# 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:** Coastal Marine Ecosystems, Mangrove Forest, Remote Sensing, Sustainable Development, Spectroradiometry, Thematic Mapping.

**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 Directorate Research and Prospective 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 sustenance 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 espectro-radiómetros 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:

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

The ecosystemic importance of mangroves is therefore of the highest priority in 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. In addition, the Afro-descendant and root 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 been affecting these communities in the Colombian Pacific for decades (International Crisis Group, 2019). These communities present challenges and fears about two specific aspects of their relationship with the mangrove forest: housing and food, both strongly threatened by the global social and climatic situation (Giri et al., 2011; Golberg et al., 2020; Lee et al., 2014; Thomas et al., 2017).

The Colombian Ocean Commission's (CCO) Plan of Expeditions to the Colombian Pacific arose from the above, with the aim of strengthening the technical and scientific capacities of the scientific and academic community in the knowledge and study of the marine-coastal ecosystems on 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 Agustín Codazzi Geographic Institute (IGAC), through the Directorate of Research and Foresight, has participated in three Pacific Expeditions since 2021 with the aim of developing research in the field of Earth observation technologies and field spectroradiometry, from which significant progress has been made 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 generate images of areas of interest and have important applications in Earth observation, through them it is possible to acquire information on a small and large scale, of an object or phenomenon, without there being physical contact with it. The relationship between the energy observed and captured on different platforms and its behavior with the cover or element observed is the study objective of IGAC's participation in the Pacific Expeditions using field spectroradiometry as a means of capturing detailed hyperspectral information on mangrove species from reflectance measurements. These measurements, known as spectral signatures. Based on this, the following concepts need to be taken into account:

- **Spectral library:** Organized and catalogued collection of spectral signatures, which can be used for image classification purposes, identification of unknown spectral profiles and for correlation of biophysical vegetation information, (Brown et al., 2006).
- **Endmember**: Are type spectral signatures, representative samples in a defined study area for field spectroradiometry.
- **Spectral signature:** The way in which a sampled object emits or reflects its energy at different wavelengths and whose behavior serves to differentiate one element spectrally from another (Moran et al., 1995; Moizo, 2004).

IGAC and the Pacific Expeditions have explored different ways and methods of classifying satellite images with the signatures captured in the field. This article aims to share the experiences and results obtained in the integration of hyperspectral field data in the classification of optical Earth observation images.

## 3. MATERIALS AND METHODS:

### 3.1 Areas of study:

The IGAC has participated in three Pacific Expeditions (Pacific coast of Colombia), the first to the Sanquianga National Natural Park between 29 and 4 May 2021, which is located in the department of Nariño and has an area of 80,000 hectares of which a large part corresponds to mangrove forest, and due to this extension corresponds to approximately 20% of the mangroves of the Colombian Pacific (Parques Nacionales Naturales de Colombia, 2017). The second expedition was carried out between 5 and 12 December 2021 in the Uramba Bahía Málaga National Natural Park in the department of Valle del Cauca, with an extension of 47,094 (Parques Nacionales Naturales de Colombia, 2023).

This is the study area from which the fewest spectral signatures could be obtained, given that due to weather conditions during the expedition the spectroradiometer taken to the field suffered several malfunctions that rendered it useless on the third day of the campaign. Finally, the most recent expedition was to the Gulf of Tribugá between 7 and 16 March 2023, located in the department of Chocó with an area of 60,138.6 hectares (Parques Nacionales Naturales de Colombia, 2023), is the study area in which the largest number of spectral signatures could be obtained, thanks to logistics and the longer duration of the campaigns compared to the other two expeditions.

### 3.2 Planning of spectroradiometry campaigns:

A spectral signature survey campaign in the field begins with prior knowledge of the study area, which is very important for the sampling design. Then the equipment and accessories to be used in the field campaigns are selected and verified, and with respect to the data collected in the field, it is recommended to review the natural cover, ecosystems and any cartography that can be accessed. The capture of spectral signatures must take into account the following characteristics:

- Local meteorological conditions.
- Accessibility of sampling areas.
- Time of collection.

These parameters correspond to the definition of the rules of the experiment (measurement protocol), i.e., the definition of the species to be measured, how to measure them (observation geometry), and what information is to be obtained from the species in addition to the capture of spectral signatures (metadata).

### 3.3 Methodology for spectral signature consolidation and image classification:

Once the fieldwork and design of the campaigns has been established, a methodology for the processing and analysis of the spectral signatures is designed, and in general terms this methodology includes: the calculation of an average and unique spectral signature to generate a single endmember per species, 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 characterised species, the elaboration and compilation of spectral libraries and the classification of the satellite image.

