Monitoring mangroves with multi-sensor Earth Observation data sets: from one-shot historical cartography to online and near-real-time monitoring tools

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Keywords: Mangrove, Sentinel-2, Pleiades, extent, texture, structural types

Abstract

This study outlines advancements in mangrove monitoring using Earth Observation (EO) technologies, highlighting a transition from historical cartography to modern, near-real-time monitoring systems. Mangroves, critical for biodiversity, climate regulation, and coastal protection, face threats from climate change and human activities. The need for accurate and recurrent mapping tools is emphasized, addressing the limitations of current global datasets like the Global Mangrove Watch (GMW) by incorporating high-resolution data and field measurements. The French National Research Institute for Sustainable Development (IRD) has pioneered mangrove monitoring since the 1990s, with key methodologies including the use of Sentinel-2 and Pleiades satellite imagery for high-resolution mapping, texture-based analysis, and the incorporation of LiDAR data for accurate biomass estimation. Historical cartography is contrasted with contemporary monitoring efforts, focusing on the integration of multi-source data and the importance of localized ground-truthing. This approach enhances the capabilities of earth observation for carbon stock assessments and supports informed decision-making in conservation and climate policy. The work also highlights the need for further integration of local knowledge and advanced EO sensor data to refine carbon sequestration models and improve mangrove management strategies.

1. Introduction

Mangroves are tropical forests that are uniquely adapted to the intertidal zone in the tropical and subtropical regions (Giri et al., 2011). Mangroves cover approximately 14 million ha worldwide (Bunting et al. 2022). As reported in the scientific literature, carbon stock values range from 40 to 2000 t/ha, while burial rates vary from 0 to 10 t /ha/yr (Malerba et al. 2023). Our ability to ensure their preservation is a key issue in the fight against global warming, the preservation of biodiversity and the livelihoods of a growing human population concentrated along the coasts (Alongi, 2008; Sandilyan and Kathiresan, 2012). Nevertheless, mangroves are among the world‘s most threatened ecosystems due to climate change and human activities (Hamilton and Casey, 2016). Some estimates suggest that global mangrove area has declined by 30-50% over the last half century (Polidoro et al., 2010). Accurate and recurrent mapping tools are available for mangrove monitoring, with Global Mangrove Watch (GMW) providing the highest quality global data (Bunting et al., 2022). However, differences remain in the assessment of mangrove extent between these tools, and finer characterisation of mangrove structures is lacking, particularly for improved carbon storage estimation and management strategy design.

Since the late 1990s, IRD (French National Research Institute for Sustainable Development) has led historic developments to assess the distribution, health and spatio-temporal dynamics of mangroves, using remote sensing data and methods. In the Guiana Shield, the International Ecolab Initiative gathered French, Brazilian, Surinamese and Guianese scientists to produce the first space-borne products characterising coastal ecosystems using Landsat TM 5 data. Further International Cooperation projects in the Amazon coastal region produced in the late 2000s improved mangrove cartographies based on Spot 5 data and object-oriented analysis. Today, current developments focus on 4 directions: (1) Sentinel-2 time series analysis for rapid and generic mangrove mapping, (2) texture-based analysis of very high resolution satellite data for mangrove structure characterisation, (3) Lidar (Light Detection and Ranging) data for carbon storage assessment, and (4) end-user driven tools and services for on-line mangrove monitoring worldwide.

This paper provides a brief retrospective review of past methods and results to highlight current breakthroughs and advances by IRD in mangrove monitoring, within these 4 directions.

