Towards estimation of vegetation structure from orbit: a case study for tropical forest and Tandem-X

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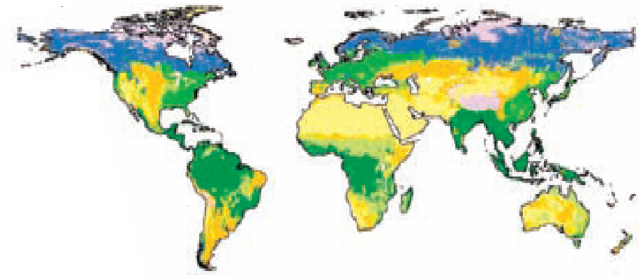
Forests in the global carbon cycle



Currently vegetation is a carbon sink! 2 - 3 Gt C / yr
(increase of carbon in atmosphere 4 Gt C/ yr, IPCC 2021, Pan 2024)

Climate change can modify productivity of vegetation:

- Europe 2003 drought:
  30 % decrease of productivity, vegetation changed from C- sink into C-source: from 0.3 to -0.5 GtC
  (Cias et al. 2005, Nature)
- Amazon 2005/2010/2015 drought:
  forests transform from C-sink into C-source, from 0.4 to -1.2 GtC
  (Phillips et al. 2009, Science, Lewis et al. 2011, Nature, Qin et al. 2021, Nature CC)
- Higher mortality rates of trees:
  no global quantification
  (van Mantgem 2009 Science, Anderegg PNAS 2012)

Does vegetation act as a carbon sink also in future ?

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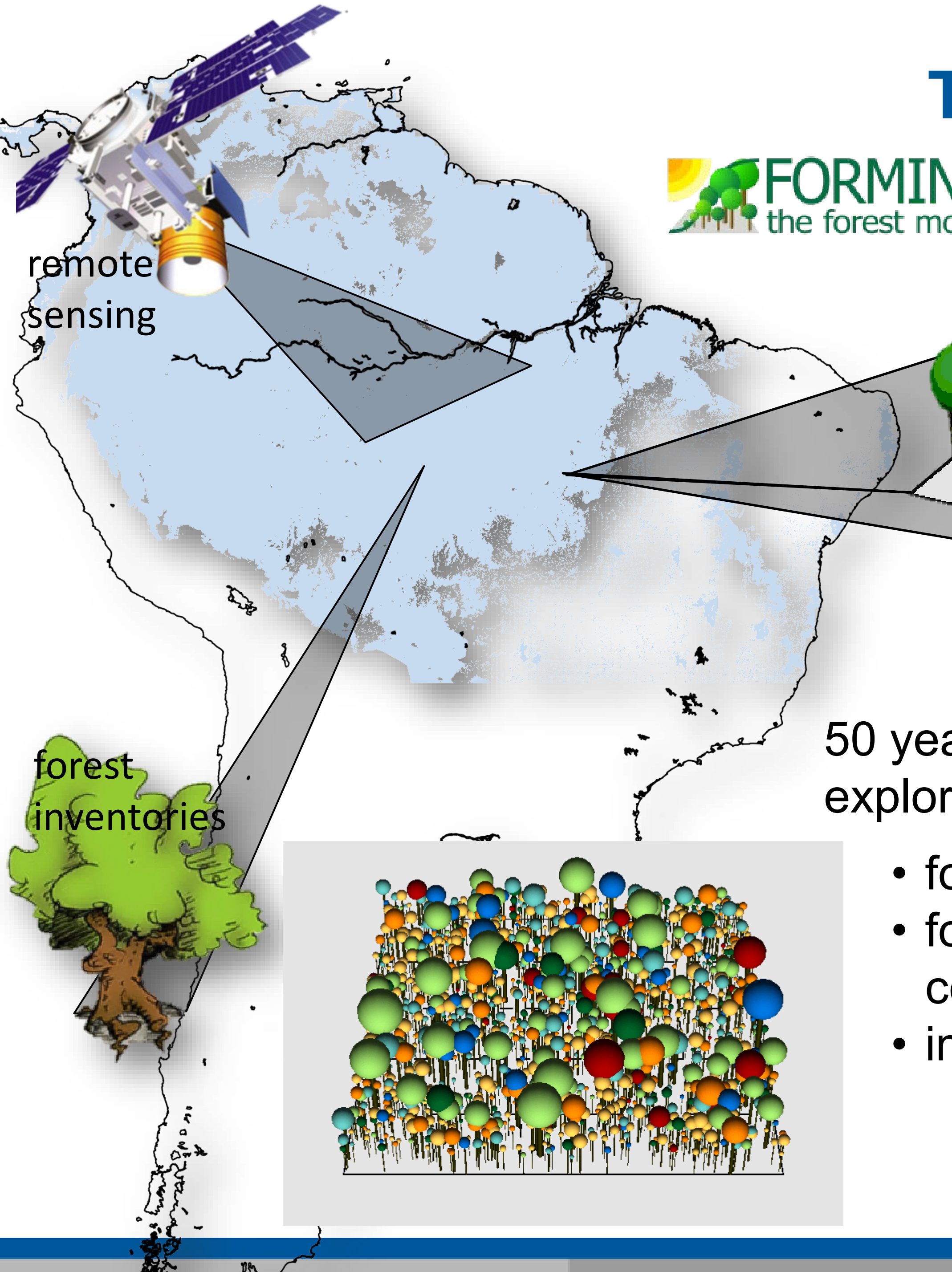
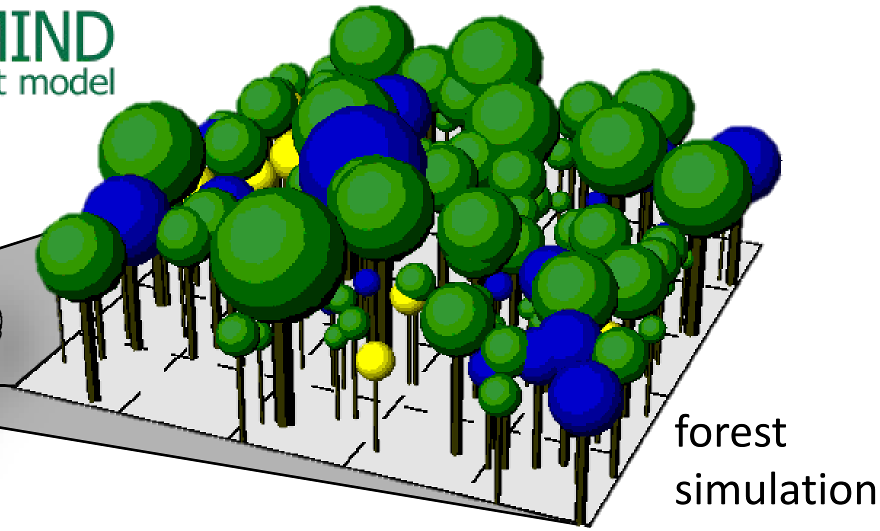
The Amazon rainforest

