Species-Poor Mangrove Forests also Provide Rich Ecosystem Goods and Services

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Abstract: Mangrove forests provide a wide range of services to coastal communities worldwide. These services include carbon sequestration and coastal protection, both of which are critical in the context of climate change. However, these wetlands are still experiencing destructive anthropogenic impacts in many areas. Senegal and Colombia, two countries in the Atlantic-East Pacific

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biogeographic region, both have abundant mangrove cover and share several mangrove species. This study assessed the use of mangrove resources (fuelwood, timber, and other non-timber forest products) by local communities in both countries. A total of 210 semi-structured ethnobotanical questionnaire-based interviews were conducted in Sokone and neighboring villages bordering the Sine-Saloum Delta in Senegal (110) and in the Cispata lagoon system in Colombia (100). The results for Senegal indicate that individuals residing near the Sine-Saloum Delta in neighboring villages rely more on mangroves compared to those living in Sokone. In Colombia, reliance on mangroves was associated with occupational activities. Despite lower species diversity compared to the Indo-West Pacific biogeographic region, mangroves provide various services in both areas, underscoring their significance to local communities and their livelihoods. Finally, the Indigenous and local knowledge emphasizes the need for alternatives to mangrove resources and the promotion of sustainable harvesting practices to ensure the conservation of mangroves and the continued provision of essential services.

Keywords: Mangrove, Ethnobiology, Face-to-face interviews, Atlantic-East Pacific, Senegal, Colombia

Introduction

Mangroves are found in more than 120 countries and territories worldwide (Bunting et al. 2022; Spalding et al. 2010). They are "plants that grow in tropical, subtropical, and warm temperate latitudes along the intertidal land-sea interface, in bays, estuaries, lagoons, and backwaters" (Dahdouh-Guebas et al. 2021). Given the alarming loss of mangrove cover in the twentieth century, Duke et al. (2007) warned of a world without mangroves. With renewed scientific attention following the Indian Ocean tsunami event (e.g., Satyanarayana et al. 2013, 2017) and global recognition to mitigate climate change in recent years (Kauffman et al. 2020; Macreadie et al. 2019; Wolswijk et al. 2022), mangrove degradation began to slow (Friess et al. 2019; zu Ermgassen et al. 2020). In this context, Friess et al. (2020) have provided a slightly more positive outlook for the future of mangroves through "conservation optimism." However, mangroves are still subject to destructive anthropogenic impacts, although the rate of loss varies considerably between countries (Feller et al. 2017; Friess et al. 2019; UNEP 2014). The main threats to mangrove forests include urbanization, agriculture, coastal aquaculture, pollution, anthropogenic climate change, and overexploitation of resources (Goldberg et al. 2020; Mukherjee et al. 2014a; Spalding et al. 2010; Thomas et al. 2017). This array of threats emphasizes the necessity for proper conservation and sustainable management of mangrove forests on a global scale.

Two decades ago, the ecosystem goods and services provided by mangroves were valued at more than US$1.6 billion per year (Costanza et al. 1997, 2014). By 2050, the annual economic benefits of mangroves are projected to reach US$2.2 billion (Sina et al. 2017). The importance of mangrove forests for carbon sequestration, up to 25.5 million tons of carbon per year, has led to an increase in mangrove conservation and restoration programs (Gerona-Daga and Salmo III 2022; Ong 1993). In addition, mangrove forests provide protection against tsunamis and storm surges (Alongi 2008; Badola and Hussain 2005; Barbier et al. 2008; Dahdouh-Guebas et al. 2005; Walters et al. 2008) and are critical for fisheries (Carrasquilla-Henao and Juanes 2017). There are an estimated 4.1 million mangrove-dependent small-scale fishers worldwide (zu Ermgassen et al. 2020). Finally, in addition to the benefits they provide to humans, mangroves serve as a refuge for numerous species of migratory birds and provide critical habitat for a variety of terrestrial, estuarine, and marine animal species (Luther and Greenberg 2009; Nagelkerken et al. 2008).

Ethnobotanical uses of mangrove species have also been identified and studied in several countries worldwide, such as Kenya (Dahdouh-Guebas et al. 2000), India (Dahdouh-Guebas et al. 2006), and Mexico (Hernández-Cornejo et al. 2005). Local communities living near mangrove forests use these ecosystems not only for subsistence but also as a source of income (Dahdouh-Guebas et al. 2006; Hussain and Badola 2010; Mukherjee et al. 2014b). Mangrove resources are valuable and diverse, including timber, fish products, honey, and fodder (Mukherjee et al. 2014b; Walters et al. 2008). In addition, some mangrove species have medicinal properties that can be used to treat a range of ailments (Bandaranayake 1998, 2002) and are attributed spiritual significance by local communities (Gallup et al. 2020; Walters et al. 2008). Mangrove use is observed in almost all areas where people live in close proximity to mangrove forests. However, species composition, policy restrictions and regulations, socio-cultural context, etc. can influence the way mangroves are used and the species selected (Dahdouh-Guebas et al. 2021; Gnansounou et al. 2024; UNEP 2014). This can lead to the emergence of distinctive mangrove uses at local, regional, or global scales, which are subsequently encompassed by Indigenous and local knowledge (Grimm et al. 2024). Indigenous and local knowledge serves as an umbrella term that encompasses Local Ecological Knowledge (LEK), Traditional Ecological Knowledge (TEK), and Indigenous Ecological Knowledge (IEK). LEK is defined as "the knowledge, practices, and beliefs gained through extensive personal observation of, and interaction with, local ecosystems, and shared among local resource users" (Grimm et al. 2024). TEK and IEK differ from LEK in that they require multigenerational accumulation and development of knowledge, with the local population being Indigenous (in the case of IEK) (Grimm et al. 2024; Narchi et al. 2014).

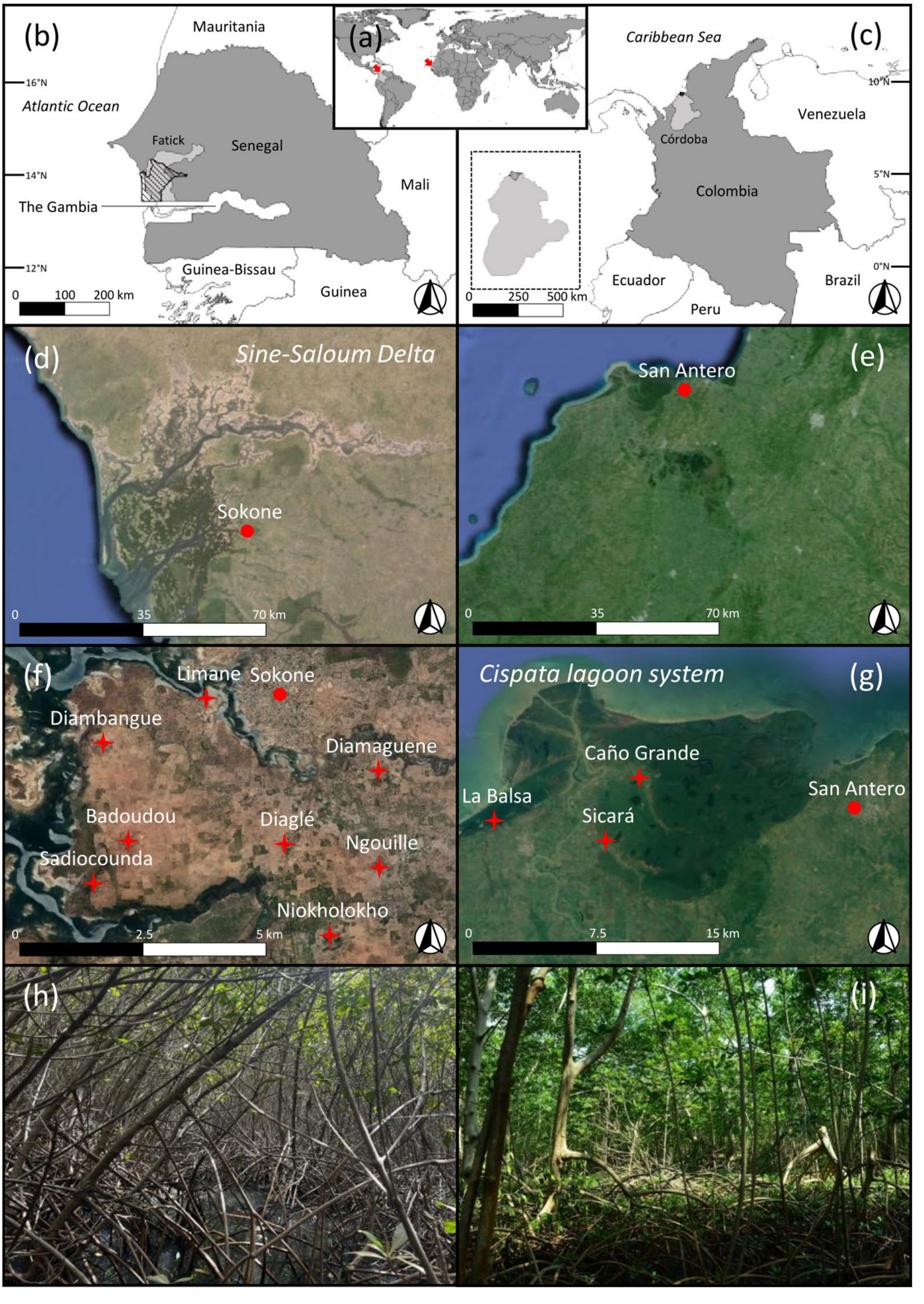
Walters et al. (2008) identified the potential to extract regional patterns and global trends in the use and valuation of mangrove resources from local studies. This study aims to achieve this by comparing the goods and services provided by the mangrove forests of the Sine-Saloum Delta in Senegal and the Cispata lagoon system in Colombia. Mangrove forests in Senegal and Colombia cover 1269.74 km^2 and 2807.54 km^2 respectively (anno 2020) (Bunting et al. 2022) and are classified as "Least Concern" in Senegal and "Vulnerable" in Colombia (anno 2024) (IUCN 2024). Both countries/regions have little documented Indigenous and local knowledge about mangroves, and as part of the Atlantic-East Pacific biogeographic region (Duke 1992), they provide a meaningful comparison. The Atlantic-East Pacific comparison is then extended to the plant species-rich Indo-West Pacific biogeographic region (i.e., 54 mangrove species) in contrast to the plant species-poor Atlantic-East Pacific biogeographic region (i.e., 17 mangrove species) (Duke 1992; Mantiquilla et al. 2021; Van der Stocken et al. 2019a). Too often, the perception is that few species mean few goods and services, which may have led to mangrove degradation in the past (e.g., The Gambia) (Satyanarayana et al. 2012). Although different kinds of mangrove forests provide different goods and services (Ewel et al. 1998), it is argued that plant species-poor mangrove forests also provide rich ecosystem goods and services.

