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Gaëlle Viennois
Cirad - La recherche agronomique pour le développement

Christophe Proisy
French Institute of Pondicherry / UMR AMAP, Institut de Recherche pou…

Rinny Rahmania
Institute of Research for Development

Ariani Andayani
Ministry of Marine Affairs and Fisheries

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Gaëlle Viennois
CNRS-UMR AMAP
Montpellier, France

Jean-Baptiste Feret
IRSTEA, UMR TETIS
Montpellier, France

Christophe Proisy, Rinny Rahmania
IRD-UMR AMAP
Montpellier, France

Juliana Prosperi
CIRAD-UMR AMAP
Montpellier, France

Ariani Andayani, Berni Subki
Research Center for Marine Technology
Ministry of Marine Affairs and Fisheries
Jakarta, Indonesia

Frida Sidik, Nuryani Widagti
Institute for Marine Research and Observation (IMRO)
Ministry of Marine Affairs and Fisheries
Bali, Indonesia

Suhardjono
Indonesian Institute of Sciences (LIPI)
Bogor, Indonesia

Olivier Germain, Philippe Gaspar
Collecte Localisation Satellites
Ramonville, France

***Abstract*—Sustainable management of mangroves depends on our ability to maintain ecosystem functions. It requires a careful monitoring of several forest characteristics such as the species composition. Very high resolution multispectral satellite images provide pivotal information at the individual tree scale that may support identification and mapping of species of mangrove trees emerging at the canopy level. In this study, we showed that fine scale spectral responses of 4 common Asian mangroves species were and remained distinct over one decade and, independently of both the satellite sensor and the angular configurations of images acquisitions. We began physical interpretation of such original and promising observations using a 3D radiative transfer modeling approach.**

Keywords — Species identification, high resolution images, leaf reflectance, DART, Bali.

I. INTRODUCTION

Maintaining of mangrove ecosystem functions is an essential requirement for sustainable coastal zone management [1]. Among key parameters of mangrove health is the species composition and its spatial assemblage across a given region [2]. Optical remote sensing has proved relative good interest in providing maps of mangrove species [3]. Moderate spatial resolution i.e. with pixel size greater than 10 m hampers the ability to clearly distinguish mangrove zones whereas classification is improved with increasing number of spectral bands. With 10 m resolution, good results for mapping large areas uniformly dominated by a single species are obtained using EO-1 Hyperion images in Southern Thailand [4]. However, spectral variability of forest canopies, as exhibited by multispectral and hyperspectral images, is something to carefully analyze using radiative transfer modeling [5] otherwise physical misinterpretation may yield to false assumption on forest processes, as explained by [6].

In this study, we show that fine scale spectral responses of four commonly found Asian mangrove species are and remain distinct over one decade in very high resolution (VHR) images. Moreover, these spectral patterns are conserved independently of the satellite sensor. We present the physically-based chain of analysis developed for simulating VHR multispectral sensor images of mangrove forests dominated by various tree species. The remaining challenges for interpreting temporal stability of mangrove multispectral signatures are discussed.

II. MATERIEL AND METHODS

A. Study site and field data

The mangrove area is located 8.679°S and 115.455°W in Nusa Lembongan Island, Southeast of Bali, Indonesia. Mangroves extend over about 2 km² at the Northeast of the island. It is part of a Marine Protected Area managed by the Coral Triangle Center and the local government (Fig 1).

We conducted a field experiment in November 2014 aiming at revealing both forest structure and biodiversity of the mangrove area. Forest inventories were undertaken in nine plots of size varying between 100m² to 900m² depending on the forest development stage. The inventories consisted of recording all diameters at breast height for any individual tree located in the delineated plots after species identification. We also measured reflectance spectra of leaves, from 30 to 50 samples for each species (Fig. 2), for most of the mangrove species found in Nusa Lembongan using the field 300-1100 nm spectro-radiometer Spectral Evolution PSR 1100-F. We focused on the following four mangroves species, i.e. *Avicennia marina* (AM) *Bruguiera gymnorhiza (BG)*, *Rhizophora apiculata* (RA) and *Sonneratia alba* (SA) since they are the dominant ones in most of the study site zones. At the leaf scale, the highest reflectance contrast between species was found in near-infrared and green bands whereas all species responses in the red and blue domain were equivalently low. In particular, BG showed a strongest near-infrared reflectance while SA showed a lowest reflectance. The AM species was distinct from others by a strong reflectance in the green domain.

