Proposition of PhD project - 2017-2020 (3 years)

TR SYNERGIE

Title: Contribution of physical modeling for biodiversity mapping of tropical forest using Sentinel-2 satellite imagery

Keywords: Tropical biodiversity, Species communities, DART, Theia Land Data Centre, Sentinel-2, Radiative transfer, Remote sensing

Discipline: Spatial information and physics applied to ecology

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PhD supervision:

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Doctoral school: GAIA, Université Montpellier II

Summary

The main objective of this PhD project is to evaluate the **potential of the image data acquired by Sentinel-2 satellites for biodiversity mapping in tropical forest environments**, including the **spatial distribution of species communities**. This project will build up from a selection of tools and data available: Sentinel-2 data provided in the **Théia land data center**[1] and the **SEAS Guyane Plateform**[2], an adaptation to the multispectral case of a methodology for tropical biodiversity mapping based on imaging spectroscopy, a simulation platform for the simulation of remote sensing imagery using the DART model, and a set of experimental data from a **coupled airborne/field campaign** performed in 2016 on a network of fully documented experimental sites of French Guiana. This dataset includes airborne LiDAR and hyperspectral data, as well as acquisitions of Terrestrial Laser Scanning and optical properties of vegetation data and forest elements.

Up-scaling from field observations to airborne data and then to satellite data will be performed. The global strategy will combine **experimental data** and **simulated data** from the radiative transfer modeling in 3D. This scaling will allow to 1) continue the validation of the processing chain for biodiversity mapping from imaging spectroscopy, using various biodiversity indicators, 2) participate in the finalization of a data simulation platform for multispectral and hyperspectral images based on radiative transfer model DART, and 3) contribute to the definition of **satellite remote sensing essential variables biodiversity** (**SRS-EBV**) led by the Group on Earth Observations - biodiversity Observation Network (**GEO BON**).

[1] https://www.theia-land.fr/
[2] http://www.guyane.ird.fr/plateformes-poles/plateformes/seas-guyane

Context

Along with climate change, the erosion of biodiversity is a major global challenge for humanity, with comparable economic and geopolitical impact (Tittensor et al., 2014). Many factors explain tis erosion, most of them directly or indirectly linked to human activity : land use and land cover change, increasing pollution, exploitation of natural resources, climate change, and development of pathogens and invasive species (Ceballos et al., 2015; Morris, 2010). These factors highlight the complex interactions between erosion of biodiversity, climate change and degradation of natural habitats (Chapin III et al., 2000).

In order to address these issues at the global scale, the Convention on biological diversity has been signed by 150 countries, with to objective of developing a strategy for conservation, restauration and sustainable use of the biological diversity, based on a variety of indicators. The implementation of this strategy has been put under the responsibility of the Group on Earth Observation – Biodiversity Observation Network (**GEO BON**) and should insure the development of an efficient monitoring system, combining ,modeling tools based on a variety of indicators of the state and dynamic of ecological processes, which implementation should be technically and financially implementable at large scale (Secades et al., 2014).

Remote sensing is a key source of information for regional to global monitoring of natural ecosystems with regular temporal frequency. Information acquired by satellites therefore appear as particularly appropriate to help defining E**ssential Biodiversity Variables (EBV)** (Jetz et al., 2016; Pereira et al., 2013; Skidmore et al., 2015). The framework of these EBVs is based on the synergy between *in situ* data, fine-scale mapping for monitoring of ecosystems from appropriate remote sensing, and then regional and global scale-up by combining global observations and modeling tools. These EBVs are defined as the measures required studying, accounting for and integrating changes in biodiversity into local to global level management plans. In order to make the best use of the potential of remote sensing data, work is also underway to define the relevant EBVs that satellite remote sensing could help to measure. These are the Satellite Remote Sensing –EBVs (SRS-EBVs) (Pettorelli et al., 2016b).

Tropical forests represent a reservoir of biodiversity and are under significant (anthropogenic, climatic) pressure (Myers et al., 2000). Moreover, their monitoring is particularly complicated because of the difficulty of access from the ground and the cloud cover present in these latitudes which makes observation by optical satellite imagery difficult. It is therefore necessary to develop effective methods to quantify this biodiversity and its evolution, particularly in terms of the spatial distribution patterns of species communities and their interactions with environmental variables.

