Study of the mangrove forest with earth observation technologies: the integration of hyperspectral field data with satellite images for a better understanding of this strategic ecosystem, its conservation and interrelation with the ethnic communities of the Colombian Pacific Region.

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Keywords: mangrove forest, remote sensing, sustainable development goals, field spectroradiometry, spectral analysis, spectral characterization, thematic mapping, coastal marine ecosystems

SUMMARY

In the framework of the Colombian Ocean Commission, since 2019 the Geographic Institute Agustín Codazzi -IGAC- has actively participated in scientific expeditions to the Pacific region on the western coast of the Colombian continental territory, characterized by its environmental richness, an important extension of mangrove forest, and a historical vulnerability in the social and economic conditions of its populations, especially the indigenous and afro-descendant communities whose food and security and economy relies heavily on the ecosystem services of the mangrove forest. From the Research and Prospective Directorate of the IGAC, the proposal arises to integrate field data obtained from hyperspectral sensors with Earth observation images as an alternative to the use of direct methods in the study, characterization, and mapping of mangrove forest. In the three scientific expeditions so far, the research team have collected 112 spectral signatures of 7 different species of mangrove, all these representatives of the Colombian Pacific in the Sanquianga, Uramba Bahía Málaga and Utría national natural parks, using *Red Tide* and *FLAME* spectroradiometers from Ocean Optics (350-1000 nanometers), thus constituting one of the most important repositories of mangrove spectral signatures in Colombia. From the spectral libraries consolidated and the implementation of separability analysis methods, including Spectral Angle Mapper, the Jeffries-Matusita distance and Ward's hierarchical discriminant analysis, the specific *endmembers* have been created for every mangrove species sampled along the Pacific Coast of Colombia. Furthermore, these *endmembers* have been employed in the exploratory analysis of the distribution of mangrove species, by using PlanetScope images of 3 meters of spatial resolution and four bands of spectral resolution (blue, green, red and near infrared), by means of the Spectral Angle Mapper for image classification with resampled spectral signatures and spectral unmixing analysis. The results obtained showed that the PlanetScope images, even though they are not the images with the best spectral and radiometric qualities in the market, allow the identification of clearly distinguishable spatial distribution patterns of mangrove species, provided that different correction and improvement methods and algorithms are applied both to the images and the spectral signatures, however, it is certain that further field data collection is necessary to improve the classification of images and to validate the results. Despite the limitations experienced in the scientific expeditions and in the research conducted, the results obtained have led to the consolidation of a set of geospatial data that can be a key input to generate updated and accurate cartography of this strategic ecosystem, which facilitates its management, conservation, and planning, and its critical role in the substances and quality of life of indigenous and afro-descendant communities.

RESUMEN

En el marco de la Comisión Colombiana del Océano , desde 2019 el Instituto Geográfico Agustín Codazzi -IGAC-participa activamente en las expediciones científicas al Pacífico, en la costa occidental del territorio continental colombiano, caracterizada por su riqueza ambiental, una extensión importante del bosque de manglar, y una vulnerabilidad histórica en las condiciones sociales y económicas de sus poblaciones, especialmente, las comunidades indígenas y afrodescendientes que dependen de la oferta ambiental de este ecosistema para alimentación y economía. Desde la Dirección de Investigación y Prospectiva del IGAC surge la propuesta de integrar datos de campo obtenidos sensores hiperespectrales con imágenes de observación de la Tierra como una alternativa al empleo de métodos directos en el mapeo y caracterización de localización y distribución y, estado del bosque. En tres expediciones se colectó 112 firmas espectrales de 7 especies diferentes de mangle, características del pacífico colombiano en los parques naturales Sanquianga, Uramba Bahía Málaga y Utría), usando espectroradiómetros Red Tide y FLAME de Ocean Optics (350-1000 nanómetros), constituyendo así uno de los repositorios de firmas espectrales de manglar más importante de Colombia. A partir de las librerías espectrales y la implementación de métodos estadísticos de análisis de separabilidad, incluyendo el Mapeo del Ángulo Espectral, la distancia de Jeffries-Matusita y el análisis jerárquico discriminante de enlace de Ward, se han generado las firmas tipo de las especies muestreadas, así como la identificación de los aspectos espectrales diferenciantes de las especies en las tres zonas de estudio. Adicionalmente, las firmas tipo se ha utilizado en el análisis exploratorio de la distribución de especies de manglar, usando imágenes PlanetScope de 3 metros de resolución espacial y cuatro bandas de resolución espectral (azul, verde, rojo e infrarrojo cercano), a partir del Mapeo de Ángulo Espectral con las firmas espectrales remuestreadas y el análisis subpíxel para la descomposición espectral de las imágenes. Los resultados obtenidos mostraron que las imágenes PlanetScope, aun cuando no son las imágenes de mayor riqueza espectral y radiométrica, permiten identificar patrones de distribución espacial de las especies de manglar claramente diferenciables, siempre que se apliquen diferentes métodos y algoritmos de corrección y mejora, tanto a las imágenes como a las firmas espectrales, no obstante, es necesario profundizar en el levantamiento de campo para mejorar las clasificaciones y validar los resultados obtenidos. A pesar de limitaciones enfrentadas en las expediciones científicas y en la investigación, los resultados obtenidos y experiencias aprendidas conducen a la consolidación de un conjunto de datos como insumo clave para generar cartografía actualizada y precisa de este ecosistema estratégico, que facilite su gestión, conservación y planificación, en respuesta al cumplimiento de los objetivos de desarrollo sostenible.

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1. Introduction.

