro, Egidio Arai**

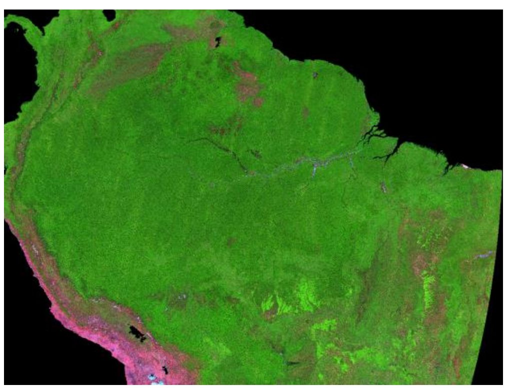
Upscale: Field data and RS data

Data from Inventory Plots
(by Ground observation & measurement)

GPS data of Inventory Plots



Remote Sensing Data



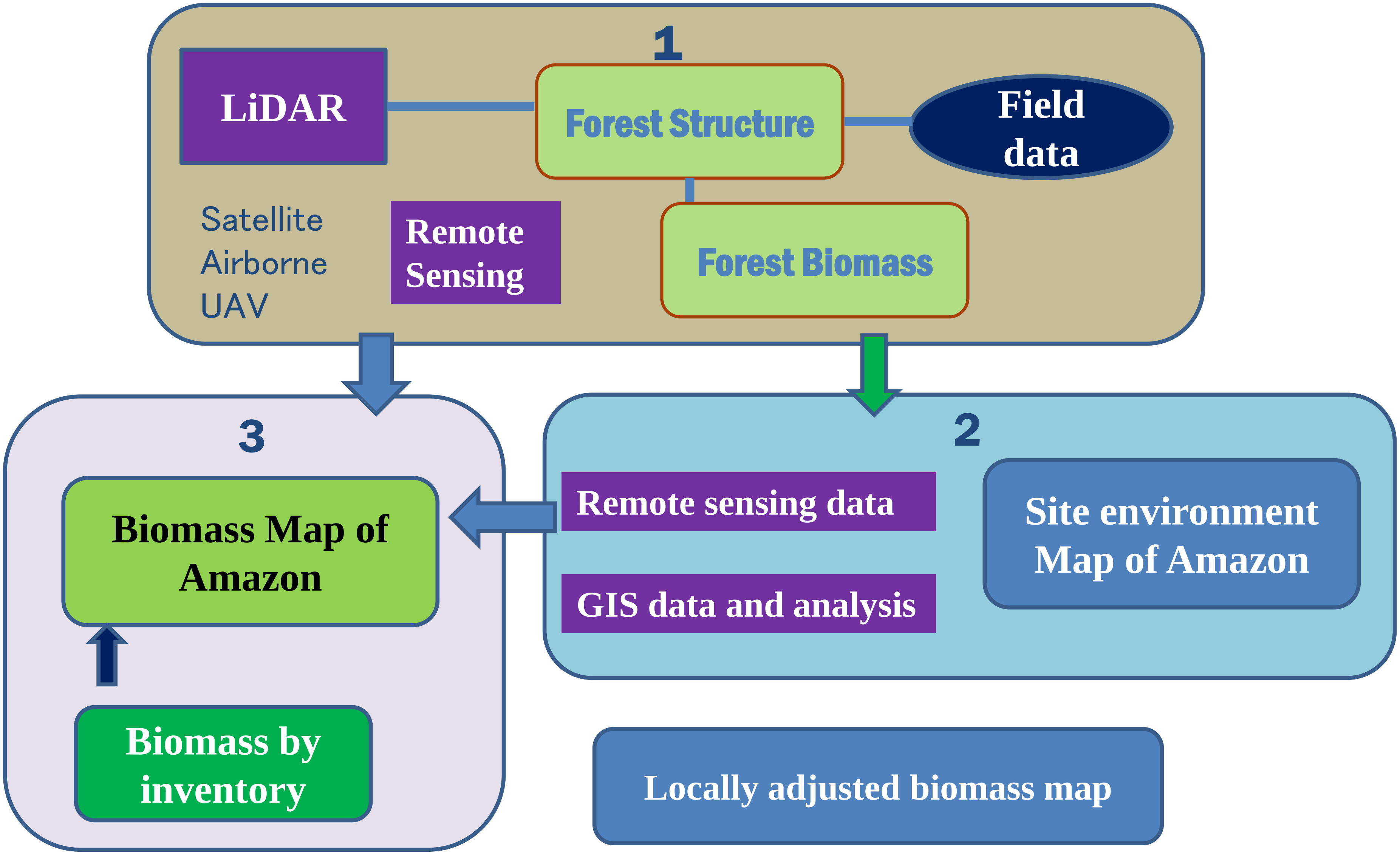
Inventory database on GIS

GIS database are created

Geospatial Modeling

Biomass Estimation

Research Flow for Biomass Estimation



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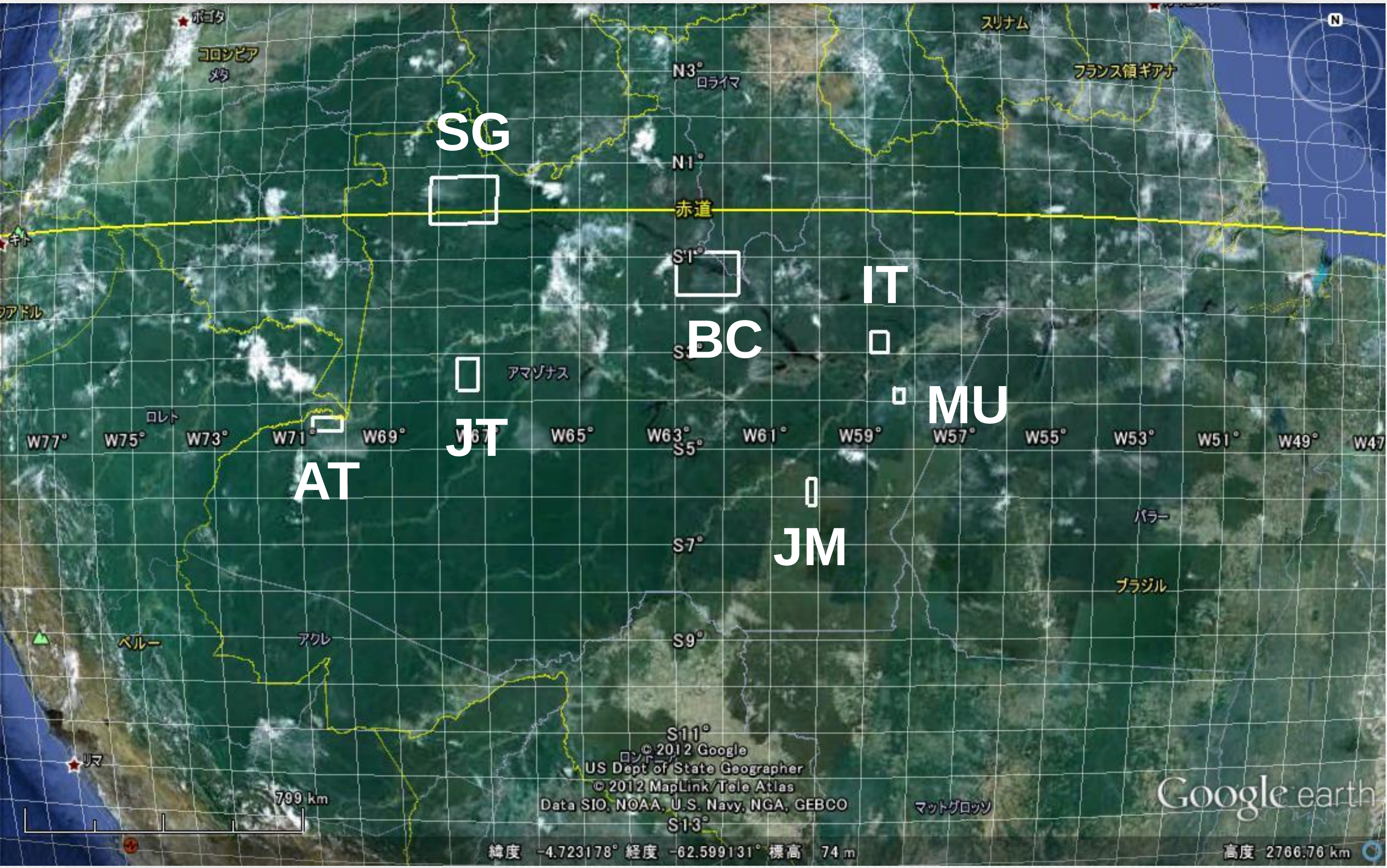
CARBON DYNAMICS OF AMAZONIAN FOREST



Field Data Collection

Forest Stand Parameter

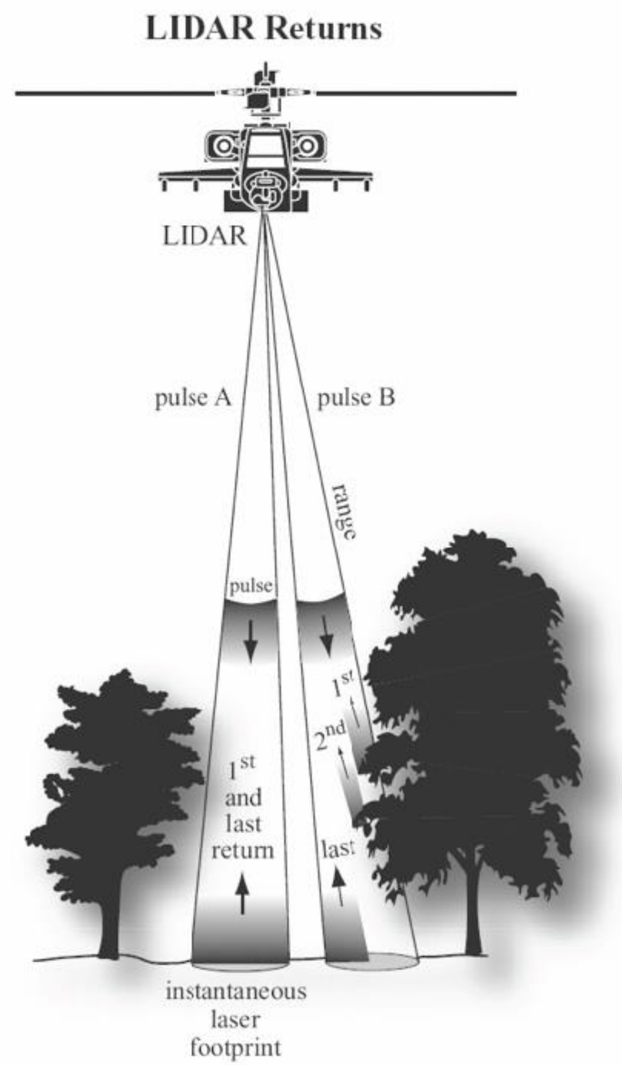
Because the average carbon stock in central Amazon forest is measured about 160tC/ha, the back scatter of L-band microwave sensor is in saturation level.

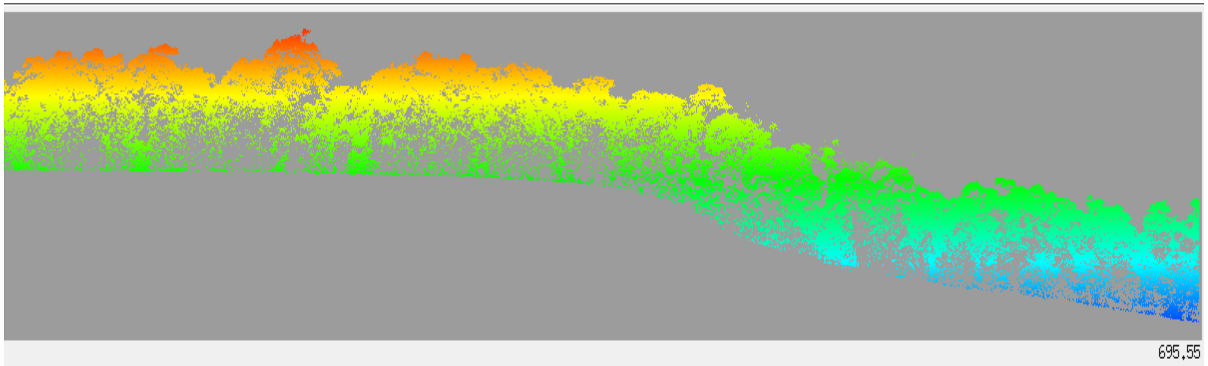
Except for the low biomass forests, the best indicator for forest biomass estimation is “canopy height”. Therefore, airborne LiDAR was considered the best instrument for AGB measurement.

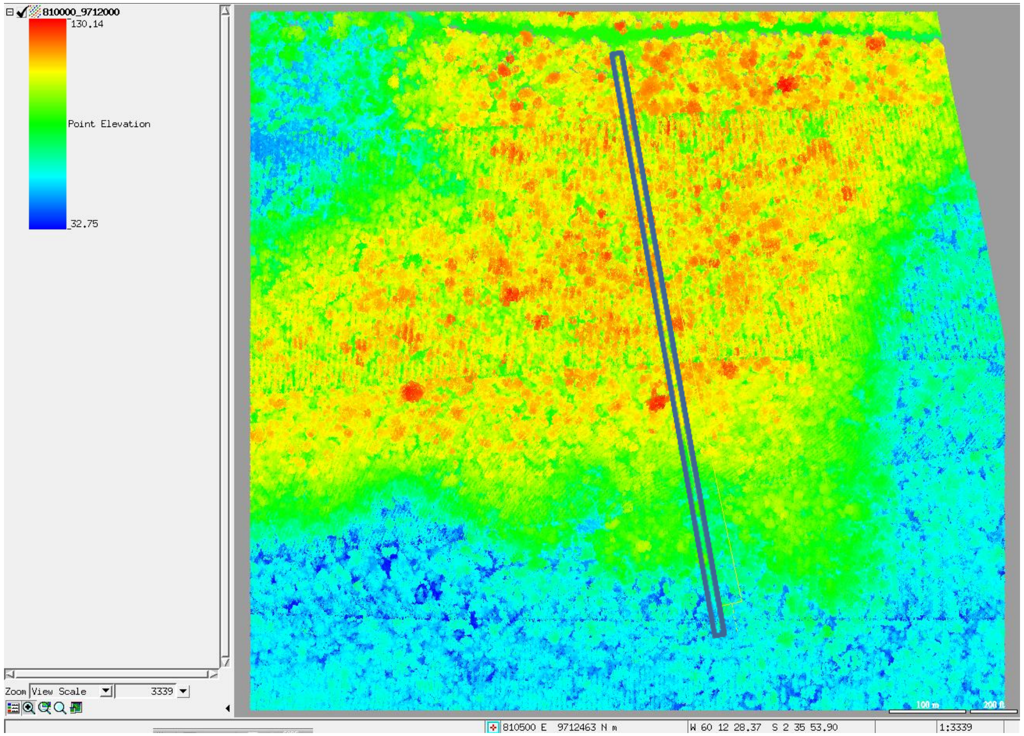
The analysis for existing airborne LiDAR supports the above idea.

- The LiDAR data with observation density of 20 spots/m^2 could create a canopy image with 50cm resolution but the data with 10 spots/m^2 was not sufficient to make canopy image with 50cm resolution.
- The measurement error of tree height was about 3 % for trees along a road.

