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# Mangroves From Rainy to Desert Climates: Baseline Data to Assess Future Changes and Drivers in Colombia

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## INTRODUCTION

Mangroves in Colombia (northern South America) have been described as the most luxuriant and wettest of the Americas (West, 1956) and as carbon-rich-tall tidal forests (Hutchison et al., 2014; Hamilton and Friess, 2018; Simard et al., 2019; Castellanos-Galindo et al., 2021a,b). Such statements mostly come from expeditions and research conducted on the Pacific coast and from global studies emphasizing on its ecological significance (e.g., Polidoro et al., 2010). However, mangroves in Colombia also occur along the Caribbean coast and in an oceanic archipelago off Nicaragua in Central America (Blanco-Libreros and Álvarez-León, 2019). Such distribution comprising mainland and oceanic settings allows for mangroves in the Colombian territory to exhibit unique features as a result of the wide variety of biogeographical regions and climates. First, mangroves are located in three biogeographical regions: the Tropical Eastern Pacific, the Southern Caribbean, and the oceanic Caribbean (i.e., San Andrés, Old Providence, and Santa Catalina Islands Archipelago; García-Hansen et al., 2002; Medina-Calderón et al., 2021). Out of the 285,040 ha, 194,880 ha are located in the Pacific region and 90,160 ha in the Caribbean region (including the oceanic territory). It is noteworthy, that the disconnection of the ancient coast of northern South America after the rise of the Panama Isthmus induced the disjunct distribution of *Pelliciera*, the only endemic genus to the New World (Duke, 2020), absent from oceanic Caribbean (García-Hansen et al., 2002; Medina-Calderón et al., 2021). Second, mangroves exist from super-humid (>7,000 mm $y^{-1}$; Castellanos-Galindo et al., 2017; Riascos et al., 2018) to desert climates (<500 mm $y^{-1}$; Guajira Peninsula), a fact little acknowledged in the literature addressing either rainfall gradients or arid zones (e.g., Osland et al., 2018; Adame et al., 2021). Moreover, mangroves are found throughout a wide range of geomorphic settings such as large to small deltas, estuarine, lagoons, open coasts, and carbonate islands (following the classification by Worthington et al., 2020). Finally, there are marked contrasts between the Pacific and Caribbean biogeographical regions relative to land use and land cover, particularly urbanization (Blanco-Libreros and Ramírez-Ruíz, 2021).

The unique settings of mangroves in Colombia provide a remarkable opportunity to study biogeographical, macroecological, regional, and landscape-level patterns of species composition, forest structure, and ecosystem function, as well as the anthropogenic and natural drivers of spatiotemporal change. In particular, hydrological alterations due to human activities and land use change seem to be the main drivers along the Caribbean coast of Colombia (Ward et al., 2016; Jaramillo et al., 2018; Blanco-Libreros and Ramírez-Ruíz, 2021). In addition, focusing on climate change impacts on mangroves, recent global studies suggest contrasting patterns between the Caribbean and Pacific coasts of South America, particularly related to sea-level rise, storminess, altered precipitation regimes, and erosion (Ward et al., 2016; Goldberg et al., 2020). Consequently, open-access, large-scale databases and baseline information are urgently needed to understand the spatiotemporal patterns of change and drivers in Colombia. However, a major challenge is to deal with the difference in sampling periods and methods by different surveys, and it is thus very important to assemble data obtained with standardized methods or obtained during a single study (e.g., Kauffman et al., 2020).

Accordingly, in previous work, we curated a database obtained during the major mangrove survey available to date in Colombia, conducted by the Ministry of the Environment (HELIO_SP.CO v.1; Blanco-Libreros and Álvarez-León, 2019). The survey was conducted in the mid-1990s, but no similar effort has been undertaken afterward. Subnational or departmental (administrative level 2) surveys have been carried out since year 2000 but reports and data are not easily accessible (**Supplementary Material**). Moreover, mangrove research comprising regional and national levels are scant in Colombia due to limited funding and complex logistics (reviewed by Castellanos-Galindo et al., 2021a), leading to a situation where only a few highly committed researchers have been able to gradually expand the geographic coverage of their research programs (e.g., Polanía et al., 2015; Urrego et al., 2018).