The unification of the spectral signature to arrive at an endmember per sampled target is approached through dendogram analysis with Ward's hierarchical discriminant analysis method, although separability analysis has also been done with the Jeffries-Matusita distance, to first identify signatures with inconsistencies between samples and then to determine the clusters that will form the image classes, which consists of obtaining the average of the data series (wavelength reflectance) captured at each sampling point spectrally characterised against each 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, for this case the Spectral Angle Mapping (SAM) algorithm was used, although several tests were also made with spectral unmixing at the sub-pixel level. The SAM algorithm determines the similarity between the two spectral data as a function of the angle formed by the endmember (spectral field signature) and the image signature, treating the result as classification vectors where sharper angles and smaller divergence represent higher spectral 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 the spectral correspondence between the hyperspectral field data with the satellite image to be classified by an operation called spectral resampling. For this it is necessary to obtain the band centres of each of the bands of the image to be classified and that is atmospherically corrected, and in the case of the Pacific Expeditions the best images available are from the PlanetScope programme (analytic product), which according to the metadata of the images, the band centres are the following:

| Spectral Region | PlanetScope Range | Centre of band |
|---|---|---|
| Ultra-violet (<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 the project.**

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

### 3.4. Development of expeditions:

The 3 expeditions were developed according to the logistical planning of the CCO without major inconveniences except for the damage of the spectroradiometer taken to Bahía Málaga mentioned above. An important challenge for this type of research in the Colombian Pacific is the constant cloud cover and rain throughout the year. It is widely known that optical satellite images are affected by cloud cover, which considerably limits their availability, but in addition to this, the conditions of rain, clouds, haze and general water vapour in the atmosphere cause the spectral measurements in the field to have excessive noise at the time of capture.

However, due to logistical conditions, such as boat transport, tidal behavior, and security restrictions in the study areas, it was necessary to carry out fieldwork every day of the expeditions, and the only days on which signatures were not taken were those when there were torrential rains or when equipment had to be checked. Also, accessibility to each of the programmed points, in many cases, lengthened sampling and equipment preparation times, considerations that could not be foreseen until they were present at each of the points.


**Figure 1: Example of access and mobility conditions in the expeditions. Top left: Sanquianga, bottom left: Malaga Bay, right: Gulf of Tribugá.**

Due to the physical and social conditions of the area, the points visited were associated with the monitoring plots of Parques Nacionales Naturales, World Wildlife Fund (WWF) and the expert knowledge of local community leaders. Although we would have liked to capture a high volume of spectral signatures, the security limitations established by the National Navy and the communities did not allow for a higher density of sampling points. As a result, a total of 99 spectral signatures of six different mangrove species from the Colombian Pacific were 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 signatures captures in the expeditions.**

Signatures corresponding to "other" categories were captured for two purposes: to contrast spectral information from other features/coverages in both spectral analysis and image classification, and to spectrally characterize other geographic features of interest to IGAC for future complementary research.

### 3.5 Analysis and processing of information:

The processing and analysis of the spectral signatures obtained begins with the filtering and selection of the type signatures of the mangrove species identified in the fieldwork. For this purpose, only the signatures corresponding to the forest species are selected first, excluding those of soil samples, house canopies, flora species other than mangrove and other samples in the field. When reviewing the signatures, it is first necessary to identify bad bands and 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 nanometers), so the bad water absorption bands of the SWIRs will not be present (Pahlevan et al, 2017). Noise and outliers in the signatures can be due to variations in the weather and environment at the time of signature capture, human error in the procedure, soil effect across the leaf area, and even equipment problems, so the first step is to refine the spectral signatures before generating the endmembers, the figure below shows the refined signatures from the Sanquianga Expedition:

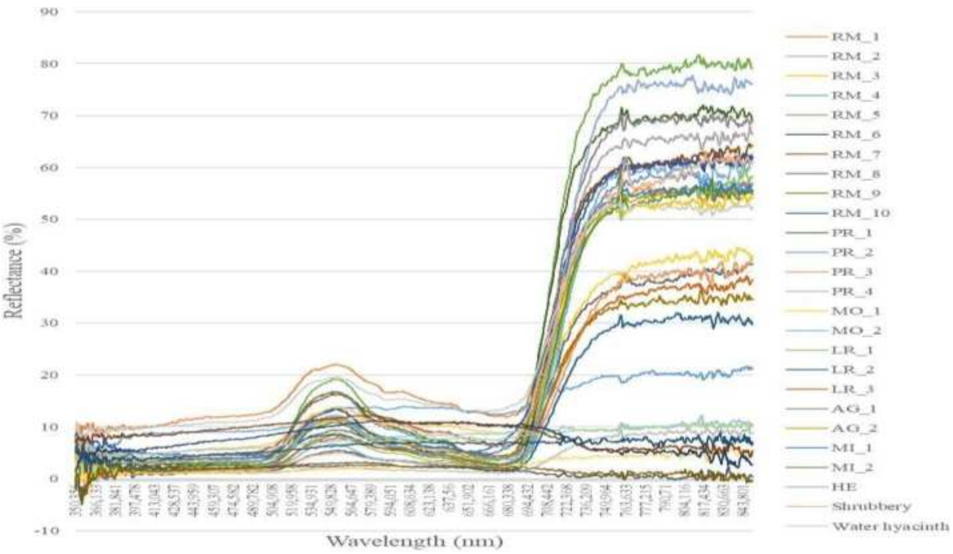


**Figure 2: Example of the status of selected Sanquianga signatures before endmembers were obtained.**

Typical vegetation and soil behavior can be observed in the Sanquianga signatures, and noise is present at the extremes of the spectral range (below 400 nanometers and above 830 nanometers). One of the major risks in noise reduction and cleaning is the loss of spectral information in the resampling, as wavelength values can be lost in the bands between the field signatures and the optical satellite images, thus losing spectral accuracy in the resampling.

