SAR remote sensing for land applications, with a focus on climate change and the global carbon budget

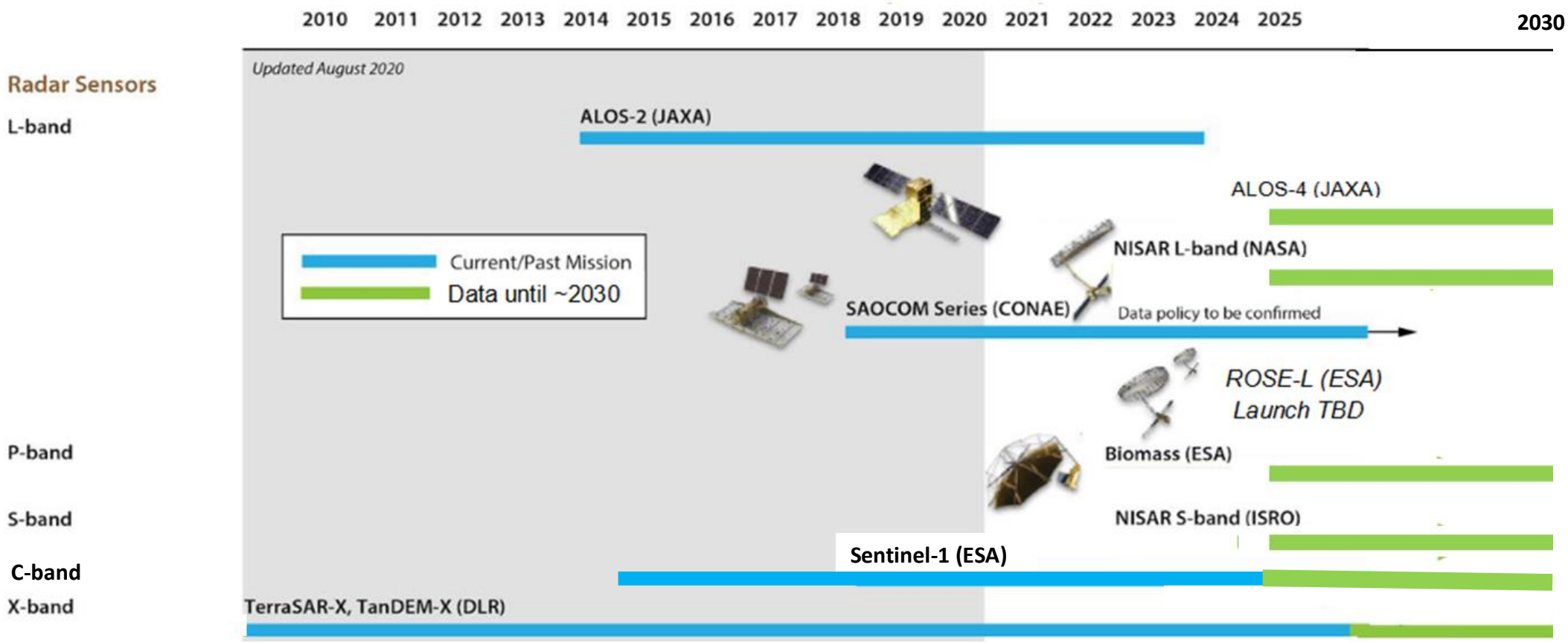
Thuy Le Toan
CESBIO/GlobEO, Toulouse, France

ESA BIOMASS Mission Advisory Group

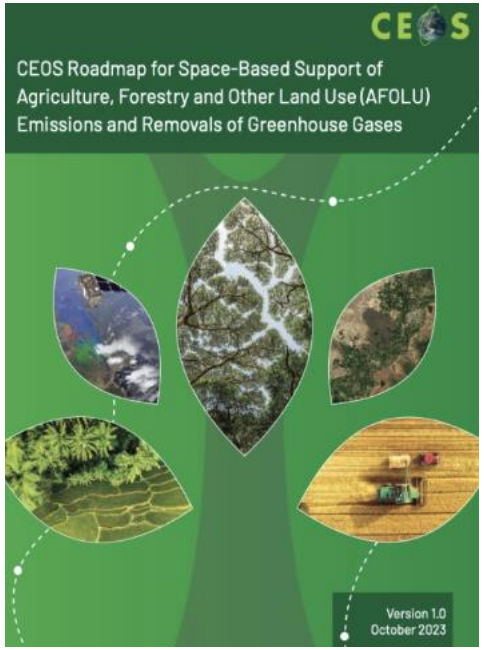
Vice-lead of Asia-RiCE

Third International SAR Workshop, Saga, Japan, 6 November 2024

Present and near future SAR satellites provide more and more multi frequency, multi polarization, multi temporal data to support applications



SAR for land surfaces monitoring



Among the components of the Earth system (atmosphere, ocean, land), SAR can provide information of land surfaces ranging from a detailed local focus to a global view, from near real-time information to long-term archives, available to quantify changes and understand the causes of these changes, at the scale where the changes are occurring. The ultimate goal is to take adaptation and mitigation measures to reduce adverse effects.

Questions to be addressed in the presentation:

How to use the best of (multifrequency, polarimetric) SAR data to provide information to support actions to reduce GHG emissions?

(the actions are in line with the CEOS Roadmap for Agriculture, Forestry and Other Land Use)

Two specific themes will be addressed:

1. *Where and to what extent are forests sources and/or sinks of carbon,*
2. *How and where to carry out mitigation actions to reduce methane emissions from rice fields:?*

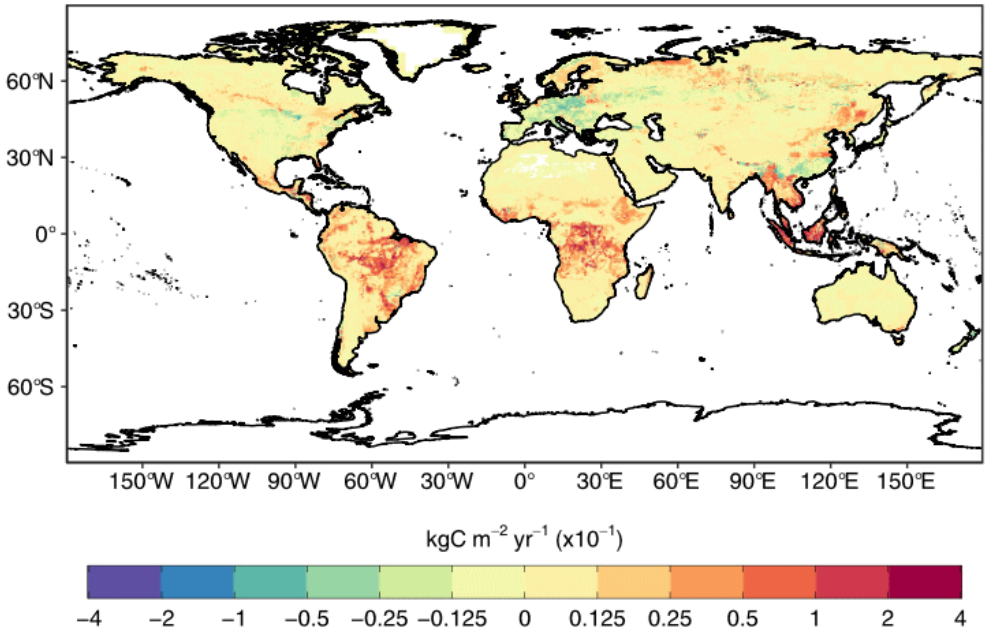
The carbon sources from deforestation

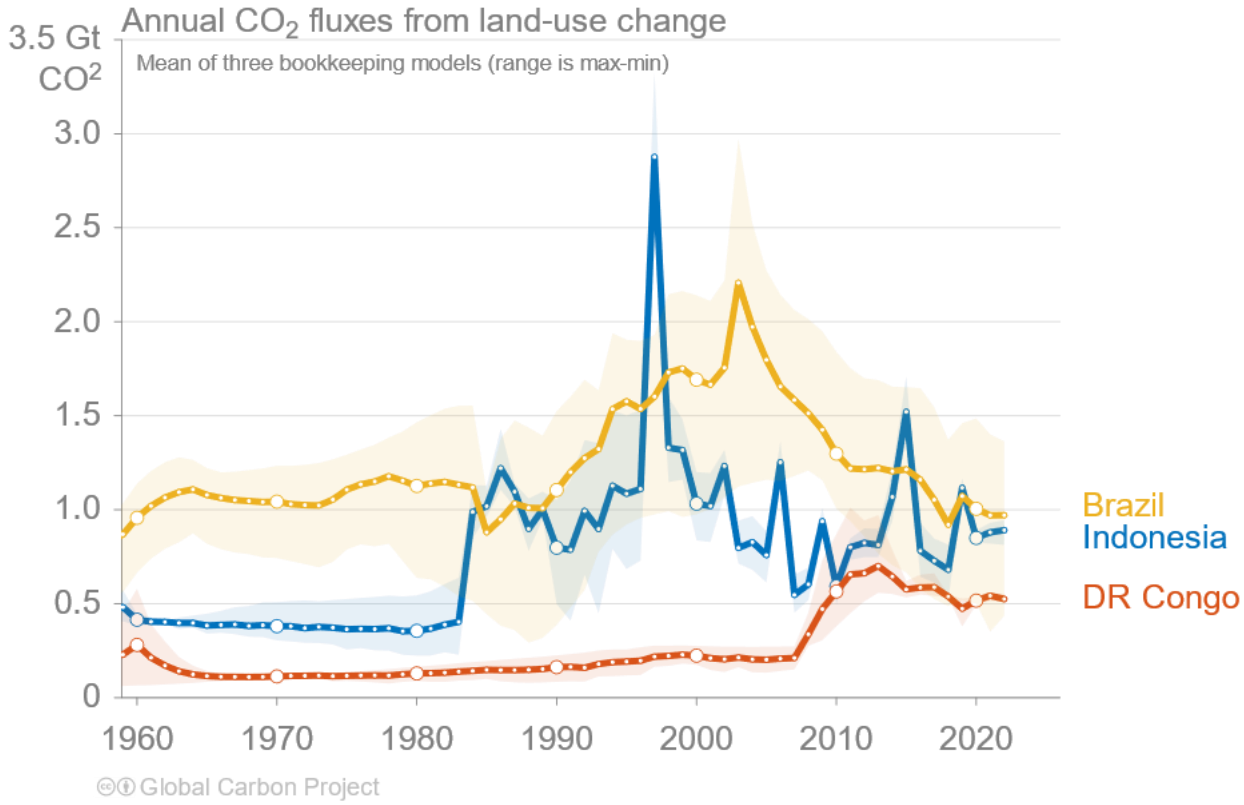
Regional patterns of land-use change emissions

Land-use emissions are high in the tropics, driven largely by deforestation.

The top three emitters over 2013–2022 – Brazil, Indonesia, and the Democratic Republic of the Congo – contribute 55% of the global net land-use emissions.

Land-use emissions, decadal average 2013–2022





The peak in Indonesia in 1997 was the Indonesian peat fires.

Estimates from three bookkeeping models

Source: Friedlingstein et al 2023; Global Carbon Project 2023

C loss from deforestation and forest degradation is uncertain





Deforestation

Forest Degradation

$$\Delta C = \sum \Delta A.B.E + \sum A.\Delta B.E$$

ΔA = deforested area

B = biomass before deforestation

E is an efficiency factor

The key variables are **Above Ground Biomass**, and **Change in forest area**

What information do we need ?

1. **Estimates of forest biomass (AGB) and disturbances, for:**
   . Improved knowledge of terrestrial carbon pools
   . Improved estimates of carbon emissions from land use change and forest degradation
   . Improved estimates of land carbon uptake from forest growth
   . Improved vegetation modelling and long-term climate predictions through data assimilation,
2. The crucial information need is in the tropics,
3. Measurement are needed where the changes occurs at the scale of change (hectare scale) for mitigation actions,
4. Wall to wall mapping with repeated measurements over multiple years to quantify changes in carbon stocks from deforestation and regrowth.

SAR instruments have advantages over other systems:

- *Optical not directly linked to AGB,*
- *Passive microwaves providing global view, but at low resolution,*
- *Lidar not wall to wall accquisitions*

What SAR frequency to be used for forest biomass ?



Austrian pine

X band
λ= 3 cm

C band
λ= 5 cm

L band
λ= 27 cm

P band
λ= 70 cm

VHF
λ > 3 m

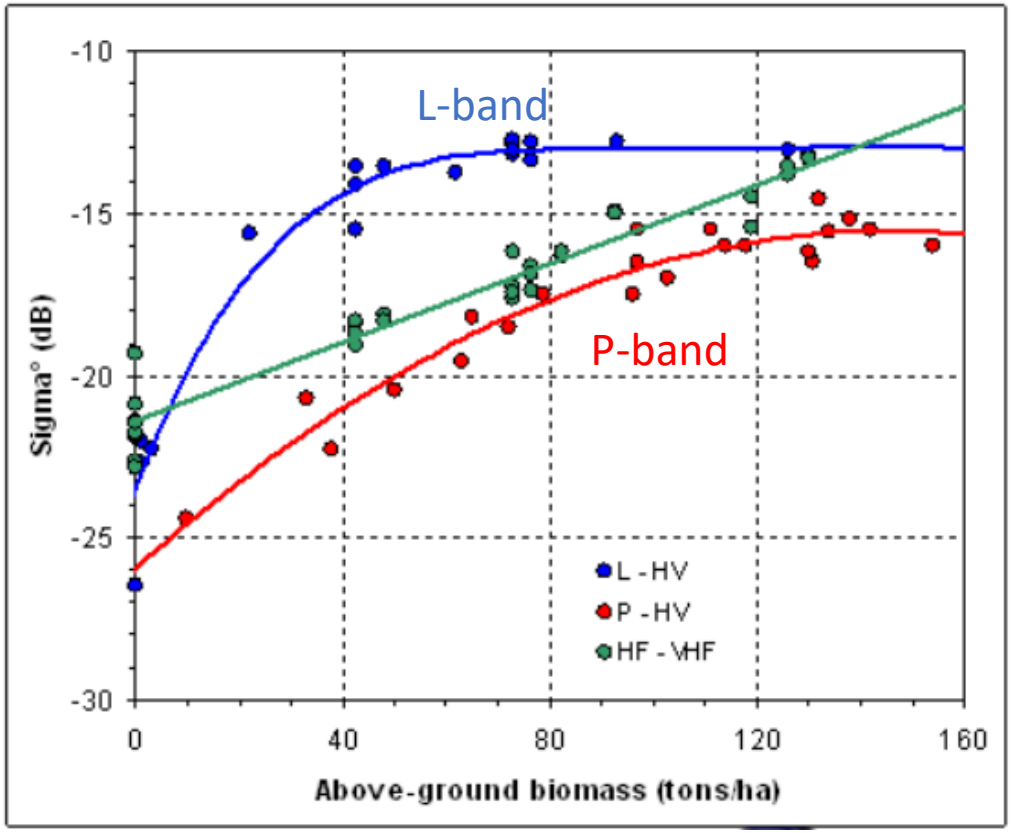
The type and amount of scatterers involved can explain that the radar backscatter at shorter wavelength ‘saturates ‘ at lower AGB