From these reflectance measurements, we derived transmittance profiles by following the procedure explained in [7]. We did not have enough time to sample satisfactorily ground surface optical properties due mainly to the fast changing and the heterogeneity of soils (dry/wet/inundated, loamy/sandy, hypersaline, etc.).

B. Imagery

Four VHR satellite images (Table 1) acquired between 2001 and 2013 were used, including an Ikonos (2001, note IK), a Geoeye (2009, GE), a Quickbird (2003, QB) and a Worldview-2 (2013, WV2) image, in which each one was provided in a bundle of 5 Geotiff images (Table 1). Pixel sizes varied from 50 cm to 1m for panchromatic channels whereas resolution of multispectral channels ranged between 2 and 4m. Pixel intensity was converted to sensor spectral radiance (expressed in $W.m^{-2}.sr^{-1}.\mu m^{-1}$) using rescaling gain and offset coefficients available in images metadata files. We manually pan-sharpened the 5 channels for producing color composite images at 50 cm images for GE, QB and WV2 and 1m for IK satellite images (Fig. 3).

TABLE 1: IMAGE PARAMETERS. θ_s, θ_v and $\phi_{s\text{-}v}$ are, respectively, the sun and viewing zenith angles and the sun-viewing azimuth.

Satellite	Acquisition Date	θs(°)	Θv (°)	$\phi_{s\text{-}v}$(°)	*Pixel size (m)*
Ikonos (IK)	1 Mar. 2001	27	16	147	1 (PAN) 4 (MS)
Quickbird (QB)	29 May 2003	40	14	73	0.5 (PAN) 2 (MS)
Geoeye (GE)	15 Oct. 2009	18	25	151	0.5 (PAN) 2 (MS)
Worldview 2 (WV2)	17 Oct. 2013	18	28	50	0.5 (PAN) 2 (MS)

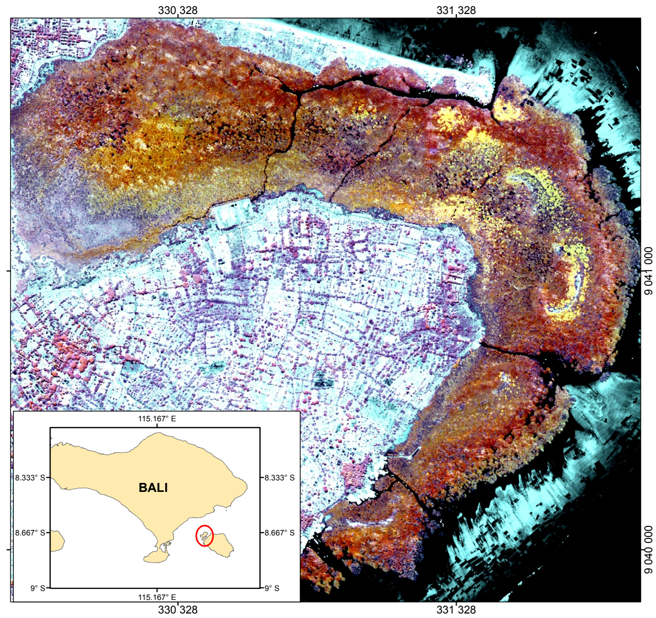

Fig.1. Location of Nusa Lembongan Island, Indonesia. Graduations are in kilometers, WGS84 UTM 50S.

C. Methods

In the images, we delineated four training polygons for each of the four following mangrove habitats dominated by a given species. First one was a dwarf (with the height of less than 3 m) but dense *Avicennia marina* (AM) formation growing over a hypersaline ground. Others were dominantly composed by *Bruguiera gymnorhiza (BG)*, *Rhizophora apiculata* (RA) and *Sonneratia alba (SA)*. Forest stands reached between 12 to 20 m high. Statistical analysis was then applied to examine differences between spectral signatures of each mangrove type in the blue, green, red and near infrared channels.

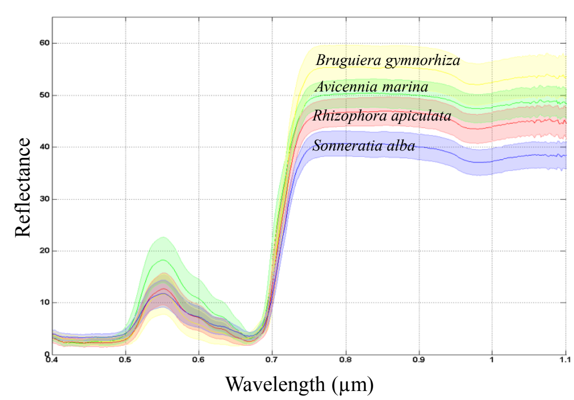

Fig. 2. Measured leaf reflectance of four typical mangrove species. Lines correspond to median values computed over 30 to 50 samples for each species.

