Retrieval of Mediterranean forest traits using hybrid inversion: a comparison of multi-sensor and radiative transfer modeling

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- Mediterranean forests are increasingly impacted by human activities, climate change, and water scarcity
- Forest monitoring systems are essential for evaluating biodiversity, preventing wildfires, and developing effective conservation and management plans
- Optical remote sensing provides information on various biophysical and biochemical traits identified among Remotely Sensed Essential Biodiversity Variables (RS-EBV)[GEO BON].
- Hybrid inversion for vegetation trait estimation reduces dependency to on-site measurements compared to empirical methods, improves generalization at ecosystem level
- Challenges include selecting the appropriate radiative transfer model based (RTM) depending on forest complexity, accurately parameterizing the model according to atmospheric, scene, and sensor conditions, and fine-tuning machine learning algorithms to effectively capture the spectral and spatial features of real remote sensing images.

The objective is to compare the accuracy of two canopy RTMs (1D – SAIL and 3D – DART) coupled with leaf RTM PROSPECT to estimate tree vegetation traits from a rare multi-sensor dataset having multi-/hyperspectral and airborne/satellite imagery. Such a study has been poorly investigated in particular for Mediterranean forests.

Study sites

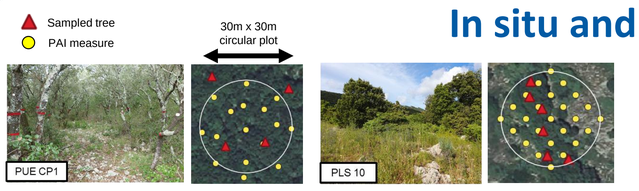
Puéchabon (PUE)

- Homogeneous dense forest (ICOS/FLUXNET networks)
- 2 plots: 100% evergreen oak (*Quercus ilex - QI*)
- Tree canopy covers: 98 - 100%

Pic Saint Loup (PSL)

- Heterogeneous open to dense forest
- 11 plots: mix of evergreen oaks (*QI)* and deciduous oaks (*Quercus pubescens - QP*)
- Tree canopy covers: 71 - 100%

In situ and laboratory data



Date: 7-8-9th June 2021

Plant Area Index (PAI) measurements:

- LAI-2200/2000 plant canopy analyzers (LI-COR Biosciences)
- Sunset & dawn, view cap of 270°, effective PAI computation with FV2200 2.1.1 software assuming homogeneous canopy

Leaf biochemistry estimations from spectral measurements:

- 4-6 sampled trees/plot, 1 shoot/tree, 4 leaves/shoot
- Directional-hemispherical optical properties with ASD Fieldspec 3 spectroradiometer and LI-COR integrating sphere
- Trait estimation from inversion of leaf RTM PROSPECT-D: chlorophylls content (Cab), water (Cw) and dry matter (Cm)

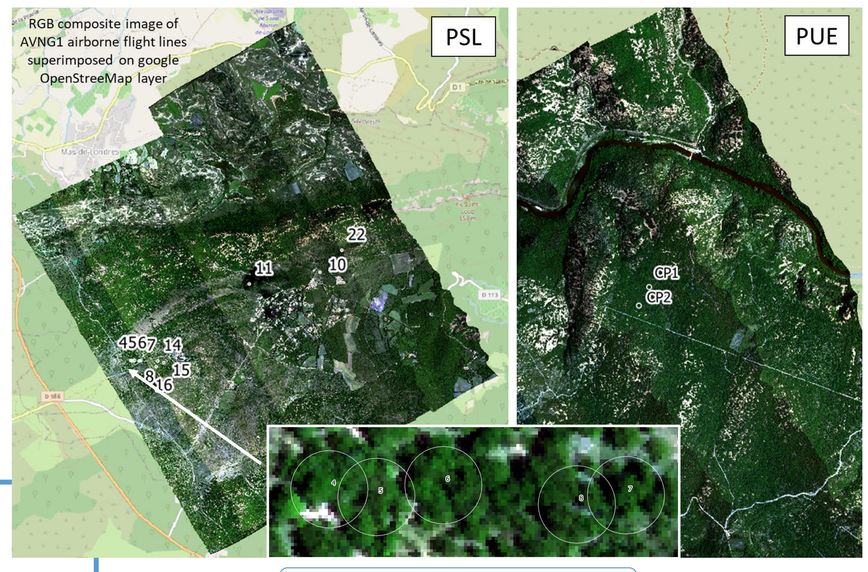
Data availability: https://remotetree.sedoo.fr/catalogue/ (SENTHYMED)

Remote sensing data

Airborne imaging spectroscopy : Hypersense campaign (ESA/NASA/Univ. Zurich)
Satellite hyperspectral and multispectral imagery

