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Cover

Seaflower Scientific Expedition 2021- II, Bajo Nuevo Bank. (Photo: CCO).

Editorial Dimar

design and composition

Dinamica S.A.S.

The CIOH Scientific Bulletin is a serial scientific journal, specialized in the different areas of research in marine sciences (oceanography, hydrography, integrated coastal zone management, protection of the marine environment, etc.), aimed at the scientific community and academia at the global level. It publishes unedited and refereed scientific articles every six months, the product of research projects carried out by the marine scientific research centers of the General Maritime Directorate and other institutes, and researchers who make original contributions to the development of new knowledge. It is published in digital format under the online ISSN 2215-9045, in Spanish and English. Its distribution is done from the Open Journal System (OJS) platform (http://ojs.dimar.mil.co) and the Maritime Digital Library Repository (RBDM) (CIOH Scientific Bulletin). This intellectual product has an Open Access (OA) for consultation. Its conditions of use and distribution are defined by the Creative Commons license.

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We would like to give special recognition to Captain Juan Camilo Forero Hauzeur, Executive Secretary of the Commission; Lieutenant Johan Sebastián Reyes Núñez, Head of Marine and Coastal Affairs; and Juliana Torres Acero, Coordinator of the Seaflower Biosphere Reserve. Their commitment and dedication have been key contributors to the success of this volume, facilitating the collection and presentation of essential knowledge about marine biodiversity in the Seaflower Reserve.

Thanks to their collaboration, the understanding of richness and fragility of our marine environment has been deepened, inspiring concrete actions toward the preservation of our natural heritage.

EDITORIAL

Seaflower Programme: 10 years of marine scientific research

Programa Seaflower: 10 años de investigación científica marina

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Colombia is a country widely recognized in the world for its natural and cultural wealth, as well as for its extensive geography, made up of five continental biogeographic regions that merge with the Pacific Ocean along the western coast and with the Atlantic Ocean on its northeast coast through the great Caribbean Sea. These two macro-basins directly support about 39% of the Colombian population (CCO, 2018)[2]. This natural heritage is a great challenge since, in order to establish strategies that allow economic development and ensure the preservation of ecosystems, it is necessary to study and understand the territory in its economic, biological, social and cultural contexts.

In 2014, the Colombian Ocean Commission (CCO) projected the National Plan for Marine Scientific Expeditions (PNEC) as a strategy to strengthen territorial integrity and projection, economic development, governance and sustainable use of resources, through the generation of comprehensive knowledge of the marine-coastal territory of Colombia. In this way, with two scientific programs -SEAFLOWER PROGRAM AND PACIFIC PROGRAM-, the PNEC is based on a model of intersectoral cooperation, which allows the country to articulate the necessary sectoral efforts for the generation of knowledge about the marine and coastal territory, in such a way that territorial needs and demands are integrated for decision - making, institutional scientific and technical capacities, and the traditional knowledge of local communities.

By virtue of the above, the SEAFLOWER PROGRAM aims to know and study the physical, chemical, biological and social characteristics of the Archipelago of San Andrés, Providencia and Santa Catalina, which was declared a Seaflower Biosphere Reserve (SBR) by the United Nations Educational, Scientific and Cultural Organization (UNESCO) within the framework of the Man and Biosphere Program (MAB), in order to preserve its biological, ecological and cultural diversity. Additionally, in 2005, the Ministry of Environment and Sustainable Development declared the Seaflower Marine Protected Area (AMP), which covers 65,000 km². Finally, in 2014, the area was assigned as an Integrated Management District, thus constituting the largest and most populated of the country's marine island reserves.

The SBR has 180,000 km² and is made up of the islands of San Andres, Old Providence and Ketlina, Courtown Cays, Southwest Cays, Roncador Bank, Queena Reef, Serrana Bank, Serranilla Bank, Bajo Nuevo Bank and Alice Shoal, and all the other islets, cays, banks and adjacent atolls. These feature ecosystems of high productivity, biological diversity and the most important extensions of coral ecosystems in the national territory.

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[2] Colombian Ocean Commission. (2018). National Policy of the Ocean and Coastal Spaces. PNOEC.

The SeaFlower Program is a national strategy of great value for the generation of scientific knowledge in the SBR, which promotes the fulfillment of the three objectives of biosphere reserves: *(i)* conservation of biological and cultural diversity, *(ii)* sustainable development and *(iii)* logistical support for research and education. This program has ensured that local communities are directly involved in its development, recognizing the value and importance of their traditional knowledge and territorial authorities. 30% of the researchers who have participated in the expeditions are *Raizal* and islanders, being the department with the greatest scientific representation. This guarantees that the community benefits from the research projects and that they serve as tools to strengthen their processes of governance, territorial management and socioeconomic progress.

Thanks to the articulation between the defense, environment, productive, academic, private and civil sectors, among others, since 2014, ten marine scientific expeditions have been carried out in eight geographical areas of the SBR. In these, 131 research projects have been developed on marine and coastal biodiversity; the physical component of the marine environment, culture and education; marine and coastal environmental quality; the sustainable use of hydrobiological resources; the application of engineering and technologies; and the threats and risks in marine and coastal areas. In this way, 95 national and international institutions and organizations have participated, including 24 research groups recognized by the Ministry of Science, Technology and Innovation. Likewise, the academic knowledge of 200 researchers has been integrated with the *Raizal* and island community.

Through the development of the ten Seaflower scientific expeditions, 11,000 biological records belonging to 13 taxonomic groups have been obtained, of which 425 are new species records, either for the Cay Islands, the SBR, the country or the Great Caribbean Sea. In this way, the expeditions have made it possible to increase the inventory of marine-coastal species reported in the archipelago by 18%.

With the aim of strengthening the processes of social appropriation of the marine and coastal territory of the SBR, the purpose of this volume of the CIOH ScientiFic Bulletin is to disseminate multiple results, findings and discoveries of the Seaflower Program, an inter-institutional strategy that completes a decade of generating scientific knowledge at the SBR.

I therefore highlight the work carried out by 41 researchers, who contributed with the main results of their research projects, allowing the formation of this interesting document of scientific dissemination, which will allow the generation and propagation of new scientific-marine knowledge of our biooceanic maritime country.

Understanding that the sea is not only a body of water, but also a vital source that provides employment, livelihood, energy, as well as economic and social development, from the Executive Secretariat of the CCO we continue to work in a coordinated manner with the different entities of the national government, the academic community and the civilian population, with the firm conviction of continuing to contribute to the consolidation of Colombia as a biooceanic power for the benefit of all Colombians.

Research Article

Polychaetes (Annelida) of the Southwest Cays and Serranilla Bank, Seaflower Biosphere Reserve, Colombian Caribbean

Poliquetos (Annelida) de las islas Cayos de Alburquerque y Cayos de Serranilla, Reserva de la Biósfera Seaflower, Caribe Colombiano

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Abstract

Polychaetes are the most abundant marine invertebrates, with a valuable contribution of biomass to the food chain and the balance of ecosystems. In the Colombian Caribbean, the islands have been identified as areas where there is a lack of information regarding marine biodiversity. In order to understand the polychaete communities of the Seaflower Biosphere Reserve, located within the Colombian insular Caribbean, studies were carried out between 2017 and 2018 in the Serranilla (CS) Bank and Southwest (CA) Cays with the objective of generating an inventory of polychaetes present in these two areas. The collection in both cays was made using dredges, nets, scuba diving and freediving, and revealed a total of 30 families, 152 genera and 226 species. The families with the highest number of species were Syllidae (56 species), Eunicidae (23 species), Spionidae (16 species) and Sabellidae (14 species). This list includes 86 new records of genera and 172 species of polychaetes in the Colombian Caribbean.

Keywords: Polychaetes, Caribbean, Seaflower BR, Serranilla Bank, Southwest Cays.

Resumen

Los poliquetos son los invertebrados marinos más abundantes, con un aporte valioso de biomasa a la cadena trófica y al equilibrio de los ecosistemas. En el Caribe colombiano las áreas con mayor deficiencia de información sobre biodiversidad marina son las insulares. Con el propósito de conocer las comunidades de poliquetos de la Reserva de la Biosfera Seaflower, en el Caribe insular colombiano, se realizaron estudios entre 2017 y 2018 en las islas Cayo Serranilla (CS) y Cayos de Alburquerque (CA) para generar un inventario de poliquetos de estas dos áreas. Utilizando dragas, red, buceo autónomo y por apnea la recolecta en ambas islas cayos reveló un total de 30 familias, 152 géneros y 226 especies. Las familias con mayor número de especies fueron Syllidae (56 especies), Eunicidae (23 especies), Spionidae (16 especies) y Sabellidae (14 especies). El presente listado contiene 86 nuevos registros de géneros y 172 de especies de poliquetos en el Caribe colombiano.

Palabras claves: *poliquetos, RB Seaflower, Caribe, isla Cayos de Serranilla, isla Cayos de Alburquerque*

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Introduction

Coral reefs are one of the most biodiverse and productive ecosystems on the planet, providing the human population with a wide range of goods and services, such as the protection of the coastline and other ecosystems against erosion, the provision of food and income, and the generation of economic gains from diving and tourism (Burke *et al*., 2011). Colombia's total coral reef area covers 4,405 km² across both continental and oceanic zones, with 77% of these coral areas located within the archipelago of San Andres, Old Providence and Ketlina Islands. This archipelago was designated as the Seaflower Biosphere Reserve (SBR) by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2000, a designation that has been maintained due to the region's status as one of the most extensive marine and island reserves on the planet (Gómez-Cubillos *et al.,* 2015; Vides *et al.,* 2016).

The SBR is constituted by a series of islands, cays, banks and lowlands that exhibit a notable biodiversity and a diverse array of marine ecosystems, underscoring their significance as biodiversity reservoirs in the Colombian Caribbean (Díaz *et al.,* 2000; Coralina-Invemar, 2012; Vega-Sequeda *et al*., 2015). However, the biodiversity of these environments remains under-explored, primarily due to the focus of research efforts on shallow habitats up to 60 meters deep and on the most visible groups of organisms (Vides *et al.,* 2016). Consequently, certain invertebrates inhabiting benthic communities, such as polychaetes, have been overlooked in efforts to enhance the marine faune inventories of Colombia.

Polychaetes are among the most abundant groups of marine invertebrates and exhibit great diversity in body forms, habitat occupation, and life-history strategies. They play key roles in ecosystem functioning by serving as a food source for higher trophic levels, contributing to bioturbation, nutrient recycling, and the degradation of organic matter. Likewise, they are widely recognized as effective bioindicators of environmental pollution, particularly in relation to organic matter and heavy metals (Rouse & Pleijel, 2001; Báez & Ardila, 2003; Dean, 2008; Martins & Barros, 2022). Although polychaetes in the marine ecosystems of the SBR have been studied since the 1970s, a definitive estimate of species richness is still lacking, as new records continue to emerge with each publication from different sectors of the SBR. The most recent record for this region is found in the publication by Londoño-Mesa *et al*. (2016), which contains 340 records between families, genera and species. However, in comparison to the number of studies conducted in the continental coastal area of the Colombian Caribbean, the studies available for this island region is limited. This is due to the fact that accessibility and travel costs play an important role when planning ocean expeditions.

The high ecosystem value of coral reefs, combined with the geophysical, ecological, cultural and economic characteristics of the SBR, underscores the critical need for continued monitoring and research to ensure their preservation (Coralina-Invemar, 2012). In this context, the Presidency of the Republic of Colombia, initiated the scientific expedition plan led by the Colombian Ocean Commission (CCO) in 2015. In conjunction with the Colombian Navy (ARC), the Government of the Department of Archipelago of San Andrés, Providencia y Santa Catalina, the Corporation for the Sustainable Development of the Archipelago of San Andrés, Providencia y Santa Catalina (Coralina), and the General Maritime Directorate (Dimar). The Caribbean Oceanographic and Hydrographic Research Centre (CIOH) has been instrumental in fostering collaboration with academic and research institutions to promote the generation of new knowledge within the SBR. This initiative has contributed to enhancing the management and conservation of the region's marine resources (CCO, 2015).

This study was conducted during two scientific expeditions to the Serranilla Bank and Southwest Cays, which took place in 2017 and 2018 respectively. A variety of institutions participated in the study with the aim of strengthening the management of the comprehensive scientific knowledge of the SBR with the updating of the baseline information.

Study Area

The Serranilla Bank (CS) is located north of the SBR, between 15°50’ and 16°’04’N and 80°03’ and 79°40’W. This bank covers an area of 1,200 km^2, an includes several nearby small cays (West Breaker, Middle Cay, East Cay and Beacon Cay). The shallow zone consists of a carbonate platform at a depth of about 8 meters, with benthic habitats comprising algae, sponges, small patches of hard corals, and seagrass beds in the southeastern sectors (Abril-Howard *et al.*, 2012; CCO, 2015) (Fig. 1).

The Southwest Cays (CA) are located approximately 35 km southwest of San Andres Island (12°10'N – 81°51'W). This is the only atoll within the SBR with an almost circular shape, measuring over 8 km in diameter, formed by a continuous peripheral reef to windward and discontinuous to leeward. The basin and lagoon terrace of this atoll contain North Cay and South Cay, surrounded by patch reefs, sand and coral debris, bioturbated sediments with calcareous algae, and seagrass meadows; the latter border a part of North Cay (Díaz *et al.,* 2000; CCO, 2015) (Fig. 1).

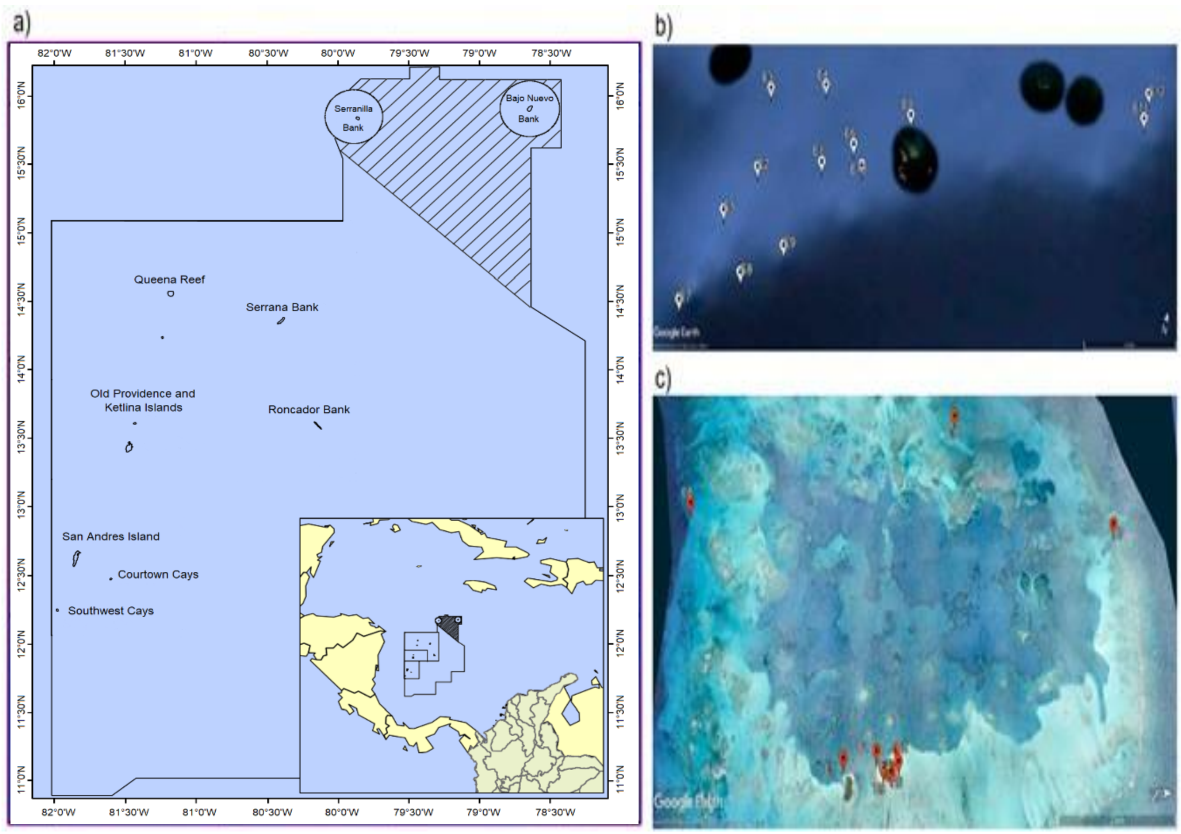

Figure 1. (a) Map of the Seaflower Biosphere Reserve; **(b)** Location of the sampling areas on the Serranilla Bank; **(c)** Southwest Cays. (SBR map modified from: Seaflower Foundation, 2019; images with sampling sites: Google Earth, 2024).