FORMIND
the forest model



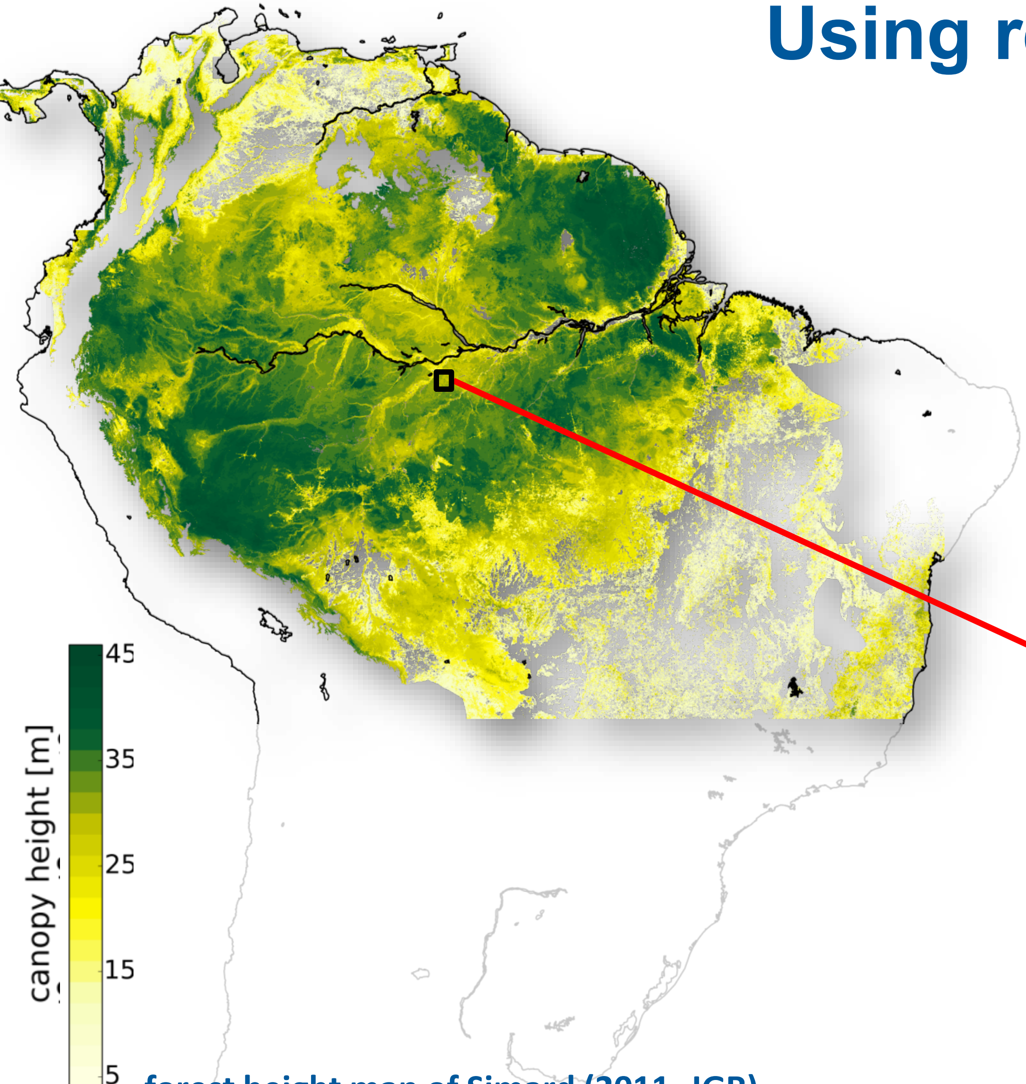


50 years tradition of forest gap models exploring:

- forest dynamics and biomass
- forest structure and species compositions
- impact of disturbances

forest gap models : Shugart 1998, CUP
Shugart et al. 2018, ERL
review Formind: Fischer et al. 2016, Ecol Mod

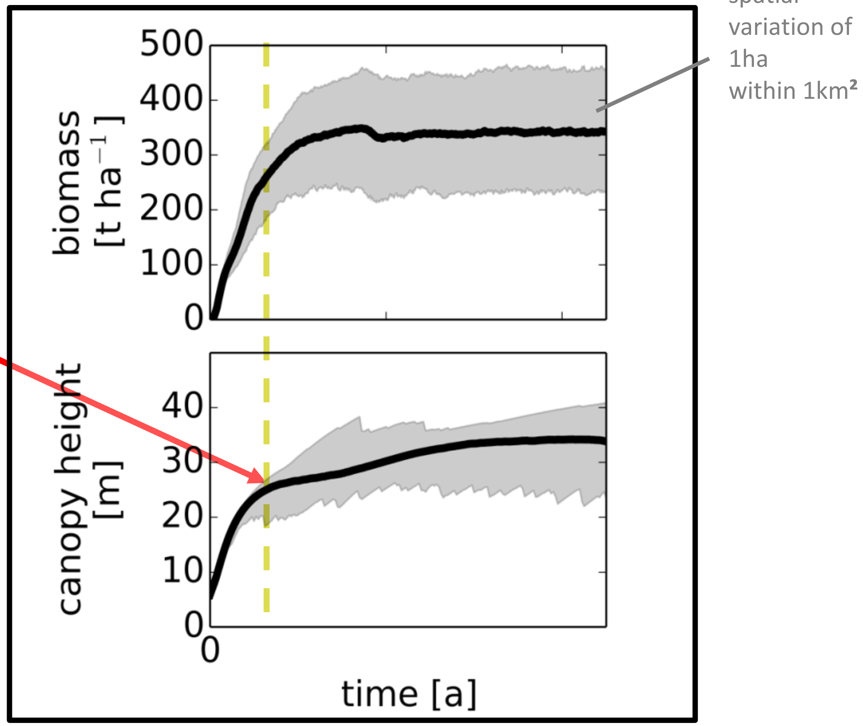
Using remote sensing as filter for forest simulations



forest height map of Simard (2011, JGR) based on ICESAT

simulated local forest dynamics

(scale 1 ha, including local climate and soil cond.)