The mangrove forest is one of the most productive and diverse ecosystems on the planet, they contribute to carbon fixation and are the refuge of numerous species that use these as passage systems or as breeding and feeding areas, the ecosystem services they provide are critical for the support of nearby populations and protection of coastal areas against adverse climatic conditions (Lacerda et al., 2001). Due to these characteristics, the mangrove forest is a complex ecosystem formed mainly by tree vegetation, interrelated fauna and flora, as well as for the physical environment on which it is established (Hoff et al., 2002), which in turn is fundamental for the food security and maintenance of population that inhabited from food supply and construction materials, and is a social niche of cultural interrelation between different ethnic groups and of ancestral heritage (Palacios & Cantera, 2017; Huxham et al., 2017; Tavera, 2010; Walters et al. al., 2008; zu Ermgassen et al., 2020).

The ecosystem importance of mangroves is therefore of the highest priority in the research and management of natural resources for the protection and preservation of the environment, but equally important in recent years has been the management in Colombia for the protection of this ecosystem and its relationship with the population that inhabits and lives from this ecosystem. The ethnic communities in Colombia with the greatest presence in the Colombian Pacific are the Emberá, Waunan, Eperara-Shapidara, Tule and Awá. Additionally, the Afro-descendant communities form an important part of the population that lives in the mangrove forest in Colombia, which is in a very vulnerable situation due to the loss and deterioration of this ecosystem, the threat of the effects of climate change, and the historical social conflict in Colombia that has affected these communities in the Colombian Pacific for decades (International Crisis Group, 2019). These communities face challenges and fears about two specific aspects in their relationship with the mangrove forest: housing and food, both strongly threatened by the global social and climate situation (Giri et al, 2011; Golberg et al., 2020; Lee et al.., 2014; Thomas et al., 2017).

Based on the above, the Expeditions Plan to the Colombian Pacific of the Colombian Ocean Commission of Colombia (CCO, acronym in Spanish) emerged, whose purpose is to strengthen the technical and scientific capabilities of the scientific and academic community in the knowledge and study of coastal marine ecosystems in the Colombian Pacific coast, with the aim of contributing to the protection, conservation and sustainable use of natural resources and contributing to the quality of life of the population of the Colombian Pacific. The Geographic

Institute Agustín Codazzi (IGAC, acronym in Spanish), through the Research and Prospective Directorate, has participated in three Pacific Expeditions since 2021 with the objective of conducting research in the field of Earth observation technologies and field spectroradiometry, from which important advances have been achieved in the spectral characterization and construction of a bank of mangrove spectral signatures to contribute to the knowledge of the mangrove forest.

2. Remote sensing and field spectroradiometry.

The sensors that generate images are remote sensing instruments that allow images of areas of interest to be generated and have important applications in Earth Observation. Through them it is possible to acquire information on a small or a large scale, of an object or phenomenon, without having physical contact with it. The study of the relationship of the energy observed and captured on different platforms and its interaction with the land cover or element observed from field spectroradiometry is the main objective in the participation of the IGAC in the Pacific Expeditions, this, as an additional means of capturing detailed hyperspectral information of mangrove species from reflectance measurements also known as spectral signatures. Regarding this, the following concepts need to be considered:

- Spectral library: an organized and cataloged collection of spectral signatures, which can be used for image classification purposes, identification of unknown spectra and in the correlation of biophysical information of the vegetation, (Brown et al., 2006).
- Endmember: is the characterized spectral signature, uniquely representative of a sampled target.
- Spectral signature: it is the way in which a sampled object emits or reflects its energy at different wavelengths and whose behavior serves to spectrally differentiate one element from another (Moran et al., 1995; Moizo, 2004).

During these scientific expeditions we have explored different forms and methods of classifying satellite images with signatures captured in the field. This paper aims to share the experiences and results obtained in the integration of hyperspectral field data in image classification.

2. Materials and methods.

2.1 Study areas.

The IGAC has participated in three Pacific Expeditions (in the pacific coast of Colombia), the first one to the Sanquianga National Natural Park between May 29 and 4 of 2021, which is located in the department of Nariño (southeasth of Colombia) and has an area of 80,000 hectares, and due to this extension this national park have approximately the 20% of the mangrove forest in the Colombian Pacific (Parques Nacionales Naturales de Colombia, 2017). The second expedition was carried out between December 5 and 12 of 2021 in the Uramba Bahía Málaga National Natural Park in the department of Valle del Cauca, with an area of 47,094 (Parques Nacionales Naturales de Colombia, 2023), this study area is the one with the fewest spectral signatures obtained, given that due to the weather conditions during the expedition, the spectroradiometer used suffered several defects that left it useless on the third day of the campaign. Finally, the most recent expedition was to the Gulf of Tribugá between March 7 and 16 of 2023, located in the department of Chocó, with an area of 60,138.6 hectares (National Natural Parks of Colombia, 2023) it is the area of study with the largest number of spectral signatures obtained, thanks to logistics and longer duration of the campaigns compared to the other two expeditions.

2.2 Planning field spectroradiometry campaigns.

A campaign to collect field spectral signatures begins with prior knowledge of the study area, something very important for the sampling design. Then checking the equipment and accessories to be used in the field campaigns, and with respect to the data collected in the field, it is recommended to review the natural covers, ecosystems and any cartography that can be accessed. The capture of spectral signatures must consider at least the local weather conditions, accessibility to sampling areas, and time of data collection. Additionally, the measurement parameters must be defined prior to executing the campaigns. These parameters correspond to the definition of the settings of the experiment (measurement protocol), that is, the definition of the species to be measured, how to measure them (observation geometry), and what information must be obtained from the species in addition to the spectral signatures (metadata).

