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Adequacy of Mediterranean forest simulations from DART radiative transfer model and UAV laser scanning data to hyperspectral images

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ABSTRACT

Mediterranean-type ecosystems are among the most affected by global climate change due to an increase in droughts and fires. Sentinel-2 satellites are currently among the best alternative for operational vegetation properties monitoring because of their temporal revisit and global coverage. The increasing availability of spaceborne imaging spectrometer (e.g. DESIS, PRISMA, EnMAP) and the preparation of missions ensuring global accessibility (e.g. CHIME, BIODIVERSITY) will enable the estimation of vegetation traits with better accuracies. The SETHYMED project aims to study the complementarity between multi- and hyperspectral images to evaluate Mediterranean forest functional traits. The objective is to estimate canopy pigment, leaf water and dry matter contents from physical model inversion using DART radiative transfer model. A preliminary step is to study the influence of DART optical properties parametrization on remote sensing image simulation in order to simulate scenes as accurately as possible. Two forests in the South of France, mainly composed of evergreen oaks and pubescent oaks, with heterogeneous canopy structure, were studied. UAV LiDAR data were first acquired and converted into voxel matrices of plant area density values with AMAPVox. Pytools4dart was then used to build the mock-ups, handle DART parameterization and generate images in spectral reflectance unit at canopy level. Several simulations were implemented, assigning different optical properties to the underground and to the canopy. These images were compared to airborne AVIRIS-Next generation acquisitions, acquired close to the field campaign that took place in June 2021 and where in-situ measurements were collected for calibration and validation of DART simulations.

Keywords: Imaging spectroscopy; Unmanned aerial vehicle laser scanning; Radiative transfer; Mediterranean forests

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1. INTRODUCTION

In the current context of climate change, the increase in droughts and fires affect forests, in particular Mediterranean ones. In order to study their health status and evolution, remote sensing imagery can be used, allowing to study large areas in a relatively limited amount of time compared to field-based observations. Sentinel-2 images are often used because of their global coverage and the high temporal revisit. They have however a limited spectral resolution and a relatively low number of bands. Thus, the development of imaging spectroscopy could enhance vegetation monitoring. The SENTRYMED project aims to study the complementarity between multi- and hyperspectral images to evaluate Mediterranean forest functional traits from field and LiDAR data and using DART radiative transfer model. One work package of the project is dedicated to canopy level and includes the estimation of canopy pigment, leaf water and dry matter contents from DART model inversion. However, to accurately assess these contents, it is necessary to simulate scenes precisely. Several parameters influence the simulated reflectance, including scene structural and optical properties. Many studies in forest modeling use simplified geometric representation of trees and make assumptions regarding structural parameters such as leaf angle distribution, tree height or crown shape^{1, 2}. Scene structure can otherwise be reconstructed using airborne or terrestrial LiDAR data^{3, 4}, leading to a more realistic representation of the forest. Optical properties definition is also decisive in radiative transfer modeling, at the leaf level but also at the understory level, as some studies demonstrated an influent effect of canopy background on simulated radiance, even in closed forests³. Several articles also highlighted the importance of not omitting woody structures when simulating radiative transfer in forests^{5, 6}. Therefore, a preliminary step is carried out to evaluate the impact of DART optical properties parametrization on remote sensing image simulation. This article presents this preliminary step of the project and the results on one plot.

2. DATA

2.1 Study sites

Two forests in the South of France, near Montpellier (Pic Saint Loup (PSL) and Puechabon) are studied. They are mainly composed of evergreen oaks (*Quercus ilex*) (QI) and pubescent oaks (*Quercus pubescens*) (QP). The 10 studied plots, defined as 30m side squares, have variable canopy covers between 47% and 98%. The plot 8 whose results are presented in this article is in the PSL forest, has a canopy cover around 70% and is composed of 90% of QP.