The objectives of this study are to: (1) identify patterns of mangrove use in Colombia and Senegal; (2) compare patterns of mangrove use within the Atlantic-East Pacific (Senegal vs. Colombia) and with the Indo-West Pacific (Atlantic-East Pacific vs. Indo-West Pacific); and, (3) inform how the recorded Indigenous and local knowledge can be used for future mangrove conservation and management. Three hypotheses are presented. The first hypothesis suggests that mangrove use patterns (and numbers) depend on species composition, socio-cultural context and, to a lesser extent, policy restrictions and regulations. The second hypothesis suggests that mangrove use patterns (and numbers) in Senegal and Colombia are similar because of species composition. The third hypothesis suggests that mangrove use patterns (and numbers) are similar between species-poor Atlantic-East Pacific and species-rich Indo-West Pacific. The research questions addressed in this study aim to contribute to a regional and global understanding of mangrove resource use by highlighting similarities and differences. In addition, the collected Indigenous and local knowledge is used to inform the conservation and management of species-poor mangrove forests.

Materials and Methods

Study Area

This study focuses on the Sine-Saloum Delta in Senegal and the Cispata lagoon system in Colombia, both of which are part of the Atlantic-East Pacific region as described by Duke (1992). Along with the Indo-West Pacific region, the Atlantic-East Pacific is one of the two major


(a)
(b)
Mauritania
Atlantic Ocean
Fatick
Senegal
Mali
The Gambia
Guinea-Bissau
Guinea
(c)
Caribbean Sea
Venezuela
Córdoba
Colombia
Ecuador
Peru
Brazil
(d)
Sine-Saloum Delta
Sokone
(e)
San Antero
(f)
Limane
Sokone
Diambangue
Diamaguene
Badoudou
Diaglé
Ngouille
Sadiocounda
Niokholokho
(g)
Cispata lagoon system
Caño Grande
La Balsa
Sicará
San Antero
(h)
(i)

◂ **Fig. 1**. **a** world map showing Senegal (West Africa) and Colombia (South America) (source: https://datacatalog.worldbank.org/dataset/world-bank-official-boundaries), **b** map showing the Sine-Saloum Delta (hatched) in relation to the region (Fatick Region) where it is located in Senegal (source: https://www.diva-gis.org/gdata), **c** map showing the Cispata lagoon system (hatched) in relation to the department (Córdoba Department) where it is located in Colombia (source: https://www.diva-gis.org/gdata), **d** Google Earth imagery (dated 2013) of the Sine-Saloum Delta and the location of the town of Sokone (source: Landsat/Copernicus Data SIO, NOAA, US Navy, NGA, GEBCO), **e** Google Earth imagery (dated 2013) of the location of the town of San Antero (source: Landsat/Copernicus Data SIO, NOAA, US Navy, NGA, GEBCO), **f** Google Earth imagery (dated 2020) of the study area in Senegal showing the town of Sokone and the villages (Sadiocounda, Badoudou, Diambangue, Limane, Diamaguene, Niokholokho, Ngouille, and Diaglé) where interviews were conducted (source: Maxar Technologies), **g** Google Earth imagery (dated 2015) of the Cispata lagoon system and the study area in Colombia showing the town of San Antero and the villages (Sicará, La Balsa, and Caño Grande) where interviews were conducted (source: CNES/Airbus Airbus Maxar Technologies Data SIO, NOAA, US Navy, NGA, GEBCO), **h** photograph displaying Rhizophora mangle in the Sine-Saloum Delta in Senegal (photograph by Khady Diallo), **i** photograph displaying Rhizophora mangle in the Cispata lagoon system in Colombia (photograph by Jaime Polanía).

biogeographic regions. The Sine-Saloum Delta and the Cispata lagoon system were selected for comparison because of their rich history of scientific research and similar species composition, zonation (both belong to the Atlantic-East Pacific and North Atlantic), latitude, and climate.

Senegal

Part of the study was conducted in and around the town of Sokone in the Toubacouta district, adjacent to the Sine-Saloum Delta (13°42′ N, 16°38′ W) in the Republic of Senegal, West Africa (Fig. 1). The Sine-Saloum Delta is a World Heritage Site (since 2011), a UNESCO Biosphere Reserve (since 1981), and a Ramsar Site (since 1984), all of which cover part of the delta (DPWM and DPN 2011). The Sine-Saloum Delta, which covers an area of approximately 1800 km^2, consists of three main branches: the Saloum, the Diomboss, and the Bandiala (Simier et al. 2004). The southwestern region of the delta, where Sokone is located, is characterized by a dense network of creeks, locally called "bolongs" (Simier et al. 2004). The climate of the delta is classified as tropical savanna according to the Köppen-Geiger climate classification (Peel et al. 2007). The region is characterized by a dry season from November to May and a rainy season from June to October. The average annual temperature and rainfall are about 27 °C and 700 mm, respectively (Doumouya et al. 2016).

Since all UNESCO Biosphere Reserves consist of three distinct management zones/areas (core area, buffer zone, and peripheral area), the Sine-Saloum Delta Biosphere Reserve (RBDS) must also adhere to this structure (Fall 2006). The core area of the RBDS is the Saloum Delta National Park (PNDS). No human activities are allowed within the PNDS, although some exceptions, such as tourism, exist (DPWM and DPN 2011). Although the validity of this demarcation is unclear, a buffer zone surrounds the core area (DPWM and DPN 2011; Fall 2006). The buffer zone allows activities that align with the conservation goals of the core area. The PNDS is managed by the National Forest Service and the Directorate of National Parks (DPN) (see "Code Forestier" (RdS 1998a)) (Arumugam et al. 2020; DPWM and DPN 2011; Ndour et al. 2011). Mangrove fisheries resources are managed by the Fisheries Service (see "Code de la Pêche maritime" (RdS 1998b)) (Ndour et al. 2011). The peripheral zone includes several villages, such as Sokone. A significant number of people in these villages are engaged in activities related to the use of natural resources for domestic or commercial purposes (DPWM and DPN 2011; Fall 2006). In contrast to the core area and the buffer zone, the management of natural resources in the peripheral zone is the responsibility of local communities (region, municipality, and rural community) (Arumugam et al. 2020). The mangrove forest, including the unclassified protected area, in the vicinity of Sokone is managed by the municipality of Sokone in consultation with the local population. The classified protected area is managed by the Department of Water and Forest (municipal level) (Arumugam et al. 2020). In addition to the zones/areas defined in the RBDS, classified forests, nature reserves, and marine protected areas (MPAs) are also found in the region, each with its own management (Fall 2006).

Table 1. Mangrove diversity (families and species) in Senegal and Colombia and their corresponding IUCN categories (LC = "Least Concern" and VU = "Vulnerable"). Species present in the Sine-Saloum Delta (Senegal) and the Cispata lagoon system (Colombia) are marked with an asterisk.

Country	Family	Species	IUCN category
Senegal	Acanthaceae	*Avicennia germinans* (L.) Stearn.*	LC
	Combretaceae	*Conocarpus erectus* L.*	LC
		Laguncularia racemosa (L.) Gaertn. f.*	LC
	Pteridaceae	*Acrostichum aureum* L	LC
	Rhizophoraceae	*Rhizophora mangle* L.*	LC
		Rhizophora racemosa G. Mey.*	LC
		Rhizophora × *harrisonii* Leechm.*	
Colombia	Acanthaceae	*Avicennia germinans* (L.) Stearn.*	LC
	Combretaceae	*Conocarpus erectus* L.*	LC
		Laguncularia racemosa (L.) Gaertn. f.*	LC
	Pteridaceae	*Acrostichum aureum* L.*	LC
	Rhizophoraceae	*Rhizophora mangle* L.*	LC
		Rhizophora racemosa G. Mey	LC
		Rhizophora × *harrisonii* Leechm	
	Tetrameristaceae	*Pelliciera rhizophorae* (Triana and Planchon) NC Duke*	VU

The mangroves on the outskirts of Sokone are dominated by three species, namely *Rhizophora mangle* L., *Rhizophora racemosa* G. Mey., and *Avicennia germinans* (L.) Stearn. *Rhizophora* is mostly found along the creeks, while *Avicennia* is found in the landward areas behind the creeks (Rabinowitz et al. 1978). Six out of the seven mangrove species found in Senegal are located in the Sine-Saloum Delta (Table 1) (Gallup et al. 2020). The three additional species reported for the delta include *Conocarpus erectus* L. and *Laguncularia racemosa* (L.) Gaertn. f. along with the hybrid *Rhizophora* × *harrisonii* Leechm.

