Monitor Mangrove Forest Dynamics from Multi-temporal Landsat 8-OLI Images in the Southern Coast of Sancti Spíritus Province (Cuba)

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Abstract. In the coastal tropics and subtropical regions, fragile ecosystems such as deltas, mangrove forests, and swamps are common, whose ecological stability strictly depends on the quality management of hydrological resources at the basin level. The National Hydrographic Basin Council in Cuba, protect the hydrographic basins, considered as the reference unit for the integrated management of water resources. Moreover, the council aims at preventing negative impacts on of these vital ecosystems for their key services to the overall social and economic wellbeing. As an example, the Zaza River basin in the of Province of Sancti Spiritus, the mangrove forest is suffering from significant decay, in particular on the southern coasts. A significant improvement of the water resources sustainable management in Cuba, is a more reliable and timely monitoring. Considering the extreme conditions and the limited accessibility of mangroves, remote sensing and others earth observations techniques represents a suitable tool for monitoring the mangrove forest in coastal areas. In our study, we used a set of 10 multispectral Landsat – 8 OLI images from November 2014 to December 2015.

By collecting campaigns on mangroves' phenology, we have: 1) studied the relationships between phenology and spectral behavior of species; and, 2) set up a classification framework to assess the forests composition remotely, with special attention to mangroves. The methodology here implemented could be effectively applied in all coastal natural ecosystems of this island to improve the knowledge about the critical issues of these very fragile ecosystems.

Keywords: Mangrove forest · Remote sensing · Landsat – 8 OLI images

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1 Introduction

Hydrographic basins in Cuba are considered the functional reference unit for programming and planning the social, economic and ecological integrate management of natural resources. Among the natural resources, water is a key resource for human wellbeing and productivity. Basin and watersheds are noteworthy for the overall water cycle and "*constitutes the area of land from which all surface run-off flows through a sequence of streams, rivers and, possibly, lakes into the sea at a single river mouth, estuary or delta*" [1]. In the Caribbean islands (i.e. Cuba, Grenada, Antigua-Barbuda), a freshwater shortage is critical since supply depends mainly on rainwater. Integrated Water Resources Management (IWRM) at river basin scale is a key management strategy to preserve water resources and their long-term social, economic, and environmental exploitation [2]. As defined by the Global Water Partnership [3], the IWRM is "*a process that promotes the coordinated development and the management of water, land and related resources, to maximise the resultant economic and social welfare equitably without compromising the sustainability of vital ecosystems*". Unfortunately, a sectoral approach is still prevailing worldwide. For instance water management policies does not comply with the fundamental IWRM principles in Cuba. The Hydrographic Council and territorial councils at national and provincial level respectively, adopt manage water distribution looking only at the agriculture and urban water supply without considering the ecological needs of natural ecosystems, like coastal mangrove forests. Temperature, salinity, sediment, and energy conditions, mostly depend on the ways water is managed, impact on the ecological balance of the ecosystems. Any alteration in mangrove forest composition, distribution, and extension, could get problems in specific aspects of water management. According to Feller and Sitnik [4], mangroves are a mix of tropical trees and shrubs growing in the inter sea zone. The mix composition can be up to 16 families and 40 to 50 species approximately. Cuban mangroves, in general, settles in the biogenetic and accumulative coast estuaries, where the tides and freshwater determine their spatial pattern. Mangrove forest constitutes a precious backup, representing 26% of forest surface in Cuba [5]. Monodominant or mixed mangroves can establish a great variety of communities or ecological types. *Rhizophora mangrove* (red mangrove) generally occupies the first shoreline forming practically a monospecific fringe. It also located in the borderlines of rivers, canals, estuaries, and coastal lagoons. For this reason, a special focus should be dedicated to the dynamics of red mangroves along the coasts as one of the most interesting potential indicators of water management issues at the basin level. To this end, an efficient management of the mangrove ecosystems, requires effective monitoring and decision support frameworks. Because of the extension of the studied area and the difficulty of manned survey operations in mangrove forests [24] and their rich biodiversity [25] earth observation, remote sensing and GIS have widely proven to be essential tools [6–23]. Conventional spaceborne multispectral data (e.g. Landsat and SPOT series, IRS, ASTER) play pivotal role in earth observation. In fact, medium spatial resolution (several meters) imageries are effective for extensive areas [26]. Furthermore, the availability of temporal data series, three decades at least, and the detail of yearly acquired data (same Path and Row) allow users to perform Change Detection [27].