Here, we update the aforementioned database in response to requests made by colleagues for assembling mangrove forest structure datasets at national and sub-national levels. Such datasets are useful for estimating and modeling blue carbon, fine-tuning global models, and validating national and global mangrove maps (Rovai et al., 2016, 2021a,b; Bolívar et al., 2018; Hamilton and Friess, 2018; Mejía-Rentería et al., 2018; Simard et al., 2019). Analysis of datasets over broad extents has allowed recent progress of mangrove macroecology, particularly concerning blue carbon (e.g., Rovai et al., 2016, 2021a; Macreadie et al., 2019; Sasmito et al., 2019).

In HELIO_SP.CO v.1, we only included mainland locations (1.41–12.23 N; 71.28–79.00 W), while in this updated version we added locations in the oceanic Caribbean (12.32 N, 81.41 W, García-Hansen et al., 2002). The oceanic Caribbean was surveyed alongside with mainland locations, using the same methods, but only summary data were included in the original report (see Methods). This is a timely update because San Andrés and Old Providence islands (the largest within this territory and the only sustaining mangrove patches) were hit by hurricanes Eta and Iota in November 2020 (Garcés-Ordoñez et al., 2021). On that ground, the inclusion of historical data will also serve as a baseline for ecological impact assessments and ecosystem modeling of succession trajectories. In addition, we expanded the number of forest-structure attributes for the entire database to seven variables for five species (see Methods). All variables appeared in the original reports, but we only included tree density, mean tree diameter at breast height (dbh) and Importance Value Index (IVI). Mean tree height was only reported for locations on the Caribbean coast. The main objective of the HELIO_SP.CO v.2 is to serve as a baseline to assess changes in mangrove species occurrence, forest structure attributes, and coastalscape features after 2000. This database can serve as an input for future analyses to better understand the anthropogenic and natural drivers, to support decision-making in conservation and restoration, and to support climate change mitigation strategies.

## METHODS AND DESCRIPTION OF THE DATABASE

HELIO_SP.CO v.2 (**Supplementary File**) comprises mangrove inventory data for 113 locations (11 more than in version 1) covering a broad variety of physiognomic types under contrasting climates and geomorphic settings (**Figure 1** and **Supplementary Figure 1**). Each location corresponds to a georeferenced entry-point (Garmin 5 GPS, WGS 84 System, with a 100-m precision) in the mangrove fringe where the forest inventory was carried out. This database reports tree density, mean tree diameter at breast height (dbh, measured at 1.3 m above ground, with modifications depending of height of aerial roots and branching patterns), basal area, frequency, relative density, dominance and importance value index for *Rhizophora* spp., *Avicennia germinans*, *Laguncularia racemosa*, *Pelliciera rhizophorae* and *Conocarpus erectus*. For the Caribbean it has well stablished the presence of *R. mangle*, but for the Pacific, this species coexists with *R. harrisonii* and *R. racemosa*, therefore the report for this coast referred to the species complex as *Rhizophora spp*. The original forest inventory was carried out following either the Point-Centered Quadrat Method (20 m diameter) or the Alternated Square Plots (25 $m^2$), but all data were originally reported upon 0.1 ha. Mangroves were sampled at least in 10 points along a transect perpendicularly to the shoreline. Trees sampled within each quadrat or plot were divided into three diameter categories (>15, 5.1–15, and 1–5 cm). We only included dbh > 15 cm because they can be more representative of long-term trends or steady-state canopy conditions (see discussions on large tree inventories in terrestrial forests:). In addition, small-diameter trees (1–5 cm) were not measured in the Pacific coast. Fieldwork was carried out simultaneously in both coasts and the oceanic Caribbean between November 1995 and August 1996. Further descriptions are available in the printed reports by Saìnchez-Paìez et al. (1997a,b) cited by Blanco-Libreros and Álvarez-León (2019); **Supplementary References**).