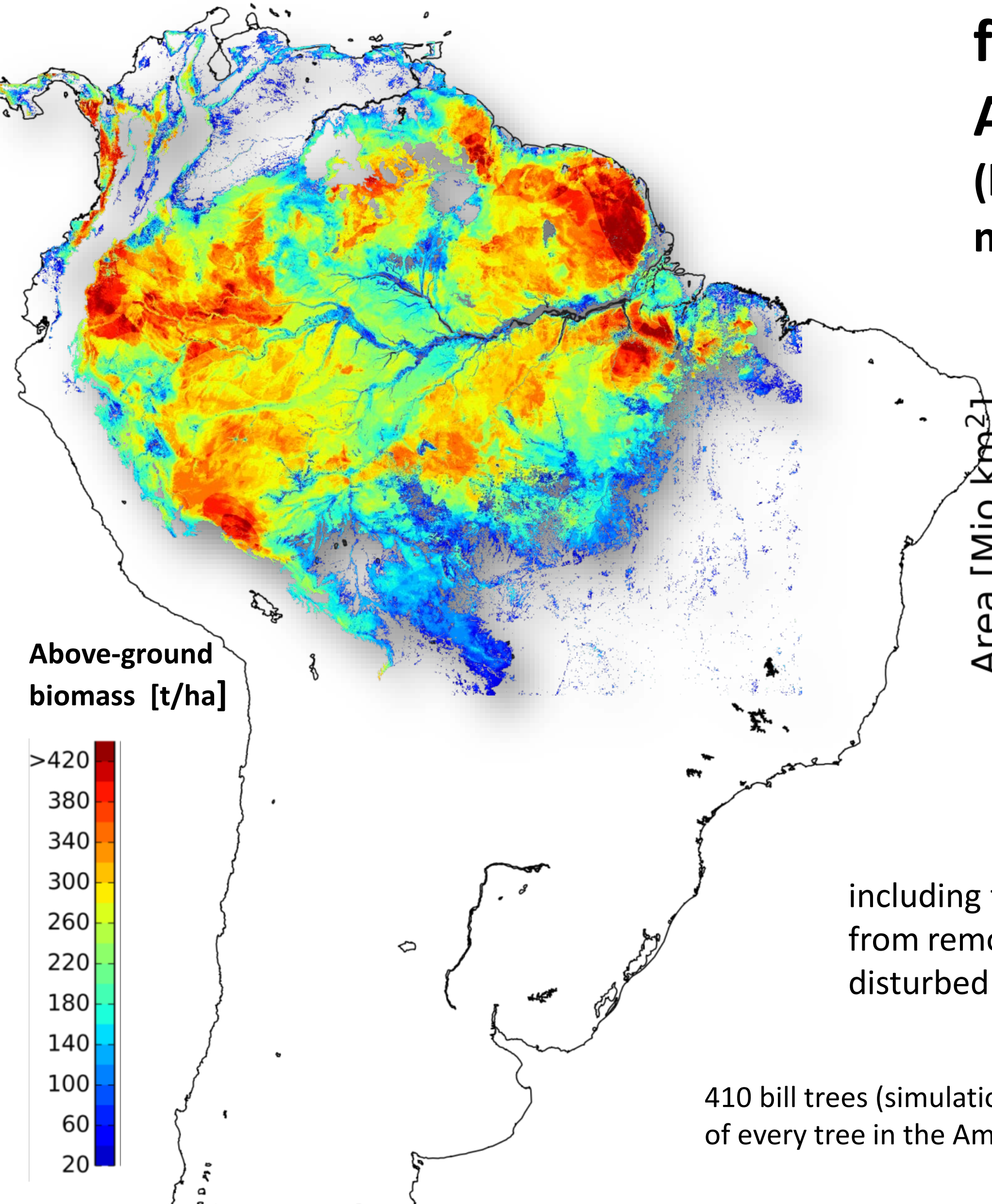
using canopy height to identify successional state of forest

Remote sensing product ⟷ **Vegetation modelling**

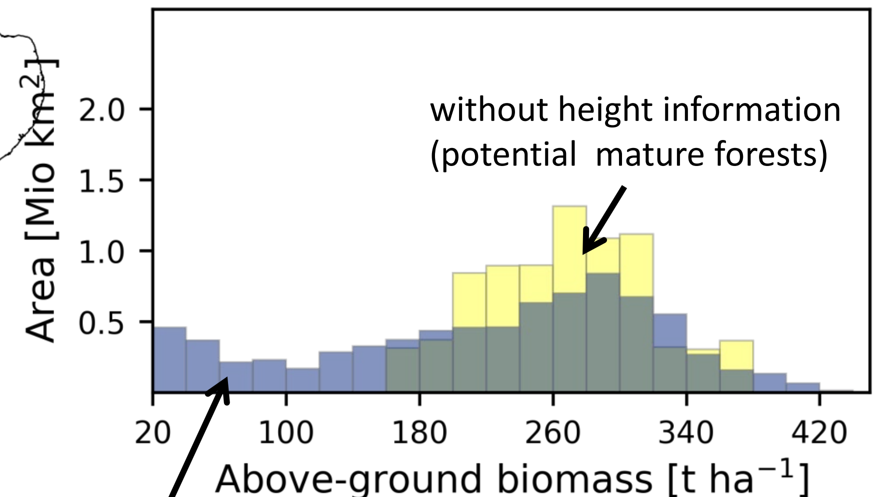
Biomass in the Amazon rainforest

forest biomass map of current Amazon rainforest

(based on linking remote sensing and forest modelling)