Methodology

At each study site in CS and CA, sample collection covered a minimum area of 0.1 m^2, as recommended for macrofauna studies for sandy or muddy bottoms (Eleftheriou & Moore, 2013). For sample preservation and handling, the methodologies proposed by Cortés *et al*. (2013) for soft-bottomed organisms, and Merchán-Cepeda *et al*. (2013) for rocky littoral organisms were followed.

Serranilla Bank

In September 2017, sampling was conducted in CS and surrounding areas from a research vessel, covering both the eastern (E11 and E12) and western sectors (E0 to E10). Samples were collected using a Van Veen dredge at depths of 10 m, 20 m and 30 m; and a Chipec dredge was used at a depth of 320 m in the central area of the bank's plain (E7) (Table 1). On the eastern and western sides of CS, linear transects were carried out along the rocky shore, where polychaetes were collected from supratidal and infralittoral zones. In some cases, rocks were fractured manually or basic diving equipment was used to collect biological material.

Table 1. Date, coordinates, depth and type of dredger used at sampling sites in the Serranilla Bank.

Date	Site	Coordinates	Depth	Dredge
19/09/2017	E0	15° 48′ 21.00′′N - 79° 51′ 7.56′′W	12 m	Chipec
21/09/2017	E1	15° 45′ 58.80′′N - 79° 54′ 1.62′′W	22 m	Van Veen
21/09/2017	E2	15° 45′ 1.98′′N - 79° 56′ 22.62′′W	30 m	Van Veen
21/09/2017	E3	15° 47′ 13.86′′N - 79° 56′ 52.62′′W	17 m	Van Veen
21/09/2017	E4	15° 48′ 2.88′′N - 79° 54′ 45.78′′W	11.5 m	Van Veen
22/09/2017	E5	15° 43′ 34.80′′N - 79° 57′ 6.60′′W	27 m	Van Veen
20/09/2017	E6	15° 46′ 50.22′′N - 79° 53′ 0.84′′W	16 m	Van Veen
20/09/2017	E7	15° 41′ 2.22′′N - 79° 57′ 35.52′′W	323 m	Chipec
20/09/2017	E8	15° 42′ 21.90′′N - 79° 55′ 44.64′′W	28 m	Van Veen
25/09/2017	E9	15° 43′ 29.58′′N - 79° 54′ 30.00′′W	30 m	Van Veen
25/09/2017	E10	15° 46′ 24.30′′N - 79° 52′ 28.38′′W	18 m	Van Veen
25/09/2017	E11	15° 51′ 19.20′′N - 79° 42′ 6.00′′W	22 m	Van Veen
25/09/2017	E12	15° 52′ 6.00′′N - 79° 42′ 2.40′′W	20 m	Van Veen

Southwest Cays

In September 2018, sampling was conducted at six shallow stations located in the North Cay and South Cay sectors. Samples from sandy bottoms were collected by freediving, using a hand net mounted on an iron frame (0.1 m² opening) fitted with a 500 µm mesh. A plexiglass sheet was inserted between the net and the substrate to aid in sample extraction. Additionally, coral rocks were manually removed at each station. At stations E3, E7, and E8, samples were collected manually by SCUBA diving due to the greater depth at those sites (Table 2).

Table 2. Date, coordinates, depth and collection method at sampling sites in the Southwest Cays.

Date	Site	Coordinates	Depth
09/25/2018	E1	12º 09’ 52.50’’N - 81º 50’ 27.66’’W	2.0 m
09/26/2018	E2	12º 09’ 57.00’’N - 81º 50’ 27.84’’W	1.1 m
09/26/2018	E3	12° 10’ 24.99”N - 81° 52’ 15.99”W	6.4 m
09/27/2018	E4	12º 09’ 58.14’’N - 81º 50’ 23.94’’W	1.2 m
09/28/2018	E5	12º 9’ 37.74’’N - 81º 50’ 25.14’’W	1.5 m
09/29/2018	E6	12º 09’ 58.01’’N - 81º 50’ 21.74’’W	1.5 m
09/30/2018	E7	12º 11’ 45.64’’N - 81º 51’ 40.75’’W	4.3 m
10/01/2018	E8	12° 8’ 16.62”N - 81°52’ 15.99”W	18.8 m
10/01/2018	E9	12° 9’ 55.38”N - 81° 50’ 24.48”W	1.8 m

Storage and preservation of samples

Marine benthic sediment samples in CS and CA were washed through a 500 µm mesh sieve to retain the macrofauna. The retained material was placed in heavy-gauge (1 mm) transparent plastic bags, to which a narcotizing solution (up to 500 ml of Magnesium Chloride) was added to relax the organisms for 15 to 20 minutes. Subsequently, a 12% formalin solution (500 ml) prepared with seawater, was added as a fixative. The solution was neutralized with a borax and stained with rose bengal to facilitate tissue visualization during laboratory analysis.

Rocks manually collected in CS and CA were transported in buckets to the shore, where they were carefully to extract polychaetes using soft forceps. The specimens were then placed in deep plastic trays containing a solution of magnesium chloride and seawater to anesthetize them. Subsequently, they were preserved in pre-labeled storage jars with 96% ethanol, as some organisms were intended for additional studies not addresed in this document.

In the laboratory, the samples from both expeditions were rinsed with distilled water in plastic trays to remove residual formaldehyde. Macrofauna was separated from the sediment under a stereoscope, and polychaetes were preserved in labeled storage jars with 70% ethanol. The process of species-level identification was conducted by using a stereoscope, a microscope, and microphotography equipment, following the taxonomic keys of Uebelacker and Johnson (1984), Salazar-Vallejo (1996), De León-González *et al.* (2009; 2021), and Gil (2011). To determine the presence of new records for the Colombian Caribbean, the publications on polychaetes by Londoño-Mesa *et al.* (2016); León *et al*. (2019) and Coneo-Gómez *et al*. (2022) were reviewed.

Results

In the expeditions to CS and CA, a total of 231 organisms were recorded, distributed in 30 families, 152 genera and 226 species (Table 3).

Table 3. Polychaete species recorded in the expeditions to the Serranilla Bank and the Southwest Cays. **NR:** new record for the Colombian Caribbean; **(X)** previously recorded in Colombia; **(**)** New record of genus and species for the Colombian Caribbean; **(*)** new record of species for the Colombian Caribbean.

N°.	Species	CS	CA	No.	Species	CS	CA
1	*Amphinome rostrata*		x	124	*Lepidametria commensalis* **	NR	
2	*Benthoscolex sp.*		x	125	*Polynoe erythrotaenia* **		NR
3	*Chloeia entypa* *	NR		126	*Subadyte mexicana***	NR	
4	*Eurythoe complanata*	x		127	*Thormora johnstoni* *	NR	
5	*Hermodice carunculata*		x	128	*Claudrilus draco* **	NR	
6	*Hipponoe gaudichaudi* *		NR	129	*Acromegalomma fauchaldi* *		NR
7	*Linopherus paucibranchiata* *	NR	NR	130	*Anamobaea orstedii*		x
8	*Pareurythoe elongata**		NR	131	*Bispira crassicornis* *	NR	
9	*Pareurythoe spirocirrata* *	NR		132	*Bispira melanostigma*	x	
10	*Branchiomaldane vincentii* **		NR	133	*Branchiomma curtum*	x	
11	*Amastigos delicatus***		NR	134	*Branchiomma nigromaculatum*	x	
12	*Capitella aciculata* *	NR	NR	135	*Chone gracilis* *	NR	
13	*Capitella caribaeorum* *	NR		136	*Fabricinuda limnicola* **	NR	
14	*Capitella teres* *		NR	137	*Jasmineira bilobata* *	NR	
15	*Dasybranchethus pacifica* **		NR	138	*Notaulax nudicollis* *	NR	NR
16	*Dasybranchus lumbricoides*	x		139	*Notaulax paucoculata* *		NR
17	*Decamastus gracilis* *		NR	140	*Potamethus spathiferus*	x	x
18	*Neonotomastus glabrus* **	NR		141	*Pseudobranchiomma emersoni* **	NR	
19	*Notomastus hemipodus*	x		142	*Terebrasabella heterouncinata* **	NR	
20	*Notomastus landini* *		NR	143	*Saccocirrus major* **		NR
21	*Bhavania riveti**		NR	144	*Hydroides mucronata* *	NR	
22	*Chrysopetalum occidentale* **	NR		145	*Pseudovermilia fuscostriata*	x	
23	*Aphelochaeta multifilis* *	NR		146	*Pseudovermilia multispinosa*	x	
24	*Cirratulus exuberans* *		NR	147	*Salmacina huxleyi* *	NR	
25	*Cirriformia afer* *		NR	148	*Siboglinum sp.*		x
26	*Cirriformia chicoi* *		NR	149	*Sthenelanella uniformis*	x	
27	*Dodecaceria diceria* *		NR	150	*Sphaerephesia similisetis* **	NR	
28	*Dorvillea cerasina* *	NR		151	*Aonidella cirrobranchiata* **	NR	
29	*Dorvillea clavata**	NR		152	*Aonides californiensis* **	NR	
30	*Dorvillea largidentis* *	NR		153	*Aonides paucibranchiata* **		NR
31	*Dorvillea moniloceras**	NR		154	*Dipolydora giardi* **		NR
32	*Dorvillea rubra* *	NR		155	*Dipolydora socialis* **	NR	
33	*Dorvillea sociabilis* *	x		156	*Dispio lenislamellata* **		NR
34	*Parougia batia* **	NR		157	*Lindaspio dibranchiata* **		NR
35	*Eunice brevis* *	NR		158	*Malacoceros cariacoensis* *		NR
36	*Eunice collini* *	NR		159	*Microspio paradoxa* **	NR	
37	*Eunice filamentosa*	x		160	*Polydora ciliata* *	NR	
38	*Eunice fucata* *		NR	161	*Polydora heterochaeta* *	NR	
39	*Eunice gagzoi*	x		162	*Prionospio vermillionensis* *		NR

N°.	Species	CS	CA	No.	Species	CS	CA
40	*Eunice hartmanae* *	NR		163	*Pygospio elegans* **		NR
41	*Eunice hawaiensis*	x		164	*Rhynchospio harrisae* **		NR
42	*Eunice imogena* *	NR		165	*Scolelepis andradei* *		NR
43	*Eunice kinbergi*		x	166	*Xandaros acanthodes* **		NR
44	*Eunice lanai**	NR		167	*Amblyosyllis lineata* *	NR	
45	*Eunice pulvinopalpata* *	NR		168	*Amblyosyllis madereinsis* *		NR
46	*Eunice rubrivittata* *	NR		169	*Branchiosyllis diazi*		x
47	*Eunice semisegregata*	x	x	170	*Branchiosyllis exilis* *	NR	
48	*Eunice stigmatura* *	NR		171	*Branchiosyllis pacifica* *	NR	
49	*Eunice tenuis* *	NR		172	*Brania russelli* **	NR	
50	*Eunice vittatopsis* *		NR	173	*Brevicirrosyllis weismanni* **		NR
51	*Leodice antennata*	x		174	*Dentatisyllis carolinae* **	NR	NR
52	*Leodice rubra*		x	175	*Dentatisyllis mangalis* **	NR	NR
53	*Lysidice collaris*	x		176	*Dentatisyllis morrocoyensis* **	NR	
54	*Lysidice ninetta*	x		177	*Dioplosyllis octodentata* **		NR
55	*Lysidice unicornis*	x	x	178	*Eusyllis assimilis* **	NR	
56	*Nicidion angeli* *	NR		179	*Eusyllis blomstrandi***	NR	
57	*Nicidion longula*	x		180	*Eusyllis spiocirrata* **	NR	
58	*Glycera brevicirris* *	NR		181	*Exogone arenosa* **	NR	
59	*Glycera lapidum* *		NR	182	*Exogone dispar* **	NR	
60	*Glycera oxicephala* *	NR		183	*Exogone longicornis* **	NR	
61	*Glycera papillosa* *	NR		184	*Exogone naidinoides* **		NR
62	*Glycera tesselata*	x		185	*Haplosyllides floridiana* **		NR
63	*Goniada teres*	x		186	*Haplosyllis agelas* *	NR	
64	*Hesiocaeca bermudensis* **		NR	187	*Haplosyllis spongicola*	x	
65	*Heteropodarke formalis* **		NR	188	*Inermosyllis curacaoensis*	x	
66	*Leocrates atlanticus* **	NR		189	*Inermosyllis mexicana* *	NR	NR
67	*Leocrates longocirratus* **	NR		190	*Myrianida brevipes* *	NR	
68	*Syllidia armata* **		NR	191	*Nuchalosyllis lamellicornis* **	N	
69	*Syllidia liniata* **	NR		192	*Nudisyllis divaricata* **	NR	
70	*Abyssoninoe hibernica* **	NR		193	*Opisthodonta mitchelli* **	NR	
71	*Abyssoninoe sp.* *		NR	194	*Opisthosyllis arboricola* *		NR
72	*Eranno lagunae* **	NR		195	*Paraehlersia ferrugina* **	NR	
73	*Gallardoneris nonatoi* **	NR		196	*Parapionosyllis floridana* **	NR	
74	*Lumbricalus campoyi conf.* **		NR	197	*Parapionosyllis longicirrata* **	NR	
75	*Lumbrinerides uebelackerae* **		NR	198	*Parapionosyllis uebelackerae* **	NR	
76	Paraninoe brevipes **	NR		199	Parasphaerosyllis indica **	NR	
77	Axiothella somersi **		NR	200	Parexogone exmouthensis **		NR
78	Notoproctus sp. *		NR	201	Parexogone longicirris **		NR
79	Clymenella torquata		x	202	Perkinsyllis spinisetosa **	NR	
80	Euclymene coronata *		NR	203	Plakosyllis brevipes **		NR
81	Euclymene rubrocincta *		NR	204	Prosphaerosyllis sotoi **		NR

