SENSITIVITY OF CYGNSS TO ABOVE GROUND BIOMASS AND CANOPY HEIGHT OVER TROPICAL FORESTS

H. Carreno-Luengo, G. Luzi, and M. Crosetto

Centre Tecnòlogic de Telecomunicacions de Catalunya (CTTC)/CERCA,08860, Castelldefels (Barcelona), Spain

hugo.carreno@cttc.cat

members of Institució CERCA Centres de Recerca de Catalunya

Accredited by

Certified by

Awarded with HR EXCELLENCE IN RESEARCH

Outline

I. EXPLOITING CYGNSS FOR BIOMASS STUDIES

II. METHODOLOGY

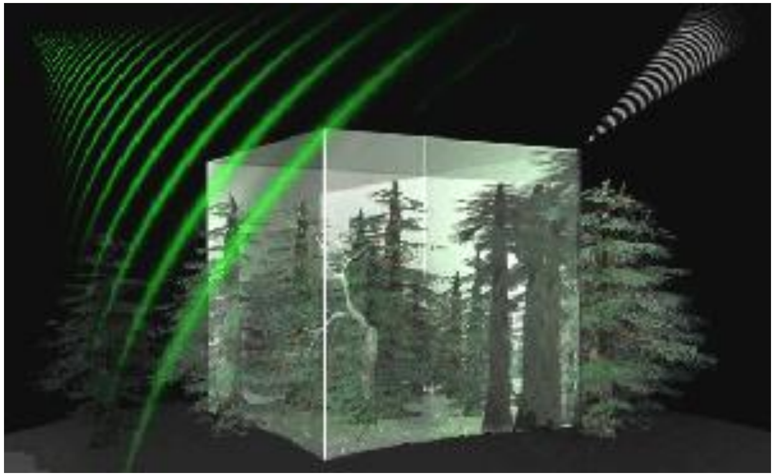
- Definition Selected CyGNSS Observables
- Strategy
- Reference Data

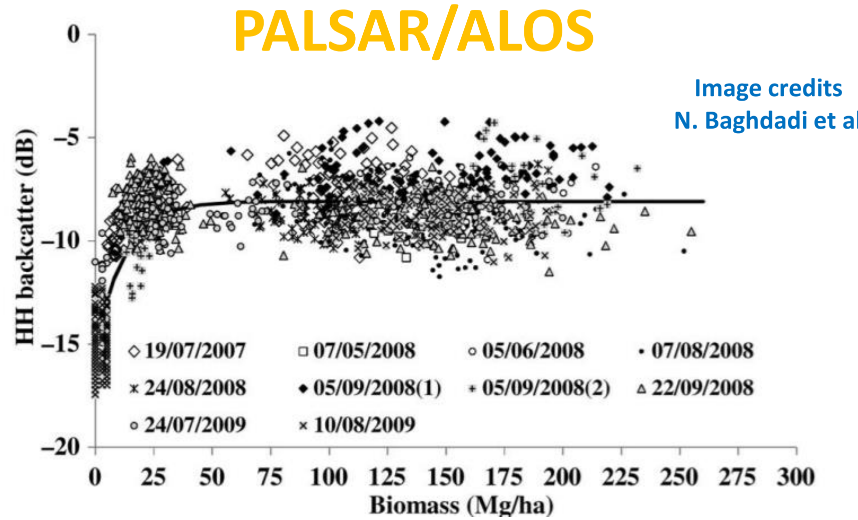
I. PERFORMANCE ANALYSIS

- Sensitivity as Function of Elevation Angle
- Evaluation with Microwave Vegetation Indices

II. CONCLUSIONS

CyGNSS for Biomass Studies





- **PALSAR/ALOS**: L-band SAR, signal **saturation level ~ 100 ton/ha**
- ESA **BIOMASS**: Future ESA mission, **P-band** inSAR, **~ 12 m** deployable **antenna**, ~ 350 ton/ha**?**
- NASA **CyGNSS**: 8 microsatellites, **L-band** GNSS-R, **~ 0.3 m** antenna
  - **DDMs' response** to interaction GPS signals with **tropical forests?**
  - GPS signals **saturation** level (if any) over tropical rainforests**?**
  - **Optimum** GPS satellites **elevation angle** for biomass estimation over tropical rainforests**?**

CyGNSS for Biomass Studies

- **Bistatic scattering coefficient**: $\sigma^0 = \boldsymbol{\sigma}^{coh,0} + \sigma^{incoh,0}$
- **Hypothesis**: $\langle|Y_r(\tau,f)|^2\rangle$ sensitivity to forests biomass could overpass P-band SAR
  - **Backscatter** intensity monostatic SAR **increases up to saturation level** ~ 100 ton/ha
  - L-band **GPS signals** can partially **penetrate vegetation** cover (semi-transparency)
  - Increasing **VWC**: Larger **signal attenuation** $\boldsymbol{\gamma}$
  - Bistatic scattering pattern:
    - Coherent term: **Delta function** along specular direction
    - Incoherent term: **Spreads** along other directions
  - Coherent term can **overpass** incoherent one even from space-borne platform:

$$\langle|Y_{r,coh}(\tau,f)|^2\rangle = \frac{P_T\lambda^2 G_T G_R|\chi(\tau,f)|^2}{(4\pi)^2(\boldsymbol{R_T}+\boldsymbol{R_R})^2}|R_p(\theta_e)|^2\boldsymbol{\gamma}\exp(-2k\sigma\sin\theta_e)^2$$

  - Incoherent:
    - Surface scattering: Areas with moderate-to-high roughness + topography
    - Direct **scattering** from **vegetation**: Leaves, branches, trunks
    - Multiple scattering (RHCP-LHCP-**RHCP**) **negligible**: CyGNSS **LHCP antennas**

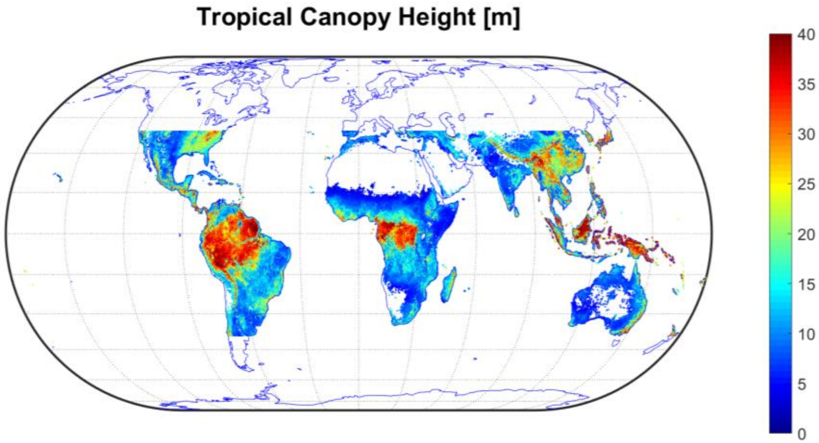
Methodology: CyGNSS Observables

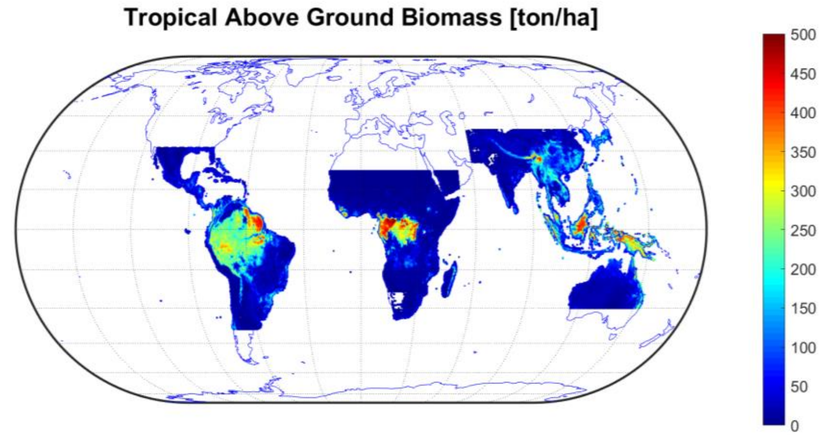
- CyGNSS **Level 2.1** Science Data Record
- Equivalent overall **quality flags** over land surfaces
- Reflected delay waveforms: $WF_{r,raw} = \langle |Y_r(\tau, f = 0)|^2 \rangle$
- **Re-sampling** delay bin resolution from 17-lags to 1700-lags (~ 1 m resolution) **+** spline **interpolation**
- Several observables to **evaluate** sensitivity $\boldsymbol{\sigma}^{\boldsymbol{coh,0}}$ & **volume scattering** term to biomass:
  - **Width trailing edge**: $TE = \tau_{WF_{r,threshold}} - \tau_{WF_{r,peak}}$
    - **70%** power threshold selected, 50% cut-off data, 90% lower dynamic range
    - Incoherent term $\sigma^{incoh,0}$ **main** contribution to $WF_{r,threshold}$
    - Incoherent $\sigma^{incoh,0}$ **&** coherent $\boldsymbol{\sigma}^{\boldsymbol{coh,0}}$ significantly contribute to $WF_{r,peak}$
  - **Reflectivity**: $\Gamma = WF_{r,peak}/WF_{d,peak}$
    - Antenna gain patterns compensated and noise power floor (reflected signal)
    - Use **direct signal** for calibration instead EIRP
    - Direct estimation **without** inverting scattering **model**
    - Forests biomass: Complex scenario, **model uncertainties**

Methodology: Strategy

- TE & Γ **classified** different groups elevation angles, **steps** θ_e = 10 °
- θ_e important parameter **determines** coherent-to-incoherent scattering **ratio**
- Soil surface contribution to $\sigma^{incoh,0}$ is **filtered out**: Terrain Ruggedness Index lower 15 (**empirical** threshold) from Digital Elevation Model
- **Topography** disturbs σ^0 : **Local** surface **slopes** modify scattering area
- Objective: **Quantify** & **analyse** relationship between TE & Γ as function Above Ground Biomass (AGB) and Canopy Height (CH)
- **Gridding**: 0.1°x 0.1° spatial grid, averaging moving window 0.2° in steps 0.1°
- Spatial resolution (equatorial latitudes) 20 km x 20 km:
  - **Across-track** ~ 20 km: Multiple azimuthal overpasses, limited by $\langle|Y_{r,incoh}(\tau,f)|^2\rangle$
  - **Along-track** ~ 7.6 km: (1 s incoherent integration time), limited by $\langle|Y_{r,coh}(\tau,f)|^2\rangle$
- **6 months** (01/08/2018 to 31/01/2019), AGC disabled, no fluctuations AGB &CH