The significant spectral mix of mangrove canopies [28] is the reason why alternative high-resolution optical data processing are adopted in addition to the usual pixel-based methods, including neural network [28] and linear spectral unmixing [29].

We have applied the Multiple Endmember Spectral Mixture Analysis (MESMA), by Somers & Asner [30], to improve the classification accuracy and quality mapping. In our experiment, Hyperion satellite rainforests spectral images, for different periods of the growing season, have been coupled with the specific phenological phases of mangroves. Three main characteristics of the spectral response (foliage, soil, and water) interactions of seasonal and daily tides [6, 17], and cloudiness are considered. The method consists also of aerial photo detection [15] and human interpretation [31, 32]. In particular a multitemporal set of Landsat – 8 OLI multispectral images have been processed by MESMA to improve the spectral separability of high of classified pixels to better identify the different land covers, with special attention to the possibility of distinguish among mangrove species in the coastal southern Sancti Spíritus. The outcome are as follow: 1) we could evaluate the relationship between phenology of mangrove forest species and their reflectance on images within a specific climatic period (December 2014-July 2015); 2) we could get improved results using the MESMA methodology.

The general objective is to set up a significant approachable to be applied in any region with the presence of forests of mangroves in tropical and subtropical countries.

In our beliefs, the present work can contribute to the general objective to set up an effective monitoring standard, replicable in others tropical and subtropical regions of the world with significant forests of mangroves. Secondly to contribute to the debate for improved water management policy in Cuba.

2 Study Area

The study area (Fig. 1) is of 1608.17 square km located in the Southern coast of the Sancti Spíritus province in Cuba (upper left East vertex 591094.32 m, Nord vertex 2380724.03 m; low right East vertex 706320.94 m, Nord vertex 2414462.33 m as UTM zone 17N WGS84 projection). The political-administrative boundaries are represented by Cabagán river which borders with Cienfuegos province (West side), and the port of Palo Alto (Est side) close to the borders of Ciego de Ávila province. Within this area are located Trinidad, on the coast, Sancti Spíritus and La Sierpe municipalities in the central inner region. The geology of this area is characterised by the presence of rocks and structures from the Cuban Neoautocton period, which originated after the consolidation of the plicated substratum in Superior Eocene. The Southern plains are characterised by red ferallitic soils occupying the abrasive terraces. The yellow leached ferallitic and quartz soils occupy the intermediate terraces in the marine plains. Besides, we find dark plastic vertisoils with high content of montmorillonite clay, determining an insufficient drainage, linked to hydromorphic soils of swamps. The littoral swamps with accumulative delta and plain are characterised by hydromorphic soils made by peat-silt and muddy clay.

Cuban rivers are sourced by only natural rain, this reflects their irregular hydric regime with floods and draught periods depending on climate conditions. The climatology of the Cuban archipelago is characterised by two climatic periods with very clean-cut

differences: the rainy season (from May to October) and the dry season (from November to April). The yearly average temperature is 25.8 ºC, the lower average temperature is 21.9 ºC and higher average temperature is 30.7 ºC, according to 1981–2010 historical series. The highest temperatures occur in July and August while the lowest temperatures occur in January. In the study area, the yearly rainfall is 1106.88 mm, but during the dry period the average rainfall is 224.80 mm (21%) while in the rainy period the average rainfall is 882.08 mm (79%).