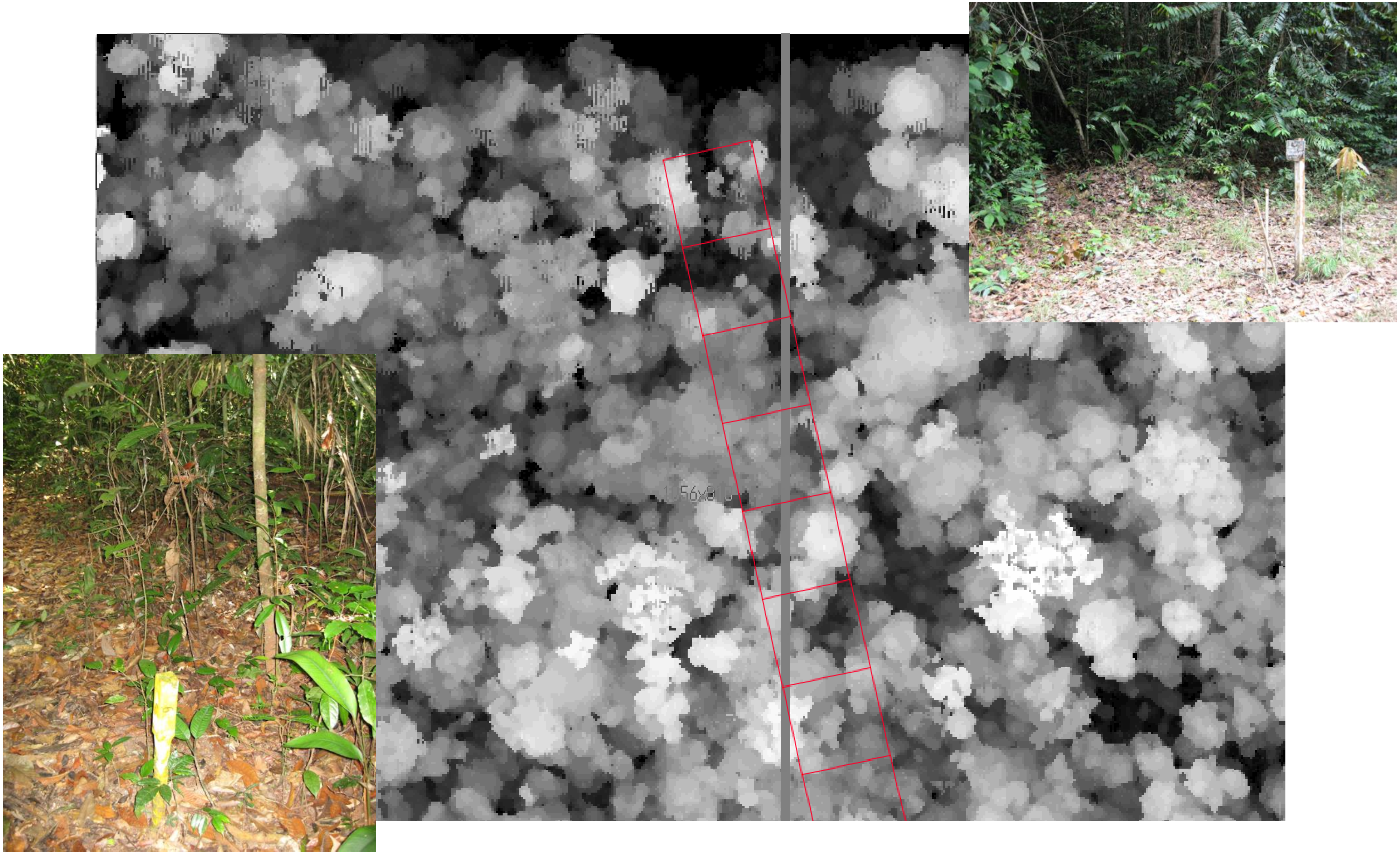
Profile of forest by LiDAR at ZF2



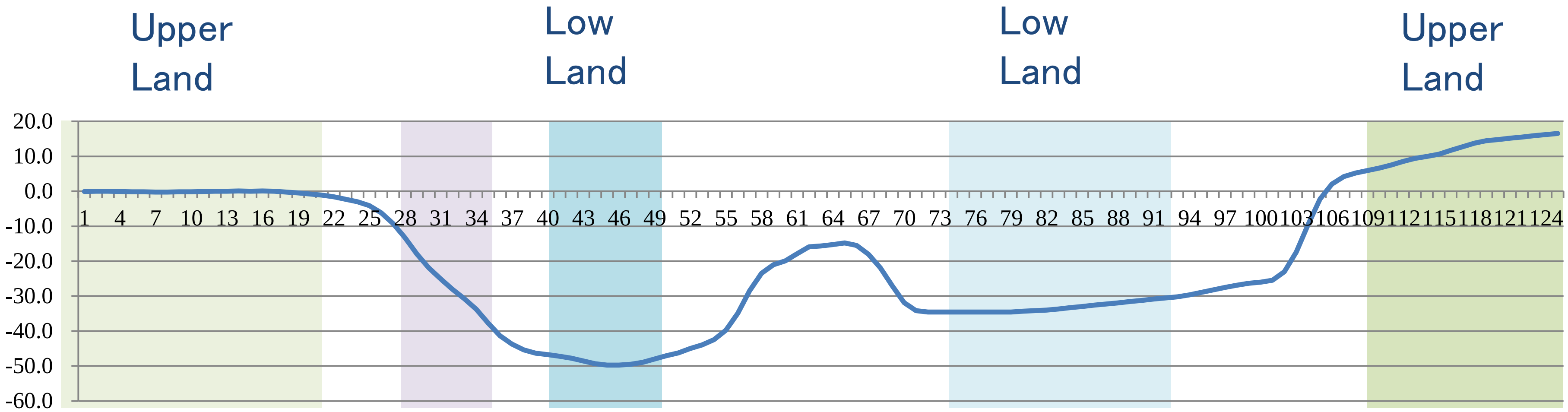


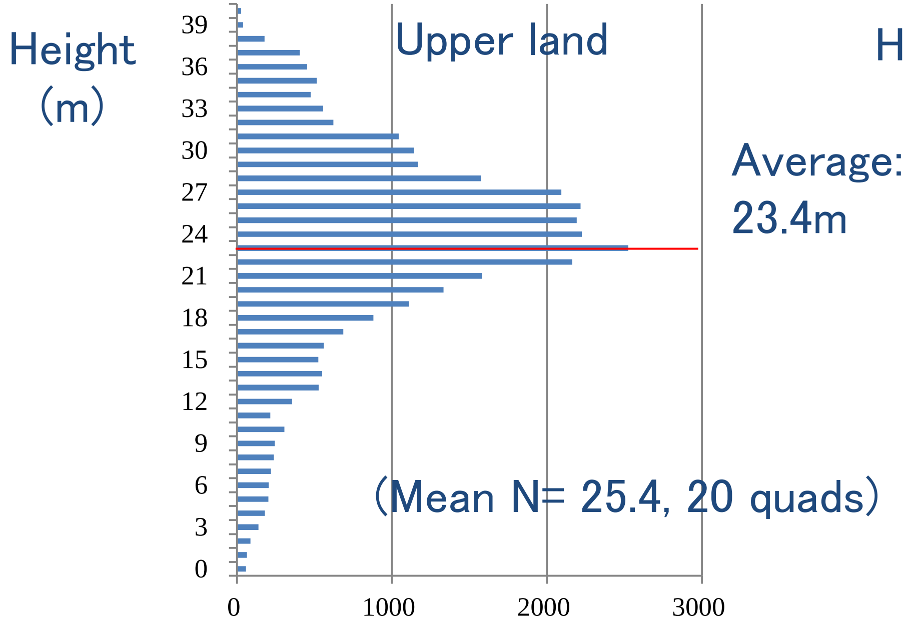


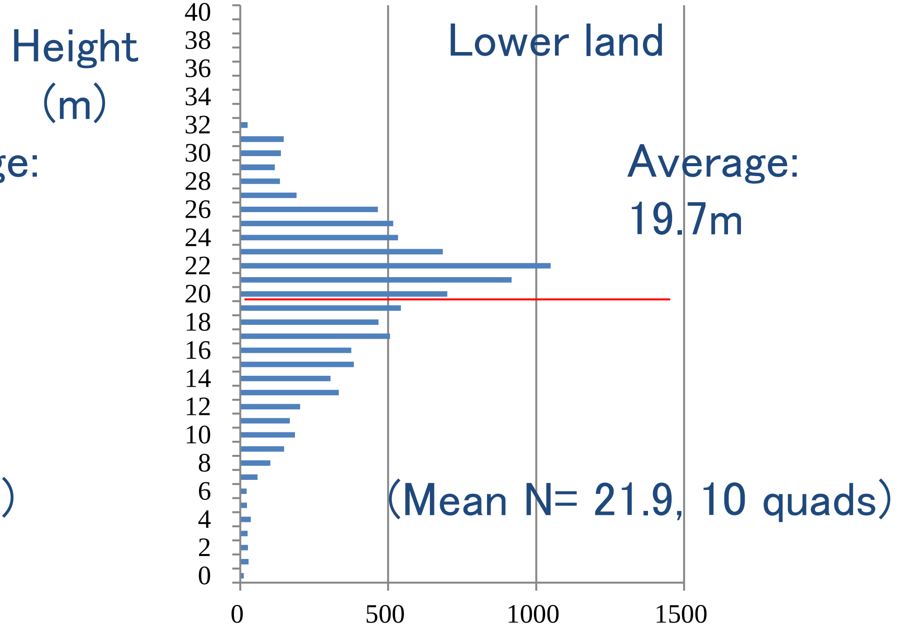
Plots (20m*20m) and LiDAR (0.5m Raster)



Terrain Condition and Forest Structure







Forest Stand Parameter in plot level

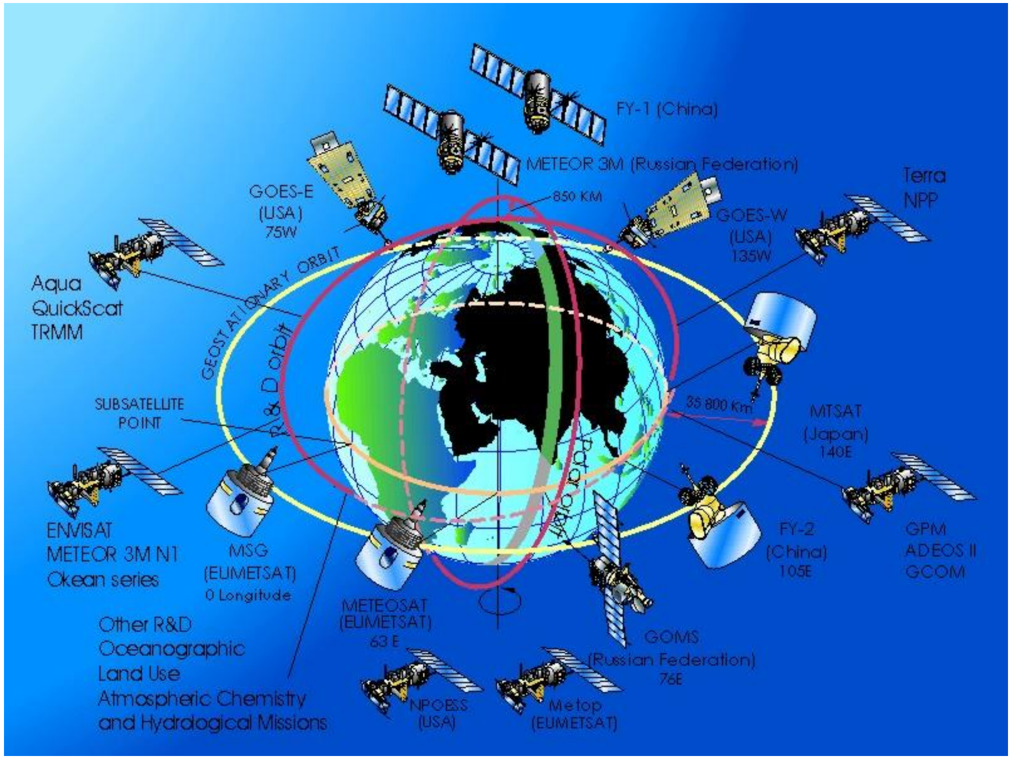
- the UAV system was introduced as already mentioned

Earth Observation Systems

The remote sensing technology advances very rapidly and the technologies and systems which we introduced several years ago are becoming out of data.

Data used in this study:
2000-2010

Terra & Aqua/ MODIS
Landsat/ TM, ETM+
Terra/ ASTER
IKONOS
TerraSAR-X
ALOS/ PALSAR
ALOS/ PRISM
ICEsat/ GLAS
Airborne/ LiDAR



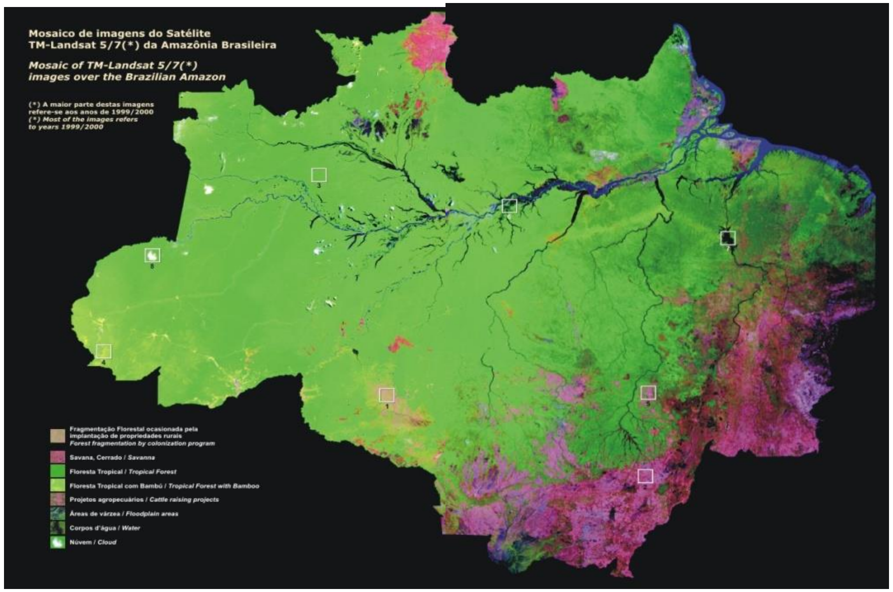
Forest Site Environment Map

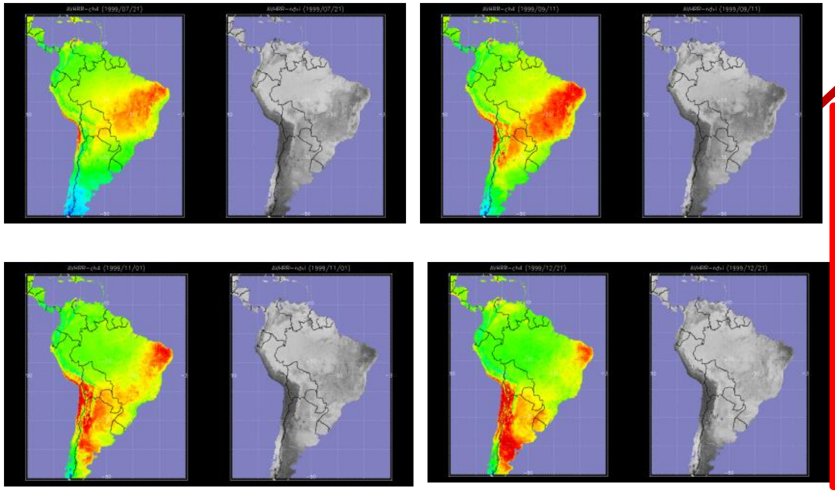
The LMF-KF processed time series 8-day composite MODIS cloud free satellite images for nine years (2001-2009) were created as the base dataset for the carbon stock and environment mapping of entire Amazon.

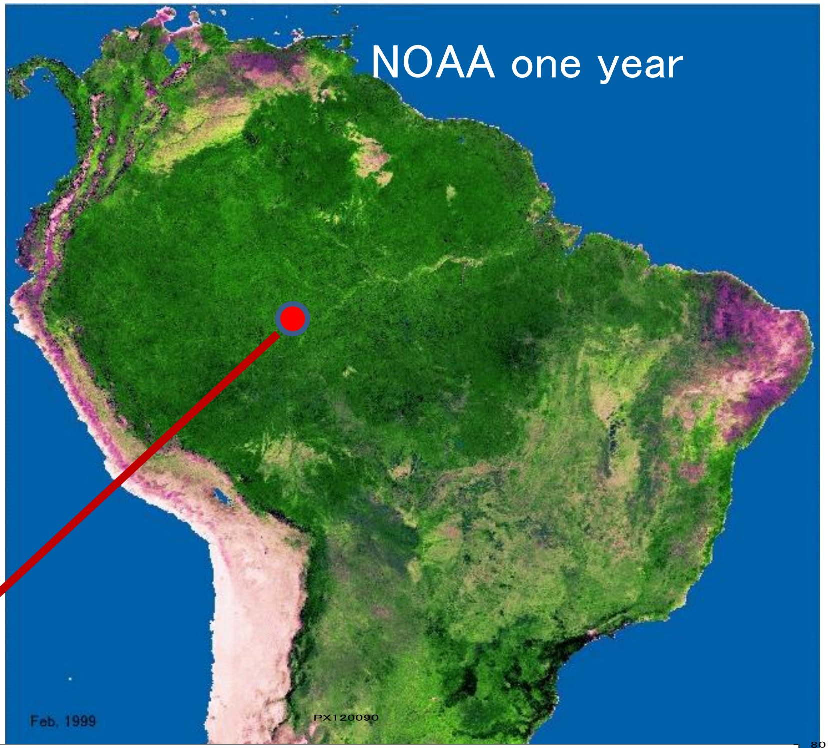
From this dataset, the waterlogged forest images, day and night surface temperature images, NDVI seasonal characteristic images. etc. were developed.

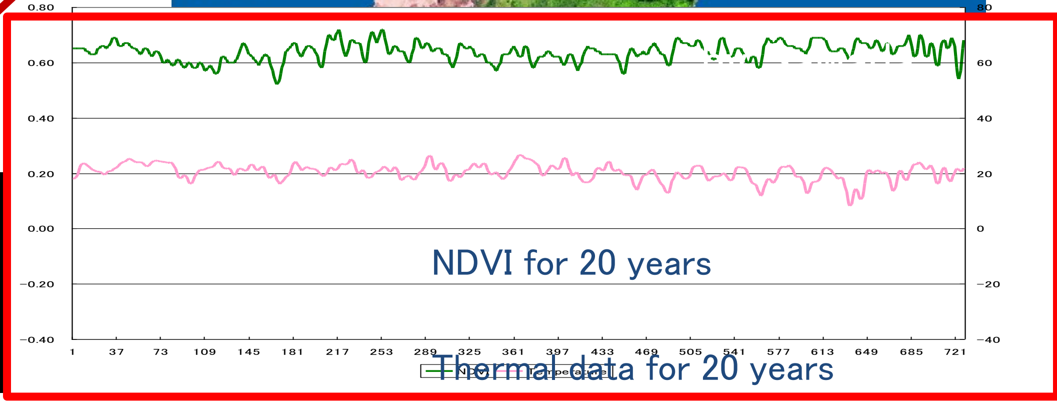
Then, Amazon forest environment map was produced by combining the environment parameter maps derived from MODIS cloud free images, SRTM elevation data and other environmental data covering whole Amazon.

Vegetation indices and thermal conditions in a long period of time









Site environment Map

DBH

Forest height

AG & BG Biomass

Queastion:
These relations are same all over Amazon?

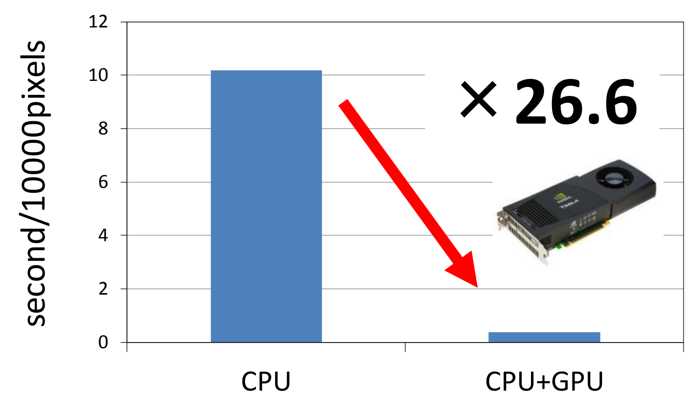
Environment conditions create potential natural forest structure. ?

Site environment map

- Elevation
- Terrain condition (slope angle & podition)
- Greenness (Min, Max & mean NDVI)
- Humidity(Min, Max & mean NDII)
- Day & night temperature (Max. & Mean)
- Rainfall (Annual & Monthly)
- **Duration of waterlogging**

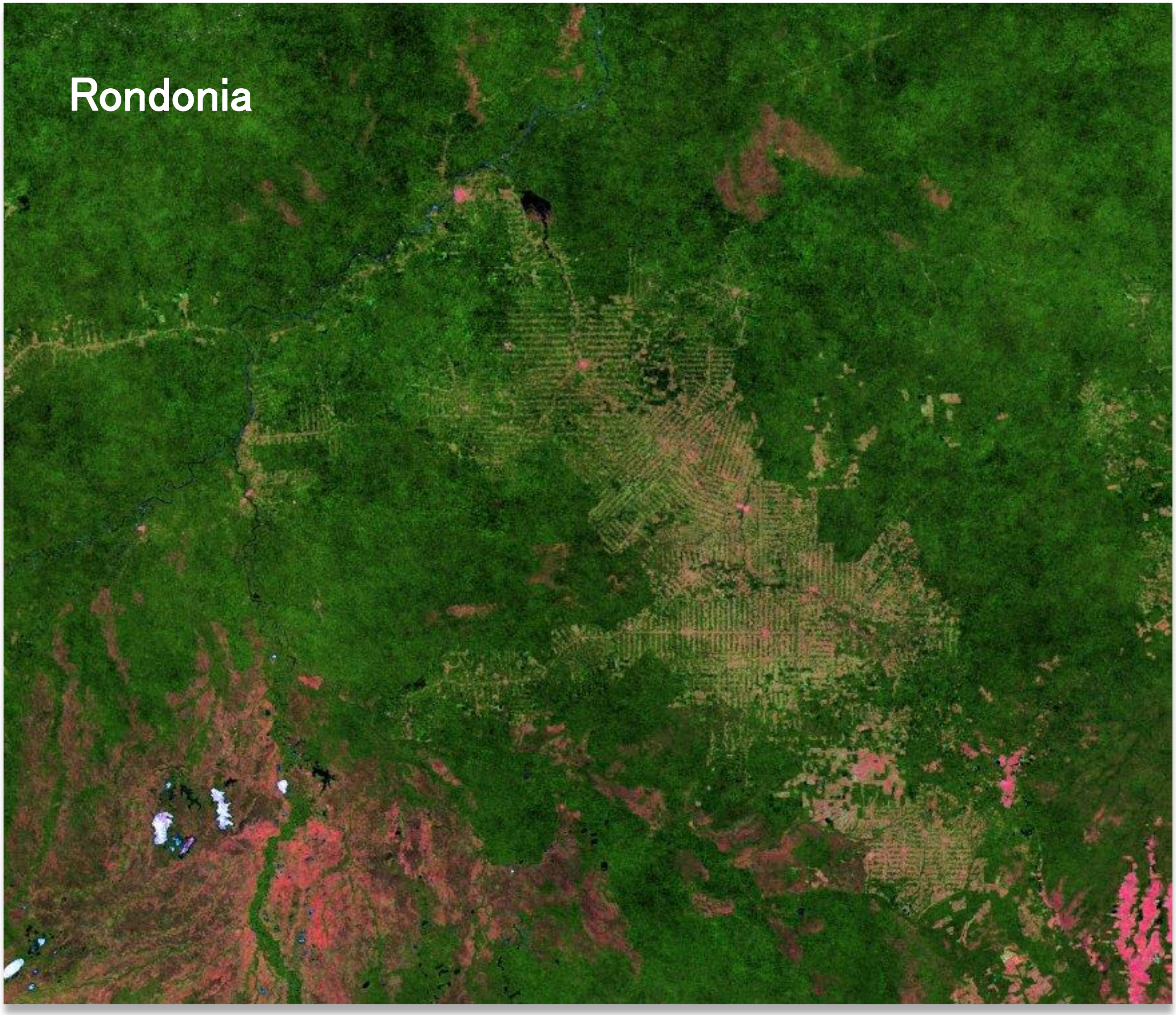
Time series data processing using GPGPU

- The processing of MODIS data of more than 500 BG (8-day composite in 2001-2009) takes a long time (more than a half year for only cloud-free image production by the state spatial model).
- Then, we introduced GPGPU(General Purpose Graphics Processing Unit).
  - GPGPU uses GPU(Graphics Processing Unit) for calculation and process several hundreds to thousands calculation at the same time for one unit.
- Time series processing by the state spatial model is suitable for parallel processing because of individuality of pixel.
  - Especially because the discrete state spatial model (DS4) uses mainly single real value and integer, it is suitable for GPGPU in high speed processing. Then we use GPGPU for the state estimation in the Hidden Malakoff Model (HMM)
- Although the original source code for the discrete state spatial model was written in dual precision real values, the logarithm function was introduced for probability calculation to get enough accuracy with single-precision values on GPGPU.
  - Special considerations were applied in mapping of the device memory of GPGPU and data transfer efficiency between host computer and GPGPU.
  - Then we succeeded 26.6 times speeding up in maximum (Sawada et al, 2012). The entire discrete state space model process succeeded 16 times speeding-up .



