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Earth Sciences

Original article

Quantifying Colombian blue carbon sinks from coastal mangroves

Cuantificación de sumideros de carbono azul en Colombia a partir de manglares costeros

Joel Bernal O.[1], Leidy P. Alfonso A.[1], Valentina I. Burbano A.[1], Santiago Vargas-Domínguez[2,*], María Fernanda González[3,4], Juan Esteban Agudelo[2,3,4], Jose Iván Campos-Rozo [3,4,5]

[1] Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[2] Observatorio Astronómico Nacional, Universidad Nacional de Colombia, Bogotá, Colombia
[3] Fregata Space, Spain
[4] Planetai Space, Spain
[5] Astronomical Institute of the Academy of Sciences of Czech Republic, Ondrejov, Czech Republic

Abstract

Mangroves along the Colombian Caribbean and Pacific coasts are vital ecosystems with numerous environmental, economic, and social benefits. Their dense root systems act as natural buffers, safeguarding coastlines from storms and preserving aquifer integrity. Additionally, mangroves are pivotal in mitigating climate change by efficiently storing carbon, absorbing up to 10 times more than terrestrial ecosystems. Government decision-makers face the challenge of balancing economic development with environmental preservation when approving infrastructure projects. Quantifying the monetary value of mangroves is crucial for assessing potential impacts on these ecosystems. This study used Sentinel-2 composites to train a random forest classifier, identifying and quantifying a total mangrove area of 2756.84 km^2 in Colombia by 2020. This information was later used to assess the carbon storage in mangroves for the same year. The estimated value was $96{,}351.66 \pm 13{,}632.63$ kt or $353{,}610.59 \pm 50{,}031.78$ kt CO_2. Ultimately, we evaluated two contingents on the mangrove extent: one depicting their disappearance and the other illustrating their growth. These findings underscore the critical importance of mangroves and highlight the need for their conservation and sustainable management to achieve emissions reduction goals by 2030.

Keywords: Mangroves; Climate change; Blue carbon; Remote sensing; Machine learning; Natural capital quantification; Environmental impact; Sustainability; Carbon sinks.

Resumen

Los manglares a lo largo de las costas del Caribe y el Pacífico de Colombia son ecosistemas vitales con numerosos beneficios ambientales, económicos y sociales. Sus densos sistemas de raíces actúan como amortiguadores naturales, protege las costas de las tormentas y preservan la integridad de los acuíferos. Además, los manglares desempeñan un papel fundamental en la mitigación del cambio climático al almacenar carbono de manera eficiente, absorbiendo hasta diez veces más que los ecosistemas terrestres. Los responsables de decisiones gubernamentales enfrentan el desafío de equilibrar el desarrollo económico con la preservación ambiental al aprobar proyectos de infraestructura. Cuantificar el valor económico de los manglares es crucial para evaluar los posibles impactos en estos ecosistemas. En este estudio utilizamos composiciones de Sentinel-2 para entrenar un clasificador de bosques aleatorios, identificando y cuantificando un área total de manglar de 2756,84 km^2 en Colombia para el año 2020. Esta información se utilizó posteriormente para evaluar el almacenamiento de carbono en los manglares en el mismo año. El valor estimado fue de 96.351,66 ± 13.632,63 kt o 353.610,59 ± 50.031,78 kt de CO_2. Por último, evaluamos dos escenarios dependientes de la extensión del manglar: uno que mostraba su desaparición y otro su crecimiento. Estos hallazgos subrayan la importancia crítica de los manglares y resaltan la necesidad de su conservación y manejo sostenible para alcanzar los objetivos de reducción de emisiones al 2030.

Palabras clave: Manglares; Cambio climático; Carbono azul; Teledetección; Aprendizaje automático; Cuantificación del capital natural; Impacto ambiental; Sostenibilidad.

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***Corresponding autor:**
Santiago Vargas Dominguez;
svargasd@unal.edu.co

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Introduction

Climate change is undoubtedly one of the greatest (if not the greatest) challenges before humanity. It has rapidly evolved from an uncomfortable truth to a real threat to the lives of millions of people. In response, an international and interdisciplinary movement has emerged to mitigate the damage and losses, to halt the advance of global warming, or to find a solution in the medium to long term.

The United Nations (UN), as the largest international organization in existence, has been actively involved in addressing climate change, convening world leaders, and a diverse range of experts, including scientists, economists, environmentalists, philanthropists, and various institutions to discuss potential solutions. The most recent of these Conferences, the UN Climate Change Conference in Glasgow (COP26: https://www.un.org/en/climatechange/cop26), resulted in the Glasgow Climate Pact, where countries reconfirmed their commitment to achieving the goals of the Paris Agreement (https://www.un.org/en/climatechange/paris-agreement), which, among other provisions, obliges parties to protect and improve, as deemed suitable, greenhouse gas sinks and reservoirs.