2. Materials and Method

2.1 Data

Based on historical experiments in the Guiana Shield using Landsat TM 5 data at 30m resolution, IRD is currently developing processes at various pilot sites in South America, Africa, Asia and Oceania regions, to provide products dedicated to mangrove monitoring based on Sentinel-2 time series and Pleiades satellite images. On the one hand, high resolution L2A Sentinel-2 time series starting in 2018, at 10m resolution, updated every 5 days, are downloaded from PEPS (https://peps.cnes.fr/). The Sentinel-2 mission is composed of two optical satellites : Sentinel-2A launched in June 2015 and Sentinel-2B launched in March 2017. The combination of those two satellites offer a five day revisit time period. Both satellites carry the MultiSpectral Instrument (MSI), which measures Earth reflected radiance in 13 different spectral bands in the visible/infrared part of the electromagnetic spectrum. Spatial resolution is 10, 20 or 60 metres, depending on the spectral bands. The Sentinel-2 Level-2A product provides atmospherically corrected surface reflectance observations, extracted from Level-1C Top Of Atmosphere (TOA) reflectance images. We used Sentinel-2 time series to generate mangrove extent and change maps at different time steps. On the other hand, very high resolution Pleiades images were provided by the DINAMIS programme (https://dinamis.data-terra.org/). The CNES (Centre National d'Études Spatiales) Pléiades mission is composed of a

This contribution has been peer-reviewed.
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constellation of two satellites : Pléiades-1A launched in December 2011 and Pléiades-1B launched in December 2012. The two satellites carry the High Resolution Imager, which measures the Earth reflected radiance at a very high spatial resolution (VHSR) of two metres on four different spectral bands : three bands in the visible domain and one band in the near-infrared (NIR) domain. The instruments also provide a panchromatic band at 0.5 metre spatial resolution. In this study, we used a panchromatic Pléiades image acquired in may 2023 to characterise mangrove structural types at a fine scale.

2.2 Method

Our current approach is based on generic and recurrent processing chains using standardised products on specific pilot sites (Fig. 1). Pilot sites can then be used to replicate the approach and a regional scale, combining very high with high resolution remotely-sensed data and products, expressing carbon stocks as a function of above ground biomass estimated from satellite imagery and in-situ measurements.

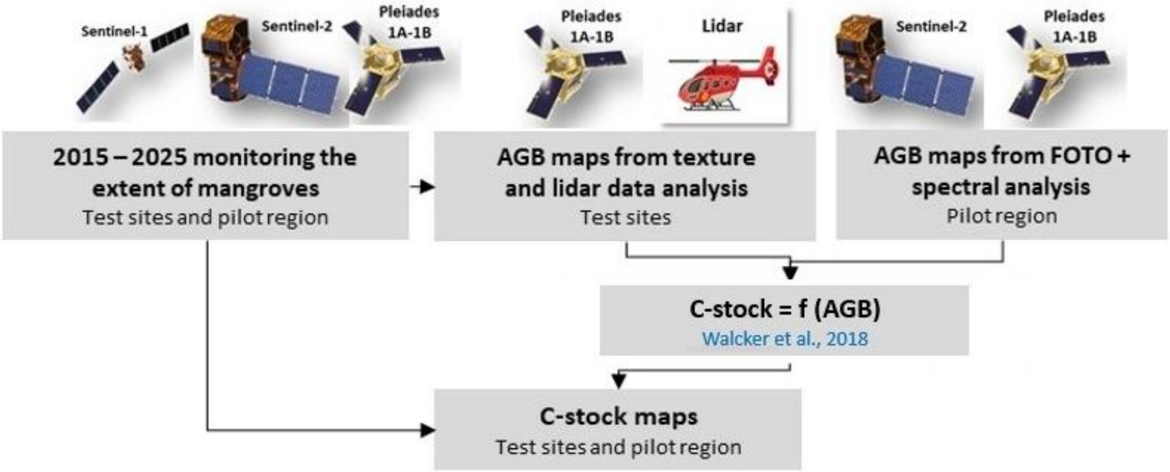

Figure 1: Simplified methodological framework dedicated to mangrove monitoring at different scales.