→ Long λ for forest biomass

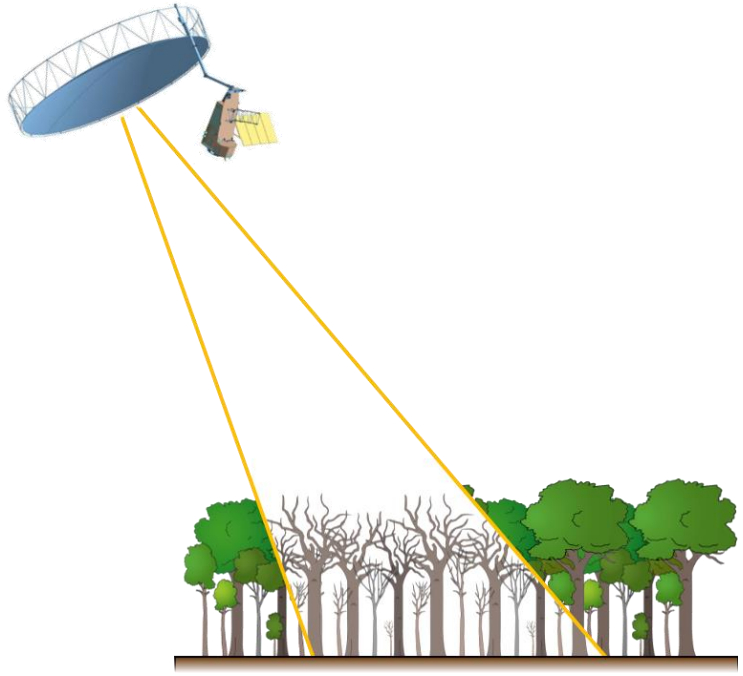
Early multi-frequency SAR experiments advocated the use of long wavelength SAR for Above Ground Biomass estimates

Landes forest, France

L-band SAR: RAMSES
P-band SAR: AirSAR
VHF SAR: Carabas



The BIOMASS mission was proposed to ESA in 2005

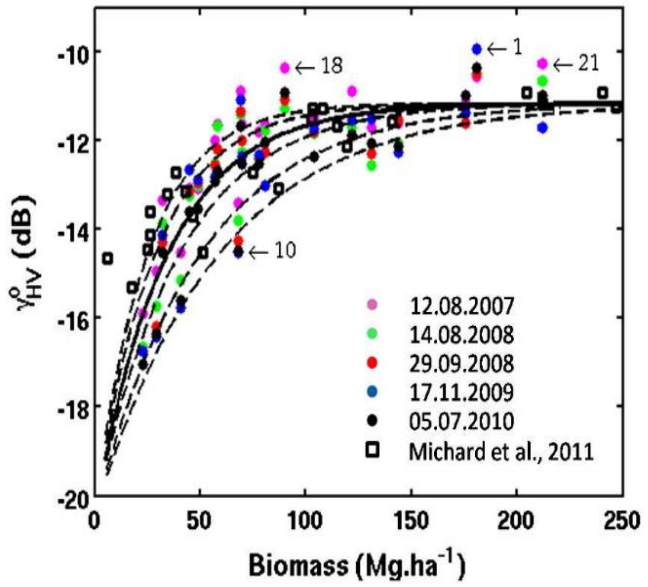


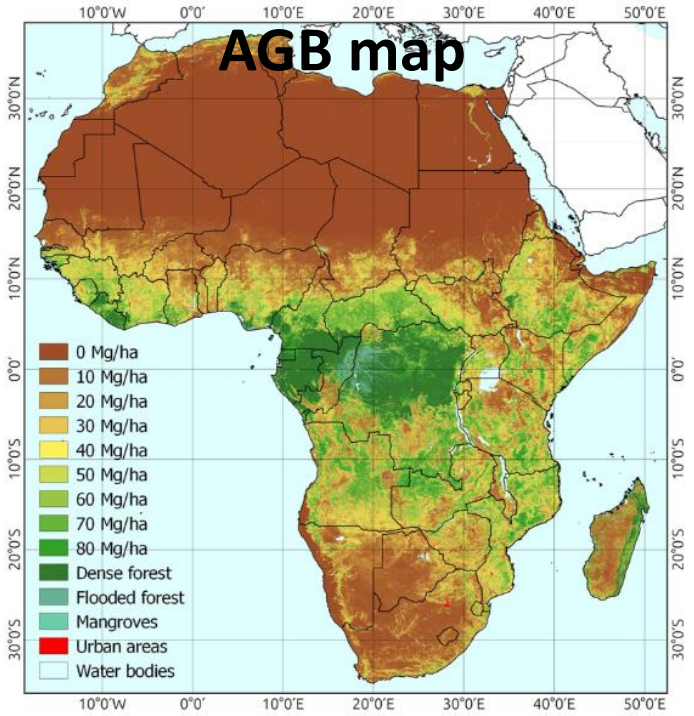
Le Toan, T., Quegan, S., Woodward, I., Lomas, M., Delbart, N., & Picard, G. (2004). Relating radar remote sensing of biomass to modelling of forest carbon budgets. *Climatic change*, *67*(2), 379-402.

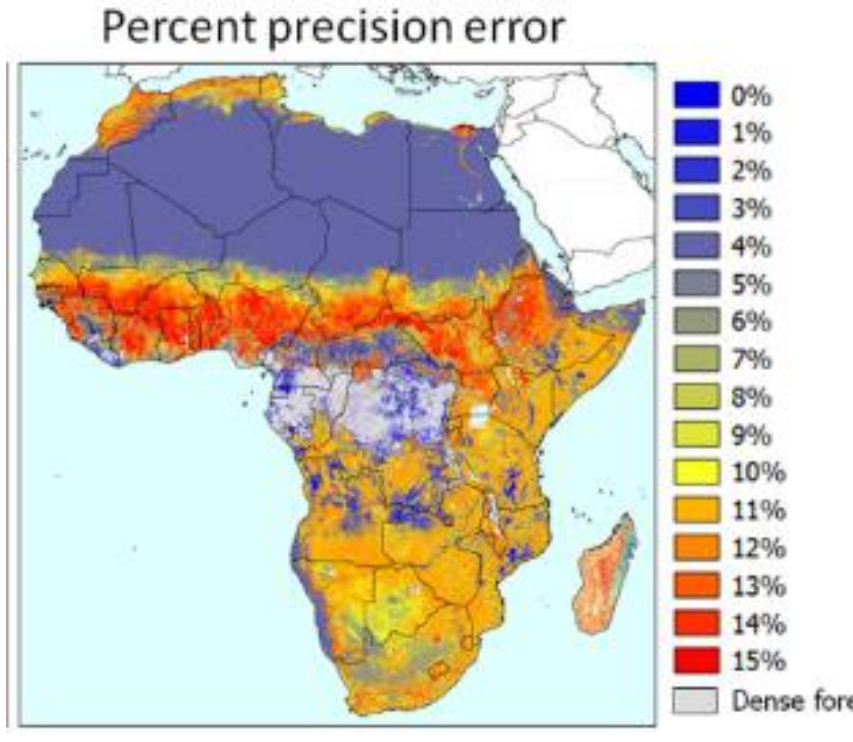
Up to now, the lowest frequency SAR data are at L-band (JERS-1, ALOS-PALSAR, SAOCOM)

- Extensive experience of the community in the use of L-band SAR for AGB
- Good sensitivity in the range of AGB < 100 t/ha → AGB map with small errors in this range (Focus of NISAR)

Example: Limited to AGB < 80 Mg/ha of savannah and woodland in Africa

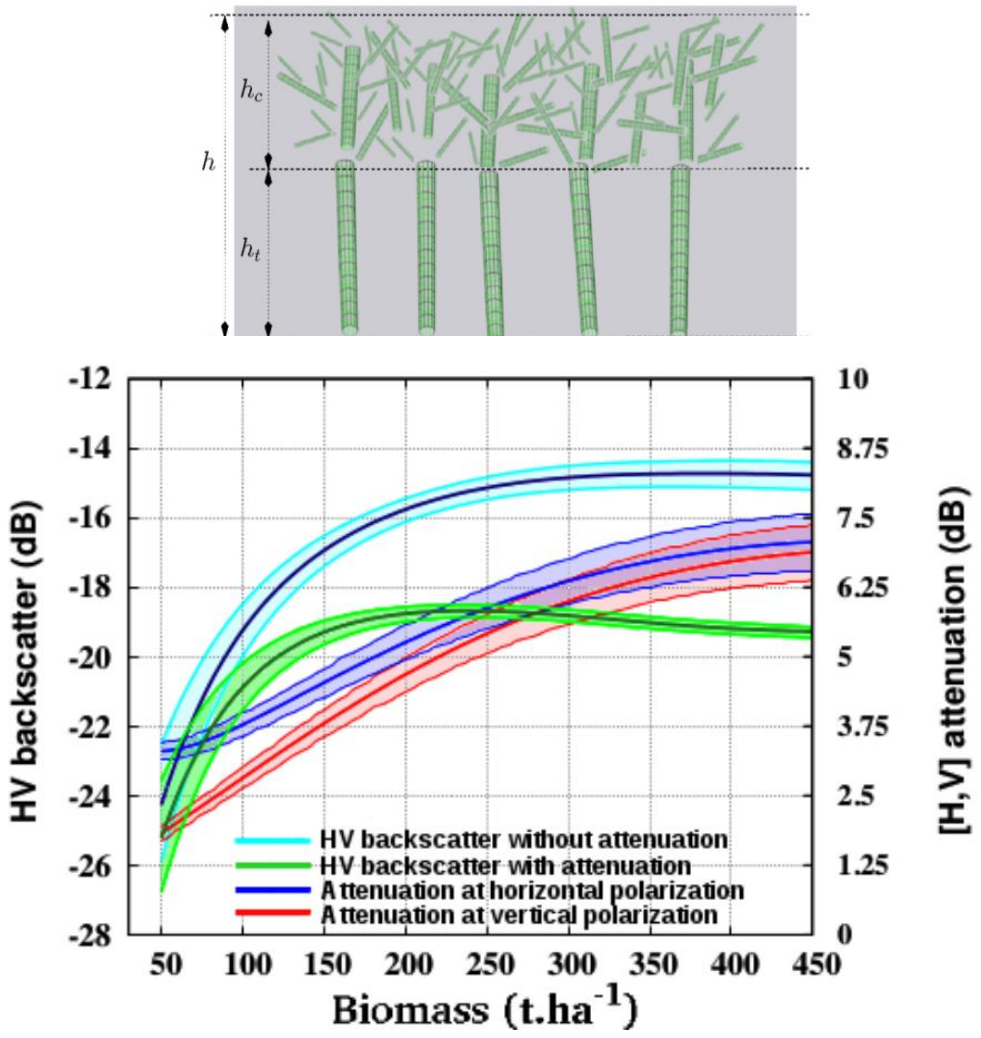


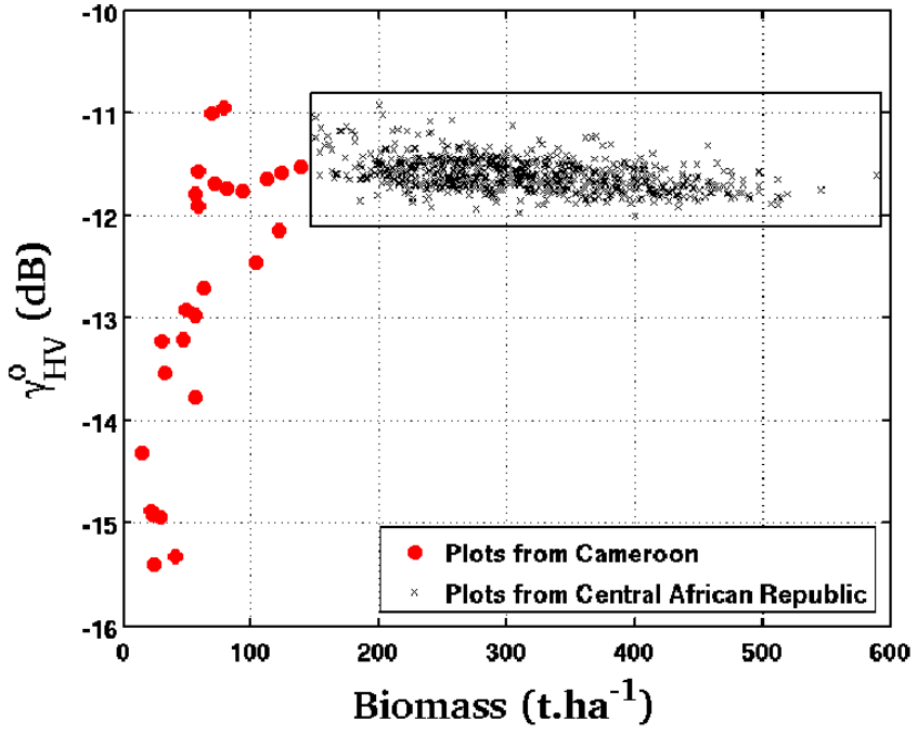




- *Bouvet, A., Mermoz, S., Le Toan, T., Villard, L., Mathieu, R., Naidoo, L., & Asner, G. P. (2018). An above-ground biomass map of African savannahs and woodlands at 25 m resolution derived from ALOS PALSAR. Remote sensing of environment, 206, 156-173.*

However, a (slight) sensitivity of L-band backscater to AGB is observed for AGB > 200 t/ha, interpreted using physical model as resulting from attenuation by the dense canopy





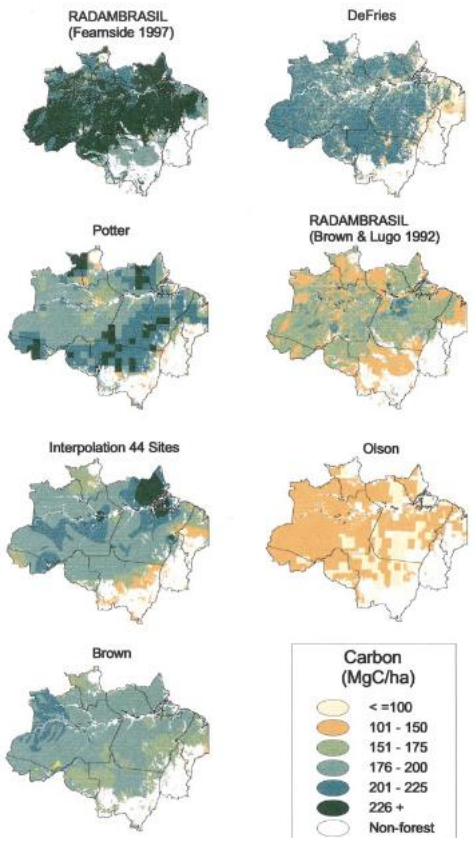
Mermoz, S., Réjou-Méchain, M., Villard, L., Le Toan, T., Rossi, V., & Gourlet-Fleury, S. (2015). Decrease of L-band SAR backscatter with biomass of dense forests. *Remote Sensing of Environment*, *159*, 307-317.