Methodology: Reference Data





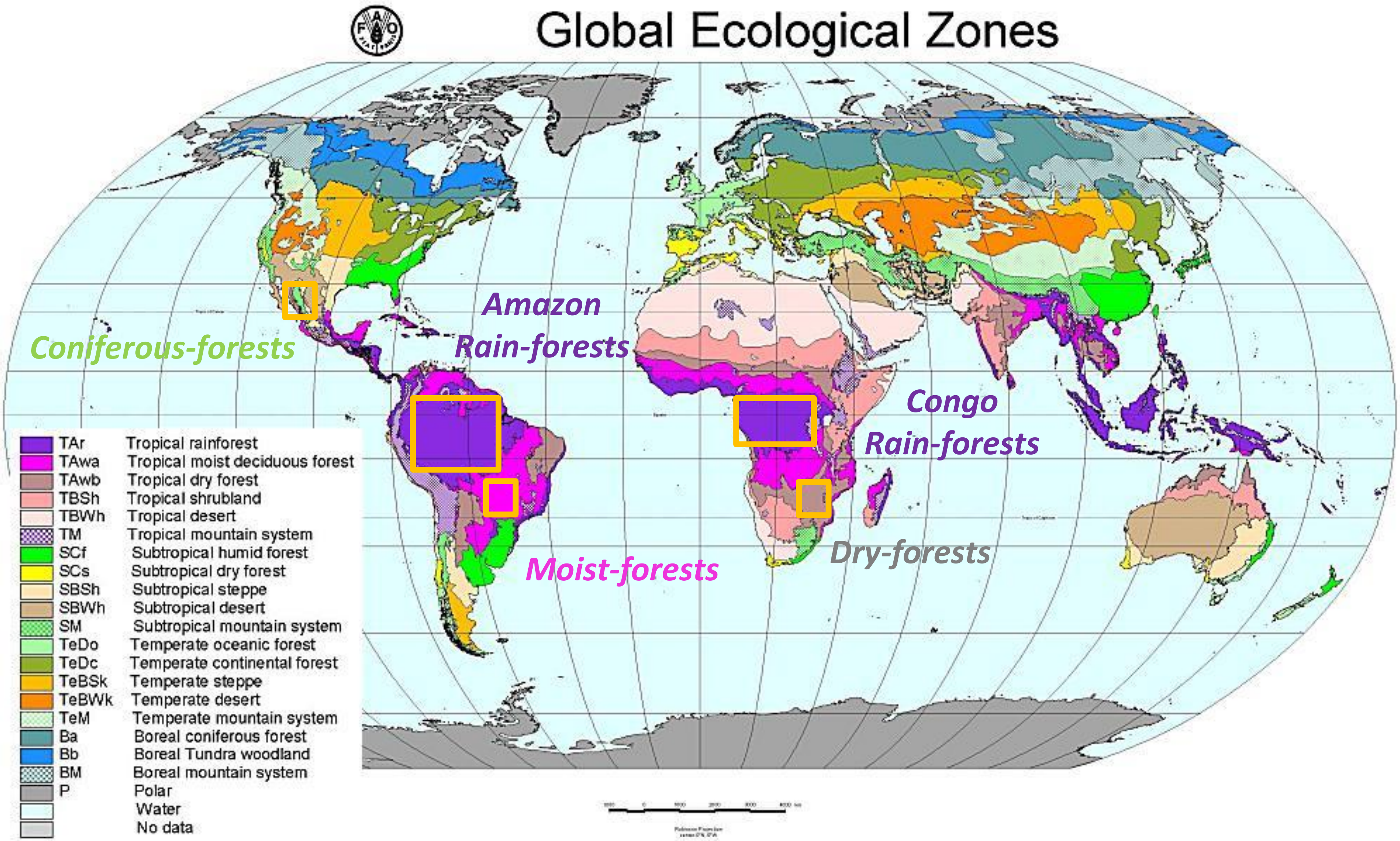
- **Canopy Height** form **ICESat/GLAS**:
  - 2004-2008
  - **Lidar** data, spatial resolution ~ 60 m along-track x 170 across-track
  - Level 1a data to compute **Lorey's Height**
  - Height **correction** factor for **topography**: Non-homogenous sampling properties GLAS

- **Above Ground Biomass** from **Avitabile et al.** :
  - **Integrated pan-tropical map**: Combines Saatchi & Baccini maps derived from GLAS into **~ 1 km** resolution map
  - Use of **independent reference field observations** for validation & **highly resolution maps** locally-calibrated, harmonized, and upscaled up to ~ 14,466 ~ 1 km AGB estimates as inputs for fusion algorithm
  - Algorithm applies bias removal + weighted linear averaging
  - **Validation**: Lower RMSE and bias than Saatchi & Baccini

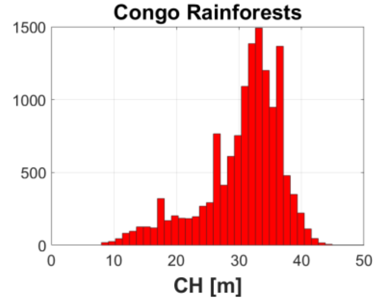
Performance Analysis: Introduction

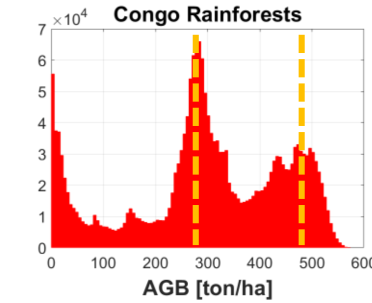
- **Mean values** in steps of TE ~ 1 m & Γ ~ 0.05 dB
- **Reduce noise** at pixel-level: **Speckle** in $\langle |Y_r(\tau, f)|^2 \rangle$ **&** potential **errors in GLAS-derived AGB**
- Extension target areas large (enough data) **&** errors assumed to be randomly distributed
- Noise can be reduced after averaging: Find **underlaying functional correlation**
- Study at a **pan-tropical** scale:
    - Study **optimum** observational **elevation angle**
    - Estimation GNSS-R **sensitivity** to AGB as a function AGB levels
    - Visible **&** infrared sensors only upper canopy **+** suffer weather conditions: Trigger study at-a-time **SMAP-derived microwave indices** & **CyGNSS**