Data from San Andrés Island were not included in version 1 of the database because the printed volume for the Caribbean did not include summary tables and it just described major features while the data mentioned in the text referred to an unpublished honors thesis. Since geographic coordinates were not reported in text for the sampling sites in San Andrés, we estimated the proximate coordinates for 11 sites by comparing the printed map included in the report and in additional publications (García-Hansen et al., 2002; **Supplementary References**) with Google Earth Pro. We further cross-checked the estimated location

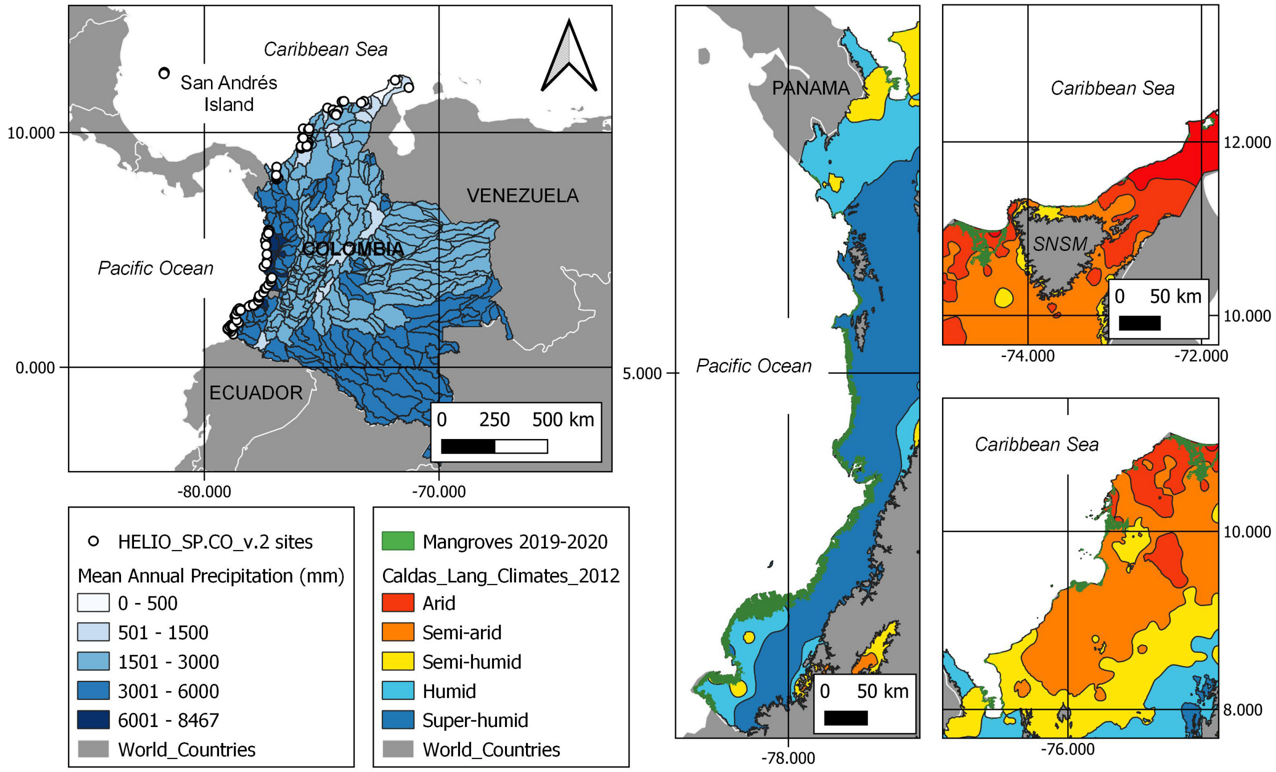

**FIGURE 1 |** Sites included in HELIO_SP.CO v.2 database are shown relative to mean annual precipitation within watersheds (left: note the location of San Andrés Island, oceanic territory in the Caribbean Sea-OC). Climates according to Caldas-Lang classification are shown for the entire Pacific coast and northern and southern stretches of the continental Caribbean coast (center and right). Sierra Nevada de Santa Marta (SNSM: a major coastal massif in the northern Caribbean coastal plain), Western Cordillera (one of the branches of the Northern Andes), and Serranía del Baudó (a satellite system running parallel to the northern Pacific coast) were excluded from the representation of climates in the insets (shown in gray color). Climate data from IDEAM, and mangrove map (2019–2020) from Valencia-Palacios and Blanco-Libreros (2021). Drawn with QGIS Zürich.

with the current official mangrove cover map (**Supplementary Figure 2**).[1] The senior author visited the sites in September 2021 to inspect anthropogenic changes, and concluded that conservation efforts have maintained mangrove extent and ecological conditions similar to the descriptions by García-Hansen et al. (2002). Maps and descriptive statistics were included as **Supplementary Material**.