This can explain that, despite saturation, L-band data have been used to map the whole range of biomass in global AGB products

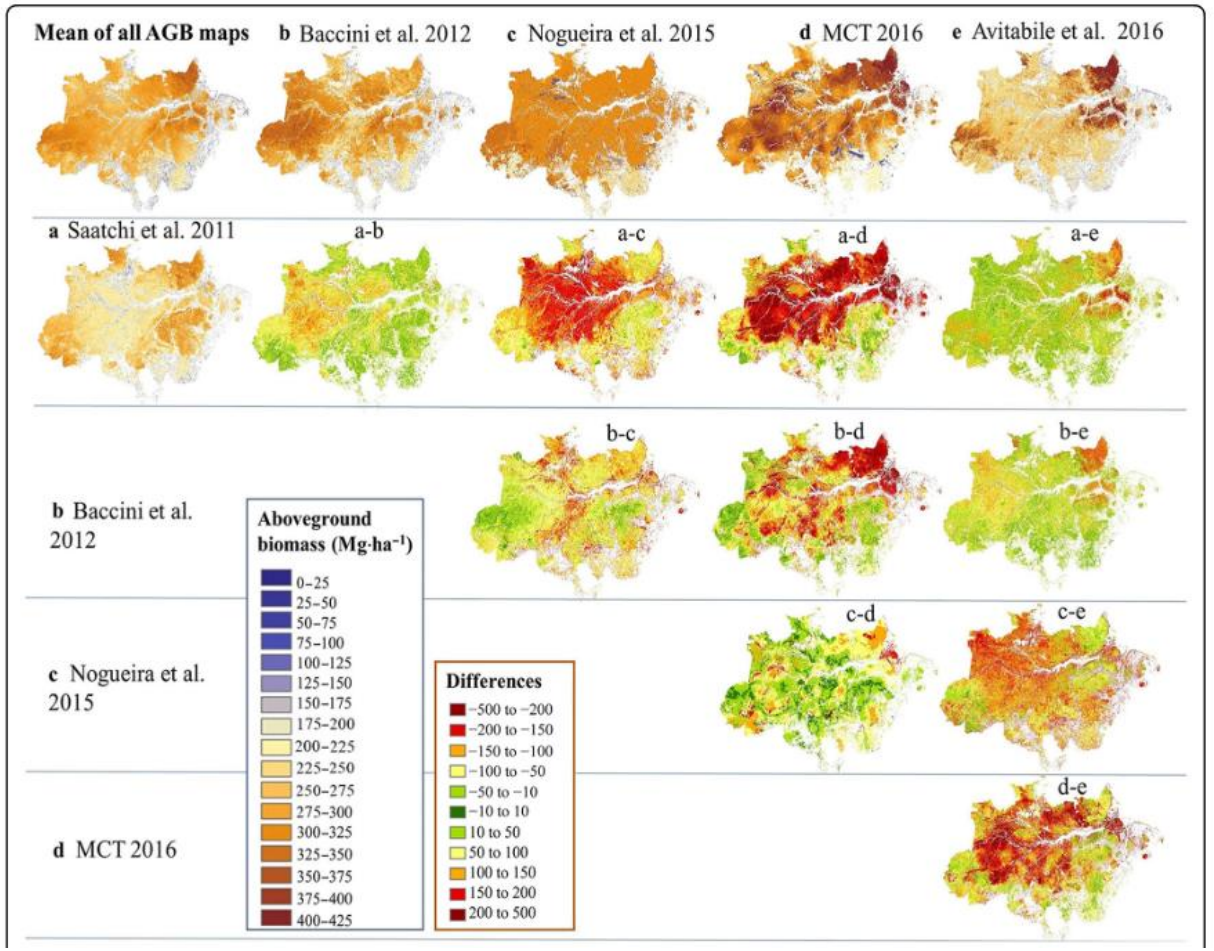
In high-biomass tropical forests, global biomass products show large errors

Discrepancies in AGB maps in Brazilian Amazon

observed 20 years ago by Houghton et al., and at present despite much data with L-band, C-band SAR (+ Lidar, and optical).



Houghton, R. A., Lawrence, K. T., Hackler, J. L., & Brown, S. (2001). The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. *Global Change Biology*, *7*(7), 731-746.

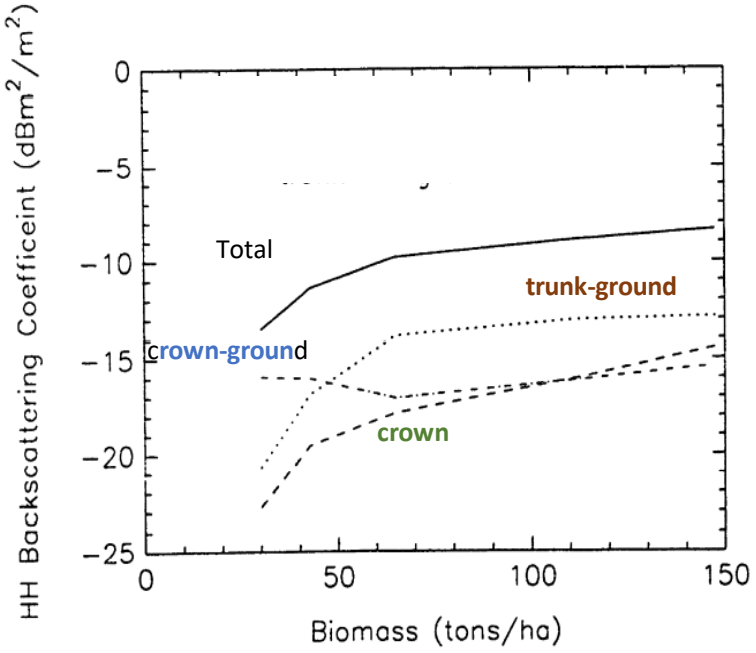


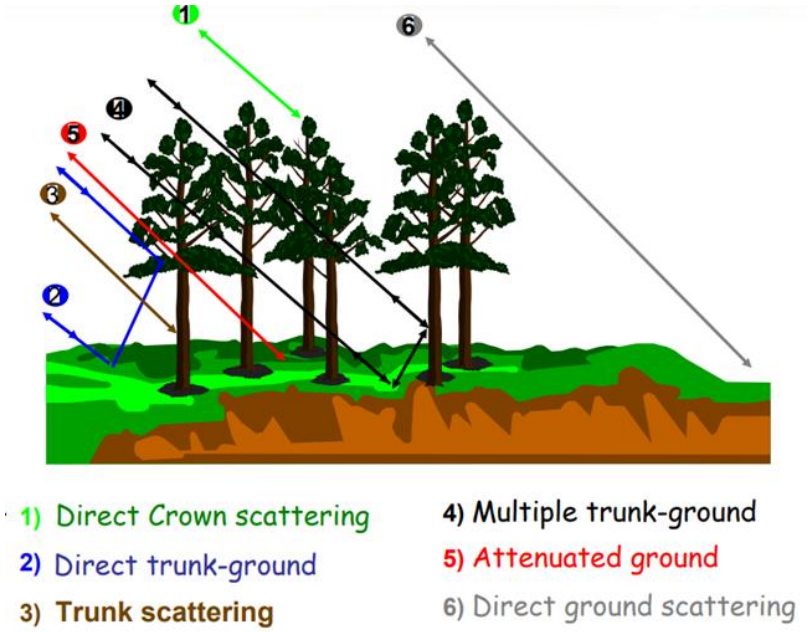
Tejada, G., Görgens, E. B., Ovando, A., & Ometto, J. P. (2020). Mapping data gaps to estimate biomass across Brazilian Amazon forests. *Forest Ecosystems*, *7*, 1-15.

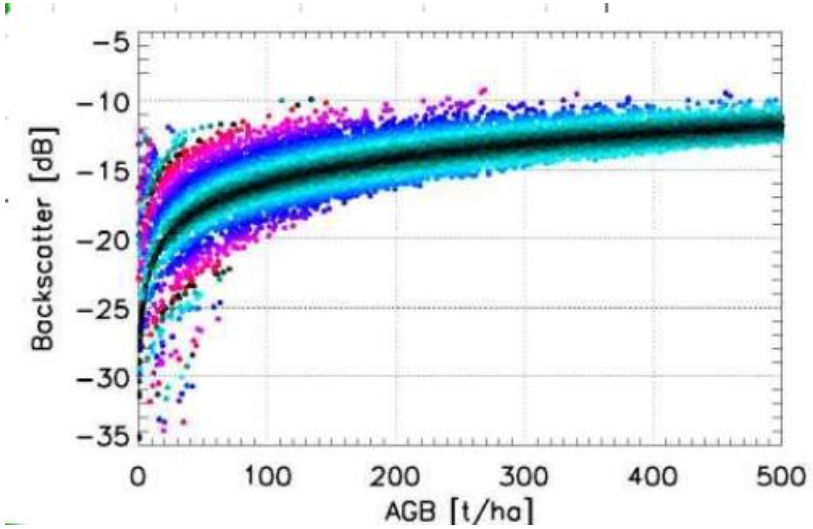
At P-band, no saturation observed, but the ground contribution reduces the sensitivity of the backscatter to AGB

Scattering mechanisms simulated by a R.T. model

- Le Toan, T., Beaudoin, A., Riom, J., & Guyon, D. (1992). Relating forest biomass to SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, *30*(2), 403-411.
- Hsu, C. C., Han, H. C., Shin, R. T., Kong, J. A., Beaudoin, A., & Le Toan, T. (1994). Radiative transfer theory for polarimetric remote sensing of pine forest at P band. *International Journal of Remote Sensing*, *15*(14), 2943-2954.







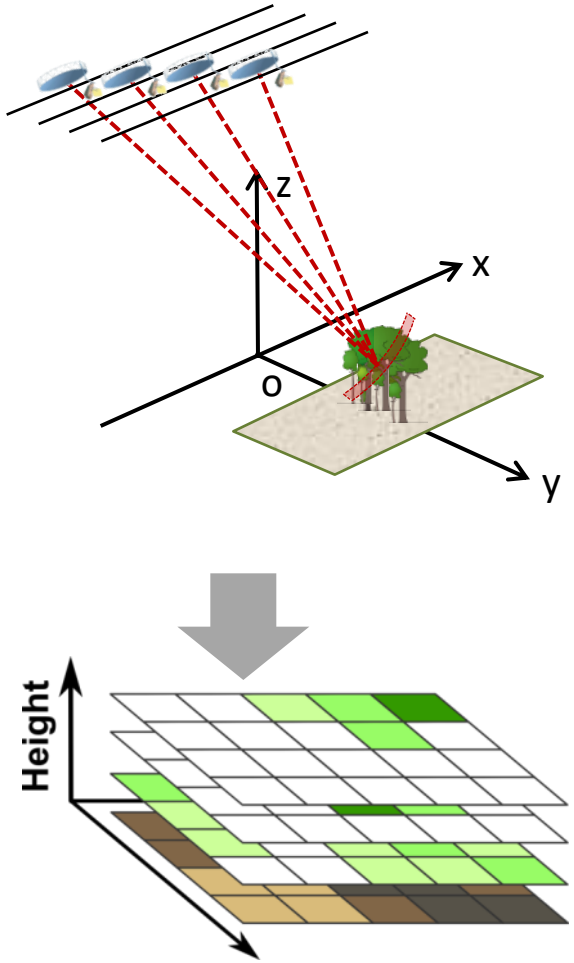
Simulation of temporal variation of vegetation water content, soil moisture, topography…

→ Sensitivity to AGB increased if ground contribution is rejected. For BIOMASS, 2 solutions:

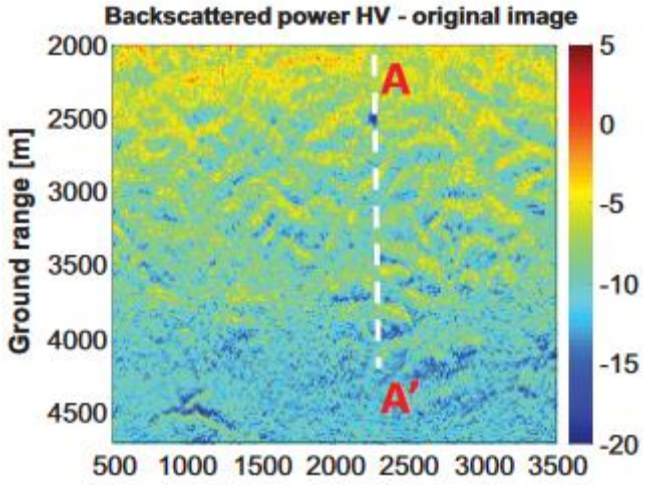
- SAR tomograpghy
- Interferometric ground cancelling

Innovative SAR tomography techniques allow to map 3D structure of tropical forest

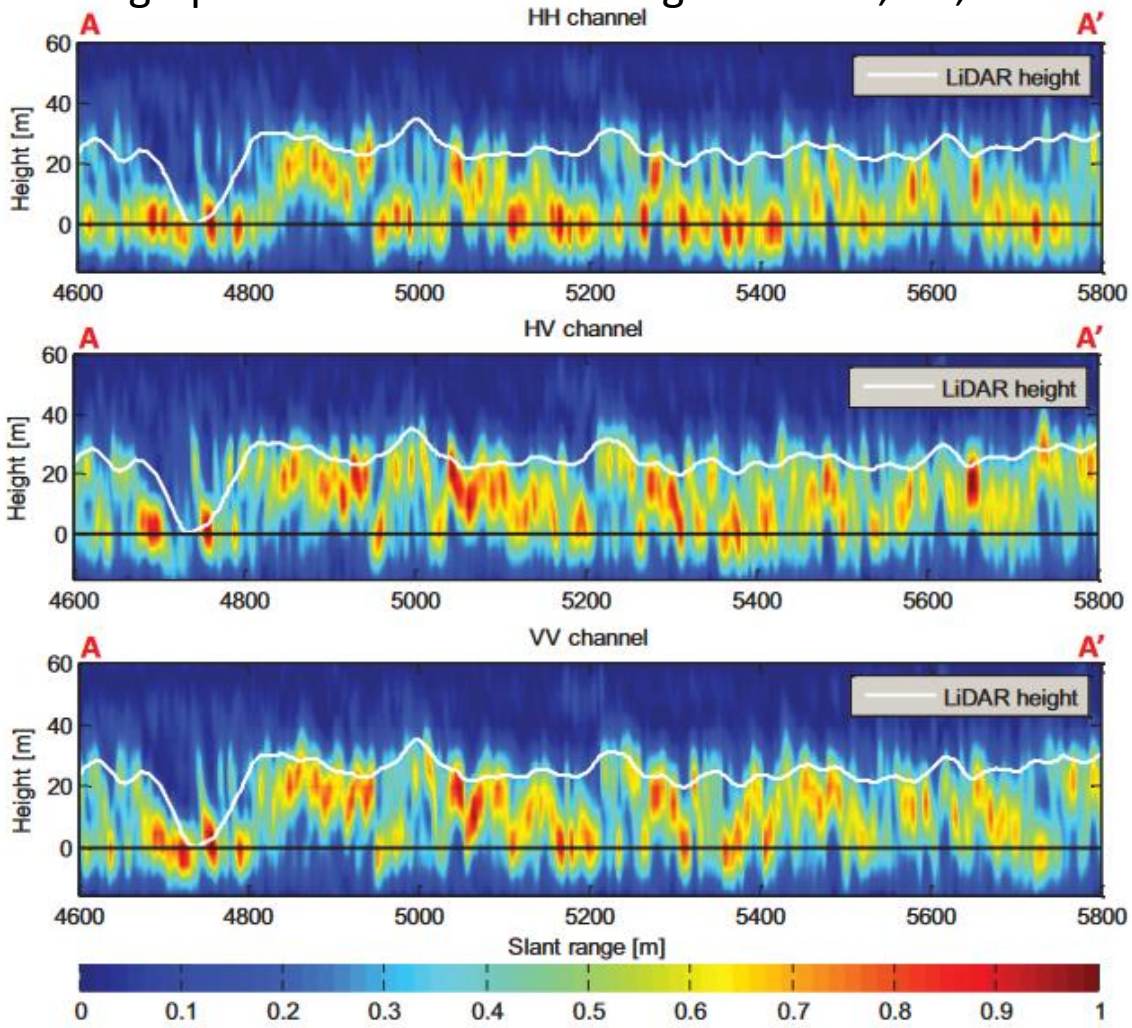
TomoSAR



HV P-band image
French Guiana



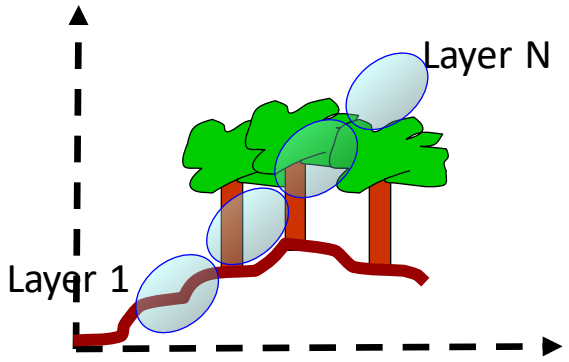
Tomographic reconstruction along AA' in HH, HV, and VV.