### 3.6 Generation of Endmembers:

To obtain endmembers, Ward's hierarchical linkage separability analysis was carried out to identify signatures that may present confusion in the spectral differentiation of the different mangrove species and other cover crops. The figure below presents the low apparent separability between the selected Sanquianga signatures, where it could be concluded that MR signatures are confused with all other signatures for example, however, closer inspection shows that some of this similarity is present with water and soil (mud) signatures, which is an error in spectral characterization. After a detailed review of each of the signatures with their respective metadata and photographic field record, we were able to identify and discard the signatures with the greatest confusion between them, in order to obtain the endmembers from the average value of the signatures:

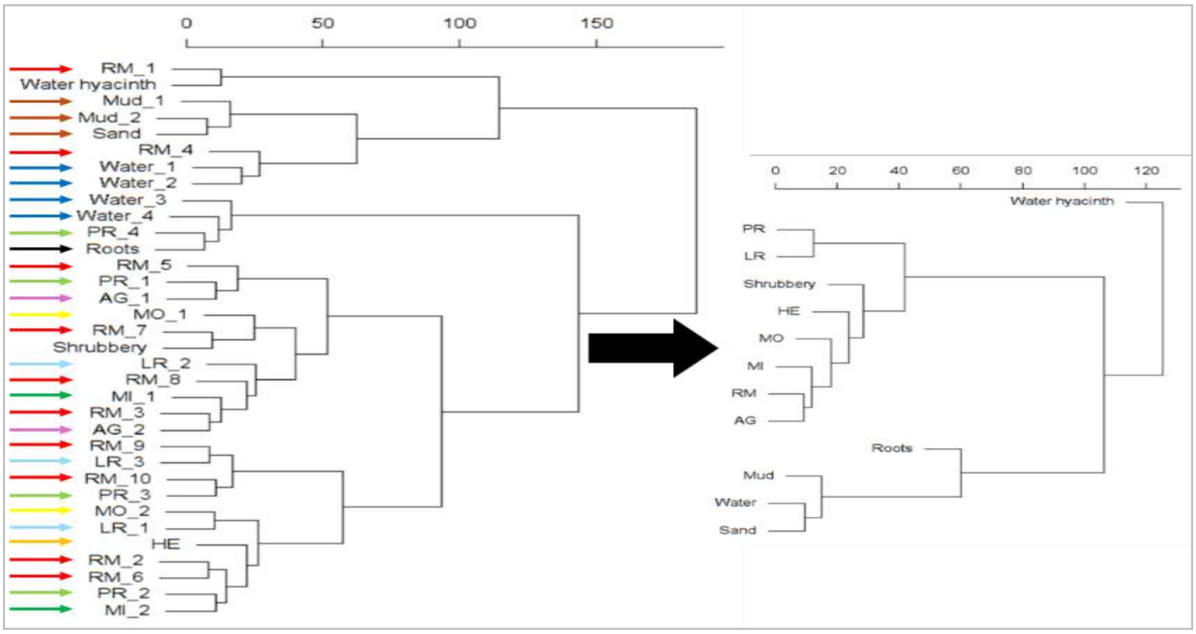


**Figure 3: Example of separability analysis from Ward's hierarchical discriminant analysis of Sanquianga signatures, the colored arrows correspond to species as follows: red: RM, yellow: MO, light green: PR, dark green: MI, purple: AG, light blue: LR, dark blue: water, orange: HE, black: roots.**

The reasons for this 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 and developmental status of the species sampled, the effect of surface humidity (wetness) on the leaves, and the background effect through leaf area. Regarding separability, it was found that in Sanquianga the MR individuals sampled are more similar to AG, as well as in Bahía Málaga PR is closer to AG, while in the Gulf of Tribugá a greater separability was found among the mangrove species observed. Regarding these findings, however, it is necessary to take into account that the environmental and ecosystemic conditions of each study area are unique, in the same way, there are different challenges and difficulties in all expeditions, and thanks to the fact that in the Gulf of Tribugá more time was available, a greater amount of information was obtained, so that spectral characterization could be more accurate than in previous expeditions.

### 3.7 Spectral resampling of endmembers:

In the R software, the resampling instruction was created from the definition of the Gaussian density distribution from the band centres of the PlanetScope images presented above. As expected, a significant amount of information is lost when resampling field spectral signatures captured with hyperspectral equipment to satellite images of only four bands, however, as can be seen in the following figure, the general shape of the type signatures was preserved after resampling:

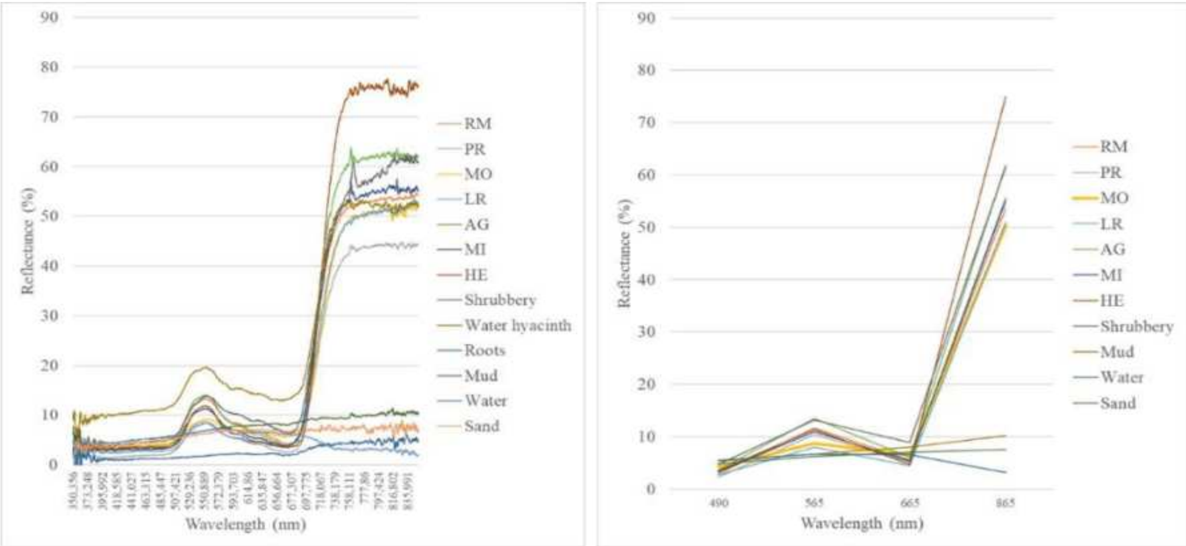


**Figure 4: Endmembers before (left) and after resampling (right), Sanquianga.**

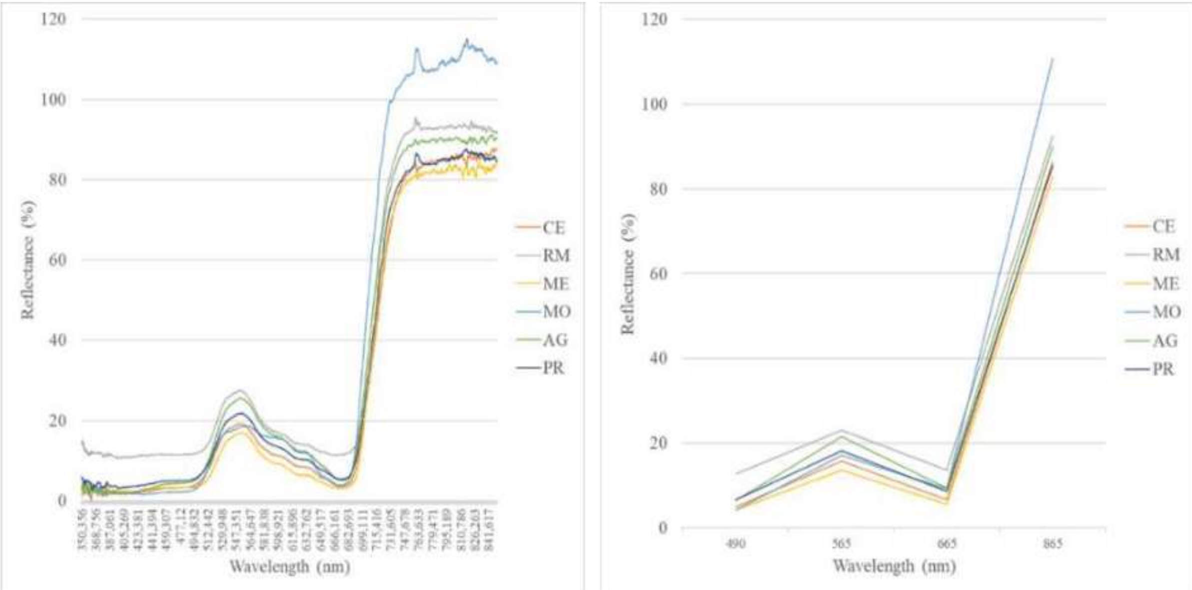


**Figure 5: Endmembers before (left) and after resampling (right), Bahía Málaga.**

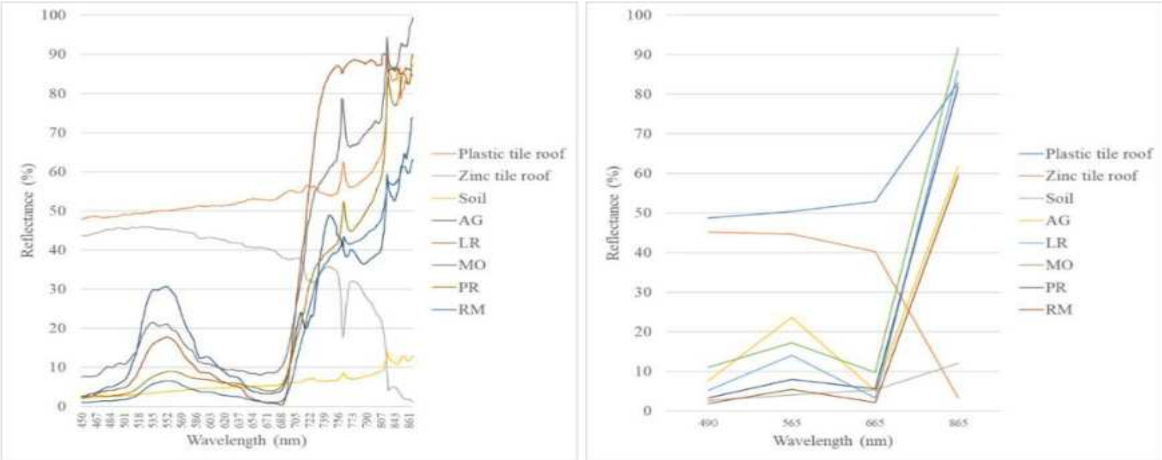


**Figure 6. Endmembers before (left) and after resampling (right), Gulf of Tribugá.**

It is important to note that the key regions of the electromagnetic spectrum in the study of vegetation (red and near infrared) retain their representativeness in the resampled type signatures). Therefore, although much information is lost, the fundamental spectral characteristics of the species and coverages included in the final signatures are preserved.

### 3.8 Classification:

The IGAC Cartography Subdirectorate 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 in the temporality of the available images, in the Gulf of Tribugá there was about a year difference in the date of acquisition with respect to the field work, however, despite these limitations (in addition to the limited spectral and spatial resolution) it is the best input that could be counted on.

Subsequently, we proceeded to perform the radiometric adjustment of the images with the atmospheric correction using the correction coefficients of the metadata of the images, then they were trimmed 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 are obtained in the assignment of pixels of the images to each of the mangrove species used in the classification.

An approach to this study area shows these differences in the classification results, where it can be seen that despite the limitations in the spatial, spectral and radiometric resolution of the PlanetScope images, spectral differentiation can be found in the image after implementing the SAM algorithm at the pixel level, which can be associated with the configuration of mangrove species, allowing to find mainly pixels associated with MR and LR (Figure 8).