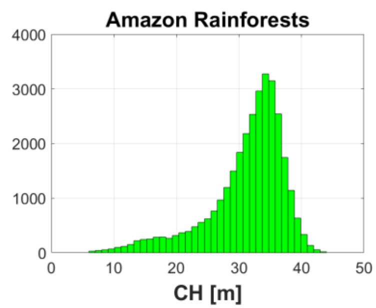
Performance Analysis: Introduction

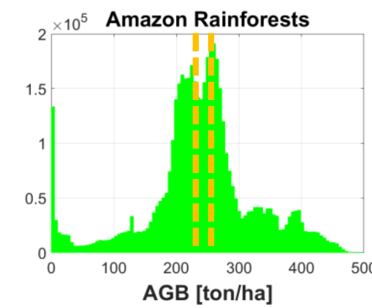


Tropical Rainforests



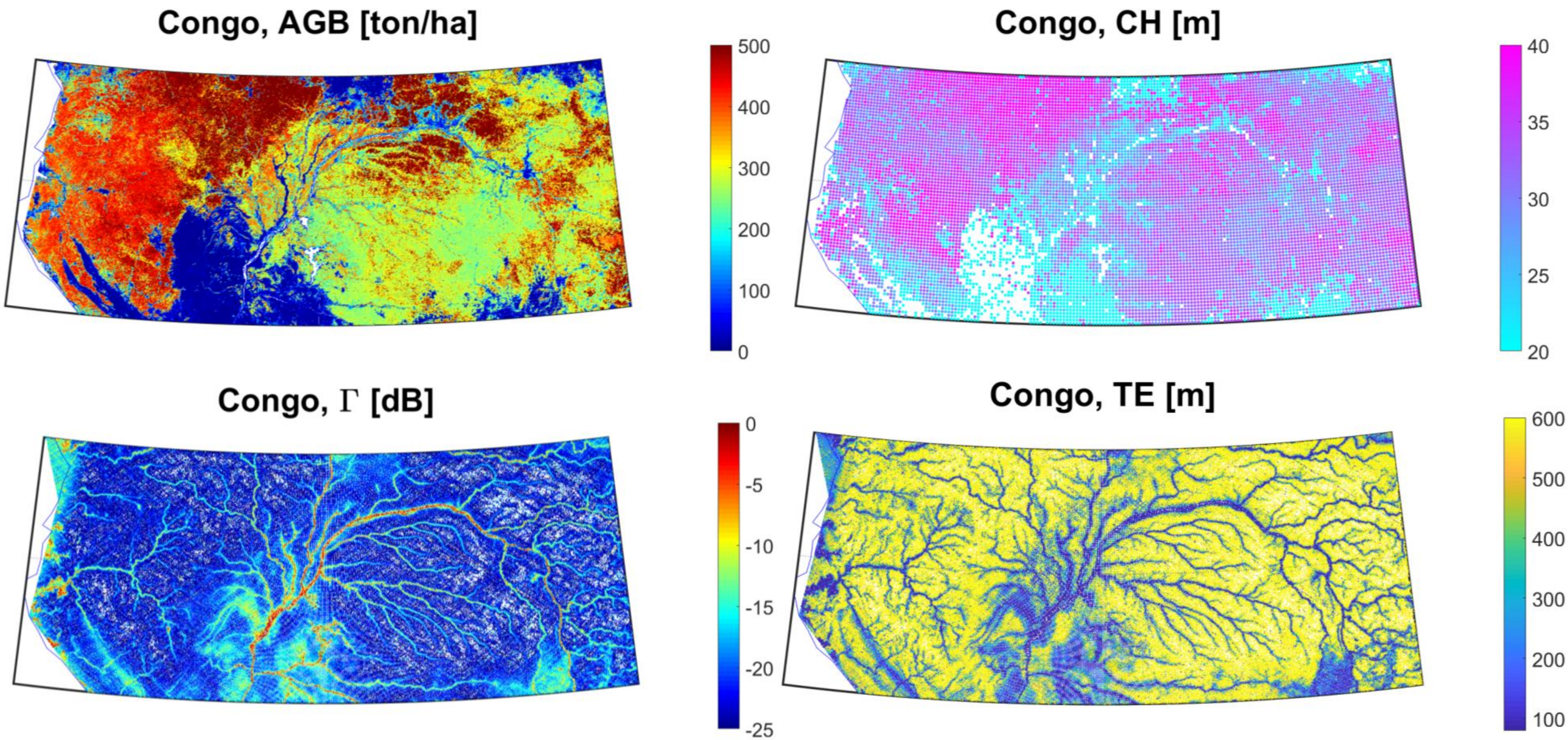






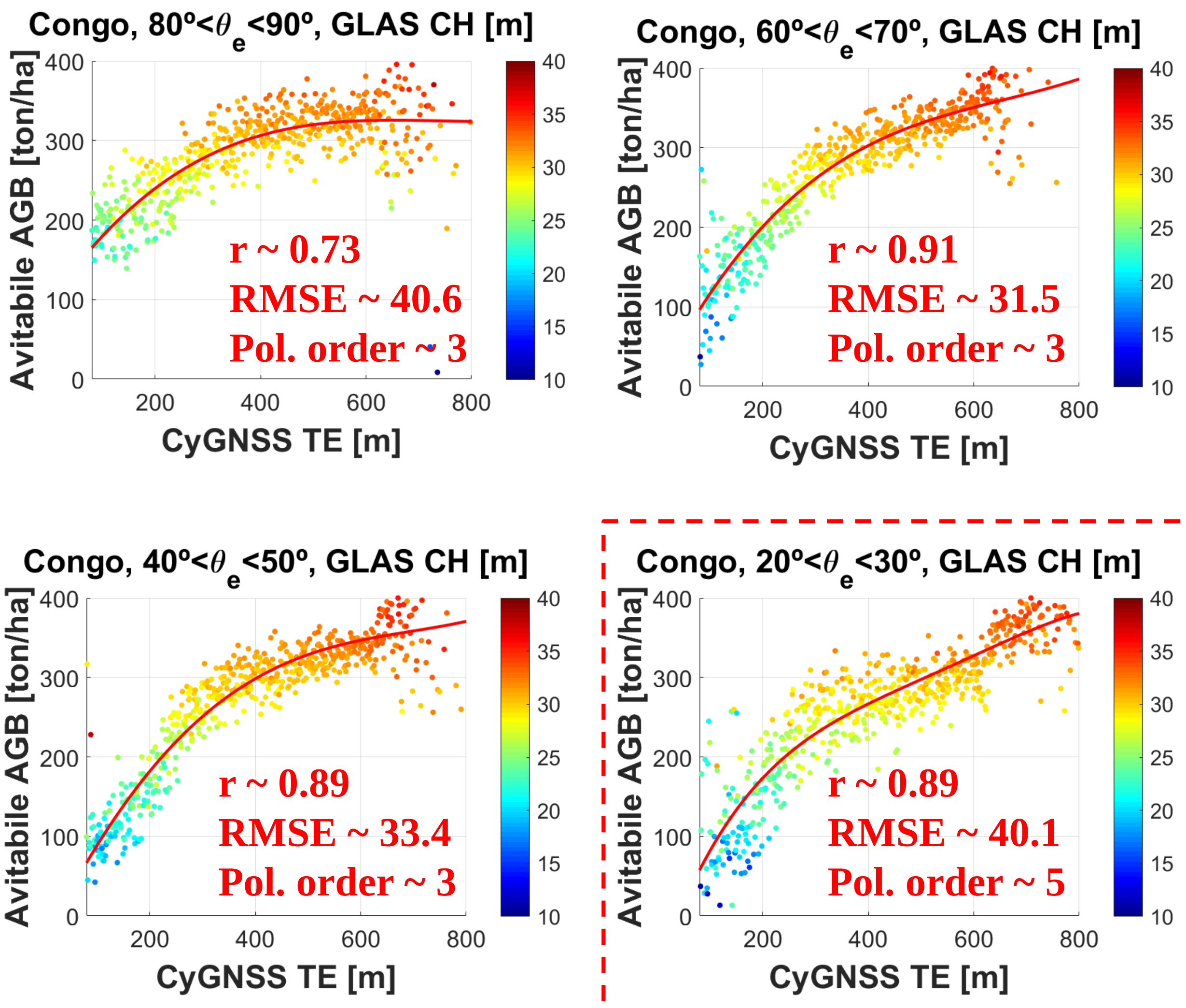
- True rainforests Lat. ~ [-10, 10]
- Mean monthly temperature ~ 18 °C, ~ 1680 mm rainfall
- Dominant International Geosphere Biosphere Program (IGBP): **Evergreen broadleaf forest**
- Characterized by wet biomass: Signal **attenuation effects are dominant**
- Rather unique structural pattern: **Vertical layers** including overstory, canopy, understory, shrub layer, and ground level
- **Complex** dielectric and structural properties
- Amazon very **different AGB** distribution than Congo & **similar CH** distribution

Congo Rainforests



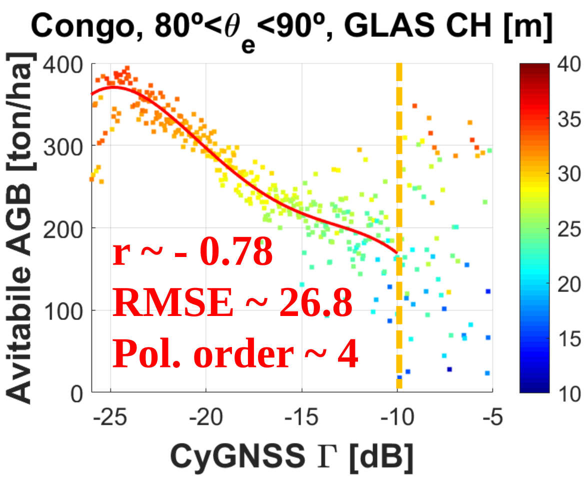
- TE & Γ increases & decreases respectively significantly up to high levels of biomass
- Differentiated effects to be evaluated
- AGB & CyGNSS **sampling properties** perform well
- **CH** selected **auxiliary product** to evaluate AGB vs. CyGNSS observables

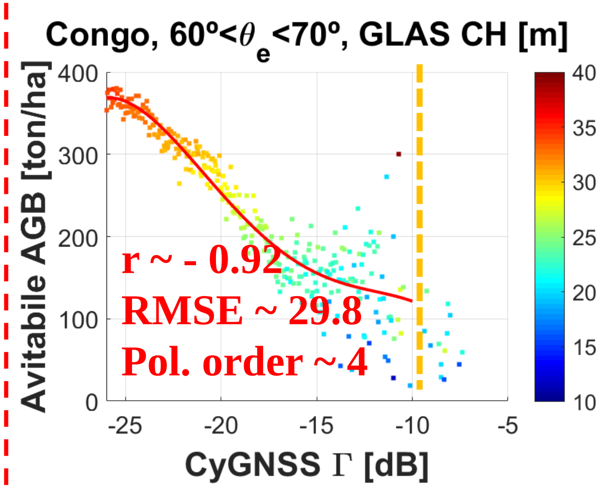
Congo Rainforests: Trailing Edge vs. Elev.

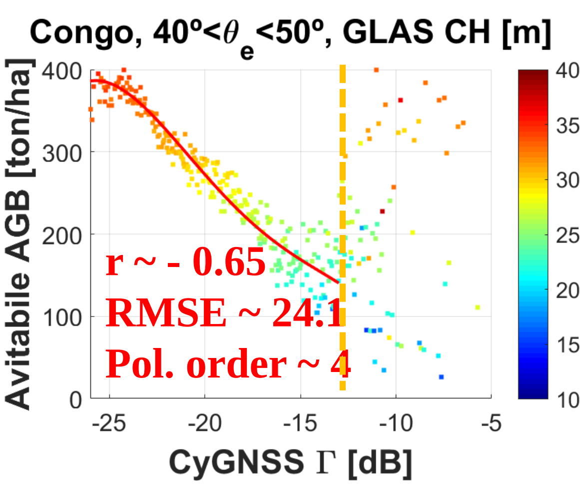


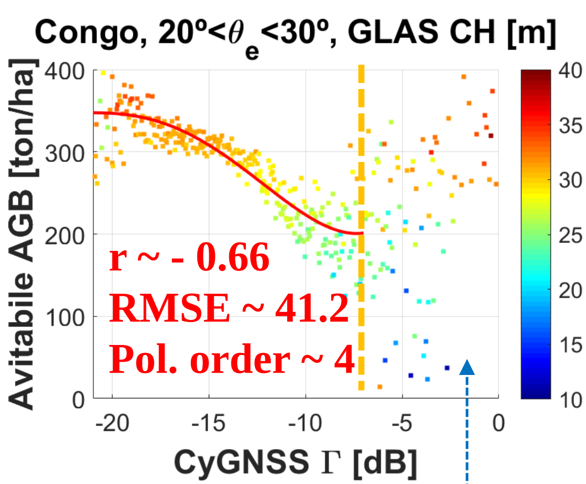
- Empirically-derived polynomial functions
- TE increases up to ~ 800 m at θ_e ~ 20°:
  - Higher volume scattering $\sigma^{incoh,0}$ increases tail WFs
  - Higher coherent scattering $\sigma^{coh,0}$ attenuated
- AGB dynamic range increases with lower θ_e : Higher coherent reflectivity
  - Larger dynamic range SNR: Higher sensitivity to upwelling attenuation cover (wet biomass)

Congo Rainforests: Reflectivity vs. Elev.