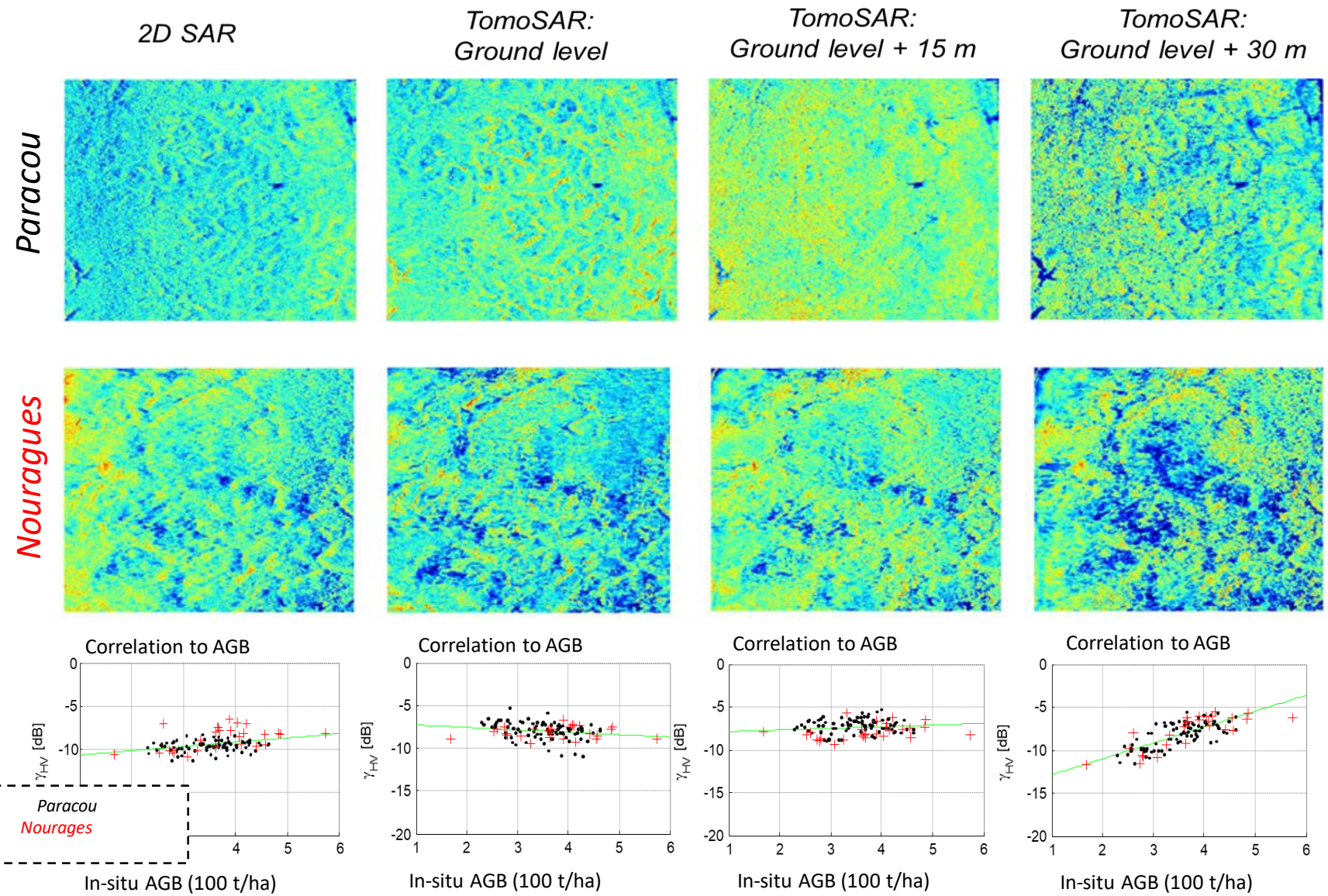


Tomography will be used to isolate the canopy layer (for AGB), and the ground layer (for DEM) in the Biomass mission

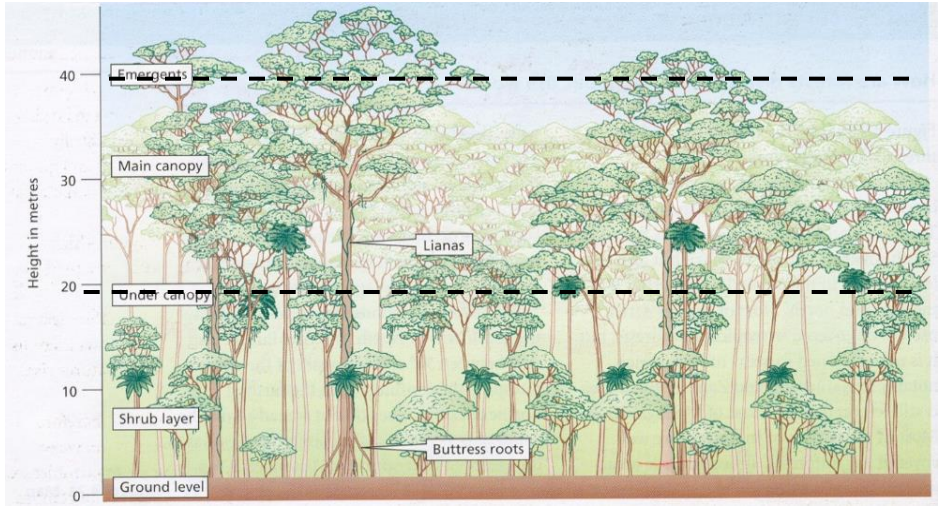
Minh, D. H. T., Le Toan, T., Rocca, F., Tebaldini, S., d'Alessandro, M. M., & Villard, L. (2013). Relating P-band synthetic aperture radar tomography to tropical forest biomass. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(2), 967-979.

Minh, D. H. T., Le Toan, T., Rocca, F., Tebaldini, S., Villard, L., Réjou-Méchain, M., ... & Chave, J. (2016). SAR tomography for the retrieval of forest biomass and height: Cross-validation at two tropical forest sites in French Guiana. *Remote sensing of environment*, *175*, 138-147.



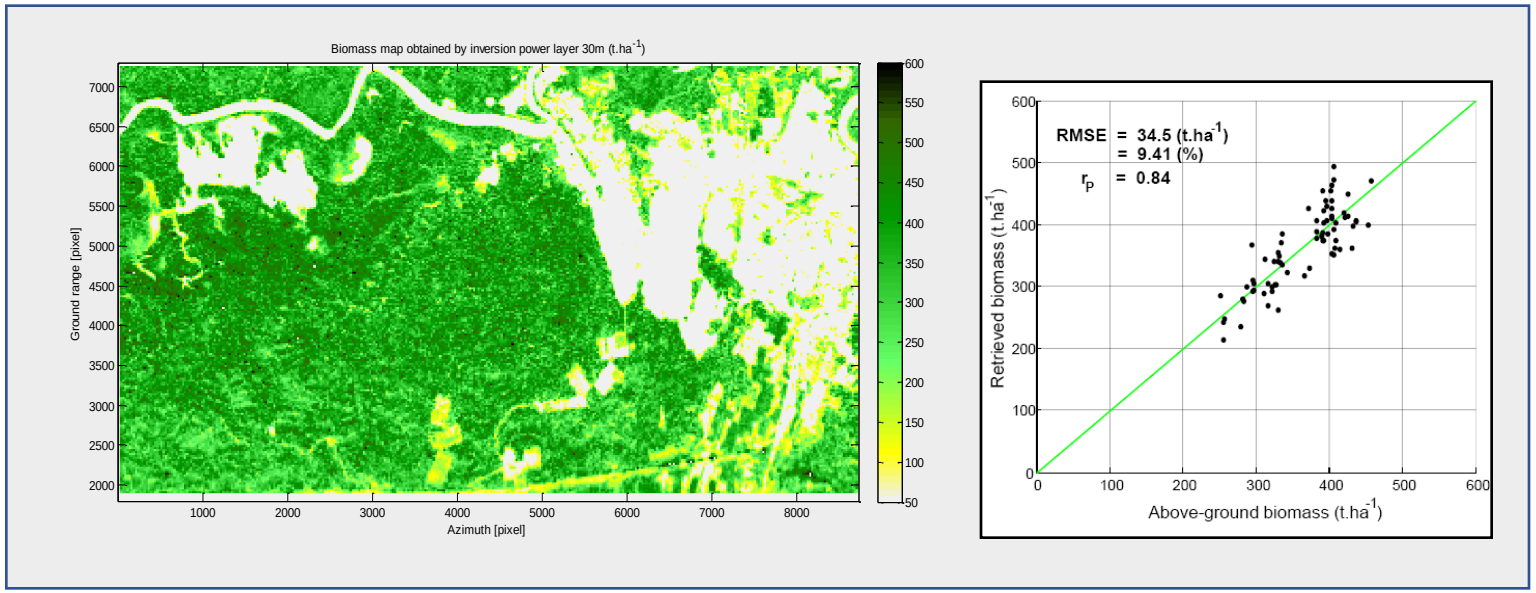


Why the 30-40 m layer ?



This canopy layer contains most of the major tree crowns
The biomass of this layer is proportional to AGB.

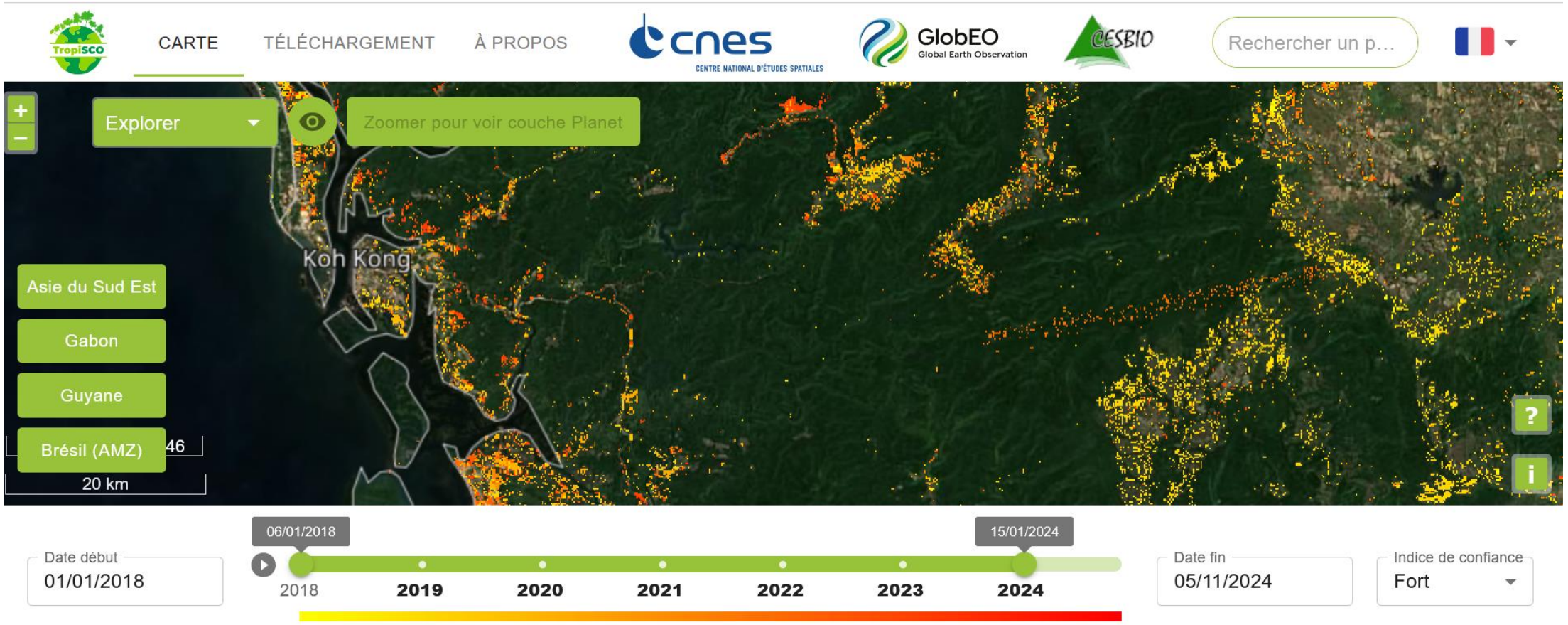
Biomass map of Paracou tropical forest in French Guiana



By isolating the canopy contribution, TomoSAR increases the sensitivity of the backscatter to biomass, leading to mapping of AGB (up to 500 t/ha)

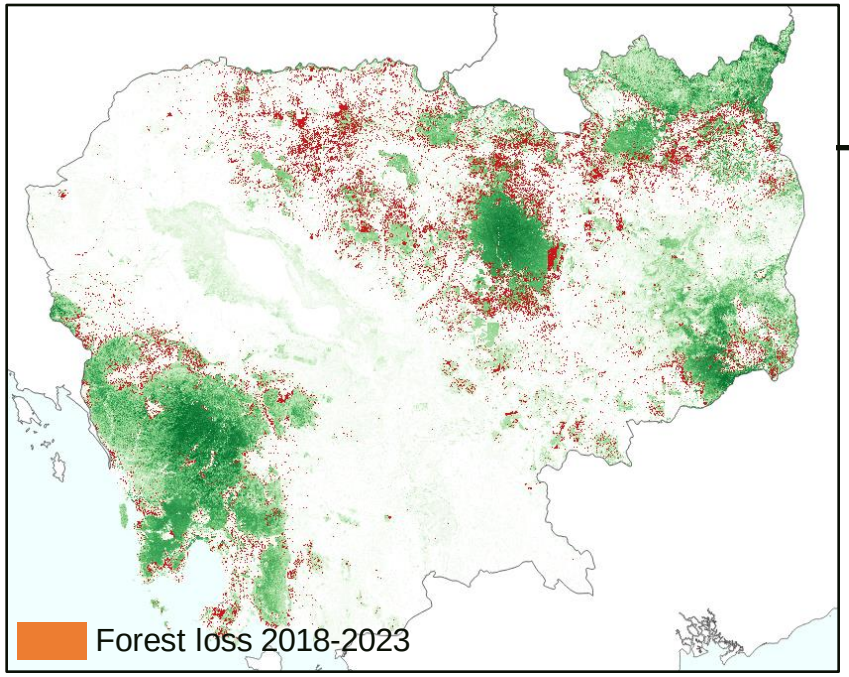
For carbon loss due to deforestation, AGB change from BIOMASS can be refined and timely assessed by combining it with forest cover change from SAR data with dense time series

Ex: TropiSCO developed by GlobEO and CESBIO to provide maps of forest cover loss using Sentinel-1 data every 6 or 12 days. https://www.tropisco.org/



Carbon loss estimation by combining deforested area (e.g. using Sentinel-1), with AGB values expected from BIOMASS