2.3 Methodology for consolidating spectral signatures and image classification.

Once the field work and campaign design is established, a methodology is required for the processing and analysis of spectral signatures, and in general terms this methodology includes: the calculation of an average and unique spectral signature to generate a single endmember per species, going through the editing of the spectral signatures to eliminate noise and bad bands, the quality control of the signatures and their comparison with the general spectral patterns for each characterized species, the development and compilation of spectral libraries and the classification of the satellite image. The unification of the spectral signature to reach an endmember per sampled objective is proposed through dendrogram analysis with Ward's hierarchical discriminant analysis method, although the separability analysis has also been done with the Jeffries-Matusita distance during these years of research, to first identify signatures with inconsistencies between samples and then to determine the clusters that make up the image classes, which consists of obtaining the mean value of the measured reflectance of the depurated spectra per mangrove species (Douay et al., 2022; Rahmandhana et al., 2022).

Now, the classification of an optical image with spectral signatures is a process of matching the two spectral data. In this case, the Spectral Angle Mapping (SAM) algorithm was used, although several tests were also done with spectral unmixing at thesubpixel level. The SAM algorithm determines the similarity between the two spectral data based on the angle formed by the endmember (spectral field signature) and the image signature, treating the result as classification vectors where smaller angles represent greater similarity (Rahmandhana et al., 2022; Sanjoto et al., 2021; Sanjoto et al., 2022; Zulfa et al., 2021). To obtain a good result from this algorithm it is necessary to identify first the spectral correspondence between the field hyperspectral data and the satellite image to be classified through an operation called spectral resampling, for this it is necessary to obtain the band centers of each of the bands of the image to be classified and that it is atmospherically corrected, and in the case of the Pacific Expeditions the best images available are from the PlanetScope program (product *analytic*), which according to the metadata of the images, the band centers are the following in nanometers (nm) units:

Spectral region	**PlanetScope spectral range**	**Wavelength center**
Ultraviolet (<450)		-
Blue	450-520	490
Green	540-600	565
Red	640-700	665
NIR<900	840-900	865
NIR>900	900-1000	-

Table 1: Spectral range and band centers of the PlanetScope images used in this research.

Classifying any optical Earth observation image at the level of vegetation species is an ambitious and complex task, and if hyperspectral field information (spectral signatures) is available, the ideal is that the image should also be hyperspectral, however, this is very rare in this type of research given that these images, particularly satellite images, are very scarce and/or expensive, and airborne hyperspectral sensors are even rarer.

2.4. The scientific expeditions to the pacific coast.

The three expeditions were carried out in accordance with the CCO's logistical planning without major inconveniences except for the damage to the spectroradiometer taken to Bahía Málaga mentioned previously. An important challenge for this type of research in the Colombian Pacific is the constant cloudiness and rain throughout the year. It is widely known that optical satellite images are affected by cloudiness, which considerably limits their availability, but in addition to this, the conditions of rain, clouds, fog, and general water vapor in the atmosphere cause spectral measurements in the field to have excessive noise at the time of capture. For this reason, in the three expeditions the meteorological conditions were constantly monitored for the optimal window of capturing signatures (between 10:00 am and 01:00 pm), however, due to logistical conditions, such as boat transportation, the behavior of the tides, and the security restrictions in the study areas, it was necessary to carry out field work every day of the duration of the expeditions, and the only days in which signatures were not taken were those when torrential rains occurred or in those in which equipment was inspected. Likewise, accessibility to each of the scheduled points, in many cases, lengthened sampling and equipment preparation times, considerations that could not be foreseen until the field campaign was on course.

Figure 1: Example of access and mobility conditions during the expeditions. Top left: Sanquianga, bottom left: Bahía Málaga, right: Gulf of Tribugá.

Due to the physical and social conditions of the area, the points visited corresponded with the monitoring plots of National Natural Parks, World Wildlife Fund (WWF) and those found from the expert knowledge of local community leaders. Although the goal was to capture a high volume of spectral signatures, the security limitations established by the National Navy and the communities did not allow a greater density of sampling points. Due to this, there is a total of 99 spectral signatures of six different species of mangrove forest from the Colombian Pacific captured with Red Tide and FLAME spectroradiometers (350 to 1000 nanometers):

Sanquianga Natural Park			
Name	**Scientific Name**	**Abbreviation**	**Number of signatures**
Black mangrove	Avicennia germinans	AG	4
Majagua (non mangrove)	Hibiscus elatus	HE	1
White mangrove	Laguncularia racemosa	LR	5
Nato mangrove	Mora oleífera	MO	8
Red mangrove	Rhizophora mangle	RM	23
Piñuelo mangrove	Pelliciera rhizophorae	PR	18
Red and nato mangrove	Mora oleifera y Rhizophora mangle	MO_RM	1
Piñuelo and red mangrove	Rhizophora mangle y Pelliciera rhizophorae	RM_PR	5
Other: Plastic roof, zinc roog, soil	-	-	29
Total (mangrove):			64

Málaga Bay			
Name	**Scientific Name**	**Abbreviation**	**Number of signatures**
Black mangrove	Avicennia germinans	AG	2
Majagua (non mangrove)	Hibiscus elatus	HE	1
White mangrove	Laguncularia racemosa	LR	3
Nato mangrove	Mora oleífera	MO	2
Red mangrove	Rhizophora mangle	RM	10
Piñuelo mangrove	Pelliciera rhizophorae	PR	4
Grafted mangrove	-	MI	2
Other: Water, sand, mud, water hyacinth, shrubbery	-		9
Total (mangrove):			23
Tribugá Gulf			
Name	**Scientific Name**	**Abbreviation**	**Number of signatures**
Black mangrove	Avicennia germinans	AG	4
Nato mangrove	Mora oleífera	MO	1
Red mangrove	Rhizophora mangle	RM	2
Piñuelo mangrove	Pelliciera rhizophorae	PR	2
Botoncillo mangrove	Conocarpus erectus	CE	2
Dwarf mangrove	-	ME	1
Total (mangrove):			12
Total number of collected signatures			
By mangrove species for all three expeditions:			99
Total other targets for all three expeditions:			40

Table 2: Total number of spectral signatures captured during the expeditions.