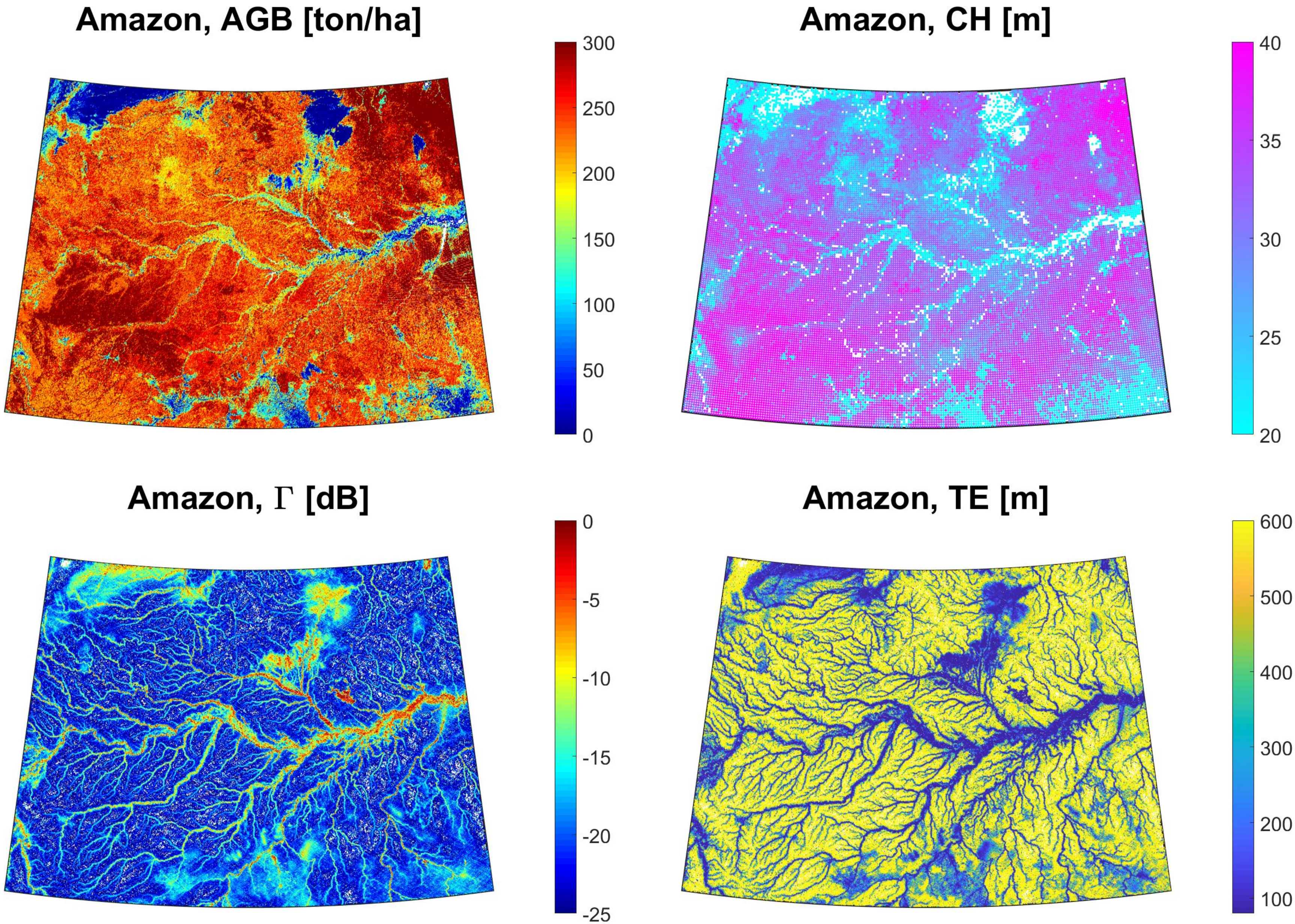




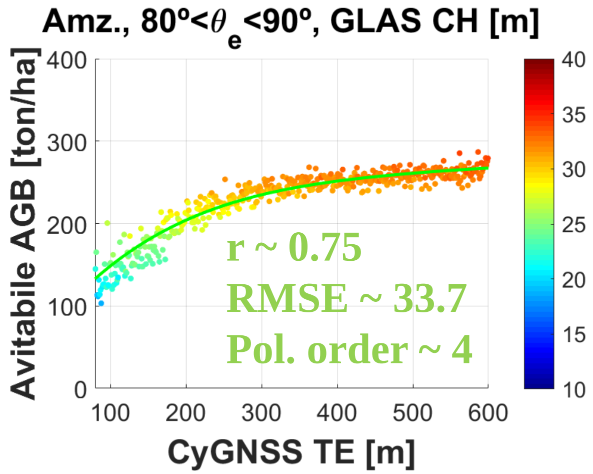
Surface scattering … higher Γ !!

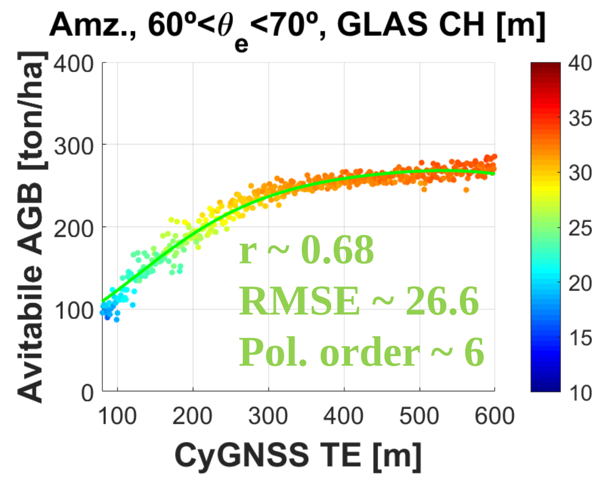
- Reduction Γ : Absorption & scattering effects
- AGB dynamic range increases from θ_e ~ 90° to θ_e ~ 60 ° & decreases with lower θ_e
- Γ significantly higher at θ_e ~ 20 ° : Symptom coherent scatt. dominant
- Sensitivity to AGB improves when incoherent scatt. $\sigma^{incoh,0}$ dominant:
  - Larger propagation path: Vegetation effects
  - Coherent scatt. mainly inked to surface scatt.

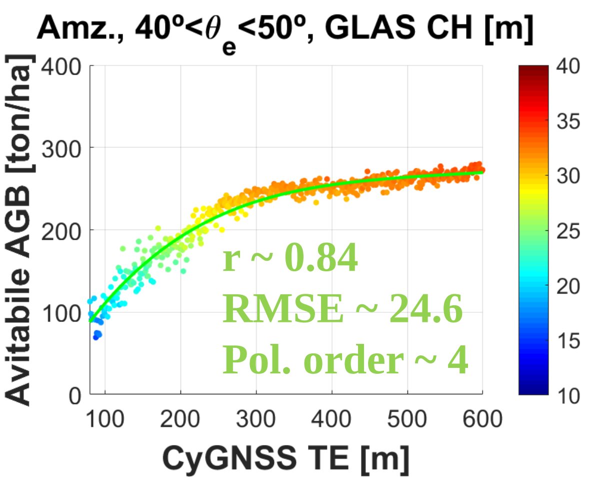
Amazon Rainforests

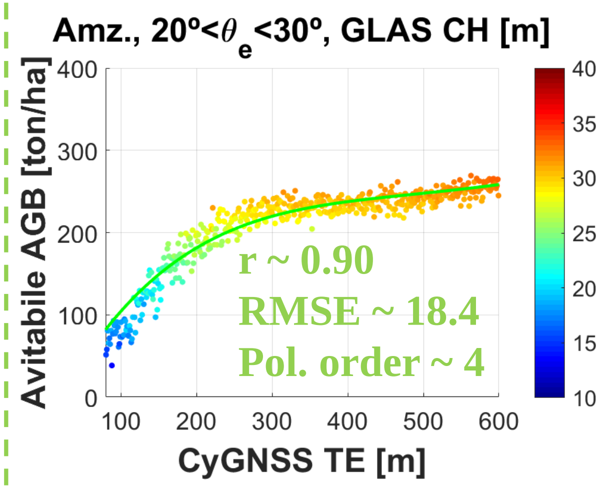


Amazon Rainforests: Trailing Edge vs. Elev.



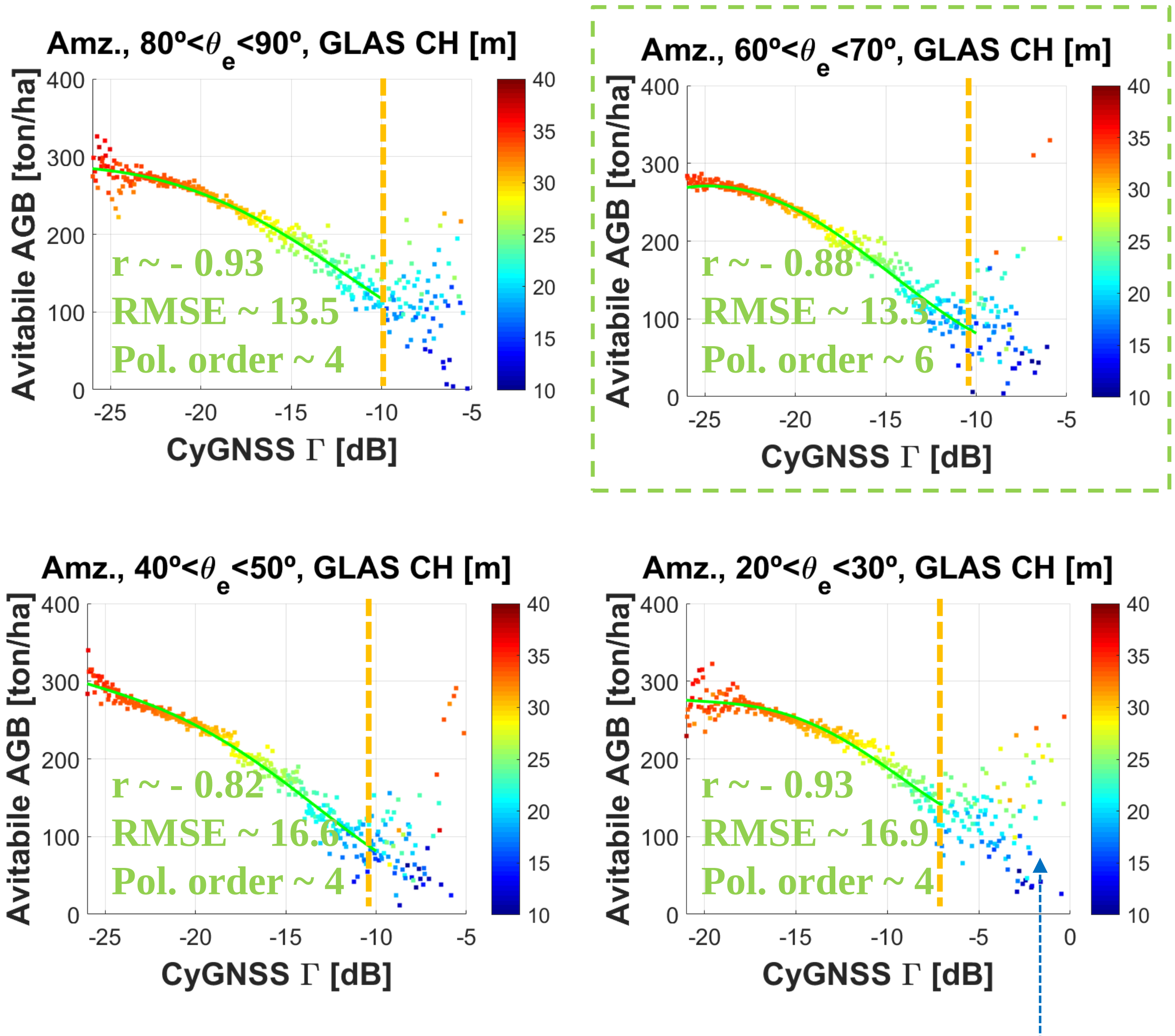






- TE lower spreading ~ 600 m as compared to Congo
- Improved AGB dynamic range at lower angles: ~ 140 ton/ha at θ_e ~ 90 ° vs. 170 ton/ha at θ_e ~ 20 °
- **Smaller angular variability** as compared to Congo:
  - **Amazon:** Re-radiation pattern could have **isotropic properties**
  - **Congo:** Much more **complex structural properties** vegetation cover belonging to higher angular variability

Amazon Rainforests: Reflectivity vs. Elev.