Remote sensing is a particularly interesting tool for studying biodiversity, in particular by its ability to measure changes in reflected radiometric signal and relate it to biophysical properties of vegetation. It is therefore important to identify the type of data that could be used to define regional or global SRS-EBVs, as well as associated methodologies. Remote sensing data from **airborne imaging spectroscopy** have shown great potential for studying complex ecosystems, including tropical forests. Recent publications have thus demonstrated the possibility of i) mapping tropical biodiversity, including local taxonomic richness and spatial distribution of species communities (Féret and Asner, 2014; Vaglio Laurin et al., 2014) (Figure 1); estimating leaf chemical composition (Asner et al., 2015a, 2015b; Chadwick and Asner, 2016) ; discriminating among tree species of particular ecological interest (Baldeck et al., 2015). Airborne imaging spectroscopy is a high quality data source, but its availability on a regional scale is currently unimaginable for logistical and financial reasons. However, it provides spatially explicit site-level information that can then be exploited for scaling lower spatial and spectral resolutions sensor data (Vaglio Laurin et al., 2016). In 2016, the **Centre National d'Etudes Spatiales (**French space agency, **CNES)** funded an airborne hyperspectral campaign over documented experimental sites in French Guyana to assist in the design of future hyperspectral satellite sensors and to study the potential of the currently operational satellite sensors.

Sentinel-2 multispectral sensors have been initiated in 2015 under the Earth Observation program **Copernicus** under the European Union's governance in partnership with the European Space Agency (ESA) and should be maintained for the next few decades. Sentinel-2 satellites currently represent **one of the strongest opportunities for tropical biodiversity mapping**, due to instrumental characteristics and frequency of revisiting, a key element for acquisitions in particularly nebulous tropical environments.

The Sentinel-2 data are made available by the **Theia land data centre**. Theia also offers a number of remote sensing data products as part of its data infrastructure. These remote sensing products are obtained using methods derived from research, whose operational porting is carried out in collaboration with the **centers of scientific expertise (CES)**. Following the same dynamic, the **SEAS Guyane platform** is getting equipped with the necessary resources to set up an observatory in the Antilles-French Guiana zone, and to a broader extent in the Amazon zone. This observatory includes a reception antenna, an archive center and equipment for storage, pre-processing and processing of remote sensing data, in particular Sentinel-2, Spot 6-7 and Pléiades data. One objective of the projects carried out under SEAS Guyana is to identify and help transfer high-potential processing chains to the Amazon region by 2021. In this context, the development of a "tropical biodiversity" product derived from remotely sensed data and its integration within the framework of a CES Theia focusing on the mapping of different components of the biodiversity of tropical forests would constitute an important application objective to be prepared during this PhD project.