N°.	Species	CS	CA	No.	Species	CS	CA
82	*Heteroclymene glabra* **		NR	205	*Pseudosyllis brevipennis* **	NR	NR
83	*Isocirrus reticulatus* **		NR	206	*Salvatoria euritmica* **	NR	NR
84	*Maldane sarsi*	x		207	*Salvatoria vieitezi* **		NR
85	*Maldanella fibrillata* **		NR	208	*Syllides bansei* **	NR	
86	*Aglaophamus foliosa* *	NR		209	*Syllides fulvus* **	NR	NR
87	*Alitta succinea*		x	210	*Syllis adamantea* *		NR
88	*Ceratonereis mirabilis*	x	x	211	*Syllis castroviejoi* *	NR	NR
89	*Leonnates decipiens* **	NR		212	*Syllis fasciata*		x
90	*Micronereis piccola* **	NR		213	*Syllis gracilis*		x
91	*Neanthes acuminata*	x	x	214	*Syllis hyalina*	x	
92	*Neanthes unifasciata* *	NR		215	*Syllis pectinans* *		NR
93	*Nereis casoae* *	NR		216	*Syllis truncata* *	NR	NR
94	*Nereis sp.*		x	217	*Syllis vivipara* *	NR	
95	*Platynereis dumerilii*	x	x	218	*Trypanedenta gemmipara*	x	x
96	*Arabella mutans*	x		219	*Trypanosyllis vittigera*	x	
97	*Diopatra cuprea*		x	220	*Trypanosyllis inglei* *	NR	
98	*Diopatra papillata* *	NR		221	*Trypanosyllis parvidentata*	x	x
99	*Hyalinoecia bermudensis* *		NR	222	*Xenosyllis scabra* **	NR	
100	*Mooreonuphis elsiae* **	NR		223	*Eupolymnia magnifica*		x
101	*Mooreonuphis nebulosa* **		NR	224	*Loimia medusa*		x
102	*Nothria occidentalis* *		NR	225	*Paraxionice artifex* **	NR	
103	*Onuphis elegans* *	NR		226	*Pista palmata*	x	
104	*Rhamphobrachium agassizi* **		NR	227	*Polycirrus holthei* *	NR	
105	*Armandia agilis*		x	228	*Polycirrus purpureus conf.* *	x	x
106	*Ophelia limacina***		NR	229	*Streblosoma hartmanae*	x	
107	*Ophelina abranchiata* *		NR	230	*Thelepus setosus*	x	
108	*Ophelina acuminata* *	NR	NR	231	*Thelepus verrilli* *	NR	
109	*Ophelina alata**		NR				
110	*Ophelina cylindricaudata**	NR					
111	*Ophelina hachaensis*		x				
112	*Polyophthalmus pictus*	x	x				
113	*Hypereteone lactea**	NR					
114	*Nereiphylla fragilis*	x					
115	*Paranaitis speciosa* **	NR					
116	*Cabira incerta* *	NR					
117	*Litocorsa acuminata* *	NR					
118	*Litocorsa antennata* *	NR					
119	*Antinoe uschakovi* **	NR					
120	*Chaetacanthus pilosus*	X					
121	*Eunoe eura* **	NR					
122	*Harmothoe crucis*	x					
123	*Hermenia verruculosa* **	NR					

The results of the expeditions revealed a similar abundance of families, genera and species of polychaetes between both areas of the SBR. In CS, 20 families, 83 genera, and 150 species were recorded, while in the CA, 27 families, 90 genera, and 103 species were identified. (Fig. 2).

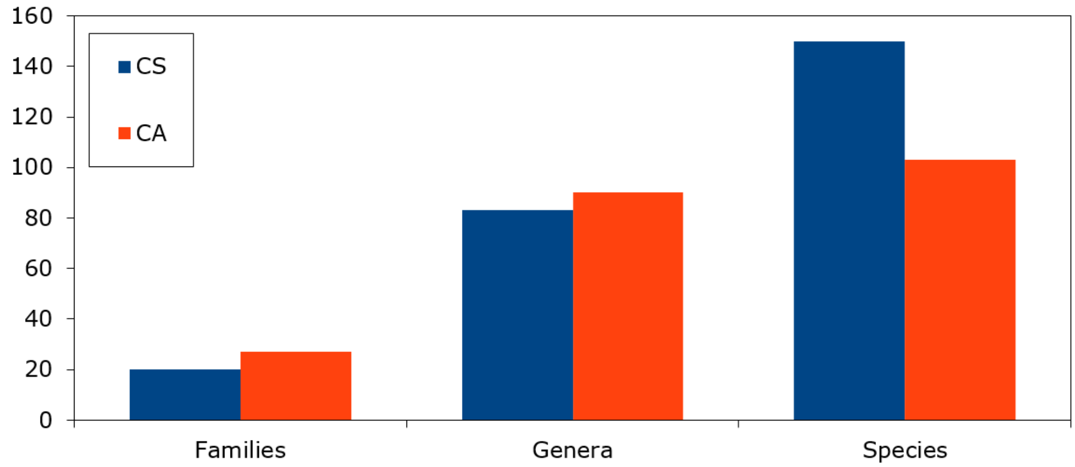

Figure 2. Number of records of polychaetes found in Seaflower expeditions in Serranilla Bank and Southwest Cays.

Regarding the polychaete families, the highest number of species recorded for both cays was provided by the Syllidae family (56 species), followed by the families Eunicidae (23 species), Spionidae (16 species) and Sabellidae (15 species). The remaining families obtained a smaller number of records (n= <10) (Fig. 3).

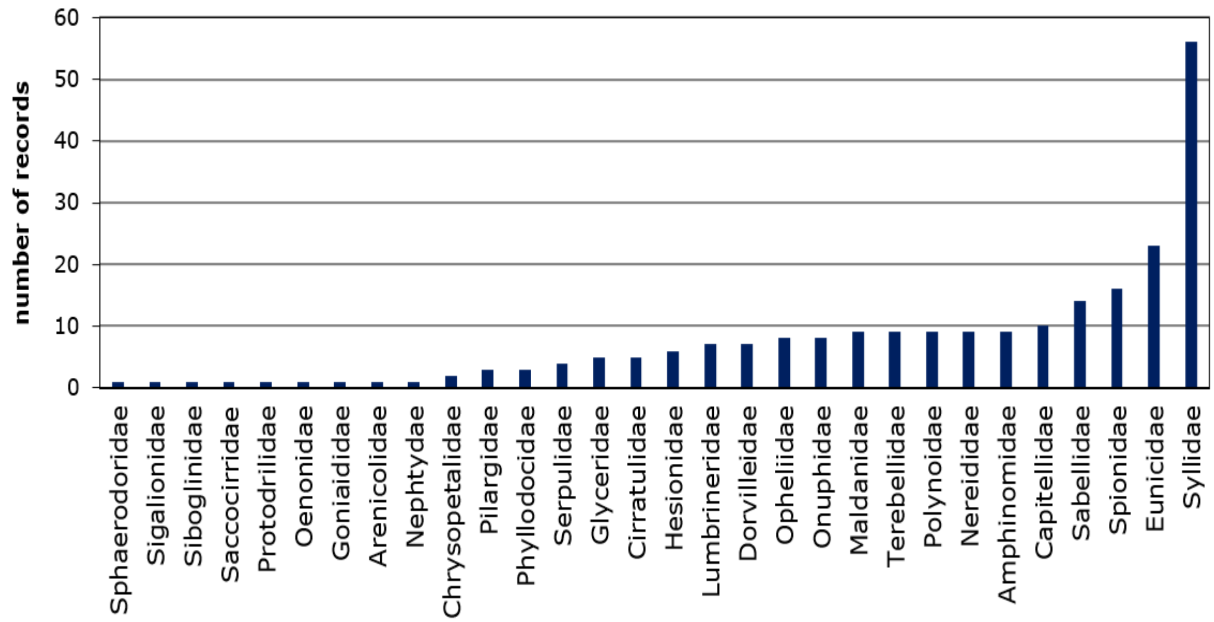

Figure 3. Number of records by families of polychaetes found in the Seaflower expeditions in Serranilla Bank and Southwest Cays.

A total of 86 new records of genera and species were reported for the Colombian Caribbean (representing 37.2% of the total found in the expeditions) which were distributed among the families Arenicolidae, Capitellidae, Chrysopetalidae, Dorvilleidae, Hesionidae, Lumbrineridae, Maldanidae, Nereididae, Onuphidae, Opheliidae, Phyllodocidae, Polynoidae, Protodrilidae, Sabellidae, Saccocirridae, Sphaerodoridae, Spionidae, Syllidae and Terebellidae, some of these species are illustrated in Figures 4 and 5.

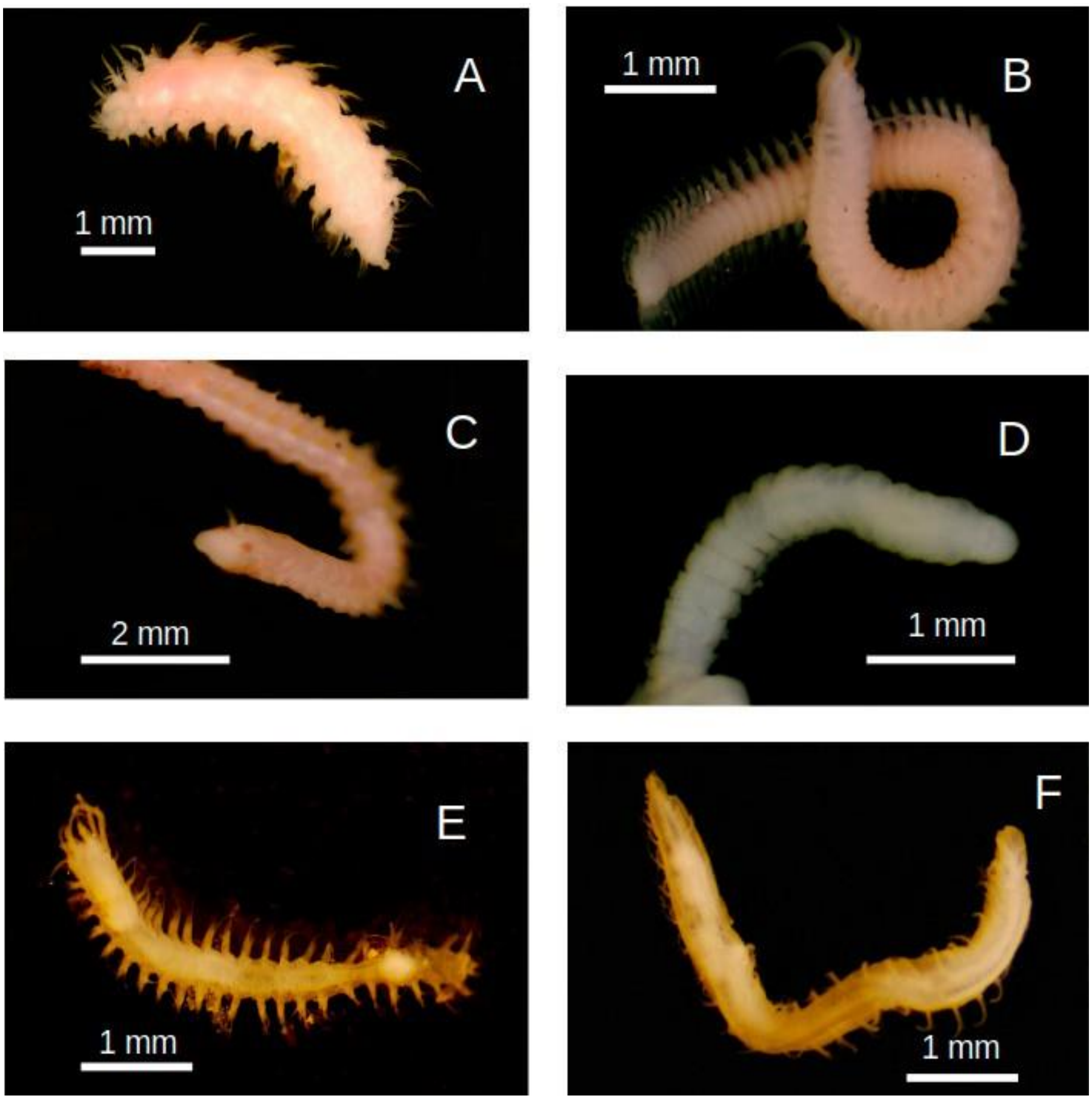

Figure 4. A) Amphinomidae, *Eurythoe complanata*; **B)** Dorvilleidae, *Dorvillea sociabilis*; **C)** Eunicidae, *Lysidice collaris*; **D)** Lumbrineridae, *Lumbrinereis nonatoi*; **E)** Nereididae, *Platinereis dumerilii*; **F)** Opheliidae, *Ophelina cylindrica*.

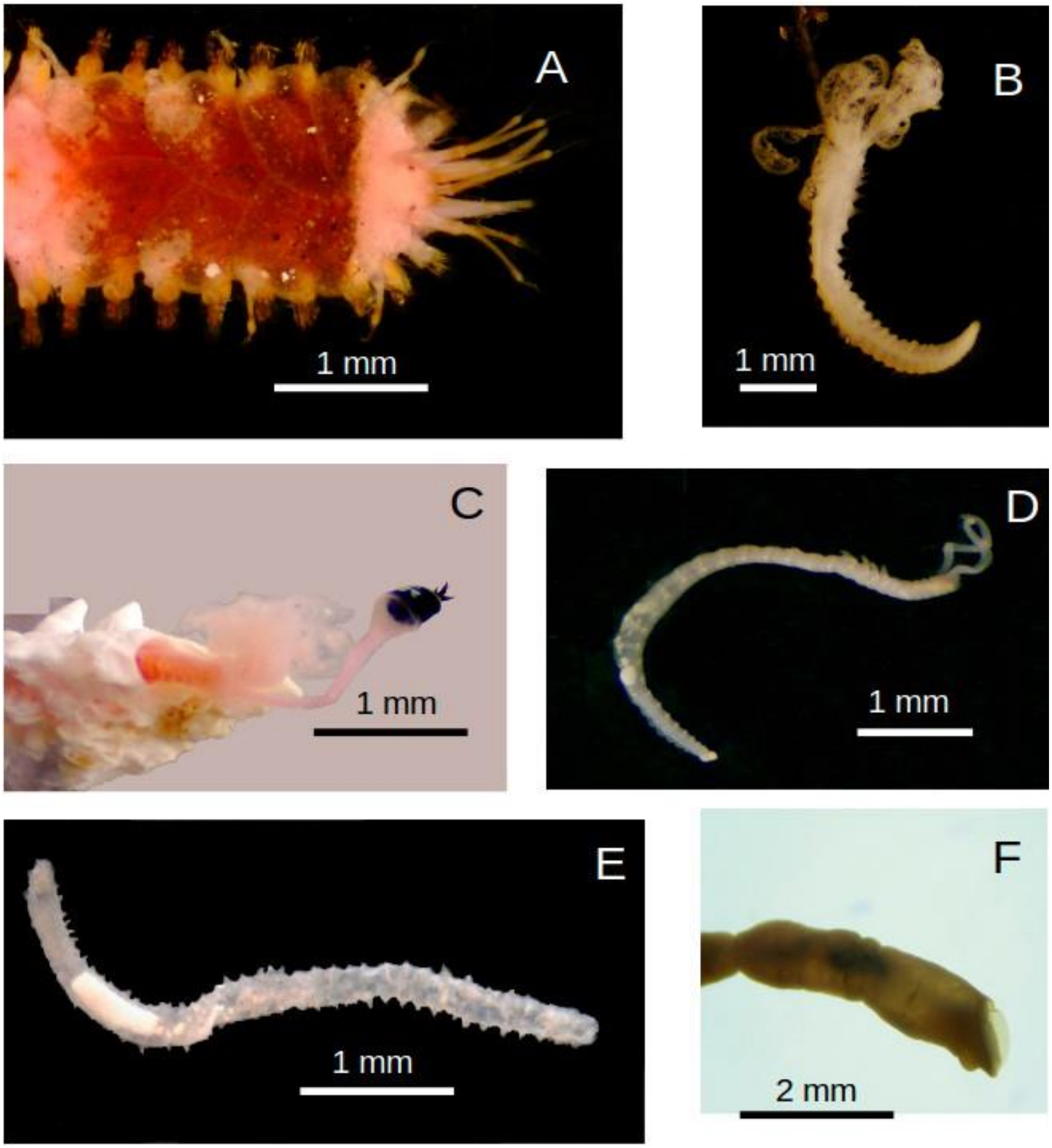

Figure 5. A) Polynoidae, *Eunoe eura*; **B)** Sabellidae, *Branchiomma curtum*; **C)** Serpulidae, *Pseudovermilia multispinosa*; **D)** Spionidae, *Polydora ciliata*; **E)** Syllidae, *Haplosyllis spongicola*; **F)** Maldanidae, *Maldane sarsi*.