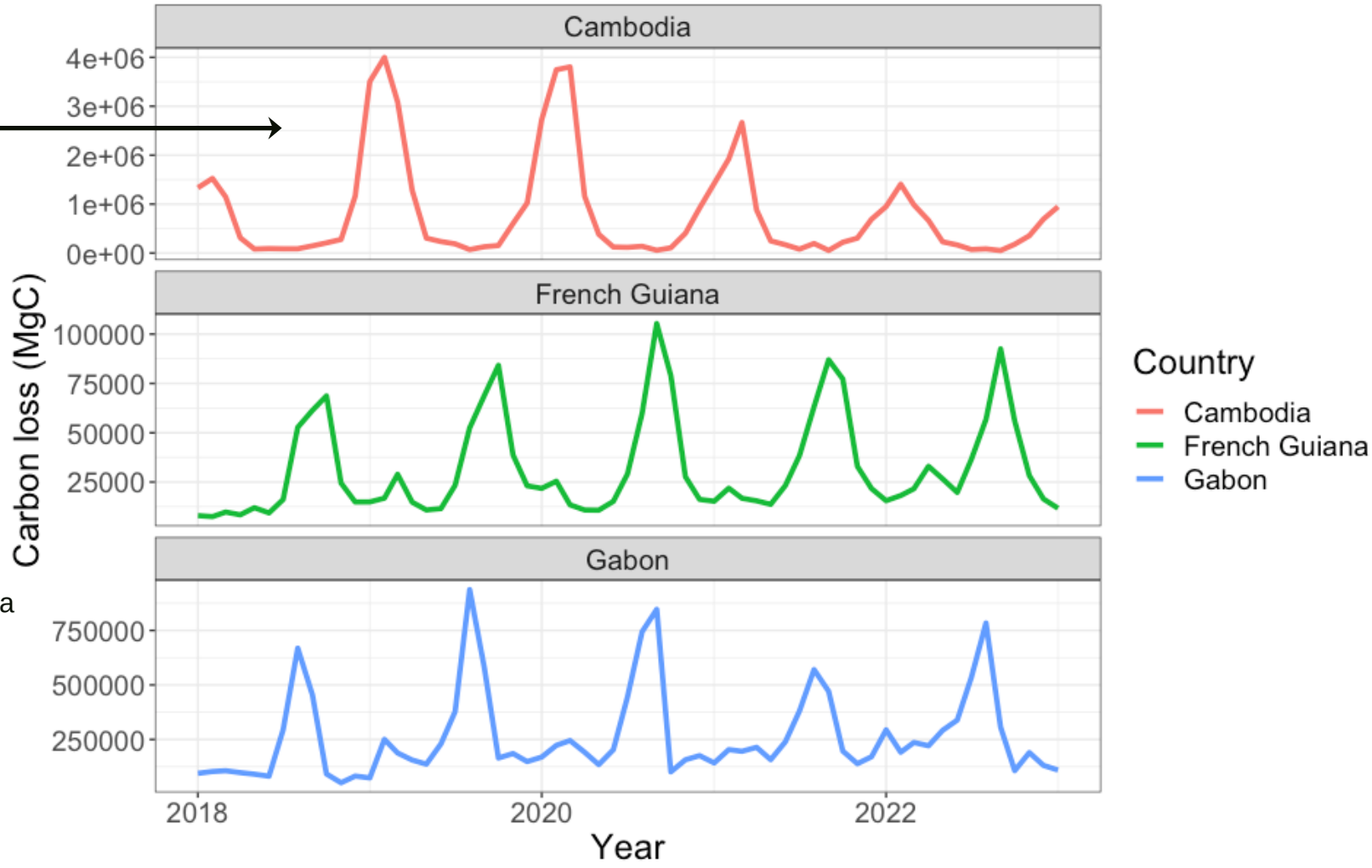
AGB x Forest loss areas



0 400 Mg/ha

AGB from CCI Biomass 2017

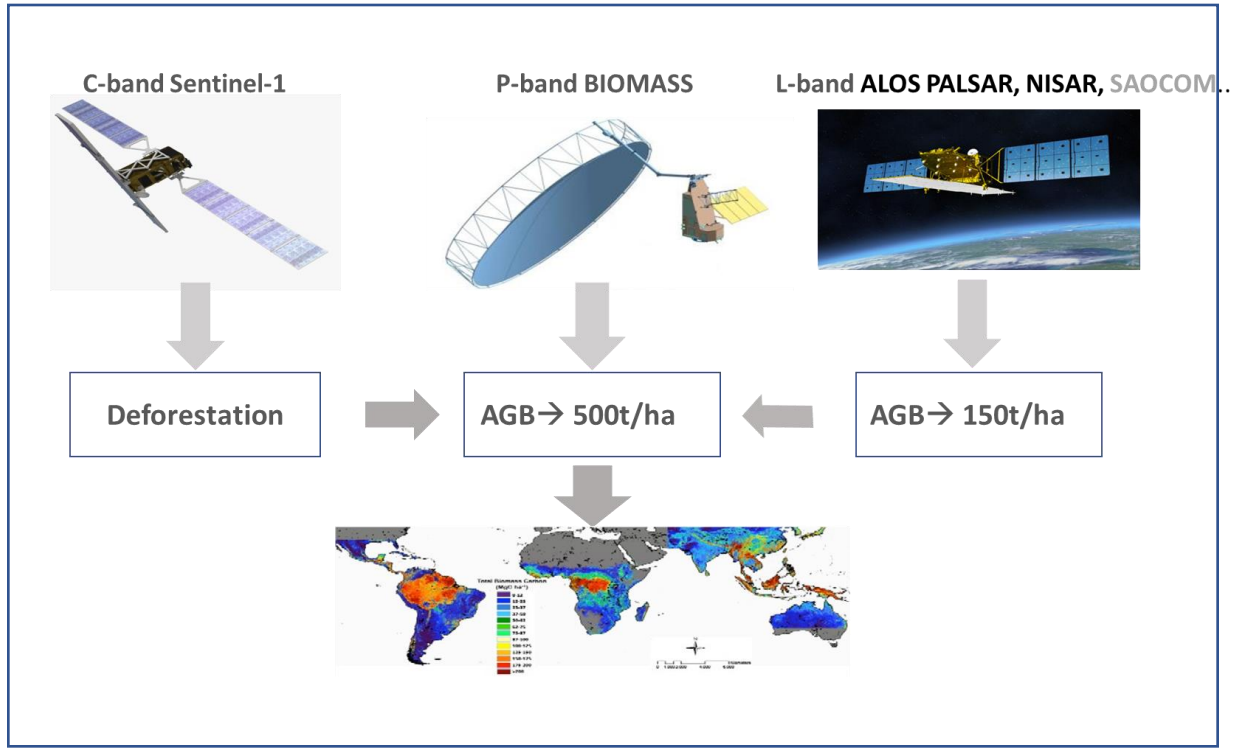
Carbon loss estimates



To monitor forest C loss and gain : Synergy of SAR sensors

- P-band SAR (Biomass): unique to tackle the issue of high AGB in tropical forests,
- L-band SAR (ALOS 4, NISAR) : higher resolution and higher sensitivity in the lower range of AGB (< 100 t/ha),
- C-band SAR: denser time series with Sentnel-1 (A, C, D) for finer resolution loss of forest area, to improve
  BIOMASS disturbance product,

P, L, C band for AGB, AGB change and quantification of C loss by forest degradation and quantification of regrowth



Synergy of P, L, C data to be studied by research community and exploited by agencies

Methane emissions by paddies rice - How and where to conduct mitigation actions ?

1. Methane (CH4) is the second most important anthropogenic GHG leading to global warming

2. CH4 is a 28 times more powerful GHG than CO2 over 100 years, but 80 times more powerful than CO2 over 20 years.

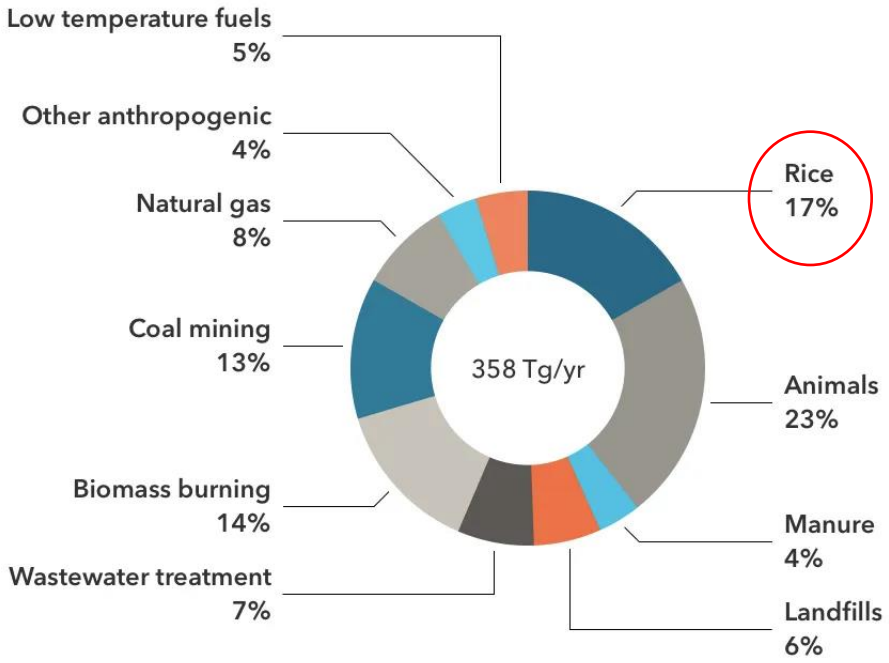
3. CH4 emissions from human activities have increased by 20% (61 million metric tons of CH4 per year) in the past two decades.

4. Agriculture (livestock and rice paddies) is the main anthropogenic source and contributes 40% of global anthropogenic emissions

5. The global increase in methane emissions from 2000 to 2020 arises largely from China (28%), South Asia (15%), South East Asia (12%) based on inventories

The Methane pledge engages 155 countries to collectively reduce global anthropogenic emissions by 30% relative to 2020 levels by 2030

Solution for agriculture sector includes water management of rice fields (e.g. Alternate Wetting & Drying)



Anthropogenic methane emissions

Using SAR data for assessment of Methane emissions

Mapping rice fields, growth stage and water management

1. **Mapping and monitoring of rice growth using SAR data**
   Sentinel-1 dense time series the most effective.
   Multiple research works at local scale. Larger scale demonstrated (GEORICE)
2. **Mapping of inundation status of rice fields** : L-band SAR penetrates through rice plants
   Currently ALOS-2/PALSAR-2 (with 14 days repeat frequency)

For MRV

Assessment of annual methane emissions

1. **Using by default emission factors of IPCC good practices x** information from Sentinel-1 (rice growth , water management, hydroperiod, cropping density)
2. **Using experimental data (chambers, eddy covariance**..) to replace/ complete IPCC factors

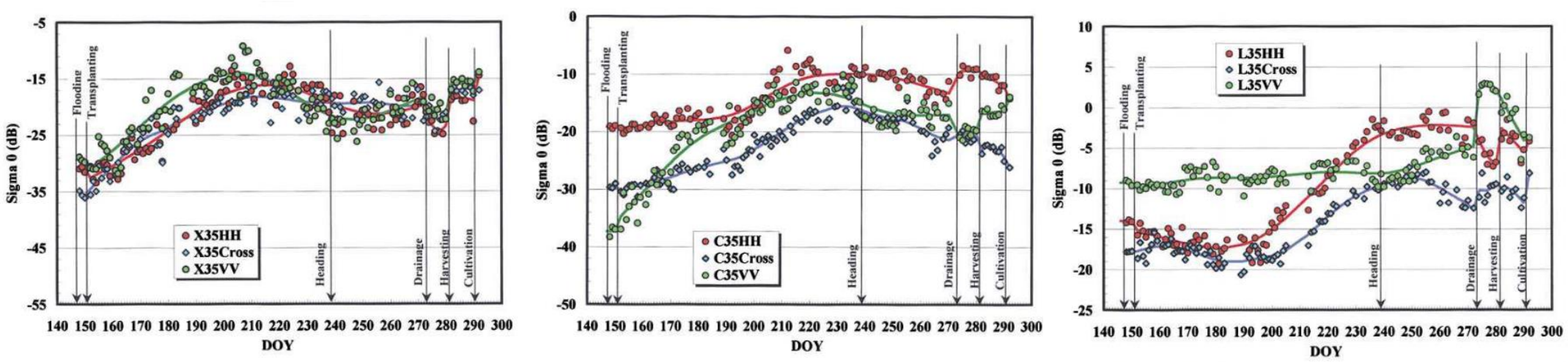
For mitigation measures

Mapping spatio-temporal methane emissions

1. Assimilation of L-band SAR data for water level daily dynamics (ALOS-4 14 days launched in 2024 and NISAR 12 days launched in 2025)
2. **Using process-based models (DNDC)** for estimation of methane emission with input from L and C-band SAR data

Mapping of rice and rice phenology can be done with time series X, C, L data

However, C-band data is best in terms of wave penetration



Inoue, Y., Kurosu, T., Maeno, H., Uratsuka, S., Kozu, T., Dabrowska-Zielinska, K., & Qi, J. (2002). Season-long daily measurements of multifrequency (Ka, Ku, X, C, and L) and full-polarization backscatter signatures over paddy rice field and their relationship with biological variables. *Remote sensing of environment*, *81*(2-3), 194-204.

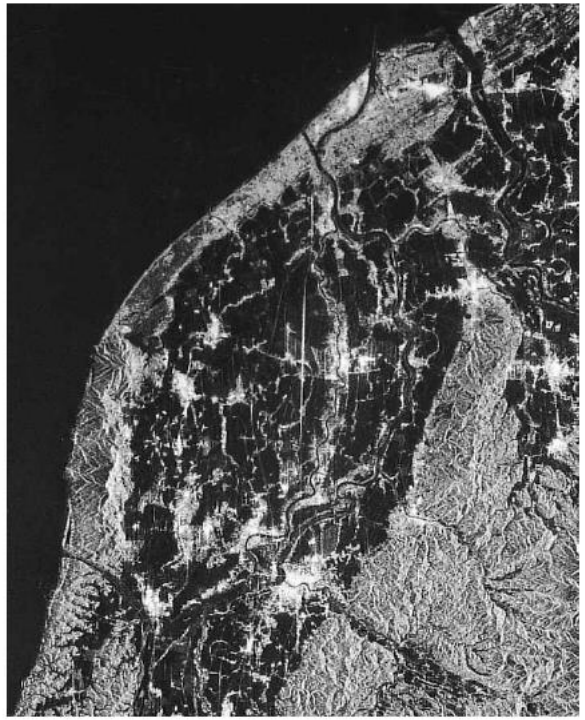
- Requirements for large area application:

1. Data access/cost
2. Dense time series
3. Large swath width
4. Spatial resolution enables field observation

C-band Sentinel-1 data preferred

- For local application, X-band data can be used, e.g. on a commercial basis

L-band SAR for rice monitoring in Japan: issue with the regular spacing of rice row

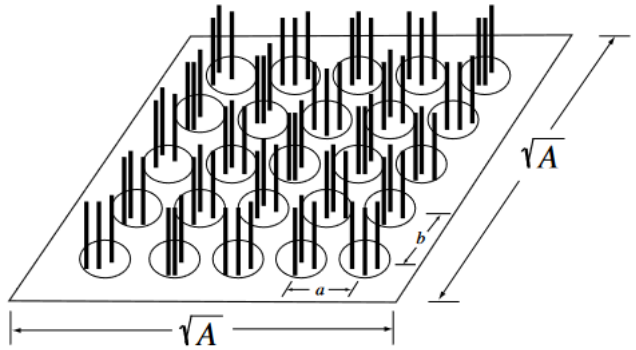


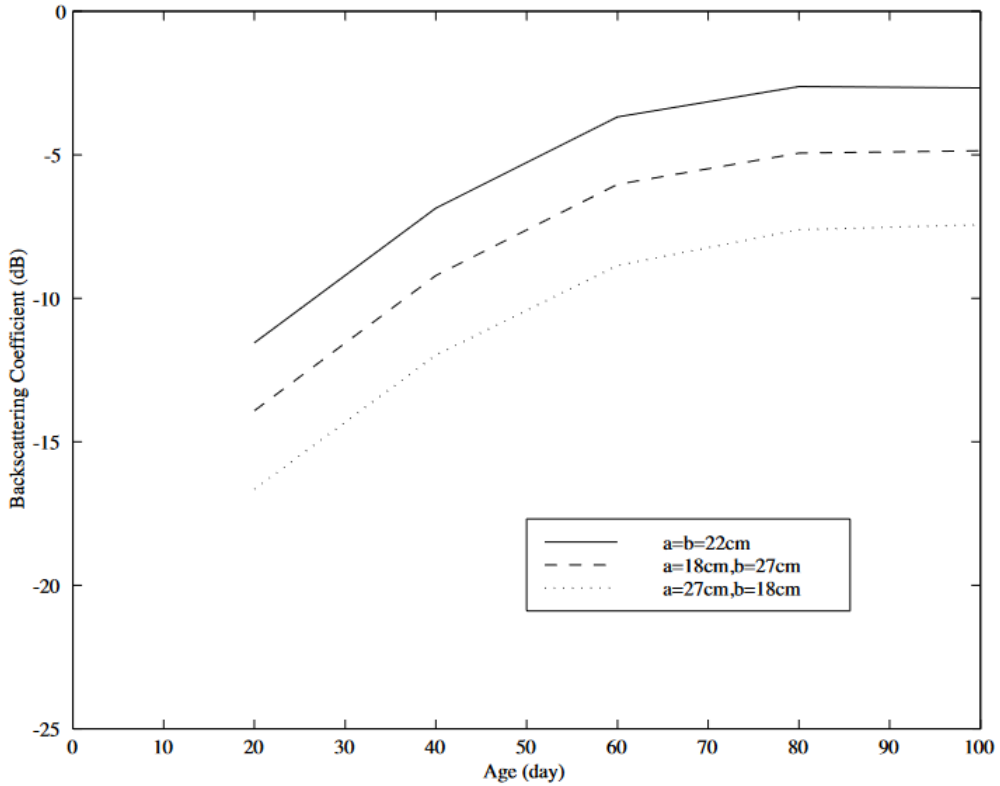


Rosenqvist, A. (1999). Temporal and spatial characteristics of irrigated rice in JERS-1 L-band SAR data. *International Journal of Remote Sensing*, *20*(8), 1567-1587.