2.2 Field data

The main trees of the plots were inventoried between the 7th and the 10th of June 2021, by recording their species, and their trunk position and crown delineation with a GPS. 4 leaves of 4 dominant trees by plot (i.e. visible from top of canopy) were sampled in the top sunlit part of the crown, wrapped in aluminum foil, put in a ziplock bag and stored in a cooler. Optical measurements of their directional-hemispherical reflectance and transmittance were performed in laboratory with an ASD spectroradiometer coupled with an integrating sphere. Reflectance of nine different forest understories (grass, limestone, litter and different mixes of these components with bare soil) and reflectance of QI and QP trunk were measured in the field with an ASD spectroradiometer, coupled with a contact probe for trunk measurements.

2.3 Imaging spectroscopy data

Airborne hyperspectral images were acquired on June, 9th and 10th, 2021, with AVIRIS-Next Generation (AVNG) sensor. The at-surface reflectance images were downloaded on <https://ares-observatory.ch>, have a spatial resolution of 1m and are composed of 425 bands between 380 and 2510nm with a bandwidth of 5nm⁷.

2.4 Unmanned aerial vehicle laser scanning data

Unmanned aerial vehicle (UAV) laser scanning data were acquired on June, 16th, 23rd and 25th, 2021, with a YellowScan Surveyor sensor embarked on a DJI Matrice 600 Pro UAV (<https://doi.org/10.15454/AGBW7G>; <https://doi.org/10.15454/DMYWPB>). The flight trajectory was at 50m height above ground level and followed a double grid with interline distances of 40 meters. The final point density of each plot was between 400 and 740 points per m².

3. METHODOLOGY

3.1 Reflectance spectra pre-processing

Leaf, trunk and understory spectra were first sorted to remove spectra with anomalies and then smoothed by applying Savitzky-Golay filter. Median spectra were calculated for QI and QP trunk, for each understory type, for each dominant tree from their four sampled leaves, and for QI and QP species from all the QI or QP leaves sampled across the two sites. Two datasets of mix spectra were also computed by calculating a weighted average between two median spectra: leaf/trunk mix spectra and QI/QP mix spectra. Leaf/trunk mix spectra were generated by including different ratios of QI or QP trunk median spectrum (between 10 and 50% by step of 10%) in the trees and species median spectrum. QI/QP mix spectra were calculated by including different ratios of QI leaf/trunk mix spectra in QP leaf/trunk mix spectra (between 10 and 90% by step of 10%).

The following steps were implemented at each plot, on areas bigger than the plots defined as 100m side square to take into account the influence of neighboring trees in the simulation.

3.2 LiDAR point cloud voxelization

LiDAR data were first classified with the Multiscale Curvature Classification algorithm to distinguish ground and non-ground points. A 1m resolution Digital Elevation Model (DEM) was then constructed with the Inverse Distance Weighting algorithm. Both steps were implemented with the lidR package⁸.

LiDAR point clouds were then voxelized with the AMAPVox software⁹. This R package retrieves laser pulses from LiDAR data and UAV trajectory and calculates transmittance or attenuation of the signal for each cell of a 3D grid (voxel, here cube of 25cm side). Plant Area Density (PAD) is then computed for each voxel using the Free Path Length estimator¹⁰.

3.3 3D mock-up construction and DART simulations

DART¹¹ (Discrete Anisotropic Radiative Transfer) is a physically based 3D model simulating the Earth-atmosphere radiation interaction from visible to thermal infrared wavelengths. It can be used to simulate remote sensing images of natural landscapes. DART simulations were implemented through pytools4dart¹² python package, developed for complex and massive simulations.

The PAD matrix was used as DART input to construct the 3D mock-up of the scene, leaves being simulated by facets. The mock-up was intersected with the field crown delineation to attribute each tree optical properties depending on the simulations. Different simulations were carried out to test the influence of optical properties parametrization by varying simultaneously the canopy spectrum (tree, species or mix QI/QP, with different leaf/trunk ratio) and the understory one.

Simulations were implemented with the DART-Lux mode and an analytical model of the atmosphere. DART output were images with a 25cm spatial resolution and the same spectral resolution as AVNG images, with bands between 450nm and 1770nm. They were finally resampled to get a 1m spatial resolution.