While capturing carbon from the air and sequestering it in the soil is a well-documented process in several ecosystems, recent research has unveiled the remarkable efficiency of this carbon sequestration process within coastal and marine ecosystems. Sequestering carbon from the atmosphere into carbon sinks occurs through various physical or biological mechanisms, among which photosynthesis stands out as fundamental. This conversion process not only facilitates the synthesis of essential nutrients for the organism but is also pivotal in mitigating atmospheric carbon dioxide levels, thus contributing to the regulation of Earth's climate. Sequestration rates are usually quantified in grams of carbon per unit area (e.g., square meters or hectares) per year. Estimates range from an average of 5.1 g C/m^2/year for temperate forests to 163 g C/m^2/year for mangroves (**Mcleod *et al.***, 2011).

'Blue carbon' is the term often used in the current context, to refer to the carbon stored within coastal and marine ecosystems. Carbon dioxide is removed from the atmosphere by plants through photosynthesis and stored in both their aboveground and belowground biomass, but when blue carbon ecosystems are degraded or lost, they release carbon back into the atmosphere.

Mangroves, along with tidal, salt marshes, and seagrasses, constitute blue carbon (vegetated coastal) ecosystems. A mangrove is a type of vegetation consisting of trees, shrubs, palms, or ground ferns, which typically grow to a height of more than half a meter. They are commonly found in intertidal zones along marine coasts and estuarine margins. Mangroves contribute to enhancing climate adaptation and resilience in coastal regions by providing a range of essential services. These services include protection against storm surges and rising sea levels, water quality regulation, nutrient recycling, and sediment trapping, among others (**Howard *et al.***, 2014). It is known that an additional crucial service is provided by capturing and storing blue carbon from the atmosphere and oceans.

As a member of the United Nations, Colombia is fully committed to the Paris Agreement, and consequently, to the fight against climate change, including the pursuit of carbon neutrality by 2050, a 51% reduction in greenhouse gas emissions, and the goal of zero deforestation by 2030. However, the country's vast biodiversity gives it a special role to play. According to the Colombian Ministry of Environment (**Ministerio de Ambiente y Desarrollo Sostenible de Colombia**, 2022), mangroves in Colombia cover an area of 285,049 hectares, with 90,160.58 hectares along the Caribbean coast and 194,880 along the Pacific coast. The Minister of Environment emphasized the significance of mangroves in achieving the emissions reduction goal by 2030. The Colombian government has developed both general and specific plans to protect and restore approximately one-third of the total mangrove area.

Still, carbon emissions resulting from mangrove deforestation contribute to approximately 10% of global deforestation-related emissions although mangroves cover only 0.07% of land area (***What is Blue Carbon?*** n.d.). Besides, it is estimated that approximately

67% of the historical global mangrove extent has been lost (**Howard *et al.***, 2014). Furthermore, the restoration and conservation of mangrove forests is a significant challenge due to their vast and remote nature, which makes on-site assessments both challenging and time-consuming. Promisingly, the use of remote sensing in conjunction with various digital image classification methods holds the potential to provide more accurate results for mapping and monitoring the mangrove ecosystem. Considering the importance of the mangrove ecosystem in carbon dioxide sequestration and the advancements in remote sensing technology for ecosystem mapping, we have created a code using Google Earth Engine (**Mutanga & Kumar**, 2019) to assess the extent of mangroves in Colombia. Employing this data, we estimate the total carbon sequestered by mangroves along the Colombian coast.

To achieve such an aim, firstly, an artificial intelligence algorithm was developed capable of identifying the distribution of mangroves throughout the national territory. Secondly, the evolution of the amount of carbon stored by mangroves was quantified using experimental values obtained from research conducted in the study areas.

Finally, the high importance of mangroves is revealed through the values of carbon sequestration and the total greenhouse gas emissions in Colombia evaluated through two scenarios based on the increase and decrease of the mangrove extension, highlighting their vital role in meeting the objectives established by the European Union for the year 2030.

Insights into mangrove research in Colombia

Research on mangroves in Colombia has historically been scarce despite their importance (**Castellanos-Galindo *et al.***, 2021). Until the late 1970s, the significance of these ecosystems was not reflected in the number of studies or laws protecting them. Research in this field has been shaped by a combination of factors, including the way the country has developed and specific efforts by researchers and initiatives. For instance, the Scor/UNESCO working group on mangrove ecosystems played a significant role in promoting research initiatives in Colombia and the wider Latin American region (**Snedaker *et al.***, 1984). Similarly, the Mangroves of Colombia Project (MCP), carried out by the International Tropical Timber Organization, was a significant initiative that took place in two phases from 1991 to 2001 (**Sánchez-Páez *et al.***, 2000). The large datasets generated by the MCP can be useful for a variety of purposes related to mangrove science and management (**Blanco-Libreros & Álvarez-León**, 2019). These early research programs conducted by different organizations were vital in updating the extent of mangroves in the country, fostering the implementation of management policies, and starting pilot restoration projects.