Colombia

Part of the study was conducted in the Cispata lagoon system, or Bahía de Cispata, in the Republic of Colombia, South America (Fig. 1). The lagoon system (9°24′ N, 75°49′ W) is located on the northwestern Caribbean coast at the mouth of the Sinú River basin (Niño-Miranda et al. 2020; Ruiz-Fernández et al. 2011). Bahía de Cispata covers 125 km^2 of the 880 km^2 mangrove area of the Colombian Caribbean coast (Sánchez-Páez et al. 2004). The climate of the lagoon system is classified as tropical savanna according to the Köppen-Geiger climate classification (Niño-Miranda et al. 2020; Peel et al. 2007; Urrego et al. 2009). The dry season (December–April) is characterized by northern and northeastern trade winds, while the rainy season (May–November) is characterized by weak southwestern winds (Niño-Miranda et al. 2020; Urrego et al. 2009). The average annual temperature and precipitation are about 28–30 °C and 1337–1400 mm, respectively (Niño-Miranda et al. 2020; Ruiz-Fernández et al. 2011).

The "Corporación Autónoma Regional de los Valles del Sinú y del San Jorge" (CVS) is the governing body responsible for monitoring and managing natural resources in the Department of Córdoba (Salcedo Hernández et al. 2020). In consultation with the local population, the CVS has developed a management plan for Bahía de Cispata called the "plan de manejo integral" (Salcedo Hernández et al. 2020). It divides the Cispata lagoon system into four management zones: "la zona de preservación," "la zona de recuperación," "la zona de uso sostenible no forestall," and "la Zona de Uso Sostenible del Sector Estuarino de la Bahía de Cispata" (ZUSSEBC) (Salcedo Hernández 2011). The plan for the ZUSSEBC identifies thirteen subsectors with specific extraction volumes, exploitation periods, and extraction shifts (Salcedo Hernández 2011). Due to the regulated use of mangrove resources and limited exploitation periods, each subsector can recover over a period of 14 years (Salcedo Hernández 2011). In total, there are eight associations that extract and commercialize mangrove wood within the ZUSSEBC through permits issued by the CVS (Salcedo Hernández 2011; Salcedo Hernández et al. 2020). Domestic use of mangrove wood is allowed, but it also requires a permit and must comply with the established rules of the management plan (Salcedo Hernández 2011).

The floristic composition of the Cispata lagoon system is dominated by *Rhizophora mangle*, along with *Laguncularia racemosa* and *Avicennia germinans* (Salcedo Hernández 2011). In total, six out of the eight species found throughout Colombia on both the Caribbean and Pacific coasts are present in the lagoon system (Table 1) (Alvarez-León and Garcia-Hansen 2003; Rodríguez-Rodríguez et al. 2016). The species present to a lesser extent are *Acrostichum aureum* L., *Conocarpus erectus*, and *Pelliciera rhizophorae* (Triana and Planchon) NC Duke. The mangroves in this lagoon system are relatively young, having been established between 1937 and 1945 when the Sinú River was diverted (Piccardi et al. 2020; Salcedo Hernández 2011).

Data Collection: Social-Ecological Interviews

Semi-structured ethnobotanical questionnaires (Supplementary Methods S1 and S2) were used to conduct interviews in Senegal from August to September 2013 and in Colombia from March to June 2014. The questionnaires were inspired by a questionnaire model used in various ethnobotanical studies of mangroves in different countries over the last 20 years (Dahdouh-Guebas and Koedam 2008; Dahdouh-Guebas et al. 2000, 2006; Hernández-Cornejo et al. 2005; Satyanarayana et al. 2012). The questionnaires contained both multiple-choice and open-ended questions designed to collect information on (a) socio-economic background, (b) primary uses of mangroves, (c) fishery-related activities, and (d) various aspects related to mangrove conservation, development, and importance. The questionnaires administered in both countries were identical. However, some questions were omitted because they were not considered relevant to either Senegal or Colombia.

Senegal

In Senegal, a total of 110 household interviews were conducted in Sokone (52 interviews) and eight nearby villages (58 interviews) within a radius of less than 10 km (Fig. 1). A systematic approach was followed, starting with the villages closest to the delta and moving inland. Within the eight villages, two populations can be distinguished based on their location in relation to the delta: the "maritime" rural population (Sadiocounda, Badoudou, Diambangue, and Limane), located relatively close to the mangrove creeks, and the "continental" rural population (Diamaguene, Niokholokho, Ngouille, and Diaglé), located relatively far from the mangrove creeks (Fig. 1). The same systematic approach was followed for Sokone, which represents the third population group, the urban population.

In each village, land plots defined by structural features such as roads (each with different households) were identified. The plots were systematically interviewed by walking from the mangrove to cover the entire village and approximately 10% of the population. This target is consistent with common practice in the social sciences for populations under 1000 to reach statistical significance. However, there are other methodological principles to consider, such as "saturation," where 9 to 17 interviews have been shown to be sufficient to reach saturation in studies with a homogeneous study population and narrowly defined objectives (Hennink and Kaiser 2022). Within each plot, only one household was interviewed, as households in the same plot are assumed to share similar mangrove uses and knowledge. In Sokone, a similar systematic approach was used to cover the entire town, using land plots defined by structural features. However, Sokone was first divided into two zones (eastern and western zone) based on the national road that divides the town. All interviews were conducted with the head of the family or a designated representative in each household (such as the wife or first-born child) who could speak on behalf of the head of the family.

Colombia

In Colombia, a total of 100 household interviews were conducted in San Antero, Sicará, La Balsa, and Caño Grande, around the Cispata lagoon system (Fig. 1). Interviews were conducted with both mangleros (55 interviews), individuals who collect mangrove wood with a permit from the local government, and non-mangleros (45 interviews), individuals who rely on mangrove resources without a permit. The term "mangleros" or "mangleras" (referring to the female peer) is an official designation for this group. In contrast, the term "non-mangleros" is an unofficial designation. The mangleros came from five of the eight associations recognized by the CVS: "Asociación de Mangleros Independientes de San Antero" (MID), "Asociación de Mangleros y Pescadores de Base de Cantarillo" (ASOMAPEBCA), "Asociación de Mangleros y Pescadores de Caño Lobo" (ASOMAPESCA), "Cooperativa de Producción y Comercialización Agrícola de Caño Lobo" (COOPROCAÑO), and "Asociación de Mangleros Unidos de San Antero" (ASOMAUSAN).

Households were selected randomly or systematically (in some cases with the assistance of association leaders) based on the location and the number of members per association. Since most of the mangleros live in San Antero, about 75% of the interviews were conducted there. Mangleros from Sicará and La Balsa were also interviewed. Similarly, most of the non-mangleros were interviewed in San Antero (about 75%); the remaining non-mangleros were interviewed in Caño Grande. The work of the mangleros is labor-intensive, carried out with an axe and a machete (according to the management plan). This is why most of the mangleros in the region are men, resulting in an unbalanced sex ratio.

Data Analysis

To make the two datasets comparable, data quality analysis (i.e., cross-checking questionnaire responses) and data streamlining (i.e., cleaning and aligning questionnaire responses and converting questionnaire responses to binary values) were performed. In general, for any given question, respondents who did not respond to that question were excluded from the analysis, resulting in *n* values that were less than the total number of respondents.

All analyses were conducted using RStudio version 1.4.1106. Multiple correspondence analyses and hierarchical cluster analyses were used to identify patterns of mangrove use in Colombia and Senegal. Multiple correspondence analyses were performed to identify and visualize associated variables, i.e., questionnaire responses. The "FactoMineR" package (Lê et al. 2008) and the "factoextra" package (Kassambara and Mundt 2020) were used for this analysis. Hierarchical cluster analyses were then performed on each multiple correspondence analysis to identify groups of respondents with similar responses. The same set of variables (i.e., questionnaire responses) was used for both multiple correspondence analysis and hierarchical cluster analysis. Multiple correspondence analysis is an extension of correspondence analysis that allows the analysis of data sets consisting of two or more categorical variables (Abdi and Valentin 2007; Greenacre and Blasius 2006), which is applicable to the present data set. The categorical variables are projected onto a low-dimensional (i.e., two- or three-dimensional) map to identify relationships and patterns among them. To categorize the set of observations into different groups, multiple correspondence analysis is often complemented by a clustering method, in this case hierarchical cluster analysis. Multiple correspondence analysis has been widely applied in several fields, including ethnobotanical research (e.g., Mafaziya Nijamdeen et al. 2023), often in combination with hierarchical cluster analysis. To compute the distance matrix for the hierarchical cluster analysis, the "daisy" function from the "cluster" package was used (Maechler et al. 2019). This function was selected because it allows for the use of Gower's distance, which is appropriate for mixed variables (Gower 1971). To conduct the hierarchical cluster analysis, the complete linkage method was chosen, and the "hclust" function from the "stats" package (R Core Team 2019) was used. To enhance the interpretability of the dendrogram, the function "sample_colours" from the "dendextend" package was used (Galili 2015). Finally, the function "fviz_nbclust" from the "factoextra" package (Kassambara and Mundt 2020) was used to visualize and determine the optimal number of clusters in the hierarchical cluster analysis. In this case, the average silhouette method was used to evaluate the number.

Significant differences between groups generated by the hierarchical cluster analysis were analyzed using a χ^2 test or a *G*-test, conducted with the "stats" package (R Core Team 2019) and the "DescTools" package (Signorell 2021). A *G*-test with Williams' correction is preferred over the χ^2 test when the expected frequencies are less than five. All tests used two-tailed hypothesis testing with a 5% significance level. Finally, descriptive statistics, such as means and percentages, were calculated for some of the questionnaire responses.