Based on the Sentinel-2 time series, starting in 2018 and updated every 5 days, products are automatically processed for each available image:

1) 11 spectral indexes to characterise the mangrove environment are calculated every 5 days, using the Sen2Chain algorithm (https://framagit.org/espace-dev/sen2chain): Normalized Difference Vegetation Index (NDVI, Wilson and Sader 2002), Inverted Red-Edge Chlorophyll Index (IRECI, Frampton et al., 2013), Normalized difference Red edge index (NDRE, Barnes et al., 2000), Brightness Index Green Red (BIGR, Crist et al., 1986), Normalized difference water index (NDWI, Gao 1996), Normalized difference water index 2 (NDWI2, McFeeters 2013), Modified Normalized Difference Water Index (MNDWI, Xu 2006), Normalized difference water index 2 (MNDWI2, Reddy et al. 2018), Soil Adjusted Vegetation Index (SAVI, Huete 1988), Mangrove Vegetation Index (MVI, Baloloy et al., 2020,) and Combined Mangrove Recognition Index (CMRI, Gupta et al., 2018);

2) temporal composites are calculated from all spectral indexes, at monthly, quarterly, bi-annual and annual frequencies;

3) a vector of mangrove extent is calculated on a quarterly basis, using the least cloudy Sentinel-2 image from that quarter as the basis for the calculation. The mangrove detection methodology comprises two stages. The first stage employs a double thresholding process using the NDVI and NDWI indexes to identify vegetation pixels. The second stage utilises a double thresholding process using the SWIR1 band and the COPDEM (Global Digital Elevation Model, https://doi.org/10.5270/ESA-c5d3d65) to detect mangrove pixels (Fig. 2). All of these products and their associated services are available on the MangMap platform (https://mangmap.org).

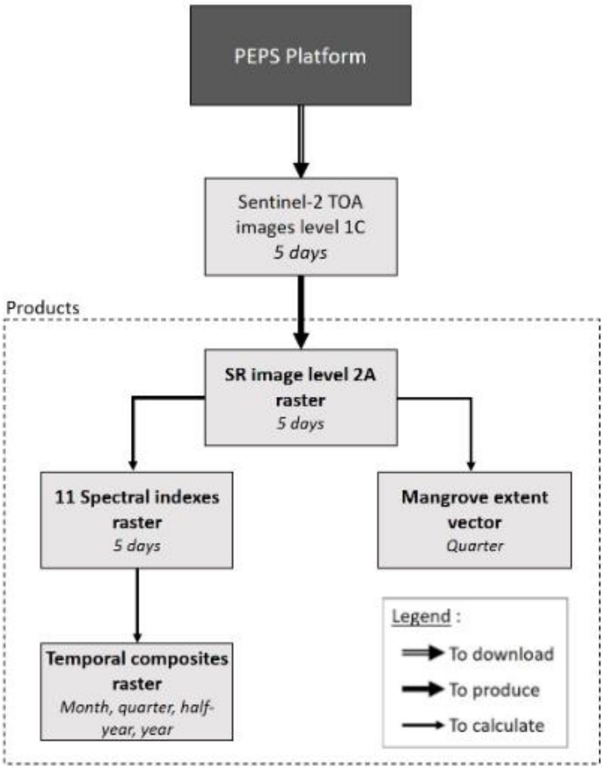

Figure 2: The processing chain of the MangMap platform, from Sentinel 2 images to products. TOA: Top Of Atmosphere, SR: Surface Reflectance

Inside the mangrove extent, after extracting mangrove pixels using a reference layer such as the Global Mangrove Watch (Bunting et al., 2018; 2022) or the Mangmap product, panchromatic Pléiades images are used to define the different structural types of mangroves using a texture-based approach (FOurier-based Textural Ordination, FOTO algorithm, Proisy et al., 2007; Teillet et al., 2021, Fig.3). A Fourier transform is combined to a PCA (Principal Component Analysis) and a K-means classification to produce an unsupervised texture-based map of mangrove types. The analysis from texture is complemented by in-situ structural measurements and Lidar data, to (1) label and describe mangrove structural types obtained from texture and (2) apply models to derive Above-Ground Biomass (AGB) maps at fine scale (Fig.1).

These maps are the input variables for the biomass and carbon storage model that we intend to use (Walcker et al., 2018).