# BRIEF ANALYSIS

## Country-Wide Patterns

The current database includes 61 sites along the Pacific coast under superhumid (total annual precipitation, $P > 5{,}000$ mm $y^{-1}$) and humid ($P > 2{,}500$ mm $y^{-1}$) climates, and 52 sites along the Caribbean coasts (including oceanic and continental areas) extending over semi-humid (in Antioquia, Southwestern Caribbean), semi-arid and arid (Cordoba-Magdalena), and desert (Guajira, Northeastern Caribbean) climates (P range: $< 500$–$< 2{,}500$ mm $y^{-1}$) (**Supplementary Figure 3** and **Supplementary Table 1**). Country-wide, *Rhizophora* spp. exhibited the greatest IVI (mean: 165.7; range: 0–300) given the high relative density, dominance and frequency, in continental (CC) and oceanic (OC) locations in the Caribbean (means: 89.7 and 134.4, respectively), but most significantly along the Pacific (222.7) (**Supplementary Figures 3,4**). *Avicennia germinans* was the second-most important species (mean: 27.3; range: 0–195), with the higher contribution in the OC and CC (even forming monospecific fringes in basin settings, **Supplementary Figure 1**) than in the Pacific (means: 81.3, 36.1 and 11.7, respectively). The third species was *Laguncularia racemosa* (mean: 19.2; range: 0–205) with greatest values in the OC, followed by CC and the Pacific (means: 85.6, 22.9 and 4.7, respectively), seemly as a response to the natural and anthropogenic disturbances. *Pelliciera rhizophorae* is scant and of little importance country-wide, but forms monospecific stands in some areas along the Pacific coast. *Conocarpus erectus* was recorded in a few sites along the Caribbean and the Pacific coasts, mostly due to its habit of colonizing the inner-most areas with well-drained sediments.

We previously reported that IVI for *Rhizophora* and *Avicennia* was partially correlated with mean annual temperature, mean annual rainfall, and rainfall seasonality (collating data from WorldClim 2; Blanco-Libreros and Álvarez-León, 2019), therefore clear differences in species composition and metrics

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[1] http://sigma.invemar.org.co

are expected among Colombia's climatic zones. Using the current database, the correlation of IVI with latitude and longitude coordinates (**Supplementary Figure 5**) shows marked biogeographical patterns. For instance, *Rhizophora* displayed a negative correlation with both latitude and longitude, while *A. germinans* showed a positive correlation with latitude. *L. racemosa* and *P. rhizophorae* exhibited positive and negative correlations with latitude, respectively. Stronger patterns would be expected when crossing HELIO_SP.CO v.2 data with Caldas-Lang climate and total annual precipitation data (**Figure 1**), as well as other sources (e.g., Koppen-Geiger climate classification). The addition of OC data to the database provides an opportunity to explore the influence of dry and maritime climate (influenced by cyclonic activity) on mangrove attributes.

We recommend using structural variables such as density, mean tree diameter, and basal area for understanding the climatic and biotic drivers of macroecological patterns. For instance, by using crossed linear correlations between density for the three dominant species (*Rhizophora* spp. *A. germinans* and *L. racemosa*) and geographic coordinates, insights are gained about the overall role of climate on large-scale distributions and ecological interactions at plot or local scales (**Figure 2**). Density in *Rhizophora* spp. was negatively correlated with latitude and longitude country-wide, indicating the negative effect of reduced rainfall, particularly along the CC. Density in *A. germinans* showed no significant correlation but it increased significantly to the northeastern coast of the CC (toward arid and desert climates). As a consequence, both species showed an antagonistic pattern country-wide but more markedly along the Caribbean region. Along this coast in particular, *R. mangle* forms extensive monospecific stands toward the southwest and *A. germinans* does it toward the northeast. In the Central Caribbean where both species coexist, they are spatially segregated, with *R. mangle* forming monospecific seaward fringes and *A. germinans* forming monospecific basin stands. Such patterns demonstrate the differences in ecological niches described in the literature. Finally, *L. racemosa*, a species that has not been studied in depth in the literature, shows significant correlations with latitude and longitude at different spatial scales and with *A. germinans*. Such patterns suggest a complex interaction between climatic, biotic and disturbance regime drivers. For instance, while country-wide *L. racemosa* is positively correlated with *A. germinans*, it is negatively correlated along the CC. This might result from the out-competition by *Rhizophora* spp. along the Pacific coast, but the release of local competition with *A. germinans* in the Caribbean coast with increased disturbance due to logging or cyclonic activity (e.g., Blanco-Libreros and Estrada-Urrea, 2015). Spatial patterns for *P. rhizophorae* and *C. erectus* are weaker due to the scarcity of occurrences country-wide (**Supplementary Figure 6**). However, the use of HELIO_SP.CO v.2 data in combination with other sources of information may be helpful for studying such patterns [see Blanco-Libreros and Ramírez-Ruíz (2021)]. We recommend the exploration of interactions among climatic, geomorphic and biotic drivers by using multiple regression models (both linear and non-linear, geographically structured or not). Finally, we also recommend studying how the disturbance regime in OC seems to promote species coexistence among the three dominant species island-wide in San Andrés and how they are locally segregated [see Medina-Calderón et al. (2021)].