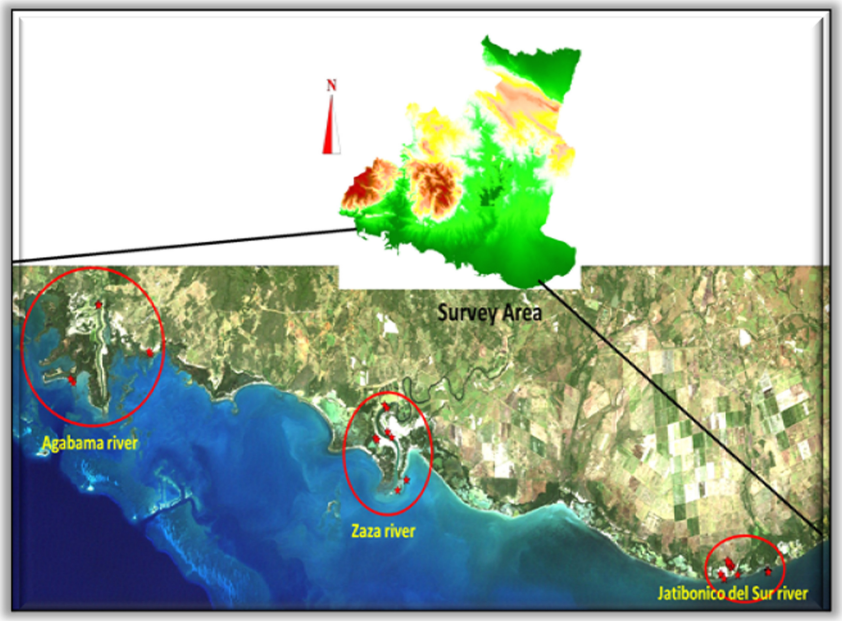


Fig. 1. The study area at the Southern coast of Sancti Spíritus province in Cuba.

3 Materials and Data

3.1 Satellite Data

We used a time series of 10 multispectral Landsat – 8 OLI (path: 14 / Row: 45) images with 30 m resolution on the ground, from the Geological Service of the United States (USGS) (http://earthexplorer.usgs.gov/). The cloudiness thresholded was set to 10%. As shown in Table.1. November and December was chosen for 2014 and January, February, March, April, May, July, October, and December for 2015, including images from the rainy season, the most interesting for spectral discrimination among different species of mangroves [28].

Table 1. Market share [%] of the main three container shipping alliances along the East-West routes. Year 2018. (% TEUs of capacity).

Date	*Sensor*	Path	Row	Projection	Lat./Long.
November, 11-2014	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
December, 13-2014	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
January, 14 -2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
February, 19-2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
March, 19-2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
April, 20 -2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
May, 03-2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753 -79.9260
July, 25-2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753, -79.9260
October, 29 /2015	Landsat 8 - OLI	14	45	UTM-17N/WGS-84	21.6753, -79.9260
December, 16-2015	**Landsat 8 - OLI**	**14**	**45**	**UTM-17N/WGS-84**	**21.6753, -79.9260**

From every multispectral Landsat 8-OLI image, we selected the most suitable bands to investigate the spectral behavior of wetland vegetation [11, 19, 20]. In particular: the bands are as follw: B2 (0.452 – 0.512 μ), B3 (0.533 – 0.590 μ) and B4 (0.636 – 0,673 μ) in the visible (VIS) region; B5(0.851 – 0.879 μ) in the near infrared (NIR) region; B6 (1.566 – 1.651 μ) and B7 (2.107 – 2.294 μ) in the short wavelength infrared (SWIR) region. Rough data were pre-processed to perform a radiometric conversion (from radiance to reflectance) and a geometric correction (georeferencing in WGS84, UTM Projection, Zone 17 N).