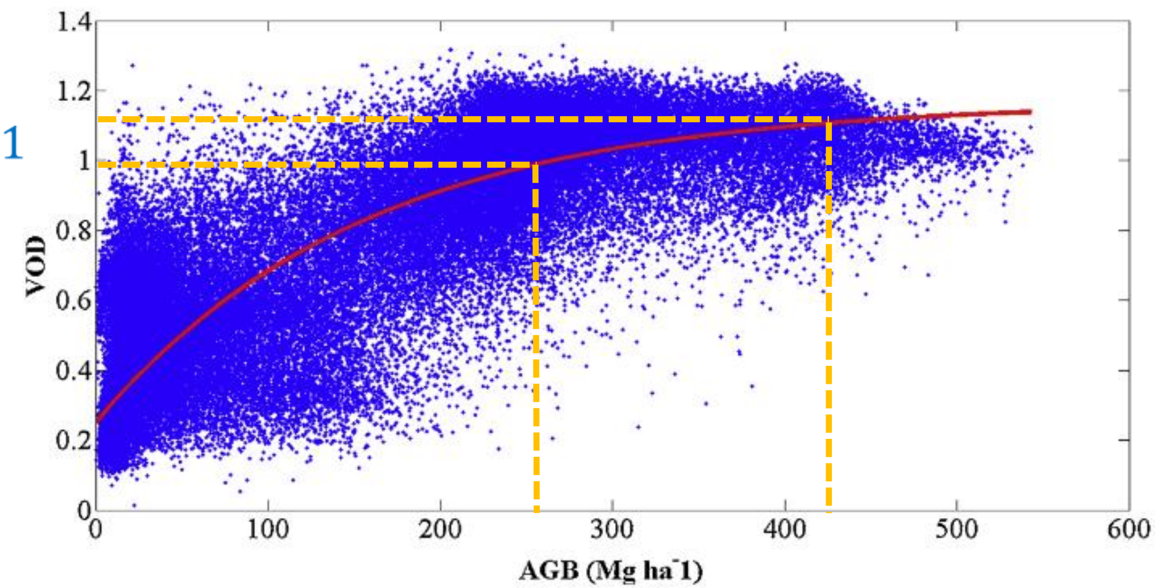


Surface Scattering … higher Γ !!: Higher RMSE

Rainforests: Sensitivity

- **Focus:** CyGNSS sensitivity to AGB
- **Model** fits **ignoring noise**
- Noise **not** represent **"true" noise**: CyGNSS and Avitabile et at. separated time **&** space
- **First derivates** polynomial fitting functions as a function of AGB levels and θ_e
- **SMOS** VOD **example** observational accuracy separate AGB levels:

$\sigma_{VOD} \sim 0.1$



$\sigma_{AGB} \sim 175\ ton/ha$

Image credits
C. Vittucci et al.

Rainforests: Sensitivity

Congo: TE

Congo, TE	50	100	150	200	250	300	350
[20, 30] º	1.53	1.21	0.90	0.55	0.35	0.33	0.30
[40, 50] º	x	1.05	0.93	0.77	0.58	0.37	0.17
[60, 70] º	x	1	0.87	0.71	0.53	0.35	0.19
[80, 90] º	x	x	x	0.62	0.45	0.22	x

Amazon: TE

Amazon, TE	50	100	150	200	250	300	350
[20, 30] º	x	**1.07**	**0.75**	**0.40**	**0.10**	x	x
[40, 50] º	x	1.15	0.85	0.53	0.18	x	x
[60, 70] º	x	x	0.70	0.60	0.20	x	x
[80, 90] º	x	x	0.70	0.42	0.12	x	x

Congo: Γ

Congo, Γ	50	100	150	200	250	300	350
[20, 30] º	x	x	x	x	17.1	15.5	x
[40, 50] º	x	x	x	19.3	25.2	27.4	23.1
[60, 70] º	x	x	10.5	21.2	26	26.1	17.5
[80, 90] º	x	x	x	x	16.2	21.3	16.2

Amazon: Γ

Amazon, Γ	50	100	150	200	250	300	350
[20, 30] º	x	x	15.8	16	9.5	x	x
[40, 50] º	x	17.2	18	16	11.5	9	x
[60, 70] º	x	16	17.8	16	10.4	x	x
[80, 90] º	x	x	15.8	14	9.5	x	x

- Derivate values [(ton/ha)/m **or** (ton/ha)/dB]
- e.g. σ_{TE} ~ 1 m: σ_{AGB} ~ **0.3 ton/ha** at θ_e ~ 20 ° (ideal case, ignoring RMSE) for ~ 350 ton/ha
- **GNSS-R sensitivity requirements reduces** with higher levels AGB
- Amazon **smaller errors** as compared to Congo: Potential effects **biomass structure**

Rainforests: SMAP Vegetation Indices

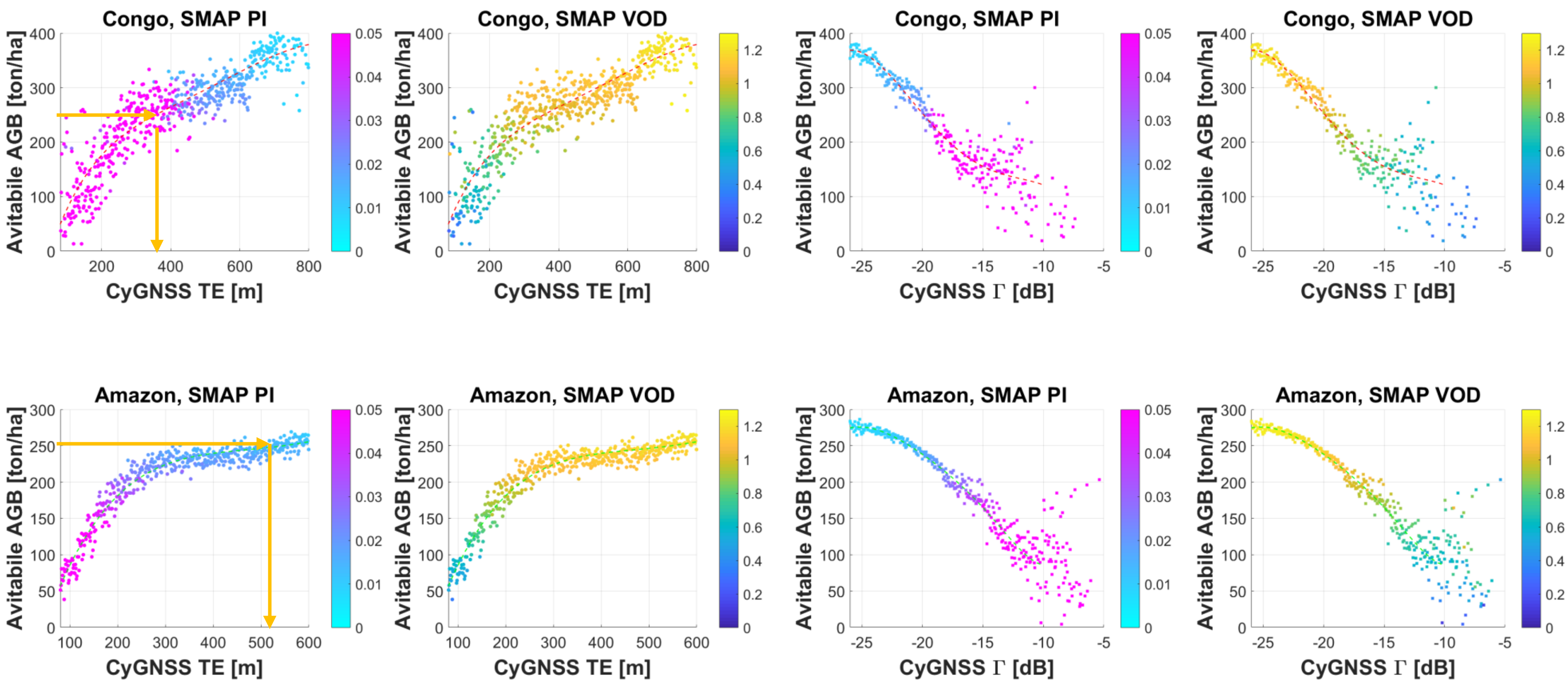
- Functional relationship evaluated at specific **angular ranges with optimum performance** in terms correlation & dynamic range

- Visible & infrared indices only for upper canopy + suffer weather conditions: **Microwave vegetation indices SMAP** Enhanced L3 Radiometer Global Daily

- SMAP VOD used to retrieve transmissivity signal vegetation: $\gamma = \exp(-2VOD/\sin\theta_e)$
  - $VOD = b\,VWC$, b **depends** on **structural effects** upwelling vegetation

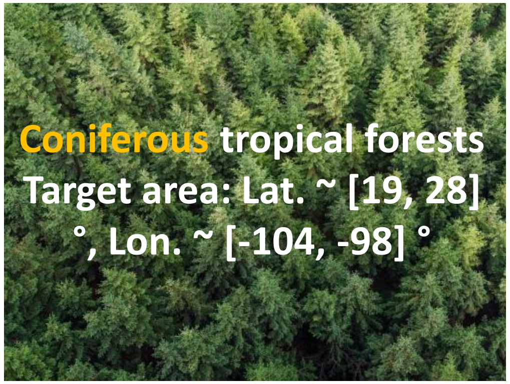
- SMAP PI: $PI = \dfrac{T_{BV} - T_{BH}}{(T_{BV} + T_{BH})/2}$
  - PI independent physical temperature: Normalized measurements brightness temperature
  - Polarized emissivity soil attenuated vegetation: **Potential sensitivity to forest canopy**
  - Some studies **suggest** PI decreases with higher AGB levels **independently vegetation type**
  - Effect scattering & absorption T_B according relative **size plants elements & wavelength**