Results

Demographic Information

The rural and urban populations in Senegal can be divided into two groups based on their socio-economic profile and available assets (Fig. 2a and Fig. S1). Details on the socio-economic background of the 110 interviews conducted in Senegal can be found in Supplementary Tables S1 and S2. Group 1 included only the urban population, while group 2 included both maritime and continental rural populations. The urban population had higher literacy rates than their rural peers ($G=16.22$, df = 3, $p=0.001022$). In addition, the urban population was involved in a wider range of income-generating activities, while the rural population was mainly engaged in agriculture ($G=74.593$, df = 3, $p=4.441e-16$). Ownership of assets such as televisions ($\chi^2=31.076$, df = 1, $p=2.481e-08$) and refrigerators ($\chi^2=28.086$, df = 1, $p=1.161e-07$) was more prevalent among the urban population, indicating better living conditions compared to the rural population. Conversely, the rural population owned more agricultural land ($\chi^2=60.77$, df = 1, $p=6.415e-15$), livestock ($\chi^2=22.047$, df = 1, $p=2.66e-06$), and donkey carts ($\chi^2=17.122$, df = 1, $p=3.506e-05$). There was no difference between the rural and urban populations in how they referred to the mangrove (as wood, vegetation, or ecosystem), nor did they perceive the condition of the mangrove differently (very degraded, degraded, slightly degraded, or not degraded) ($G=3.054$, df = 2, $p=0.2172$; $G=1.2426$, df = 3, $p=0.7428$). Nevertheless, 89% of the respondents agreed that the mangroves had been degraded to some extent.

In Colombia, households were classified into two groups based on their socio-economic profile and assets: mangleros and non-mangleros (Fig. 2b and Fig. S3). Supplementary Tables S3 and S4 provide additional details on the socio-economic background of the 100 interviews conducted in Colombia. With the exception of housing type ($G=11.301$, df = 4, $p=0.02338$), the living conditions of the two groups were similar. Mangleros and non-mangleros live in houses constructed with different materials. Mangleros' houses are made of wood, mud, and iron plates, while non-mangleros' houses are constructed from bricks, iron plates, and other materials. Although, according to the interviews, mangleros tend to have higher average annual incomes than non-mangleros, no significant difference was observed ($G=8.3495$, df = 4, $p=0.07958$). Both groups refer to the mangrove in the same way (as wood, vegetation, or ecosystem) ($G=0.055892$, df = 2, $p=0.9724$) and have a good understanding of the mangrove species, although they are less familiar with *Conocarpus erectus* and *Pelliciera rhizophorae* ($G=2.4818$, df = 3, $p=0.4786$). Respondents recognize the negative impact of mangrove loss on their health, ecosystem services, and livelihoods. Regarding the current status of mangroves, 46% of respondents reported deterioration, 39% reported improvement, and 15% reported no change ($G=2.9186$, df = 3, $p=0.4044$).

Mangrove Resources Use

There is a clear distinction between the rural and urban populations of Senegal in their use of mangrove resources (Fig. 3a and Fig. S2). The rural population relies more on mangrove fuelwood and construction wood (including service wood used for daily activities such as furniture and cultural and ornamental items) compared to the urban population ($\chi^2=25.803$, df = 1, $p=3.782e-07$; $\chi^2=29.863$, df = 1, $p=4.637e-08$). Of the respondents, 44% reported using mangrove wood for fuelwood and the same percentage for construction wood, with different mangrove species preferred for different uses (Fig. 4a–b). The frequency of fuelwood

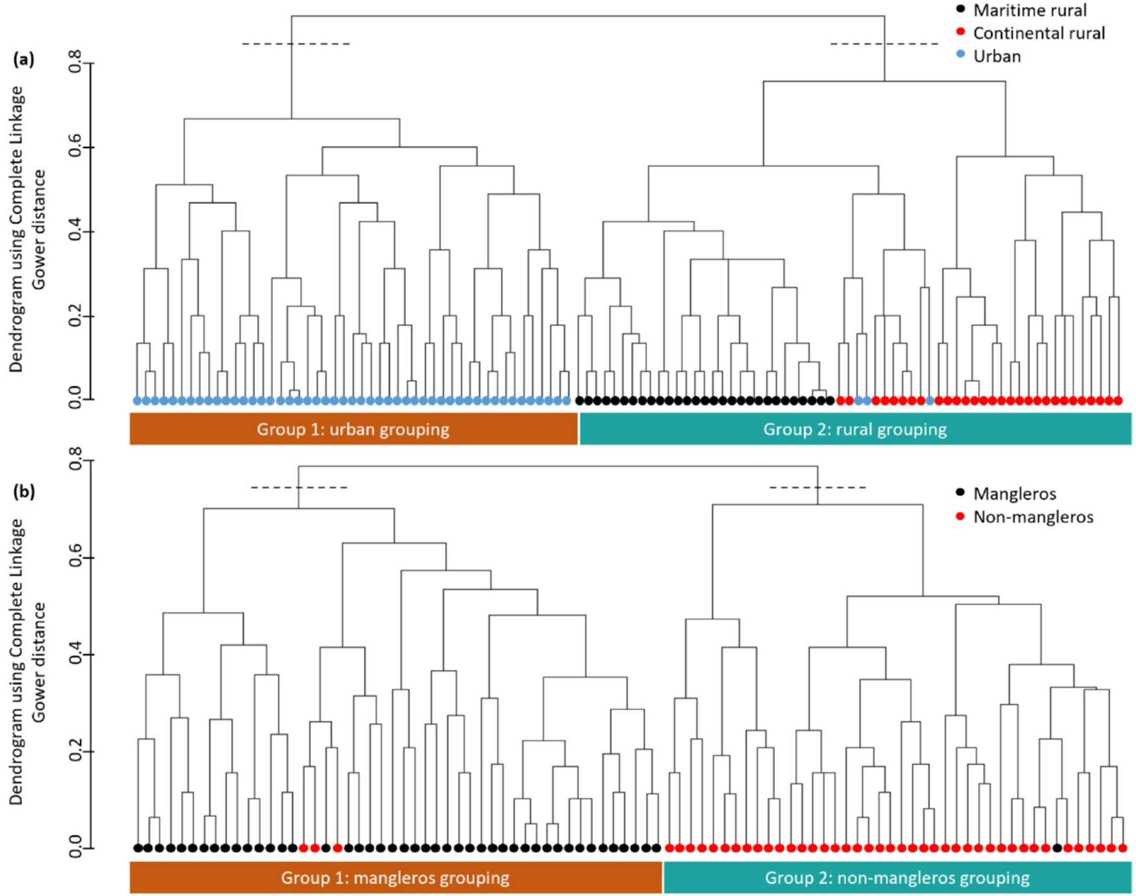


Fig. 2. **a** Hierarchical clustering dendrogram of selected socio-economic variables and household assets (e.g., TV, fridge, bicycle) in Senegal (n = 110). Group 1 (orange bar) mainly comprises individuals from urban areas, while group 2 (green bar) mainly comprises individuals from rural areas (maritime and continental). **b** Hierarchical clustering dendrogram of selected socio-economic variables and household assets (e.g., TV, fridge, bicycle) in Colombia (n = 90). Group 1 (orange bar) consists mainly of mangleros, while group 2 (green bar) consists mainly of non-mangleros.

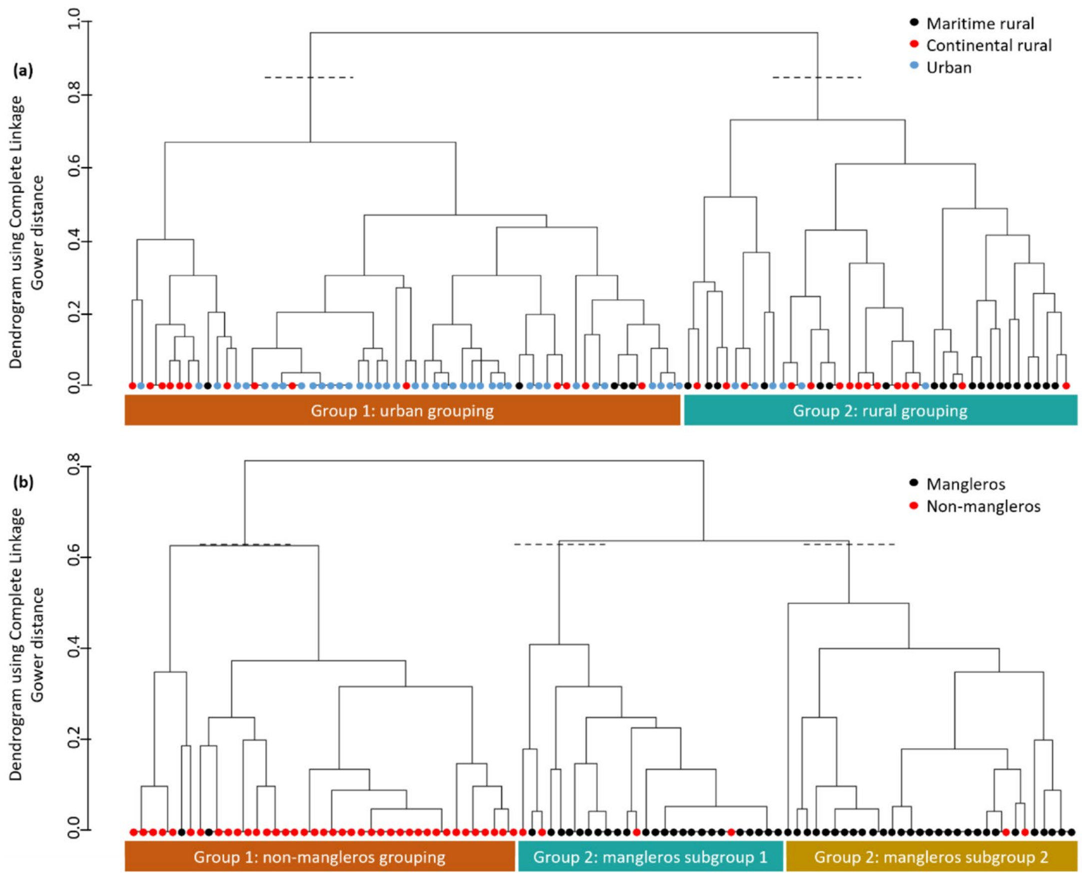


Fig. 3. **a** Hierarchical clustering dendrogram of selected variables related to the use of mangrove resources in Senegal (n = 100). Group 1 (orange bar) mainly comprises individuals from urban areas, while group 2 (green bar) mainly consists of individuals from rural areas (maritime and continental). **b** Hierarchical clustering dendrogram of selected variables related to the use of mangrove resources in Colombia (n = 100). Group 1 (orange bar) consists mainly of non-mangleros (not involved in the sale of mangrove wood), while group 2, with two subgroups (blue and yellow bars), consists mainly of mangleros (involved in the sale of both fuelwood and construction wood, or involved in the sale of construction wood only, respectively).