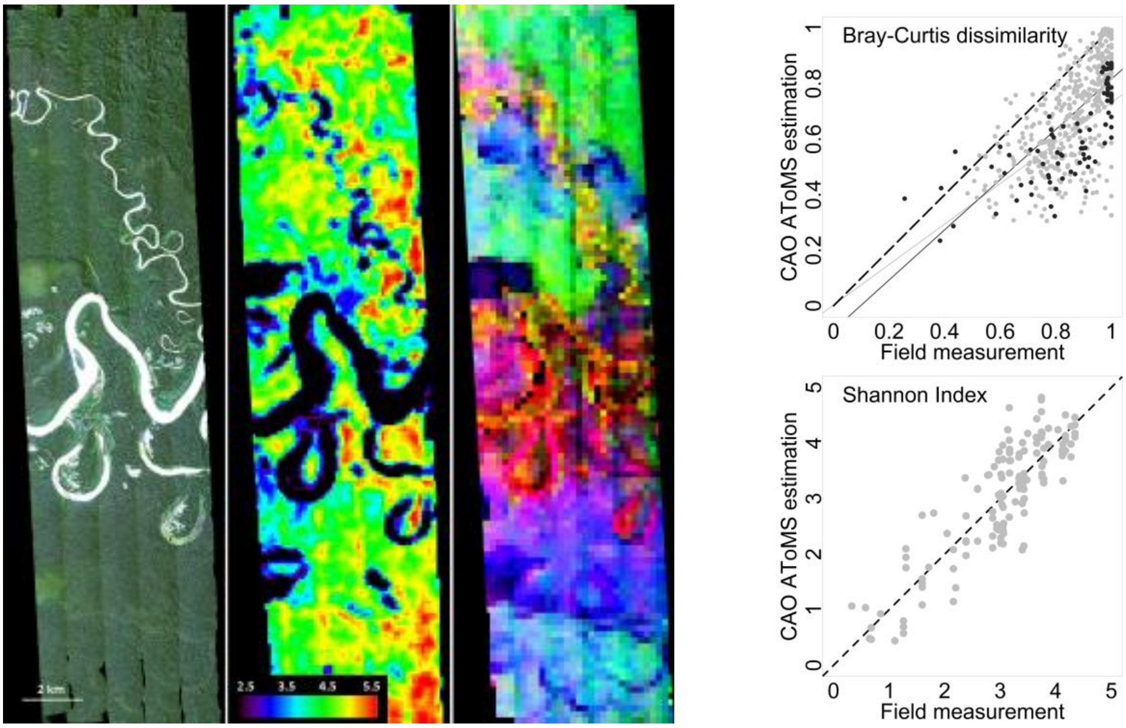

Figure 1. Biodiversity mapping derived from imaging spectroscopy acquired over Amazonian Peruvian tropical rainforest (Féret and Asner, 2014). From left to right on the maps: RGB representation; Shannon index representing local taxonomic diversity (α diversity); Bray-Curtis dissimilarity representing the spatial distribution of species communities (β diversity); Right panels: experimental validation of values derived from remote sensing data.

Objective

The main objective of this PhD project is to **develop and validate a methodology for biodiversity mapping in tropical forests based on Sentinel-2 imagery**, with an ambition to contribute to the definition of the SRS-EBVs, in the frame of the international network GEO BON. This PhD project results from the convergence of a certain number of research results and data acquired during field campaigns performed in 2015 and 2016 in the forests of French Guyana, and in the frame of collaborative projects (CNES / TETIS / AMAP / CESBIO / ESE). Besides the main objective defined earlier, a certain number of intermediate thematic and technical objectives need to be mentioned and include : i) validation of the 3D radiative transfer model DART (Gastellu-Etchegorry et al., 2015) with experimental data, ii) production and validation of fine scale mapping of taxonomic diversity and spatial distribution of species communities for various experimental sites in French Guiana at first, then at regional scales. Therefore this project is built from the collaboration of several scientific communities, including remote sensing, physical modeling of vegetation, and ecologists. These communities are mainly located in Montpellier (TETIS, AMAP, Espaces-Dev, CEFE), and in the region (CESBIO, EDB). We expect contribution to the **Theia Land data Center**, to the monitoring station of Amazonian environment (**SEAS Guyane**), and to the Copernicus program.

In order to reach these objectives, the PhD student and supervising scientific team can count on:

- A simulation infrastructure of remote sensing data (passive optical sensors & LiDAR) built to help using the 3D radiative transfer model DART developed by CESBIO. This platform has been developed in the frame of the projects StemLeaf (LiDAR) and HyperTropik (imaging spectroscopy), both funded by the TOSCA program of CNES. This infrastructure still requires an effort in terms of development and operational implementation, in collaboration with the joint research unit AMAP. The PhD student is expected to actively contribute to this simulation infrastructure.
- A biodiversity mapping/remote sensing data processing library initially developed for applications in imaging spectroscopy (Féret and Asner, 2014) and including new functionalities to process multispectral data. a collaborative work with AMAP is currently on-going in order to continue implementing new functionalities to the current versions, including a wider variety of biodiversity indicators (Pélissier et al., 2003). The PhD student will have to finalize the integration of the « biodiversity » library in the « image processing » library.
- A set of experimental data including airborne campaigns (LiDAR, hyperspectral, very high spatial resolution) and ground validation data (terrestrial LiDAR, leaf/trunk/liter optical properties, plot inventories, a vector layer of delineated individual tree crowns, leaf wet chemistry). The PhD student will have to familiarize with all these sources of data.

The assimilation of a broad variety of data sources into various tools and using different methodologies is the main technical challenge that will face the candidate. Open source software and methodologies will be favored during the development of the different components of the processing chain in order to prepare for the methodological transfer of a **tropical biodiversity mapping product to the Theia Land Data Centre**.

State of the Art

This project aims at sustaining the convergence among several scientific disciplines, including ecology, image processing, and radiative transfer modeling.