Recent studies have highlighted the importance of quantifying carbon stocks in mangrove ecosystems, particularly in the Colombian Pacific and Caribbean regions. **Mejía-Rentería *et al.*** (2018) conducted a comprehensive comparison of mangrove extent estimations in the Colombian Pacific, emphasizing the critical role of precise mapping for effective conservation. **Blanco-Libreros *et al.*** (2015) provided detailed measurements of above-ground biomass and carbon reservoirs in the mangroves of the Gulf of Urabá, offering essential data, while **Perdomo-Trujillo *et al.*** (2021) investigated the impact of restoration actions in the Ciénaga Grande de Santa Marta, demonstrating the significant potential of restoration efforts to enhance carbon sequestration. Additionally, **Palacios-Peñaranda *et al.*** (2019) quantified carbon stocks in mangrove forests of the Colombian Pacific, underscoring the substantial carbon storage capabilities of these ecosystems. Lastly, **Moreno-Muñoz** (2022) evaluated the total carbon stored in the mangrove ecosystem in the Pacific region of Nariño by using allometric equations and biomass-to-carbon conversion factors to measure carbon stored in both aboveground and belowground biomass.

In recent years, Colombian mangrove research has gained increasing visibility in the international scientific community, with a growing number of publications appearing in international peer-reviewed journals. This has contributed to a further understanding of the socioeconomic and biological importance of these ecosystems (**Pérez & Giraldo**, 2009) and their role in climate change mitigation and adaptation, among other areas of study.

However, accessing these ecosystems can pose challenges for researchers and practitioners. Compared to other forest environments, some aspects of mangroves remain poorly characterized (**Pham *et al.***, 2019) partly due to their unique and complex nature, which leads to practical difficulties in mapping, measuring, and monitoring their biomass and carbon stocks. To conserve mangroves, it is crucial to establish policies and actions that rely on the effective monitoring of their biophysical parameters and mapping of their extent.

Over the past few years, remote sensing approaches have become increasingly important in collecting data from distant areas without direct contact (**Pham *et al.**,* 2023). In 2007, several environmental institutes in Colombia collaborated to create mangrove cover maps using remote sensing techniques (**IGAC *et al.***, 2007). Similarly, machine learning and artificial intelligence have further improved the analysis and interpretation of remotely sensed data, enabling more precise insights into mangrove ecosystems. A recent study combined optical and Synthetic Aperture Radar (SAR) data with machine learning algorithms to accurately measure changes in mangrove cover from 2009 to 2019 (**Selvaraj & P**é**rez**, 2023). With the advancements in satellite imagery and diverse classification methods, there is significant potential for the mapping, monitoring, and extraction of parameters for these types of ecosystems.

Theoretical framework

Indexes

A spectral index is an equation that merges pixel values from different spectral bands within a multispectral or hyperspectral image. It employs diverse algorithms, typically emphasizing band ratio or feature scaling approaches, such as normalized or standardized algorithms (**Tran *et al.***, 2022). These indexes are valuable tools for extracting and enhancing significant information from remote sensing data, especially in the domains of environmental monitoring, agriculture, and land management. For our project, we calculated the Normalized Difference Vegetation Index (NDVI) for quantifying vegetation (**Rouse *et al.*,** 1974) and the Modified Normalized Difference Water Index (MNDWI) for water information (**Xu**, 2006). To enhance the separability between mangrove forests and terrestrial vegetation, we utilized the Normalized Difference Mangrove Index (NDMI) (**Shi *et al.***, 2016), and the Combined Mangrove Recognition Index (CMRI) (**Gupta *et al.**,* 2018).

Carbon stocks

Assessing the carbon stored in mangroves is crucial for recognizing their role in addressing climate change and promoting human welfare. This evaluation, known as a "carbon inventory", can be conducted at various levels. According to UNESCO (**Howard *et al.***, 2014), there are three levels of detail, representing varying degrees of certainty or accuracy in assessing carbon stock. These levels are:

- Tier 1 assessments are marked by reduced accuracy and certainty. These evaluations rely on simplified assumptions and utilize default values, especially concerning activity data (information about land coverage and use) and emission factors (changes in carbon due to modifications in land use). While Tier 1 provides a general perspective, it lacks the precision associated with more intricate and comprehensive approaches. If it is not feasible to make Tier 2 or 3 estimates, Tier 1 estimates can be conducted.
- Tier 2 assessments are more accurate and detailed than Tier 1 because they use specific data from a country or site, enhancing precision.
- Tier 3 assessments concentrate on acquiring precise details about carbon dynamics through careful and continuous monitoring. These evaluations require detailed data on the carbon stored in each particular ecosystem or land use area. Additionally, they entail taking repeated measurements over time to understand how carbon levels change in the area of interest.

The concept of carbon inventories, coupled with their tiered assessment approach, presents a systematic framework essential for comprehending and managing carbon dynamics within ecosystems. By quantifying carbon stocks and fluxes, these assessments provide valuable insights into the impact of human activities on ecosystem processes and functions. This structured approach not only facilitates the monitoring of carbon storage and emissions but also enhances our ability to implement effective management strategies aimed at mitigating climate change and preserving ecosystem health and resilience.