Rainforests: SMAP Vegetation Indices

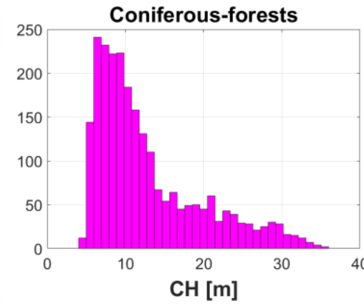


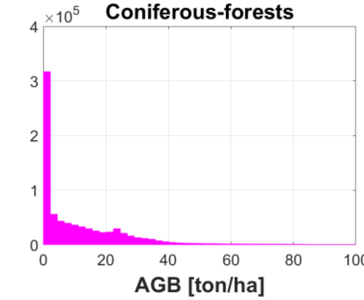
- SMAP VOD & PI show sensitivity up to **high** AGB levels: Attenuation GPS signals
- **Impact of CH on** VOD & PI : Different levels for similar AGB over Congo & Amazon
- Preliminary results **suggest** PI depends on **structural effects** vegetation such as e.g. CH

Other Tropical Forests

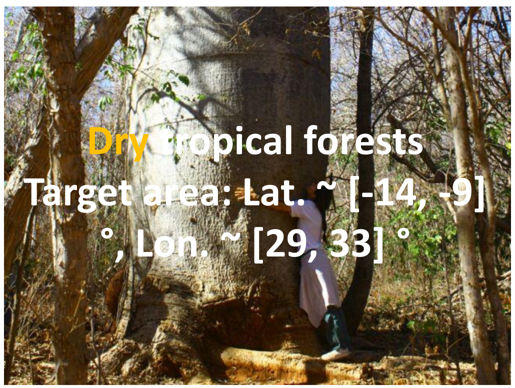


Coniferous tropical forests
Target area: Lat. ~ [19, 28] °, Lon. ~ [-104, -98] °

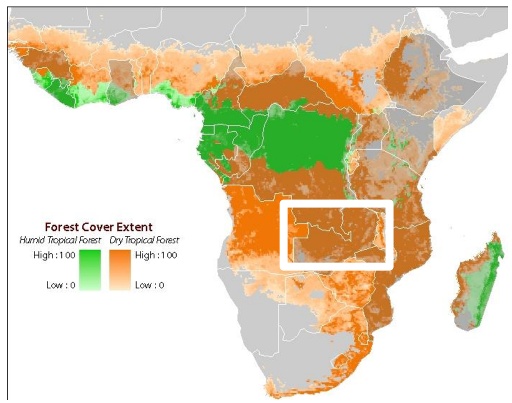


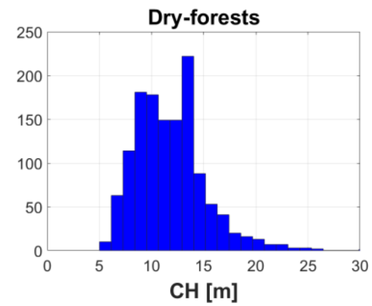


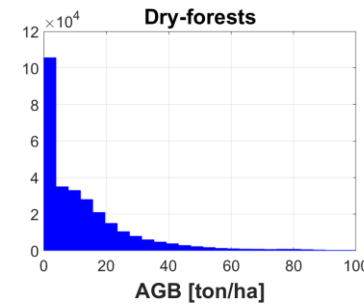
- Firs, pines, spruces



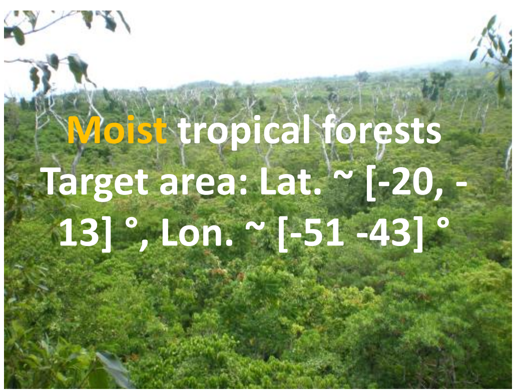
Dry tropical forests
Target area: Lat. ~ [-14, -9] °, Lon. ~ [29, 33] °