3.4 Comparison between DART simulations and AVNG images

To assess the agreement between simulated and real images, two metrics were calculated for each pixel of the image: the Root-Mean-Square Error (RMSE) and the Spectral Angle Mapper (SAM). The smaller their values, the better the simulation matches the AVNG image.

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^N (\rho_{simu,i} - \rho_{ref,i})^2} \quad ; \quad SAM = \cos^{-1} \left(\frac{\sum_{i=1}^N \rho_{simu,i} * \rho_{ref,i}}{\sqrt{\sum_{i=1}^N \rho_{simu,i} * \rho_{simu,i}} * \sqrt{\sum_{i=1}^N \rho_{ref,i} * \rho_{ref,i}}} \right)$$

with N the number of bands, ρ the reflectance, $simu$ the result of DART simulation, ref the AVNG image

Means of RMSE and SAM values were also computed at the plot level.

4. RESULTS

The comparison of mean RMSE and SAM values for different combinations of understory spectra and trunk ratio in the canopy spectrum highlights a low influence of the understory on the final simulation reflectance (Figure 1), which is in line with the relatively high canopy cover. Conversely, the ratio of trunk in the canopy spectrum strongly impacts the results. Mean RMSE and SAM values are minimized for a mix bare soil and grass understory and for a ratio of trunk of 10%.

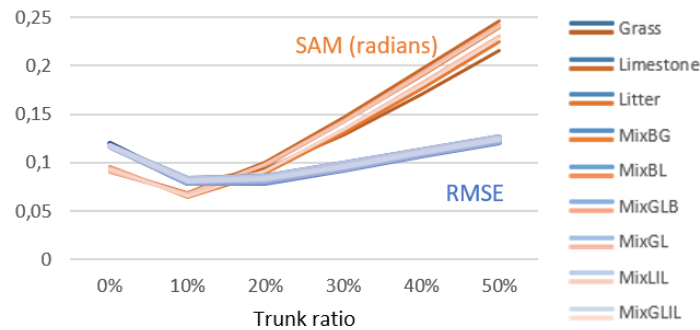


Figure 1: Influence of understory spectrum and trunk ratio in the canopy spectrum on simulation accuracy
 B: Bare soil; G: Grass; L: Limestone; LI: Litter

When testing the different canopy spectra (tree, species or QI/QP mix) for a given understory (mix of bare soil and grass) and trunk ratio (10%), only slight differences between mean RMSE and SAM are visible (Figure 2). The best combinations low mean RMSE – low mean SAM are for a species spectrum or for a QI/QP mix spectrum with a low QI ratio. This result indicates that it may not be necessary to have a precise spectrum for each tree; results of similar accuracy may be obtained by assigning to the trees the corresponding species spectrum or by assigning to the canopy of the whole plot a mix spectrum respecting the ratio of species coverage in the plot.

The simulation minimizing the mean RMSE and SAM (bare soil and grass mix spectrum for the understory, species spectrum with a 10% trunk ratio for the canopy) presents variations in RMSE and SAM values per pixel (Figure 3). Some pixels have a very good spectrum adequation between the simulation output and the AVNG image. On the contrary, other pixels have a quite high RMSE or SAM value, mainly corresponding to shadowy or open areas.