## Potential Uses

We propose four main potential uses of the present database: (1) species distribution modeling and species conservation status assessment, (2) above-ground blue carbon and ecosystem services estimation, (3) land cover and use assessments in the coastalscape, and (4) current and future responses to coastal climate change. Presence and absence data can be used in large-scale species distribution modeling (SDM) efforts using various mathematical approaches, and they have been recently applied to neotropical mangroves (Rodríguez-Medina et al., 2020). WorldClim, CHELSA, and other climate data sources are commonly used for SDM. Presence and absence data, in combination with records in the Global Biodiversity Information Facility (GBIF), can also be used as spatial references for designating areas of interest (buffers) to study threats to vulnerable species such as *Pelliciera* spp. (see Blanco-Libreros and Ramírez-Ruíz, 2021). For this species, we used landscape metrics to understand mangrove habitat fragmentation relative to urbanization, quantifying the magnitude of this specific threat, an approach that can be applied to other mangrove tree species.

Second, plot-level mean density and mean tree diameter are useful for estimating carbon in the above-ground biomass (AGC) using allometric equations (e.g., Yepes et al., 2016; Rovai et al., 2021b). Given the scarcity of field studies in Colombia, the present database may help to reduce spatial uncertainty in national and sub-national level modeling efforts (Bolívar et al., 2018). We have estimated that plot-level AGC may range between $< 10$ and 225 Mg $\text{ha}^{-1}$ in the mainland (G. F. Pérez-Vega unpublished monograph, **Supplementary Figure 7** and **Supplementary References**). In addition to the climate mitigation ecosystem service provided by AGC, the basal area is correlated with wave dissipation capacity, functioning as coastal protection (Sánchez-Nuñez et al., 2020). Basal area (particularly in *Rhizophora mangle*) in this database may help to assess such service in OC and CC areas seasonally impacted by storm surges.

Third, land cover and land use change within mangroves and in its surroundings is a major driver of deforestation and fragmentation worldwide (Bryan-Brown et al., 2020). Species occurrences and forest attributes can be used as response variables to past drivers or as baseline information to assess future change. A recent assessment of the coastalscape configuration around *Pelliciera* spp. occurrences in response to urbanization may serve as an example (Blanco-Libreros and Ramírez-Ruíz, 2021). We encourage the use of the recently published official land cover data[2] to assess the current state of the coastalscape and to use urban expansion data[3] to understand threats to urban mangroves in the largest coastal cities in Colombia (e.g., Cartagena, Buenaventura). Finally, global layers such as the

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[2] http://www.ideam.gov.co/web/ecosistemas/coberturas-nacionales