The signatures that correspond to the "other" category were captured with two purposes: to contrast the spectral information of other elements/covers both in the spectral analysis and in the classification of images, and to spectrally characterize other geographical aspects of interest of the IGAC for future complementary research.

3.2 Analysis and processing of information.

The processing and analysis of the spectral signatures obtained begins with the depuration and selection of the most representative signatures of the mangrove species identified in the field work. For this, only the signatures corresponding to the forest species are first selected, excluding those from soil samples, housing covers, flora species other than mangroves and other field samples. When reviewing the signatures, the first thing to do is to identify the bad bands and the reflectance values that are outside the expected range. Regarding the bad bands, the equipment that has been taken to the field in the three expeditions only covers the visible and near-infrared region (350 to 1100 nm), so the commonly bad bands associated with the water absorption bands of the SWIR region are not present (Pahlevan et al, 2017). The noise and atypical values in the signatures can be due to variations in the climate and environment at the time of capturing the signatures, human errors in the procedure, effect of the soil through the leaf area, and even due to problems with the equipment, for instance. Therefore, the first step consists of depurating the spectral signatures before generating the endmembers. The following figure presents the depurated signatures of the Sanquianga Expedition:

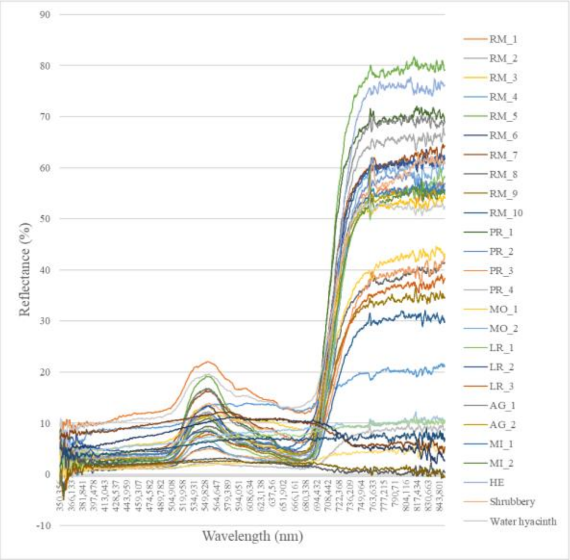

Figure 2: Example of the selected Sanquianga signatures before obtaining the endmembers.

The typical behavior of the vegetation and soil can be observed in the Sanquianga signatures, and noise is present at the extremes of the spectral range (less than 400 nanometers and greater than 830 nanometers). One of the biggest risks in noise reduction and bad band elimination is the potential loss of spectral information in the resampling step, since wavelength values in the corresponding bands can be lost between field signatures and optical satellite images, thus losing spectral precision during the resampling process.

3.3 Generation of Endmembers.

To obtain endmembers, Ward's hierarchical separability analysis was carried out, with the purpose of identifying the signatures that may present confusion in the spectral differentiation of the different mangrove species and the other sampled targets. The following figure presents the apparent poor separability between the selected signatures of Sanquianga, where it could be concluded that the *Rhizophora mangle* (RM) signatures are confused with all the others for instance, however, a closer inspection shows that part of this similarity corresponds to signatures of water and soil (mud), which would be an error in the spectral characterization error. After a detailed review of each of the signatures with their respective metadata and field photographic record, it was possible to identify and discard the signatures that present the greatest confusion among themselves, to obtain the endmembers from the mean value of the signatures:

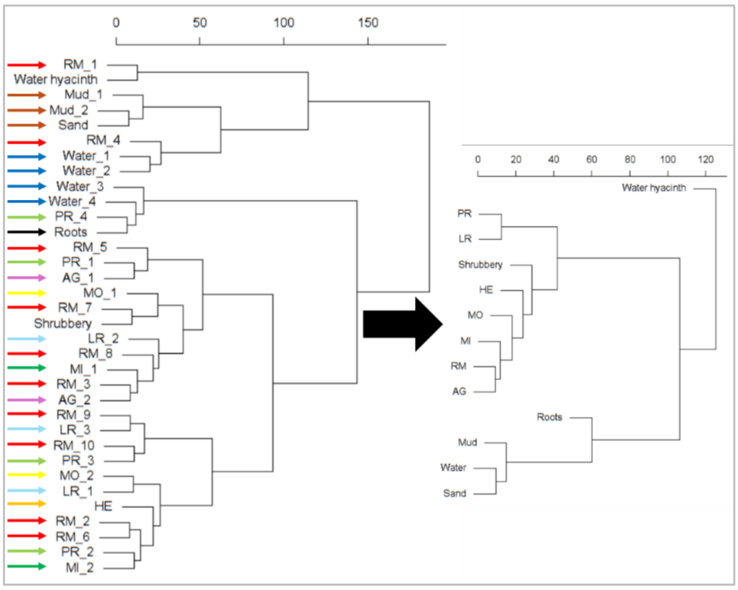

Figure 3: Example of separability analysis from Ward's hierarchical discriminant analysis of Sanquianga signatures, colored arrows correspond to species as follows: red: RM, yellow: MO, light green: PR, dark green: MI, purple: AG, light blue: LR, dark blue: water, orange: HE, black: roots. For the acronyms see table 2.