500 mill. ha, scale 1 km x 1km



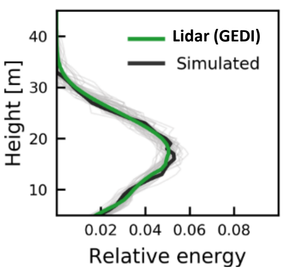
including forest height information from remote sensing (incl. disturbed forests)

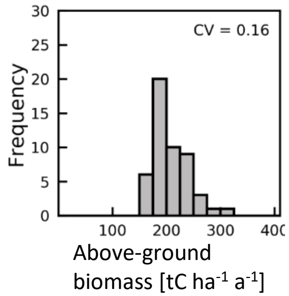
410 bill trees (simulation of every tree in the Amazon)

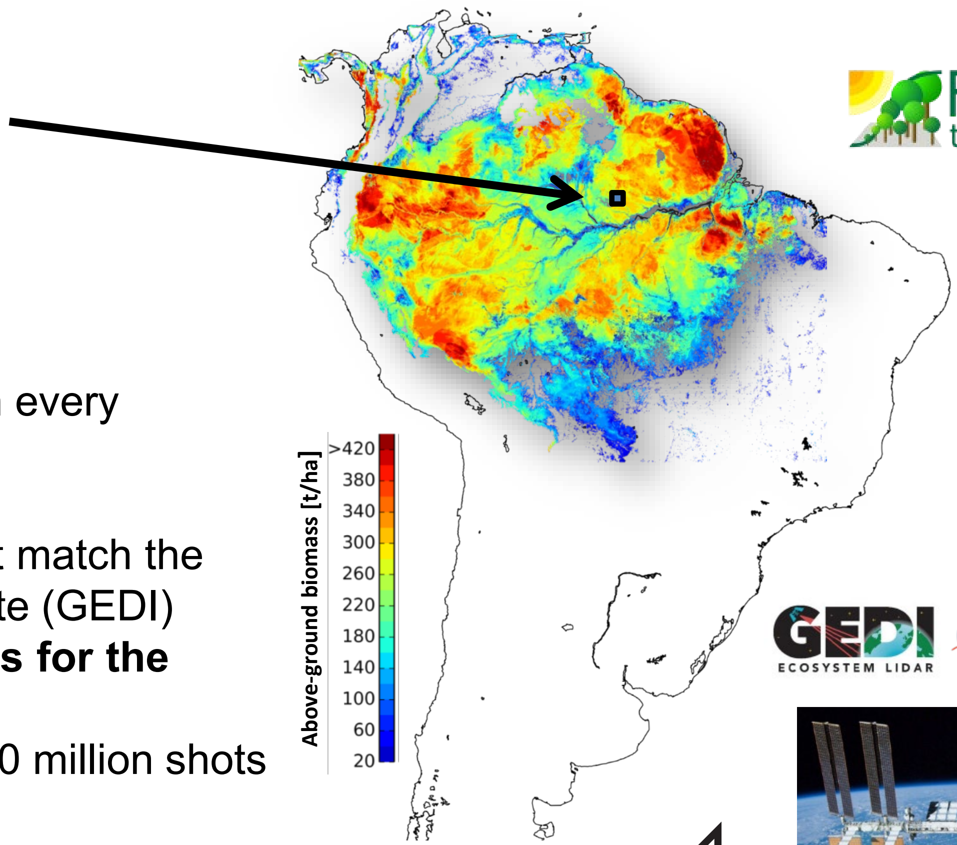
analysis can be done also for smaller scales (e.g. 1 ha, 20 m x 20 m)

Rödig et al. (2017), Global Ecol Biogeogr

Linking forest modelling and Lidar profiles (GEDI)





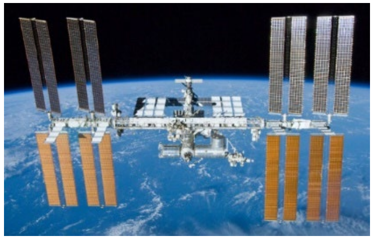


FORMIND
the forest model

approach:

- simulate forest succession in every location
- apply Lidar simulator
- we filter the forest states that match the measured profile from satellite (GEDI)
- from this we derive **estimates for the forest state**
- **here:** biomass map using 110 million shots GEDI Lidar for 2021

GEDI ECOSYSTEM LIDAR



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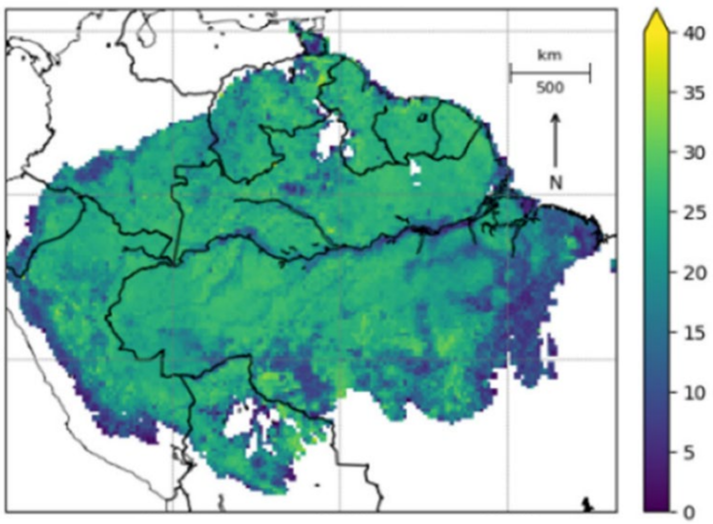
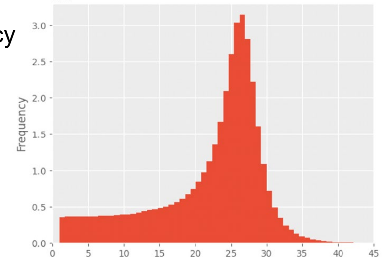
Bauer et al. 2021, Rem. Sensing, Roedig et al. 2019, Nat Comm, Knapp et al. 2017, Rem Sens Env

Forest productivity maps for the Amazon using Lidar profiles and forest modelling

Gross primary productivity (GPP)



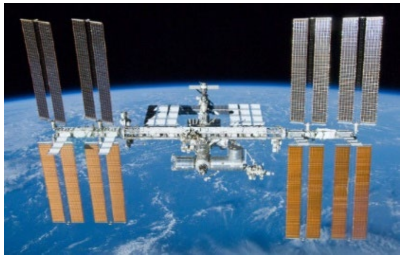
frequency



gross primary productivity [tC / (ha yr)]