Fig. 4. Species-level uses of mangrove resources in Colombia and Senegal include: **a** fuelwood, **b** construction wood, and **c** medicine. Additional species-level uses identified in Colombia are: **d** service wood (wood used for daily activities such as furniture and cultural and ornamental items) and **e** fishery products (i.e., fishing gear). In Senegal, service wood is included in **b** construction wood, and mangrove fisheries exist, but no mangrove plant species have been reported for their use. Each graph shows a white bar representing "all mangrove plant species" for the respective country, followed by the percentage of use per species (genus names: R. = Rhizophora, L. = Laguncularia, A. = Avicennia, C. = Conocarpus, and P. = Pelliciera).

collection did not differ between rural and urban respondents ($G = 0.89362$, df = 1, $p = 0.3445$). The main criteria for fuelwood harvesting were identified as heat retention (38%), slow burning (36%), availability (35%), and low smoke emission (14%). For construction wood, respondents cited durability (38%), resistance (34%), availability (25%), and esthetic value (17%) of mangrove wood. Construction wood is used for house construction by 42% of respondents. Only a small percentage of respondents (4%) sell fuelwood and none of them reported selling construction wood (prices of fuelwood and construction wood are shown in Supplementary Table S5). The price of fuelwood and construction wood varies and is negotiated between the sellers and the buyers (Pers. comm., Djedje Kungula Makoso, June 13, 2021). Fuelwood is sold in bundles (locally called "fagot") and in bulk from a donkey cart (locally called "charette"). Construction wood is sold by the piece (locally called "tige") or in bulk from a donkey cart.

No differences were observed in the use of mangrove medicine between urban and rural populations ($\chi^2 = 9.5665e-31$, df = 1, $p = 1$). Furthermore, there was no difference in the amount of mangrove components harvested for medicinal purposes ($G = 0.93828$, df = 1, $p = 0.3327$). Among the respondents, 29% reported using mangrove components for medicinal purposes (Fig. 4c), with leaves being the most commonly used plant part. Seeds, roots, and bark were also mentioned, but to a lesser extent. Although mangrove fisheries exist, respondents did not report using mangrove components in fishing.

The use of mangrove wood for both fuel and construction is widespread in the Cispata lagoon system. Of the respondents, 95% used fuelwood, and 92% reported using construction wood to build their houses. On average, mangleros collect fuelwood 102 times per year, while non-mangleros collect it 85 times per year ($G = 2.2228$, df = 1, $p = 0.136$). Regarding construction wood, mangleros collect it an average of 129 times per year, while non-mangleros collect it only 2 times per year ($\chi^2 = 60.984$, df = 1, $p = 5.755e-15$).

Although both mangleros and non-mangleros in Colombia depend on mangrove resources, their use patterns differentiate them into two main groups (Fig. 3b and Fig. S4). This division is based on whether they sell fuelwood and construction wood ($\chi^2 = 9.4276$, df = 1, $p = 0.002137$; $\chi^2 = 57.341$, df = 1, $p = 3.664e-14$). The further subdivision into two subgroups within the mangleros indicates whether they are involved in selling the mangrove for fuelwood or not (prices of fuelwood and construction wood are shown in Supplementary Table S6). Prices for mangrove wood in the Cispata lagoon system are set to guarantee fair trade. However, there may be some variation in prices depending on market conditions and availability (Pers. comm., Betsabé López Macías, March 30, 2021). Construction wood is classified by diameter in inches and harvested according to market demand, but within the limits set by the management plan. Fuelwood, on the other hand, is not sold per unit but in bundles of about 100 pieces, measuring approximately 2 inches by 1 m (Pers. comm., Betsabé López Macías, March 30, 2021), the standard imperial-metric unit for sale. Overall, 30% of the respondents reported selling fuelwood, 56% reported selling construction wood, and only 5% reported selling service wood.

In addition to species-level exploitation for fuelwood and construction wood, there was a reliance on mangroves in Colombia for service wood, medicine, and fishery products (i.e., fishing gear) (Fig. 4a–e). Among the respondents, 23% use mangrove wood for service wood, 2% for medicinal purposes, and 18% for fishery products.

Mangrove Fishery Resources

In Senegal, about one-third (35%) of the respondents fish, and fishing is most common among the rural population ($\chi^2 = 15.735$, df = 1, $p = 7.285e-05$). However, there is no difference in the frequency of fishing between the rural and urban populations ($G = 1.1204$, df = 1, $p = 0.2898$). Among those who fish, 34% do so for personal consumption, while 12% fish to sell at the local market. Tannins (derived from mangrove wood and roots) are used for dyeing fishing nets by only 3% of the respondents. In addition, only one respondent reported using mangrove wood to smoke fish. Among respondents who fish, the majority agree that fish catches have decreased compared to the past ($G = 1.1204$, df = 1, $p = 0.2898$) and also agree that changes in fish abundance are associated with changes in mangrove cover ($G = 0.3996$, df = 2, $p = 0.8189$). Finally, respondents unanimously acknowledged the deterioration of water quality and the rise in sea levels in recent years.

In Colombia, fishing is practiced by almost all respondents (88%), but more and more frequently by non-mangleros than by mangleros ($\chi^2 = 9.1866$, df = 1, $p = 0.002438$; $G = 8.4074$, df = 1, $p = 0.003737$). On average, non-mangleros go fishing 5.1 days per week, while mangleros go 2.2 days per week. The majority of respondents reported a decrease in fish catch compared to the past ($G = 2.4586$, df = 2, $p = 0.2925$). Among the respondents, 53% did acknowledge the significance of the relationship between mangroves and the presence of fish ($\chi^2 = 1.1391$, df = 1, $p = 0.2859$). Changes in hydrodynamics, water quality, overfishing, and modern fishing methods are considered to be the main reasons for the decline of fish populations. Finally, there was no difference between the two groups in their perceptions of how sea levels have changed, with the majority agreeing that sea levels have risen ($\chi^2 = 2.8963$, df = 2, $p = 0.235$).

Mangrove Conservation

In Senegal, 94% of respondents considered mangroves to be very important for their survival, and almost half of them (45%) had participated in a conservation program. There was no difference in participation between the two groups ($\chi^2 = 0.67139$, df = 1, $p = 0.4126$). Regarding future mangrove conservation strategies, the majority of respondents (76%) chose strategy 1 (i.e., limited access with extraction license), followed by strategy 2 (i.e., no access) (22%). The least preferred strategy, strategy 3 (i.e., open access and extraction for commercial purposes), was chosen by only 2% of respondents. Finally, no difference in preference for strategies was observed between the rural and urban populations ($G = 4.2401$, df = 2, $p = 0.12$).

Both mangleros and non-mangleros in Colombia recognize the importance of mangroves to their livelihoods. While 97% considered mangroves to be important to very important, only 3% did not consider mangroves important. Both groups ($\chi^2 = 5.7752$, df = 2, $p = 0.05571$) had positive (42%) and negative (40%) perceptions about the future of mangroves. Out of the total, 18% had neutral perceptions. The positive outlook is attributed to the implementation of the "plan de manejo integral," which has led to reduced destruction of mangroves and decreased extraction of mangrove products. The negative outlook is attributed to pressure from mangleros, deteriorating water conditions, and climate change. In contrast to the non-mangleros, the mangleros are more familiar with forest regulations ($\chi^2 = 5.5687$, df = 1, $p = 0.01828$), official permits ($\chi^2 = 8.1869$, df = 1, $p = 0.004219$), and the locations of wood extraction ($\chi^2 = 23.463$, df = 1, $p = 1.273e-06$). Improved cooperation, communication, and working conditions resulting from the management plan were considered beneficial by 68% of respondents, with a higher percentage among mangleros than non-mangleros ($\chi^2 = 4.6103$, df = 1, $p = 0.03178$). Issues with the "plan de manejo integral," such as prolonged waiting times for permits and licenses to harvest mangrove wood, were reported by 36% of respondents. These issues affected both mangleros and non-mangleros equally ($\chi^2 = 0.02433$, df = 1, $p = 0.876$). Finally, almost all respondents agreed that it is important to protect natural resources (96%) and to involve local communities in mangrove management (98%).

Discussion

Mangrove Importance to Senegalese Communities

The residents of Sokone and the surrounding villages exhibited diverse socio-economic statuses and levels of dependence on the mangrove for fuelwood, construction wood, and fishing resources. The town of Sokone not only provides alternatives to mangrove resources but also offers a wide range of employment and educational opportunities. This has ultimately resulted in an urban population that is less directly dependent on mangroves. Similar conditions were also observed by Satyanarayana et al. (2012) in neighboring The Gambia and by Hernández-Cornejo et al. (2005) in Mexico. Despite the fact that the residents of Sokone are less dependent on mangroves, they are equally aware of the importance of mangrove ecosystems and their degradation. This differs from the observations of Satyanarayana et al. (2012) but may be explained by the proximity of Sokone to the mangroves.