3.2 Ground Reference Data

The ground truth collection is a critical step of supervised classification for processing the imagery and validate the results. Often a key issue is the limited accessibility to that characterises these ecosystems. In particular, ground truths are essential in studying the spectral behavior of mangrove canopies, which include a great number of species not so different for what concerns phenology and physiology which usually grow in a very complex habitat. The collection of ground reference data was carried out on August and September 2015 in the following deltaic zones of the Southern coast of Sancti Spiritus province: Jatibonico del Sur river, Agabama river, Zaza river. Globally, this surveys interested 61 plots with a surface of 10 m x 10 m (100 m2) each one, in the field work was adopted the Cuban "Protocol for monitoring the mangrove ecosystems" [33–35]. The geographic location of plots was determined by using Global Position System (GPS) tools to define the centroid coordinates of each plot. Monospecific and mixed canopies of

species shaping the local mangrove ecosystems (Rhizophora mangrove, Avicennia germinans, Laguncularia racemosa, Conocarpus erectus) were surveyed. In each plot, some structural and phenological parameters were determined: flora species in the centroid, dominant flora, height (m), water flood (permanent, temporal, seasonal), total ground coverage (%), red mangrove (Rhizophora mangrove) coverage (%), black mangrove (Avicennia germinans) coverage, patabán (Laguncularia racemose) coverage (%), yana (Conocarpus erectus) coverage (%), abundance of fruits, abundance of flowers, adult trees coverage (%), young trees coverage (%) and the number of individuals died. An additional set of plots was surveyed in order to collect reference data for the others typologies of coverages of interest in the study area like not vegetated soils, deep water, lagoon water, other vegetation, not photosynthetic vegetation alias dead vegetation (NPV).

Finally, by integrating "on field" information with the specific bibliography concerning the mangrove's phenology, it has been possible outlining the main phenological stages for the four species of mangroves considered in our study. In Fig. 2 examples for Red and Black Mangrove are shown.

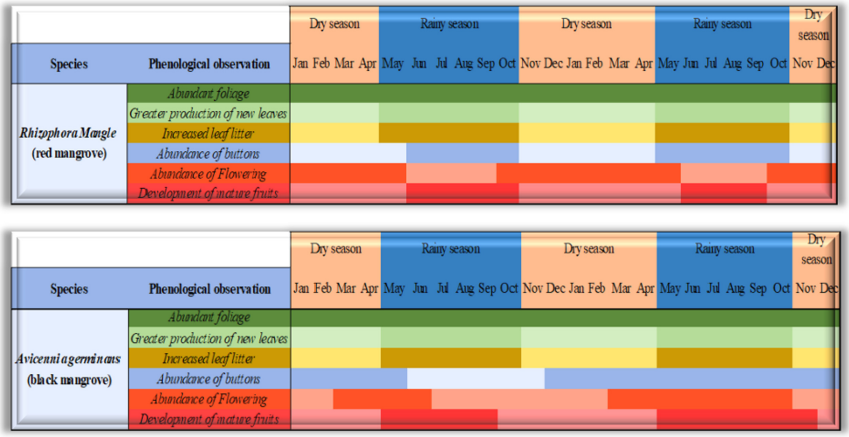


Fig. 2. Main characteristics of the Red and Black mangrove phenology.

In the reporting area, the four most representing species of tree composition in the mangroves forest (R. mangle, A. germinans, L. racemosa, C. erectus) shown abundant foliage during the whole year, boosting their condition of evergreen species. The leaves falling occurs all year long and the new leaves appear during the main rainy period (May-October) but the most significance falling of leaves also occurs in the same time as general tendency. The most abundant flowering of Red mangroves (*Rhizophora mangle)* occurs during the dry period, conversely the flowering of Black mangroves (*Avicennia germinans*) extends also in the rainy period, as well as *Laguncularia racemosa* and *Conocarpus erectus* (White mangroves) usually do. All phenological phases of the four mangrove species may present small displacements within each year, by adapting to climatic condition, and the differences among years, on the other hand, are very limited. Finally, all four mangrove species show the rainy period as the period of maximum

production of fruits, since this stability is related to natural regeneration needs according to the survival strategies of these species in own habitat.