In parallel, we started simulating mangrove images using 3D radiative transfer modeling [8] to calibrate the DART model as described in [9]. The DART scene consisted in four sub-scenes, each of 50x50m, in which we positioned a representative mockup of a given mangrove habitat (Fig. 4). Leaf optical properties obtained from field measurements were included in the DART spectral database and used. Crown geometric characteristics (leaves dimensions, orientation, crown porosity, soil optical properties, etc.) remained strictly the same. Without field measurements of LAI, we imposed for the AM dwarf forest with a value of 2 whereas for BG, RA and SA forest, LAI was set to 4. From this basis configuration, we tested the influence of different leaves orientation, crown porosity (i.e. the number of empty turbid cells inside the crown).

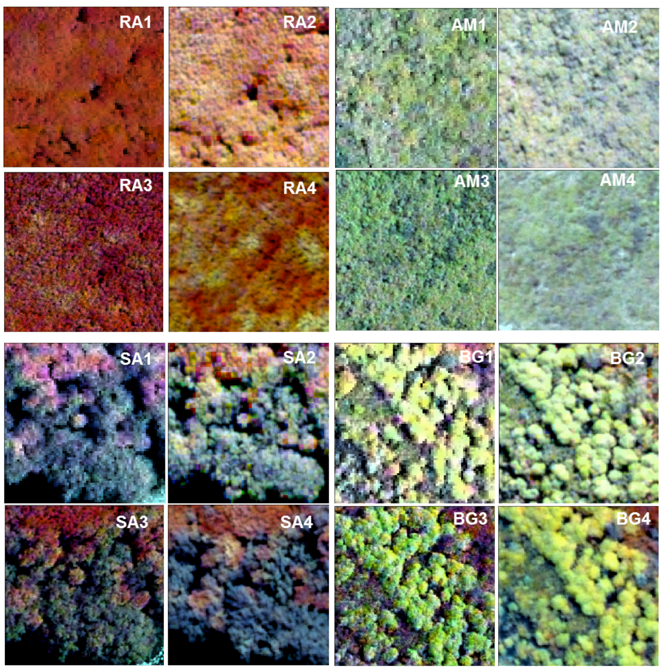

Fig.3. Color composite image extracts of 75 x 75m over mangrove types. The numbering corresponds to image dates i.e., 2001, 2003, 2009, 2013.

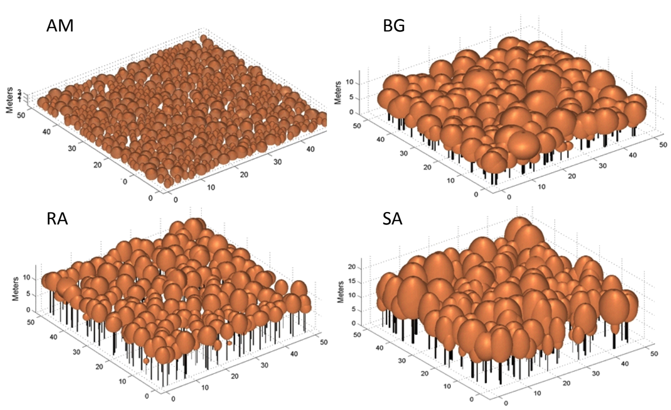

Fig. 4. Mockups of the 4 mangrove forests.

We decomposed the UV-NIR domain into 21 spectral bands of varying bandwidth ranging from 0.02 to 0.04 µm. The radiative transfer was then computed in each of the 21 bands after selecting a typical set of tropical atmosphere parameters. Top of Atmosphere (TOA) reflectance images of 100x100m have been obtained for each sun-viewing geometry configuration listed in Table 1. This procedure was done three times to produce 25cm, 50cm and 1m pixel size images. Simulations were done under Windows 7 64 bits operating systems (Fig. 5) and required RAM from about 8 to 36 Gb, with processing time from a few minutes to 8 hours (1h30 for simulating 50cm images) using multi-threading processing and depending of the spatial resolution requested.