Methodologies for biodiversity mapping using remotely sensed data

Biodiversity mapping using remote sensing is relatively new due to the complexity of the task, from field data collection, to data analysis (difficulty to define a valid sampling strategy, definition of biodiversity indicators to be used…) (Chiarucci, 2007; Palmer et al., 2002; Pélissier et al., 2003) to availability of remote sensing data and associated methods for image processing. Tropical ecosystems are particularly difficult to study because of their complexity, and the quality of the remote sensing data (usually suboptimal due to the presence of clouds). However, improved data availability due to LandSat imagery allowed scientific advances on that topic during the past 20 years (Muro et al., 2016; Thessler et al., 2005; Tuomisto et al., 1995). Thessler et al. (2005) proposed a method to map floristic gradients in a tropical rainforest, based on field observations combined with satellite imagery. Since then, various studies demonstrated the potential of remote sensing for biodiversity mapping, in particular for tropical forests. Imaging spectroscopy also confirmed a strong potential for mapping biodiversity and floristic gradient over various ecosystems, including savannah, tropical forests, and temperate grasslands (Baldeck et al., 2014; Feilhauer et al., 2011; Féret and Asner, 2014; Vaglio Laurin et al., 2014). Most of these methods are based on an adaptation of the **Spectral Variation Hypothesis** (Palmer et al., 2002) and relate spatial heterogeneity of spectral properties to ground observations.

The increasing availability of remote sensing data, in particular the Sentinel-2 multispectral data as part of the Copernicus program, open the path to the development of new methods dedicated to biodiversity mapping (Rocchini et al., 2016; Skidmore et al., 2015; Vaglio Laurin et al., 2016). In the context of upscaling information from site scale to regional scale, it is important to propose a method with minimal requirements in terms of field calibration, due to the very low availability of such data and the difficulty to access it. The methods selected and adapted in the frame of this project have been developed with this constraint in mind.

Advances in physical modeling of vegetation for the simulation of remotely sensed images

Radiative transfer modelling tools play a key role in the use of remote sensing data, in particular by contributing to improved interpretation of the physical signal, and to the development of robust methods for the estimation of various properties of vegetation (Combal et al., 2003; Féret et al., 2011; Jacquemoud et al., 2009; Morton et al., 2014).

Modeling complex ecosystems, such as tropical rainforest with string structural heterogeneity and high taxonomic diversity, is a scientific and technical challenge. Succeeding in such task can contribute to pave the way for many theoretical and methodological advances. Three dimensional radiative transfer modeling (Gastellu-Etchegorry et al., 2015) are necessary under these conditions, but extremely complicated to parameterize due to the large quantity of data to provide as input information (Jetz et al., 2016; Schneider et al., 2014). On a structural point of view, recent developments take most of experimental data obtained from LiDAR acquisitions and help building a fine representation of the 3D structure of heterogeneous surfaces (Grau et al., 2014). On a radiometric point of view, improvements of the modeling of leaf optical properties, leading to the integration of a larger pool of leaf pigments, including chlorophyll, carotenoids and anthocyanins, allow realistic simulation of leaf optical properties through complete lifecycle (Féret et al., Under review). Finally, advances in the simulation and fusion of data acquired with passive optical sensors (multi and hyperspectral) and with LiDAR (Yin, 2015).

Hypotheses

Remote sensing data acquired by the Sentinel-2 satellite constellation is currently one of the best opportunities for mapping the biodiversity of complex environments, particularly tropical forests. The very recent launch of these satellites opens the way to the exploration of many scientific hypotheses. In order to assist in the operational development of a mapping methodology based on these data it is necessary to gain a better understanding of the spectral and spatial components of the signal measured by this satellite. This good understanding will then make it possible to optimally rely on the **Spectral Variation Hypothesis (SVH)**, in order to best estimate the taxonomic richness of forests and the distribution of species communities at fine spatial scale (Palmer et al., 2002; Rocchini et al., 2016, 2010). This hypothesis suggests that the information contained in the spatial variability of the surface spectral properties measured by a sensor can be used as an indicator of the heterogeneity of habitats, environment or taxonomic diversity depending on the study scale. The SVH is a rather general concept which led in practice to many variants both in terms of the type of data used (multi/hyperspectral, moderate to very high spatial resolution…) and of appropriate methodologies to derive indicators of variability fitting with the ecosystem considered.

The framework built for the development of such method is built upon an **upscaling strategy** combining **experimental data** acquired at various scales (field observations, airborne and satellite remote sensing) with an approach based on **physical modeling of the interactions between solar radiation and these complex ecosystems (structurally and taxonomically)**.

Experimental data will provide a source for the validation of the methodologies applied at different scales and the validation of the physical modeling. Once validated, these physical models will be used in a prospective mode in order understand methodological and instrumental limitations for the estimation of vegetation properties of interest. More broadly, the methodological framework developed with perspectives of application to tropical forest could be considered for other types of ecosystems. A certain number of studies sharing a similar / compatible methodological framework actually sowed good performances for species community mapping over other types of ecosystems, such as savannah (Baldeck et al., 2014; Baldeck and Asner, 2013) and temperate grasslands (Feilhauer et al., 2011).