4 Methodology

The main steps of the method used for processing monotemporal and multitemporal Landsat 8-OLI imagery are shown in the Fig. 3. Before applying the unmixing processing, a study to analyse the spectral behavior of mangrove species has been carried out. The goal of this analysis was to improve the knowledge on spectral discriminability among the three species of mangroves considered in our study, an information not yet frequent in the Cuban literature on mangroves.

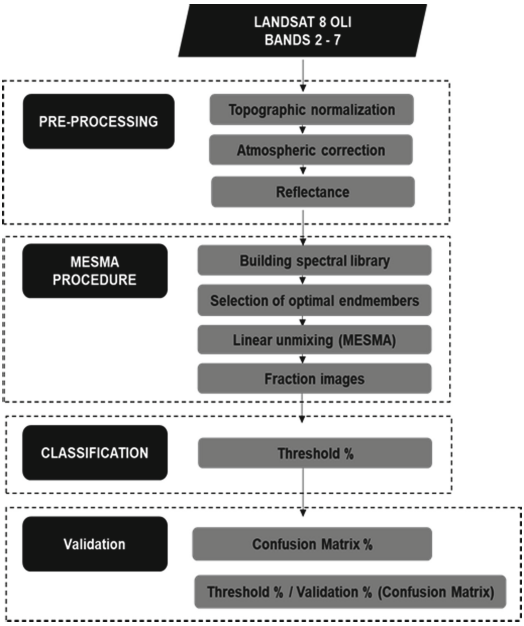


Fig. 3. Main steps of Landsat 8-OLI processing.

The Multiple Endmember Spectral Mixture Analysis (MESMA) method, although not previously applied in Cuba, is widely used. This modeling allows to transform original satellite images into new images with full physical meaning which, in our case, could facilitate the study of mangroves in the Southern coastal zone of the province of Sancti Spíritus by improving the extremely complicated and time consuming field work did in these regions.

The analysis of spectral mixture by MESMA was successfully applied to the phenological effects on spectral behavior of species in the Californian chaparral. Other Authors [36] evaluated the seasonal leaf-level spectral separability in the Panamanian dry forests and Somers & Asner [30] have shown the benefits obtained by integrating time series

of Hyperion images in the data set for endmembers definition in a MESMA application. In mapping, invasive species located in the Hawaiian jungle, they have successfully observed a significant increase in invasive species identification when they have incorporated in MESMA some spectral information related to different stages of growth of such species, thanks to the multi-temporality of the data set.

The Methodology MESMA, implements the process of inversion to estimate the abundances making use of a set variable of endmembers. Using the following procedure to do the crossbred process, according to [37]:

i. It is a technique enabling spectral analysis as a linear combinations of pure signatures, called endmembers, while allowing the types and number of endmembers to vary on a per pixel basis.
ii. The vegetation is characterised by a unique set of endmembers as well as by the fractions.
iii. The endmembers are selected from a library of field and laboratory measured spectra of leaves, canopies, nonphotosynthetic materials (NPV), water and soils and used to develop a series of candidate models.
iv. Each candidate model was applied to the image, then, on a per pixel basis, assessed in terms of fractions, root mean squared (RMS) error, and residuals.
v. If a model met all criteria, is listed as a candidate for that pixel.
vi. To facilitate model selection from a large pool of candidates, an optimal set is selected to provide maximal areal coverage.
vii. These models were used to generate fraction images and vegetation maps showing evergreen and drought deciduous senesced vegetation.
viii. The technique is capable of discriminating a large number of spectrally distinct types of vegetation while capturing the mosaic-like spatial distribution typical of a particular vegetation.

After the pre-processing of images and the digitisation of each surveyed plot during the field campaigns by the software ENVI we could define specific regions of the forest canopy. These are pure pixel composition of Red Mangrove, Black mangrove, White Mangrove, Non-Photosynthetic Vegetation, defined Region of Interest -ROI. In addition, other classes was defined as ROI to complete the menu of covers: soils, water, vegetation and water in lagoons are created.