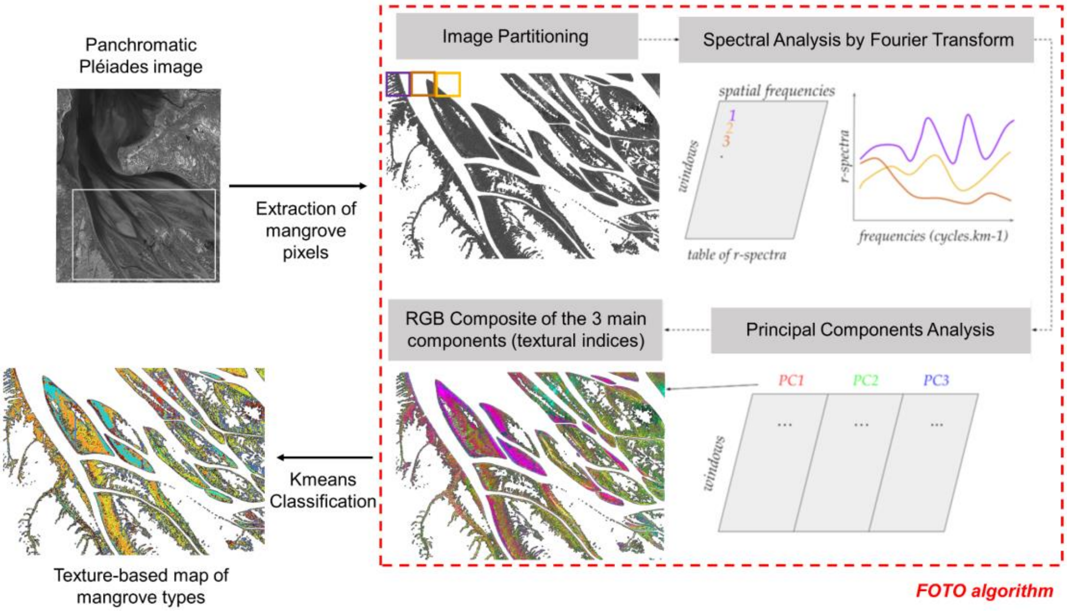

Figure 3: Unsupervised texture-based analysis of mangrove types using Pléiades images and the FOTO algorithm (from Teillet et al., 2021).

3. Results

Figure 4 illustrates the main results obtained by combining Sentinel-2 time series and Pleiades images using the example of the Bombetoka Bay, Madagascar. Products based on the Sentinel-2 time series range from pre-processed Sentinel-2 images (Fig. 4a), time series of spectral indexes (Fig. 4b), vector of mangrove extent (Fig. 4c) and maps of mangrove structural types from Pleiades imagery and in-situ data (Fig. 4d).

3.1 Sentinel-2 time series analysis for rapid and generic mangrove mapping

Maps of mangrove extent have been produced using Sentinel-2 time series data on a quarterly basis since 2018 (Fig. 4c). This enables the regular monitoring of the spatio-temporal evolution of mangroves. Furthermore, spectral indices derived from Sentinel-2 time series can be used to monitor degradation in this ecosystem. For example, the temporal monitoring of the monthly NDVI along a 6.3 km transect delineated in a mangrove region clearly demonstrates a reduction in chlorophyll activity within this mangrove between September 2023 and March 2024 (Fig. 4b).

3.2 Texture-based analysis of very high resolution satellite data for mangrove structure characterisation

From VHSR image Pléiades, 8 classes were originally identified solely using texture analysis and k-means silhouette score analysis (Rousseeuw, 1987) (Fig. 3). A set of structural variables over more than 200 plots was collected on the ground, including mangrove species, mangrove height, mangrove density and Diameter at Breast Height (DBH). The description of those 8 classes based on in-situ structural variables revealed that only 5 classes could actually be identified (Fig. 4d), and that mangrove height, mangrove density and DBH were the most relevant variables to map structural types of mangroves in the Bombetoka estuary, where 90 % of the mangrove cover is made of *Avicennia marina*, with other sporadically observed species being *Ceriops Tagal*, *Sonneratia Alba* and *Rhizophora Mucronota*. The estuary gathers 3 types of environments in which mangrove is present: the banks of the estuary, recent islets downstream, and old islets upstream. Each type is characterised by a different type of mangrove, as shown by Fig. 4d. The banks are covered by the same main mangrove type (the same class of mangrove on the map, in green), with a secondary class in yellow. This yellow class is the main mangrove type identified on recent islets, where the hydrological and sedimentary dynamics of the bay causes accretion and growth of the islets, where young, very dense and low mangrove (> 5 meters) is found. The green class corresponding to adult mangrove, with high density and height (7 to 9 meters) is also found at the core of recent islets and on the islets edges submitted to strong erosion. On old islets, mangrove types are composed of a mixture of different classes, where adult and mature individuals are found, with lower densities and wide range of heights. This mangrove is degraded both due to its late development stage, changes in hydrological and sedimentary dynamics and anthropic actions (cuts and burning sites were observed on the field). On those islets, we observed signs of mangrove regeneration. A few mangrove reiteration sites were also observed on some cut trees.