Processing time (HMM modeling)
Unit: second/10,000 pixel

Creation of cloud free images

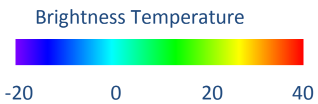


Surface Temperature

- **Cloud contamination effects are reduced by the LMF-KL model.**
- **Especially, this method works well in cloudy seasons as February.**

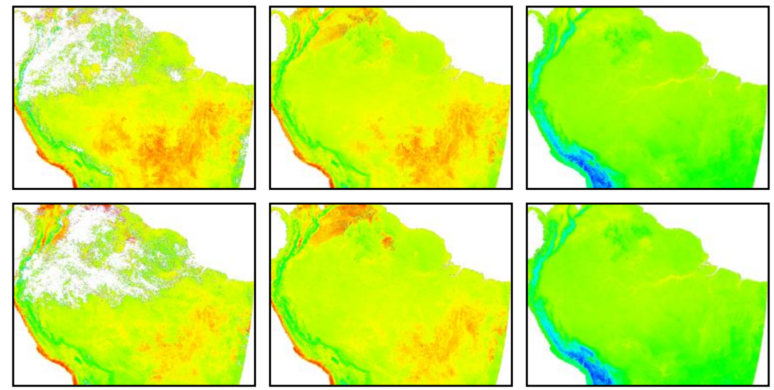
> In 2005, the year of severe drought, MODIS brightness temperature is higher than in 2009

Temperature



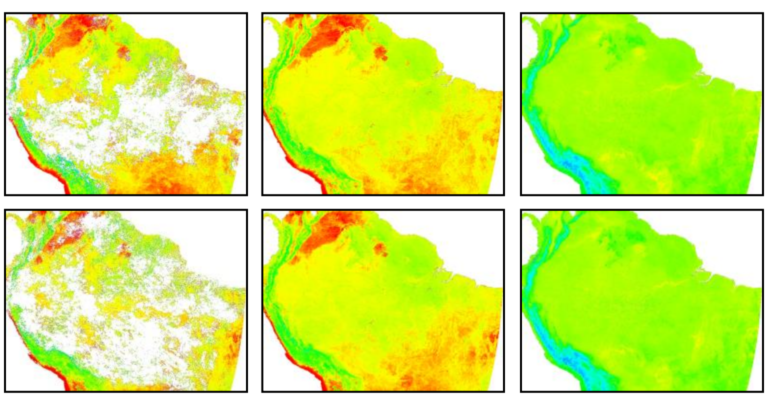
Jun. 6

	original (day)	processed (day)	processed (night)
2005			
2009			



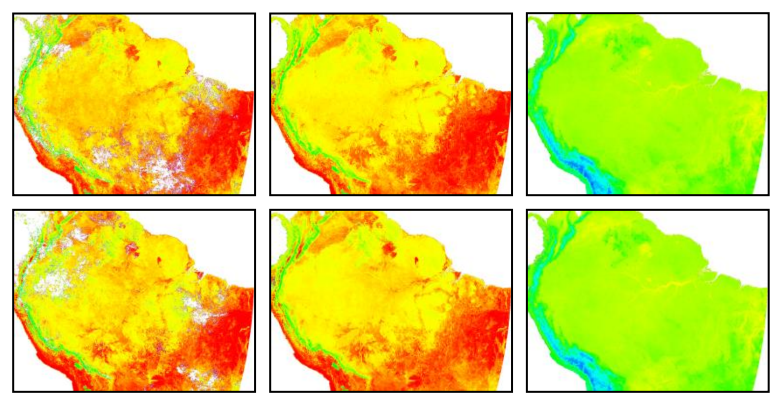
Feb.14

	original (day)	processed (day)	processed (night)
2005			
2009			

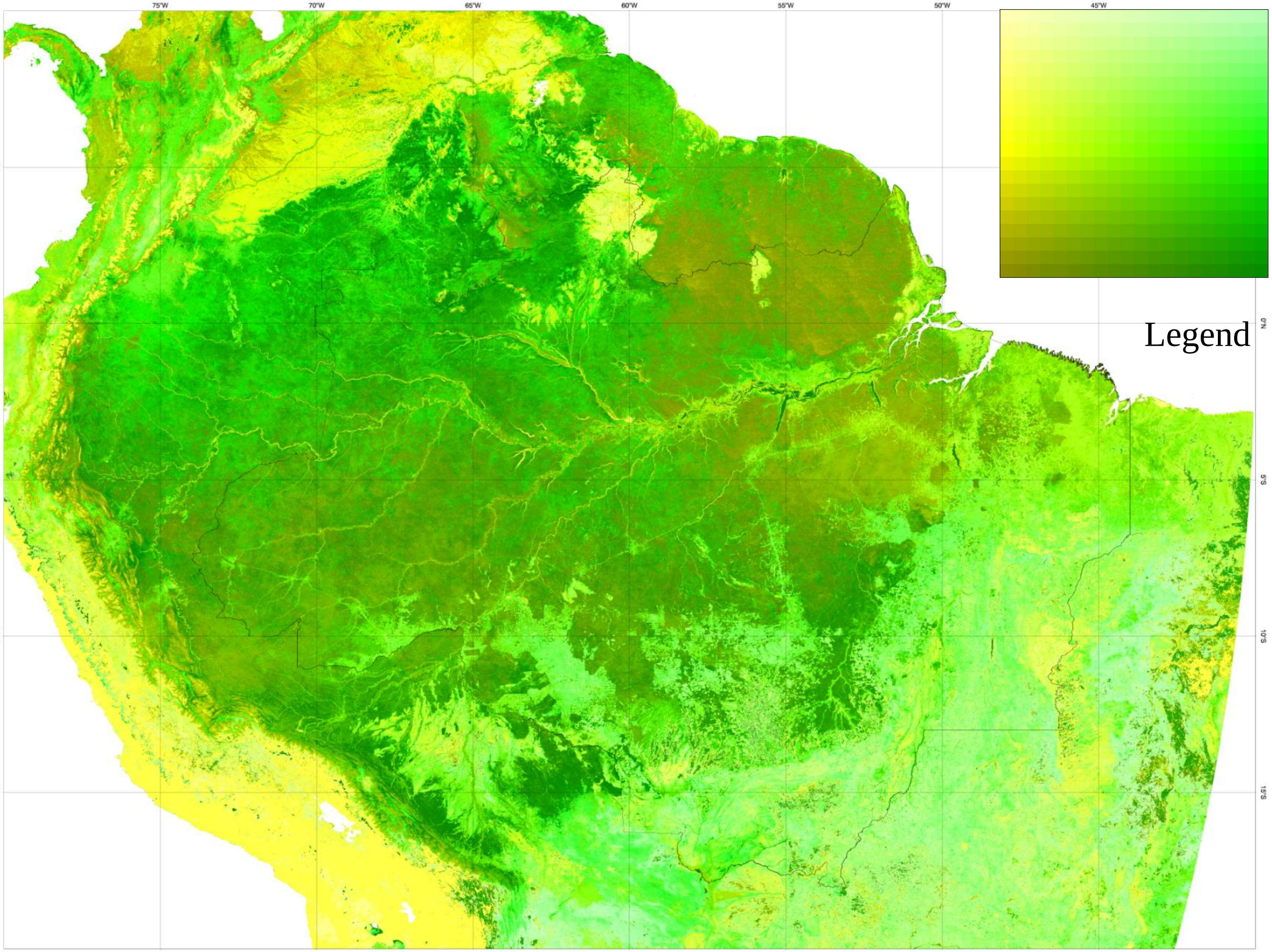


Oct. 4

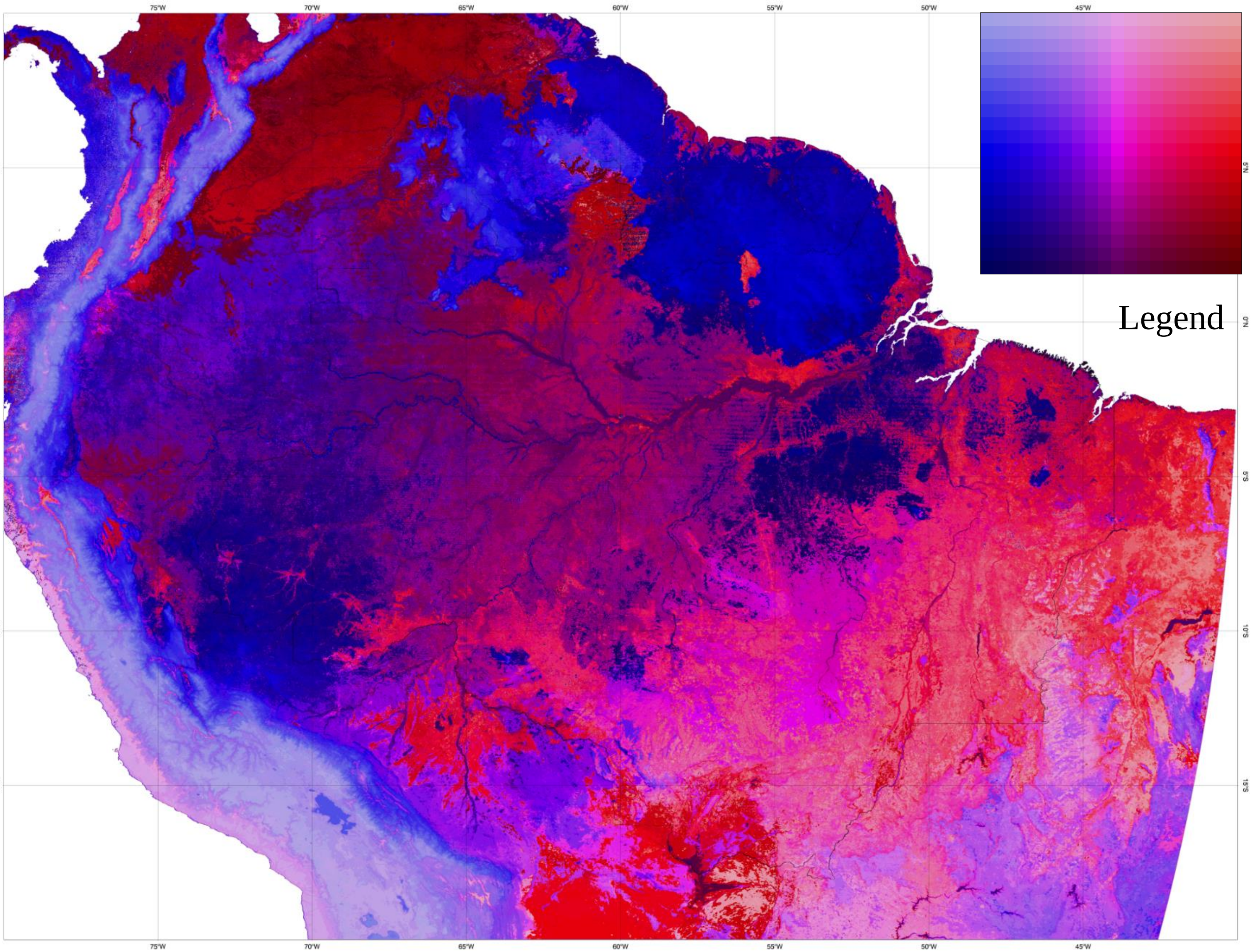
	original (day)	processed (day)	processed (night)
2005			
2009			



NDVI & NDII Seasonal Profile Clusters (2009)

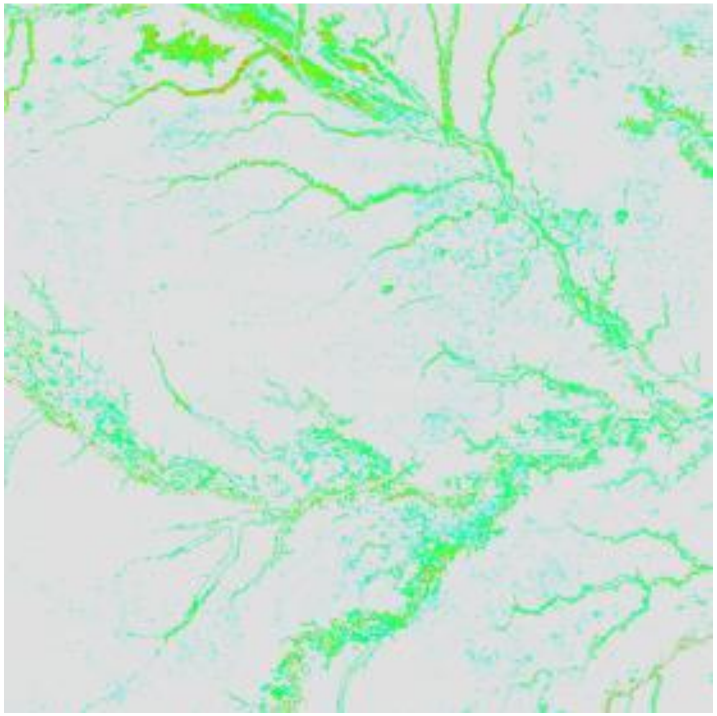


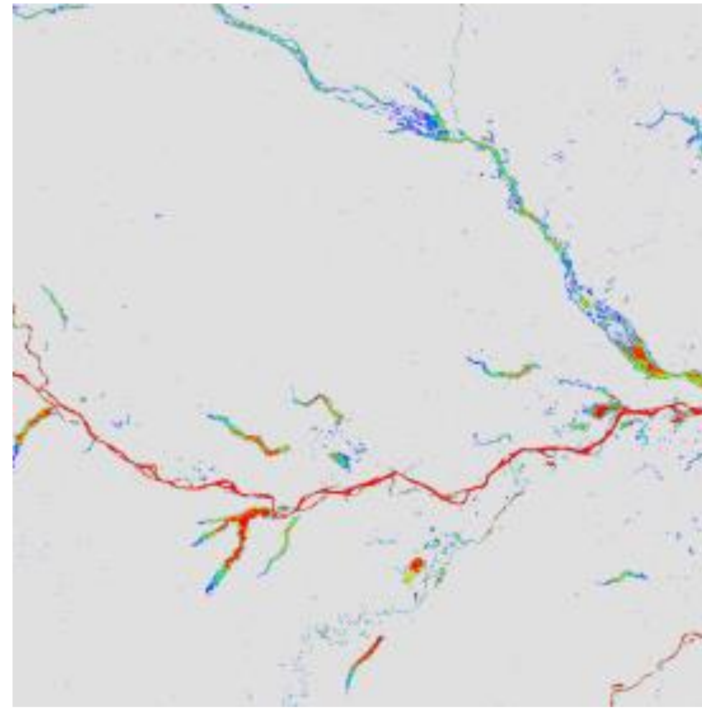
Temperature Seasonal Profile Clusters(2009)



Detection of waterlogged forests in Amazon

Water coverage map derived from MODIS





Waterlogged days

10days 270days

Environmental data for whole Amazon

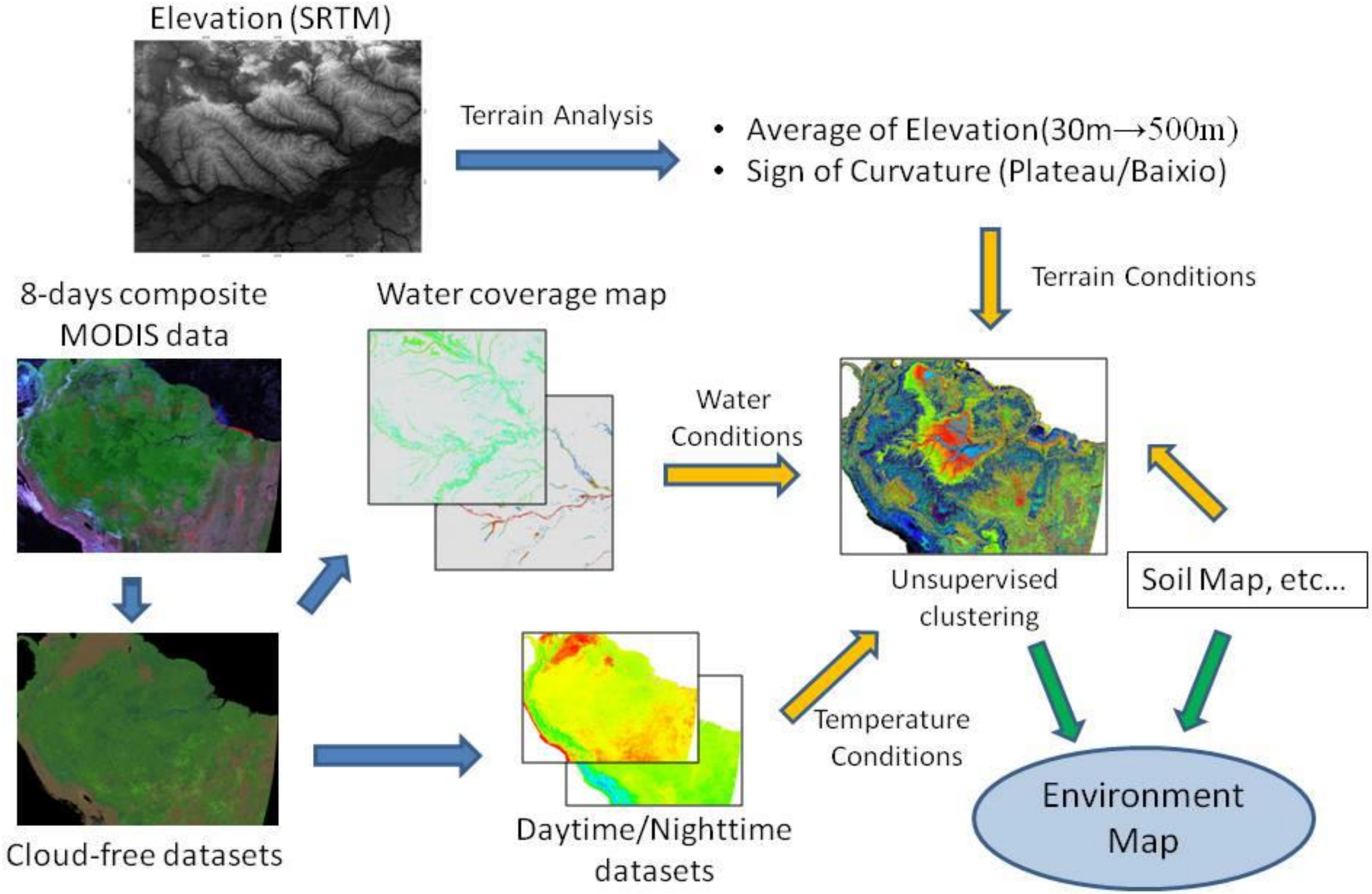
(6)