To describe spectral behaviors of mangrove species the average response (at 95% of confidence) of pure pixels for each species and all Landsat selected bands (VIS, NIR and SWIR) were computed.

4.1 Analysis of Spectral Behavior of Mangrove Species

We obtained multitemporal plots (Fig. 4) showing the relationships between the phenology [34] and the specific spectral response the mangrove forest in the study area (Rhizophora mangrove, Avicennia germinans, Laguncularia racemosa, Conocarpus erectus). This has allowed shed light on the spectral phenology of each mangrove species.

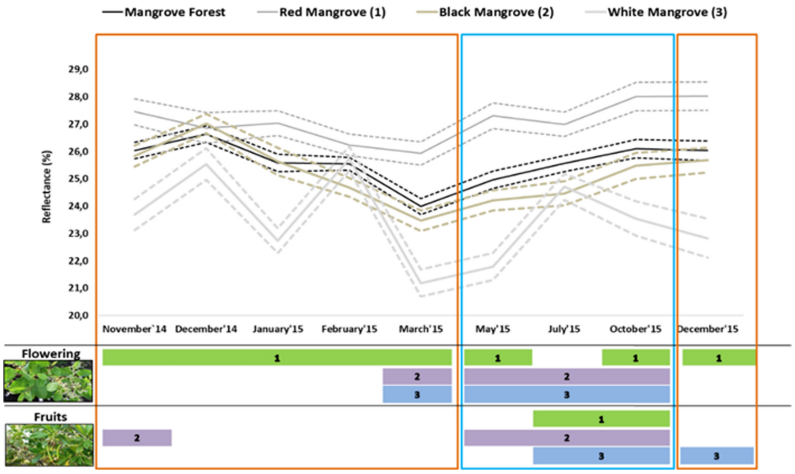


Fig. 4. Relationship between the spectral response in visible blue (reflectance (%)) and the phenology of the mangrove forest and its species (red mangrove (Rhizophora Mangle), black mangrove (Avicennia germinans), white (Laguncularia racemosa and Conocarpus erectus)), in the climatic period (November 2014 - December 2015). (Color figure online)

In the VIS spectral region there are no differences among the species. On the other hand, Red Mangroves and White Mangrove show significant differences from each others in the NIR and SWIR regions. It was also possible to link the spectral behavior of mangroves to the different climatic seasons and phenological stages. In the dry season (e.g. February) all species show higer reflectance in VIS region, while reflectance decrease during the rainy period (e.g. July). An opposite situation can be observed in the NIR region, mainly for Red Mangrove, whose reflectance become higher in the rainy period when flowering, fructification and new leaves production are particularly active.

4.2 MESMA Application

In our experiment we have computed MESMA to Landsat - 8 OLI multispectral images using a stand-alone open Software VIPER [38]. MESMA was applied to a Landsat image in February 2015 representing the dry season, and an image of July 2015 for the rainy season. Moreover a multitemporal image composition for the 2015 (February, March, May and July) was processed. According to the methodology, this allowed for generating a series of fraction images related to monotemporal images or multitemporal images. The fraction images were used firstly in a qualitative way, assembling several RGB compositions to visualise the spatial distribution of each fraction (class). Secondly, a segmentation (density slice) was applied to each fraction image (mono and multitemporal, classes number ranging from 4 to 8) for computing the Confusion Matrix accuracy at different level of spectral pureness (or mixing) of different mangrove species. This allowed to improve spectral separability among the species.

According to [39], MESMA algorithm is characerised by:

- The number of endmembers used to unmixing the image can be considerably greater than the actual number of endmembers of each single pixel.
- On the other hand, it is possible to use a different set of endmembers for each pixel.
- The computational complexity of the algorithm is remarkable for it is based on a iterative test and error procedure, using different sets of endmembers, to get to the as lower as possible RMSE error.
- The key issue for an quality outcome is the availability of adequate spectral libraries, to optimize the process of pixel unmixing.