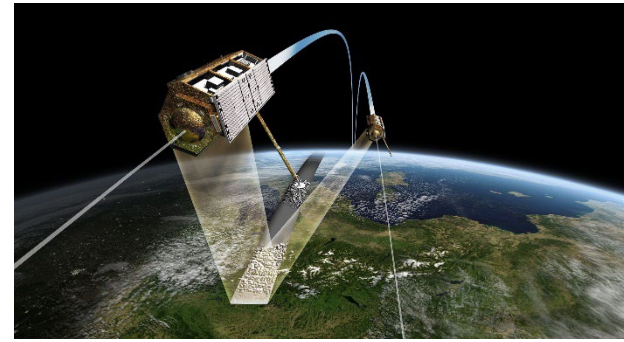
derived GPP distribution for the Amazon (2021)

- **unique features:** analysis can be done also for other forest attributes: stem number, basal area, productivity (GPP, NPP), carbon uptake (NEE), mortality...
- mean GPP for Amazon forests : 22 tC / (ha yr).
- according to this approach the Amazon is still a **carbon sink** (0.5 GtC /yr NEE).



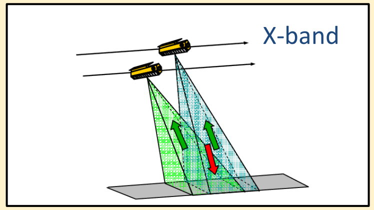
Bauer et al. 2024, Rem Sens, Hiltner et al. 2022, BGC
Bauer et al. 2021, Rem Sens, Roedig et al. 2019, Nat Com
Roedig et al. 2018, ERL

Radar simulator for forest models



Two
Synthetic Aperture Radar
Satellites

TerraSAR-X &
TanDEM-X



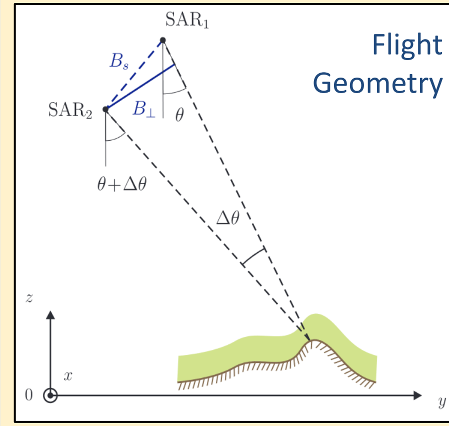
Bistatic observation interferometry

Coherence (Bistatic signal correlation)

$$\gamma = |\gamma| e^{j\varphi} = \frac{\langle s_1 s_2^* \rangle}{\sqrt{\langle s_1 s_1^* \rangle \langle s_2 s_2^* \rangle}}$$

Effective vertical wavenumber

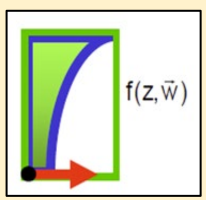
$$k_z = \frac{4\pi\Delta\theta}{\lambda \sin\theta}$$

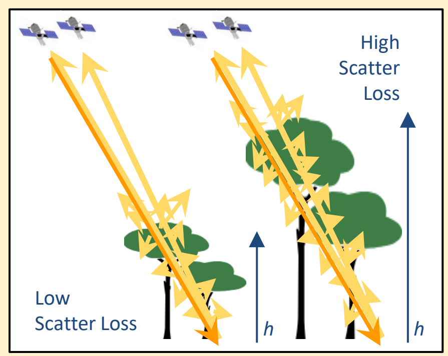


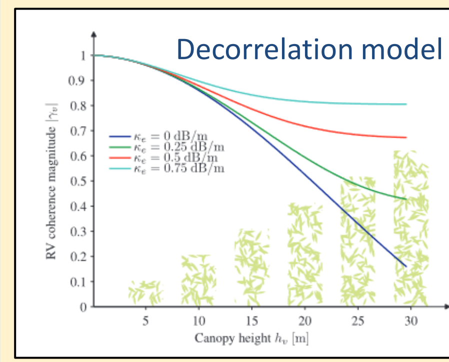
Vegetation Scatter Model

Random-Volume-over-Ground

$$\tilde{\gamma}_{Vol}(\vec{w}, \kappa_z) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z,\vec{w})\, e^{ik_z z} dz}{\int_0^{h_v} f(z,\vec{w})\, dz}$$





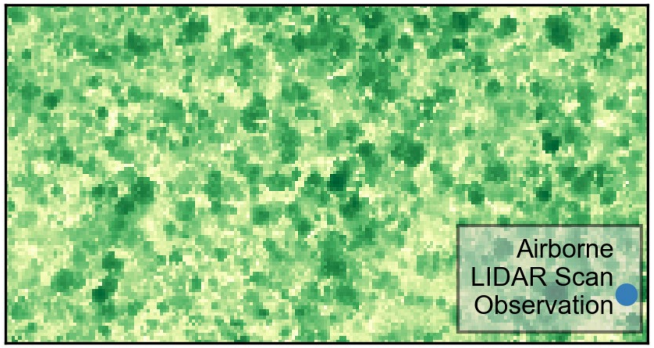


Lavalle (2010)

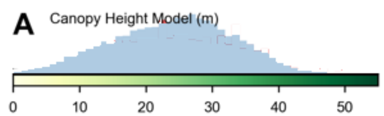
We developed a Radar simulator for our forest model.
First applications are done for Panama and French Guyana.