Only one-third of respondents in Sokone and surrounding villages are involved in fishing, and none uses fishery products derived from mangroves, even though the residents of the Sine-Saloum Delta heavily rely on mangroves for fish, which is served at nearly every meal (Gallup et al. 2020). This observation may be attributed to the inland location of Sokone. Moreover, the practice of smoking fish is virtually non-existent in Sokone and surrounding villages, whereas it has been reported in the Sine-Saloum Delta, primarily by migrant fishers and foreign fish traders (Conchedda et al. 2011; Gallup et al. 2020). The decline in fish stocks is supported by the literature and is linked to overfishing and drought, leading to the subsequent loss of mangrove cover (Conchedda et al. 2011; Ecoutin et al. 2010; Simier et al. 2004). In addition, the perceived rise in sea levels and deterioration in water quality in the region may also contribute to the loss of mangrove cover and associated fish.

In Sokone, the municipality formally assumes responsibility for the mangrove forest in collaboration with the local population because it is located outside the protected area of the PNDS (Arumugam et al. 2020). However, dissatisfaction with past management practices has been identified in the municipality of Sokone by Arumugam et al. (2020). Respondents are dissatisfied with the past management because it does not guarantee access to mangrove resources for local communities (due to restrictions), which leads to illegal exploitation. Furthermore, management is reportedly failing due to the absence of alternative resources to mangroves for subsistence and income. Respondents are requesting greater involvement in the decision-making processes related to mangrove management and the consideration of acceptable alternatives. The results of this study further highlight the importance that the people of Sokone and surrounding villages place on mangroves. It also underscores their recognition of the necessity for appropriate conservation and management practices. This is because the majority of respondents believe that the management strategy of "limited access with an extraction license" is the way forward. The management strategy of "no access," chosen by some respondents, not only reinforces this idea but also calls for alternatives to mangrove resources for subsistence and income.

Mangrove Importance to Colombian Communities

The differentiation between mangleros and non-mangleros in San Antero and neighboring villages is not primarily based on socio-economic status. Rather, it is determined by their use (or non-use) of the mangrove for fuelwood, construction wood, and fishing resources for subsistence and income. The absence of differences based on socio-economic status is attributed to the majority of respondents, both mangleros and non-mangleros, living in San Antero and having access to the same amenities. Given that mangleros heavily rely on the extraction and commercialization of mangrove products, particularly construction wood (Salcedo Hernández 2011), it is logical that they engage in this activity more frequently. Despite this, the frequency of fuelwood collection does not differ between mangleros and non-mangleros. Both mangleros and non-mangleros continue to rely on mangrove fuelwood for daily cooking, although the use of electric and, in particular, gas cookers is on the rise (Pers. comm., Betsabé López Macías, March 30, 2021). This shift is primarily due to state policies that promote universal access to gas lines rather than environmental education initiatives by local NGOs, as observed in other countries such as India (Dahdouh-Guebas et al. 2006). This trend is distinct from that observed in other countries, such as Cameroon, Sri Lanka, and India, where the preference for mangrove fuelwood persists despite the availability of gas and electric cookers (Dahdouh-Guebas et al. 2006; Nfotabong-Atheull et al. 2011; Satyanarayana et al. 2013). The preference for mangrove wood, noted in many countries, is attributed to several factors, including the perceived superiority of mangrove fuelwood in terms of taste and its ready availability at no cost.

As for the mangleros, the relationship between the non-mangleros and the mangrove is determined by the occupational activities of the latter. The majority of non-mangleros are fishermen and go fishing more often than mangleros. The decline of fish populations in the Cispata lagoon system has been attributed to a number of factors, including altered hydrodynamics, poor water quality, overfishing, and the use of more advanced fishing methods. Indeed, the installation of the Urrá I hydroelectric plant led to a change in the freshwater input from the Sinú River into the Cispata lagoon system (Torres-Agudelo 2010). As the Sinú River channels play a vital role in maintaining the health of the mangrove ecosystem, this alteration has had an impact on fish stocks (Salcedo Hernández 2011). It is for this reason that mangleros are responsible for maintaining the channels in good condition in the region, and over half of the respondents acknowledged the significance of mangroves for fish populations. Moreover, the region has witnessed an increase in the influx of pollutants from various sources, such as tourism, commercial fishing, oil spills, domestic and industrial wastewater, and agricultural pesticides (Arteaga Palomo et al. 2017; Burgos-Núñez et al. 2017; Cadavid-Velásquez et al. 2019; CVS and INVEMAR 2010; Salcedo Hernández 2011). Finally, Torres-Agudelo (2010) demonstrated that the use of nets with smaller mesh sizes (which allow the capture of smaller fish) within the Cispata lagoon system has resulted in further declines.

The "plan de manejo integral," developed by the CVS in collaboration with the local population, is based on the collective participation of the local population to achieve sustainable management, meet domestic needs, and provide a source of income (Salcedo Hernández et al. 2020). In addition to the extraction and commercialization of mangroves, the mangleros are engaged in a range of activities, including reforestation, water resource cleaning and maintenance, and forest resource management (Salcedo Hernández et al. 2020). The majority of respondents expressed satisfaction with the current management plan, which provides them with non-financial assistance. However, the findings indicate that the management plan is more beneficial for mangleros than for non-mangleros. This is because the assistance is primarily directed towards mangleros, while non-mangleros are denied certain freedoms (i.e., the obligation to obtain a license for domestic use). In conclusion, the management plan has created a positive outlook for the future of mangroves in Colombia. However, despite the prohibitions outlined in the management plan, some households in the Cispata lagoon system still collect *Conocarpus erectus* and *Pelliciera rhizophorae* for domestic and commercial purposes (Sánchez-Páez et al. 2004). This may be due to a lack of awareness of the prohibitions, but also because the species are less common and therefore less known, leading to the unintentional harvest of these species. In addition, practical difficulties such as mangrove harvesting in prohibited areas, non-compliance with established harvesting volumes, and harvesting without a license (cf. Salcedo Hernández 2011) may impede the sustainable management of the mangrove forest in the Cispata lagoon system. Consequently, the utilization of remote sensing data and real-time observations by unmanned aerial vehicles (UAVs) is advantageous for the effective monitoring of the lagoon system (Lucas et al. 2020; Otero et al. 2018; Ruwaimana et al. 2018).

Senegalese vs. Colombian Mangrove Ecosystems

A total of seven distinct mangrove use patterns have been identified: fuelwood, construction wood, service wood, medicine, chemicals, fishery products, and food. Of the seven identified use patterns, five were observed in the Sine-Saloum Delta, and similarly, five of the seven use patterns were observed in the Cispata lagoon system. Further research conducted in Senegal (Sine-Saloum Delta) by Gallup et al. (2020) and in Colombia (Málaga Bay and Buenaventura Bay) by Palacios and Cantera (2017) expands upon this finding. It demonstrates that mangroves are used for fishery products (e.g., poles for fish and shrimp nets) and food (e.g., sauce, honey, tea) in Senegal, and for chemicals (e.g., tannins) and food (e.g., honey and nectar, tea) in Colombia, using the same species (i.e., *Avicennia germinans* and *Rhizophora* spp.). Consequently, all use patterns are observed in both species-poor countries, although to different extents (e.g., medicine).

In both countries, the trade and sale of mangrove resources primarily revolves around the use of mangrove fuelwood, construction wood, and service wood. Service wood differs from fuelwood and construction wood and refers to wood used for daily activities such as furniture and cultural and ornamental items (Satyanarayana et al. 2012). In both Senegal and Colombia, fuelwood is sold in bundles. In Senegal, it is also sold in bulk from a donkey cart. Although the number of units in bundles in

Colombia is approximately 100, the quantity in Senegal is unknown, making it challenging to make a meaningful comparison of prices. When it comes to construction and service wood, both Senegal and Colombia sell it by units. In Senegal, it is also sold from a donkey cart. In Colombia, the price of wood is determined by its diameter and length, resulting in eight distinct products. A comparable pricing structure is observed in Senegal.

In Colombia, the collection of mangrove wood is not limited to men, but the number of mangleros is dozens of times higher than the number of mangleras. The reason given is that the work is labor intensive and must be done with axes and machetes. In contrast, in West and Central Africa, women are more involved in wood collection, e.g., in Cameroon, although there is a large difference between men and women (Feka et al. 2011). Women collect wood during specific seasons, focusing mainly on small- to medium-sized trees (using rudimentary tools/equipment such as machetes), while men collect wood throughout the year, focusing mainly on large trees (using axes and chainsaws in addition to rudimentary tools/equipment). Again, labor (and therefore the physical strength required) plays a role in the differentiation between men and women. However, the greater involvement of women in Cameroon suggests that in addition to the physical strength required to collect mangrove wood (of larger calibers), social conventions must also play a role in the gender imbalance observed in wood collection in Colombia. Differentiated gender roles are not unique to wood collection, nor to Colombia, as they are observed in Senegal (Gallup et al. 2020) and neighboring The Gambia (Satyanarayana et al. 2012) for fishing, which is exclusively done by men, and for selling fish and oyster collection, which is primarily/exclusively done by women.

Species-Poor vs. Species-Rich Mangrove Ecosystems

The Atlantic-East Pacific biogeographic region is one of two major biogeographic regions with a total of 17 mangrove species, encompassing both the Sine-Saloum Delta in Senegal and the Cispata lagoon system in Colombia (Mantiquilla et al. 2021). Both countries have species-poor mangroves, with seven mangrove species in Senegal and eight in Colombia, seven of which are shared (except for *Pelliciera rhizophorae* in Colombia). Nonetheless, these species-poor forests have historically provided a variety of ecosystem goods and services to local communities. In Senegal and Colombia, mangrove components are used to varying degrees for medicine, chemicals (e.g., tannin extraction), fishery products (i.e., fishing gear), and food, in addition to fuelwood, construction wood, and service wood.