Data

Here, we leverage two remarkable sources of geospatial data to support our remote sensing and classification tasks. First, we have the Sentinel-2 satellites, which are part of the European Space Agency's impressive endeavor. Launched in 2015 with Sentinel-2A and followed by Sentinel-2B in 2017, these satellites have the MultiSpectral Instrument (MSI). They capture a diverse range of data bands, including red, green, blue, and near-infrared, all with a remarkable 10-meter spatial resolution. Additionally, they record other spectral bands at 20 and 30 meters, allowing us to analyze Earth's features in detail. This ongoing mission is a vital component of the Copernicus program and pivotal in various essential services and applications, including land management, agriculture, forestry, disaster monitoring, humanitarian relief efforts, and risk assessment, besides addressing security-related concerns.

Second, we complement our dataset with the Global Mangrove Watch (GMW) established in 2011 by the Japan Aerospace Exploration Agency (JAXA). GMW is a robust online platform dedicated to providing open-access geospatial information about mangroves (**Bunting *et al.***, 2022) and stands out as the most extensive mangrove monitoring tool globally, offering universal access to near real-time data on mangrove status and changes worldwide. It relies on remote sensing information and cutting-edge tools to empower initiatives focused on safeguarding and restoring mangroves, underlining the pivotal role of these ecosystems in various contexts.

Delving into Random Forest

Random Forest (RF) stands as a powerful pillar within the realm of supervised machine learning algorithms, leveraging the innovative concept of ensemble learning to achieve remarkable results. At its core, RF operates by amalgamating a multitude of decision trees, each serving as a discerning arbiter in the classification process. These decision trees intricately divide the input space into increasingly refined partitions, guided by the nuanced values of the input features. While decision trees offer a straightforward interpretation of predictive rules, they are susceptible to the pitfall of overfitting, wherein the model excessively tailors itself to the training data, thereby compromising its generalizability.

To circumvent this challenge, the RF model implements a strategic approach: it subjects each decision tree to a random subset of both the training data and the features, thus instilling a sense of diversity among the constituent trees. This deliberate randomness serves a dual purpose: it curtails the correlation between individual trees while fostering a robust, collective decision-making process. By synthesizing the majority output gleaned from each decision tree, the RF model arrives at its final classification outcome with confidence and precision.

The RF algorithm has been widely used in previous studies with highly accurate results ranging from Land Use Cover Classification (LULC) to Mangrove Species Discrimination (**Maurya *et al.***, 2021).

Methodology

To achieve our goal, a custom code was developed from scratch using the Google Earth Engine platform (https://earthengine.google.com/platform) in the JavaScript language. We used the dataset "Sentinel-2 MSI: MultiSpectral Instrument, Level-2A" containing satellite data from March 28, 2017, to November 18, 2023. A cloud removal process was applied to

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the satellite images, addressing the high cloud cover in the Colombian Pacific through the QA60 band values. Atmospheric correction was not performed, as it involves addressing factors such as Rayleigh scattering, atmospheric gasses (ozone, oxygen, water vapor), and correction of absorption and scattering caused by aerosol particles in Sentinel-2 level-2A products. Subsequently, a composite image spanning a two-year timeframe was created for classification purposes. **Figure 1** presents a visual contrast of the study area, juxtaposing the original satellite image containing visible clouds with the enhanced composite image obtained after undergoing cloud removal procedures.

The NDVI, MNDWI, NDMI, and CMRI indices were added to this composite image. Furthermore, given that mangroves are not found at elevations exceeding 100 meters in Colombia, a mask was applied to determine the corresponding altitude for each pixel, and binary classification was conducted based on this condition. The altitude data was derived from the NASA SRTM Digital Elevation 30 m dataset, which provides digital elevation models on a near-global scale. However, it is crucial to acknowledge that determining the precise altitude at which mangrove forests are most likely to be found can be subject to variation and requires adjustments that consider geographical, hydrological, and soil differences. This is especially pertinent in regions like the Colombian Pacific, where at certain altitudes, tropical humid forests may prevail over mangrove ecosystems. Adjusting the altitude range based on regional characteristics can significantly improve the model's accuracy and produce better results.

Since we understand that new mangrove growth or the decline of existing mangroves tends to occur near established areas, a buffer was created around the known mangrove region. This buffer, set at a distance of 1000 meters, was then refined by excluding non-land areas. Subsequently, this refined area was applied to the composite image, specifically tailoring it for classification within the mangrove buffer.