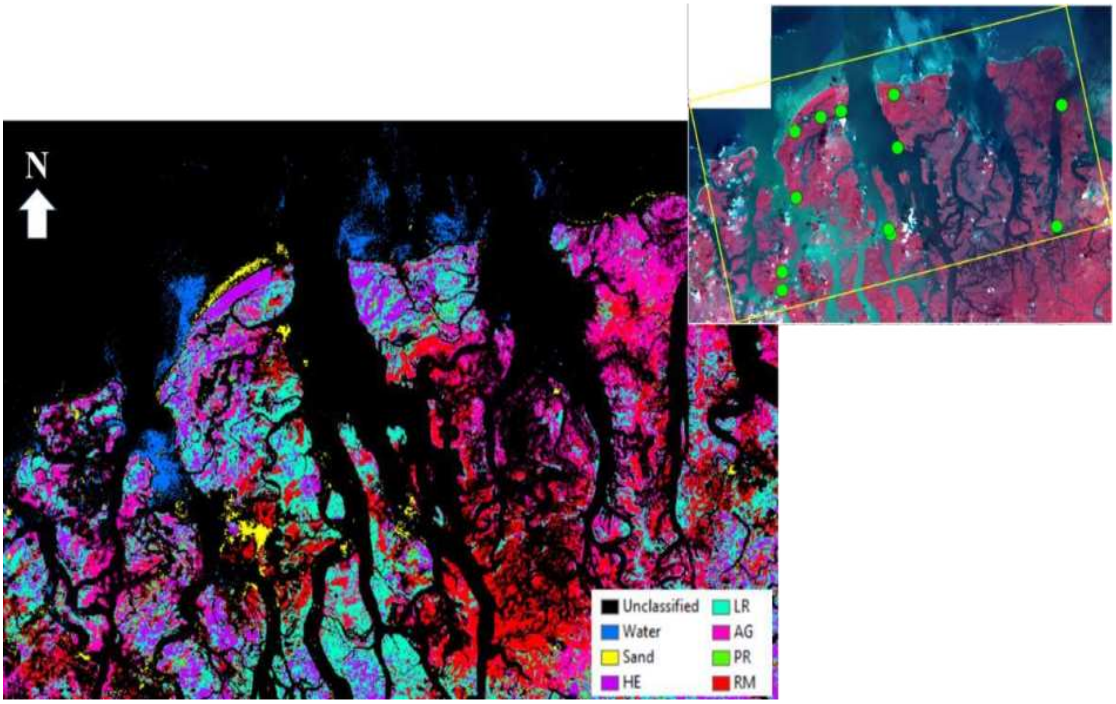


**Figure 7. Overall classification result (bottom) and list of sites sampled in the field (top), Sanquianga.**

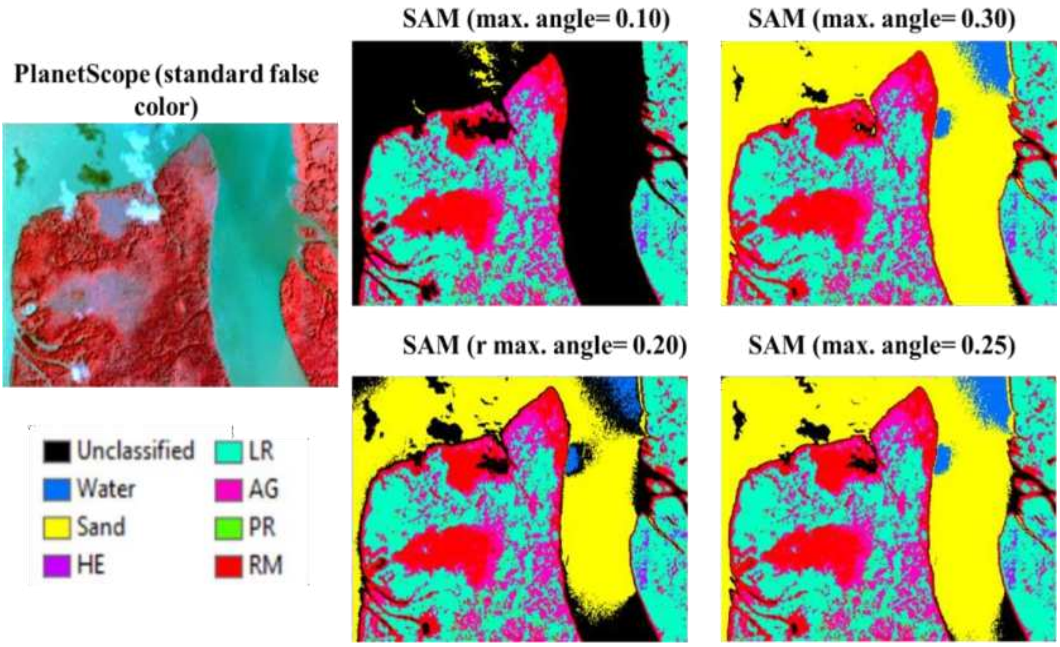


**Figure 8. Comparison of classification results with different values of maximum spectral angle, Sanquianga.**

Regarding Bahí Málaga, and taking into account that it is the study area with the lowest number of signatures, therefore, the lowest spectral characterization of mangrove species, where the predominant resulting classes are RM and MO:

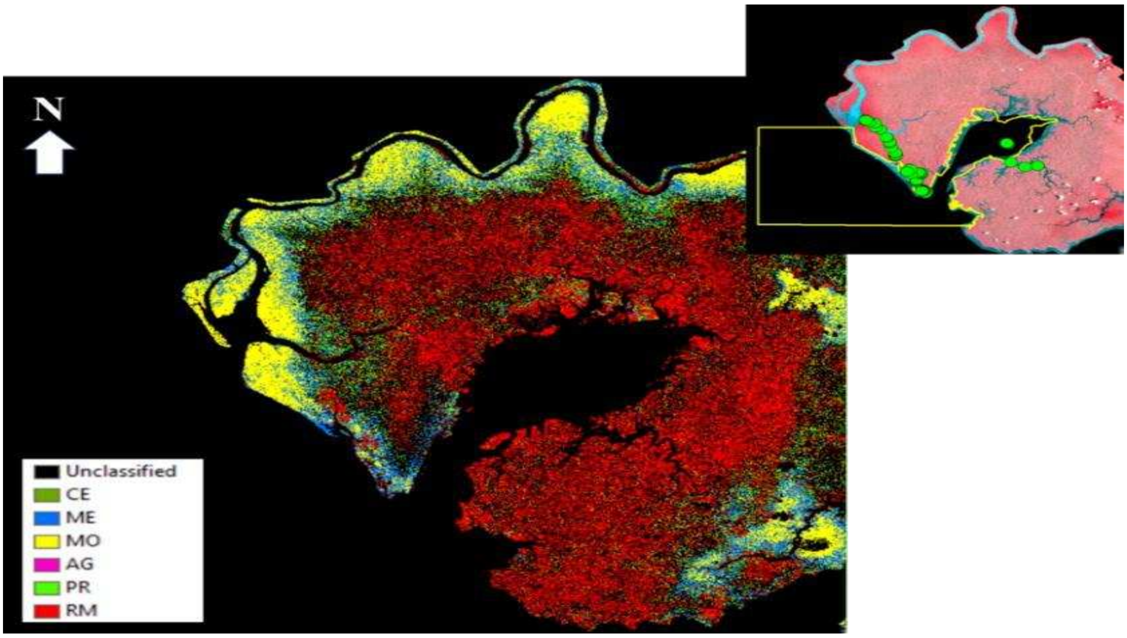


**Figure 9. Overall classification result (bottom) and list of sites sampled in the field (top), Bahía Málaga.**

At the date of publication of this article this study area is still pending revisit to extend the number of spectral signatures and deepen the spectral characterization of its mangrove species. Nevertheless, the image classification with the few available signatures yielded promising results in terms of pixel differentiation by spectral response, which is evidenced by a clear MR pattern in areas along the banks of the internal mangrove drainages, characteristic of Bahía Málaga:

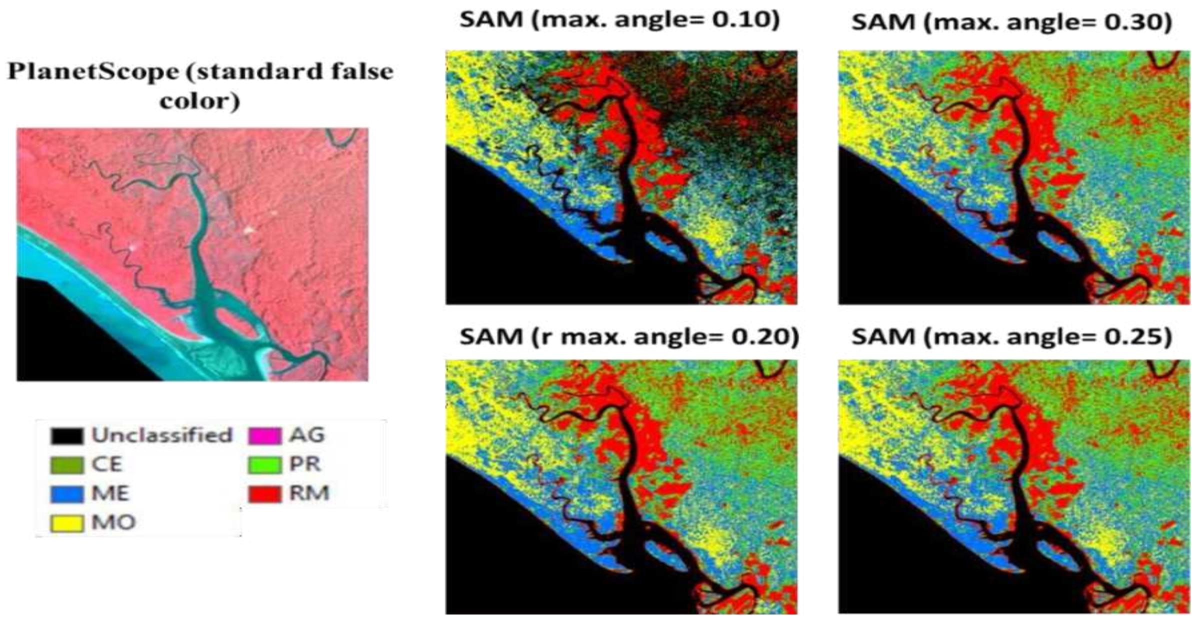


**Figure 10. Comparison of classification results with different values of maximum spectral angle, Malaga Bay.**

Regarding the Tribugá Gulf, and considering that no significant difference was found in the SAM classification when testing with different maximum angles, the image was classified only with the resampled species signatures:

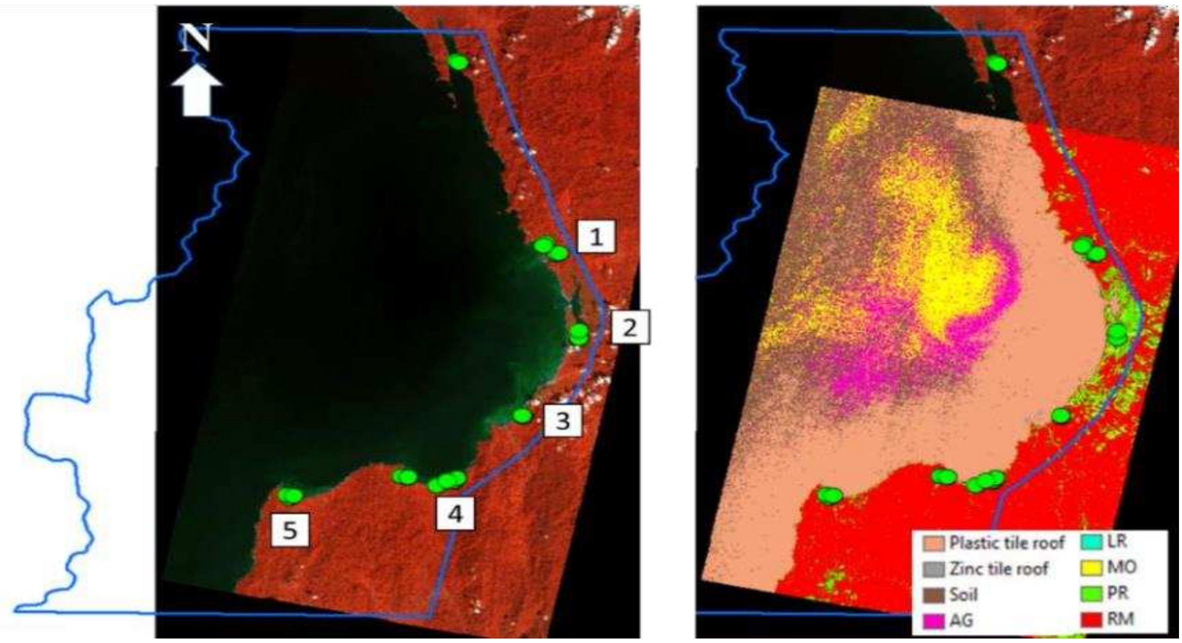


**Figure 11. Overall classification result (right) and relationship of field sampled sites (left), Tribugá Gulf.**

The behavior of the classification in this study area was quite interesting, since 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 an approach to the classification in the surroundings of the Jurubida population center in the department of Chocó in Figure 12, where consecutive strips of mangrove AG, MO, PR and RM with individual LR pixels are evident.