Discussion

Londoño-Mesa *et al.* (2016) recorded 49 families, 66 genera and 131 species of polychaetes (Annelida) for the SBR, mostly from the sectors of the islands of San Andres, Old Providence and Ketlina, where the largest number of investigations have been generated. Coneo-Gómez et al. (2022) recorded 51 families, 230 genera and 297 species for the Colombian Caribbean. The present study contributes with 86 genera and 172 species to these records, demonstrating the significant value of scientific expeditions in remote island coral ecosystems such as those of the SBR.

The three families with the highest number of species (Syllidae, Eunicidae and Spionidae) have a wide global distribution, with presence in all types of substrates. In the case of the Syllidae, due to their minute size ensures their dominance within benthic communities, where they are able to colonise a wide variety of soft and hard substrates, including sand, rocks, live and dead corals, macroalgae and seagrasses, among others. (De León-González *et al.,* 2021).

On the other hand, for the families Arenicolidae, Goniadidae, Nephtydae, Oenonidae, Protodrilidae, Saccocirridae, Siboglinidae, Sigalionidae and Sphaerodoridae, only a single specimen was collected for each, supporting the trend observed in highly diverse ecosystems where species richness tends to be higher than organism abundance.

Conclusions

The high richness of polychaetes present in the SBR is largely due to the fact that the SBR is an area recognized as a biodiversity hot spot, characterized by low levels of anthropogenic disturbance and restricted access, in contrast to more heavily impacted continental coastal areas.

A total of 30 families, 152 genera and 226 species were recorded during both expeditions, of which 8 families, 18 genera and 20 species are present in both study areas; 86 genera and 172 species represent new records for the Colombian Caribbean.

A significant contribution was made to the list of marine benthic polychaete species for the SBR in two areas that had not been previously considered for the study of these invertebrates such as Southwest Cays and Serranilla Bank.

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Authors' contribution

Conceptualization: N.H.C.; methodology: N.H.C. and A.D.L.; analysis: N.H.C., A.D.L., and P.R.D.; research: N.H.C., A.D.L., and P.R.D.; resources: N.H.C.; data curation: P.R.D.; drafting and preparation of the original draft: P.R.D.; writing, revision and editing: P.R.D., N.H.C. and A.D.L.; project management: N.H.C.; fundraising: N.H.C. All authors have read and accepted the published version of the manuscript.

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RESEARCH ARTICLE

Contribución al conocimiento de la riqueza de fitoplancton en la isla Cayos de Serranilla, Reserva de la Biósfera Seaflower, Caribe Colombiano

Contribution to the knowledge of phytoplankton richness in Serranilla Bank, Seaflower Biosphere Reserve, Colombian Caribbean

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ABSTRACT

The Archipelago of San Andrés, Providencia y Santa Catalina, declared Seaflower Biosphere Reserve in 2000, has a marine extension of about 300,000 km^2 in the Caribbean Sea. In its northernmost part, there is Serranilla Bank, an ancient atoll formed by small, emerged cays and a marine extension of about 1,200 km^2, 400 km north of San Andres Island. Most of its marine extension includes deep water, but there is a shallow platform on the southwestern part of the bank. Due to its isolation and its distance to the closest inhabited islands of the Archipelago (San Andres and Old Providence islands), it is one of the least studied regions of the Reserve. In September 2017, the Colombian Ocean Commission (CCO) organized a scientific expedition to Serranilla, to start studying its biodiversity and the ecological processes governing its ecosystems. Among the goals of the expedition, there was the characterization of the phytoplankton community in shallow water. Samples were taken with a phytoplankton net with a mesh size of 27 mm. The samples were taken vertically, from the bottom to the surface of the water at 13 sampling points. Water samples were preserved in transeau solution and observed at optical inverted microscope after sedimentation. A total of 28 genera of diatoms and 8 genera of dinoflagellates were identified. Among the species observed in most samples there are Bleakeleya notata, Nitzschia longissima, Striatella unipunctata, Podolampas palmiper and Tripos teres.

KEYWORDS: Phytoplankton, richness, diatoms, Serranilla Bank, Seaflower Biosphere Reserve.

RESUMEN

El Archipiélago de San Andrés, Providencia y Santa Catalina, declarado Reserva de Biósfera Seaflower en el año 2000, tiene una extensión marina de unos 300.000 km^2 en el mar Caribe. En su parte más septentrional, se encuentra el Cayo Serranilla, un antiguo atolón formado por pequeños cayos emergidos y una extensión marina de unos 1.200 km^2, 400 km al norte de la isla de San Andrés. La mayor parte de su extensión marina incluye aguas profundas, pero hay una plataforma somera en la parte suroccidental del cayo. Debido a su aislamiento y a su distancia de las islas habitadas más

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cercanas del Archipiélago (islas de San Andrés y Providencia), es una de las regiones menos estudiadas de la Reserva. En septiembre de 2017, la Comisión Colombiana del Océano (CCO) organizó una expedición científica a la isla Cayos de Serranilla, para comenzar a estudiar su biodiversidad y los procesos ecológicos que rigen sus ecosistemas. Entre los objetivos de la expedición, se encontraba la caracterización de la comunidad de fitoplancton en aguas poco profundas. Las muestras se tomaron verticalmente con una red de fitoplancton con un tamaño de malla de 27 mm, desde el fondo hasta la superficie del agua, en 13 puntos de muestreo. Las muestras de agua fueron preservadas en una solución Transeau y se observaron en un microscopio óptico invertido después de la sedimentación. Se identificaron un total de 28 géneros de diatomeas y 8 géneros de dinoflagelados. Entre las especies observadas se reportan Bleakeleya notata, Nitzschia longissima, Striatella unipunctata, Podolampas palmiper y Tripos teres.

Palabras clave: Fitoplancton, riqueza, diatomeas, isla Cayos de Serranilla, Reserva de la Biósfera Seaflower

Introducción

El mar Caribe es el mar adyacente más grande del océano Atlántico. Está delimitado por la costa de Centroamérica al oeste, la costa norte de Colombia y Venezuela al sur, la península de Yucatán al norte y el arco antillano al norte y al este. El área está dividida en nueve ecoprovincias (Spalding *et al.,* 2007). El mar Caribe es considerado una cuenca oligotrófica con evidencia de limitación de nitrógeno para los sistemas planctónicos (Margalef, 1969; Corredor, Howarth, Twilley y Morell, 1999).

La cuenca está influenciada por la descarga de los ríos Orinoco y Amazonas, en el Caribe oriental, y el río Magdalena en la porción sur (Sheng y Tang, 2003). Además, el afloramiento local a lo largo de la costa de Venezuela y Colombia contribuye estacionalmente al aporte de nutrientes a los ambientes costeros (Rodríguez y Cróquer, 2008; Eidens, Bayraktarov, Pizarro, Wilke y Wild, 2012). A través de los penachos fluviales y la escorrentía de los ríos, los sedimentos y los nutrientes han ingresado históricamente a la cuenca del Caribe, pero el aumento de las cargas desde principios de la década de 1980 continúa impactando los ecosistemas costeros (Restrepo, Zapata, Díaz, Garzón-Ferreira y García*,* 2006). La industrialización, la agricultura intensiva y la deforestación han llevado a un aumento en el aporte de nutrientes (Heileman, 2007), que llegan a los ecosistemas costeros. Por lo tanto, partes de la cuenca están experimentando eutrofización, especialmente las cercanas a la costa. Lejos de la costa y de los vertidos industriales, el agua sigue siendo considerada oligotrófica.

El mar Caribe alberga alrededor de 15 de los 425 atolones que hay en todo el mundo (Díaz, Sánchez, Zea y Garzón-Ferreira, 1996). La mayoría de ellos están relativamente cerca de la costa (por ejemplo, Los Roques, en Venezuela, a unos 130 km de tierra firme; Glover's Reef en Belice, a unos 45 km de la costa). El Archipiélago de San Andrés, Providencia y Santa Catalina incluye algunos atolones oceánicos, que están lejos de las tres islas habitadas del archipiélago y aislados de la costa continental. Entre estos atolones, en la parte más septentrional del archipiélago, se encuentra Cayo Serranilla, que está aproximadamente a 325 km al noreste de Providencia y a 280 km al suroeste de Jamaica. Este atolón, junto con los bajos Nuevo y Alicia, que también son parte del archipiélago, son los atolones más aislados del mar Caribe. En esta zona, ni los penachos de los ríos Orinoco, Amazonas o Magdalena tienen impacto sobre el agua, ni los vertidos industriales o agrícolas, como tampoco los asentamientos humanos cercanos influyen directamente en su concentración de nutrientes (Beier, Bernal, Ruiz-Ochoa y Barton*,* 2017).

Debido a su distancia de la costa continental colombiana, y también de otras islas habitadas del archipiélago, Serranilla ha recibido muy poca atención desde el punto de vista científico, por lo tanto, es una de las zonas menos conocidas del mar Caribe. En 2009, CORALINA organizó una expedición a los bajos Serranilla, Alicia y Nuevo para determinar la variabilidad genética del gasterópodo *Aliger gigas* L. 1758, una importante especie comercial. En 2010, CORALINA y el Gobierno local organizaron otra expedición a la misma zona con el objetivo de caracterizar por primera vez los ensambles bentónicos (cobertura de corales y macroalgas, presencia de enfermedades coralinas) y la comunidad de peces (Abril-Howard, Orozco-Toro, Bolaños-Cubillos y Bent-Hooker, 2012; Bolaños-Cubillos, Abril-Howard, Bent-Hooker, Caldas y Acero, *2015*). En 2011, INVEMAR organizó una nueva expedición a las mismas localidades para caracterizar los hábitats marinos (Vega-Sequeda, Díaz-Sánchez, Gómez-Campo, López-Londoño, Díaz-Ruíz & Gómez-López, 2015), incluyendo la comunidad planctónica (Gutiérrez-Salcedo, Cabarcas-Mier & Suárez-Mozo, 2015). En 2017, la Comisión Colombiana del Océano, con la colaboración de Dimar, Colciencias, la Armada de Colombia y el CIOH, organizó la Expedición Científica *Seaflower* 2017 a Serranilla, para estudiar diferentes aspectos de los hábitats marinos del atolón, como los ensambles de peces asociados al arrecife coralino, la riqueza de macroalgas en ambientes bentónicos y la estimación de los servicios ecosistémicos del arrecife coralino de Serranilla.

Uno de los principales componentes biológicos del medio pelágico es el plancton, que está formado por organismos autótrofos (fitoplancton) y heterótrofos (zooplancton). El plancton es importante porque regula los flujos de energía a lo largo de las redes tróficas en el medio ambiente pelágico y también en los ecosistemas costeros (Gutiérrez-Salcedo *et al.,* 2015).

Durante la Expedición Científica Seaflower 2017, se recolectaron algunas muestras de redes fitoplánctonas para contribuir al conocimiento de este grupo en esta remota zona del mar Caribe.

Materiales y métodos

La isla Cayos Serranilla es un antiguo atolón situado entre las coordenadas 15°47'-52'N y 79°45'-80°03'O (Fig. 1). Forma parte del Área de Régimen Conjunto Jamaica-Colombia, creada a través del tratado Sanín-Robertson en 1993. En el año 2000, todo el archipiélago fue declarado Reserva de la Biósfera por la UNESCO, y Serranilla fue incluida en la Reserva. Tiene 40 km de largo y 32 km de ancho. Tiene una superficie aproximada de 1.100 km^2 y se caracteriza por una plataforma de carbonato, que se encuentra casi en su totalidad en aguas profundas. Pequeñas islas emergen del agua, siendo Cayo Beacon la más grande. En este lugar, hay un faro y un puesto permanente del Ejército colombiano para garantizar la soberanía territorial. El arrecife de coral tiene unos 23 km de largo y está fraccionado por pequeños canales, que pueden experimentar turbulencias y fuertes corrientes (Abril-Howard *et al.,* 2012).

Las corrientes oceánicas superficiales alrededor de Serranilla están dominadas por la corriente del Caribe. Durante la estación seca (diciembre-abril), la corriente fluye hacia el oeste, mientras que en la estación húmeda (agosto-noviembre) su dirección es más variable. El período comprendido entre los meses de mayo y julio es una estación de transición entre seca y húmeda, con precipitaciones ocasionales. La temperatura es relativamente uniforme durante todo el año, con una temperatura media anual del aire de 26,7ºC. Los vientos soplan principalmente en dirección este-noreste con velocidades medias mensuales que oscilan entre 3,2 y 6,2 m/s (Edit y Andrade, 2011).

El muestreo se llevó a cabo entre el 7 y el 14 de septiembre de 2017 en 13 sitios (Tabla 1) con una red planctónica de 27 mm de tamaño de malla en un perfil vertical.

Tabla 1. Estación de muestreo con coordenadas y profundidad máxima.

Sitio de muestreo	Coordenadas		Fecha	Profundidad máxima (m)
1	N 15°48'12.0"	W 79°50'13.8"	07/IX/17	11
2	N 15°48'12.0"	W 79°50'34.7"	07/IX/17	5
3	N 15°49'27.0"	W 79°51'05.6"	08/IX/17	9
4	N 15°49'21.6"	W 79°50'53.0"	08/IX/17	4
5	N 15°49'54.8"	W 79°52'27.9"	09/IX/17	10
6	N 15°49'03.2"	W 79°52'42.4"	09/IX/17	3
7	N 15°48'02.7"	W 79°51'05.0"	10/IX/17	9
8	N 15°55'57.6"	W 79°49'16.4"	11/IX/17	3
9	N 15°53'02.5"	W 79°47'13.7"	11/IX/17	12
10	N 15°48'32.8"	W 79°50'27.8"	12/IX/17	8
11	N15°48'09.3"	W 79°50'55.5"	12/IX/17	10
12	N15°48'09.4"	W 79°50'25.6"	13/IX/17	7
13	N15°52'25.0"	W 79°46'12.2"	14/IX/17	8

Las muestras de agua se conservaron en botellas de plástico opacas; se añadió una solución de etanol y formol hasta una concentración final equivalente a la solución de Transeau (concentración de agua de mar, etanol y formol 6:3:1 respectivamente). Las muestras de agua se analizaron en laboratorio con el método de Utermöhl (Edler & Elbrächter, 2010): la muestra se homogeneizó, luego se sedimentaron 25 ml durante 24 horas y posteriormente se observaron en un microscopio de luz invertida con fase de contraste, Advanced Optical XD-202, con una cámara Micrometrics S18.CU. Los aumentos utilizados fueron de 20x y 40x.