Sensor (used acronym)	Spectral characteristics (band number/range/resolution)	Spatial resolution	Date (DD/MM/YYYY)
AVIRIS-Next Generation (AVNG1)	425 bands/377-2501nm/5nm	1 m	09/06/2021 10/06/2021
AVIRIS-Next Generation (AVNG3)	425 bands/377-2501nm/5nm	3 m	09/06/2021
PRISMA	237 bands /407-2497nm/≤ 12nm	30 m	29/06/2021
DESIS	235 bands/401-1000nm/ ~ 3.5nm	30 m	29/06/2021
SENTINEL-2	10 bands/492-2186nm/13-184 nm	10 m	26/06/2021

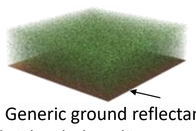
AVIRIS-Next Generation (https://ares-observatory.ch/esa_chime_mission_2021/), PRISMA (https://www.asi.it/en/earth-science/prisma/), DESIS (https://eoweb.dlr.de/egp/), Sentinel-2 (https://www.theia-land.fr/en/product/sentinel-2-surface-reflectance).



Methodology

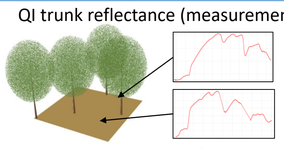
Modeling

SAIL



Generic ground reflectance (bright, dark and intermediate levels)

DART



QI trunk reflectance (measurement)

Mix of grass, limestone & bare soil reflectance (measurement)

	SAIL	DART
Forest	• Homogeneous forest representation • Canopy cover 100% • Turbid medium and flat ground • Ellipsoidal leaf angle distribution	• Simple 3D forest representation • Canopy cover ~ 90% (4 trees) • Leaf facets and flat ground • Ellipsoidal leaf angle distribution
Atmosphere	• Generic BOA irradiances • Clear sky atmospheric conditions	• Bottom of atmosphere irradiance specific to each sensor acquisition • Mid latitude summer gas profile and rural aerosols (visibility 23 km)
Sensor	• Sensor: same spectral characteristics	• Sensor: same spectral characteristics

Design of experiments

LAI range: 0-13 [m2/m2]
Cab range: 20-90 [µg/cm2]
Ant: 0.0003-2.6 [µg/cm2]
Cw range: 0.005-0.055 [g/cm2]
Cm range: 0.004-0.03 [g/cm2]
Brown: 0-1 [-]
N: 1.2-1.8 [-]
ALA: 30-80 [°]
Q: 0.1-0.5

Cf. ATBD distribution (http://step.esa.int/docs/extra/ATBD_S2ToolBox_V2.1.pdf)

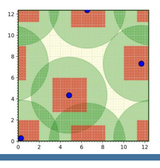
Additive: 0.005%
Multiplicative: 1%

Noising application

Simulations → 2000 spectra per sensor

Extraction

Spectral averaging for DART:
- AVNG1/AVNG3: 3x3 m buffer centered on trees
- Others: whole scene



Machine learning training

SAIL:
Support vector regression with optimized spectral intervals (except SENTINEL-2):
LAI → [0.65-1.2] µm
Cab → [0.70-0.85] µm
Cw → [1.2-2.4] µm
Cm → [1.6-2.4] µm

DART:
Partial least square regression with selection of optimal number of latent variables from the full spectral range

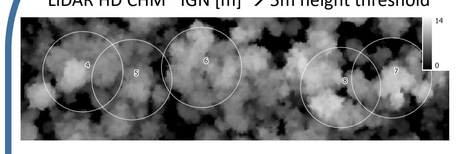
Application of best models

Spectral preprocessing

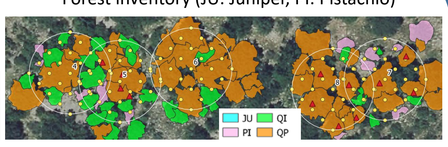
- Range: 0.5-2.4 µm
- Remove atmospheric water vapor windows
- Savitzky–Golay smoothing (except SENTINEL-2)

Maps of trait estimations

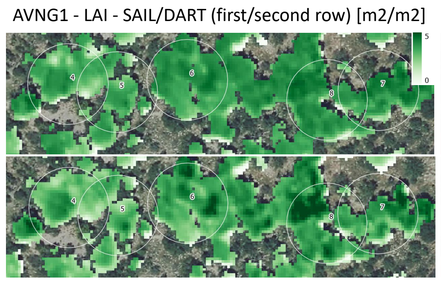
LiDAR HD CHM® IGN [m] → 5m height threshold



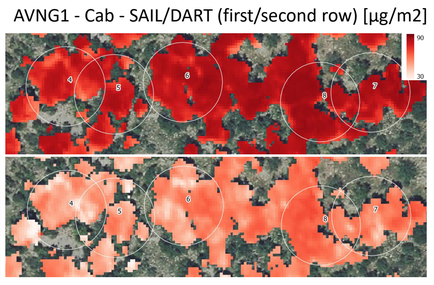
Forest inventory (JU: Juniper, PI: Pistachio)