3.3 Lidar data for carbon storage assessment

The functional and structural diversity of mangrove stands conditions coastal biodiversity, its maintenance and associated fishery resources. This is the necessary step to establish carbon storage balances (Walcker et al. 2018). However, mapping and monitoring the evolution of forest structures over time remains a remote sensing research challenge, especially where the dynamics of the coastal landscape controls the forest dynamics of coastal mangroves. Lidar can measure the height of the mangrove canopy with high precision. The vertical structure of the forest is an important parameter as taller trees typically store more carbon. By analyzing the canopy height with 3D structure data from Lidar above-ground biomass (AGB) of mangrove can be estimated. Empirical models or allometric equations relate the Lidar-derived canopy height and structural parameters to biomass (Proisy et al., 2007). Olagoke et al. (2016) combined remote sensing and terrestrial Lidar in French Guiana to improve allometric equations and the assessment of AGB. Lidar provides detailed information on the density and distribution of vegetation within the mangrove forest. Higher vegetation density usually correlates with higher biomass and thus higher carbon stock. Canopy cover data also helps in understanding the extent of vegetated areas, contributing to more accurate carbon stock calculations. Since biomass is directly related to carbon storage, accurate biomass estimation helps in assessing the carbon stock. Lidar data can be combined with other remote sensing data (such as satellite imagery from optical multispectral and SAR sensors) and field measurements to calibrate models, validate model outputs and to improve the accuracy of carbon stock assessments (Walcker et al., 2018). The spectral response of forest stands measured by optical satellite sensors depends on this set of plant forms and environmental conditions (especially flooding by tides). In mangroves, the degree of openness of the forest canopies and the response of the soil must be considered to avoid confusing populations with different structures and species (Viennois et al., 2016). There is, therefore, a strong need to better understand the fine-scale distribution of mangroves in connection with the need to better characterize the structural diversity of forest habitats.

3.4 End-user driven tools and services for on-line mangrove monitoring worldwide

Thanks to the Mangmap platform, the end user has access to a set of services for the temporal analysis of mangrove changes. All results can be easily downloaded with a set of on-demand services consisting of: (1) the calculation and restitution (graphs, .csv tables) of statistics showing the temporal evolution of temporal composite values within polygons or along transects (Fig. 4b), (2) the calculation and restitution of differences of spectral index values or its temporal composite, as an indicator of potential anomalies in the time series: raster images of differences between two dates, (3) the calculation and restitution of mangrove extent evolution: simple merging of two mangrove vector files, with attribution of the three labels: “Stable area”, “New area”, “Eroded area” (mangrove extents that have disappeared and no longer consisting of mangrove areas).

These initial services are subject to continuous improvement and upgrading. All products and services are executed on specific Sentinel2 tiles previously installed on the system, in line with MangMap’s development plan: progressive expansion to new sites around the world, with a first target of five sites opened in 2024.