Of course, the natural distribution of the mangrove forest is not so homogeneous in reality, what the SAM algorithm yields is the class with the highest spectral relationship between the pixel and the endmember, however, there is still a spectral relationship of that pixel with all other classes. In short, the classification result yields the strongest spectral response, which in terms of knowledge of mangrove forest distribution in a region where geospatial information is historically very scarce is a very promising result. In the same way, Figure 16(1) relates the population centers where field work was conducted in the Gulf of Tribugá and the general result obtained from the classification.

The aforementioned touches on a very important point that is still being worked on by IGAC and its participation in the Pacific Expeditions, and that is the validation of the classification. 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 since there is not enough primary information for this purpose, so the main form of validation so far has been through visual interpretation of the results, based on secondary information and consultation with experts.

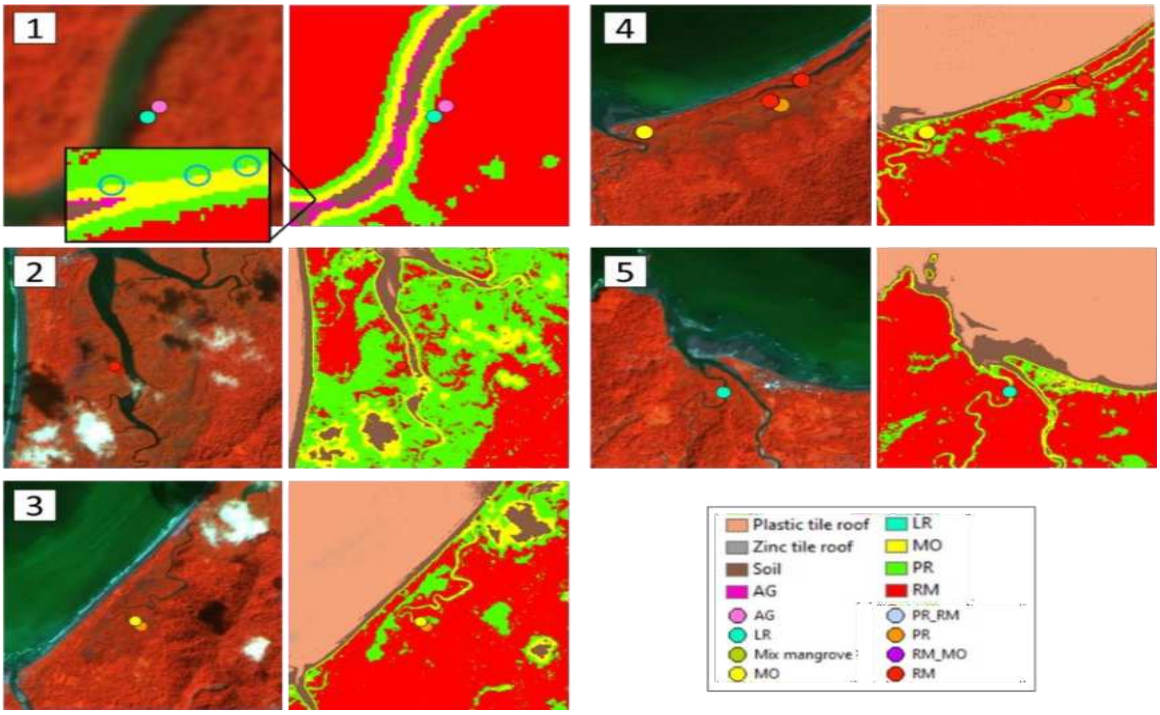


**Figure 12. Comparison of classification results in different population centers in the study area, Gulf of Tribugá. Where 1) Jurubida, 2): Tribugá, 3): Pangui, 4): Coqui, and 5): Jovi.**

Based on the results obtained and the difficulties encountered, the IGAC continues to work hard to improve the results, strengthen the processing methodology and field work to ensure a reliable quality result that contributes to the management of the mangrove forest in Colombia, for the conservation of this strategic ecosystem, strategies for adaptability to climate change and the welfare 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 IGAC has participated, different strategies, methods and processing algorithms have been tested to guarantee the quality and representativeness of the hyperspectral data captured in the field, as well as to analyze the spectral separability between them at two levels: optimal spectral resolution of the hyperspectral field data and of the final signatures resampled to the resolution of the PlanetScope images.

The results obtained showed that, despite the limitations experienced in the field, it is possible to obtain representative spectral signatures of the identified mangrove species, something that was improved with the generation of the second derivative, both in the hyperspectral and resampled signatures. On the other hand, and despite the marked limitations in the spectral, radiometric and spatial resolution of the PlanetScope images, patterns in the spatial distribution of the mangrove species sampled in the images are evident, which are consistent with the known and detected distribution of these species in the field, although unfortunately there is still the limitation of having sufficient information available for the validation of the results.

With respect to the above, the need to strengthen field work with implements and accessories for access and sampling of different strata of the forest structure of the mangrove forest is even more evident. During the expedition in the Gulf of Tribugá, access to the canopy of the sampled species was very seldom possible, so 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's Research and Prospective Direction in the processing and analysis of the information is to explore artificial intelligence algorithms for the classification of the images, in order to strengthen the results obtained with the large volume of hyperspectral information of the mangrove forest of the Colombian Pacific that is available after three scientific expeditions with the Colombian Commission of the Ocean.

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