Las algas en las muestras se identificaron al nivel taxonómico más bajo posible utilizando literatura específica (Cleve, 1878; Madera, 1968; Balech, 1988; Tomás, 1997; Okolodkov, 2010). La información sobre nomenclatura y clasificación taxonómica se obtuvo de AlgaeBase (Guiry & Guiry, 2024).

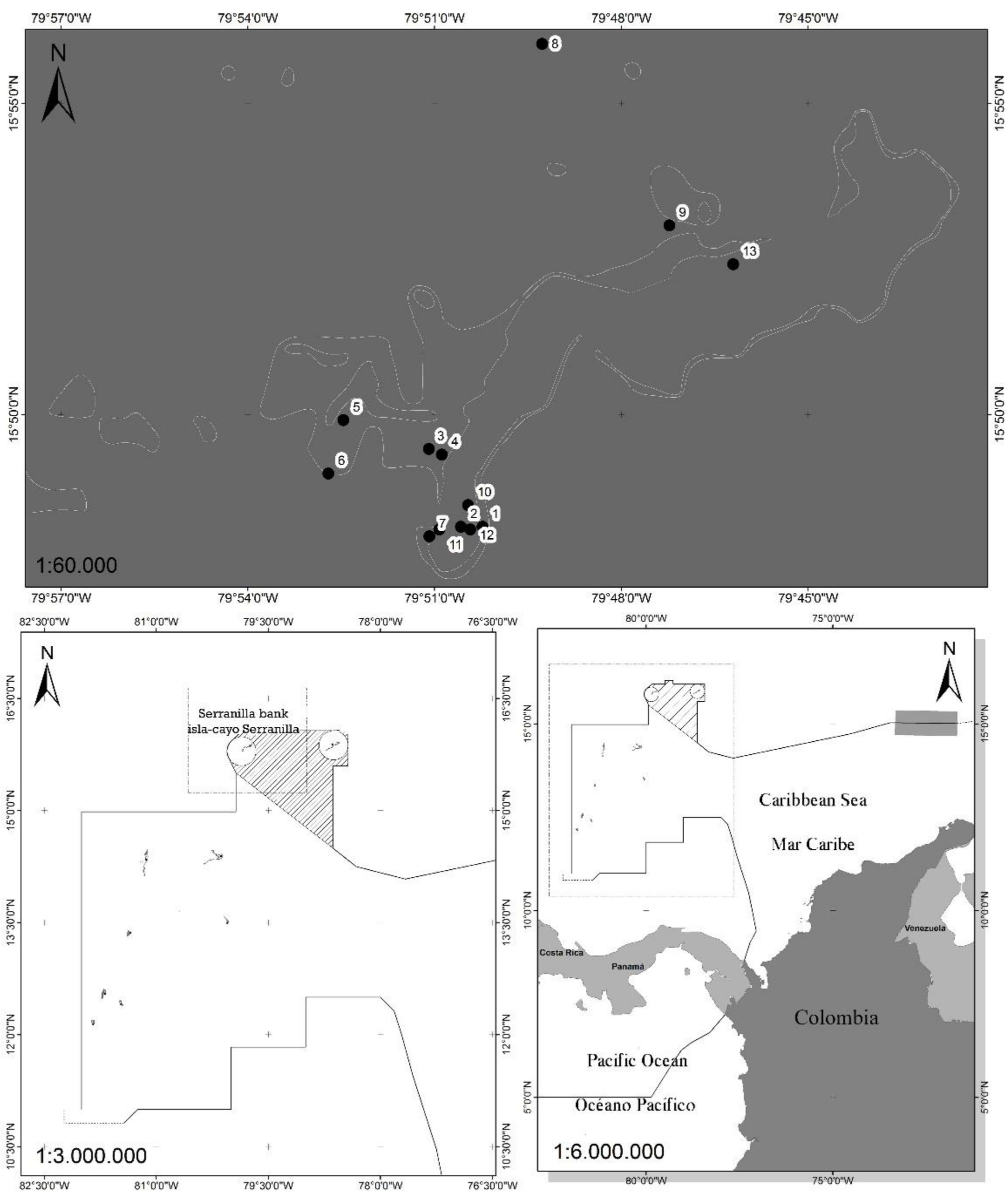

Figura 1. Ubicación de isla Cayos de Serranilla en el mar Caribe y ubicación del sitio de muestreo.

Resultados

Se identificaron veintiocho géneros y veintidós especies de diatomeas, así como ocho géneros y quince especies de dinoflagelados (Tabla 2).

Tabla 2. Listado de especies y estación donde fueron observadas.

Tasa	Sitio de muestra												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Bacillariophyceae													
Amphiprora sp.										X			
Amphora sp.								X					
Asterolampra marylandica Ehrenberg 1844						X		X					
Bacillaria paxillifera (O. F. Müller) T. Marsson 1901										X			
Bacteriastrum sp.									X				X
Bleakeleya notata (Grunow) Round 1990		X	X	X	X			X	X		X		
Chaetoceros atlanticus Cleve 1873			X	X								X	X
Chaetoceros curvisetus Cleve 1889													X
Chaetoceros pendulus Karsten 1905										X			
Climacosphenia moniligera Ehrenberg 1843										X			
*Cylindrotheca closterium (*Ehr.) Reimann & J.C. Lewin 1964									X		X		X
Eucampia zodiacus f. *cylindricornis* Syvertsen 1983										X			
Grammatophora serpentina Ehrenberg 1844		X							X				
Guinardia striata (Stolterfoth) Hasle 1996			X		X								
Hemiaulus hauckii Grunow ex Van Heurck 1882					X			X					
Isthmia enervis Ehrenberg 1838	X						X			X			
Licmophora sp.	X	X	X	X	X	X	X	X	X	X	X	X	
Mastogloia rostrata (Wallich) Hustedt 1933 - Brasil									X				
Navicula sp.										X			
Nitzschia longissima (Brébisson ex Kützing) Grunow 1862	X	X	X	X	X	X			X	X	X		
Nitzschia sigma (Kützing) W.Smith 1853		X											
Indeterminate pennate diatoms	X	X	X	X	X	X	X	X		X	X	X	X
Pleurosigma sp.		X						X					
Proboscia alata (Brightwell) Sundström 1986	X		X					X	X				
Pseudo-nitzschia complejo delicado			X	X									
Rhabdonema adriaticum Kützing 1844					X								
Rhizosolenia sp.			X			X			X				
Striatella sp.												X	

Tasa	Sitio de muestra												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Striatella unipunctata (Lyngbye) C.Agardh 1832		X		X	X	X		X	X		X	X	X
Synedra sp.		X											
Thalassionema nitzschioides (Grunow) Mereschkowsky 1902	X	X	X	X			X		X				
Thalassiophysa hyalina (Greville) Paddock & P.A.Sims 1981			X	X	X				X	X		X	
Toxarium undulatum Bailey 1854				X	X			X	X		X		
Dinophyceae													
Ceratocorys horrida Stein 1883						X		X					
Acanthodinium caryophyllum Kofoid 1907						X							
Dinoflagelados tecate indeterminados					X			X	X	X			X
Ornithocercus steinii Schütt 1900							X						
Phalacroma rotundatum (Claparéde & Lachmann) Kofoid & J. R. Michener 1911												X	
Podolampas palmipes F. Stein 1883	X			X			X		X	X			X
Podolampas spinifer Okamura 1912					X								
Prorocentrum micans Ehrenberg 1834									X				
Protoperidinium cf. *pellucidum* Bergh 1882				X									
Tripos cf. *minutus* (Jörgensen) F. Gómez 2013	X												
Tripos gracilis (Pavillard) F. Gómez 2013											X		
Tripos macroceros (Ehrenberg) Hallegraeff & Huisman 2020	X	X	X										
Tripos muelleri Bory 1826	X					X			X				
Tripos pentagonus (Gourret) F. Gómez 2021													X
Tripos setaceus (Jørgensen) F. Gómez 2013						X							
Tripos sp.	X				X	X	X	X	X		X	X	
Tripos teres (Kofoid) F. Gómez 2013	X	X		X		X		X		X	X	X	

En cuanto a las diatomeas, las especies más comunes observadas fueron *Nitzschia longissima,* presentes en nueve de los trece sitios, y *Thalassionema nitzschioides*, encontrada en seis sitios. Las especies menos comunes fueron *Chaetoceros curvisetus*, *Chaetoceros pendulus* y *Eucampia zodiacus* f. *Cylindricornis.* Además, observamos algunas especies bentónicas: *Striatella unipunctata*, *Grammatophora serpentina, Bacillaria paxillifera*, *Climacosphenia moniligera*, *Mastogloia rostrata*, *Nitzschia sigma*, *Rhabdonema adriaticum*, *Amphora* sp., *Amphiprora* sp., *Licmophora* sp. y *Synedra* sp. En cuanto a los dinoflagelados, las especies más comunes fueron *Tripos teres* (ocho sitios) y *Podolampas palmipes* (seis sitios).

Las diatomeas céntricas son el 24%, las diatomeas pennadas son el 42%, que suman el 66% de las diatomeas totales. Los dinoflagelados, a su vez, representan el 34% de las especies catalogadas.

Entre las especies potencialmente toxicogénicas, encontramos la diatomea *Pseudo-nitzschia delicatissima*, que produce ácido domoico (causante de intoxicación amnésica por mariscos) y *Phalacroma rotundatum* (ácido okadaico y/o dinofisistoxina -2 y/o pectenotoxina-2), aunque existe controversia sobre su naturaleza toxigénica (Zingone y Larsen, 2011).

Once de las veintidós especies de diatomeas encontradas son nuevos registros para Serranilla (Tabla 2); *Mastogloia rostrata* es un nuevo registro para el país (Fig. 2); y *Grammatophora serpentina* para el mar Caribe (Fig. 2). Trece de las quince especies de dinoflagelados son nuevos registros para Serranilla; *Tripos minutus* y *Podolampas spinifer* son nuevos registros para el país (Fig. 2), mientras que *Phalacroma rotundatum* es un nuevo registro para el Caribe, pero ha sido reportado previamente para el Golfo de México. Además, *Cladopyxis caryophyllum* (Fig. 2) se reporta por primera vez en el mar Caribe.

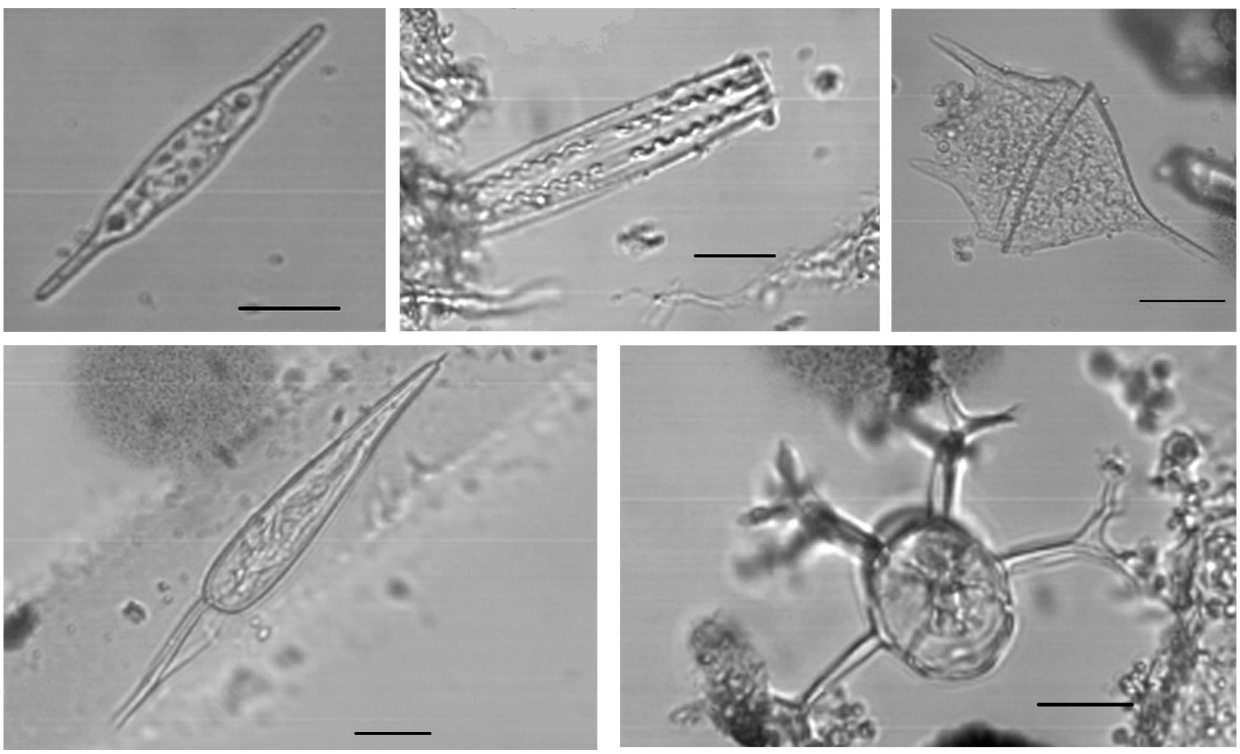

Figura 2. Arriba a la izquierda. *Mastogloia rostrata.* Arriba en el centro. *Grammatophora serpentina.* Arriba a la derecha. *Tripos minutus*. Abajo a la izquierda. P*odolampas spinifer.* Abajo a la derecha. *Cladopyxis caryophyllum*. Barras de escala: 20 mm.

Discusión

En Colombia no hay muchos estudios publicados sobre la diversidad del fitoplancton marino (Vidal y Carbonell, 1977; Carbonell, 1979a; 1979b; 1982; Vidal, 1981; Fernández y García, 1998; De la Hoz Aristizábal, 2004; Ramírez-Barón, Franco-Herrera, García-Hoyos y López, 2010). Lozano-Duque, Vidal y Navas (2010, 2011) publicaron una lista de diatomeas (312 especies) y dinoflagelados (169 especies) para el Caribe colombiano; para el archipiélago, reportan 48 taxones de diatomeas y 49 especies de dinoflagelados.

El presente estudio cuenta con 36 géneros y 37 especies de fitoplancton, todas ellas diatomeas o dinoflagelados. Estos valores son típicos de los mares oligotróficos y se acercan a lo reportado para las islas de Providencia, donde Campos-González (2007) encontró 46 géneros en 39 estaciones. A lo largo de la costa continental de Colombia, cerca de Santa Marta, se observaron entre 47 y 51 géneros de especies fitoplanctónicas, según la estacionalidad (Ramírez-Barón *et al.,* 2010).