The reasons for the spectral confusion observed in the three study areas are due to the difficulties experienced in the field, mainly the rapid variability of climatic and environmental conditions, the difficulty in locating homogeneous samples of a single mangrove species, the phytosanitary state and growth of the sampled species, the effect of surface humidity (wetness) on the leaves, and the background effect through the leaf area. Regarding separability, it was found that in Sanquianga the *Rhizophora mangle* (RM) individuals sampled are more similar to *Avicennia germinans* (AG), as well as in Bahía Málaga *Pelliciera rhizophorae* (PR) it is closer to AG, while in the Gulf of Tribugá greater separability was found between the mangrove species observed. Regarding these findings, however, it is necessary to take into account that the environmental and ecosystem conditions of each study area are unique, in the same way, different challenges and difficulties are presented in all expeditions, and thanks to the fact that in the Gulf of Tribugá we counted with more time, it was possible to obtain a greater amount of information, so the spectral characterization is more precise than in previous expeditions.

3.4 Spectral resampling of endmembers.

The resampling function was created in the R software (as most of the processing of images and spectral signatures) using a Gaussian density distribution function from the band centers of the PlanetScope images presented previously. As expected, a significant amount of information is lost when resampling field spectral signatures captured with hyperspectral sensors to satellite images of only four bands, however, and as can be seen in the following figure, the general shape of the signatures was preserved:

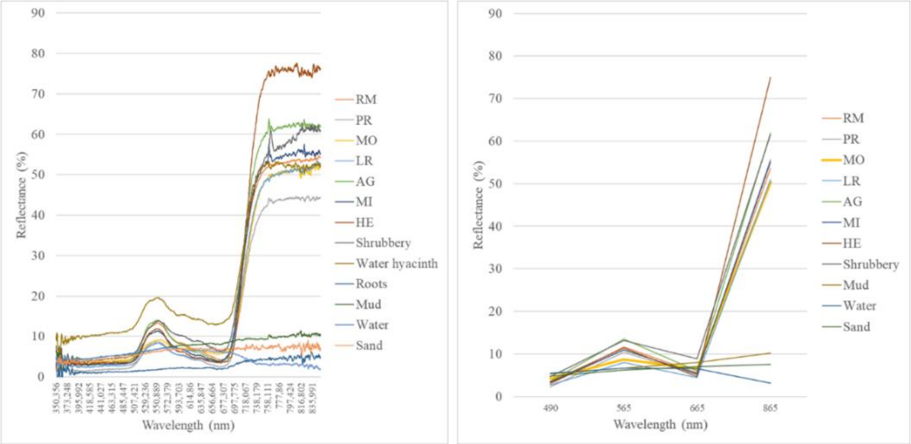

Figure 4: Endmembers before (left) and after resampling (right), Sanquianga.

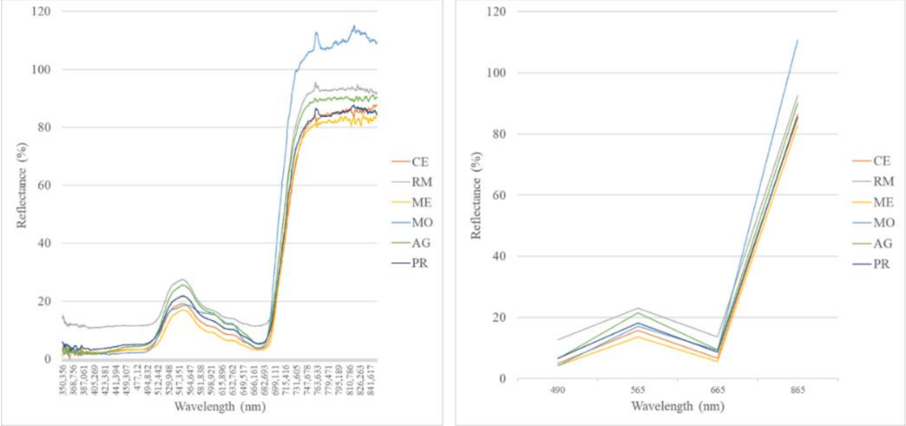

Figure 5: Endmembers before (left) and after resampling (right), Málaga Bay.

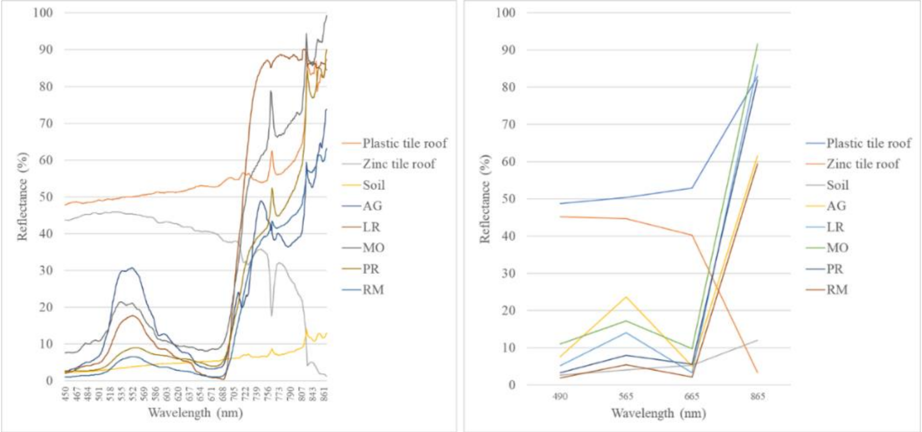

Figure 6: Endmembers before (left) and after resampling (right), Gulf of Tribugá.

Something important to highlight is that the key regions of the electromagnetic spectrum in the study of vegetation (red and near infrared) retain their representativeness in the resampled endmembers. Therefore, and although a lot of information is lost, the fundamental spectral characteristics of the species and from other field targets are preserved the final endmembers.