[3] https://marroninstitute.nyu.edu/blog/urban-expansion-work-in-colombia

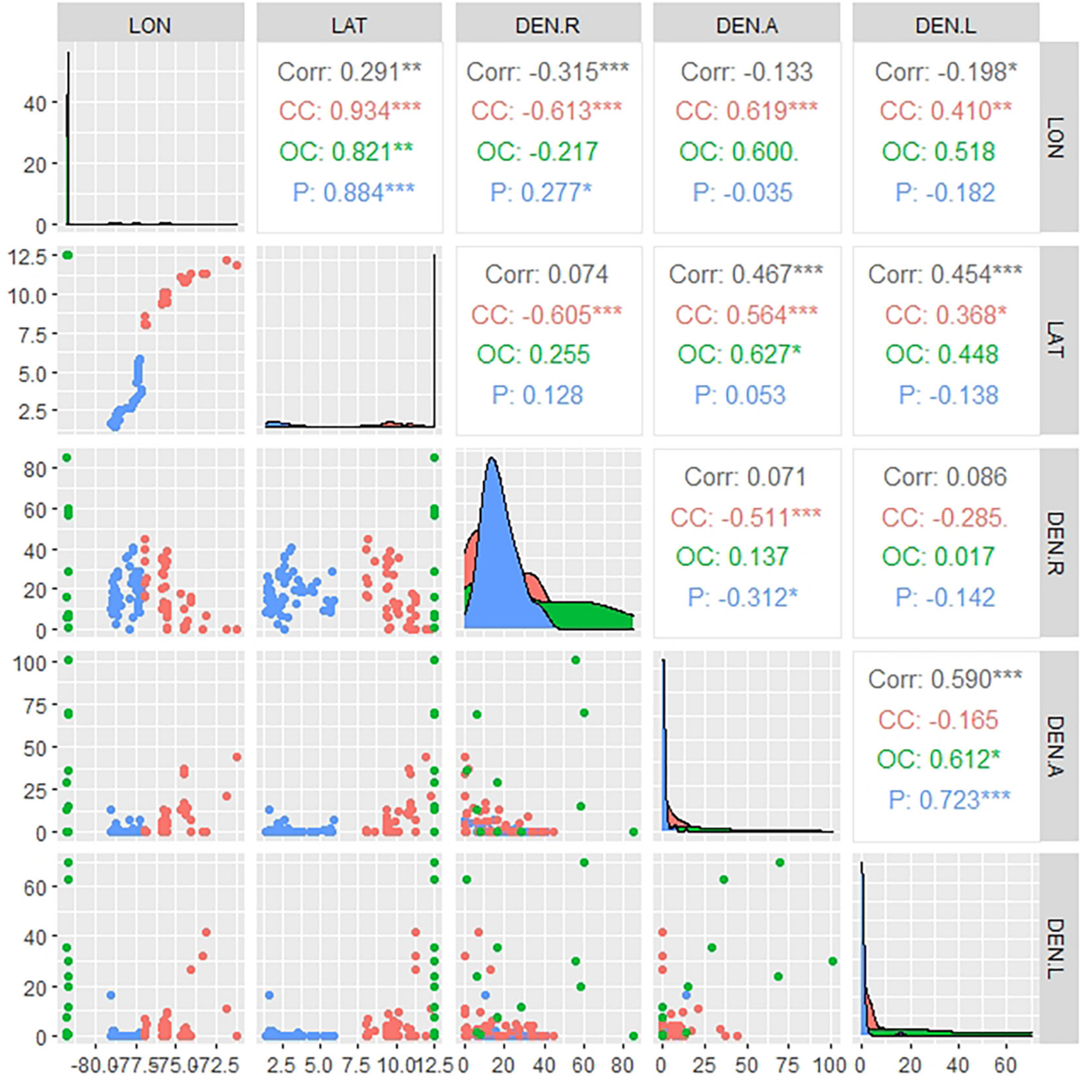

**FIGURE 2 |** Correlation matrix between the geographical coordinates and density values for the three dominant mangrove species (*Rhizophora* species complex, *Avicennia germinans*, *Laguncularia racemosa*) in the continental and oceanic coasts in the Caribbean (CC and OC, respectively) and the continental Pacific coast (P) of Colombia (note color coding). The upper half of the matrix shows the Pearson correlation indices with significance level indicated as asterisks for the total dataset and subsets for CC, OC, and P. The lower half panels show the scatter plots, and the diagonal boxes show the frequency distributions for each coast in different colors. Data available in HELIO_SP.CO v.2. Drawn using *ggpairs* function in *GGally* extension for *ggplot2* package for R.

nighttime lights,[4] and national layers of national parks, african-descendant territories and coastal watersheds,[5] and demographic variables for departments and municipalities[6] can be also useful to understand the spatial coastalscape context and socio-economic dynamics affecting variables in mangroves in Colombia (**Supplementary Figure 8**). A few studies of this type have been conducted in mangroves and terrestrial forests in the Chocó-Darién Ecoregion (e.g., López-Angarita et al., 2018; Fagua et al., 2019). Land cover and land use change have been anecdotally suggested as major drivers of changes in mangrove area and species composition along the Caribbean coast of Colombia but a few quantitative studies exist (e.g., Blanco-Libreros and Estrada-Urrea, 2015; Mira et al., 2019; Bolívar-Anillo et al., 2020; Villate-Daza et al., 2020). Therefore, we strongly encourage colleagues to use the present database to advance in this field.