En Los Roques, Venezuela, que es un atolón que se encuentra a unos 130 km de la costa principal, Cavada-Blanco, Zubillaga y Bastidas (2016) observaron que el 62% de las especies fitoplanctónicas eran diatomeas, seguidas de dinoflagelados (25,4%) y cianobacterias (8%). En nuestro estudio, no se encontraron cianobacterias, pero el porcentaje de diatomeas fue muy similar al estudio mencionado, al igual que la porción de dinoflagelados. Gutiérrez-Salcedo *et al.* (2015) reportaron 138 especies de fitoplancton para toda el Área de Régimen Conjunto, que abarca los bajos de Serranilla, Alicia y Bajo Nuevo. Para Serranilla, reportaron 121 especies, que es un número mucho mayor de lo encontrado en el presente trabajo y de lo que se ha reportado para el archipiélago por Lozano-Duque *et al.* (2010, 2011). La razón principal de la discrepancia entre el estudio mencionado y el presente es la metodología utilizada: Gutiérrez-Salcedo *et al.* (2015) utilizaron una malla de 20 µm, que bajaron a una profundidad de 50 m y arrastraron horizontalmente durante 10 minutos. Nuestra red tenía un tamaño de malla ligeramente mayor (27 µm), que se bajó verticalmente hasta el fondo (3-12 m de profundidad) y luego se recuperó. No se obtuvo la concentración de la muestra bajando la red verticalmente. Sin embargo, las especies reportadas tanto por Gutiérrez-Salcedo *et al.* (2015) y este estudio son muy pocas, a saber: *Chaetoceros curvisetum, Hemiaulus hauckii* y *Thalassionema nitzschioides* para las diatomeas; *Ceratocorys horrida* y *Ornithocercus steinii* para los dinoflagelados. Algunas diatomeas comunes identificadas solo para el género en ambos estudios son las siguientes: *Amphora, Bacteriastrum, Navicula, Pleurosigma* y *Rhizosolenia*. Todas las demás especies identificadas en este estudio incrementan la diversidad de fitoplancton en Serranilla. En las aguas oceánicas, los organismos fitoplanctónicos tienden a reducir su tamaño. En Los Roques, Venezuela, la mayoría de las especies de diatomeas identificadas (62% de todas las diatomeas contadas) eran pequeñas (6-10 y 16-20 mm), así como la mayoría de los dinoflagelados (48% del total tenían un tamaño de 16-20 µm) (Cavada-Blanco *et al.,* 2016). El número más bajo de taxones identificados aquí puede deberse al tamaño de la malla, que no capturó organismos pequeños. Hay evidencia de que la respuesta del fitoplancton al cambio climático incluye un cambio hacia tamaños más pequeños (Taylor *et al.,* 2012). Por lo tanto, este factor debe tenerse en cuenta para estudios posteriores. Sin embargo, la falta de información oceanográfica en el área de estudio no permite relacionar la comunidad biológica con su entorno, lo que dificulta su comparación con otros estudios.

Gutiérrez-Salcedo *et al.* (2015) observaron una gran abundancia relativa de los géneros *Chaetoceros*, *Bacteriastrum*, *Pseudonitzschia* y *Leptocylindrus.* Con excepción de este *último*, estos géneros también fueron encontrados en el presente estudio. Los autores sugirieron que la masa de agua alrededor de Serranilla puede presentar condiciones costeras, ya que estos géneros son más típicos de los sistemas costeros. También afirman que podría haber sido traída por la corriente desde el río Magdalena o el Giro Panamá-Colombia (Gutiérrez-Salcedo *et al.,* 2015). Sin embargo, no se ha comprobado que el penacho de agua del río Magdalena alcance los 15 grados de latitud (Cañón-Páez y Santamaría del Ángel, 2003), donde se encuentra Serranilla. Sin embargo, un estudio más reciente mostró una marcada influencia de la descarga de los ríos en la cuenca colombiana al sur de los 12 grados de latitud, y poco o ningún efecto al norte (Beier *et al*., 2017). Es claro que se necesitan estudios oceanográficos en el área para comprender mejor la composición y dinámica del fitoplancton en Cayo Serranilla.

Se observó una diatomea tóxica en las muestras: *Pseudo-nitzschia delicatissima, productora* de ácido domoico, que puede causar la intoxicación amnésica por mariscos. También se identificó una especie de *Prorocentrum*: *P. micans*. Muchos taxones del género están involucrados en la intoxicación por ciguatera y mariscos paralíticos, y se han observado en otros sitios del archipiélago (Rodríguez, Mancera-Pineda, & Gavio, 2010). De acuerdo con Pottier, Vernoux, & Lewis (2001), la ciguatera es endémica del mar Caribe, siendo Florida su límite norte y Martinica su límite sur. Sin embargo, se han observado brotes de ciguatera más al sur, especialmente en la última década (Celis y Mancera-Pineda, 2015), incluyendo la Isla de San Andrés. A pesar de que la toxicidad de *P. micans* es dudosa, Gutiérrez-Salcedo *et al.* (2015) encontraron otras especies del género en la zona que podrían ser tóxicas. Además, *Prorocentrum gracile* y *P. micans*, observados en la región, han estado involucrados en fenómenos de mareas rojas en muchas áreas alrededor del mundo (Alvial y García, 1986; Fukuyo, Sako, Matsuoka, Imai, Takamashi y Watanabe, 2003).

Los dinoflagelados no fotosintéticos, como *Phalacroma rotundatum* (encontrado en este estudio), también se han asociado con la intoxicación diarreica por mariscos (Caroppo, Congestri y Bruno, 1999), y se considera que sintetizan el ácido domoico y sus derivados. Sin embargo, nueva evidencia sugiere que *P. rotundatum* no produce toxinas *de novo,* sino que actúa como vector de sus presas tóxicas a los mariscos (González-Gil, Pizarro, Paz, Velo-Suárez y Reguera*,* 2011). Dado que Cayo Serranilla se utiliza como zona de pesca, tanto legal como ilegalmente (Abril-Howard *et al.,* 2012), se debe llevar a cabo un mayor monitoreo de las especies tóxicas o potencialmente tóxicas para evitar brotes de intoxicación.

Este trabajo está lejos de presentar una lista exhaustiva de especies fitoplanctónicas en Serranilla. Debido a la lejanía de cualquier asentamiento humano, la zona es casi desconocida desde el punto de vista científico. Solo muy recientemente (en los últimos siete años), algunas instituciones colombianas han comenzado a invertir recursos para estudiar esta región de la Reserva de la Biósfera. Se necesitan más estudios para comprender la dinámica que se desarrolla en el atolón más aislado del mar Caribe.

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Contribución de los autores

ER identificó las algas, tomó las fotografías y escribió el manuscrito. BG recogió las muestras, escribió y revisó el manuscrito. TR ayudó con la identificación y revisó el manuscrito.

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RESEARCH ARTICLE

Status of the coral community in three reef complexes of the Seaflower Biosphere Reserve, Colombian Caribbean

Estado de la comunidad coralina en tres complejos arrecifales de la Reserva de la Biosfera Seaflower, Caribe colombiano

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ABSTRACT

Despite the contemporary trends of generalized coral loss, it is presumed, in part from lack of information, that remote oceanic coral reefs must be in a better condition than continental ones, assuming that from their geographic remoteness, direct human pressures have a lower effect. This work was aimed at determining if the coral community of three oceanic atolls of the Seaflower Biosphere Reserve (Alburquerque, Bolívar and Bajo Nuevo) in the southwestern Caribbean, Colombia, have also experienced changes towards new benthic configurations. To estimate benthic cover, coral richness and prevalence of signs associated with diseases, photo quadrat transects were evaluated. To study algal turfs in interaction with live coral tissue, cores were extracted. Only in Bolívar, herbivores were quantified through stationary censuses. Forty-eight coral species were found in these reef complexes, but the benthic cover was dominated by non-reef-building organisms (59.1 - 61.7 %), especially algal turfs. Nine signs associated with seven coral diseases were identified. In the algal turf - coral interactions, 15 groups of turf morpho functional groups were identified. Twenty herbivore species of 5 functional groups were recorded, showing a low functional redundancy in comparison to continental Colombian Caribbean reefs, and thus a high vulnerability to species loss. These results show that the current state of the studied reefs, despite being remote, show changes in dominance from corals to macroalgae, especially turf algae.

KEYWORDS: Coral community, functional groups, algal turfs, herbivores, coral decline, Seaflower

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Resumen

A pesar de las tendencias contemporáneas de pérdida coralina generalizada, se presume, en parte por falta de información, que los arrecifes oceánicos remotos deben estar en mejor estado que los arrecifes continentales, asumiendo que por su lejanía geográfica hay un menor efecto de presiones humanas directas. Este trabajo tuvo como objetivo determinar si la comunidad coralina de tres atolones oceánicos de la Reserva de Biósfera Seaflower (Alburquerque, Bolívar y Bajo Nuevo) en el Caribe Suroccidental, Colombia, están experimentando cambios hacia nuevas configuraciones bentónicas. Para estimar la cobertura bentónica, riqueza coralina y prevalencia de signos asociados con enfermedades se evaluaron transectos con fotocuadrantes. Para estudiar los céspedes algales en interacción con tejido coralino vivo se extrajeron núcleos. Solo en Bolívar se incluyó el estudio de herbívoros mediante censos estacionarios. Se encontraron 48 especies de corales duros en estos complejos arrecifales, pero la cobertura bentónica estuvo dominada por organismos no constructores de arrecifes (59.1-61.7 %), especialmente céspedes algales. Se identificaron nueve signos asociados con siete enfermedades coralinas. En los bordes de interacción coral-césped se identificaron 15 grupos morfofuncionales de céspedes. Se registraron 20 especies herbívoras afines a 5 grupos funcionales, mostrando baja redundancia funcional respecto a arrecifes continentales del Caribe colombiano, y por lo tanto una alta vulnerabilidad ante la pérdida de especies. Estos resultados muestran que el estado actual de los arrecifes estudiados, a pesar de ser lugares remotos, exhiben cambios del dominio de corales hacia macroalgas, especialmente de céspedes.

Palabras claves: *comunidad coralina, grupos funcionales, céspedes, herbívoros, deterioro coralino, Seaflower.*

Introduction

Coral reefs are strategic ecosystems for the well-being of human societies. However, the current climate change scenario, the high rates of degradation documented in recent decades, and their uncertain resilience capacity to respond to disturbances derived from natural and anthropogenic hazards, make them highly sensitive and high-risk ecosystems (Jackson, Donovan, Cramer, & Lam*,* 2014; Bindoff *et al.,* 2019).

The Sixth Report on the State of the World's Corals demonstrated through meta-analyses that ~14% of global coral cover was lost between 2009 and 2018 (Souter, Serge, Wicquart, Logan, Obura, & Staub*,* 2021). Specifically in the Caribbean, the average coral cover loss between 1983 and 2019 was close to 2.1% (a calculation after the large coral loss that occurred in the early 80s), thus favoring the proliferation of macroalgae (> 50%) (Souter, Planes, Wicquart, Logan, Obura, & Staub*,* 2022), especially turf-like algae, which are currently the dominant cover on several reefs (Harris, 2015). This report points out that these changes are the product of the synergy between disturbances that operate at different scales, such as outbreaks of white-banded epizootics (1970-1980) and the loss of hard coral tissue (SCTLD, documented from 2014 to date); the mass mortality of key species such as the herbivorous sea urchin *Diadema antillarum* (1983-1984 and 2022); overfishing; extreme events such as hurricanes and mass bleaching (1998, 2003, 2005, 2006, 2023), and all those human activities linked to unplanned coastal development (Souter *et al.,* 2021).

Despite these trends of coral loss and deterioration, there are still gaps in up-to-date information on the state of ocean reefs, assuming that their geographical remoteness and difficulty for human settlement keep them exempt from the effect of direct human pressures (Brainard *et al.,* 2005). Therefore, these remote reefs are natural laboratories for investigating the effects of global and regional disturbances on the relationships between coral communities and their environment (Perry *et al.,* 2015; Williams, Gove, Eynaud, Zgliczynski, & Sandin*,* 2015).

The Seaflower Biosphere Reserve (RB) (12°-16°N and 78°-82°W) is home to 76.5% of the coral areas of the Colombian Caribbean (Díaz *et al.,* 2000). However, due to their large area (180,000 km^2), most research efforts have focused on the islands of San Andres and Old Providence (Taylor, Howard, & Baine, 2011). For this reason, since 2014, the Colombian Ocean Commission (CCO) has carried out ten scientific expeditions to generate knowledge about the RB Seaflower and demonstrate its relevance to humanity (https:// pnec.cco.gov.co/seaflower/) on a scientific basis.

Within this research platform, the Colombian Marine Fauna: Biodiversity and Uses research group, of the Institute of Studies in Marine Sciences (CECIMAR) of the Universidad Nacional de Colombia – Sede Caribe, participated in three expeditions (Alburquerque: 2018; Bajo Nuevo: 2021, and Bolívar: 2022) with the project 'Coral-algal turf interaction and its effect on reef communities in the Seaflower Biosphere Reserve'. This was made in order to collect information that allows us to advance in the understanding of the mechanisms that drive changes in reefs and their consequences, to take a glimpse into how current reef communities experience changes towards new benthic configurations that drive the proliferation of non-reef-building organisms, as well as to identify the role of coral-turf interactions in these trajectories.

Study Area

The Seaflower Biosphere Reserve, declared by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2000, has high rates of diversity and endemism of species (Acero and Garzón-Ferreira, 1994), and in 2005 the Ministry of Environment, Housing and Territorial Development of Colombia recognized it as a marine protected area (MPA) (Coralina, 2011). Seaflower is the largest MPA in the Caribbean and the second largest in Latin America (Guarderas, Hacker, & Lubchenco, 2008). It is made up of seven atolls (Alburquerque or Southwest, Bolívar or Courtown, Quitasueño, Serrana, Roncador, Serranilla and Bajo Nuevo), two inhabited islands (San Andres and Old Providence and Ketlina) and one shallow reef (Alice Shoal) (Córdoba and López, 1997).

At Seaflower, reef complexes are a series of isolated structures, aligned in a NE direction along the southern flank of Nicaragua's elevation (Díaz *et al.,* 2000). They are the result of volcanic activity during the early Cenozoic geological period, basement subsidence between the Cenozoic-Quaternary periods, and the accumulation of reef limestone on shallow tops (Díaz, 2005).

Throughout the year, the migration from the intertropical convergence zone (ICZ) determines the seasonal nature of the region's climate, which is relatively dry and follows the typical seasonality of the Western Caribbean; with a dry season with winds from the NE between December and March; a transitional season between April and August, and a rainy season from September to November (Guzmán, Ruiz & Cadena, 2014; Lonin, Andrade, & Monroy, 2022). Tides are mixed with a strong diurnal component, with intervals between 0.3 m and 0.6 m (Geister and Díaz, 2007), and storms occur mainly during the second half of the year due to Seaflower being within the Caribbean hurricane belt (Díaz, Díaz-Pulido, Garzón-Ferreira, Geister, Sánchez, & Zea, 1996).

Alburquerque or Southwest Cays (12°10'N, 81°51'W) is the only atoll with a circular contour (8 km E-W, 6 km N-S and area of 63.8 km^2), is located ~37 km SE of San Andres Island and has two densely vegetated cays (North Cay and South Cay), separated from each other by a shallow channel (IGAC, 1986; Díaz 2005) (Figure 1). The Bolívar Atoll or Courtown Cays (12°24'N and 81° 28'W) are located ~30 km SE of San Andres Island, is kidney-shaped and has four cays (La Virgen, Bolívar, Pescadores and Norte) with variable shape and size over time (Díaz, 2005) (Figure 1). On the other hand, Bajo Nuevo Bank or Petrel Islands (15°53′N and 78°38'W) is located ~475 km northeast of San Andres Island, is the northernmost reef complex of Seaflower and is part of the Colombia-Jamaica common regime zone (~225 km) (CCO, 2015). It is made up of two elongated atolls, with a continuous barrier to windward and truncated to leeward, and separated from each other by a deep channel of ~90 m (Figure 1).

In general, in these atolls, the direction and strength of the NE trade winds, and the energy of the waves that move along the Caribbean translate into geomorphological similarity and ecological structure, following a gradient from windward to leeward (Díaz *et al.,* 2000; Geister & Díaz, 2007). In Alburquerque, Bolívar and Bajo Nuevo, the ecological units present the traditional scheme of the Caribbean atolls (Díaz *et al.,* 1996), made up of a fore reef terrace and peripheral reef continuous to windward, followed by a lagoonal terrace and a lagoon basin with patches of anastomosed or reticulated reefs, surrounded to leeward by a terrace with patches of poorly developed reefs, which end in a reef slope that can reach depths of up to 1,500 m (Dainco, 1980). In the inner part of the leeward fore reef terrace of some atolls there are reef lines that reach the surface in sections, forming an incomplete leeward peripheral reef (Díaz *et al*., 1996).