3.5 Classification.

The IGAC Subdirectorate of Cartography shared the orthorectified PlanetScope images of the three study areas, dated 2021 for Sanquianga and Bahía Málaga and 2022 for the Gulf of Tribugá. The first challenge of the classification consisted of the temporality of the available images, in the Gulf of Tribugá there was about a year difference in the date of capture in relation to the field work, however, despite these limitations (added to the limited spectral and spatial resolution of this type of image) is the best input that could be had. Subsequently, the radiometric adjustment of the images was carried out with the atmospheric correction by using the correction coefficients found in the images metadata files, then they were cropped to reduce the classification time with the SAM algorithm in the R software with the resampled endmembers. The classification exercise began with the first expedition (Sanquianga, figure 7) testing different maximum values of the spectral angle, as can be seen in figure 7, clearly differentiated patterns were obtained in the assignment of image pixels to each of the mangrove species used in the classification.

Zooming on this study area makes these differences to be more evident in the results of the classification, where it can be verified that despite the limitations in the spatial, spectral and radiometric resolution of the PlanetScope images, it is possible to find spectral differentiation in the image after implementing the SAM algorithm at the pixel level, differences that can be associated with the configuration and distribution of mangrove species, allowing us to find mainly pixels associated with *Rhizophora mangle* (RM) and *Laguncularia racemosa* (LR) (figure 8).

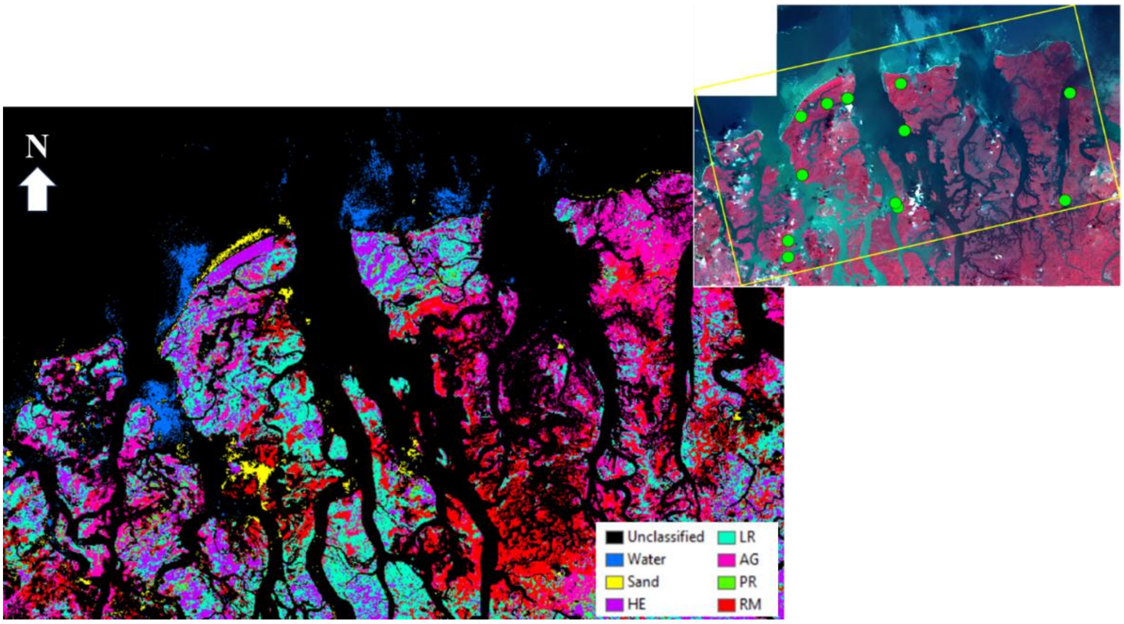

Figure 7: General classification result (below) and general location of sampled sites (top right, standard false color), Sanquianga.

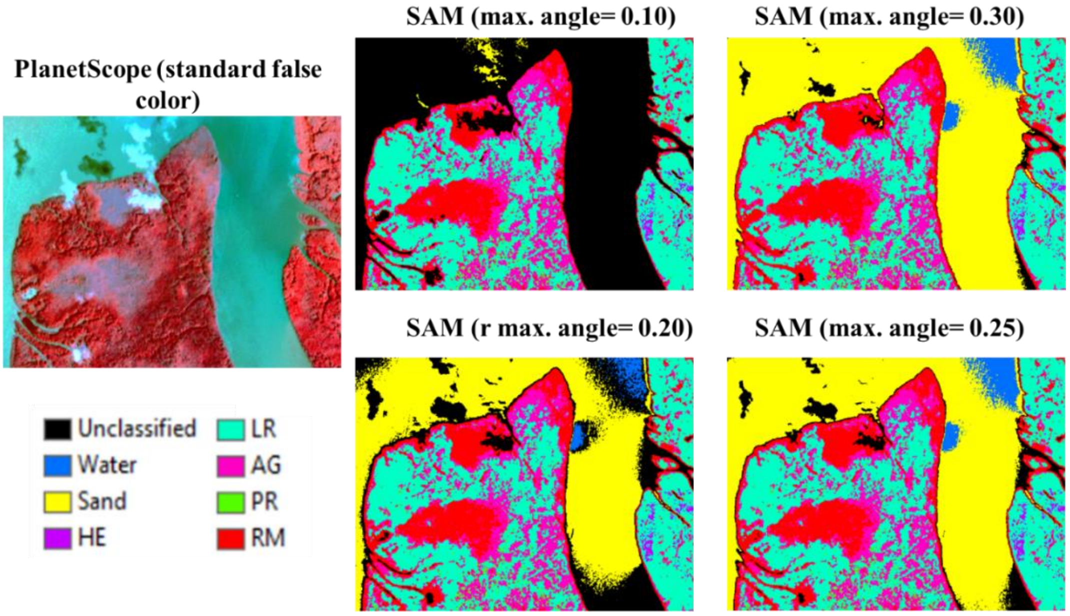

Figure 8: Comparison of classification results with different values of maximum spectral angle, Sanquianga.