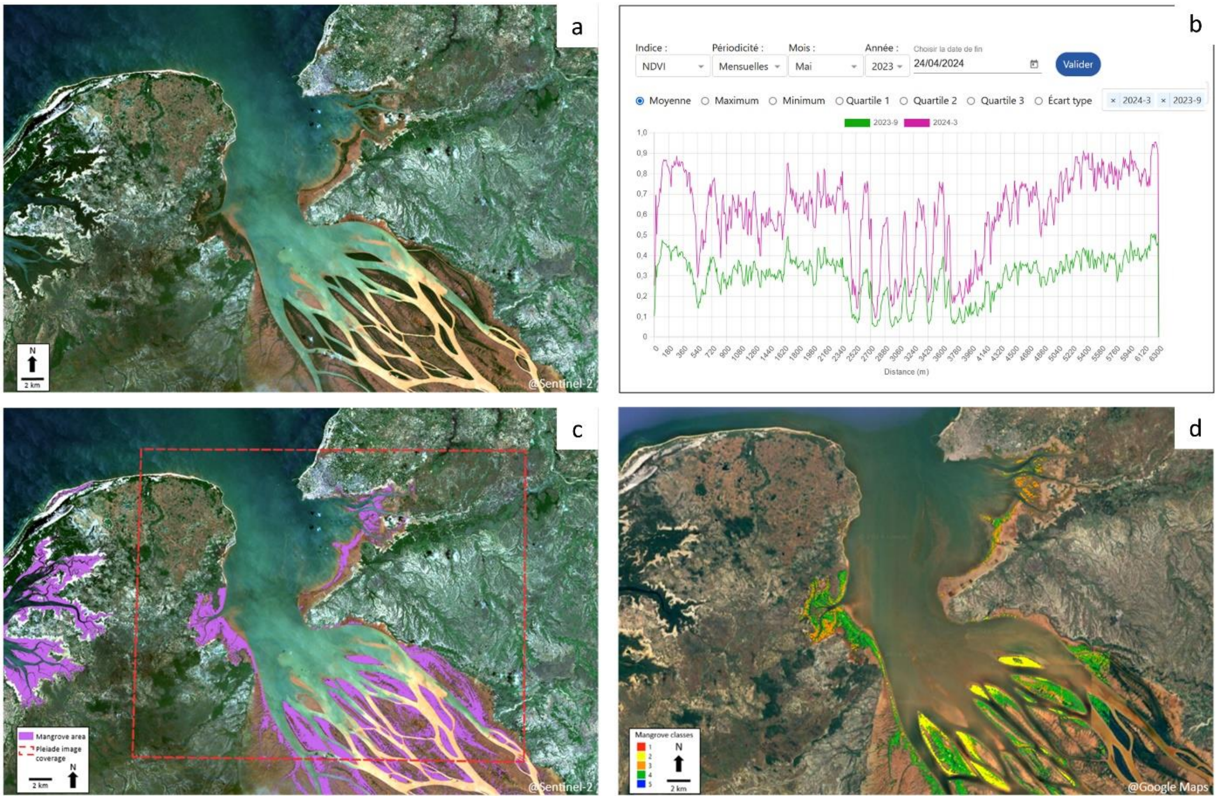

Figure 4: Main results and products available for mangrove monitoring, the example of the Bombetoka Bay, Madagascar.

The same approach is currently carried out in various sites including French Guiana and Brazil, with the addition of Lidar data, to assess the biomass and carbon storage of mangrove ecosystems in the region.

4. Discussion

Our current results demonstrate the complementarity between our products and more global datasets such as GMW. In particular, our expertise in specific areas and in-situ data (field measurements, lidar datasets) and the use of sensors with different resolutions allow us to refine the distribution, dynamics and typologies of mangroves at local scales. This addition of in-situ data and local knowledge is an essential component to be used in models of biomass and carbon storage estimations, especially in the context of climate change. This approach will benefit greatly from the future launch of the BIOMASS sensor (developed by ESA), which will provide unprecedented P-band products on vegetation. The team involved in this study is currently leading an EO4Society project, funded by the European Space Agency, to monitor coastal ecosystems for blue carbon estimation. The products presented here are the building blocks of the models to be used in this project. Much work still remains to be done in order to quantify carbon storage and sequestration in the mangrove ecosystem. The carbon pools in mangroves are linked to the above-ground and below-ground biomass, as well as soil organic and inorganic carbon. These carbon pools are subject to constant change due to factors such as biomass growth and decay, surface and subsurface gas exchange with surrounding waters, and sequestration rates in soil (Alongi, 2014). To our knowledge, very few projects have attempted to quantify the whole processes responsible for carbon storage and sequestration in mangroves. Given that the carbon fraction is approximately 0.5, Above-Ground Biomass (AGB) mapping can directly provide the distribution of carbon stored in the above-ground component of mangrove forests. AGB of mangrove forests is closely linked to the forest structure, which is defined as the size and arrangement of all vegetation components within a forest stand. This is usually described in the field through forest inventories inside plots of area, which are adjusted to the homogeneity and number of trees (Fromard et al., 1998). Mangroves are an excellent example of a forest habitat where canopy height and texture are reliable indicators of AGB values at the site level. Remote sensing can directly measure these values. However, Below-Ground Biomass (BGB) and soil carbon (SC) are much more difficult to measure using remote sensing, and the relationship between AGB, BGB and SC is not well understood. To our knowledge, there are no carbon pool models able to completely predict how the different mangrove compartments take in or release carbon in a specific coastal geomorphic setting. However, pioneering studies (Walcker et al. 2018) have provided models that allow for the coupling between the growth stage of the mangrove stand and carbon storage in the three compartments.