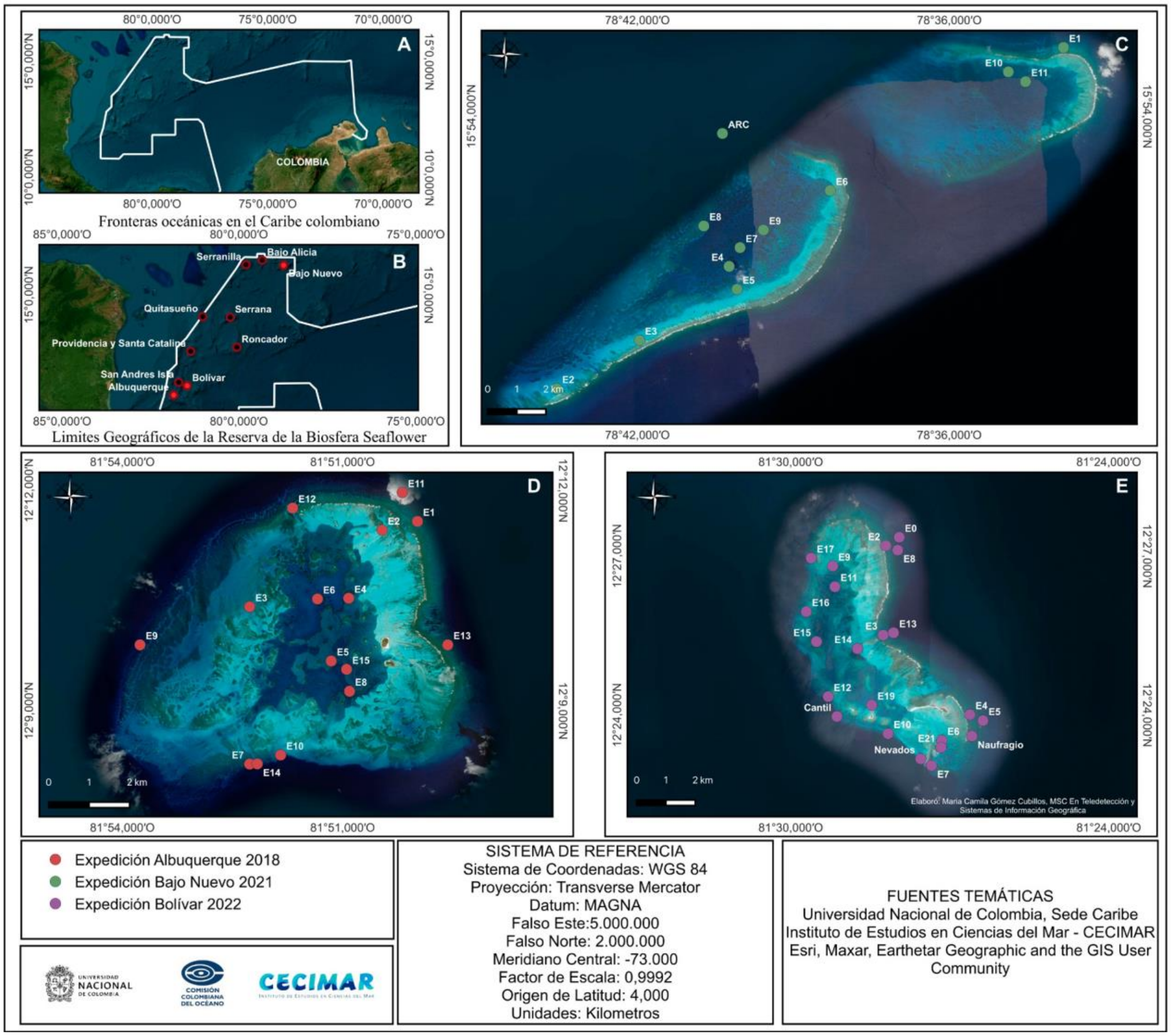

Figure 1. Study Area (A and B) and sampling stations in the atolls of Alburquerque (D), Bolívar (E) and Bajo Nuevo (C), RB Seaflower.

Methodology

To describe the current condition of a reef and infer its possible trajectories over time, the Global Coral Reef Monitoring Network (GCRMN) proposes for the Caribbean to assess the relative coverage of reef-building organisms (stony corals and coralline algae) and their main competitors (macroalgae, sponges and soft corals), coral health and abundance of key taxa of reef fish and other macroinvertebrates (with emphasis on herbivores) (ICRI, 2016).

With the Seaflower scientific expeditions, progress was made in the standardization of methodologies in the field, in accordance with the GCRMN initiative, which are easy to implement in remote reefs. Between expeditions, methods were adjusted according to logistical and environmental capacities, thus allowing the improvement of initial techniques (2018) and the integration of new methodological components (2021 and 2022) (Gómez-Cubillos, Daza-Guerra, Márquez, & Zea, 2023).

Field information was collected by scuba diving *in* the reef complexes of Alburquerque (September 25 to October 2, 2018), Bajo Nuevo (November 24 to 30, 2021) and Bolívar (September 22 to 30, 2022). The selection of the sampling stations in Alburquerque and Bolívar was based on the stations of the project 'Bioecological and environmental evaluation of reef areas of the Colombian Caribbean 1994-1996' (Díaz *et al.,* 1996), and in Bajo Nuevo the work meshes of the 2010 expeditions (Abril-Howard, Orozco-Toro, Bolaños-Cubillos and Bent-Hooker, 2012) and 2011 (Vega-Sequeda, Díaz-Sánchez, Gómez-Campo, López-Londoño, Díaz-Ruiz, & Gómez-López*,* 2015).

Benthic cover, coral richness and coral health

In each station, guided by a tape measure lying on the bottom, a belt transect (10 x 2 m) was evaluated, using the photoquadrat technique each meter, alternating them on either side of the tape measure. With a Canon Powershot G7 digital camera with an adapted waterproof box, mounted on a frame of PVC pipes, photographs of the substrate were taken in 10 quadrats (0.25 cm2) for a total of 2.5 m2 per transect (Gómez-Cubillos, Gómez-Cubillos, Sanjuan-Muñoz, & Zea, 2019) (Figure 2a).

The photographs were processed with ImageJ 1.52v. By quadrat, from a mesh of 100 random points, the coverage (%) of the benthic categories described by Caricomp (2001) and Garzón-Ferreira, Reyes-Nivia, and Rodríguez-Ramírez (2002) was calculated. By photograph, coral richness and the presence of signs associated with coral diseases were estimated (Raymundo, Couch, & Harvell, 2008; Weil & Rogers, 2011; Weil *et al.,* 2019; Bruckner, 2020). These signs were selected taking as a reference: a) changes in the coloration of the coral tissue (darkening, paleness, bleaching), b) shape of the lesion (regular and irregular) and c) exclusivity with the host (Gómez-Cubillos *et al.,* in press). Signs were assigned to one or more coral diseases reported in the Caribbean (Gil-Agudelo *et al.,* 2009).

The data were processed in Microsoft Excel. By reef complex, the following were estimated: *i)* coral richness as the number of species per sampling site, *ii)* by transect (combining the 10 photoquadrats), total and relative coverage (%) from random points, *iii)* prevalence of signs (%) by coral species (# cases with $sign_i$ / # total sp_j colonies) (Weil & Rogers*,* 2011).

Algal turf assemblages in interaction with living coral tissue

Following the methodological recommendations of Gómez-Cubillos, Gavio and Zea *(*2020); Gómez-Cubillos, Daza-Guerra, Márquez and Zea, 2023), between 1 and 2 morphologically contrasting massive coral colonies were selected per station, according to their type of colonial organization (meandroid, plocoid, cerioid), which had active interaction edges with algal turfs. Photographs of the colony and macros of the interaction edges of interest were taken. On the selected interaction, containing live coral and turf, a coral skeleton core was extracted using a hammer and impact corer of 27 mm in diameter (5.7 cm^2). The samples were fixed separately in 96% alcohol. (Figure 2b).

In the laboratory, each core was wet checked, using a Zeiss-Discovery-V8 stereoscope (1.0 - 4.0 X) and an Epson Perfection-V850Pro scanner. The structure of the algal assemblages in interaction with coral tissue was evaluated in terms of composition, relative coverage per taxa (%), canopy height (mm), and filament density (Gómez-Cubillos *et al.,* 2020). With a Zeiss-AX10 optical microscope, with a DCM510-CMOS digital camera, scale photographs of the algae taxa were taken, using the ScopePhoto 3.1 program. Taxonomic identification was carried out at the genus level, using specialized keys and expert consultation.

Based on the structure of the assemblages and the identified genera, groupings were made into empirical categories or "morphofunctional" groups, defined based on taxonomic affinities (phylum) and on the morphological bases of thallus structure, growth form, and branching pattern (Balata, Piazzi, & Rindi, 2011).

Diversity and functional redundancy of herbivores

This component was only developed during the Bolívar 2022 expedition. Using the stationary census method (Bohnsack and Bannerot, 1986) at three points per station fish and herbivorous macroinvertebrates were recorded. This method consists of observing organisms within a cylinder of 7 m radius

($79\ m^2$) for 5 minutes. With a GoPro Hero 9 camera, the species/genus richness and abundance of herbivorous fish belonging to the families Acanthuridae (surgeons), Labridae-Scarinae (parrots), Ephippidae (catalinas) and Kyphosidae (poplars) were recorded. For mobile macroinvertebrates, specimens of urchins (Echinoidea) and crustaceans *Maguimithrax* spp. were searched, with a total length greater than 1 cm (Francis, Filbee-Dexter, Yan, & Côté, 2019; Bortone, Samoilys, & Francour, 2000; Spadaro & Butler, 2021; Williams, 2021) (Figure 2c).

The organisms surveyed were categorized into functional groups according to their way of interacting with the substrate when consuming algae in: a) macroalgae browsers; b) cutters; (c) bioeroding grazers, (d) scraper grazers, and (e) sediment suckers (Bellwood and Choat, 1990; Bellwood, Hoey, & Choat, 2003; Bellwood, Hughes, Folke, & Nyström, 2004; Johansson, Van de Leemput, Depczynski, Hoey, & Bellwood, 2013; Tebbett, Siqueira, & Bellwood, 2022). It is clarified that the same family can have more than one functional group, as is the case of Labridae and Acanthuridae. The degree of functional redundancy was determined from the richness of genera and species, and the reserve capacity was carried out following the recommendations of Johansson *et al.* (2013).

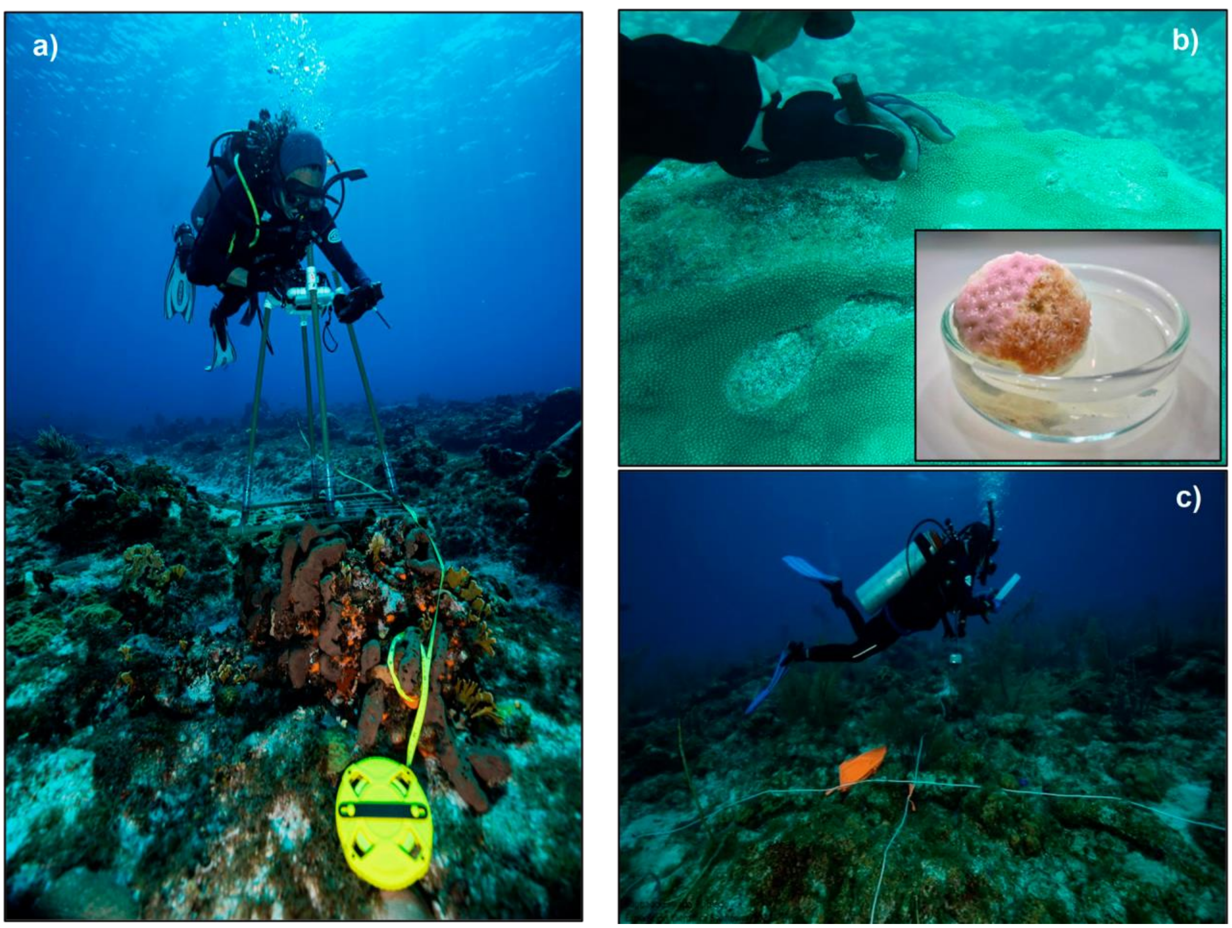

Figure 2. a) Transect with alternating photoquadrats, **b)** core extraction with coral-turf and macro interactions from the excreted core; **c)** census of fish and herbivorous macroinvertebrates.
(Photos a and c: Santiago Estrada; b: Catalina Gómez-Cubillos and Helena Benavides-Marchena).

Results and discussion

In the three expeditions, 49 stations were evaluated: 15 in Alburquerque, 22 in Bolívar and 12 in Bajo Nuevo (). Of the total number of stations, 17 were located in the lagoon basin, 12 on the leeward terrace and outer slope, 8 on the windward fore reef terrace, 7 on the lagoonal terrace and 5 on the windward peripheral reef. With 53% of the stations, medium-depth reefs (between 7 m and 12 m) were evaluated, with 24% for deepest reefs (between 12 m and 19 m) and with the remaining 22% for shallow reefs (between 2 m and 7 m). Of the total number of stations evaluated, 32 were environments with little or no exposure to the prevailing waves (excluding storms) and the other 17 were environments with a moderate to high level of exposure, according to the classification proposed by Zea (2001) (Table 1).

Table 1. Location and general characteristics of the stations evaluated in Alburquerque (2018), Bajo Nuevo (2021) and Bolívar (2022).