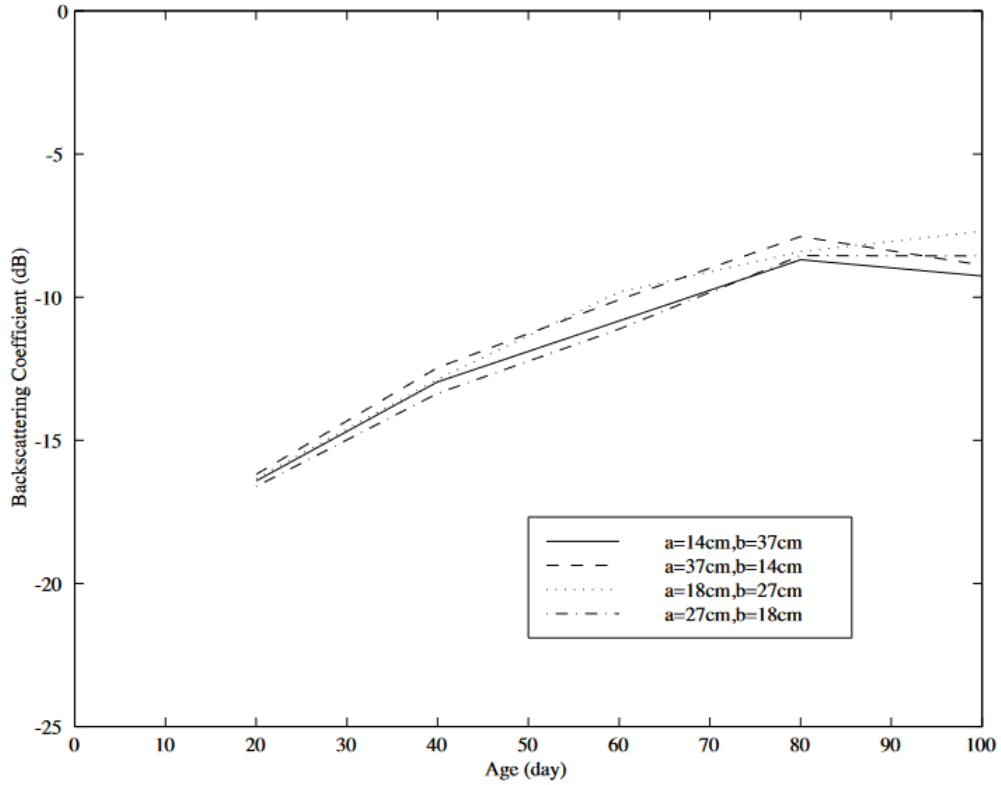
Effects of rice spacing simulated by models

Wang, L. F., Kong, J., Ding, K., Le Toan, T., Ribbes, F., & Floury, N. (2005). Electromagnetic scattering model for rice canopy based on Monte Carlo simulation. *Progress In Electromagnetics Research*, *52*, 153-171.



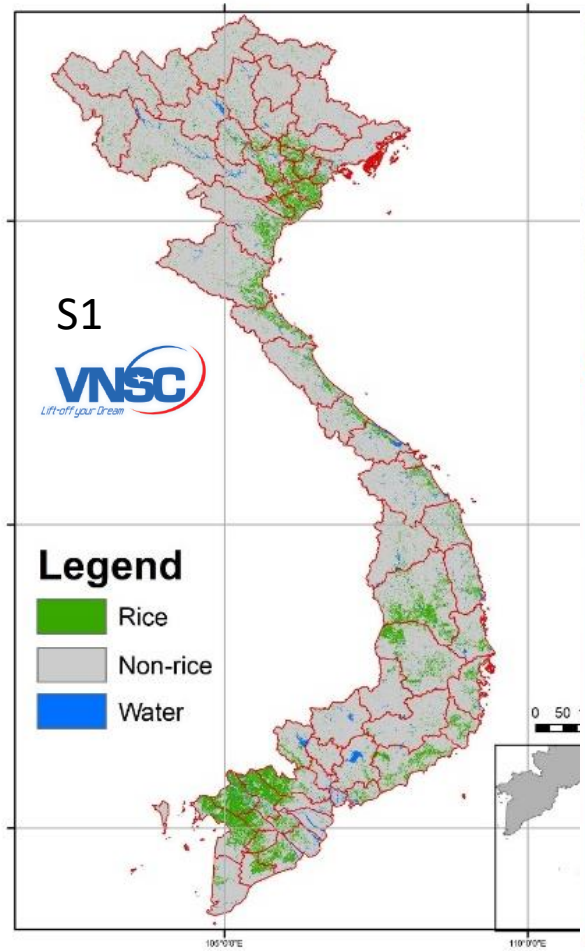


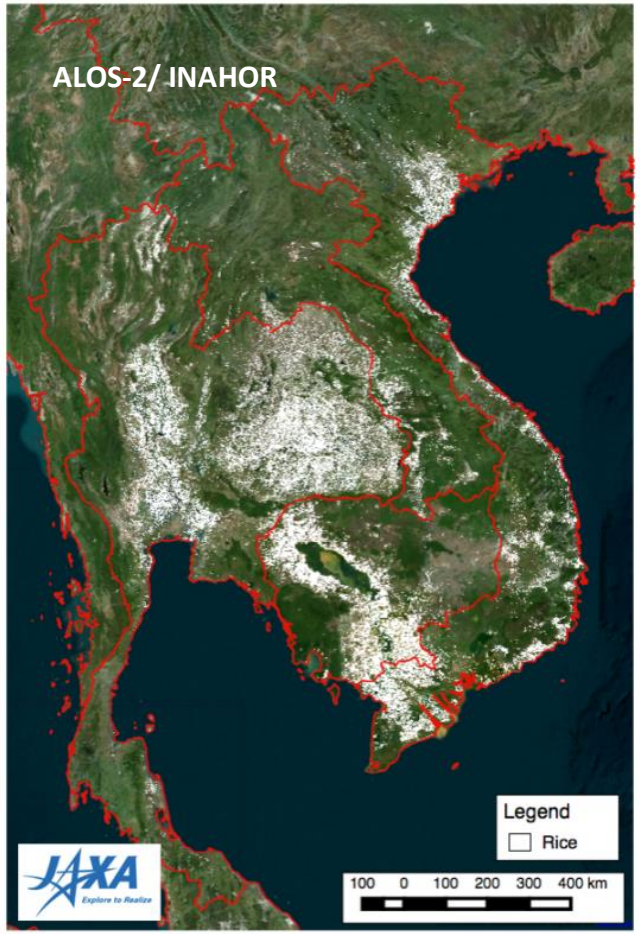
Effect of rice spacing on L-band

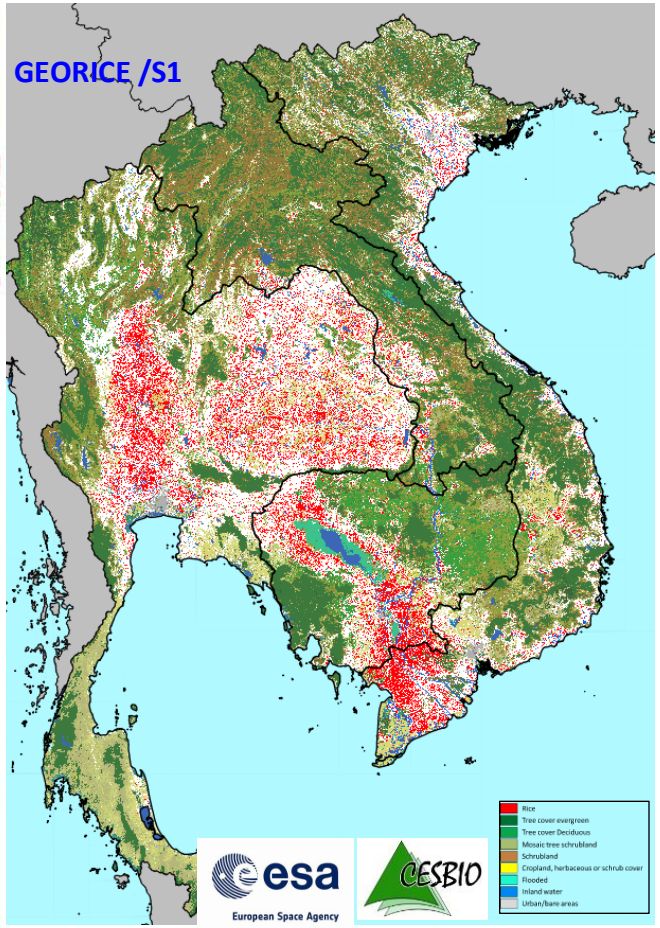


Effect of rice spacing on C-band

Rice maps using different approaches within Asia-Rice

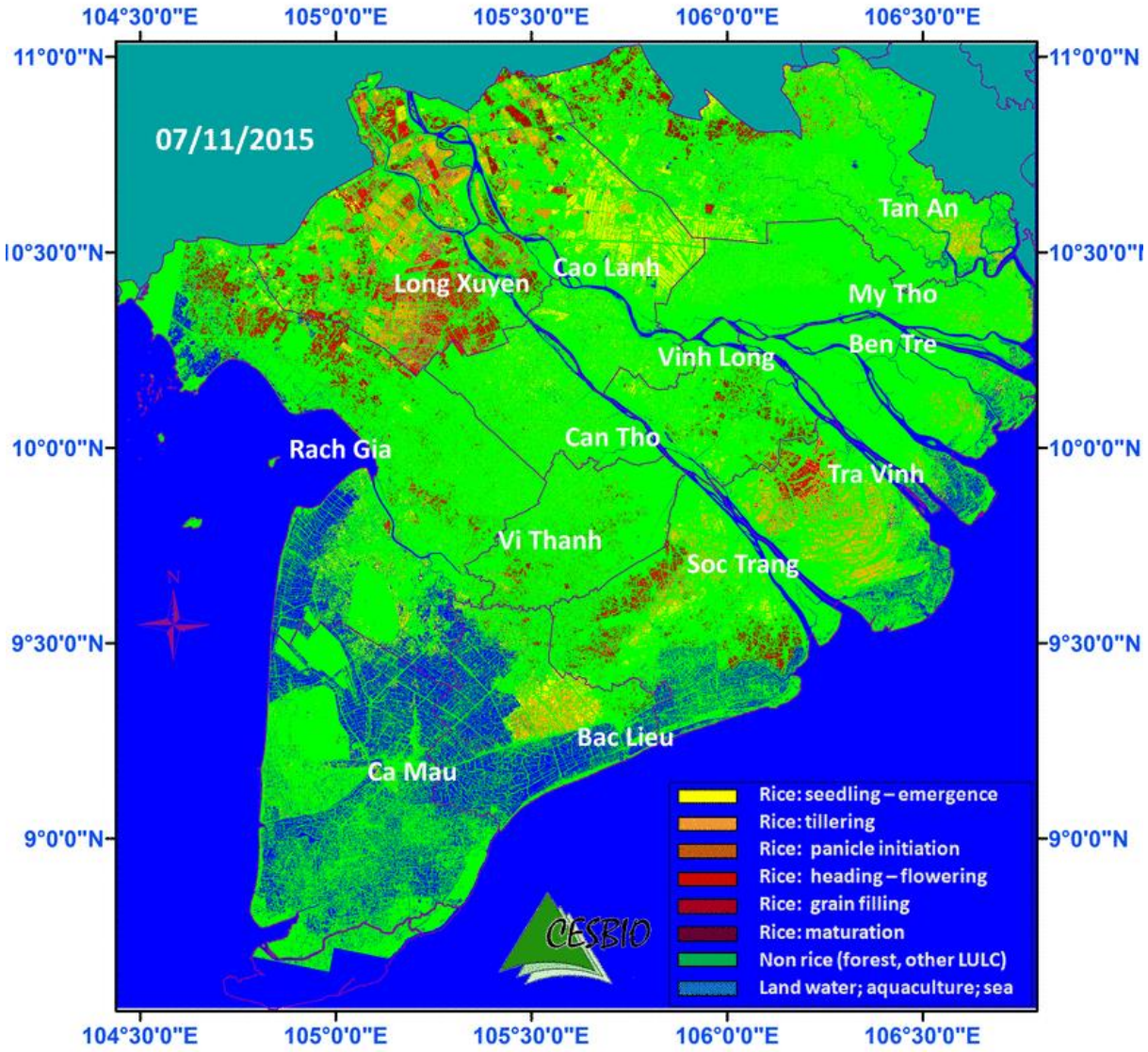




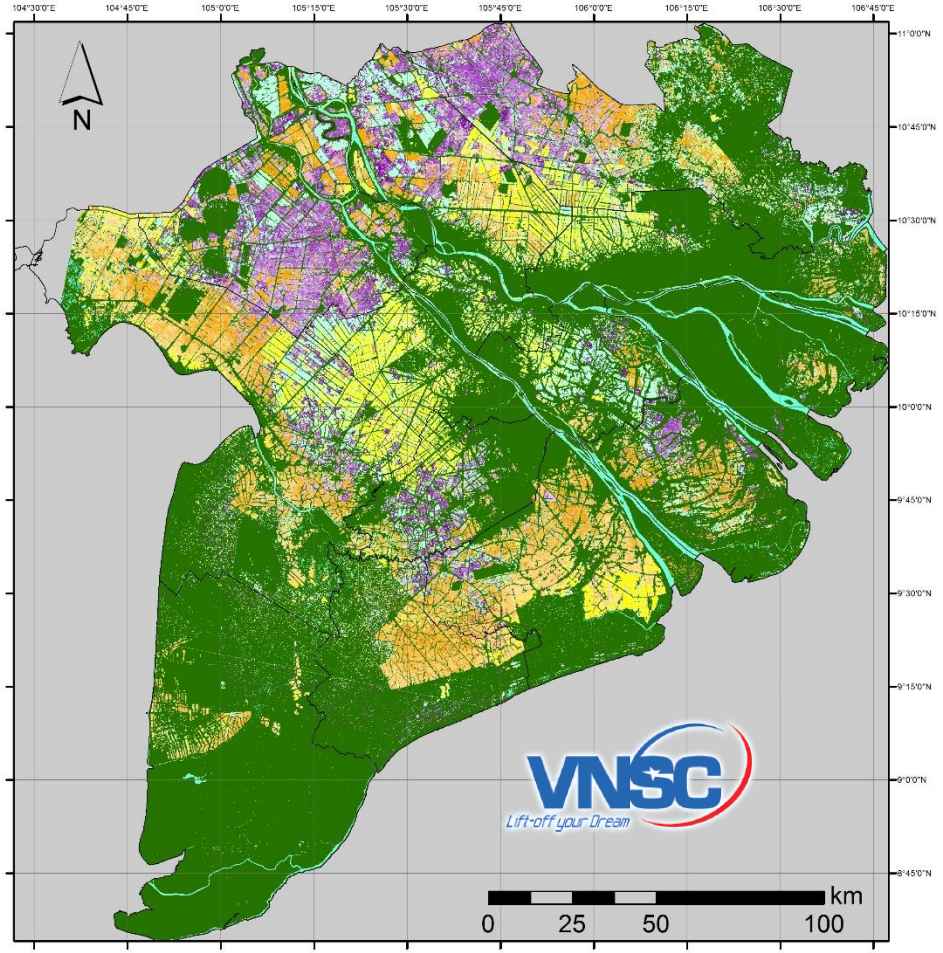


Need continuity and operational process

Detection of rice phenological stage at S1 acquisition



VNSC provides monthly map of rice age to Ministry of Agriculture



Bản đồ ngày sau khi sạ/cấy khu vực ĐBSCL (10/08/2018)