In comparison to the Indo-West Pacific biogeographic region, which is species-rich with 54 species (Duke 1992; Mantiquilla et al. 2021; Van der Stocken et al. 2019a), the use of mangrove resources in the Atlantic-East Pacific biogeographic region shows only minor differences. This is supported by other studies conducted in Bais Bay, Bindoy, and Banacon Island (Philippines), Bhitarkanika Wildlife Sanctuary (India), East-Godavari Delta (India), Galle-Unawatuna (Sri Lanka), Matang Forest Reserve (Malaysia), etc. (Dahdouh-Guebas et al. 2006; Goessens et al. 2014; Hugé et al. 2016; Martínez-Espinosa et al. 2020; Pattanaik et al. 2008; Satyanarayana et al. 2013; Walters 2003, 2005). For example, animal fodder, which can be considered an additional mangrove use pattern or under food, is observed in the Indo-West Pacific in India (Dahdouh-Guebas et al. 2006; Pattanaik et al. 2008) and not in the Atlantic-East Pacific. In addition, it is observed that the diversity of mangrove-derived foods is more pronounced in the Indo-West Pacific (e.g., mangrove fruits used as vegetables, mangrove fruits used for fruit juice, mangrove leaves used for vegetable curry) (Pattanaik et al. 2008; Satyanarayana et al. 2013) than in the Atlantic-East Pacific, where it is limited (e.g., honey and tea) (this study; Gallup et al. 2020; Hernández-Cornejo et al. 2005; Palacios and Cantera 2017; Satyanarayana et al. 2012). The small differences observed between Atlantic-East Pacific and Indo-West Pacific lead to two considerations. Firstly, there appears to be a general trend in mangrove use patterns in both the Atlantic-East Pacific and Indo-West Pacific biogeographic regions. This includes the use of mangroves for fuelwood, construction wood, and service wood, regardless of species diversity. Secondly, the diversity of use patterns appears to be linked to the presence of specific species and Indigenous and local knowledge, rather than species diversity in either species-rich or species-poor mangroves. Consequently, mangroves in species-poor regions are just as valuable for their goods and services as mangroves in species-rich regions. This argument supports the necessity of effectively enforcing management strategies in both locations.

The two major mangrove biogeographic regions differ not only in mangrove tree diversity but also in the diversity of their associated biotic assemblages (Bowen et al. 2013). Further comparative studies of the function of the species-poor Atlantic-East Pacific and species-rich Indo-West Pacific mangrove ecosystems will shed important light on the relationship between mangrove diversity and ecosystem function. It would be of fundamental theoretical and practical management interest to know when functional redundancy occurs (Lee et al. 2017). According to Mori et al. (2021), communities with low species diversity naturally have low functional redundancy (Petchey and Gaston 2002). Furthermore, other authors have linked the higher floral and faunal diversity in the Indo-West Pacific region to a broader range of species being exploited for fuel, timber, crustaceans, and coastal protection compared to the Atlantic-East Pacific region (Rivera-Monroy et al. 2017). While it is true that systems in the Atlantic-East Pacific region are naturally less species-rich, there is no evidence to date that functionality is compromised to warrant less attention to their conservation (Lee et al. 2017), and the present study corroborates that.

The importance of small mangrove patches, regardless of their size, has been emphasized by several authors (Curnick et al. 2019; Van der Stocken et al. 2019b). Cannicci et al. (2021) further demonstrate that even small mangrove patches, despite having low redundancy, support truly multifunctional faunal assemblages that are essential for providing ecosystem services. Theoretical and empirical studies (Fonseca et al. 2001; Petchey and Gaston 2002) have shown that species extinctions in natural ecosystems often result in a loss of functional diversity, indicated by a decrease in the number of functional traits (D'agata et al. 2016). Models predict that species-poor systems have low functional redundancy and are more likely to experience functional loss with species extinction (Fonseca et al. 2001; Rosenfeld 2002). Their analyses reveal that within mangrove forests, on average, 57% of the total functional trait combinations lack "insurance" and are carried out by a single species. This underscores that even a small loss of diversity could have significant negative consequences for the ecosystem, highlighting the importance of species-poor mangroves as much as species-rich ones.

The loss of individual mangrove species and associated ecosystem services has direct economic consequences for human livelihoods, especially in regions with low mangrove species diversity and low ecosystem resilience to species loss (Polidoro et al. 2010). However, the ecological implications of this mismatch in species richness for ecosystem function are poorly understood (Lee et al. 2017). A relationship between declines in tree diversity and the loss of mangrove ecosystem functionality has been assumed rather than demonstrated (Tilman et al. 2012), as measuring this relationship has proven to be challenging. However, significant positive correlations have been demonstrated between mangrove tree species richness, associated macrofauna, and their potential influence on aboveground primary productivity (Lee 2008). The relationship between biodiversity and ecosystem functionality in species-poor systems remains to be elucidated (Cannicci et al. 2021).

Indigenous and Local Knowledge on Mangrove Diversity and Uses

The rationale for collecting mangrove fuelwood and construction wood is largely consistent across different geographical regions (Dahdouh-Guebas et al. 2006; Walters et al. 2008). In Senegal and Colombia, the preference for *Rhizophora* spp. as fuelwood and construction wood is attributed to its heat retention, slow burning, low smoke emission, hardness, tannin-rich composition, and resistance to rot and pests. This preference aligns with the perceptions of people in the same region (Sine-Saloum Delta) and country (Colombia) (Gallup et al. 2020; Palacios and Cantera 2017). However, in Colombia, along the Pacific coast, the mangrove associate *Mora oleifera* (Triana ex Hemsl.) Ducke is preferred for house construction (e.g., stilt houses). *Rhizophora* spp. is also preferred in neighboring The Gambia (Satyanarayana et al. 2013), as well as in several other countries such as Kenya

(Dahdouh-Guebas et al. 2000) and Malaysia (Satyanarayana et al. 2021).

Harvesting practices need to be assessed in order to guide management and conservation efforts to ultimately sustain mangrove forests. Although the scale of extraction differs between Senegal and Colombia (small-scale logging versus "intensive" forest management), selective logging, which falls under harvesting practices, is observed in both countries. Selective logging has been linked to changes in the composition and structure of mangrove forests (Walters et al. 2008). For example, selective logging may favor species such as *Avicennia* spp. and *Laguncularia racemosa*, as small gaps in the forest canopy favor regeneration of species that successfully re-sprout/coppice from surviving stems, rather than *Rhizophora* spp. that lack reserve meristems. Harvesting practices take into account more than selective logging (e.g., frequency, extent) and should be evaluated in more detail in both Senegal and Colombia, as was done in Cameroon by Feka et al. (2011). This is in order to fine-tune management and conservation efforts (e.g., education on harvesting practices, mangrove regeneration techniques).

The analgesic and antiviral properties of *Avicennia* spp. and the antiviral, antifungal, and antimicrobial properties of *Rhizophora* spp. illuminate the potential medicinal applications of mangrove components, including leaves, seeds, roots, and bark (Bandaranayake 1998, 2002; Pattanaik et al. 2008). At the species level, *Rhizophora mangle* is used in Senegal and Colombia to treat dermatological conditions, prevent alcohol intoxication, and cure or treat malaria, while *Avicennia germinans* is used to relieve toothache, diarrhea, wounds, hemorrhoids, and pain associated with childbirth (Gallup et al. 2020; Palacios and Cantera 2017). Various preparation methods have been described, with the approach varying according to the ailments. However, a general decline in the use of mangrove medicine has been observed, which can be attributed to a multitude of internal and external factors. These factors include the availability of modern pharmaceuticals in the local market, regulatory constraints, restricted access, an aging population, and evolving occupational trends among young individuals (Satyanarayana et al. 2012, 2013). The medical applications of mangroves are also widespread in other African countries, such as Kenya (Dahdouh-Guebas et al. 2000) and Cameroon (Nfotabong-Atheull et al. 2011), among others.

Although there is a substantial body of literature on the nutritional and edible uses of mangroves, such as the preparation of a vegetable curry from the tender leaves of *Acrostichum aureum* and fruit juice from *Sonneratia caseolaris* (L.) Engler (cf. Satyanarayana et al. 2013), these uses were not documented in this study. Nevertheless, previous studies have documented the nutritional and edible uses of mangroves in Senegal and Colombia. Examples of these uses include the preparation of a sauce from *Avicennia germinans* fruits in Senegal (Gallup et al. 2020) and the extraction of honey and nectar from *Avicennia germinans* flowers in Colombia (Palacios and Cantera 2017).

Implications for a Sustainable Mangrove Conservation and Management

The management plan for the Cispata lagoon system (i.e., "plan de manejo integral") (Salcedo Hernández et al. 2020) shares similarities with the management model of the RBDS, designated as a UNESCO Biosphere Reserve (Ségalini 2012). The first major similarity between the two is the zoning of mangroves that both use. The RBDS is divided into three zones, while the management plan divides the Cispata lagoon system into four zones. The second major similarity is the functional similarities between these zones. The core area or DPNS corresponds to "la zona de preservación," which mandates the strict protection of the mangrove ecosystem. In addition, the peripheral zone corresponds to "la zona de uso sostenible no forestal" and ZUSSEBC, which differ in the type of use (forest-related or non-forest related), but both are intended for the sustainable use of resources. This is promoted through the introduction of exploitation periods, access restrictions, and the requirement to obtain permits or licenses. These similarities demonstrate a common approach to the sustainable management of natural resources, despite differences in terminology and administrative structures. In both areas, local participation is emphasized, as the local population is involved to varying extents in decision-making, resource management, and restoration. Whereas the effectiveness of such participation remains to be assessed, local participation is crucial to support the effective implementation of management practices. The dissatisfaction that is more apparent in Senegal than in Colombia is attributed to a lack of participation and the ambiguity in regulations for the different zones. This ambiguity arises from the extensive coverage of the RBDS and the inclusion of various other zoning categories beyond the RBDS, such as classified forests, nature reserves, and MPAs.