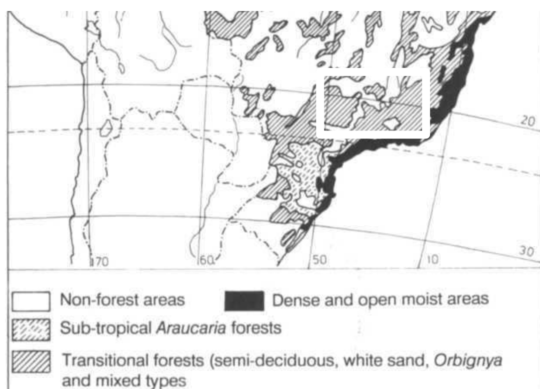


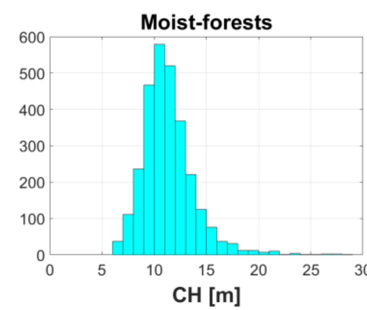


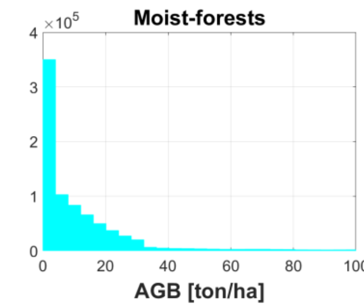
- Deciduous trees



Moist tropical forests
Target area: Lat. ~ [-20, -13] °, Lon. ~ [-51 -43] °

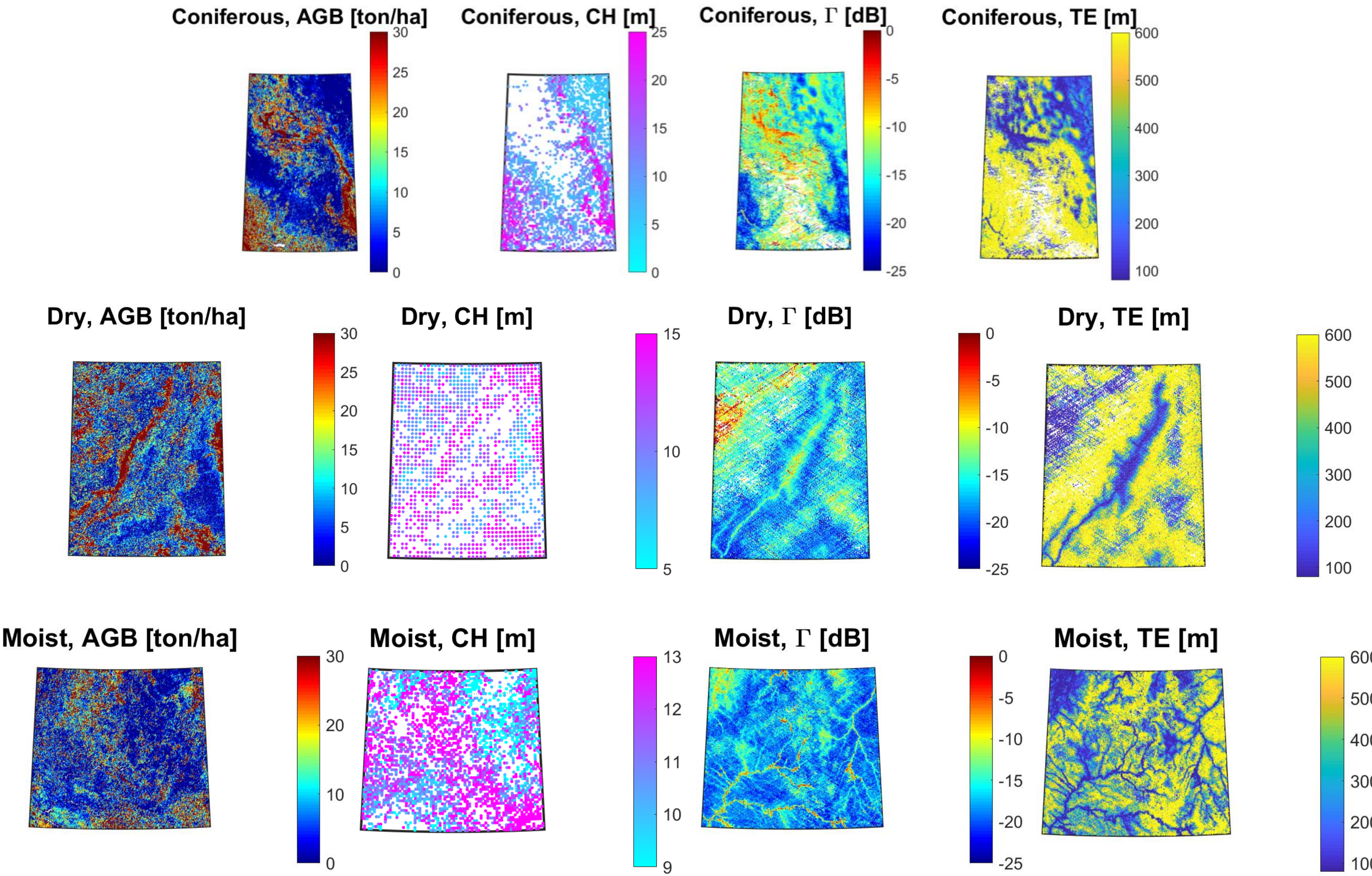




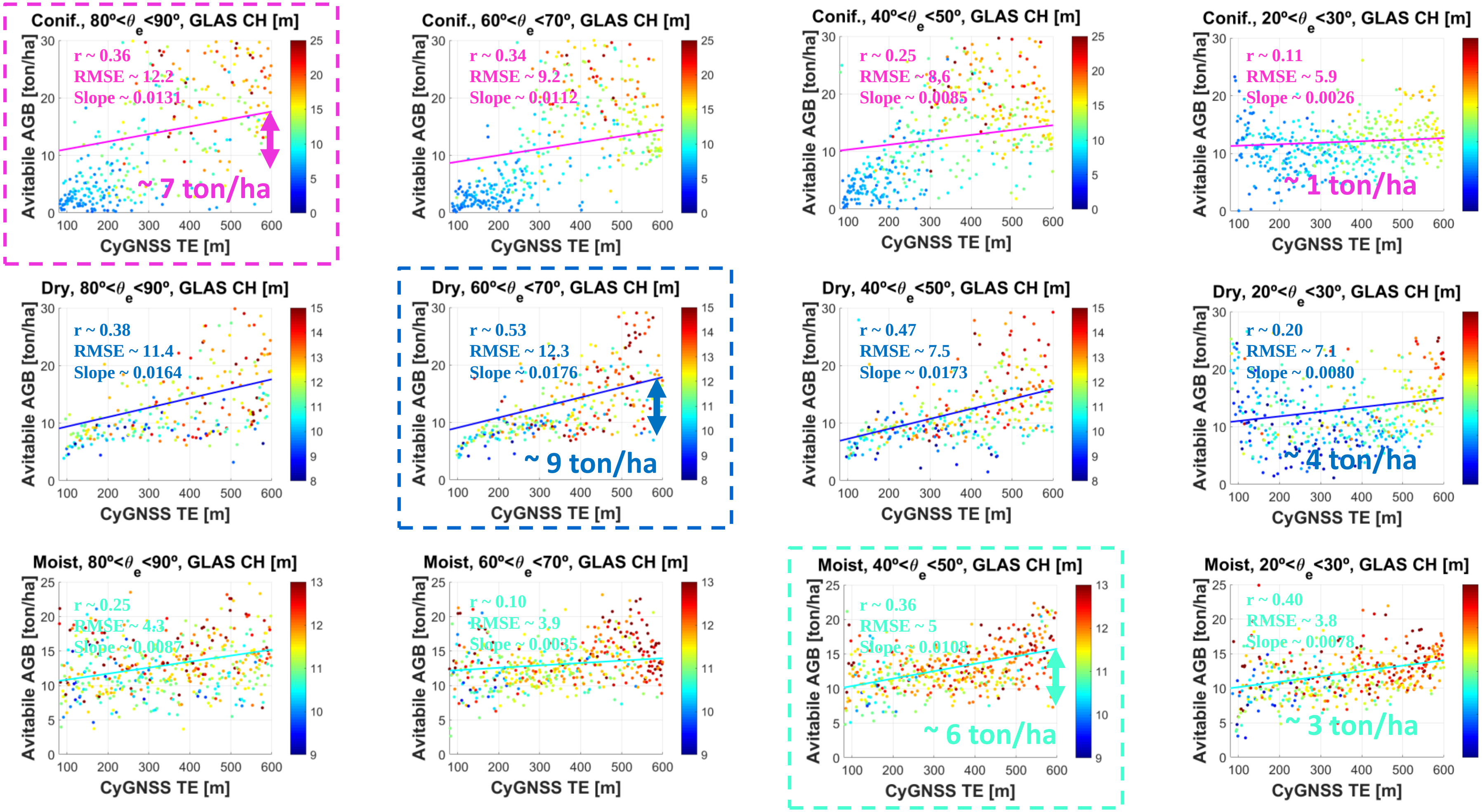


- Semi-deciduous, araucanias

Other Tropical Forests

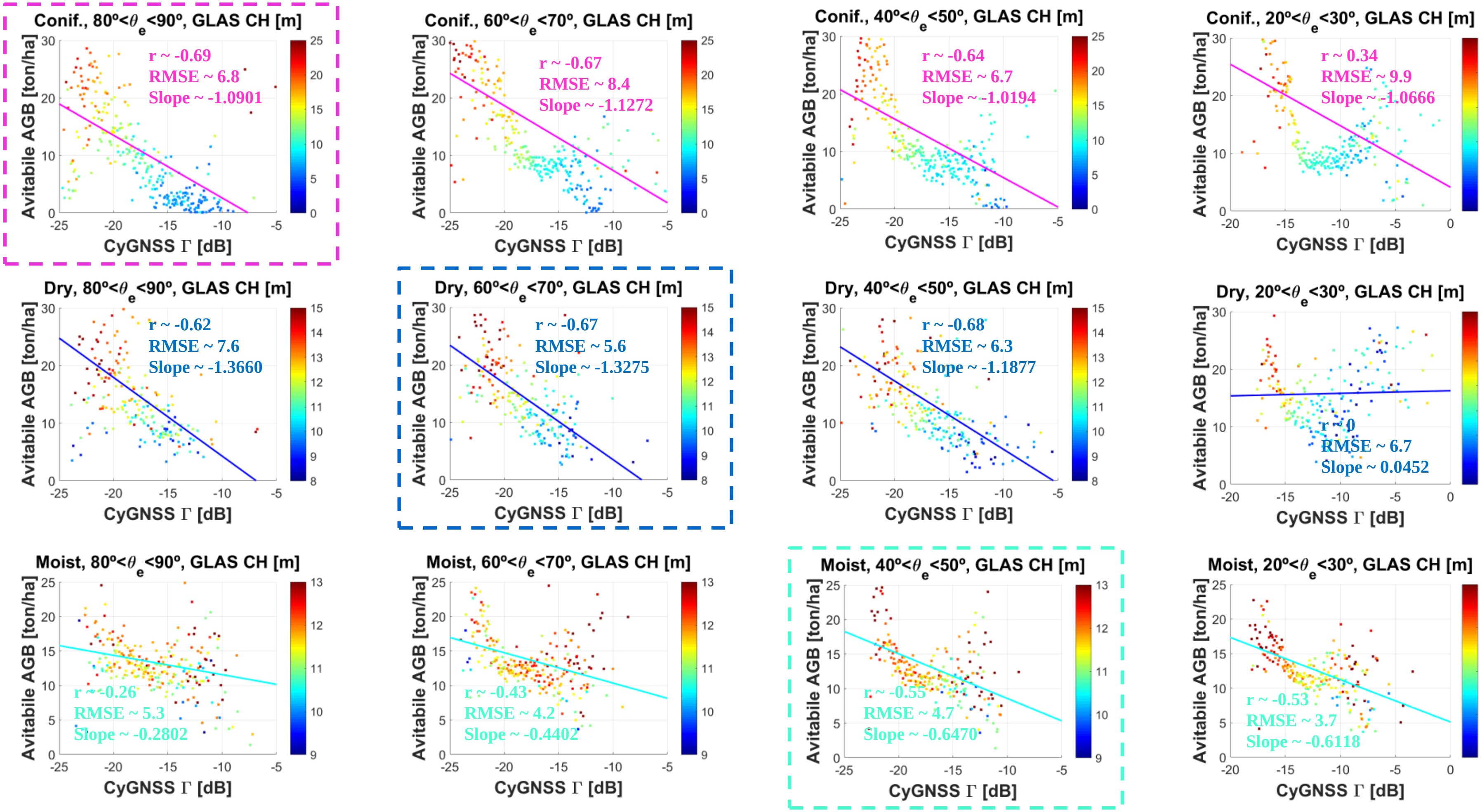


Tropical Forests: Trailing Edge vs. Elev.



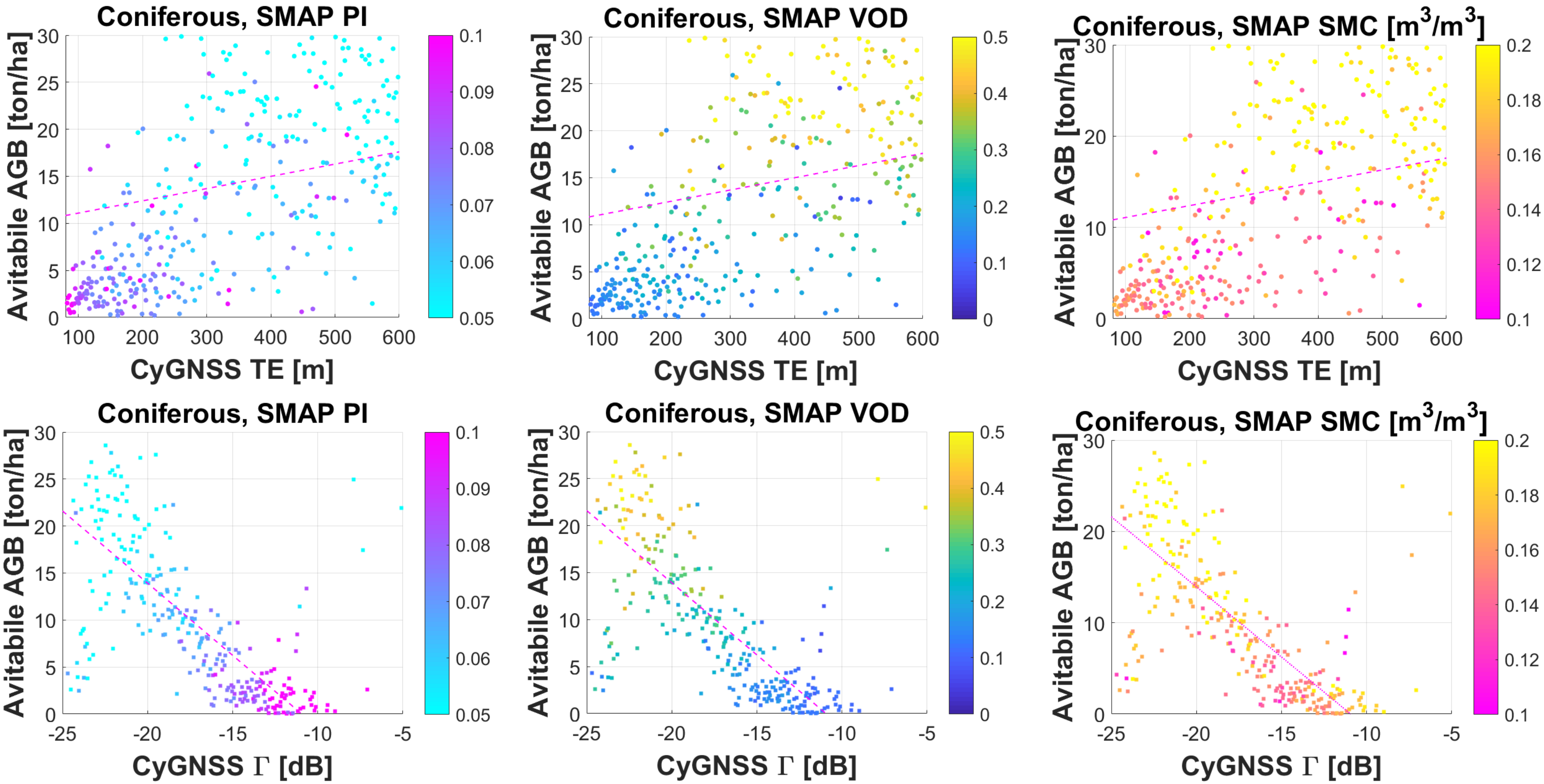
- **Inverse** behaviour rainforests: **Surface** scatt. **dominant** because low AGB ~ < 30 ton/ha
- Lower CH (**key**-parameter) levels: **Lower sensitivity**
- **Optimum sensitivity lower θ_e coniferous-dry-moist:** Larger propagation path required
- Higher RMSE at optimum configuration

Tropical Forests: Reflectivity vs. Elev.