Chú thích

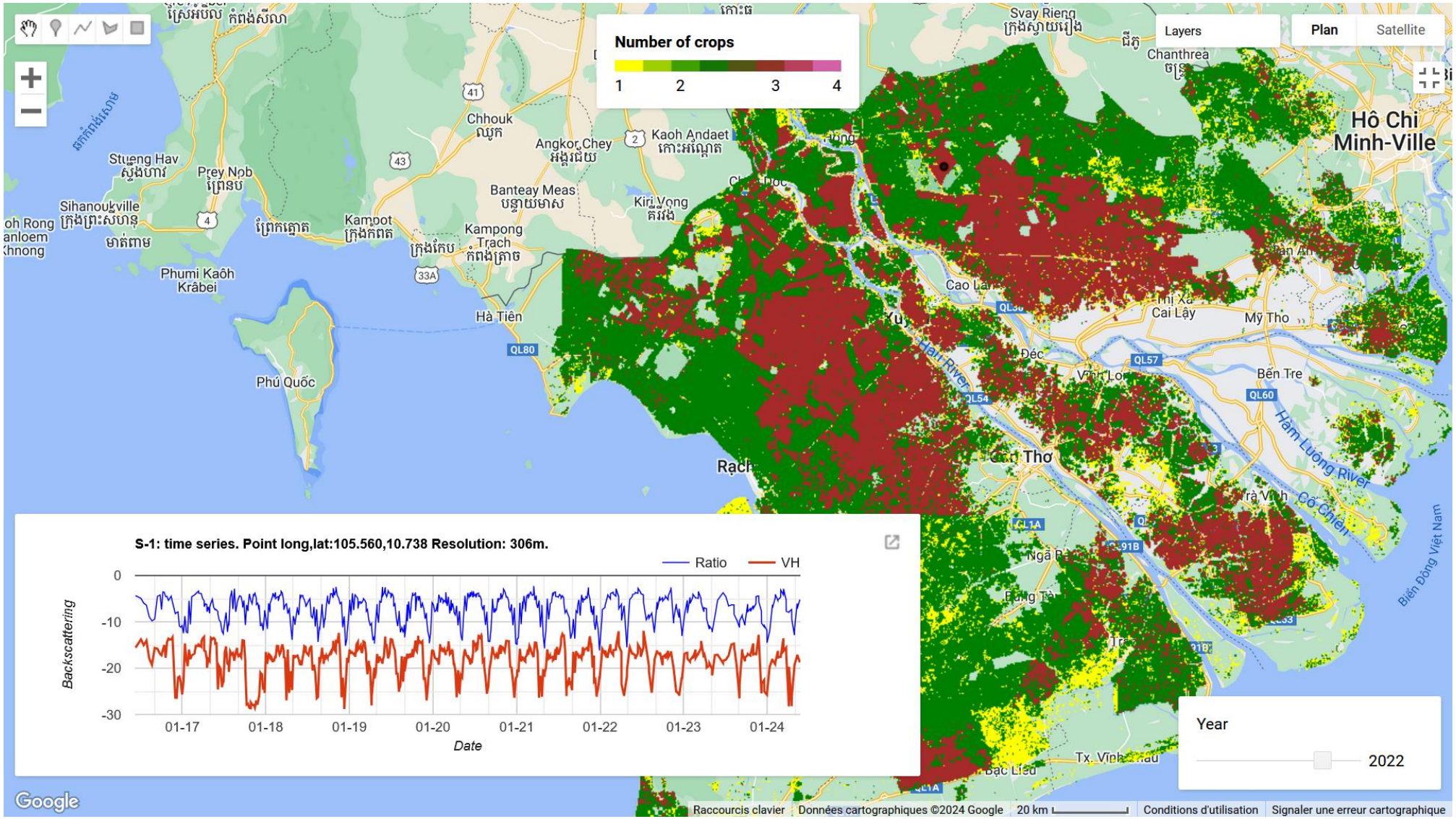
- Không phải lúa
- Mặt nước
- Đất lúa sau thu hoạch
- 01 - 10 ngày
- 11 - 20 ngày
- 21 - 30 ngày
- 31 - 40 ngày
- 41 - 50 ngày
- 51 - 60 ngày
- 61 -70 ngày
- 71 - 80 ngày
- 81 - 90 ngày
- 91 - 100 ngày
- 101 - 110 ngày
- 111 - 120 ngày
- Khu vực bên ngoài
- Ranh giới hành chính tỉnh

Cơ quan thực hiện:
Trung tâm Ứng dụng Công nghệ Vũ trụ TP. Hồ Chí Minh (STAC)
Trung tâm Vũ trụ Việt Nam (VNSC)
Viện Hàn lâm Khoa học và Công nghệ Việt Nam (VAST)

Days after rice sowing/transplanting in the Mekong Delta (Aug 10, 2018),

The VietSCO platform is maintained for the Mekong Delta by CESBIO / GlobEO

Number of rice crops per year

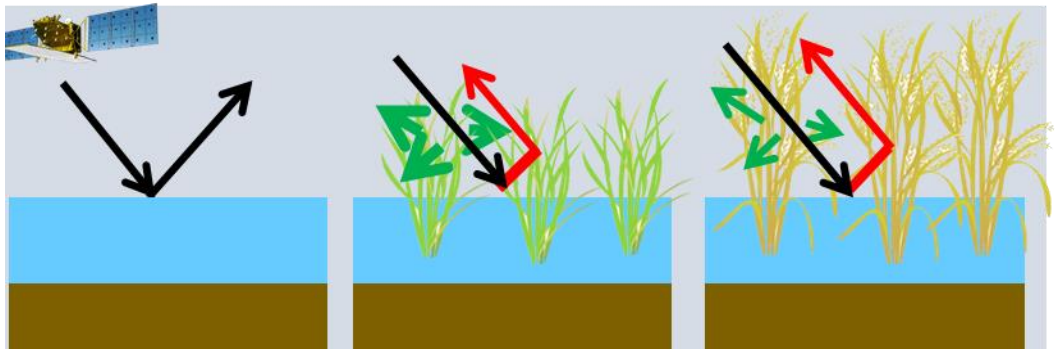


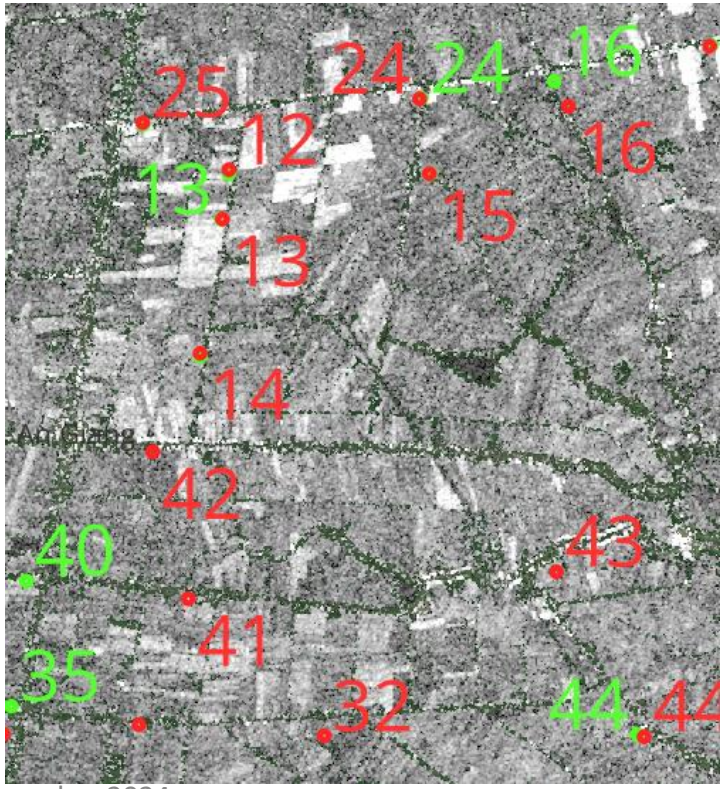
To detect inundation water in rice fields requires L-band SAR

- L-band for penetration up to 1 m of dense rice canopy
- Polarimetry provides dominant mechanisms: double-bounce scattering in inundated rice fields

ALOS-PALSAR image polarimetric decomposition
Freeman-Durden double-bounce

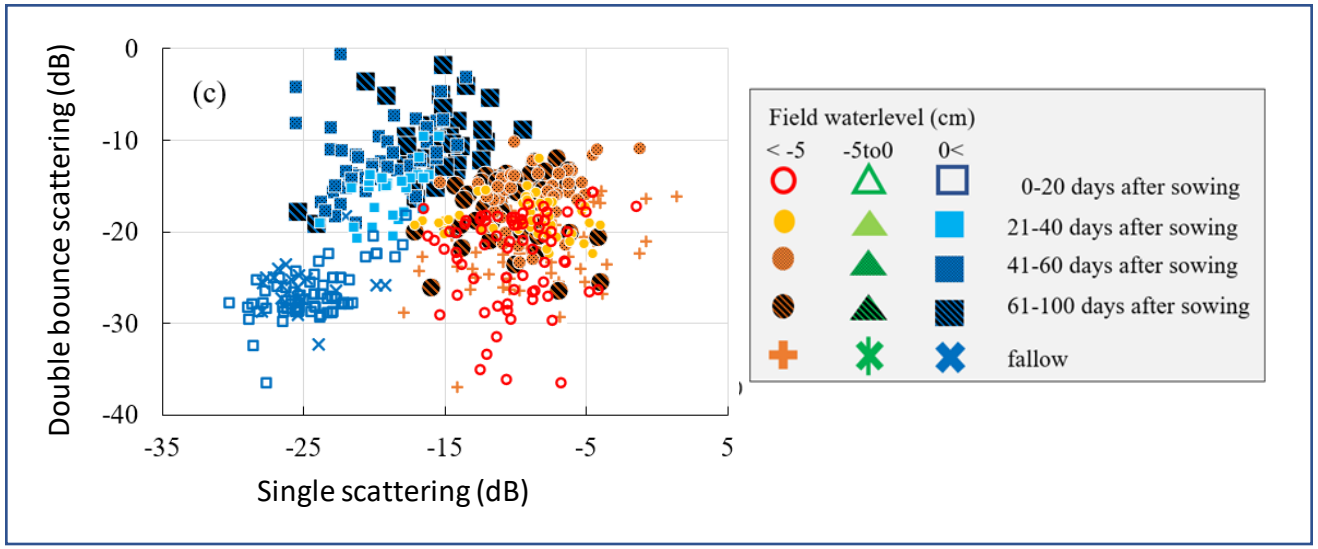
Inundated rice fields have high double bounce scattering



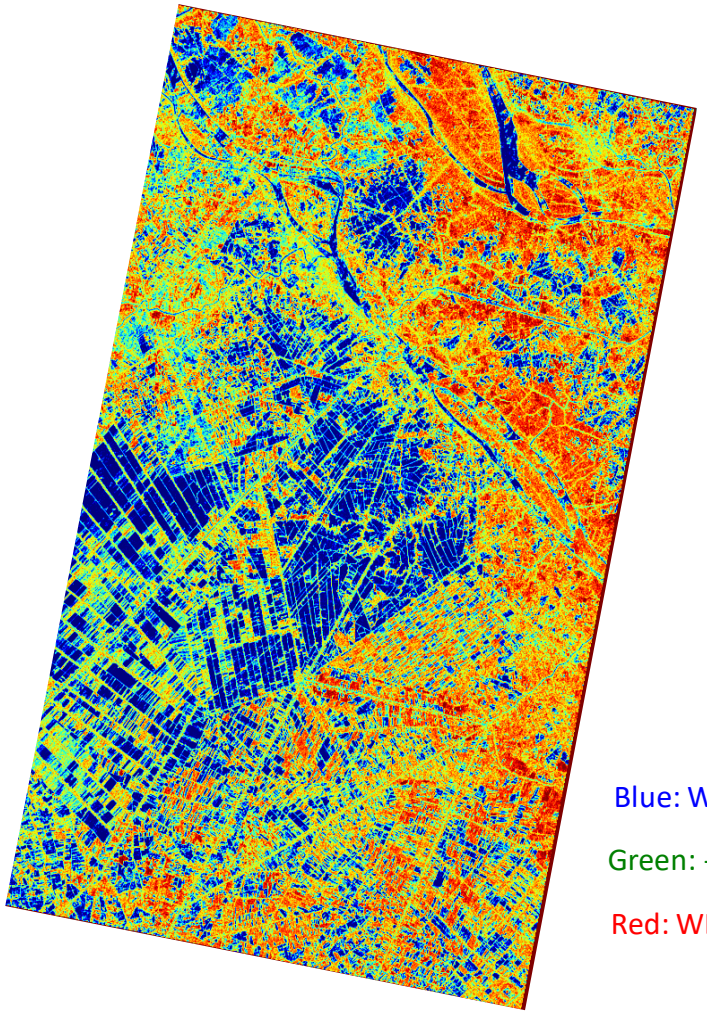


Polarimetric L-band ALOS-PALSAR for detailed characterization of water regimes

Polarimetric ALOS-PALSAR data : 4 - 5 m resolution, full polarimetry, 40-50 Km swath width, 70 Km length



- Arai, H., Takeuchi, W., Oyoshi, K., Nguyen, L. D., & Inubushi, K. (2018). Estimation of Methane Emissions from Rice Paddies in the Mekong Delta Based on Land Surface Dynamics Characterization with Remote Sensing. *Remote Sensing*, *10*(9), 1438
- Arai, H., Le Toan, T., Takeuchi, W., Oyoshi, K., Fumoto, T., & Inubushi, K. (2022). Evaluating irrigation status in the Mekong Delta through polarimetric L-band SAR data assimilation. *Remote Sensing of Environment*, *279*, 113139.



Blue: Water Level > 0cm

Green: -5 cm <WL< 0 cm

Red: WL<-5 cm

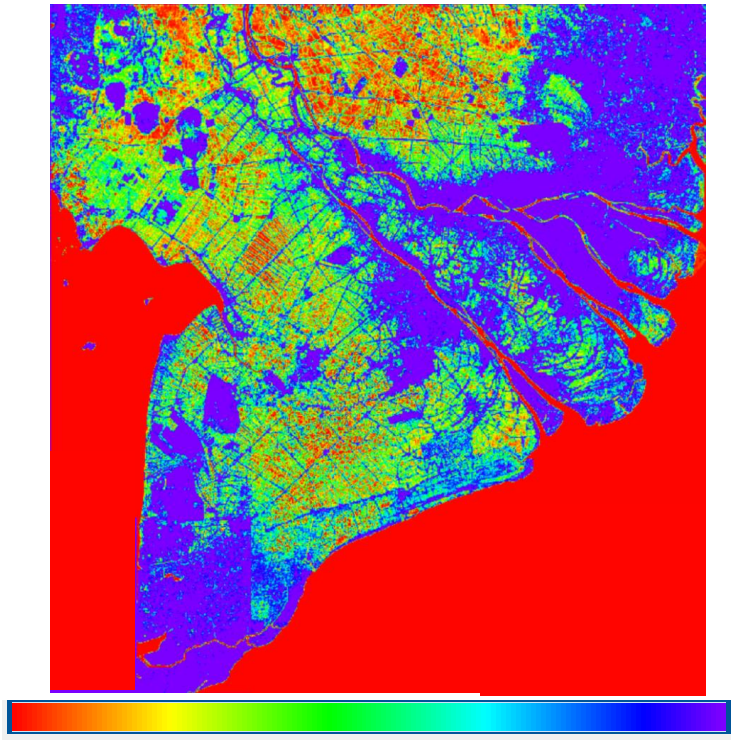
Need information on rice phenology for mapping water regimes
Joint use of C-band (Sentinel-1) and L-band (ALOS-PALSAR, NISAR)

Using L-band ALOS-PALSAR ScanSAR for large region

- **ALOS-PALSAR 2 ScanSAR :** approx. 25-100 m spatial resolution, dual polarization [HH/HV], 350 km width,