III. RESULT

The contrast of the 4 NIR/Green/Blue VHR composite images was adjusted automatically through different remote sensing software after zooming in the mangrove area and excluding waters and *terre firme* surfaces. The displayed results allowed a clear visual discrimination of mangrove types (Fig. 1 and 3). Indeed, BG forests exhibited a marked yellow color and a coarse texture. RA canopies were represented by shades of red colors whereas SA forests displayed a dark blue color and intermediate AM forests appeared green with a fine texture. We extracted the spectral signatures of each forest species, ie, BG, RA, AM and SA in each composites of the Red/NIR/Green/Blue sensor images (Fig. 6). These spectral pattern differences were conserved over time and through the different sensors responses and for the different sun-viewing geometry configurations. Differences between species were established significant using a Kruskal-Wallis test. The near-infrared was confirmed as the most indicative domain for identifying species. Furthermore, in this domain, the highest values were found for BG and the lowest values for SA (Fig.6) in agreement with leaf spectral properties (Fig. 2).

The analysis of DART-derived TOA sensor images (Fig. 5) was carried out, for each 50x50m sub-scene, by averaging pixel reflectance values in polygonal areas drawn to avoid forest gaps. The simulated reflectance variations of the four mangrove forests did not satisfactorily capture the real spectral variability observed in satellite images.

IV. DISCUSSION

This work is original since it does not take for granted color contrast in images as informative of leaf spectroscopy although all observations plaid for a very good capability of classification of mangrove species over time and whatever the sensor. There is a groundbreaking work to be carried out through the parameterizing of the DART model with satisfying and field-derived 3D descriptions of mangrove forests structure. Particularly, prior assessment of crown porosity, leaf clumping and angle distributions relative to species should be better achieved. In addition, the leaf structure itself (defined in [7]) may have a critical role at the canopy scale [5]. Additional field campaign is needed to obtain spectral properties of a large set of soil natures (from sandy to loam) under varying conditions of salinity and humidity depending on the season and the tide.

To support this study, subsequent work is undertaken aiming to a careful processing of the real images. It includes atmospheric corrections using the Dark Object Subtraction approach [10] and radiance to reflectance conversion. We will evaluate the atmosphere contribution (probably of little relevance) and remove it to focus the analysis on Bottom of Atmosphere images and forest parameters influence.

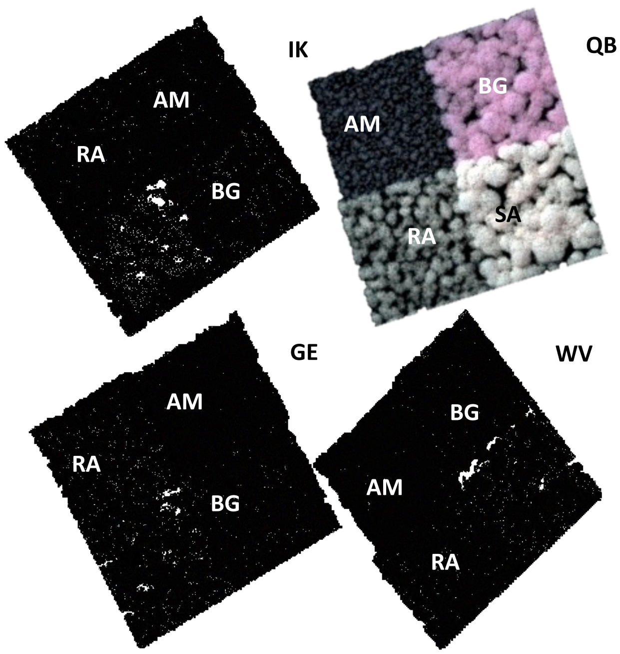

Fig. 5. 100x100m simulated satellite images with a sun zenith angle of 20° at different viewing zenith angles given in table 1.

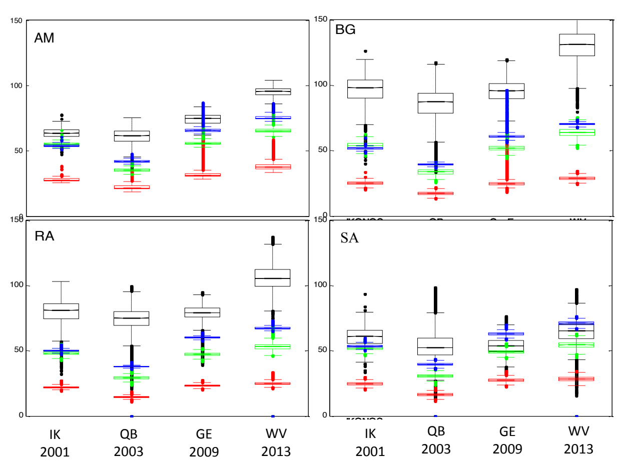

Fig. 6. Radiance signatures of the four forest types as observed by all sensors.

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