Considering the use of a supervised model, labels for each pixel (indicating whether it was mangrove or not) were obtained from the dataset provided by GMW. During the classification process, training data was generated using existing information to distinguish between mangrove and non-mangrove classes. A kernel was defined to identify core mangrove and non-mangrove areas through a dilation process. These core regions represent areas of particular significance or concentration. To carry out the classification, a Random Forest model with n=100 trees was employed. It is important

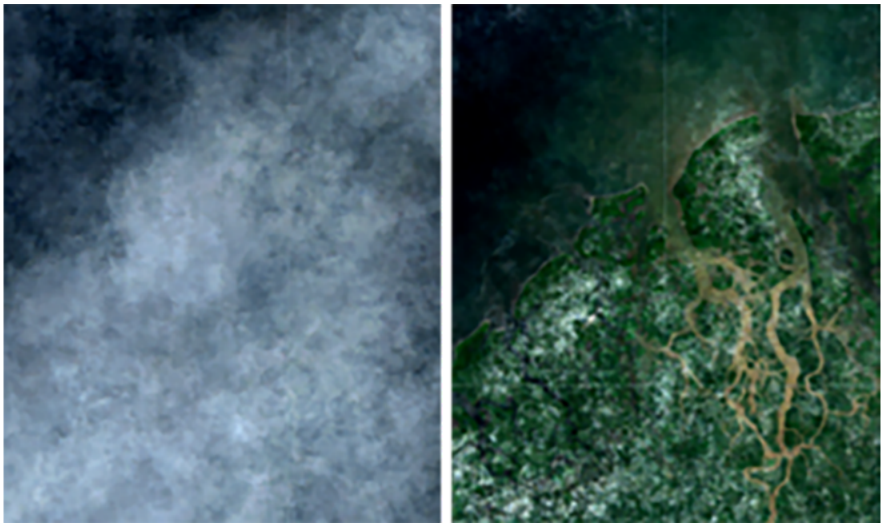

Figure 1. Comparison of a specific region within the study area. Original satellite image with visible clouds (left image) and enhanced composite image after cloud removal, offering a clearer view of the landscape in the selected area (right image)

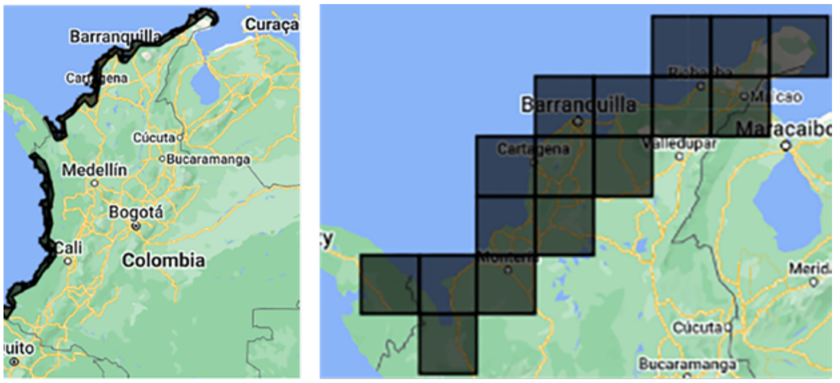

Figure 2. Map of Colombia highlighting the region of interest (in black) at 41 km from the coastline (left image) and an example of extracted sectors along the Colombian Caribbean coast (right image)

to mention in this study that the classification process was performed over pixels, rather than different images. Finally, we removed small patches of pixels to avoid isolated and solitary clusters.

The study area encompassed the Colombian coast, including both the Caribbean and Pacific regions, as shown in the left image in **figure 2**. To address potential memory issues on the platform, the region of interest was divided into small, regular sectors, as illustrated in the right image in **figure 2**. Subsequently, the intersection between both was computed to classify each pixel within these smaller images as shown in the same figure. The count of pixels identified as mangroves was then tallied to determine the total area by summing the results from each of the smaller sections.

Analysis and results

Mangrove area and carbon sequestration

In **figure 3**, we illustrate the mangrove area situated in a portion of the northern region of Nariño on the Pacific coast, renowned for hosting the largest expanse of mangroves in the vicinity according to GMW (upper left image). The upper right image in **figure 3** presents the classification result obtained through the Random Forest algorithm we employed. The bottom panel illustrates the overlay of both images, providing a comprehensive view of the mangrove distribution as observed globally and classified by the algorithm allowing us to notice differences in the classification. The training and test accuracy over 4000 pixels in both cases was equal to 0.99.

The comparison of the Pacific and Caribbean areas based on INVEMAR data taken from **Mejía-Rentería *et al.*** (2018) showed that in the Pacific, the areas measured by GMW, our model for 2020, and the **INVEMAR** (2014) study are 1965.59 km², 1904.84 km², and 2302.39 km², respectively. In the Caribbean, the corresponding areas are 818.225 km², 852.00 km², and 698.94 km². The percentage differences between the Pacific and Caribbean areas are 3.1%, 4.13%, and 17.3%, respectively. Notably, we successfully achieved perceptual differences below 5%, contributing to a total mangrove area of 2756. 84 km². The difference with INVEMAR (17.3%) can be attributed to the temporal gap between our study's estimates for 2020 and the INVEMAR data from 2014, likely reflecting changes in mangrove coverage over the six years.