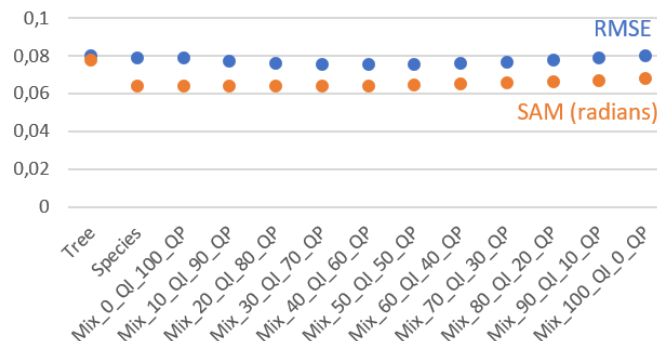


Figure 2: Influence of canopy spectrum on simulation accuracy

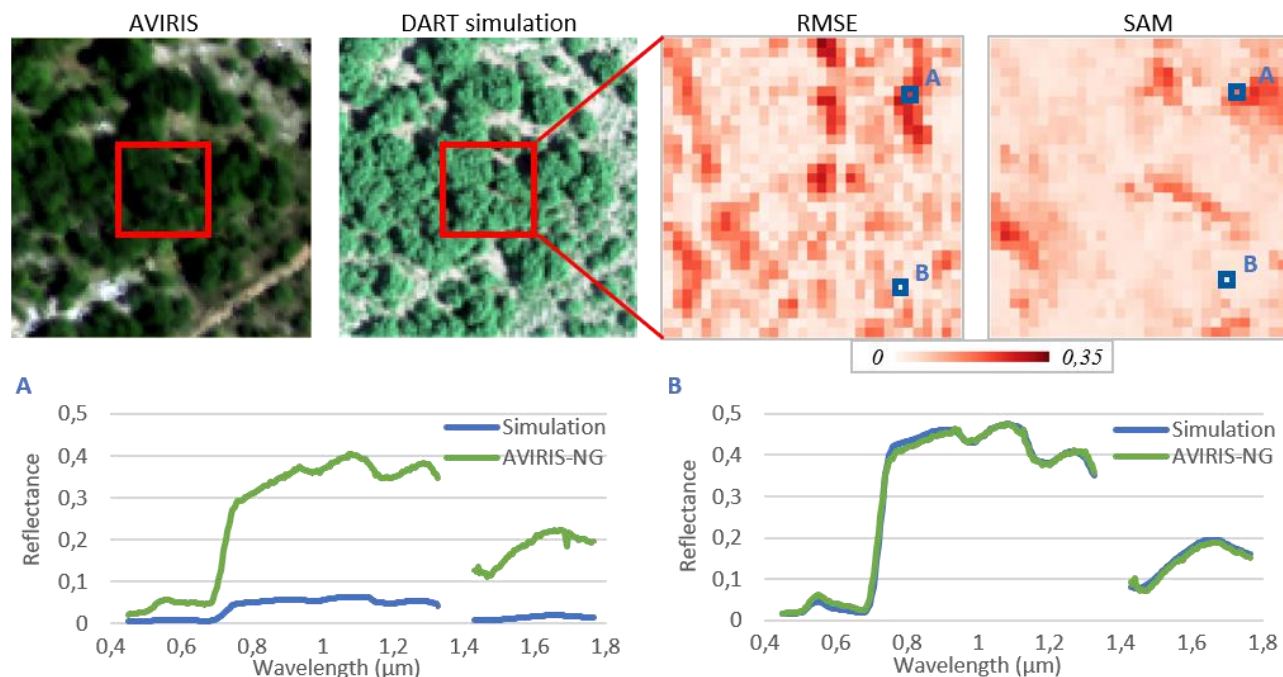


Figure 3: Results of the simulation with a bare soil and grass mix spectrum for the understory and a species spectrum with a 10% trunk ratio for the canopy
 AVNG image and DART simulation (scale of the extended plot (100x100m²); RMSE and SAM values per pixel (scale of the plot (30x30m²); Examples of spectra for high and low RMSE and SAM values

5. CONCLUSIONS

DART optical properties parametrization has an important influence on the simulation reflectance results. Understory optical properties seem to have less impact than canopy ones but this is probably due to the high canopy cover of the studied plot. Mixing a trunk spectrum with a leaf spectrum improves the results and can be a way to integrate ligneous component influence in the modelling. Finally, it may also be sufficient to have a species spectrum or a mixed spectrum of the main species of a plot respecting their coverage ratio to have a rather accurate simulation instead of determining and assigning each tree a spectrum. All the results are however to be taken very cautiously as they are only based on plot, which has one dominant species, and whose second main species has a quite similar spectrum to the dominant one. A similar analysis will be conducted on the nine other plots and will also be extended to other multi- and hyper spectral sensors (PRISMA, DESIS, SENTINEL2) to evaluate the impact of spatial and spectral resolution on the adequation between simulated and acquired remote sensing images.

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