Analysing forest structure using interoferrometric Radar (here Tandem-X)

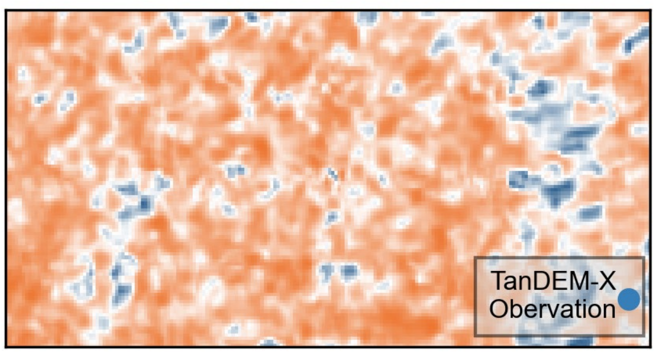
Forest height (from Lidar)

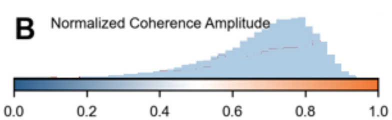


Case study:
Barro Colorado Island, Panama, tropical forest 50 ha (1000 m x 500 m), 20000 trees, 250 trees species



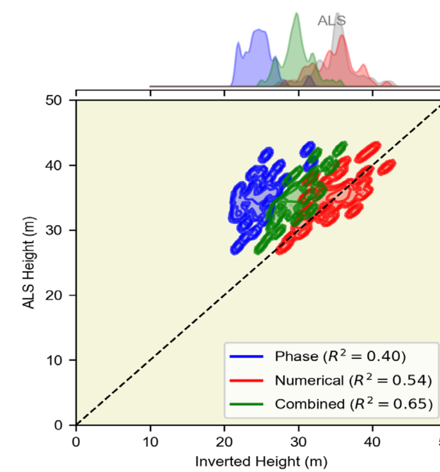
Coherence amplitude (from Radar)





Scale
1 ha

forest height from Lidar

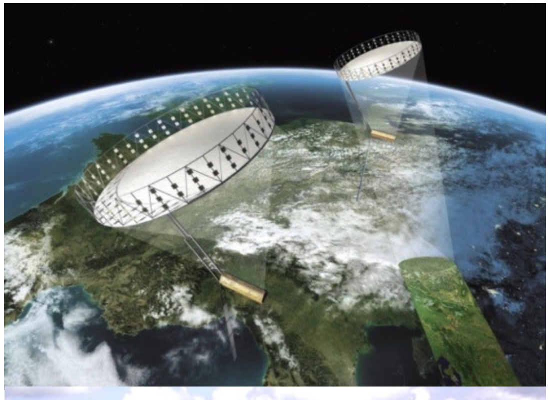


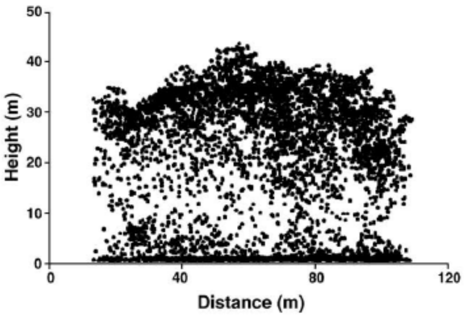
forest height from Radar

We develop new methods to for estimate forest height and forest structure with Radar combined forest modelling.

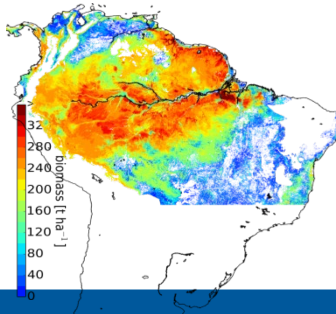
Summary

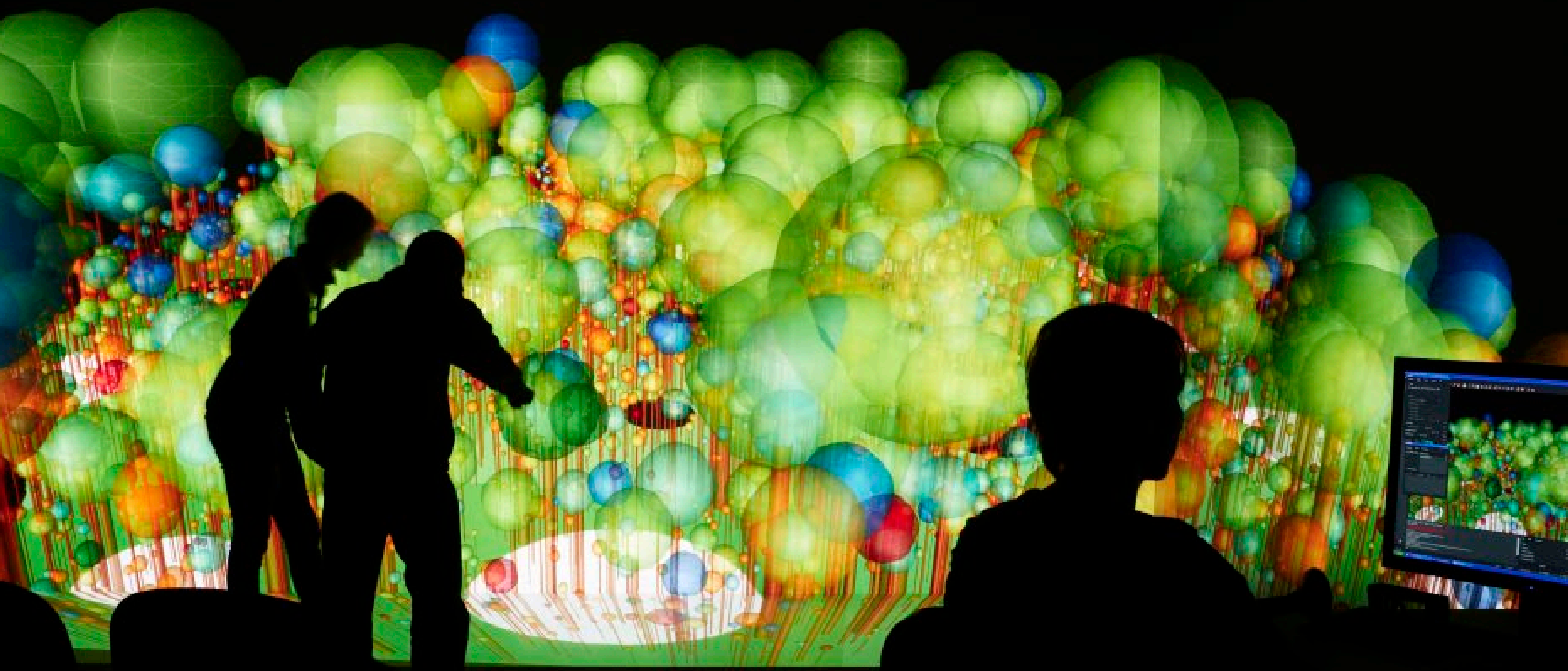
- We applied a forest gap model (FORMIND) to the Amazon (every tree in the Amazon is simulated, in total 410 bill. trees) www.formind.org
- We developed a novel framework to integrate remote sensing products into forest modelling
  - remote sensing data is used a filter (selection of states from forest succession simulations)
  - the filtered states can be used to derive important forest attributes (e.g. biomass, basal area, GPP, NEP, mortality) at high spatial resolution (e.g. 1 ha or 1 km^2)
- this has several advantages:
  (a) remote sensing of forest structure (e.g. Lidar) allows us to consider also disturbed forest states
  (b) validation experiments are possible without 'mixing' spatial scales
  (c) integration of different remote sensing products is possible: Lidar, Radar and opitical (e.g. Gedi, Tandem-X, Biomass)