To assess carbon sequestration, we opted for a hybrid approach, combining Tier 1 and Tier 2 methodologies. The total value was derived by multiplying the area with the experimental mangrove sequestration rate specific to each zone. This method ensures the utilization of more accurate data sourced from studies conducted in Colombia's primary mangrove zones. Additionally, it considers all forms of mangrove reserves, providing a more comprehensive assessment compared to using a generic value.

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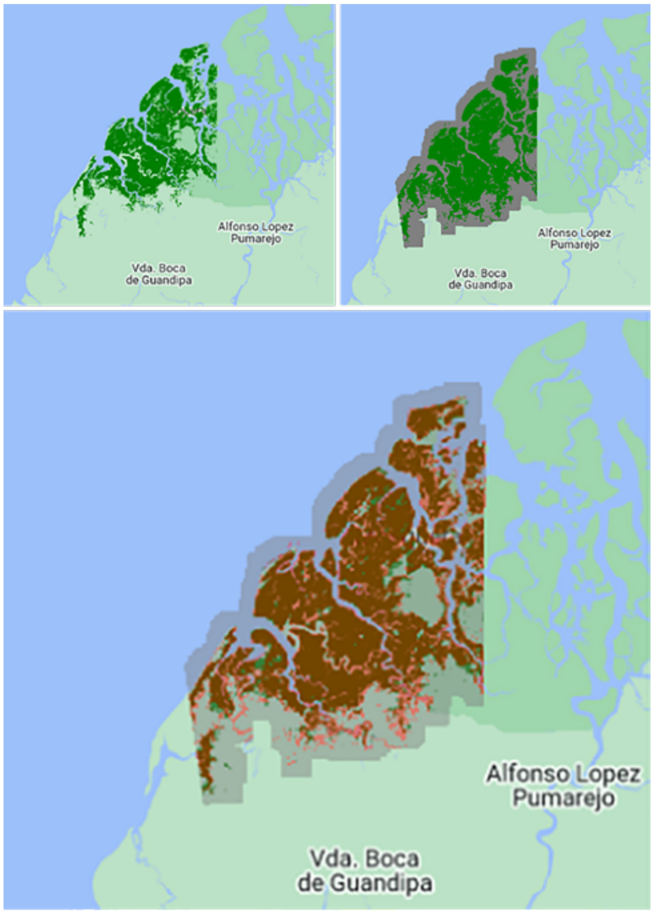

Figure 3. Comparison of different results: Global Mangrove Watch (GMW) assessment (upper left image) and our model's output (upper right image) for the mangrove area situated in a portion of the northern region of Nariño on the Pacific Coast. The bottom image illustrates the overlapping results of GMW (in green) and our model (in red), along with areas identified by both methods (in brown)

The Ciénaga Grande de Santa Marta stands as one of the largest mangrove habitats along the Colombian Caribbean coast. According to **Moreno-Muñoz** (2022) and **Perdomo-Trujillo *et al.*** (2021), the mean value of total carbon stored in this mangrove forest is estimated at 328.15± 14.1 t/ha. In contrast, findings from a study conducted in the Pacific region of Nariño (**Moreno-Muñoz**, 2022) indicate a mean total carbon sequestration value of 359.05 ± 71.29 t/ha. It is important to note that these values used to calculate the total carbon storage on the Colombian coasts are estimates and can vary depending on the study methods, species, conservation status, and specific locations of the mangroves.

For example, our results for the Rionegro Cove region, an essential carbon reservoir and sink in the Gulf of Urabá on the Colombian Caribbean Coast, showed a mangrove area extension of 5.62 km² compared to the 3.54 km² reported by **Blanco-Libreros *et al.*** (2015) and the 5.17 km² according to GMW. In terms of carbon storage, our model estimated 184,420 tons, while **Blanco-Libreros *et al.*** reported 20,461 tons, with no data provided by GMW.

The most significant difference is in the carbon storage, which is attributed to the discrepancy in the carbon sequestration values per hectare. Specifically, while we used an estimate of 328.15 t C/ha from **Perdomo-Trujillo *et al.*** (2021), **Blanco-Libreros *et al.*** (2015) calculated 57.8 t C/ha, resulting in a substantial difference in the final carbon stock. The primary reason for this discrepancy is that **Blanco-Libreros *et al.*** (2015) estimated the value by calculating only the aboveground biomass from measurements of tree diameters at breast height and their total heights. In contrast, the value we used from **Perdomo-Trujillo *et al.*** (2021) not only includes tree measurements but also incorporates direct field measurements of soil, pneumatophores, and belowground roots.