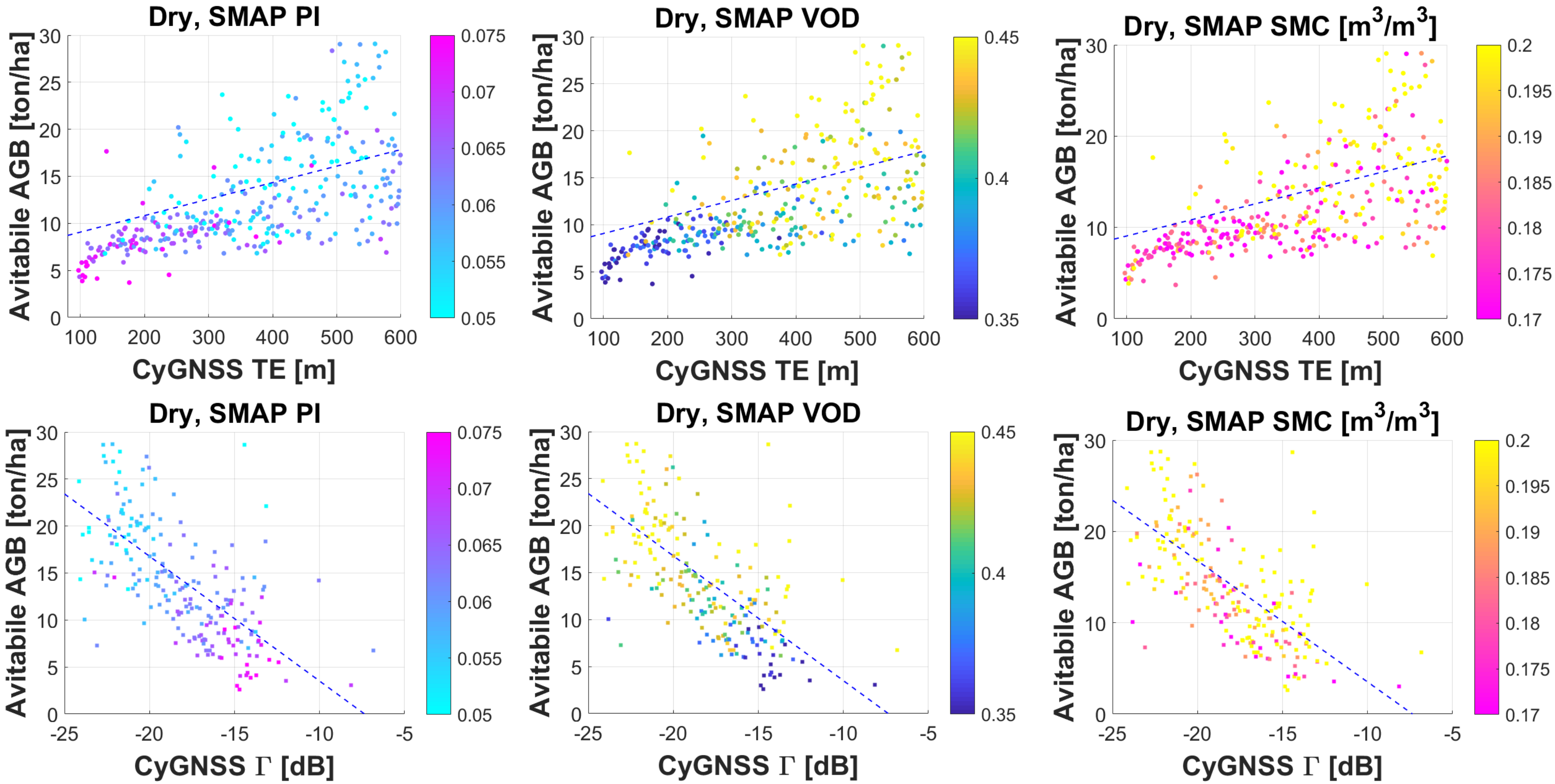
- **Higher correlation coefficients** than TE : Difference behaviour respect rainforests
- Similar impact elevation angle on Γ & TE

Coniferous: *SMAP Vegetation Indices*



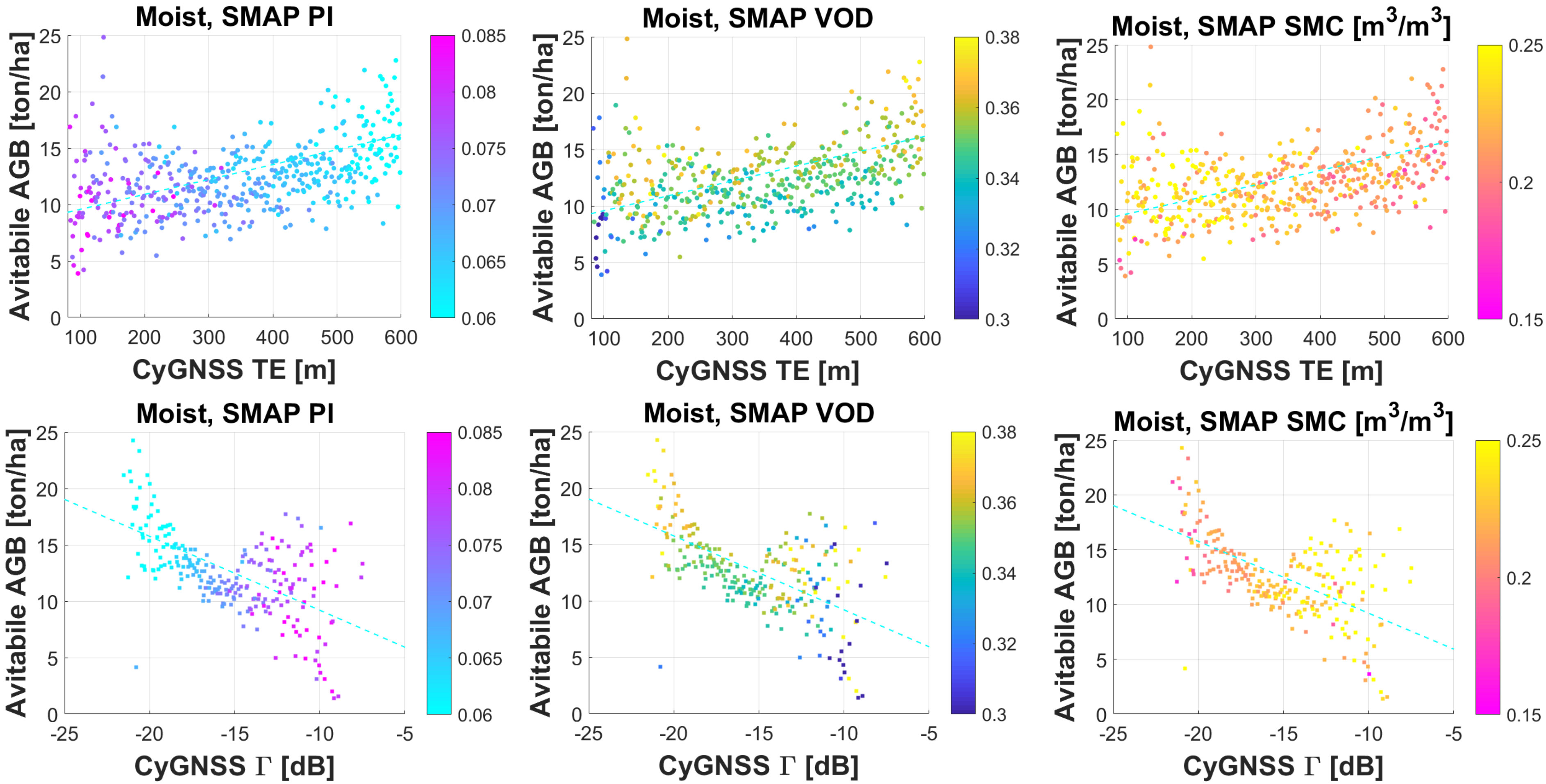
- PI **performs well** in a CH-dependent forest-type
- Results **independent SMC**: Higher TE & lower Γ with higher SMC

Dry Forests: SMAP Vegetation Indices



- PI dynamic range **slightly lower** than coniferous: **Lower CH dynamic range**
- Results **independent SMC**: Higher TE & lower Γ with higher SMC

Moist Forests: SMAP Vegetation Indices



- PI **slightly higher** than dry forests: Slightly lower CH levels
- Results **depend on SMC**: Higher PI with higher Γ and lower TE
- Despite SMC influence, **sensitivity to biomass**

Conclusions

- Earth-reflected GPS signals collected CyGNSS **low antenna gain** ~ 15 dB: Significant sensitivity to **AGB & CH over rain-, coniferous-, dry-, & moist-tropical forests**

- 70 % TE and Γ evaluated as a **function θ_e** : Different performance depending type forest
  - **Congo:** TE at θ_e ~ [20, 30]° & Γ at θ_e ~ [60, 70]°
  - **Amazon:** TE at θ_e ~ [20, 30]° & Γ at θ_e ~ [60, 70]°
  - **Coniferous:** TE & Γ at θ_e ~ [80, 90]°
  - **Dry:** TE & Γ at θ_e ~ [60, 70]°
  - Moist: TE & Γ at θ_e ~ [40, 50]°
- Study **sensitivity**: Focus mean values **ignoring noise**

- Congo & Amazon rainforests: Feasibility to retrieve AGB up to **~ 400 ton/ha & 250 ton/ha** with σ_{AGB} **~ 0.3 ton/ha &** σ_{AGB} **~ 0.1 ton/ha** at θ_e ~ 20 ° (use of TE)

- Optimum functional correlation evaluated SMAP-derived PI , VOD & SMC

- PI certain dependence with CH: **Impact of structural effects**

- PI **increases for lower CH levels**: Coniferous,dry, and moist forests

- Over low AGB forests **results independent SMC** except over moist-forests

Thanks for your kind attention!

Questions?

H.Carreno-Luengo, G.Luzi, and M.Crosetto

Centre Tecnòlogic de Telecomunicacions de Catalunya (CTTC)/CERCA

hugo.carreno@cttc.cat

This research was carried out with the support of a "Juan de la Cierva" postdoctoral research fellowship from the Spanish Ministry of Science, reference FJCI-2016-29356 (classified 1st position).

See you at IGARSS 2019, Japan

Travel expenses partially covered by the 2019 Postdoctoral Award sponsored by the open access journal Remote Sensing published by MDPI.

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

remote sensing

members of Institució CERCA Centres de Recerca de Catalunya

Accredited by tecnio catalonia ACCIÓ

Certified by AENOR

Awarded with HR EXCELLENCE IN RESEARCH