Climate change and climate variability have been described mostly along the Caribbean coast of Colombia.[7] Future reductions in annual rainfall are predicted for the mid and northern Caribbean. Increased water stress on coastal watersheds is predicted for some areas due to land use changes, particularly urbanization. In addition, although the El Niño-Southern Oscillation is a strong driver of interannual variability on rainfall

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[4] https://blackmarble.gsfc.nasa.gov/

[5] http://www.siac.gov.co/

[6] https://geoportal.dane.gov.co/geovisores/

[7] http://www.siac.gov.co/cclimatico

and runoff in Colombia its influence on Colombian mangroves has been little studied (i.e., Galeano et al., 2017; Riascos et al., 2018; Riascos and Blanco-libreros, 2019). However, strong El Niño and La Niña events are seemly responsible for species composition transitions in the mid-Caribbean coast (Bolívar-Anillo et al., 2020; Villate-Daza et al., 2020). In the specific case of San Andrés and Providence islands, as oceanic territories, an increased rate of cyclone activity is expected. Hurricanes Eta and Iota hit both islands on November 2020 affecting mangroves (Garcés-Ordoñez et al., 2021). The prevalence of such climatic and meteorologic drivers urges for the need for baseline data and for setting local, regional, and national monitoring programs. Nowadays, a long-term monitoring program only exists for Ciénaga Grande de Santa Marta (see text footnote 1). Additional permanent plots have been established in some departments of Colombia but maintenance and repeated measurements are contingent on budget constraints producing many gaps in the records or even abandonment of the monitoring programs. Long-term studies and datasets are also needed for understanding the role of oceanic drivers such as coastal erosion and sea level rise.

Finally, we are certain that HELIO_SP.CO v.2 data are also useful for validation of mangrove maps. The Ministry of Environment and Sustainable Development issued in 2018 the Decree 1,263 ushering the environmental departmental authorities to update mangrove maps by 2021. The validation of such maps requires field campaigns over extensive areas of difficult access. In order to contribute to the advance in this task, we successfully used version 1 coordinates as validation points for a 2019–2020 map built using Sentinel 2 imagery and cloud computing in Google Earth Engine [**Supplementary Figure 8**; see data in Valencia-Palacios and Blanco-Libreros (2021)]. Thus, we encourage mangrove cartographers to use the present database as an alternative validation way given the growing use of cloud-based mapping in Colombia, particularly in areas of remote access making large-scale ground-truthing either logistically difficult or prohibitively costly (e.g., Perea-Ardila et al., 2021). We also foresee applications for estimating anthropogenic pressures relative to distance from large populated centers, as well for estimating the benefits perceived from mangrove-based fisheries (**Supplementary Figures 9,10**). Despite departmental-level forest inventories have been conducted since 2000, official data are not easily disclosed to scientists (**Supplementary Figure 11**), and scientific forest structure studies published since 2000 still have a very limited geographical coverage [discussed by Bolívar et al. (2018) and Castellanos-Galindo et al. (2021a)]. We conclude that HELIO_SP.CO v.2 can be useful as a baseline for the XXI century to assess future change and drivers in Colombian mangroves.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s. HELIO_SP.CO v2 data are freely available at Harvard Dataverse: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/QXQT59.

## AUTHOR CONTRIBUTIONS

JB-L and RÁ-L conceived, more than 20 years ago, the use of this database by a broader audience and finally published the first version and conceived the present update. JB-L supervised data entry and lead curation. JB-L and SL-R wrote the first draft with input from RÁ-L. AV-P and GP-V helped with database curation, ran exploratory statistical procedures, built exploratory maps, analyzed the data, contributed ideas and procedures for potential uses, and contributed to manuscript writing. All authors provided input and approved the submission of the final manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2022.772271/full#supplementary-material

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