Regarding Málaga Bay, and considering that it is the study area with the lowest number of signatures, therefore, the lowest spectral characterization of mangrove species, the predominant resulting classes were *Rhizophora mangle* (RM) and *Mora oleífera* (MO):

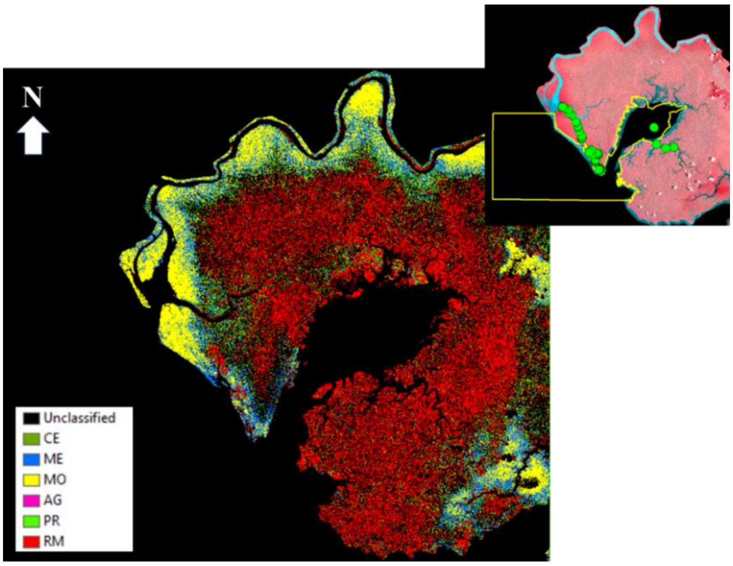

Figure 9: General classification result (below) and general location of sampled sites (top right, standard false color), Bahía Málaga.

As of the date of publication of this paper, this study area is still awaiting revisiting to expand the number of spectral signatures and deepen the spectral characterization of its mangrove species. However, the classification of the image with the few available signatures yielded promising results in terms of the differentiation of pixels by their spectral response, which is evidenced by being able to observe a clear pattern of distribution of *Rhizophora mangle* (RM) in riverbank areas of the internal drainages of the mangrove forest, as was observed during the field work in Málaga Bay:

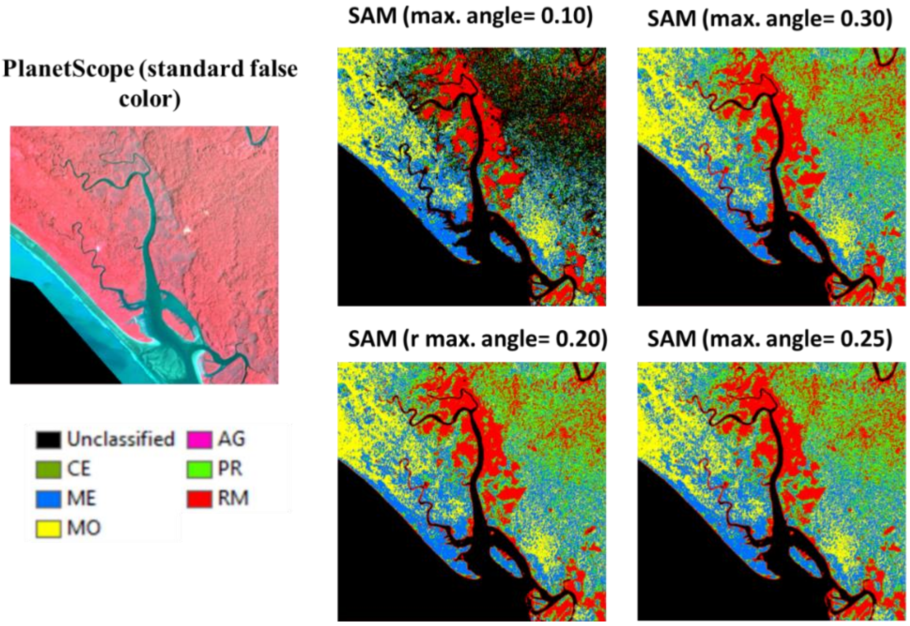

Figure 10: Comparison of classification results with different values of maximum spectral angle, Málaga Bay.

As for the Gulf of Tribugá, and since no significant difference was found in the classification process with SAM when testing with different maximum angles, the image was classified only with the resampled species endmembers:

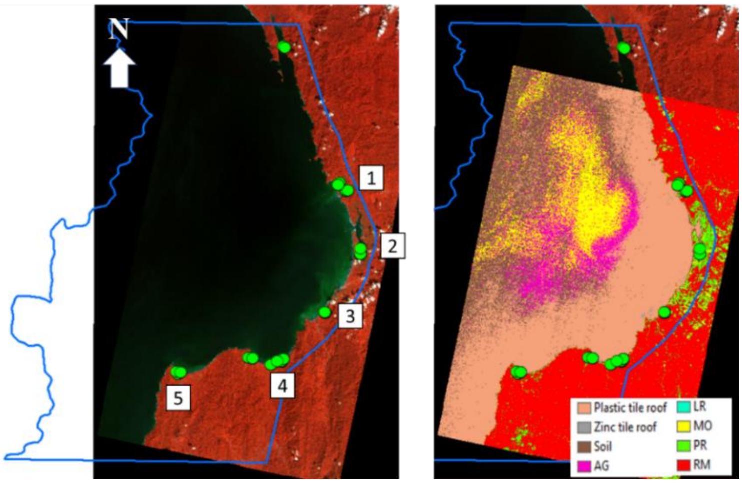

Figure 11: General location of sampled sites (left, standard false color) and general classification result (right), Gulf of Tribugá.