Spatial data about the floristic composition of tropical forests are also particularly interesting beyond the community of ecologists interested in biodiversity. This information can be extremely valuable, especially on the themes associated with aerial carbon storage and soil microbial activity associated with different geochemical cycles (carbon, phosphorus, water). Species distribution models that are the basis for many studies in theoretical ecology and in the study of dynamics in response to climate change could also benefit from facilitated access to biodiversity maps resulting from the analysis of Remote sensing data (He et al., 2015). Finally, in the context of the convergence of technologies and data available with the Copernicus program, this project may lead to subsequent or parallel collaborations within TETIS and beyond to study the synergy between the Sentinel-1 and Sentinel-2 data.

Study sites and types of systems

The main study area is located on **experimental sites located in French Guiana**. These sites have been scientifically monitored since several decades: **Nouragues, Paracou, Sinnamary, Montagne Tortue**. The **Nouragues** sites (CNRS) and **Paracou** (CIRAD) have a history scientific monitoring of more than 30 years. This includes **inventories of plot networks on a regular basis**, a **scientific expertise** on past perturbations, as well as a large number of ***in situ* measurements and airborne campaigns (Radar, LiDAR, very high spatial resolution…)**. The research communities involved in the many projects focusing on these study sites include international teams of ecologists, botanists, plant physiologists, foresters and experts in remote sensing.

More recently in 2016, CNES and labex CEBA funded a field campaign combined with an airborne campaign which led to the acquisition of a comprehensive dataset including:

- Full hyperspectral cover of four sites : 400 spectral bands from visible to shortwave infrared
- Airborne LiDAR acquisition with a ground sampling superior to 30 pts /m^2.
- Very high spatial resolution imagery (10 cm)
- Terrestrial LiDAR (TLS) on ~1ha allowing building a very highly detailed 3D mockup to be used for model validation.
- Spectroscopic measurements of leaf optical properties (directional hemispherical reflectances & transmittance in visible to shortwave infrared for dozens of species and hundreds of leaf samples from Nouragues, Paracou ad Sinnamary), trunks and litter. Sampling of leaf optical properties was particularly dense on the plot which was scanned with the TLS.
- In order to accurately characterize individuals emerging from the canopy).
- Crown delineation for large areas

National and international collaborations will be expected during this project in order to offer opportunities to **continue unifying scientific communities, in particular ecologists and experts in remote sensing**. This is a strong recommendation is particularly expected on an international level (Pettorelli et al., 2016a, 2016b; Rocchini et al., 2016).

Working Schedule

Activity 1 : review of literature: i) spatial indicators used to map biodiversity and species communities; ii) existing methodologies to map and monitor tropical forests based on hyperspectral and multispectral image analysis; iii) radiative transfer modeling heterogeneous complex ecosystems.

Activity 2 : familiarization with methods, tools and data available : i) processing chain used to generate biodiversity maps from remote sensing data; ii) remote sensing data simulation infrastructure built around the DART model; iii) experimental databases including field observations, airborne and spaceborne imagery.

Activity 3 : Validation of biodiversity maps derived from imaging spectroscopy and Sentinel-2 images : i) validation using plot inventories performed regularly on the different experimental sites; ii) validation a posteriori during a field campaign to be done by the student in collaboration with ecologists and botanists.

Activity 4 : designing DART simulations: i) model validation based on highly detailed mockups built from experimental data acquired during previous campaigns (TLS, field spectroscopy) ; design of a sensitivity study to assess the contribution of various vegetation properties (structure & chemistry) as well as environmental factors (configuration of acquisition, atmospheric properties, terrain elevation) on the radiometric signal and on the estimation of biodiversity indicators.

Activity 5 : determination of the technical feasibility of a methodological transfer of methods for tropical biodiversity mapping to the Theia Land Data Centre.

Activity 6 : production of scientific publications

Activity 7 : preparation of the PhD manuscript

	Année 1				Année 2				Année 3			
	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
Act.1												
Act.2												
Act.3												
Act.4												
Act.5												
Act.6												
Act.7												

Profile of the candidate

- Master 2 or engineering school specialized in image processing or remote sensing with strong interest for ecology.
- High proficiency in at least one programming language among Python and R, and interest for programming in general.
- Ability to work in interdisciplinary environments
- Ability to conduct field work in tropical environment.
- Production of scientific publications expected.

Host lab

UMR TETIS, Maison de la Télédétection, Montpellier France.

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