The maps of each fraction have been computed considering three classification types: 4 (vegetation, soils, water, Non-Photosynthetic Vegetation), 5 (mangrove, vegetation, soils, water, NPV) and 8 classes (red mangrove, black mangrove, white mangrove, vegetation, soils, lagoon, water and NPV), respectively.

These monotemporal and multitemporal supervised classifications have been classified considering ground thrust (Classes-ROI) from 61 surveyed plots during survey campaigns in the southern coastal mangrove forest in the province. From them we could get to a set of endmembers computed in VIPER to define the higher and lower admissible thresholds of the fraction (2) and (3) the higher admissible mean square error (RMSE) to get the image of fraction [37].

$$P'_{i\lambda} = \sum_{k=1}^{N} f_{ki} * P_{k\lambda} + \varepsilon_{i\lambda} \text{ and } \sum_{k=1}^{N} f_{ki} = 1 \tag{1}$$

$$RMS = \left(\sum_{k=1}^{\lambda} (\varepsilon_{i\lambda})^2 / N \right)^{1/2} \tag{2}$$

The fraction images obtained from monotemporal images of February and July 2015, for 4 and 8 classes and multitemporal images of the months (February, March, May, July) of 2015, for 4, 5 and 8 Classes was validated by confusion matrix in ENVI.

5 Results and Discussion

The main result from the application of MESMA concerns the good separation obtained for Red Mangrove with respect to other coverages. An accuracy of more than 80% for fraction of pixels of Red Mangrove with a good level of purity has resulted from the Confusion Matrix performed on the multitemporal image classified in 8 classes. Furthermore, interesting results were obtained for turbid water or water with suspended sediments. MESMA methodology seems to be able to put in evidence the distribution of sediments in the marine areas of deltas, this phenomena being related to rain seasons and water resource management model in all the hydrographic basin.

According to Menéndez et *al.*, [34], the phenological patterns of the main Cuban mangrove arboreal species have the following characteristics:

- The four main arboreal species which form the woods of mangroves in Cuba: *Rhizophora Mangle*, *Avicennia germinans*, *Laguncularia racemosa* y *Conocarpus erectu*; they have abundant foliage during the whole year, corroborating their condition as evergreen
- The leaves falling occurs all year long and new leaves appear during the biggest rainfall (May–October), when as a general tendency the greater leaves falling occurs.
- The phase of flowering of *Rhizophora mangrove* occurs during the months of less rainfall though they keep flowering during the whole year.
- The species of *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus* present defined periods of time during their flowering and fructification phases.
- The fenophases of the four species *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus* present displacement of the phases within years with small differences between the years.
- *Rhizophora Mangle*, *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus* show periods of maximum fructification coinciding to the period of the greater rainfall, evidencing a stationary of this main phenological phase for the natural regeneration according to the regenerative strategies of every species.

6 Conclusion

Mangroves are special environments. The species characterizing the mangroves show morphological and functional specialisations typical of pioneering species, to survive at the extreme conditions in aquatic and saline mixed environments and in muddy unstable grounds. By special devices of breathing and support, the metabolism is adapted to high concentrations of salt, viviparity and long germinative power [40, 41]. The survival of these important ecotonal habitats is of paramount importance, and a cornerstone is the possibility of monitoring their evolution in time. Our research allowed to get to a remarkable result in mangrove forest detection for developing countries. Using open source Landsat 8-OLI images we could classifying and mapping the mangrove forest in the southern coast of Cuba. Moreover, the application of MESMA has given an improved result with higher accuracy. In particular, the analysis of the spectral behavior of three species leaded to the important result to separate the Red Mangrove from others mangroves. This is very important, since Red Mangrove represents the most fragile component of mangrove forests, the first barrier against natural and human impacts. Future development of the research will challenge are in progress. In particular we aim at performing further survey campaigns to collect more ground truth samples to better validate the supervised classification process. Moreover will be important to improve the communication with the government and the water management bodies to impulse the creation of a permanent observatory of mangroves in Cuba.

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