Similarly, it is important to mention that the carbon stocks reported by **Palacios-Peñaranda *et al.*** (2019) for the Pacific region in Málaga Bay (450.26 t C/ha in belowground biomass) and the Buenaventura Bay (258.3 t C/ha in belowground biomass) closely align with the value we used from **Moreno-Muñoz** (2022). However, when considering total carbon storage, their values ranged between 496.03 t C/ha and 728.48 t C/ha, which are higher than those considered in the present investigation. Therefore, we emphasize the significance of establishing interdisciplinary collaborations, such as collecting experimental data on-site, using satellite data classification, and leveraging artificial intelligence to enable more precise calibration of modeling approaches and a better evaluation of mangrove extent and carbon reserves. Given this information, we estimated that the total carbon storage on the Colombian coast in 2020 was 96.351,66 ± 13.632,63 kt.

The calculated value corresponds to 353.610,59 ± 50.031, 78 kilotons of carbon dioxide equivalent (353,610.59 kt CO_2 e). For comparison, it is noteworthy that according to the World Development Indicators from the World Bank (***Total greenhouse gas emissions, kt of CO_2 equivalent, - Colombia***, n.d.), Colombia emitted 186.999 kilotons of carbon dioxide equivalent (186.999 kt CO_2 e) in 2020. It means that Colombia's mangroves can store 189 percent more CO_2 than the total CO_2 emitted by the country.

Unfortunately, as of the date of this study, we have not found suitable in-situ data to conduct a comparative study. This limitation is attributed to the recentness of the study year, the inclusion of carbon storage pools, and the specific region under examination.

It is important to clarify that mangroves store carbon in various forms, including carbon dioxide, methane, and nitrous oxide. Each of these gasses has a different global warming potential, meaning they contribute to climate change to varying degrees over a specified time frame. To compare and aggregate the climate impact of these gasses, they are often converted to a common unit, which is CO_2e. This unit expresses the amount of each gas in terms of the equivalent amount of CO_2 that would have the same global warming impact over a specific period.

Based on this information, when converted to carbon dioxide equivalent (CO_2e), the total carbon sequestered by the mangrove forest exceeds the reported carbon emissions of Colombia for 2020. The significant carbon sequestration capacity of mangrove forests underscores their crucial role in mitigating carbon emissions and climate change effects. This stark contrast highlights the imperative of preserving and protecting mangrove ecosystems due to their substantial positive environmental impact.

To assess the importance of mangroves in relation to climate change, we evaluated two scenarios of interest that are strongly dependent on the extent of mangroves in Colombian territory:

The first scenario involves considering the disappearance of mangroves in Colombia following the global rate until 2030. Based on the area reduction and the value of carbon sequestration in the territory using an average value, we estimated the amount of carbon released into the environment due to the partial disappearance of this ecosystem and its percentage contribution to the country's emissions.

The second scenario assumed that mangroves in Colombia grow in area at a constant rate equal to the global disappearance rate. Using available data, we estimated the total amount of carbon that mangroves will have sequestered between 2020 and 2030, assuming that the total carbon sequestration rate remains constant during this period.

According to The Global Mangrove Alliance (**Leal & Spalding**, 2022), between 1996 and 2010, the average loss rate was estimated at 327 km^2 (0.21%) per year, and it decreased to 66 km^2 (0.04%) per year between 2010 and 2020.

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In the first scenario, considering that the mangrove area in Colombia will decrease by 0.4% by 2030, the mangrove area will have diminished by 7.62 km^2 for the Pacific region and 3.41 km^2 for the Caribbean region, resulting in a total decrease of 11.03 km^2 over 10 years. Consequently, considering the reduction of mangroves and assuming the same total carbon value released in each region, the total carbon released due to the reduction would be 385.41 ± 54.53 kt, whose equivalent in kilotons of carbon dioxide equivalent is 1414,44 ± 200.12 kt CO_2e.

However, in the second scenario, the total amount of carbon stored due to the growth of mangroves would be exactly the previously calculated amount of 385.41 ± 54.53 kt, reducing the emissions by 1.414,44 ± 200.12 kt CO_2e.

Our estimation indicated that mangroves play a crucial role in Colombia's efforts to mitigate greenhouse gas emissions. In 2030, mangroves are estimated to account for approximately 1.7% of the country's total carbon dioxide emissions in 2020 (***Colombia: CO2 Country Profile***, n.d.). This calculation was based on assessing the total additional carbon sequestered by mangrove forests converted into carbon dioxide equivalent. Importantly, the total amount of carbon sequestered by mangroves exceeded the reported carbon emissions of the country for the same period. This underscores the significance of mangroves as valuable contributors to Colombia's initiatives in offsetting and reducing overall greenhouse gas emissions.

Quantification of blue carbon sinks monetary value

The blue carbon stored in mangrove ecosystems holds immense ecological and economic value, as previously mentioned. Quantifying this value provides insights into the ecosystem services provided by mangroves and can inform policy decisions and conservation efforts. In this sense, we estimated the monetary value corresponding to the blue carbon stored (blue carbon sinks).