www.FORMIND.org



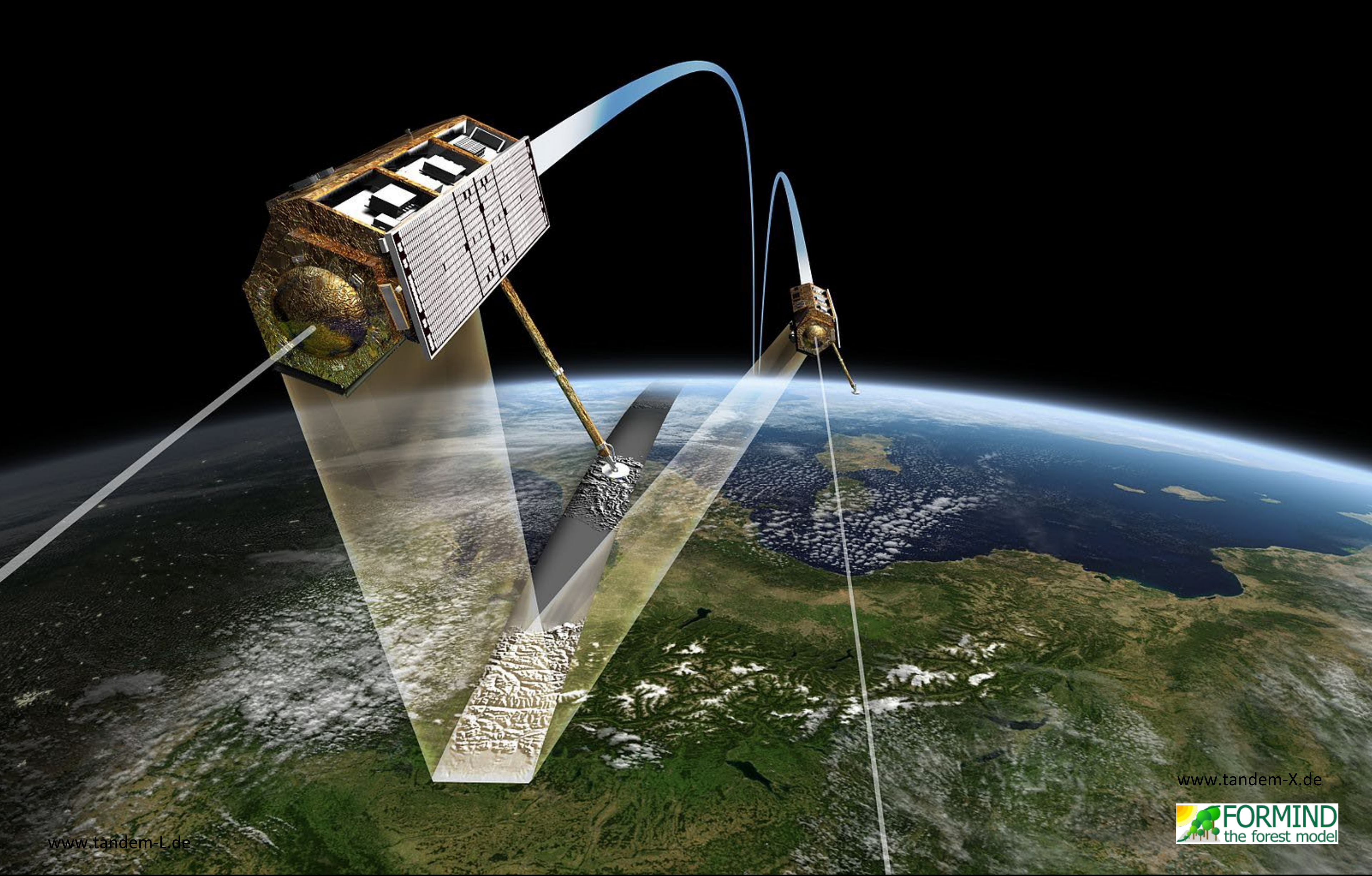


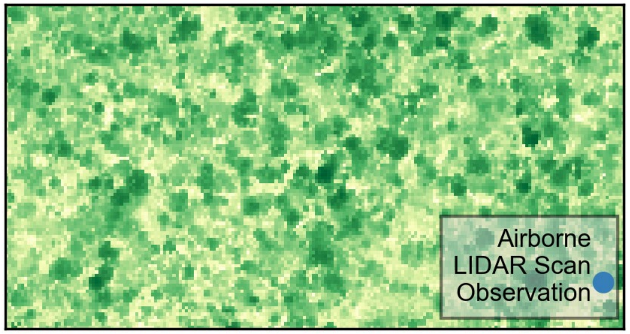
Many thanks!