No.	Dataset name	Data Type	Units	Sensor/ Original Data	Time interval	Total Number of Symbols
1	Elevation (DEM)	numeric raster	m	SRTM		400
2	Plateu Ratio	numeric raster	%	SRTM		100
3	Slope Angle	numeric raster	degrees	SRTM		90
4	Bioma Type	categorical vectors				6
5	Averaged anuall rainfall	vectors	mm			28
6	Soil Type	categorical vectors				63
7	NDVI & NDII Seasonal Change Profile Clusters	nominal raster		MOD09A1	1year	400
8	Surface Temperature Seasonal Change Profile Clusters	nominal raster		MOD11A2	1year	400
9	Water Coverge Period Map	numeric raster	days	MOD09A1	1year	46

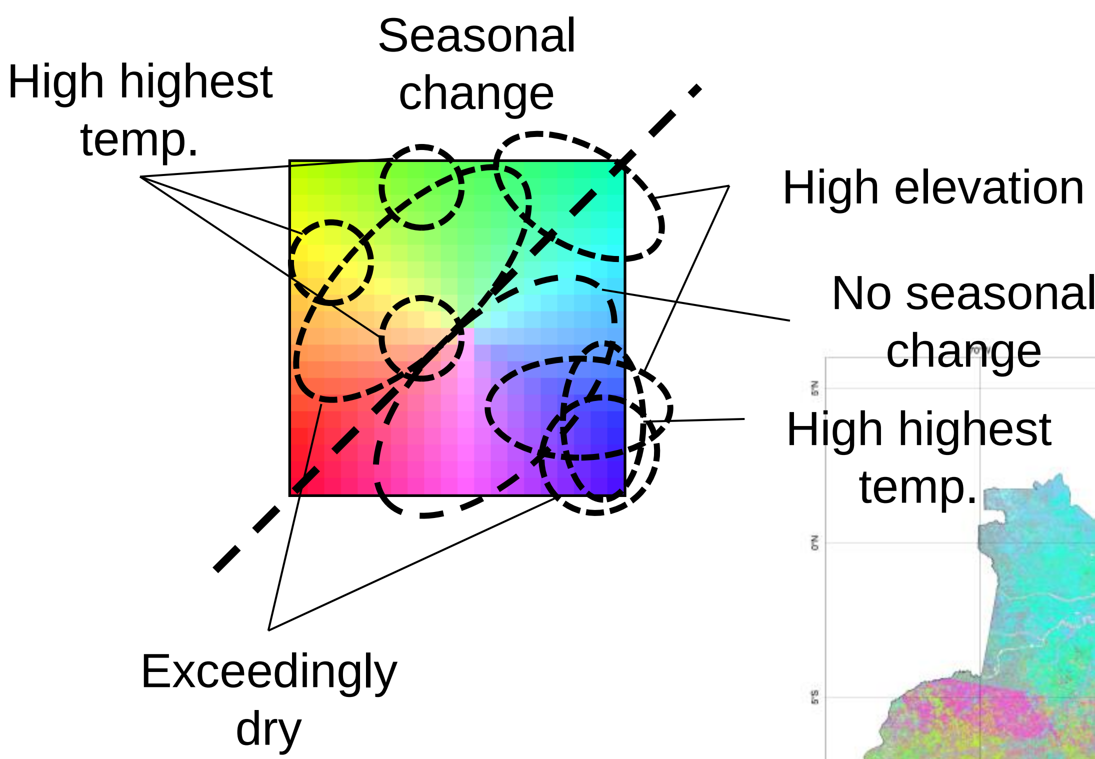
- discrete-value data are assigned to continuous values (encoding)
- nominal scale and categories are also encoded

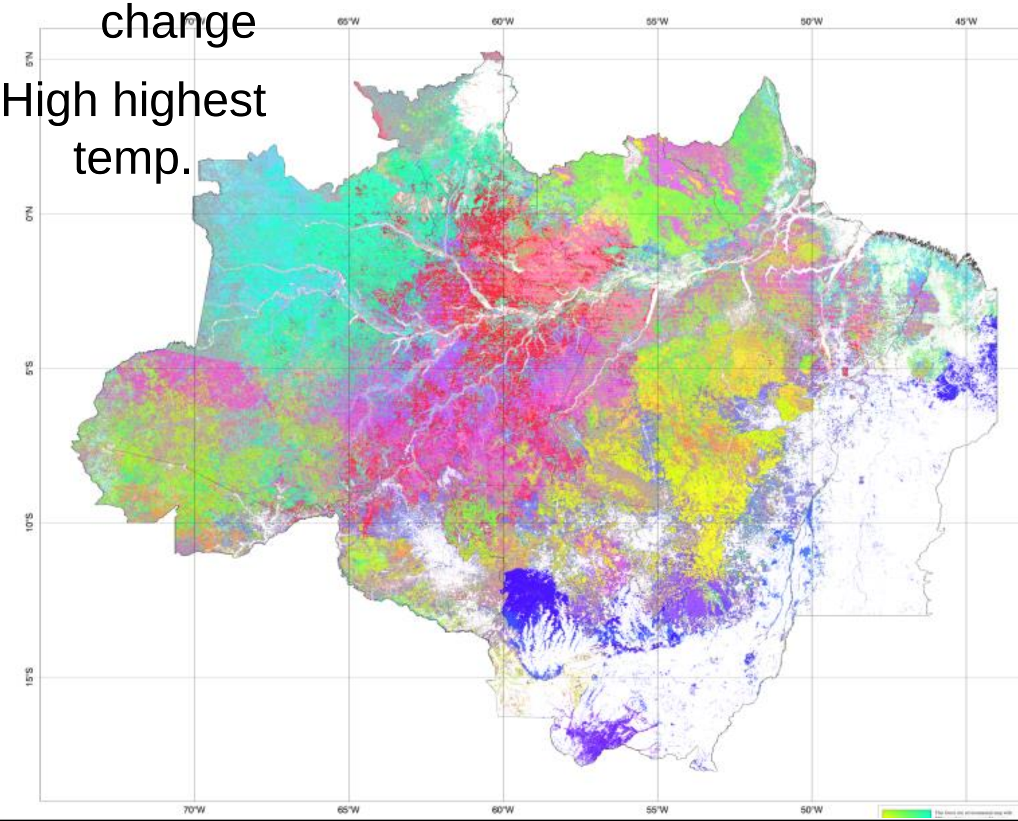
Precise rain fall data and MODIS MIR cloud-free images are under development

Integration of different types of data



Main characteristics of clusters

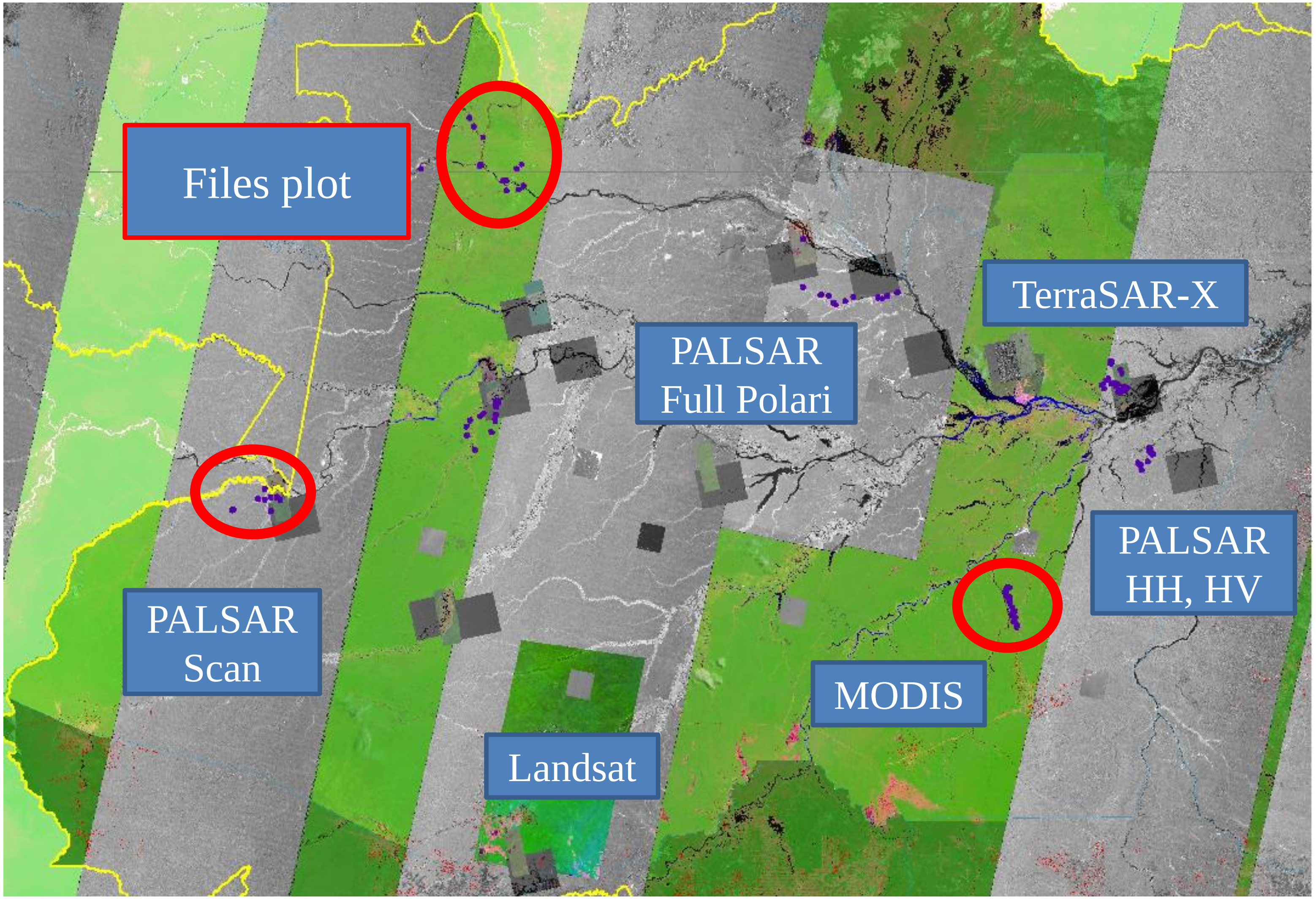




Summary: Forest Stand Environment Map

- Time-series model processing was applied to NDVI, water content index, temperature, etc. of Terra/MODIS data
  - The base data set was developed for FSEM in 2001 - 2010
- We noticed that terrain conditions, such as plateau, incline area and baixo, strongly influence forest structure in central Amazon
  - Then we introduced the elevation data (SRTM) and calculate the ratio of plateau and incline area as one of the base data for FSEM
- Because there are only a small number of meteorological stations in Amazon (comparing to the area), not enough rainfall information is obtained.
  - Then, the rainfall data set showing seasonality and annual changes was created by introducing GSMap products of 2001 to 2009.
  - For the entire Legal Amazon, we could recognize the relations between annual water cover period derived from MODIS and annual rainfall obtained by GSMaP .
- These facts indicate that we can create the forest stand environment map every year.
  - <u>It means that the robustness of forest environment can be calculated according to the fluctuation of forest stand environment caused by climate changes</u>

Remote Sensing data for global biomass estimation



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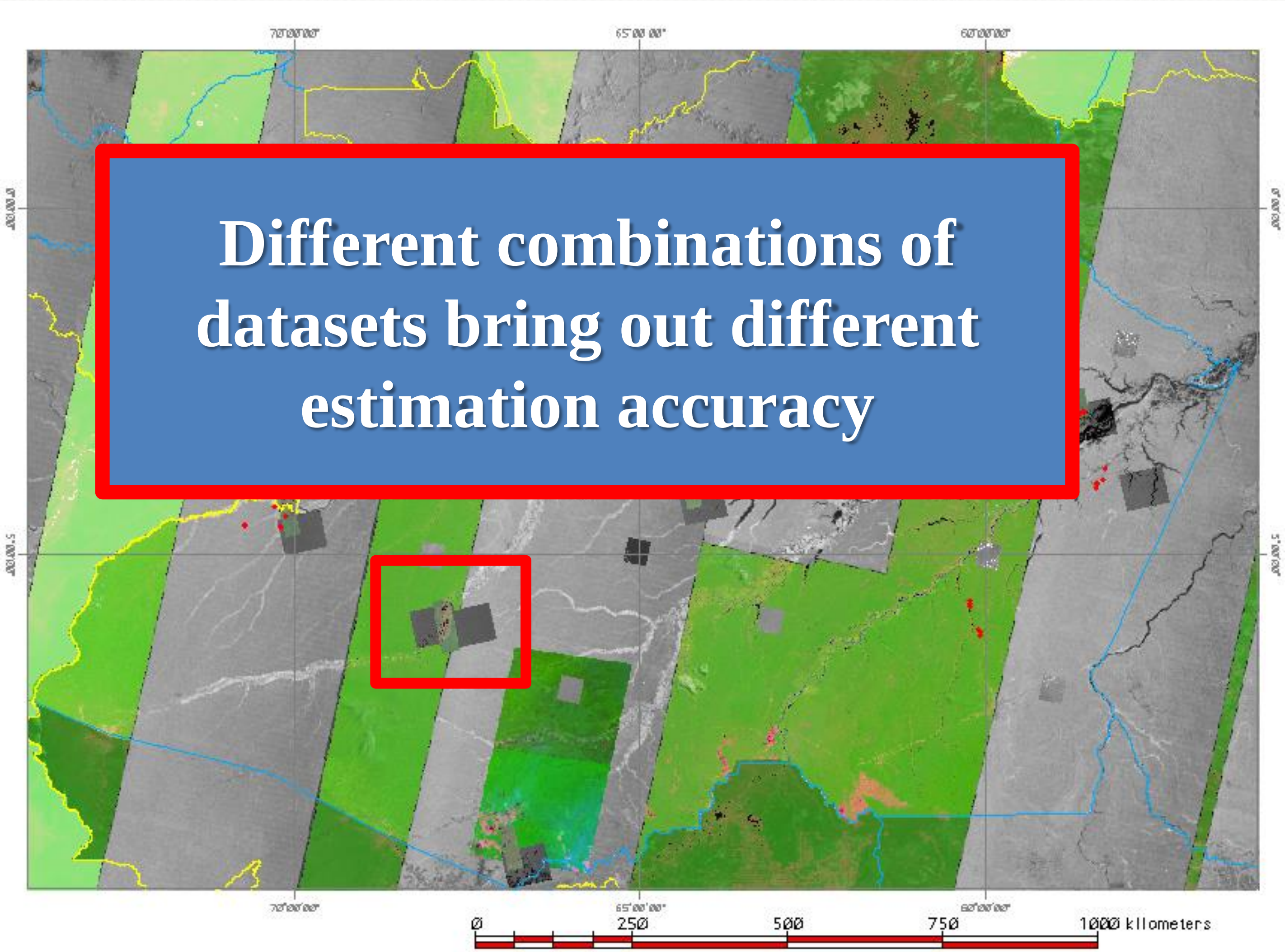
High-middle resolution RS data for up-scaling forest parameters



MODIS
Landsat
ASTER
CBERS
PRISM

PALSAR
- Scan SAR
- 50m Mosaic
- High resolution

TerraSAR-X
Airborne Radar (P/X)