To calculate the monetary value of blue carbon, we used the reference Carbon Pricing (CP) in the Carbon Stock Market. Carbon pricing is a climate policy approach that governments use to regulate carbon emissions and form carbon markets. But it's a pricing tool that's also available in the private sector for voluntary carbon reductions (https://carboncredits.com).

Assuming a value of 51 USD per ton of CO_2, we calculated the corresponding CP for 35.3610,59 ± 50.031,78 kt CO_2 emissions as follows:

Lower bound: 303.578.810 tons CO_2 × 51 USD / ton CO_2 = 15.482.519.310 USD

Upper bound: 403.642.370 tons CO_2 × 51 USD / ton CO_2 = 20.585.760.870 USD

Therefore, the CP of the 353.610,59 ± 50.031,78 kt CO_2 would represent an average value of 18 billion USD. As a comparison, in 2023, Colombia's Gross Domestic Product (GDP) amounted to 335 billion USD according to the Departamento Administrativo Nacional de Estadística), and the nation's general budget reached 97 billion USD (Law No. 2276, November 29, 2022).

It's important to note that this is just an estimate based on the assumed CP. The actual monetary value could be higher or lower depending on various factors, such as the specific location of the emissions, the impact on different sectors of the economy, and the chosen discount rate for future costs.

Conclusions

Building upon the insights gleaned from the comprehensive analysis conducted in earlier sections, we drew the following conclusions:

Mangrove forests play a crucial role in mitigating climate change by sequestering carbon, making their conservation and sustainable management critical for environmental benefits. The comprehensive assessment of mangrove areas and their substantial carbon sequestration capacity highlights the significance of these ecosystems as valuable contributors to Colombia's initiatives to reduce overall greenhouse gas emissions by 2030.

The application of a Random Forest algorithm along the Colombian coast yielded a classification model that estimated a total mangrove area of 2.756,84 km^2, achieving a perceptual difference below 5% compared to the mangrove habitat extent dataset from GMW. This highlights the effectiveness of integrating remote sensing technologies with machine learning algorithms for identifying the geographical distribution of mangrove ecosystems.

Our estimation revealed that the carbon storage within mangrove forests, quantified in kilotons of carbon dioxide equivalent (353,610.59 ± 50,031.78 kt CO_2e), exceeds the recorded greenhouse gas emissions of Colombia in 2020. This underscores the substantial potential of these ecosystems to sequester a significant amount of carbon and their crucial role in combating climate change.

It is important to note that various species in mangroves have different capacities for storing and capturing carbon. The sequestration values we used (t C/ha) with our mangrove extension data are estimates that helped us draw some results. However, they can vary significantly based on the specific location and conservation status of the ecosystems. It is crucial to recognize these potential discrepancies for refining our model and combining different techniques, such as collecting experimental data on-site, using satellite data classification, and leveraging artificial intelligence. Therefore, we emphasize the significance of establishing interdisciplinary collaborations to help obtain and verify data in the field. This will enable a more precise calibration of our model and a better evaluation of mangrove extent and carbon reserves.

A 0.4% reduction in mangrove area by the year 2030 could result in a substantial release of carbon into the atmosphere, estimated at 1.414,44 ± 200,12 kt CO_2e, potentially leading to negative environmental consequences. Conversely, directing efforts towards the conservation and growth of mangroves provides an opportunity to actively reduce an equivalent amount of carbon rather than releasing it.

The estimated Carbon Pricing of blue carbon stores in Colombia, amounting to tens of billions of dollars, underscores the immense economic significance of these natural resources, especially when considering that it is of the same order of magnitude as the general budget and the country's GDP for the year 2023.

Our study highlights the crucial role of mangroves in carbon sequestration and their potential to mitigate climate change. We successfully quantified carbon stocks across the territory, contrasting with most studies that only provide estimations for specific and smaller areas. The use of remote sensing technologies and machine learning algorithms allowed us to efficiently assess their extent and spatial distribution, and their carbon sequestration potential. Consequently, conservation and sustainable management of mangrove ecosystems are critical strides towards achieving the emissions reduction goal by 2030.

The quantification of blue carbon value underscores the multifaceted benefits of mangrove ecosystems. Beyond their ecological significance, mangroves contribute significantly to climate change mitigation efforts through carbon sequestration. By assigning a monetary value to the ecosystem services provided by mangroves, policymakers and stakeholders can better understand the trade-offs involved in mangrove conservation and land-use decisions. The estimated monetary value of blue carbon highlights the potential for financial incentives to support mangrove conservation and restoration efforts. Carbon finance mechanisms, such as carbon offset projects and payments for ecosystem services (PES) schemes, can provide funding for mangrove conservation projects while mitigating climate change.

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Authors' contributions

JBO, LPAL, and VIBA oversaw the data processing and analysis and participated in text writing. SVD, MFG, JEA, and JIC established the theoretical framework, and research tasks, and contributed to the discussion and text editing. All authors reviewed and approved the final manuscript.

Conflicts of interest

The authors declare that there are no conflicts of interest associated with the research process leading to the creation of this manuscript.

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