The remote sensing of mangrove forests is a key research area of focus for the provision of maps related to AGB-related carbon. In coastal regions where field data on above-ground biomass and exploratory C-pool modelling are available, innovative remote sensing methods for mapping mangrove forest habitats, combined with monitoring of changes in mangrove extent, could produce fine-scale and proof-of-concept maps of carbon stock distribution. As mangrove forests are complex mosaics of mangrove types, more or less dense, they must be described from the ground to the canopy, to the nearest hectare and over thousands of hectares, taking advantage of current sensor diversity and capabilities. Our study presents a contribution to this topic combining high with very high resolution earth observation data and modelling of mangrove.

Products derived from the Sentinel-2 time series are available on MangMap, a new online monitoring platform dedicated to the production and dissemination of specific products and services useful for mangrove monitoring at local scales. To date, some 5 sites have been established on the platform and new ones are in preparation. MangMap will also incorporate products derived from Pleiades image processing. However, Pleiades images are more difficult to access than Sentinel images, and the FOTO method requires field data to describe structural types. The results of our research and the processing chains we have developed are intended to support studies and institutional diagnosis with simple tools, services and products that are easily accessible and free of charge. The integration of these results into the MangMap platform aims to better contribute to decision making and policies for the conservation and restoration of coastal ecosystems. As the end-user community grows, MangMap will gather needs and suggestions in order to plan and develop news services, such as alert systems for deforestation or mangrove degradation, new indicators or new end-user functionalities.

5. Conclusion

In conclusion, while remote sensing and GIS technology have revolutionised the mapping and monitoring of mangrove forests on a global scale, their full potential can only be realised when complemented with in-situ data and local knowledge. These sophisticated technologies facilitate comprehensive and extensive insights into the spatial distribution and health of mangroves, which are pivotal for comprehending their role in coastal ecosystems and climate regulation. Nevertheless, the precision and accuracy of biomass and carbon storage models remain constrained in the absence of ground-truthing and contextual information that only localised data can provide.

Political bodies frequently utilise biomass and carbon figures to inform their decisions on environmental and climate policy. It is therefore vital that accurate estimates of biomass and carbon stocks and flows are available to support the development of effective conservation and sustainable management strategies. Inaccurate data could lead to ill-informed decisions, which would in turn compromise conservation efforts and actions to combat climate change.

Multiplying data sources and combining them with field data and local community knowledge is crucial for the effective management of mangroves and their carbon stocks. This integrated approach ensures that estimates are more accurate, which is vital for making informed decisions about conservation strategies and climate change mitigation. By leveraging both advanced technologies, in-situ measurements in mangrove forest and the invaluable on-the-ground perspectives of local populations, we can achieve a more sustainable and effective management of mangrove forests and their critical role in carbon sequestration.

Acknowledgments

The results presented in this paper were produced in projects funded by CNES (French Space Agency) in the frame of the TOSCA SOS-MAMBO (2020-2024) and SCO PROPAGUL (2022-2024). This work was also supported by ESA (European Space Agency) in the frame of the FRANCO project (2024-2026) within the Coastal Blue Carbon initiative of the EO Science for Society program.

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