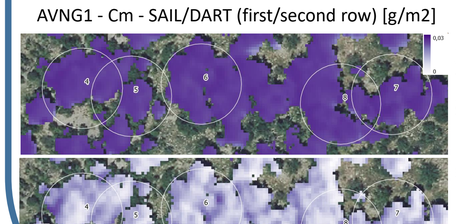
AVNG1 - LAI - SAIL/DART (first/second row) [m2/m2]



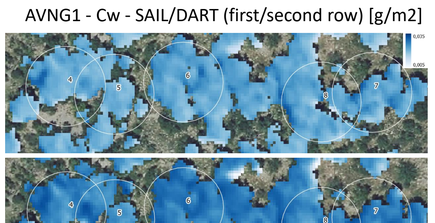
AVNG1 - Cab - SAIL/DART (first/second row) [µg/m2]



AVNG1 - Cm - SAIL/DART (first/second row) [g/m2]

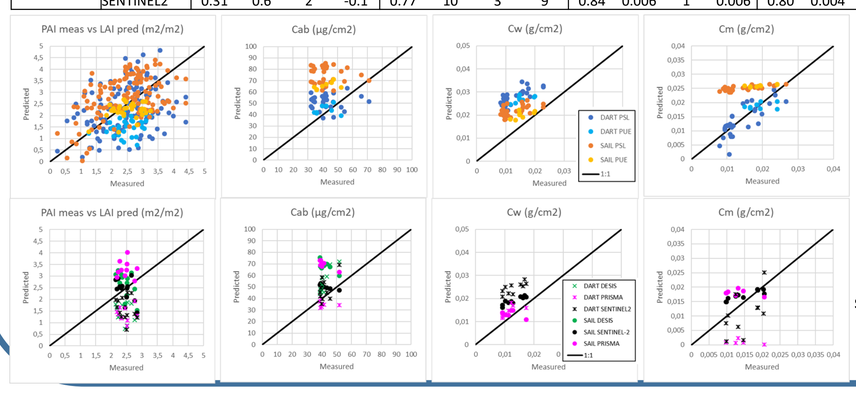


AVNG1 - Cw - SAIL/DART (first/second row) [g/m2]



Validation

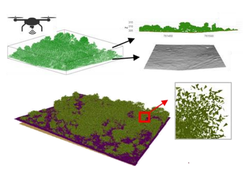
		LAI [m2/m2]				Cab [µg/cm2]				Cw [g/cm2]				Cm [g/cm2]			
		R2	RMSE	nRMSE	Bias	R2	RMSE	nRMSE	Bias	R2	RMSE	nRMSE	Bias	R2	RMSE	nRMSE	Bias
DART	AVGN1	0.13	1.1	1	-0.4	0.0	13	1	8	0.49	0.014	2	0.014	0.63	0.003	0.4	-0.000
	AVNG3	0.11	1.1	1	0.0	0.02	13	1	10	0.51	0.014	2	0.014	0.59	0.004	0.6	0.003
	PRISMA	0.00	1.4	6	-1.3	0.13	18	6	-12	0.43	0.004	1	0.003	0.10	0.013	3	-0.013
	DESIS	0.00	1.5	13	-1.3	0.11	10	13	9								
	SENTINEL2	0.05	1.0	4	-0.8	0.33	10	3	6	0.55	0.012	2	0.011	0.32	0.007	0.9	-0.004
SAIL	AVGN1	0.19	0.9	0.9	0.2	0.00	32	3	30	0.07	0.010	2	0.009	0.58	0.011	1	0.010
	AVNG3	0.13	0.9	0.9	0.3	0.05	33	3	30	0.13	0.010	2	0.009	0.16	0.011	1	0.010
	PRISMA	0.00	0.9	4	0.8	0.68	29	19	28	0.27	0.004	1	0.002	0.17	0.006	2	0.005
	DESIS	0.33	0.7	3	0.2	0.55	27	8	26								
	SENTINEL2	0.31	0.6	2	-0.1	0.77	10	3	9	0.84	0.006	1	0.006	0.80	0.004	0.5	0.002



Metrics:
- R^2 (coefficient of determination of linear regression)
- RMSE (Root Mean Square Error)
- nRMSE (normalized RMSE based on interquartile range)
- Bias (mean bias)

Sensor	PRISMA, DESIS, SENTINE-2	AVNG1, AVNG3
Validation points	Plot scale	Tree/Point scale
Leaf biochemistry	10	43
PAI	13	175

Conclusions and perspectives



Preliminary results to be adjusted with future investigations:
- for DART, test more ground optical types and tree canopy covers, include branches,
- comparison with same machine learning model and spectral features selection,
- differenciate errors coming from scene modeling, georeferencing issues and uncertainties of field measurements
- compare these results with the use of precise 3D forest mockups generated from **UAVborne LiDAR data** (tools: LidR, AmapVox, pytools4dart)
- assess the performances of future hyperspectral satellites (Biodiversity, SBG, CHIME) from AVNG1 simulations

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