Floodability map based on ALOS 2-PALSAR 2

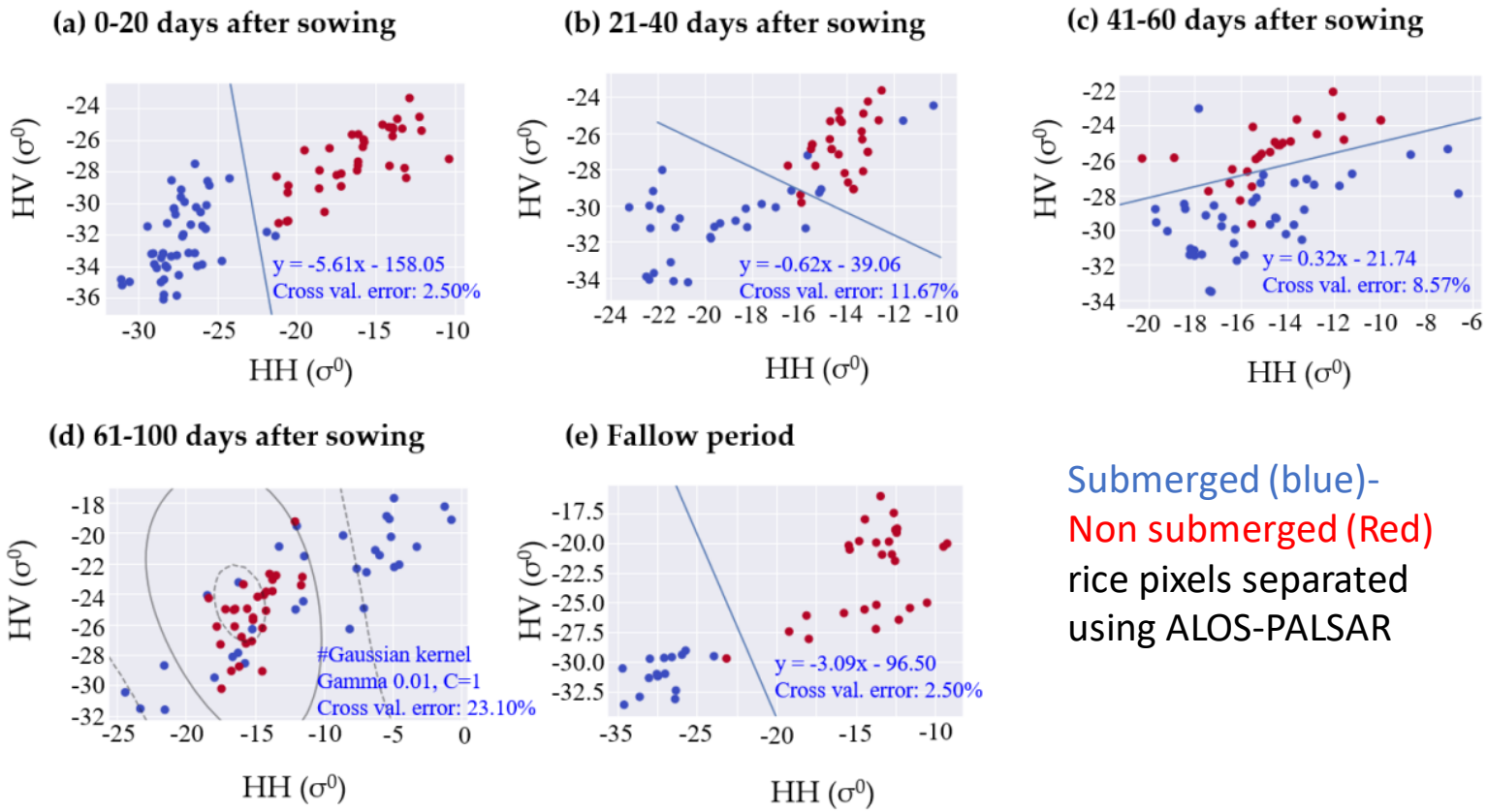
(ex: Cumulative on N=105 ScanSAR scenes)



Continuously inundated

AWD

Continuously NOT inundated



Submerged (blue)-
Non submerged (Red)
rice pixels separated
using ALOS-PALSAR

Need information on rice phenology for mapping water regimes, i.e. from contemporary Sentinel-1 data

To develop the methods for Asia-RiCE, research network has been initiated in the region

Asia-RiCE
Crop Estimation and Monitoring

SAFE CH4Rice project

- **ALOS-2 PALSAR2 (L-band, Full-Pol SAR) acquisitions by JAXA since June 2023**
- **in-situ water-level/inundation measurement devices being implementing**

Super Site Selection

BRIN Indonesia: Indramayu

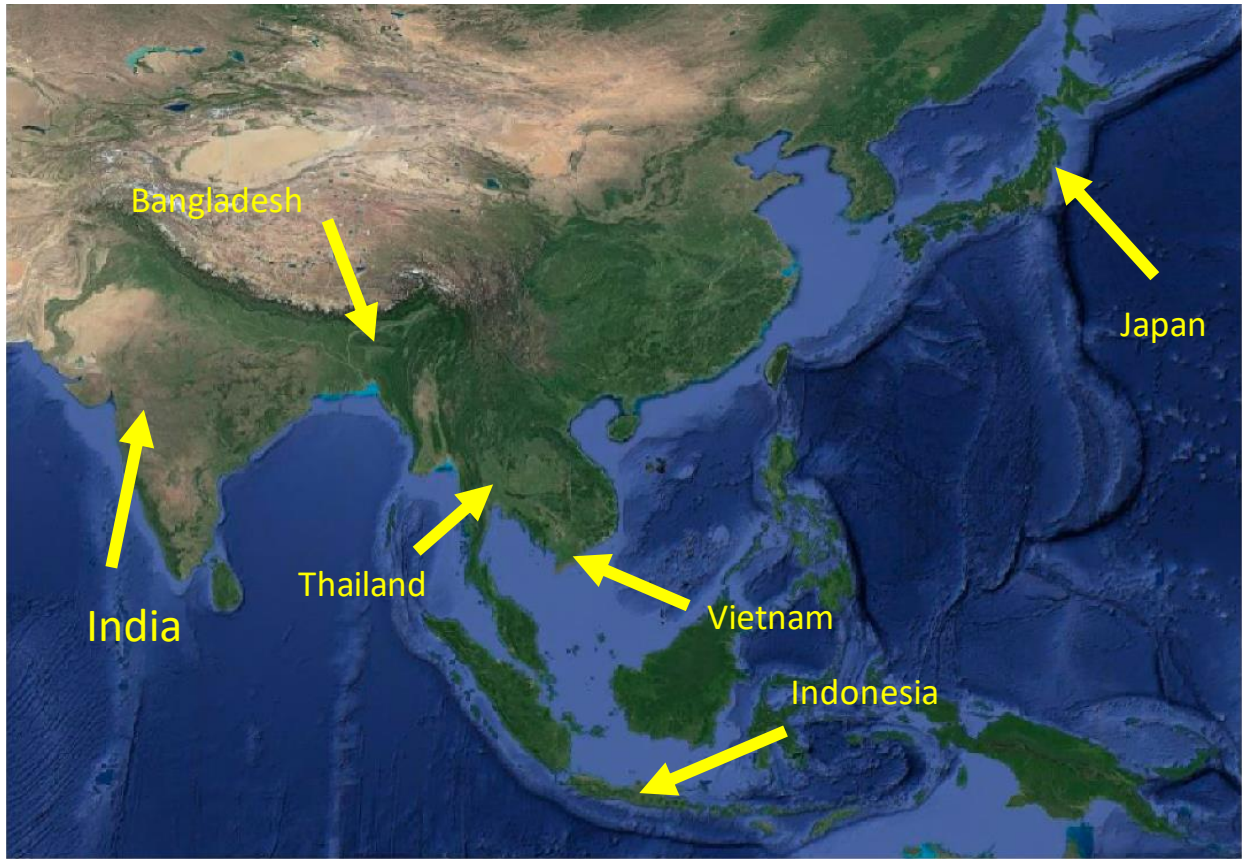
GISTDA Thailand: Chainat,Suphan Buri

ISRO India: Nawagam

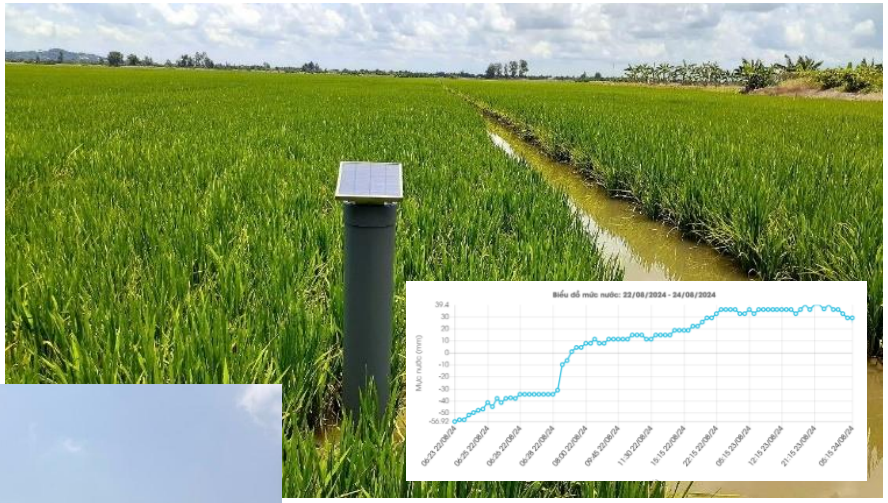
JAXA Japan: Miyagi

PUST Bangladesh: Rajshahi

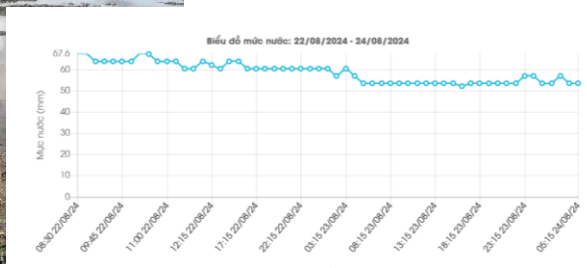
VNSC Vietnam: Mekong Delta



Automatic measurement of water level IoT implemented in Asia-RiCE countries: Vietnam, Thailand, Indonesia, Japan,..



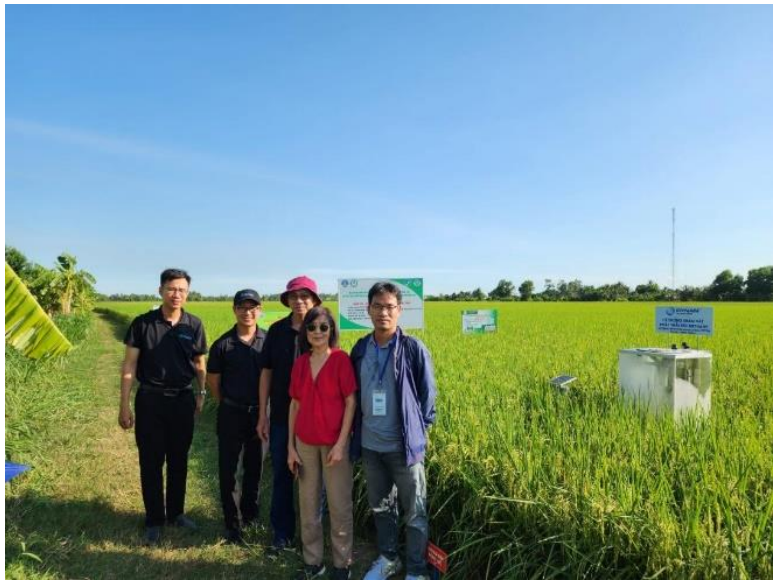








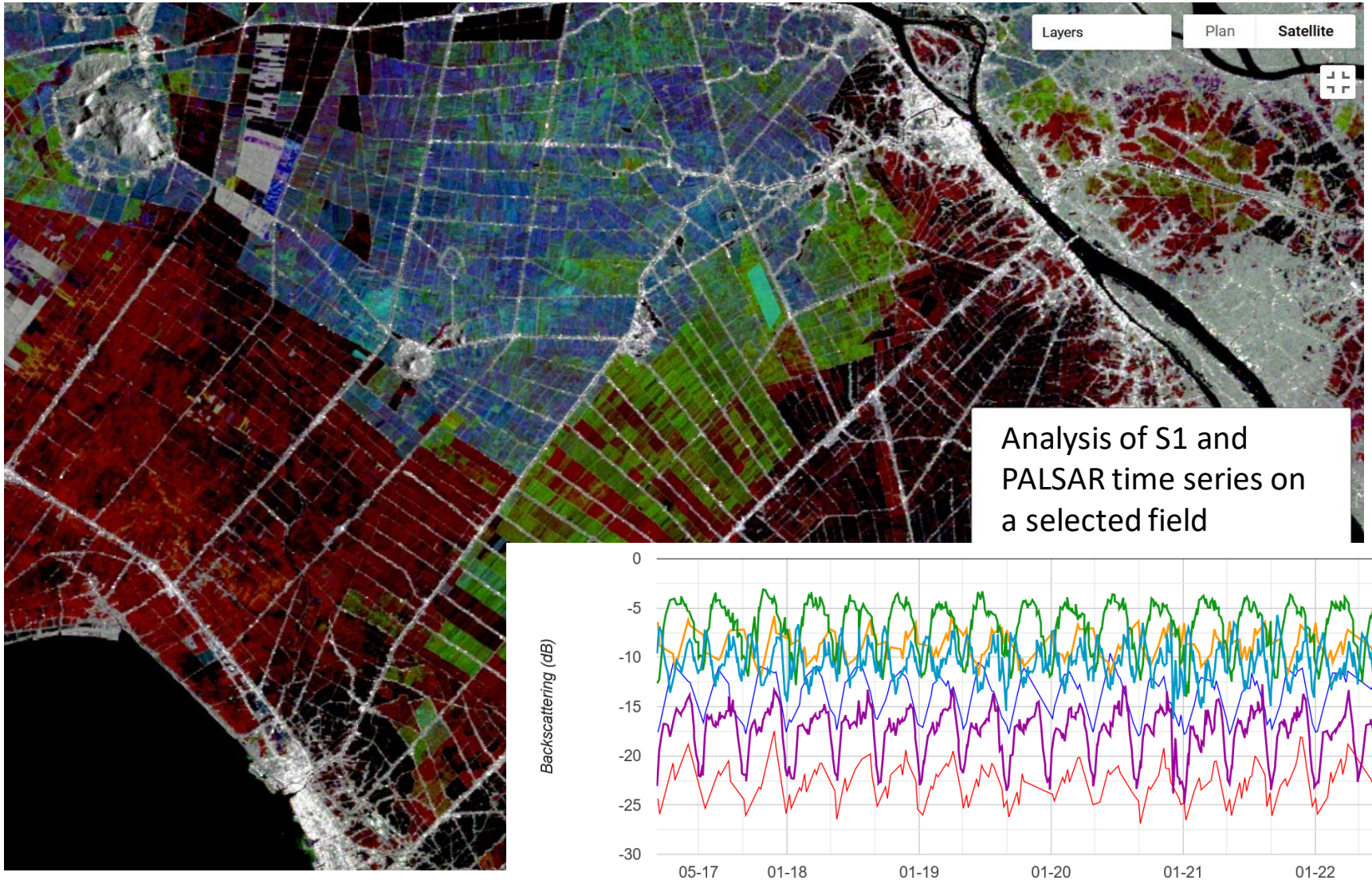




Methane measurement chamber

Asia-RiCE
Crop Estimation and Monitoring

Ongoing: Joint analysis of Sentinel-1 and ALOS-PALSAR data.



Remarks on the joint use of SAR data for applications

- The examples presented here show that the best of SAR data can be combined for specific applications:
  - P- and L- and C-band SAR in forest observatory to quantify carbon sources and sinks,
  - L- and C- band SAR to identify the water regime of rice fields to take measures to reduce methane emissions,
- To get the most out of SAR data, their information content must be understood. A few decades ago, when data were scarce, priority was given to physical modeling and simulations. Today, data-driven approaches (AI, Machine Learning, ..) are favored. Combining both approaches will be essential for the future.
- The involvement of users, stakeholders and commercial sectors is necessary to bring the research potential to an effective use of SAR (and in general EO) data and products
- Work remains to be done to foster other applications of SAR data than those based on their all-weather monitoring capacity (disaster monitoring, mapping, military).

ありがとう ！

Thank you !