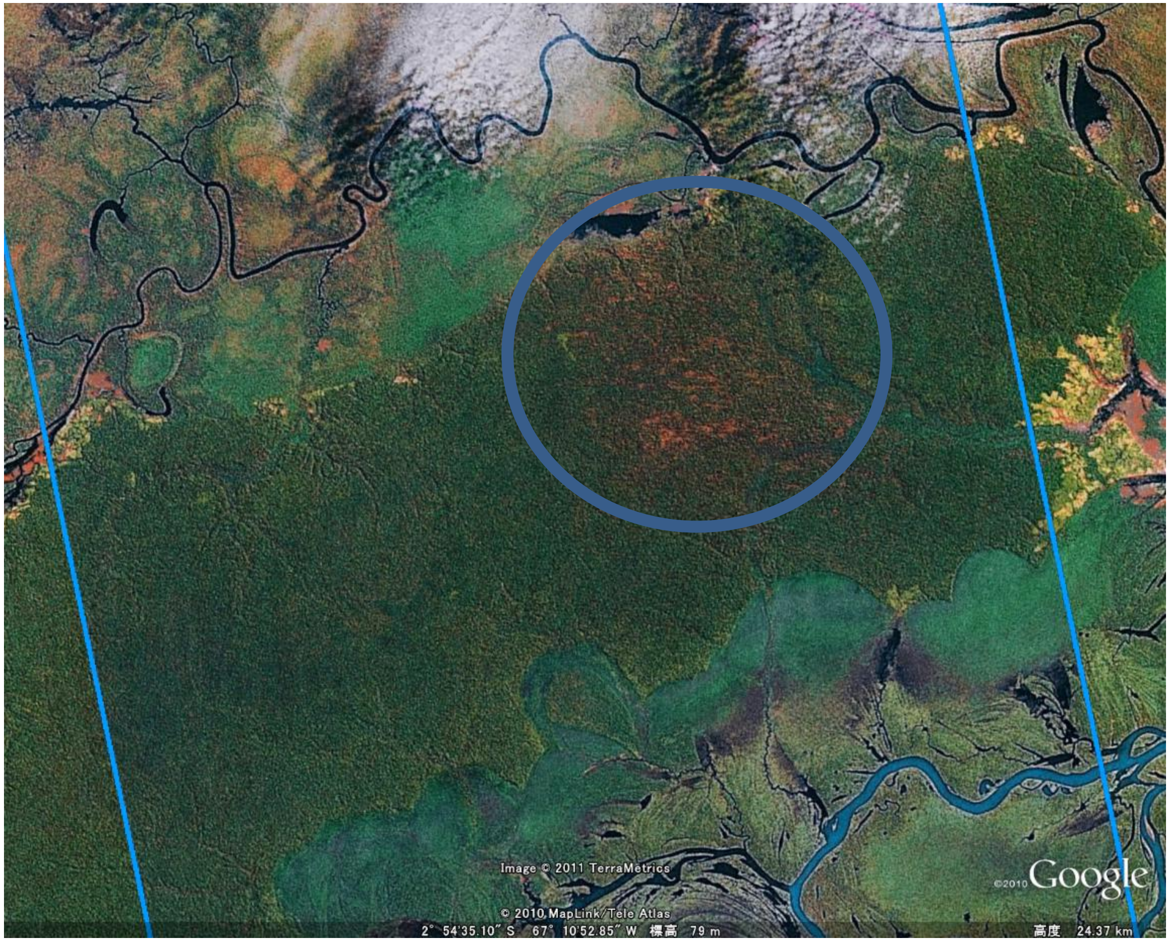
LiDAR
- Airborne LiDAR

UAV
- LiDAR
- Aerial Photo

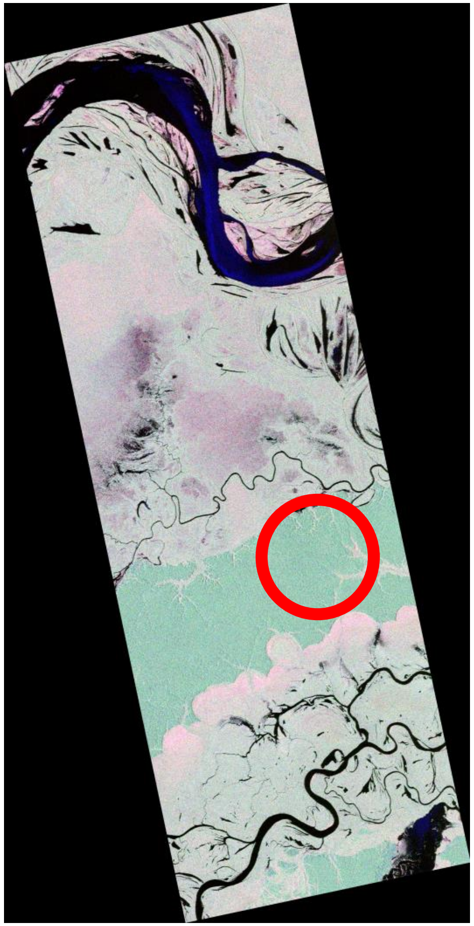
JST jica FFPRI INPA INPE

Landsat and RADAR

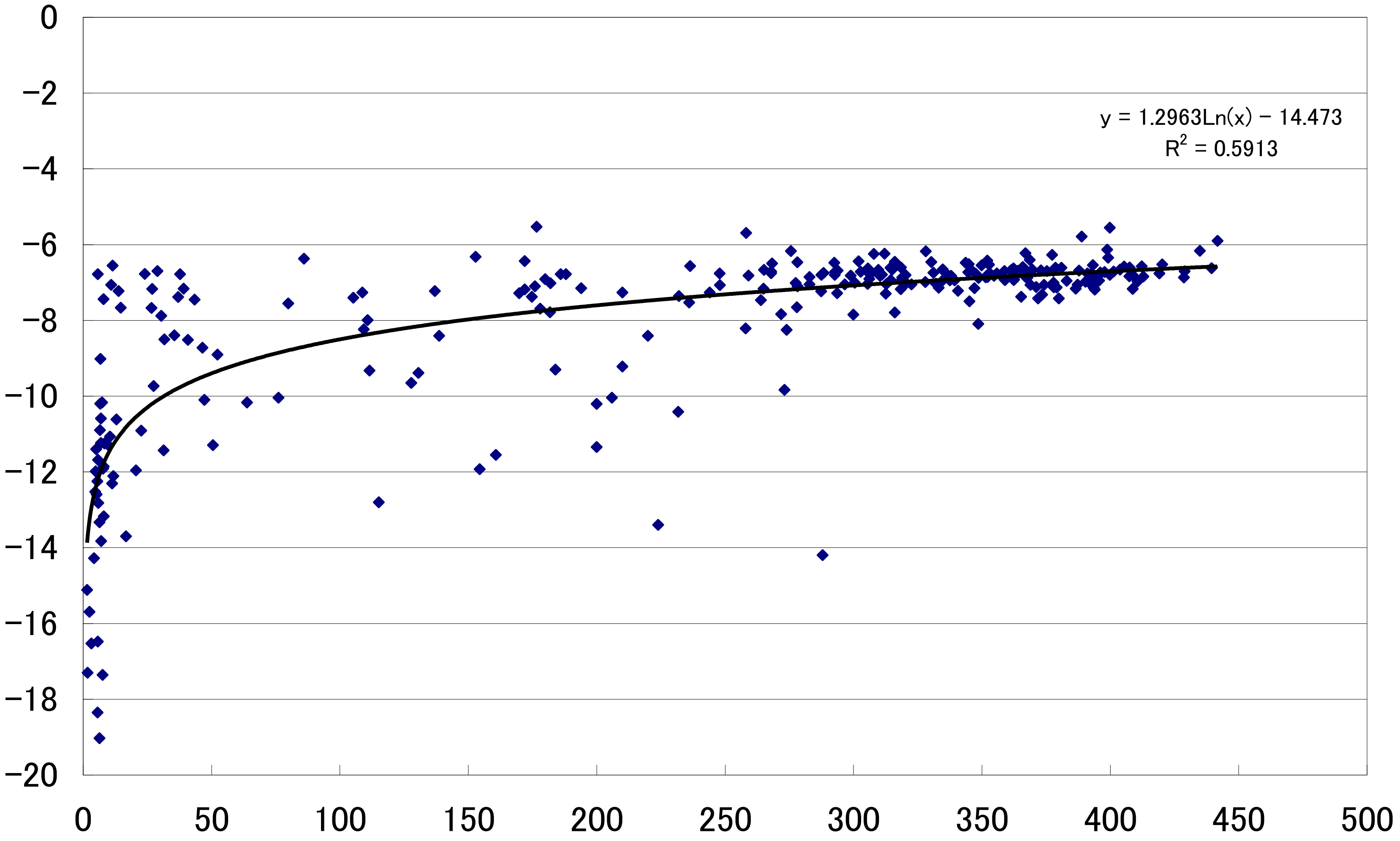
LANDSAT



PALSAR



Saturation of PALSAR for high biomass



Development of Canopy height map by GLAS

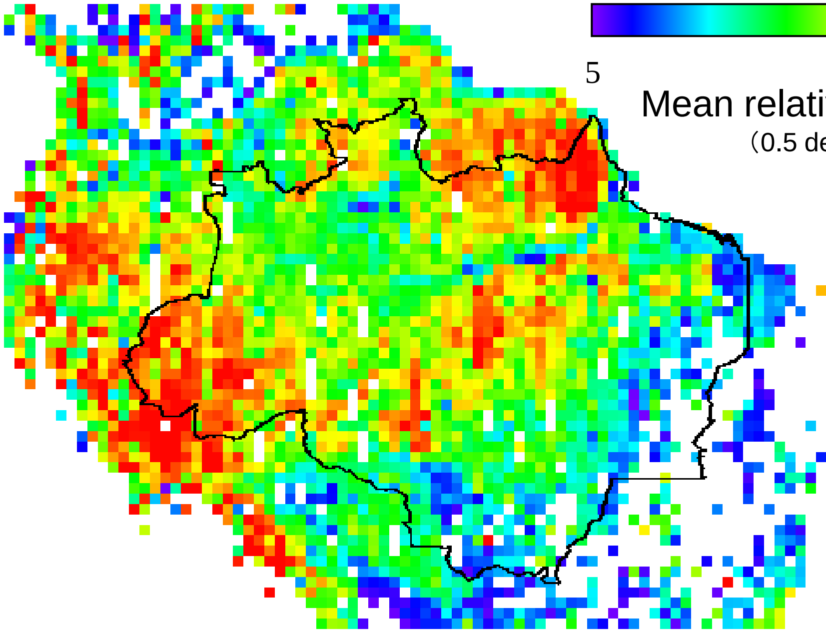
Because the satellite LiDAR (GLAS/ICESat) data were properly archived in 2013, we introduced them for estimating canopy height, covering entire Amazon with the same quality.

We have developed the software for processing full-wave form LiDAR data to get forest structure parameters. It enabled us to extract canopy height (RH100) from the ICESat/GLAS LiDAR waveform data.

By combining the canopy height spot data (RH100) with forest environment parameters, we developed a methodology to get the canopy height image of entire Amazon.

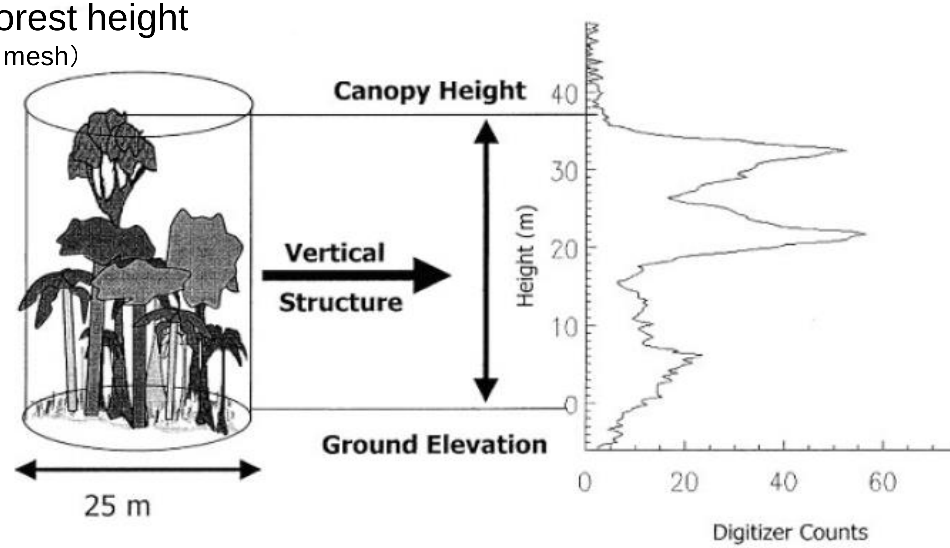
The estimated canopy height are well correlated with canopy height data obtained on the ground (upper 20% of dominant height).

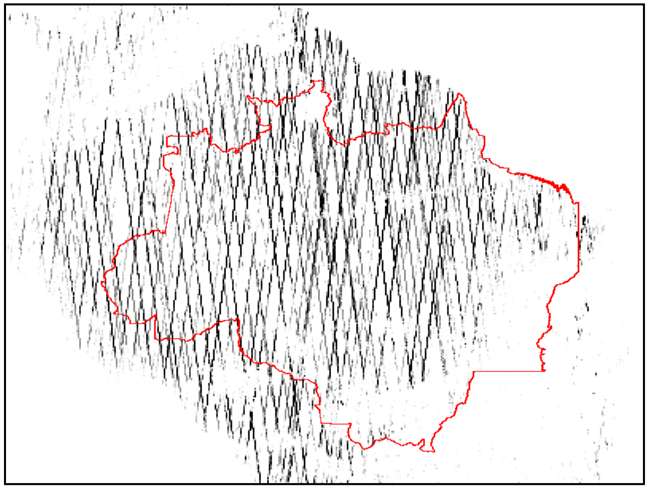
Relative forest height by ICESat/GLAS



5 40~

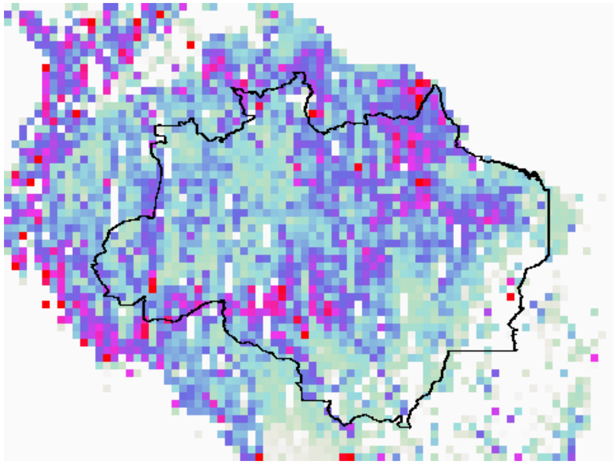
Mean relative forest height
(0.5 degree mesh)



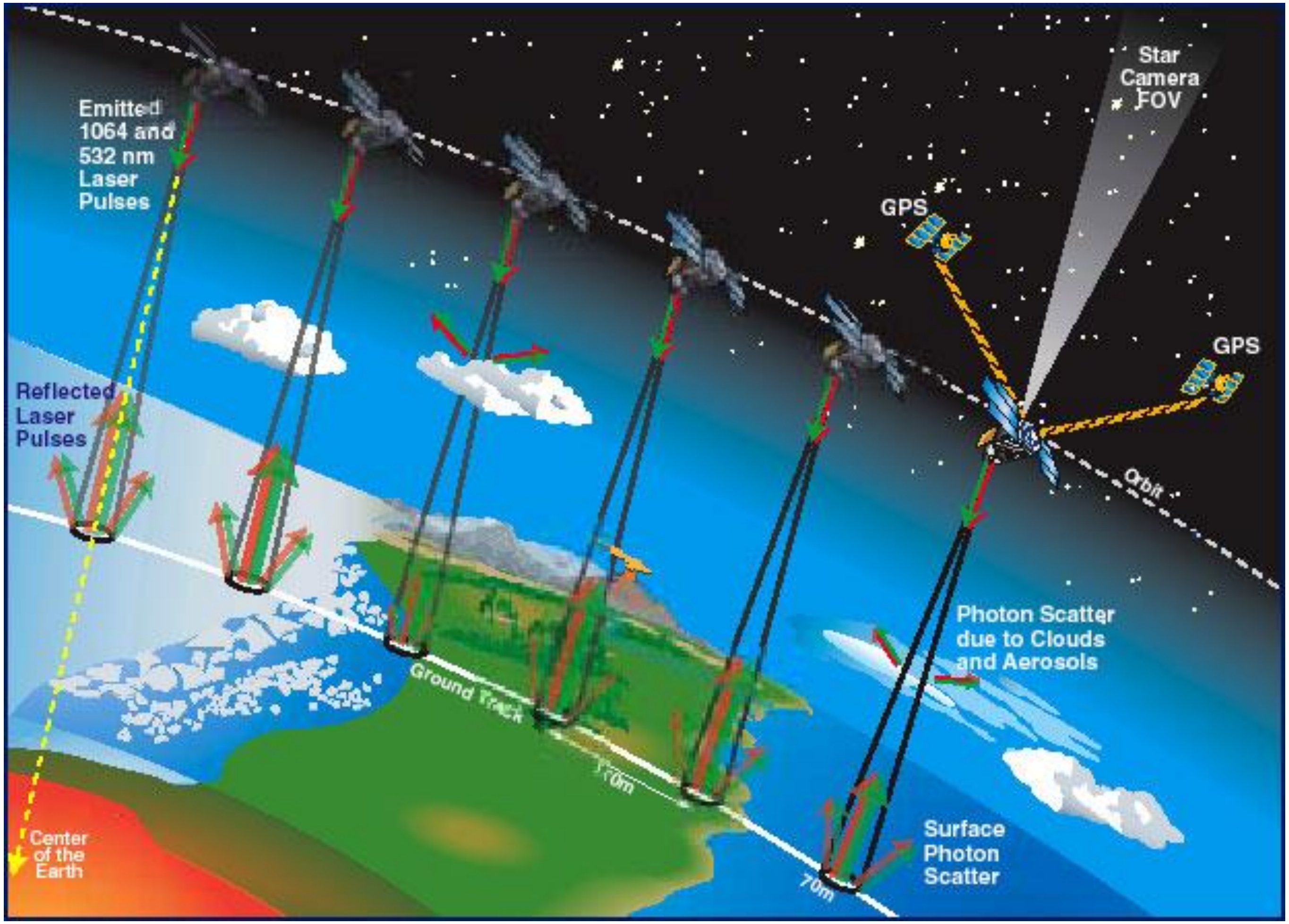


Standard deviation of relative forest height
(0.5 degree mesh)

0 15



Schematic illustration of the GLAS instrument



Graphic by Deborah

Forest height estimation by ICESat/GLAS (Lefsky, 2010)

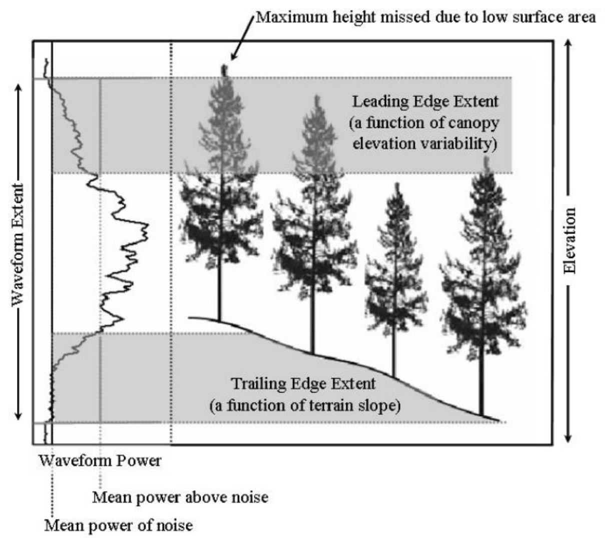


Fig. 1. Definition of total waveform, leading and trailing edge extents, and their relationship to forest canopy structure.

L15401 LEFSKY: A GLOBAL FOREST CANOPY HEIGHT MAP L15401

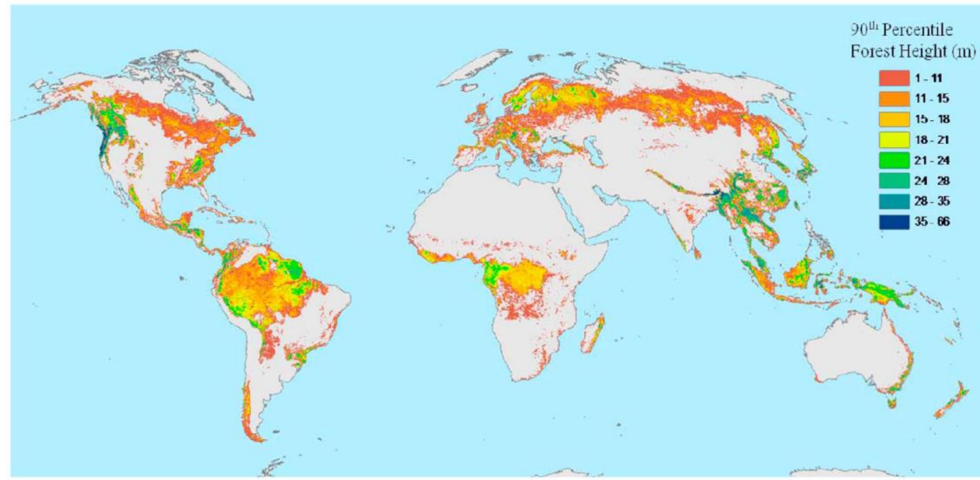


Figure 1. Global forest height map. Heights are the 90th percentile of GLAS height observations within a patch.

Original equation

LH = -4.5 + 0.55 * signal_extent - 0.102 * lead10 - 0.0895 * trail10
= -4.5 + 0.55 * (signal_extent - 0.185 * lead10 - 0.163 * trail10)

Too low estimation for Amazon forest !