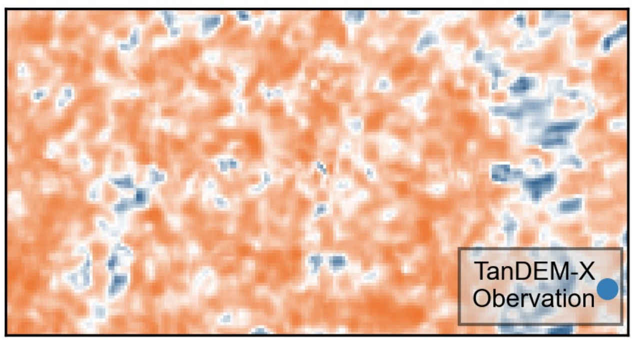
DLR

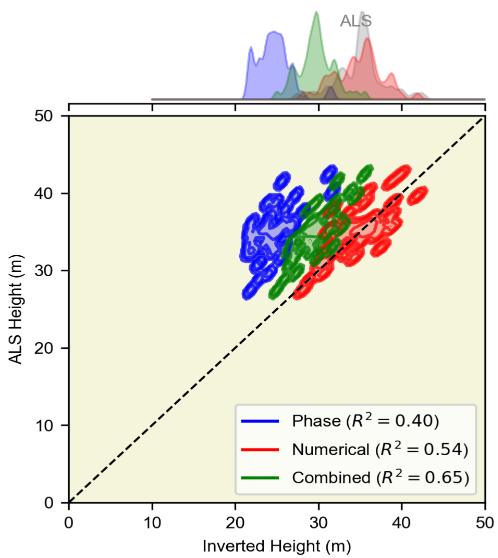
Tandem-X

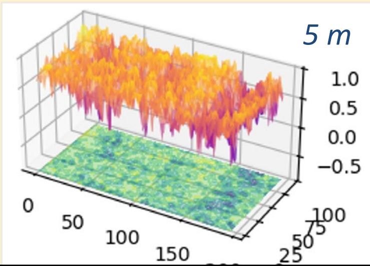
(Radar X- Band, interferometric measurements, vegetation structure)



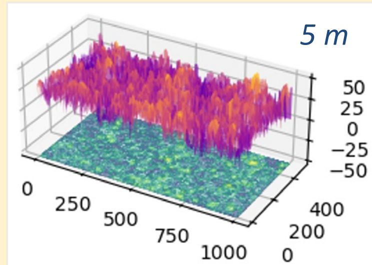

Airborne
LIDAR Scan
Observation


TanDEM-X
Obervation

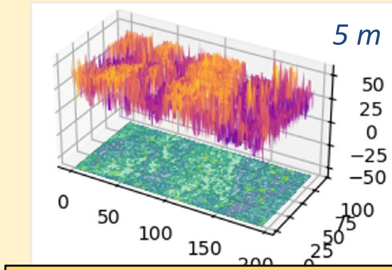

ALS
ALS Height (m)
Inverted Height (m)
Phase ($R^2 = 0.40$)
Numerical ($R^2 = 0.54$)
Combined ($R^2 = 0.65$)
0
10
20
30
40
50



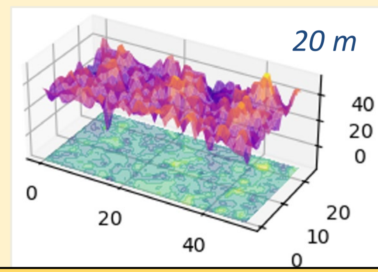
Coherence amplitude



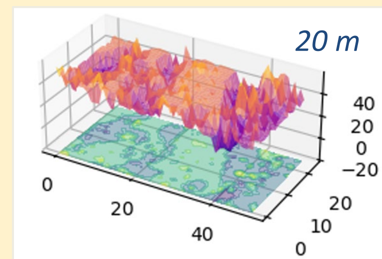
ALS canopy height



Inverted canopy height



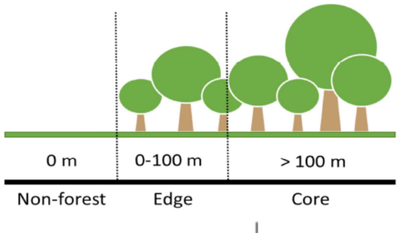
ALS canopy height

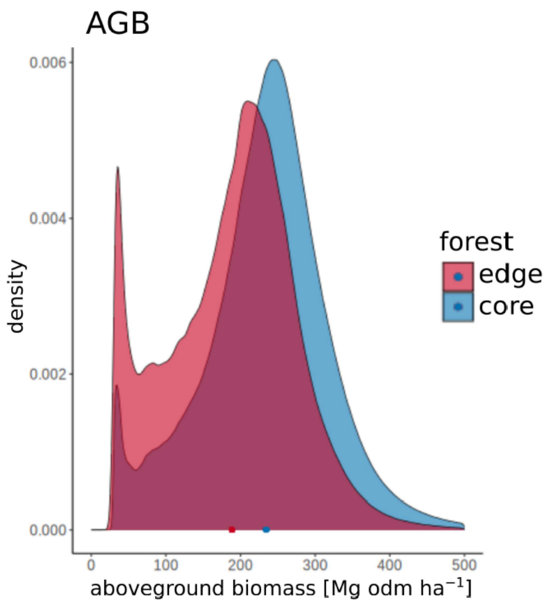


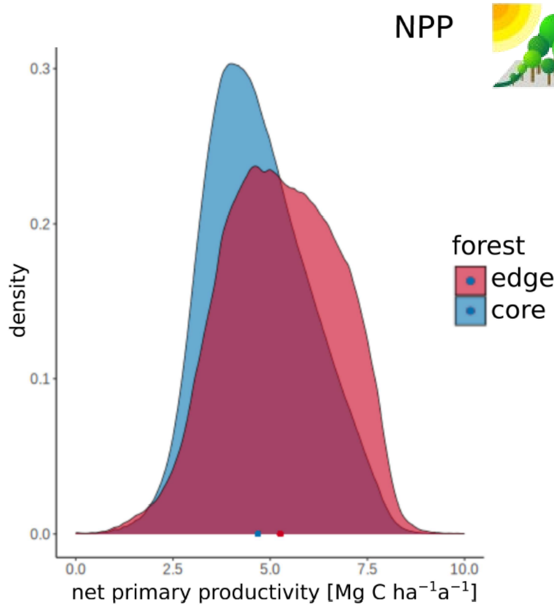
Inverted canopy height

Linking forest modelling and remote sensing: forest fragmentation in the Amazon

(GEDI, 110 million profiles, Tandem-X forest/ non-forest map, forest model FORMIND, Amazon version)







In forest edges forest biomass is often lower (due to change in forest structure), forest productivity NPP is often higher.

Fischer, L et al. (2024), Remote Sensing
Roedig et al. (2019), Nat Com