The performance of the classification in this study area was quite interesting, given that the succession of the mangrove forest can be observed according to the geomorphological and soil characteristics that condition it. An example of this can be seen in a close-up of the classification result in the surroundings of the town of Jurubida in the department of Chocó (figure 12), where consecutive strips of *Avicennia germinans* (AG), *Mora oleífera* (MO), *Pelliciera rhizophorae* (PR) and *Rhizophora mangle* (RM) mangrove are evident with individual *Laguncularia racemosa* (LR) pixels. Of course, the natural distribution of the mangrove forest is not this homogeneous in reality, what the SAM algorithm shows is the class with the highest spectral relationship between the pixel and the endmember, however, a spectral relationship of that pixel still exists with all other classes. In short, the classification result yields the strongest spectral response, which in terms of knowledge of the distribution of the mangrove forest in a region where historically geospatial information is very scarce is a very promising result. In the same way, figure 12(1) shows the clos-ups of the nearby towns where the field work was carried out in the Gulf of Tribugá, and the general result obtained from the classification process.

The aforementioned issue corresponds to a very important point that is still the subject of work by the IGAC and its participation in the Pacific Expeditions, and that is the validation of the classification results. When talking about classification of Earth observation images, generally a percentage of the classification points must be available for validation; in this case, it is a challenge that is still ongoing given that there is not enough primary information for this purpose, so the main form of validation so far has been through the visual interpretation of the results, based on secondary information and consultation with experts.

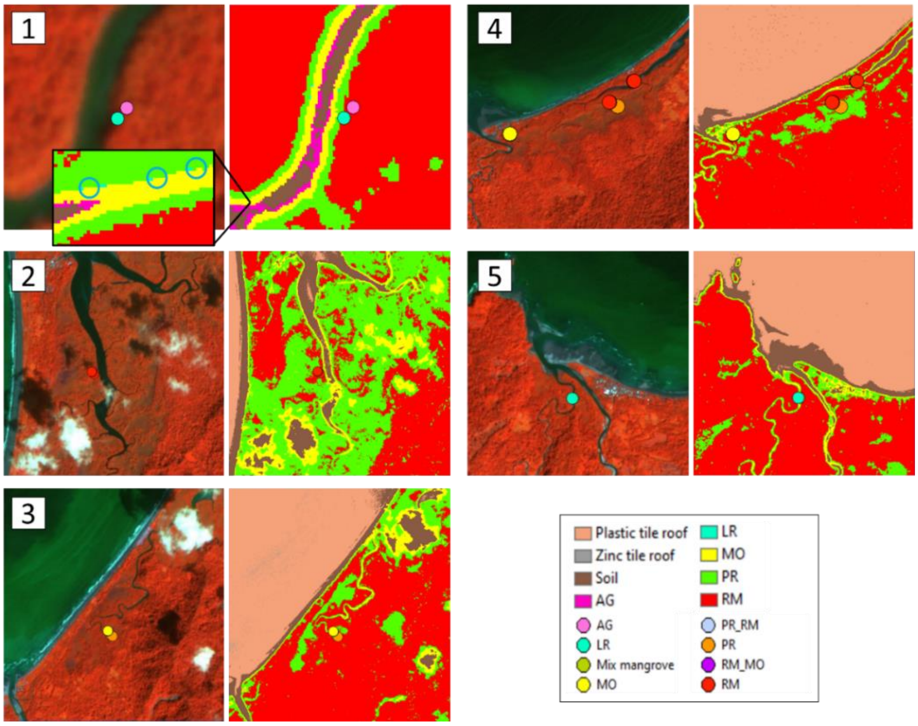

Figure 12: Comparison of classification results in the proximity of different towns in the study area, Gulf of Tribugá. Where 1) Jurubida, 2): Tribugá, 3): Pangui, 4): Coqui, and 5): Jovi.

Based on the results obtained and the difficulties encountered, the IGAC continues to work hard to improve these results, to strengthen the processing and field work methodology to ensure a reliable result that contributes to the management of the mangrove forest in Colombia, for the conservation of this strategic ecosystem, the strategies for adaptability to climate change and the well-being of the many communities whose daily lives depend on the mangrove forest.

4. Conclusions and recommendations.

During the three scientific expeditions to the Colombian Pacific in which the IGAC has participated, different strategies, methods and processing algorithms have been tested to guarantee the quality and representativeness of hyperspectral data captured in the field, as well as to analyze the spectral separability between these at two levels: optimal spectral resolution of the field hyperspectral data and the final signatures (endmembers) resampled to the resolution of PlanetScope images for their classification using the SAM algorithm. The results obtained demonstrated that, despite the limitations experienced, representative spectral signatures of the identified mangrove species were properly obtained. On the other hand, and despite the clear limitations in the spectral, radiometric, and spatial resolution of the PlanetScope images, patterns of the spatial distribution of the mangrove species sampled in the images are evident, which are consistent with the known and observed distribution of the studied species in the field, although unfortunately there is still a persistent limitation of having insufficient information to validate the results.

Regarding the above, there is a detected need to strengthen the field work with additional equipment and accessories to access and sample different strata of the mangrove forest structure. During the expeditions on very few occasions the canopy of the sampled species could be accessed, so the measurements had to be made under conditions that represented greater noise and uncertainty in the signatures obtained. Likewise, and building on the lessons learned, the next step in the IGAC Research and Prospective Directorate in the processing and analysis of these information is to explore artificial intelligence algorithms for the classification of images, in order to strengthen the results obtained with the large volume of hyperspectral information from the mangrove forest of the Colombian Pacific that is available after three scientific expeditions with the Colombian Ocean Commission.

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