New equation

Relative_LH = signal extent - 0.185 * lead10 - 0.163 * trail10

Slope correction for GLAS data (Ver. 2)

The laser intensity is shown as follows

$A_0 \exp(-\alpha r^2)$ Where r is distance from the center of footprint

The half of correction term is calculated as follows:

where $R = \frac{1}{2} D_{\mathrm{f}}$

$$\bar{h} = \frac{\int_0^R \int_0^{\frac{\pi}{2}} A_0 e^{-\alpha r^2} \cdot r \cdot \cos\phi \cdot \tan\theta \cdot r \cdot d\phi dr}{\int_0^R \int_0^{\frac{\pi}{2}} A_0 e^{-\alpha r^2} \cdot r \cdot d\phi dr}$$

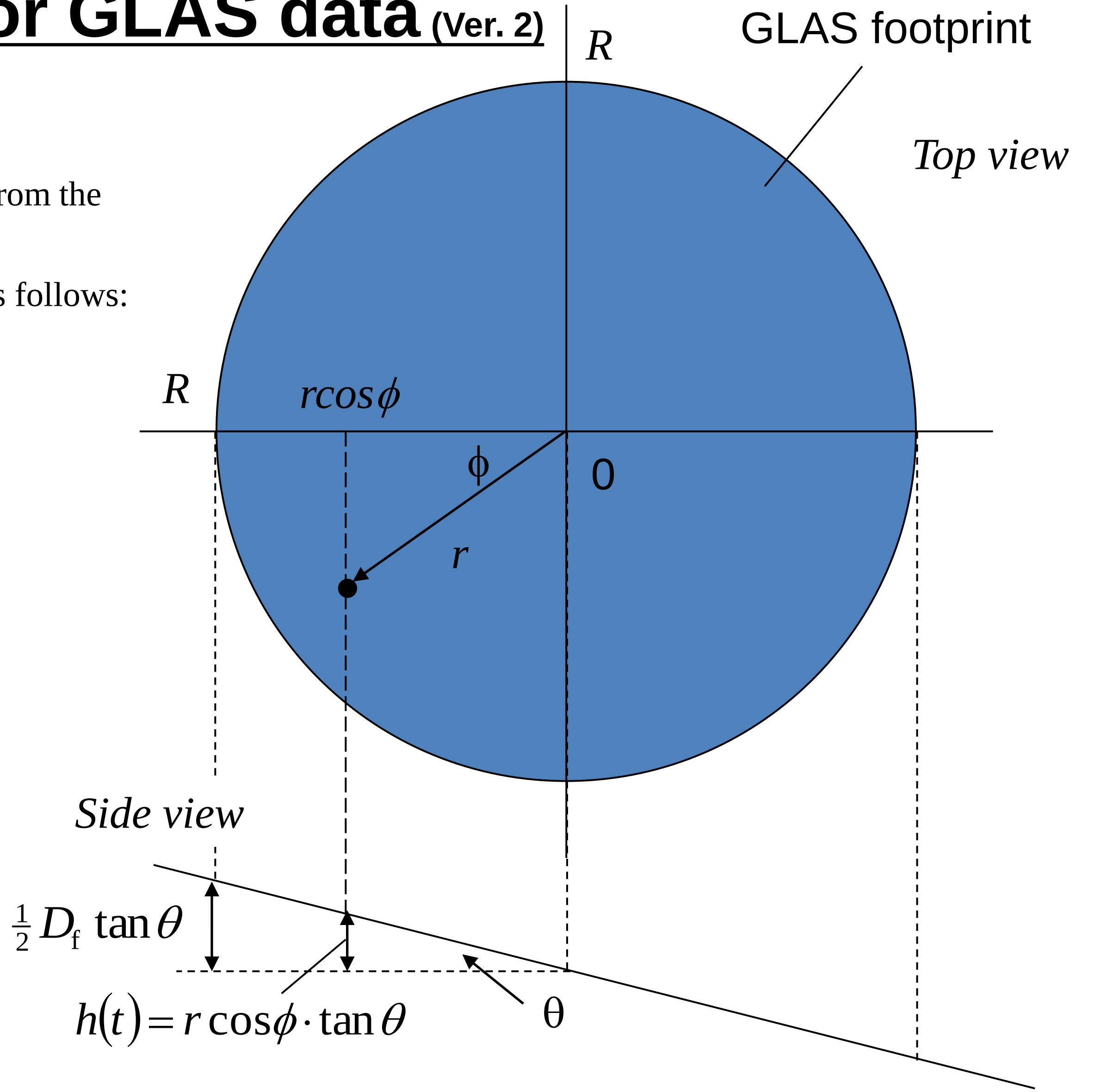
$$= \frac{A_0 \cdot \tan\theta \int_0^R \int_0^{\frac{\pi}{2}} e^{-\alpha r^2} \cdot r^2 \cdot \cos\phi \cdot d\phi dr}{A_0 \int_0^R \int_0^{\frac{\pi}{2}} e^{-\alpha r^2} \cdot r \cdot d\phi dr}$$

$$= \frac{\int_0^R \int_0^{\frac{\pi}{2}} e^{-\alpha r^2} \cdot r^2 \cdot \cos\phi \cdot d\phi dr}{\int_0^R \int_0^{\frac{\pi}{2}} e^{-\alpha r^2} \cdot r \cdot d\phi dr} \cdot \tan\theta$$

$$= \frac{\int_0^R e^{-\alpha r^2} \cdot r^2 \cdot \int_0^{\frac{\pi}{2}} \cos\phi \cdot d\phi dr}{\int_0^R e^{-\alpha r^2} \cdot r \int_0^{\frac{\pi}{2}} \cdot d\phi dr} \cdot \tan\theta$$

$$= \frac{\int_0^R r^2 e^{-\alpha r^2} \cdot dr}{\frac{\pi}{2} \int_0^R r e^{-\alpha r^2} \cdot dr} \cdot \tan\theta$$

$$= \frac{\sqrt{\pi}\, erf\left(\sqrt{\alpha} R\right) \cdot e^{\alpha R^2} - 2\sqrt{\alpha} R}{\alpha^{\frac{1}{2}} \pi \left(e^{\alpha R^2} - 1\right)} \cdot \tan\theta$$



Maclaurin's expansion

Because the beam intensity is constant

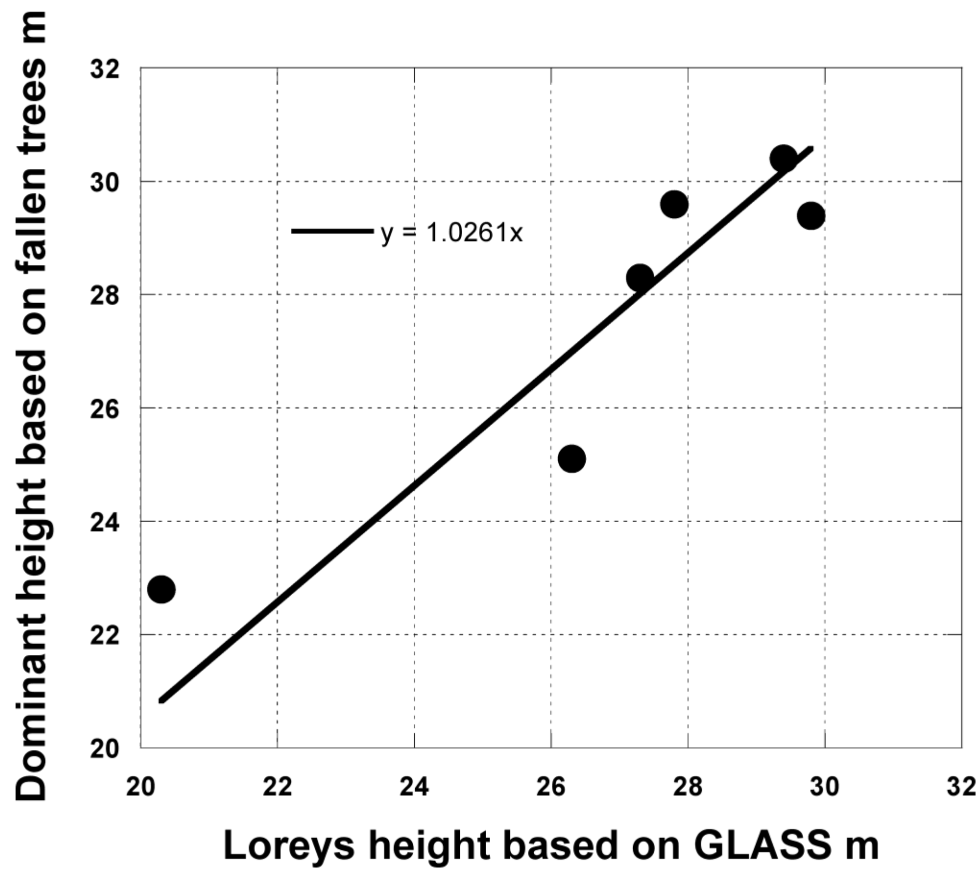
$$\bar{h} \approx \frac{1}{\pi}\left(\boxed{\frac{4}{3}} - \frac{2\alpha R^2}{15} - \frac{\alpha^2 R^4}{315} + \frac{2\alpha^3 R^6}{945} + \frac{\alpha^4 R^8}{13860} + \cdots\right) \cdot R \tan\theta$$

Comparison between dominant height and Lorey's height

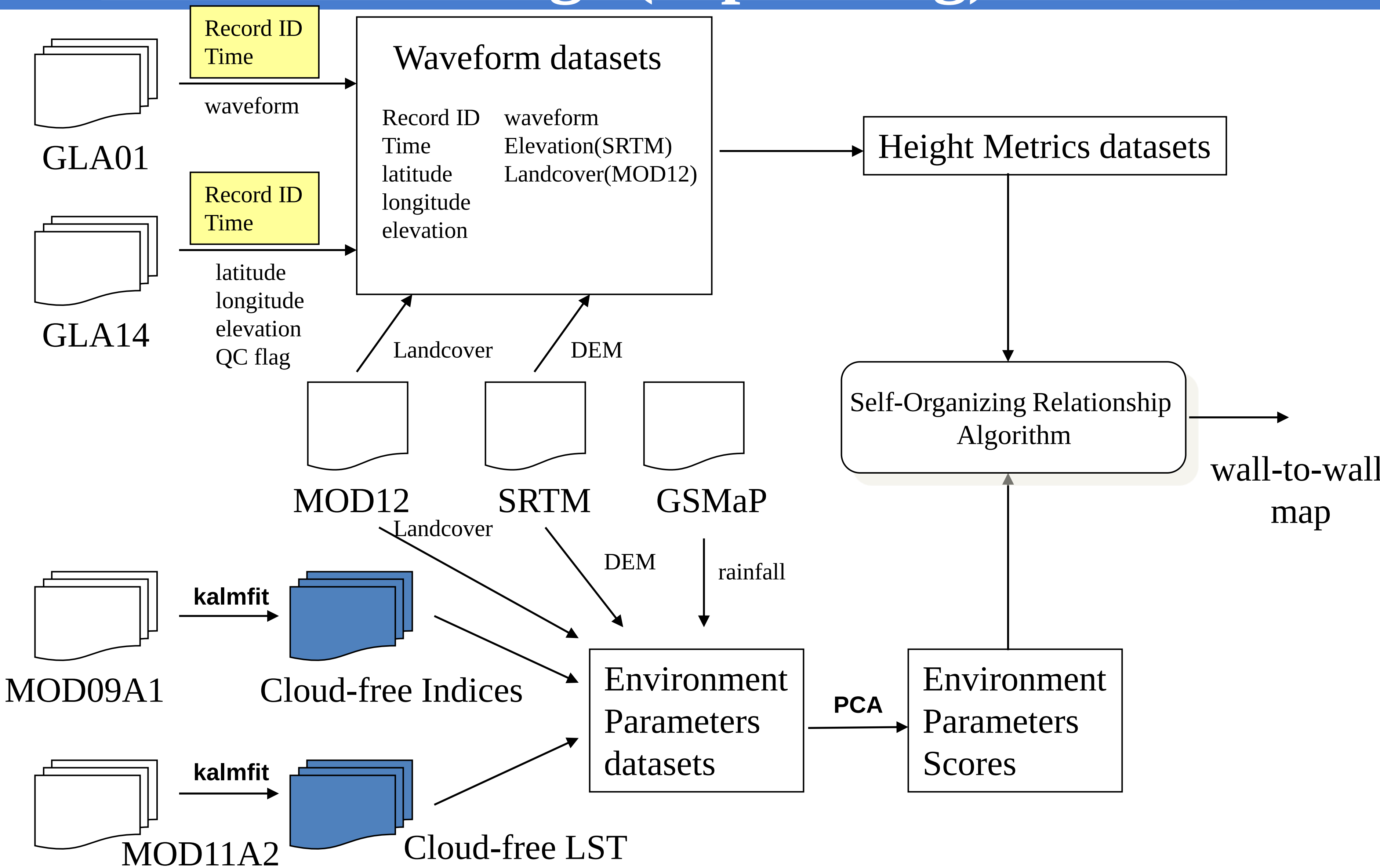
Dominant height : from Fallen tree survey

Lorey's height: from Satellite LiDAR

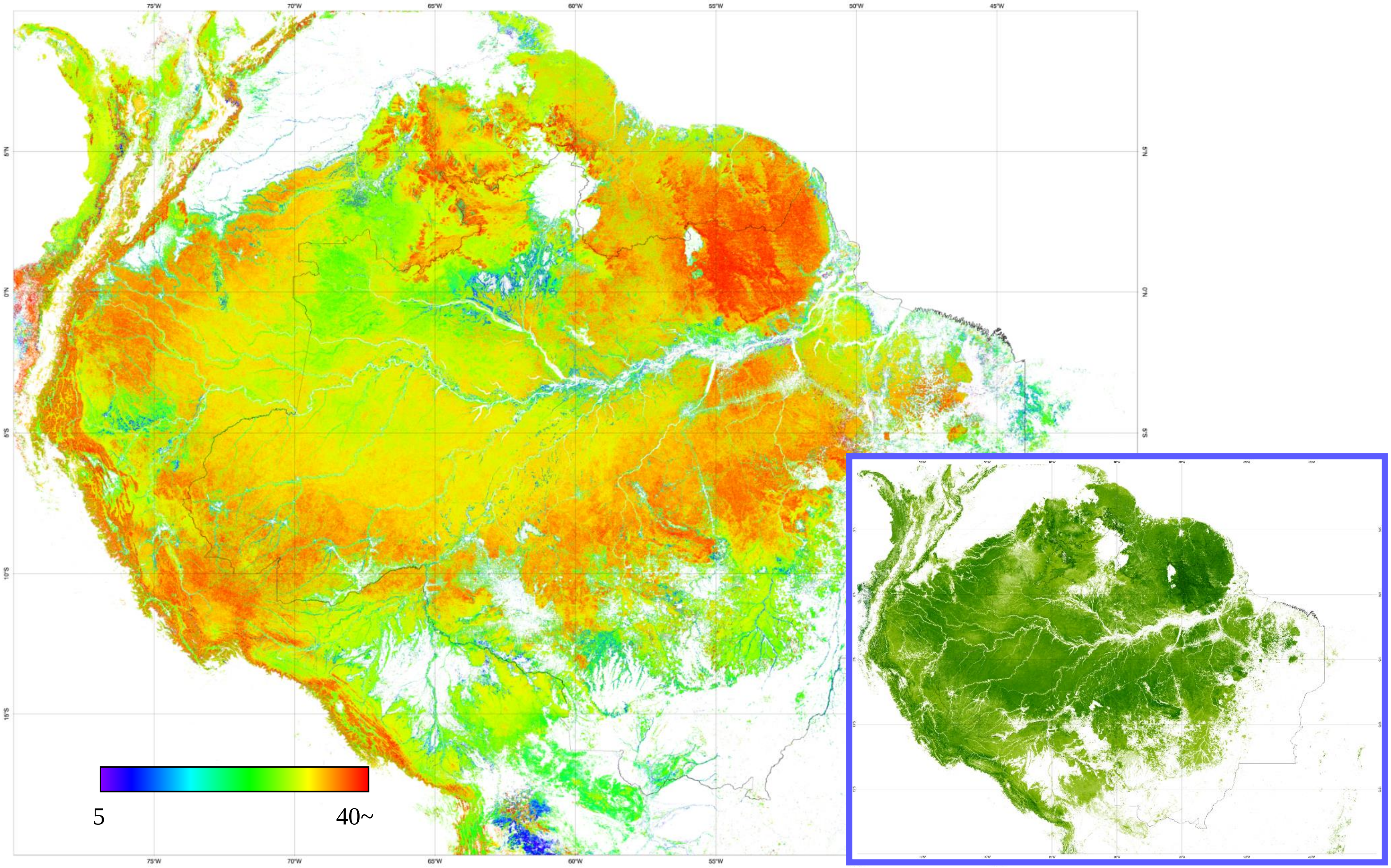
Sites	Loreys height based on GLASS m	Dominant height based on fallen trees m
AP	29.4	30.4
AT	27.8	29.6
CG	29.8	29.4
JT	27.3	28.3
SG	26.3	25.1
UN	20.3	22.8



Data Processing (expanding) Scheme



Forest height map (RH100 and RH50)

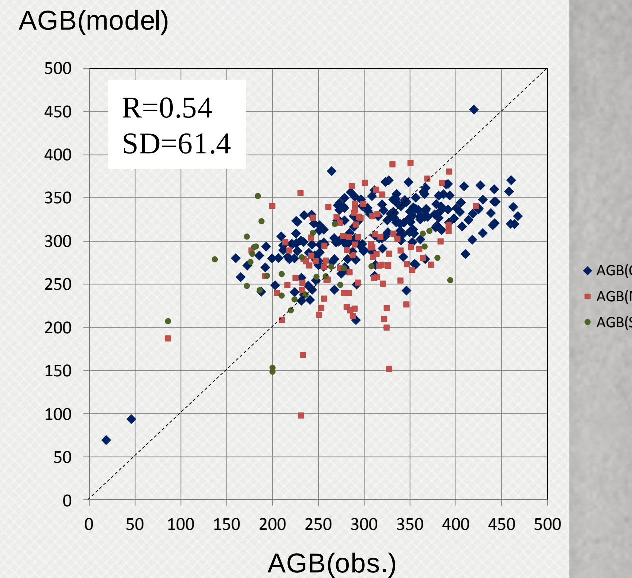


Forest Biomass Mapping

After analyzing the relations between the biomass data obtained by the inventory and the canopy height data derived from ICESat/GLAS, the biomass map of entire Amazon was created by combining forest environment parameter data.

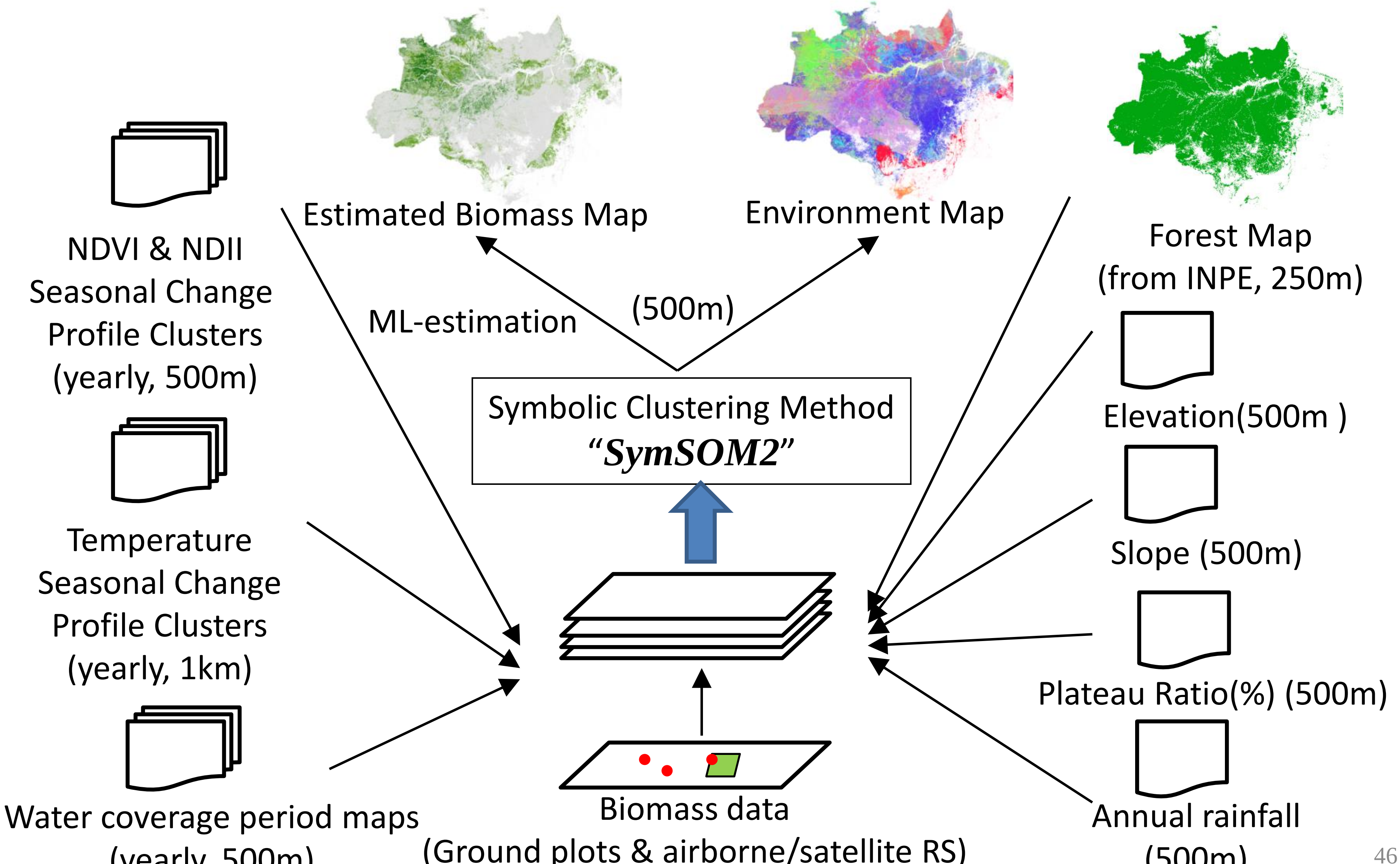
The biomass estimation model was developed by biomass data where more than 1 ha plot data were obtained in a plot unit or MODIS 500 meter resolution pixel, by introducing not only our field data but also existing former observation data (the standard deviation of the model error was 61.4t/ha).