It is of the utmost importance that the livelihoods of local communities depending on mangrove resources are not overlooked (Walters et al. 2008). Although the use of mangrove wood for subsistence and the sale of mangrove wood for income generation in both Senegal and Colombia is in accordance with local regulations (e.g., "plan de manejo integral"), evidence of illegal cutting/activities suggests the need for improved management in both regions. For example, monitoring in both Senegal and Colombia can be improved; however, this requires funding (which is often unavailable) to hire more staff and/or implement remote sensing and UAVs. Access to the mangrove cannot (or not easily) be forbidden and should be promoted within the limits of the carrying capacity of the system. Therefore, the use of licenses (currently implemented in Colombia and desired in Senegal) is recommended for the management of mangrove resources. However, the process of obtaining licenses can discourage individuals from acquiring them, leading them to choose the easier path of engaging in illegal cutting/activities. Therefore, the process of obtaining a license should be transparent and not excessively time-consuming. One way to implement this and make it inclusive is to randomly allocate licenses, as is done in some Malaysian mangrove forests used for commercial charcoal production (Chen et al. 2024; Satyanarayana et al. 2021). Lottery numbers are issued, and the person with the lowest lottery number has the first choice of which area to exploit. Personal allocation of areas to exploit may additionally encourage self-regulation and good behavior, reducing the need for monitoring. As the number of licenses for mangrove resource use cannot be unlimited, attention should also be paid to finding acceptable alternatives to mangrove resources for subsistence and livelihood (e.g., ecotourism, beekeeping). However, the uses of mangroves are diverse and not limited to their use for wood (fuel, construction, and services) as reported in this study. Therefore, all uses need to be covered by acceptable alternatives. In addition to clear licenses, it is also important to ensure that the zoning regulations governing the management of mangroves are clearly communicated, understood, and deemed acceptable by the local populations. As illustrated by the RBDS management model, the demarcation of zones is not always clear, which can also lead to illegal cutting/activities (Arumugam et al. 2020; Gallup et al. 2020).

The establishment of protected areas remains an important goal for Senegal, and their implementation could further prevent the degradation of mangrove forest resources. A new MPA has recently been established in Sokone, within the RBDS. The MPA encompasses the mangrove forests and outlines their management. Sokone's MPA can be considered a "community" MPA because it was developed in consultation with the local community, the Senegalese government, and various NGOs and associations. The decree formalizing its establishment was issued in 2023, and the subsequent confirmation of its creation was given in 2024 by the Deputy Conservator of the Bamboung MPA and the Coordinator of the Toubacouta CLPA (Pers. Comm., Captain Touradou Sonko, April 22, 2024; Pers. Comm., El Hadj Ndour, April 22, 2024). The establishment of this MPA offers an opportunity to evaluate the use of mangrove resources a decade after its implementation and two decades after this study to assess the dynamics of mangrove use.

Conclusion

The comprehensive assessment of mangrove uses in Senegal and Colombia reveals that even in species-poor mangrove forests, there is a diverse array of goods that are of great value to local communities. In Senegal and Colombia, mangroves are used for various purposes such as fuelwood, construction wood, and service wood, as well as for medicine, chemicals, fishery products, and food (depending on the region). The role of mangroves extends beyond these direct benefits; they play a crucial role in maintaining coastal ecosystems, enhancing biodiversity, and mitigating the impacts of climate change. The loss of individual mangrove species and their associated ecosystem services has direct economic consequences for human livelihoods, especially in regions with low mangrove species diversity and low ecosystem resilience to species loss. This encourages additional conservation efforts and stricter management enforcement to protect the ecosystem goods and services of species-poor mangrove forests.

In both Senegal and Colombia, the use of mangrove resources by local communities for their livelihoods varies depending on educational and occupational opportunities. In Senegal, for example, the direct use of mangrove resources is more common in rural areas, highlighting the need for alternative livelihood resources. Next, mangrove resource use is determined by species composition (and species characteristics), with *Rhizophora* spp. and *Avicennia* spp. being the most commonly used for subsistence and income in both countries. Finally, the use of mangrove resources is strongly influenced by local legislation. Management practices have proven to be effective for the sustainable management of mangrove resources, particularly in Colombia compared to Senegal. However, some aspects can be further enhanced to strengthen management in both Senegal and Colombia. This includes resolving technical issues (e.g., licenses), garnering broader support, and improving monitoring.

This study contributes to a better understanding of the use of mangrove resources in the Atlantic-East Pacific biogeographic region and elucidates the similarities and differences among them. A global meta-analysis of mangrove uses in the Atlantic-East Pacific and Indo-West Pacific biogeographic regions is, however, still recommended to gain further insights. This would further highlight the widespread uses of mangroves and their importance to local communities in light of species composition, policy restrictions and regulations, socio-cultural context, etc.

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Author Contribution Rémi Dupont: formal analysis, investigation, resources, data curation, writing—original draft, writing—review and editing, visualization. Khady Diallo: investigation, data curation, writing—review and editing. Sylvestre Georis: formal analysis, investigation, resources, data curation, writing—review and editing, visualization. Djedje Kungula Makoso: investigation, writing—review and editing. Arimatéa C. Ximenes: data curation, writing—review and editing. Behara Satyanarayana: data curation, writing—review and editing. Yegor Tarelkin: data curation, writing—review and editing. Khady Diouf Goudiaby: writing—review and editing, supervision. Jean Hugé: data curation, writing—review and editing. Jaime Polanía: resources, data curation, writing—review and editing, visualization, supervision, project administration, funding acquisition. Farid Dahdouh-Guebas: conceptualization, methodology, software, validation, resources, data curation, writing—review and editing, visualization, supervision, project administration, funding acquisition.

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Data Availability Data (except personal data) is available on request from the corresponding author at Université Libre de Bruxelles (ULB).

Declarations

Ethics Approval All interviews were conducted with the permission of local authorities in both countries and with prior oral informed consent. The latter explained to all respondents the purpose of the research and the voluntary participation in this study, as well as the confidentiality of their responses to be used anonymously for research. In Senegal, the interviews were organized as part of a twin town project between Sokone (Senegal) and Zemst (Belgium).

Competing Interests The authors declare no competing interests.

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Résumé en Français

Les forêts de mangroves fournissent une large gamme de services aux communautés côtières du monde entier. Ces services comprennent la séquestration du carbone et la protection des côtes, tous deux essentiels dans le contexte du changement climatique. Cependant, ces zones humides subissent encore des impacts anthropiques destructeurs dans de nombreuses régions. Le Sénégal et la Colombie, deux pays de la région biogéographique de l'Atlantique-Est Pacifique, possèdent tous deux une couverture abondante de mangroves et partagent plusieurs espèces de mangroves. Cette étude a évalué l'utilisation des ressources de la mangrove (bois de chauffe, bois d'œuvre et autres produits forestiers non ligneux) par les communautés locales dans les deux pays. Au total, 210 entretiens ethnobotaniques semi-structurés basés sur des questionnaires ont été menés à Sokone et dans les villages voisins bordant le delta du Sine-Saloum au Sénégal (110) et dans le système lagunaire de Cispata en Colombie (100). Les résultats pour le Sénégal indiquent que les personnes résidant près du delta du Sine-Saloum dans les villages voisins dépendent davantage des mangroves que celles vivant à Sokone. En Colombie, la dépendance à l'égard des mangroves est liée aux activités professionnelles. Malgré une diversité d'espèces plus faible que dans la région biogéographique de l'Indo-Ouest Pacifique, les mangroves fournissent divers services dans les deux zones, ce qui souligne leur importance pour les communautés locales et leurs moyens de subsistance. Enfin, les connaissances autochtones et locales soulignent la nécessité de trouver des alternatives aux ressources des mangroves et de promouvoir des pratiques d'exploitation durables afin de garantir la conservation des mangroves et la continuité des services essentiels qu'elles fournissent.

Resumen en español

Los manglares proporcionan una amplia gama de servicios a las comunidades costeras de todo el mundo. Estos servicios incluyen la captura de carbono y la protección de las costas, ambos fundamentales en el contexto del cambio climático. Sin embargo, estos humedales siguen sufriendo impactos antropogénicos destructivos en muchas zonas. Senegal y Colombia, dos países de la región biogeográfica del Atlántico-Pacífico Oriental, tienen una abundante cobertura de manglares y comparten varias especies de manglares. Este estudio evaluó el uso de los recursos de los manglares (leña, madera y otros productos forestales no madereros) por parte de las comunidades locales de ambos países. Se realizaron un total de 210 entrevistas etnobotánicas semiestructuradas basadas en cuestionarios en Sokone y en las aldeas vecinas que bordean el delta del Sine-Saloum en Senegal (110) y en el sistema lagunar de Cispata en Colombia (100). Los resultados para Senegal indican que las personas que residen cerca del delta del Sine-Saloum en las aldeas vecinas dependen más de los manglares en comparación con las que viven en Sokone. En Colombia, la dependencia de los manglares estuvo asociada a las actividades ocupacionales. A pesar de la menor diversidad de especies en comparación con la región biogeográfica del Indo-Pacífico Occidental, los manglares proporcionan diversos servicios en ambas zonas, lo que subraya su importancia para las comunidades locales y sus medios de vida. Por último, los conocimientos indígenas y locales hacen hincapié en la necesidad de alternativas a los recursos de los manglares y en la promoción de prácticas de explotación sostenibles para garantizar la conservación de los manglares y la prestación continua de servicios esenciales.