By the bootstrap method, both the confidence interval of 2.5% to 97.5% and uncertainty were added to each 500m pixel. The uncertainty was ±12.2%.

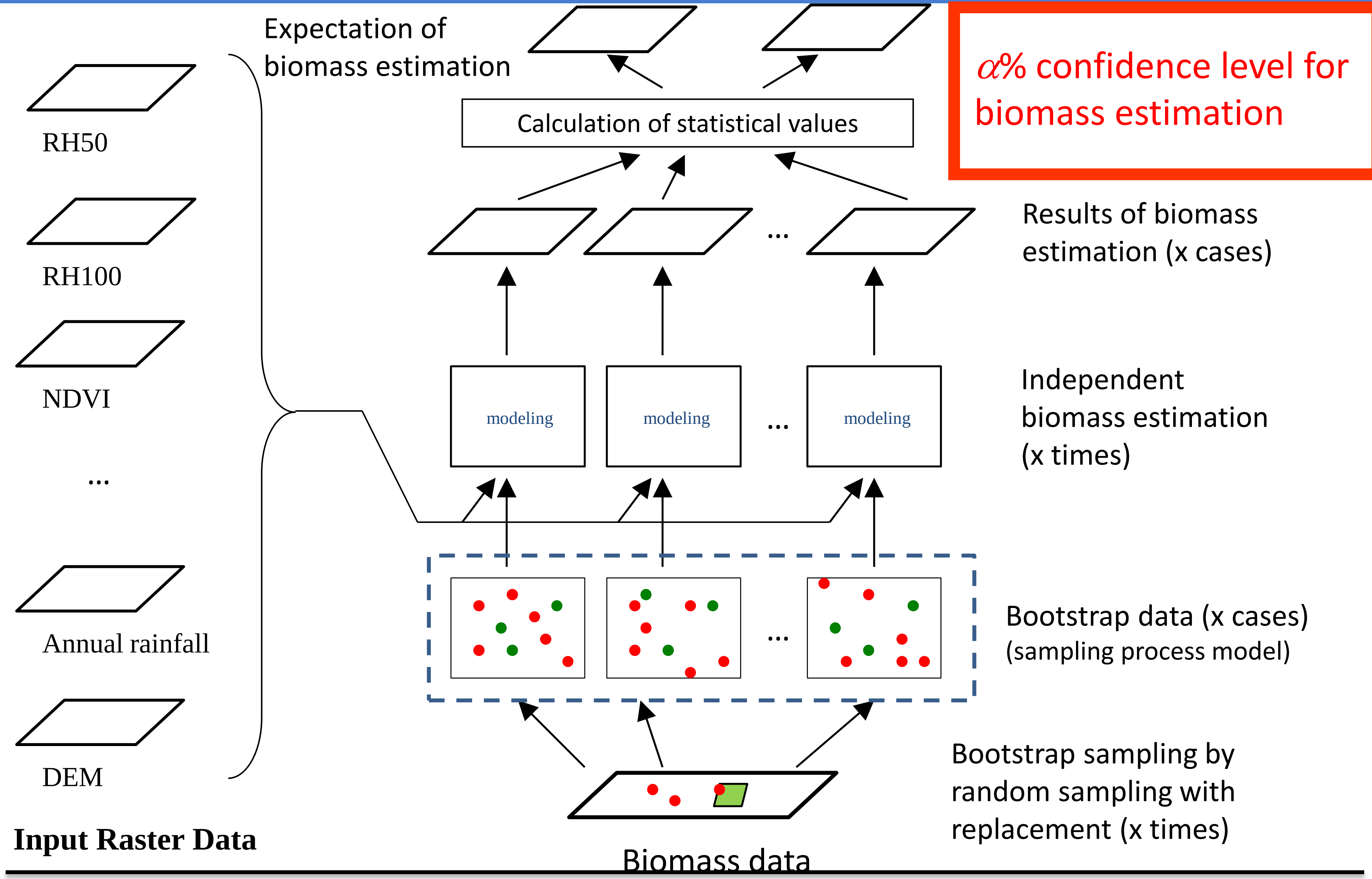


$f(\mathrm{RH10},\ldots,\mathrm{RH100})+g(\mathbf{x})$

Biomass Map and Environment Map



Confidence evaluation of biomass estimation



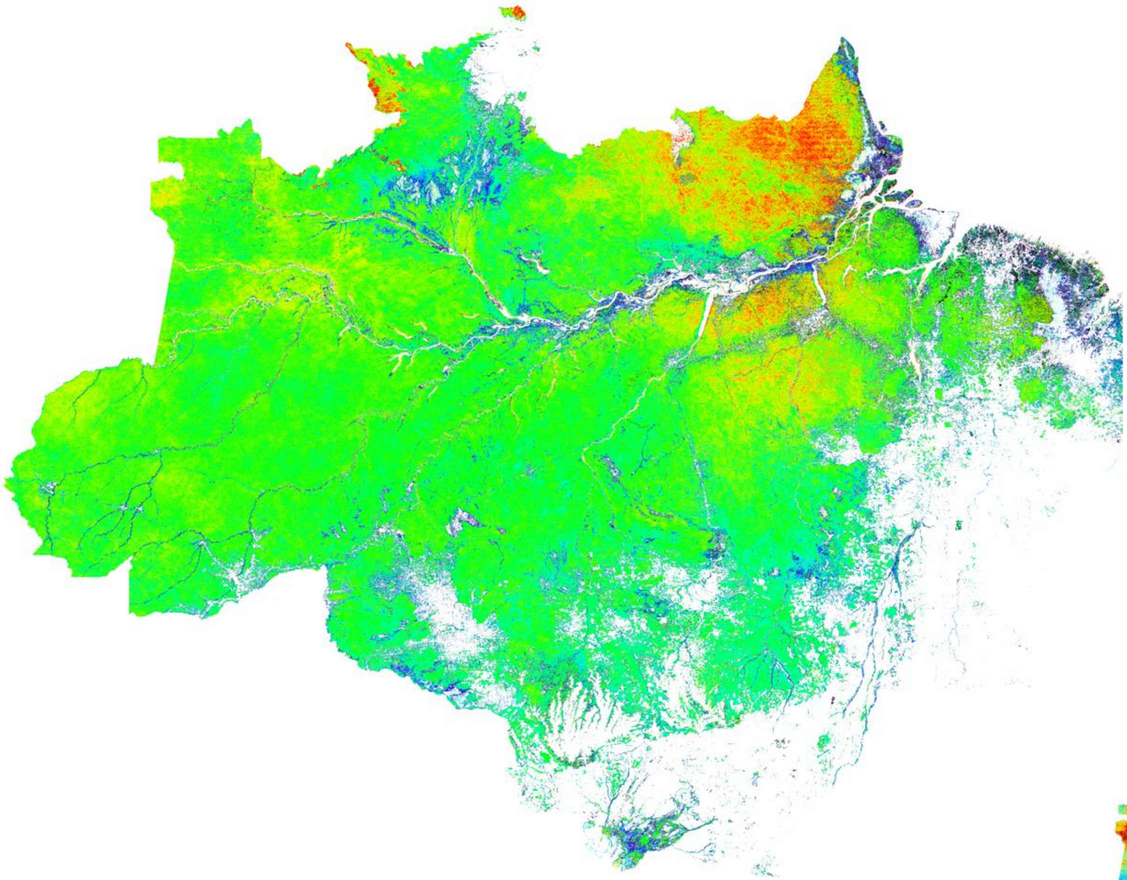
(Ground plots & airborne/Satellite RS)

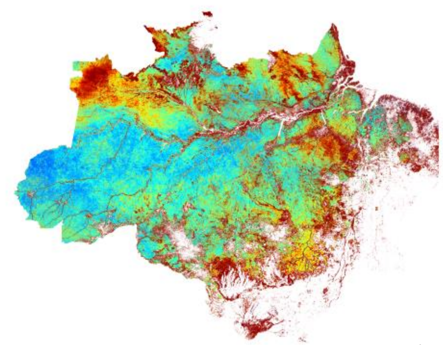
The above ground biomass map

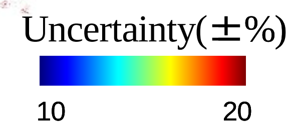
Total AGB

102.0 Gt

(Uncertainty: ±12.2%)







Uncertainty (AGB allometry): ±11.3%

Uncertainty (AGB modeling): ±4.46%

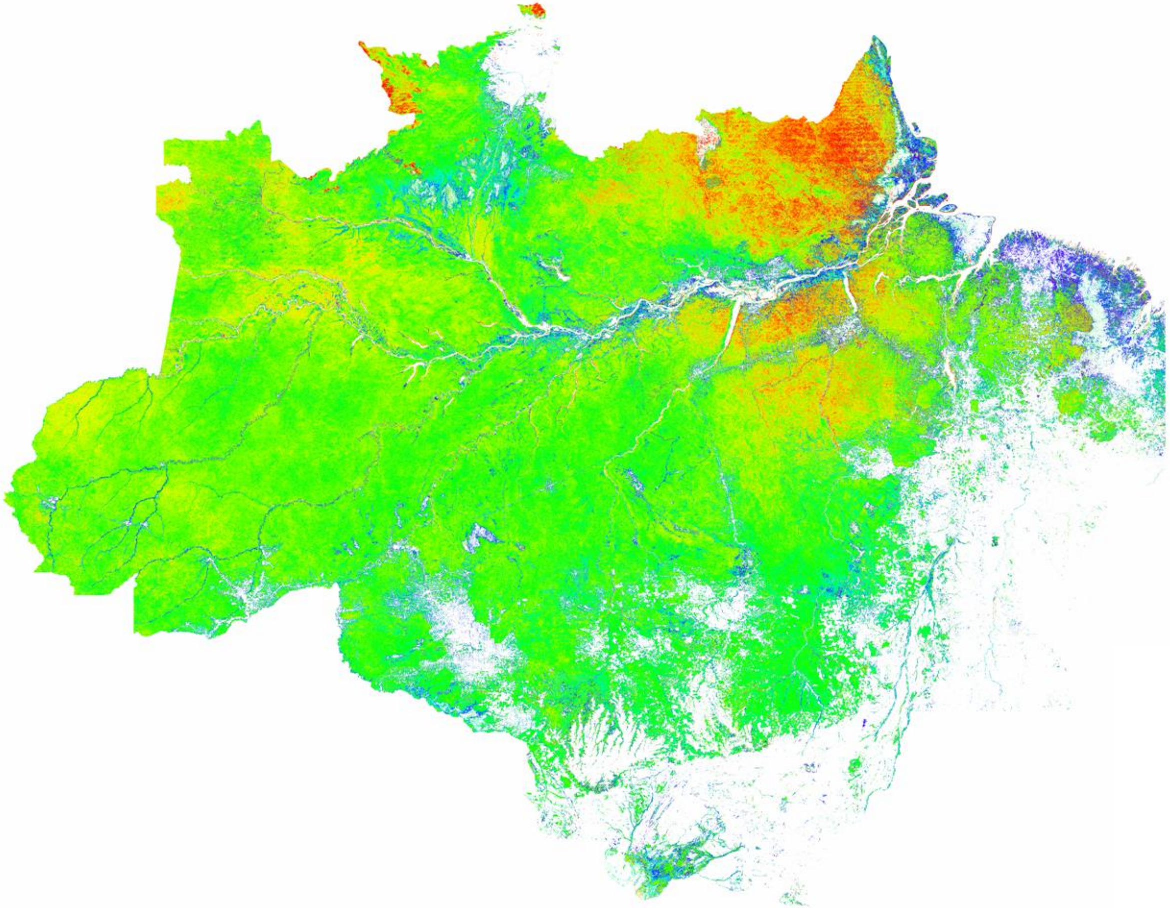
$$\varepsilon_{\mathrm{AGB}} = \sqrt{\varepsilon_{\mathrm{allometry}}^{2} + \varepsilon_{\mathrm{model}}^{2}}$$

A Carbon density map of Amazonian forest (AGB+BGB)

Total Carbon Stocks

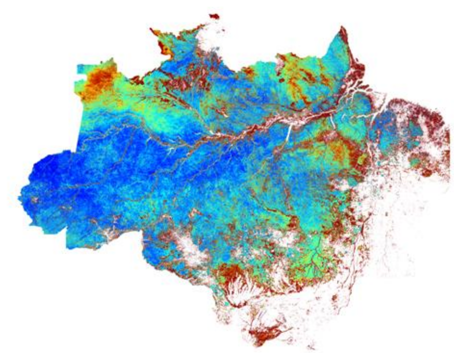
54.5C Gt

(Uncertainty: ±11.0%)



Carbon Density (C t/ha)

0 240~



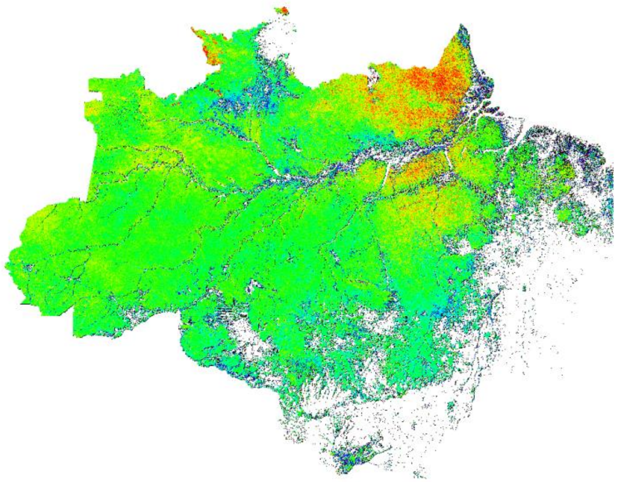
Uncertainty(±%)

10 20

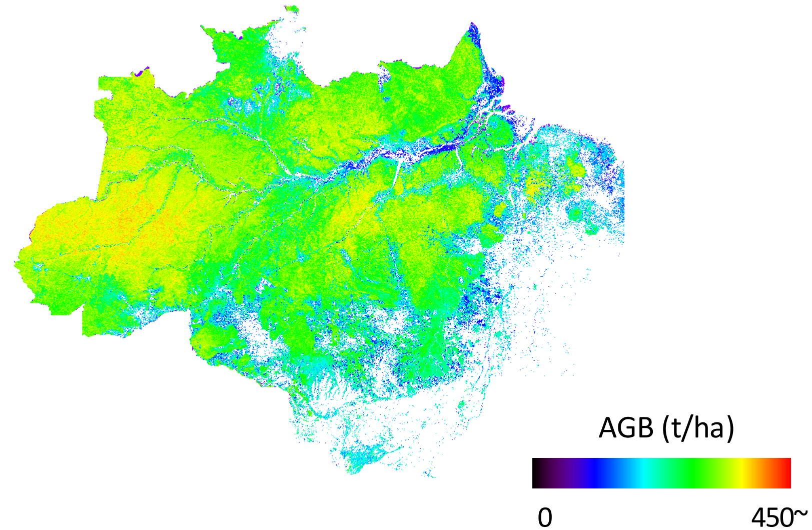
Biomass

Comparison with Baccini's product

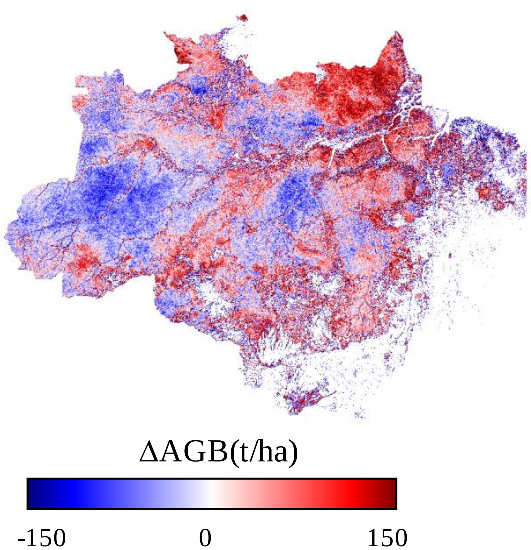
CADAF



Baccini et al.



Our results – Baccini's product

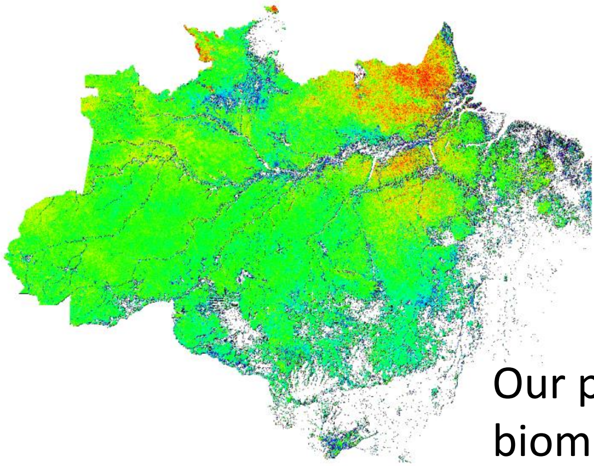


In Baccini's products, influences of clouds and inaccurate positioning are clearly found

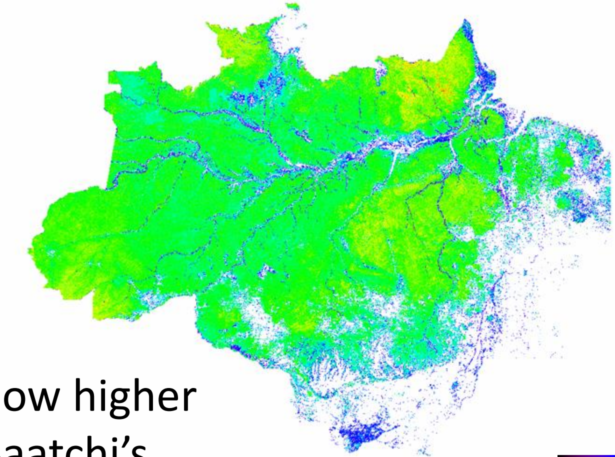
Comparison with Saatchi's product

Biomass

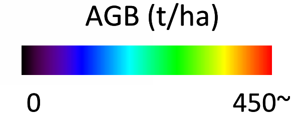
CADAF



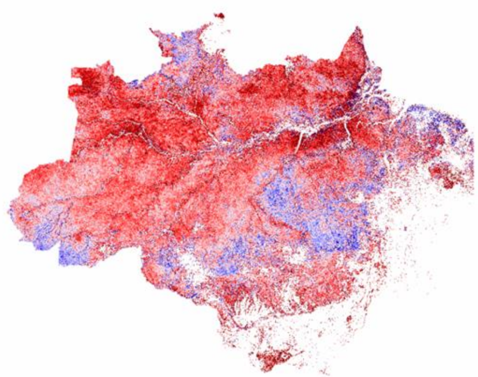
Saatchi et al.

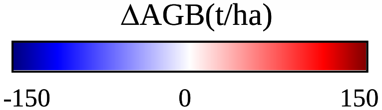


Our product show higher biomass than Saatchi's product in average.

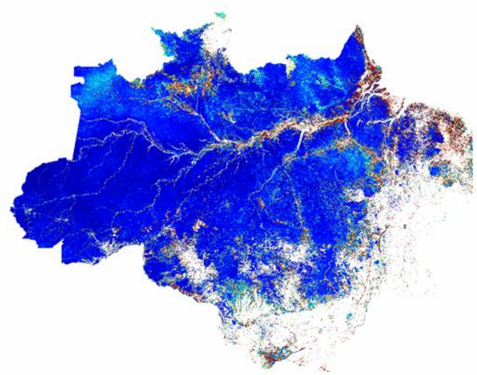


Our results – Saatchi's product





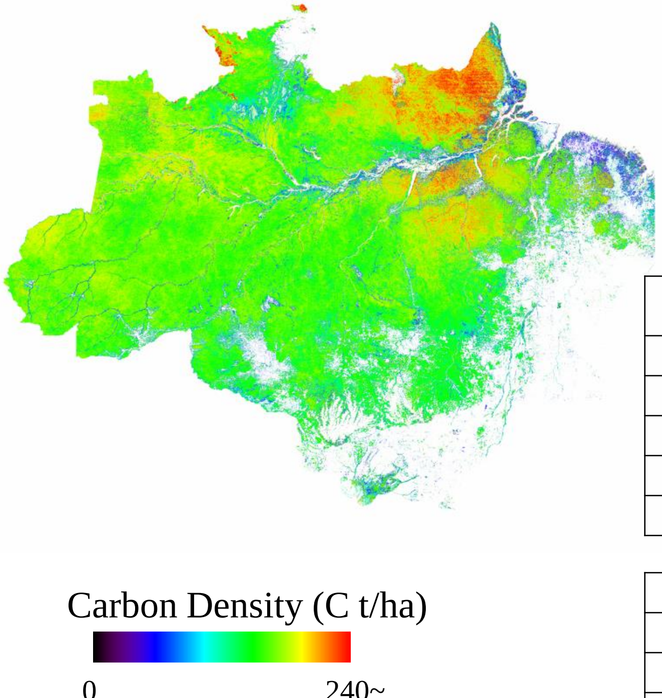
BS uncertainty(±%) by CADAF



BS uncertainty(±%) by Saatchi et al.

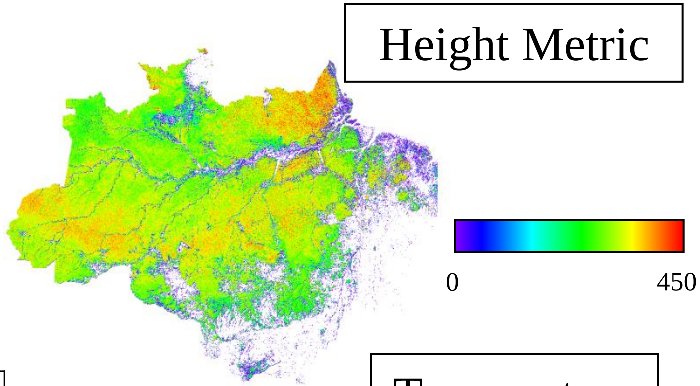
Comparison with Environment factors

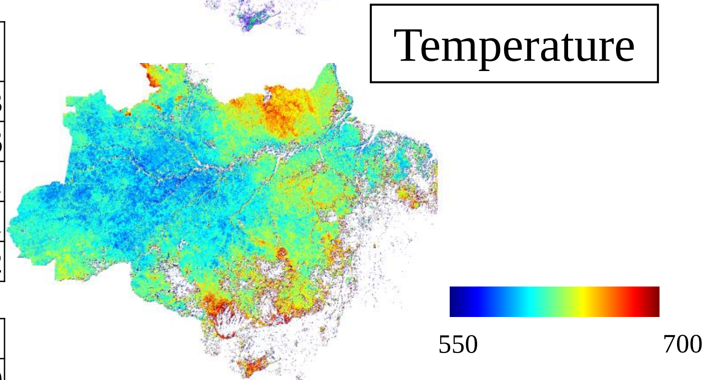
model18

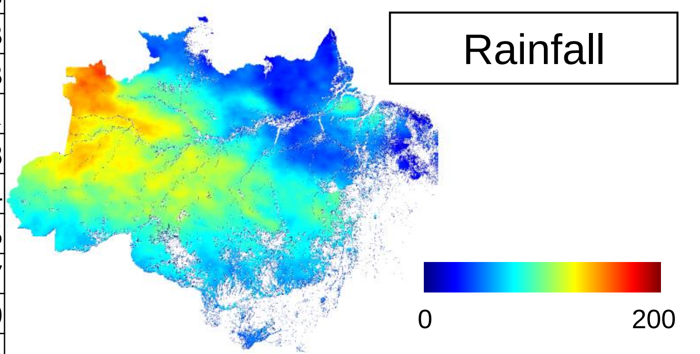


f()	
RH10	11.363
RH40	-8.976
RH60	14.531
RH80	-4.691
RH100	6.292

g(**x**)	
(Intercept)	5957.940
slope_HK	-5.955
avr_ndvi	-824.233
min_ndii_2_7	142.863
avr_day	14.081
min_Day	-23.478
min_Night	-8.884
GSMaP_M_avr_sum	0.075
GSMaP_M_avr_max	-0.227
min_b7	1238.480
max_b7	-844.761





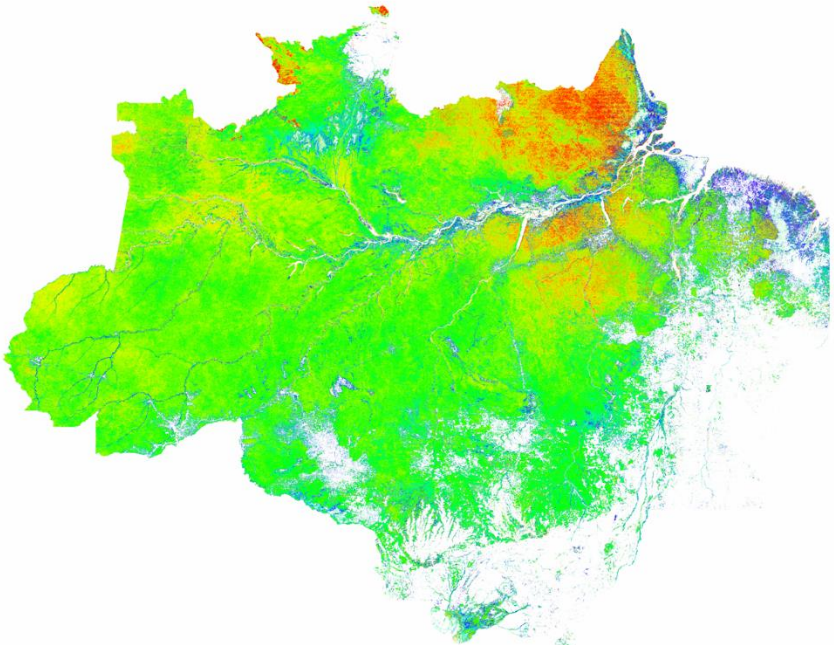


Summary: Forest Biomass Map

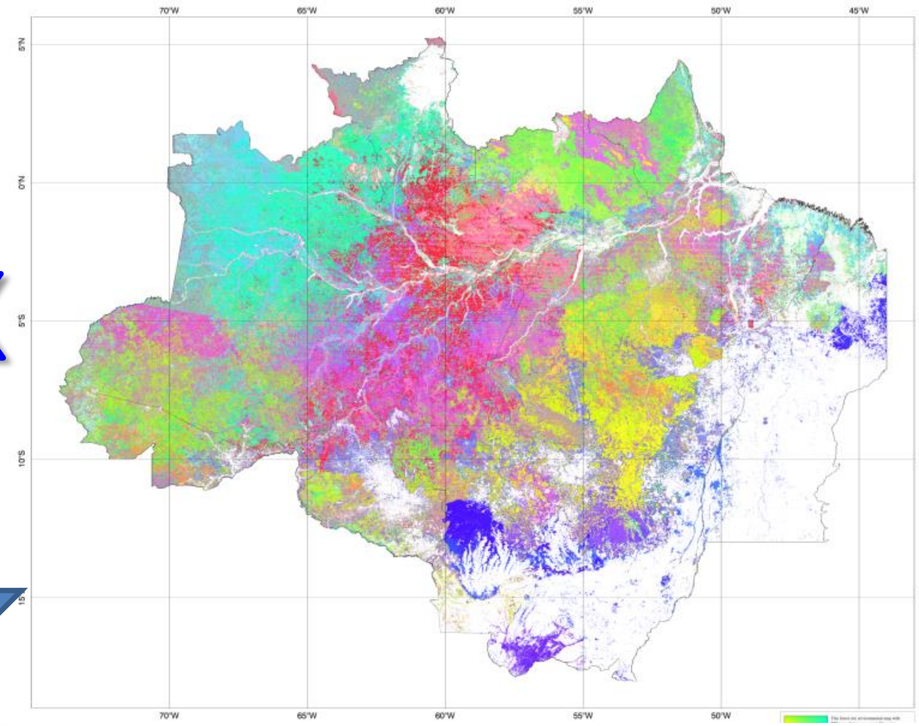
- More than 1 million satellite LiDAR (GLAS) point data were well introduced for estimating forest canopy height of Amazon.
  - The entire canopy height map was created by combining the GLAS data and environment data with 500 meter pixel as well as ground survey data.
- Both AGB map and BGB map were developed
  - Not only the estimated mean biomass but also the uncertainty map was created by the bootstrap method.
  - The uncertainty map well indicates the well estimated area and high uncertain area in biomass estimation.

Further study

Total (AGB+BGB) biomass



Site Environment



X

Locally adjusted
biomass map, ecosystem map,,

Summary

1 Forest Stand Parameter

Analytical techniques were studied to obtain forest stand parameters, (such as canopy height, density and biomass,) combining remote sensing information and forest inventory data

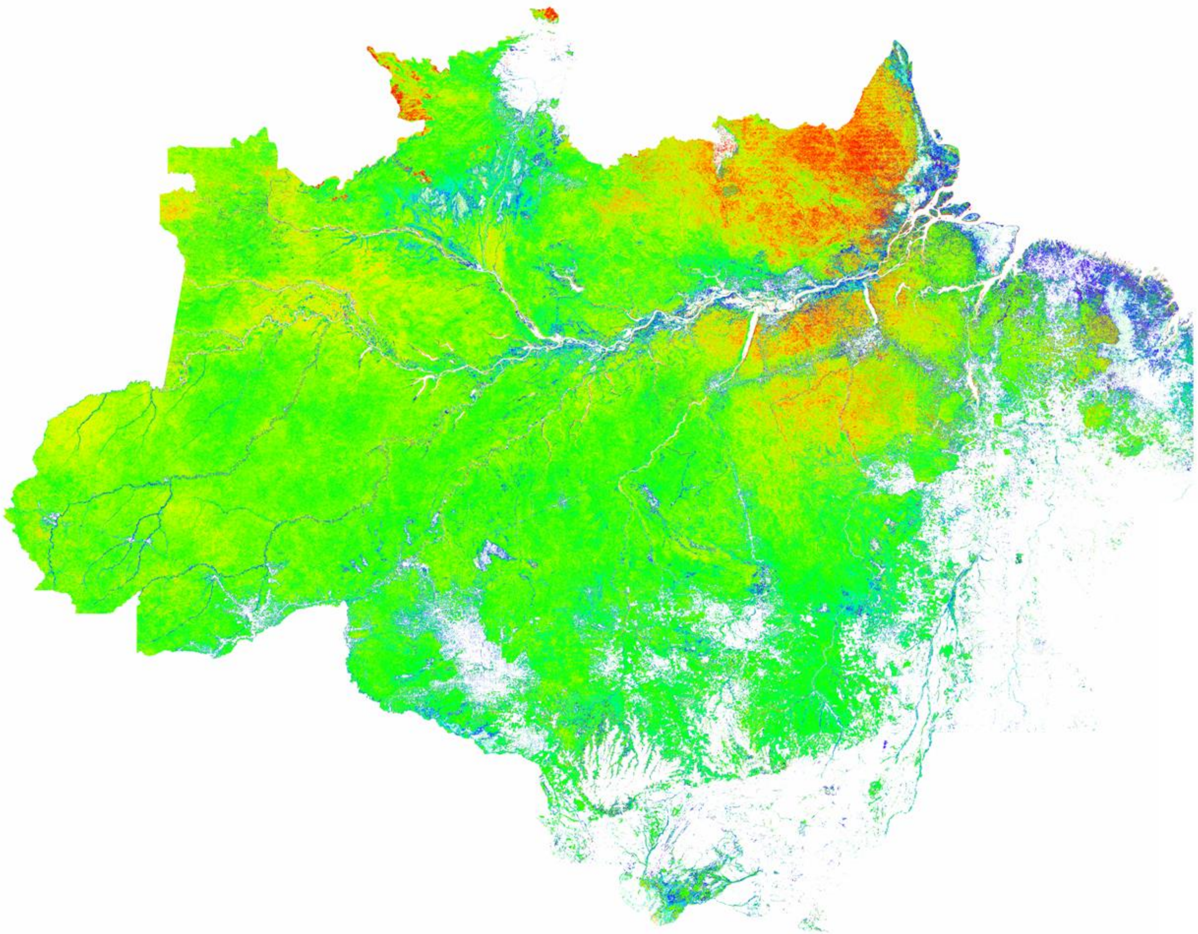
2 Site Environment Map

A methodology was developed to obtain forest site environment map using remote sensing information and various geographic information

3 Forest Carbon Stock Map

The Amazon carbon stock map (AGB + BGB) was created with uncertainty map by combining the inventory data with remote sensing data

Carbon map of Amazonian forest (AGB+BGB)



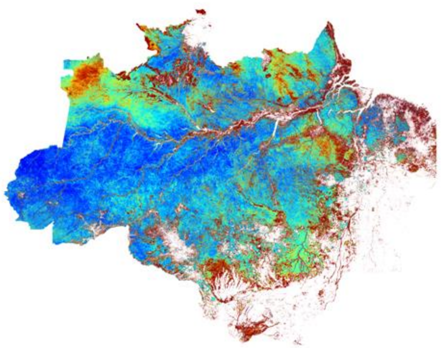
Total Carbon Stocks

54.5C Gt

(Uncertainty: ±11.0%)

Carbon Density (C t/ha)

0 240~

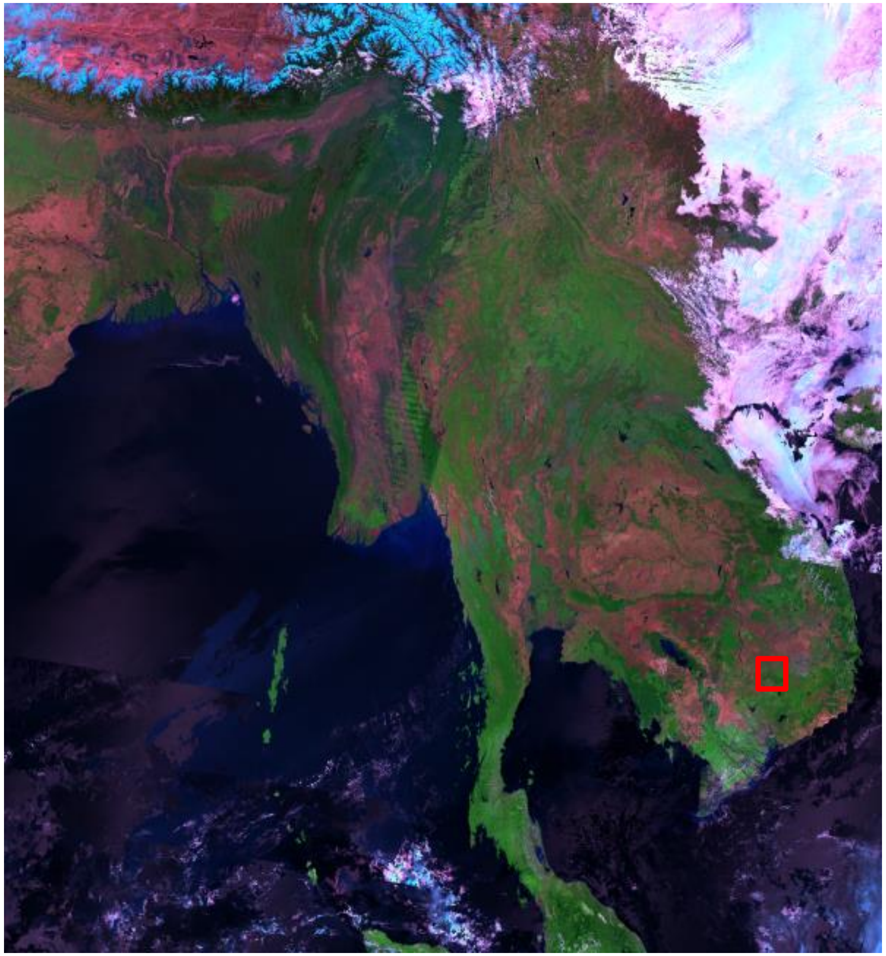


Uncertainty(±%)

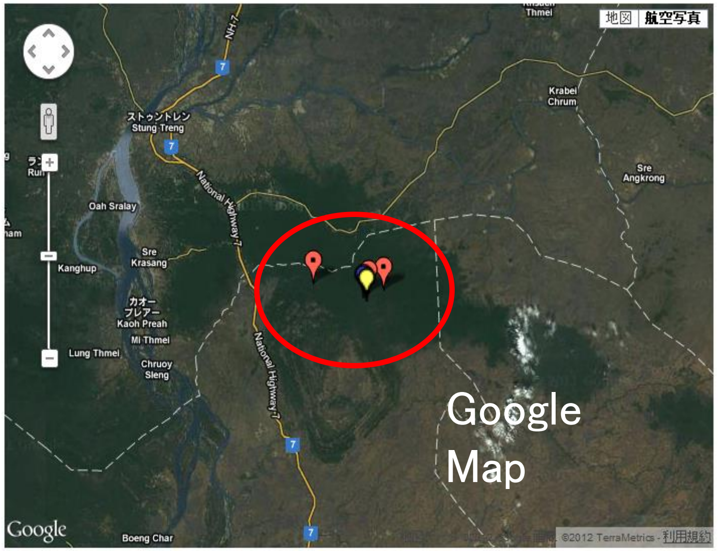
10

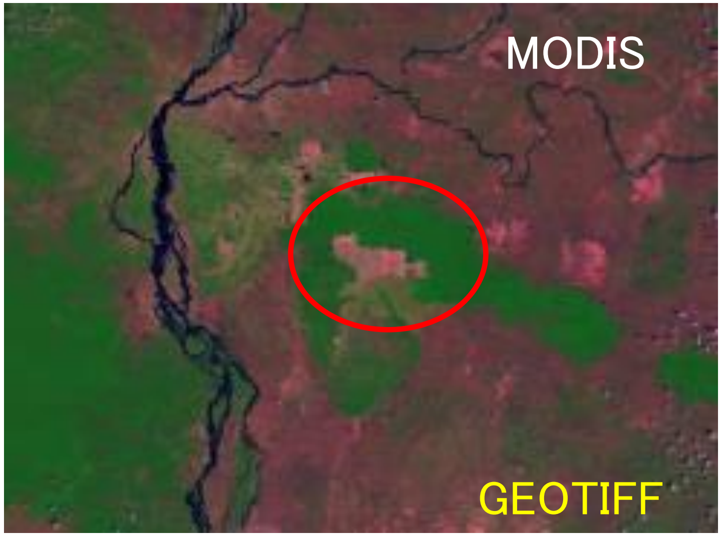
ADD-MODIS in Asia as DETER in Amazon

Automatic Deforestation Detection



Sensor: MODIS/Terra
Latest Observation Date: 2012-02-21 to 2012-02-29





RS in CADAF