Station ID	Coordinates		Level of Depth	Exposure Level	Geomorphological unit
	Latitude	Longitude			
Alburquerque Expedition 2018					
E1	12,193000	-81,83300	Middle	3	TP
E2	12,191000	-81,84100	Shallow	2	TL
E3	12,173608	-81,87111	Shallow	1	TS
E4	12,175550	-81,84861	Middle	0	Lg
E5	12,161299	-81,85259	Middle	0	Lg
E6	12,175377	-81,85570	Deep	0	Lg
E7	12,137910	-81,87111	Deep	2	TS
E8	12,154440	-81,84844	Middle	0	Lg
E9	12,164968	-81,89600	Deep	1	TS
E10	12,139963	-81,86407	Deep	0	TS
E11	12,199530	-81,83643	Deep	3	TP
E12	12,196010	-81,86132	Middle	3	B
E13	12,164968	-81,82613	Middle	3	B
E14	12,137949	-81,86936	Deep	1	TS
E15	12,15941	81,84909	Shallow	3	Lg
Bajo Nuevo Expedition 2021					
E1	15,922056	-78,563389	Middle	2	TP
E2	15,812750	-78,725889	Middle	1	TL
E3	15,828222	-78,699361	Shallow	1	TL
E4	15,851917	-78,670611	Middle	0	Lg
E5	15,844583	-78,668083	Shallow	1	TL
E6	15,876222	-78,638194	Middle	1	Lg
E7	15,857917	-78,667111	Deep	0	Lg
ARC	15,894500	-78,672750	Deep	2	TP
E8	15,864861	-78,678722	Middle	0	Lg

Station ID	Coordinates		Level of Depth	Exposure Level	Geomorphological unit
	Latitude	Longitude			
E9	15,863583	-78,659611	Middle	0	Lg
E10	15,914250	-78,581111	Middle	0	Lg
E11	15,911111	-78,575583	Middle	0	Lg
Bolivar Expedition 2022					
E0	12,431806	-81,4855	Middle	0	Lg
E2	12,45325	-81,470111	Shallow	3	TP
E3	12,425139	-81,470972	Middle	3	B
E4	12,400139	-81,443667	Shallow	3	B
E5	12,39825	-81,439556	Deep	2	TP
E6	12,392028	-81,4525	Shallow	1	TL
E7	12,384139	-81,455694	Shallow	2	TS
E8	12,451861	-81,466361	Middle	2	TP
E9	12,446861	-81,486806	Middle	0	Lg
E10	12,394139	-81,469389	Middle	0	TS
E11	12,440361	-81,486111	Middle	0	Lg
E12	12,405806	-81,488222	Middle	1	TS
E13	12,425861	-81,467694	Deep	2	TP
E14	12,420889	-81,479028	Shallow	1	TL
E15	12,423083	-81,491917	Deep	0	Lg
E16	12,432528	-81,495111	Middle	1	TS
E17	12,449361	-81,493583	Middle	1	TS
E19	12,403111	-81,474528	Middle	0	Lg
E21	12,389806	-81,452694	Shallow	1	TL
Nevados	12,38625	-81,459139	Middle	0	TS
Naufragio	12,393389	-81,442972	Middle	3	B
Cantil	12,399556	-81,485472	Deep	0	TS

Abbreviations: Depth level: Shallow < 7 m; Medium between 7 and 12 m; Deep > 12 m (Garzón-Ferreira et al., 2002). Exposure Level: 0 (none); 1 (scarce); 2 (moderate); 3 (strong), with respect to the waves and the depth of the water column (Zea, 2001). Geomorphological unit: TP (fore reef or windward terrace); B (windward peripheral reef); TL (lagoonal terrace); Lg (lagoon with coral patches) and TS (leeward terrace and outer slope) (Díaz *et al.*, 1996). Metadata can be downloaded at: Alburquerque (https://doi.org/10.15472/b3hg97); Bajo Nuevo (https://doi.org/10.15472/2ke98s); Bolívar (https://doi.org/10.15472/0skaoj)

Benthic cover

In Alburquerque, Bajo Nuevo and Bolívar, the benthos was dominated by non-reef-building organisms (fleshy macroalgae, soft corals and poriferans) (between 59.1 ± 11.3 and 61.7 ± 10.2 % - mean ± D.E., values calculated from the sampling units, this is, one transect per station, separately for each atoll); while the reef-building species (scleractinian corals, hydrocorals and coralline algae) ranged from 23.9 ± 10.4 to 26.7 ± 15.2 %. On the other hand, the abiotic substrate represented between 11.7 ± 11.6 and 15 ± 11.1 % of the substrate (Figure 3).

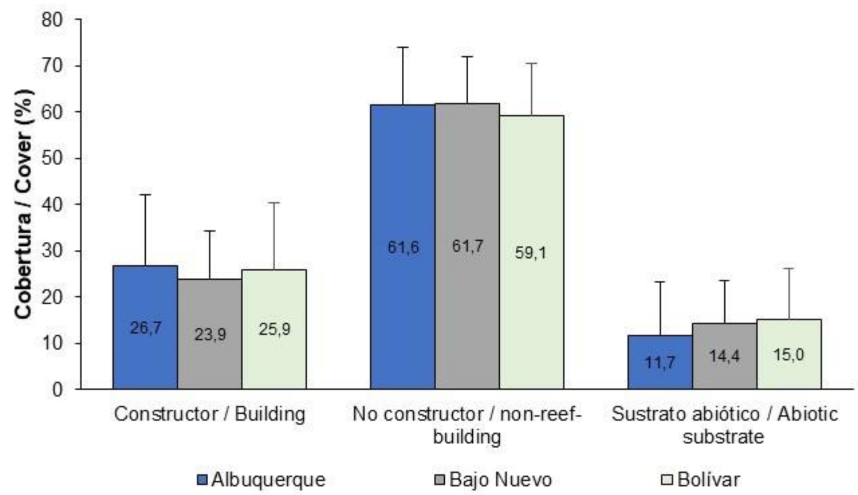

Figure 3. Overall cover (%) of the main benthic components in the Alburquerque, Bolívar and Bajo Nuevo reef complexes (Mean ± D.E.).

By excluding the abiotic substrate to recalculate the living cover, it was confirmed that macroalgae dominated in the three reef complexes (between 69.3 ± 15.8 and 72 ± 10.7 %), particularly algal turfs, with percent covers between 43.2 ± 7.1 and 44.7 ± 12.7 %. Scleractinous and hydrocoral corals (between 19.8 ± 12.4 and 21.2 ± 12.5 %) were mainly represented by massive colonies (between 14.2 ± 10.9 and 14.7 ± 9.3 %); while hydrocorals contributed less than 2%. The other benthic organisms (soft corals, sponges and others) registered the lowest coverage (between 8.2 ± 4.2 and 9.5 ± 7 %); but, in Alburquerque and Bajo Nuevo, gorgonaceans were the most representative communities (between 7.7 ± 6.4 % and 5.3 ± 4.2 %, respectively), while in Bolívar the greatest contribution was sponges (5.4 ± 6.9 %) (Figure 4).

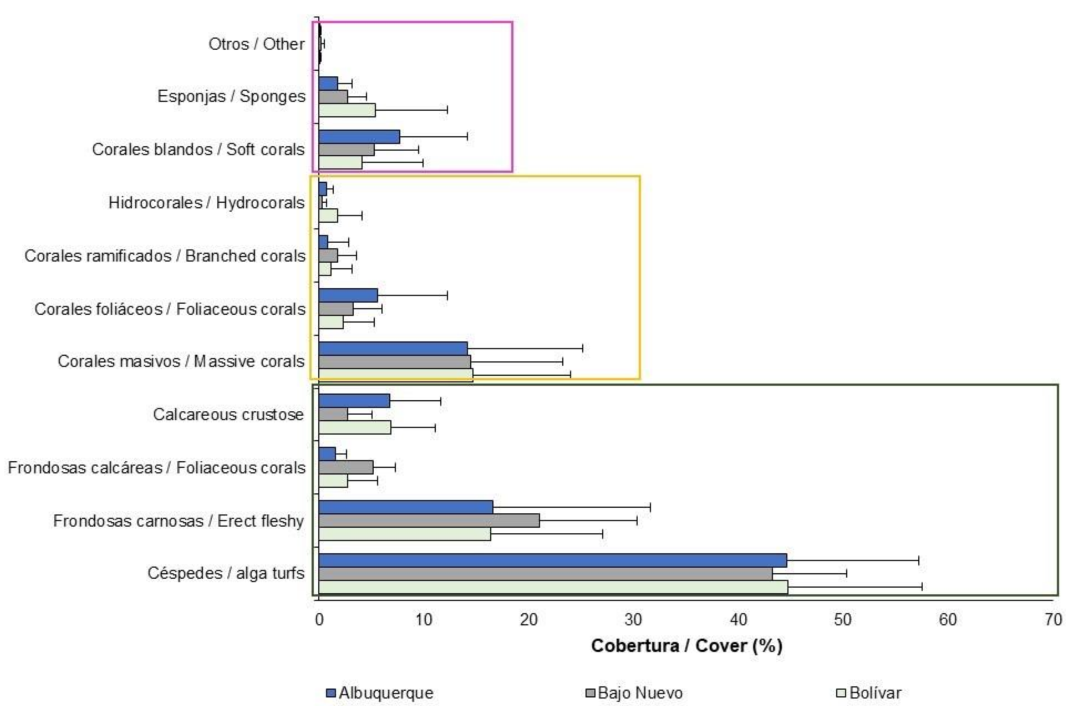

Figure 4. Cover % (relative to total living) of reef-building organisms (yellow box) and their main competitors macroalgae and other sessile organisms (green box and fuchsia, respectively) in the reef complexes of Alburquerque, Bolívar and Bajo Nuevo (Mean ± 1 D.E., of the stations of each complex).

The dominance of algal turfs suggests that these reefs are experiencing a shift from coral dominance to macroalgae, a trajectory already described for other Caribbean reefs (Souter *et al*., 2021). These changes towards the dominance of macroalgae are preceded by a loss of resilience, as a result of the increase in the frequency and intensity of anthropogenic disturbances, including the overfishing of herbivores, leaving the ecosystem vulnerable to new disturbances (Mumby *et al.,* 2006; Nyström, Folke, & Moberg, 2000). The dominance of macroalgae is maintained due to feedback mechanisms; for example, an initial disturbance (*e.g.* outbreaks of epizootics) generates coral mortality, leaving substrate available for the colonization of macroalgae (turf algae in this case); but these algae will increase their cover if the abundance of herbivores is low or if they proliferate at a sufficient speed to exceed the grazing capacity of herbivores (Williams, Polunin & Hendrick, 2001). In sum, these loops affect coral recruitment, reduce coral growth rate, and can lead to additional mortality in colonies (Tanner, 1995; Kuffner, Walters, Becerro, Paul, Ritson-Williams, & Beach, 2006; Smith *et al*., 2006; Box & Mumby, 2007; Norström, Nyström, Lokrantz, & Folke, 2009).

Diversity of coral species

In the three atolls, the presence of 48 species of hard corals, 45 species of scleractinean corals and 3 species of hydrocorals (Table 2). The greatest richness was found in Bolívar (43 spp.), followed by Alburquerque (34 spp.) and Bajo Nuevo (32 spp.).

The variation in coral species richness between reef complexes reflects a complex interaction between biotic and abiotic factors (Guzmán and Cortés, 1993). Greater diversity may be a response to more favorable environmental conditions, such as high availability of suitable substrates for coral settlement and better water quality (López-Londoño *et al.,* 2023). In addition, the particular geomorphological characteristics of each complex can lead to a wide variety of microhabitats that promote species diversification (Díaz *et al.,* 1996). Conversely, overfishing, especially of herbivores, can limit the system's ability to maintain coral richness (Roberts, 1995), which together with outbreaks of epizootics can alter community structure (Márquez and Díaz, 2005). The effect of tropical storms and hurricanes must also be recognized, which model diversity differentially between atolls, depending on the intensity and proximity of the event. For example, in 1988 Hurricane Joan's path was about ~50 km from the southern cays (Vega-Sequeda *et al.,* 2015), and in 2020 hurricanes Iota and Eta hit hardest the northern area of the RB Seaflower.

Of the 48 coral species observed, two are new records for the RB Seaflower (*Colpophyllia breviserialis* and *Porites colonensis*) and for 13 species their range is extended to the northern and southern cays (*Agaricia fragilis*, *A. grahamae*, *A. humilis*, *A. tenuifolia*, *Cladocora arbuscula*, *Dendrogyra cylindrus*, *Isophyllia sinuosa*, *Madracis formosa*, *Meandrina jacksoni*, *Mycetophyllia danaana*, *Porites divaricata, Siderastrea radians* and *Solenastrea bournoni*) (Table 2). These findings suggest that the position of these reef complexes, in terms of ocean circulation, promotes connectivity between populations, expanding the ranges of distribution and diversity of species (Lopera-García, 2020). However, it is important to recognize that the sampling methods and technologies used during the Seaflower expeditions allowed the data to be collected systematically and, therefore, to estimate coral richness more accurately.

Table 2. Species of hard corals recorded in scientific expeditions Alburquerque (2018), Bajo Nuevo (2021) and Bolívar (2022).

Species	Category and criteria IUCN	Reef complex		
		Alburquerque	Bajo Nuevo	Bolívar
Acropora cervicornis	CR ↓ (A2bce)	X	X	X
Acropora palmata	CR ↓ (A2bce)	X	X	X
Agaricia agaricites	VU ↓ (A3c)	X	X	X
Agaricia fragilis	LC ¿?	X[†]	X	X[†]
Agaricia grahamae	NT ↓ (A2bce)	X[†]	X[†]	
Agaricia humilis	CR ↓ (A3c)	X[†]	X[†]	X[†]

Species	Category and criteria IUCN	Reef complex		
		Alburquerque	Bajo Nuevo	Bolívar
Agaricia lamarcki	CR ↓ (A3c)			X
Agaricia tenuifolia	CR ↓ (A3c)		X	X[†]
Agaricia undata	LC ¿?			X
Cladocora arbuscula	LC ¿?		X[†]	
Colpophyllia natans	VU ↓ (A3c)	X	X	X
Colpophyllia breviserialis	CR ↓ (A3c)		X[†]	
Dendrogyra cylindrus	CR ↓ (A2bce)	X		X[†]
Dichocoenia stokesii	VU ↓ (A3c)	X		X
Diploria labyrinthiformis	CR ↓ (A3c)	X	X	X
Eusmilia fastigiata	CR ↓ (A3c)	X		X
Favia fragum	LC ¿?	X	X	X
Helioseris cucullata	CR ↓ (A3c)	X	X	X
Isophyllia sinuosa	LC ¿?			X[†]
Isophyllia rigida	LC ¿?	X	X	X
Madracis decactis	CR ↓ (A3c)	X	X	X
Madracis formosa	NT ↓ (A2bce)	X[†]		X[†]
Manicina areolata	LC ¿?	X	X	
Meandrina jacksoni	CR ↓ (A3c)			X[†]
Meandrina meandrites	CR ↓ (A3c)	X		X
Millepora alcicornis	VU ↓ (A3c)	X	X	X
Millepora complanata	CR ↓ (A3c)	X	X	X
Montastraea cavernosa	LC ¿?	X	X	X
Mussa angulosa	NT ↓ (A2bce)			X
Mycetophyllia aliciae	LC ¿?		X	
Mycetophyllia danaana	CR ↓ (A3c)		X[†]	X[†]
Mycetophyllia ferox	CR ↓ (A3c)			X
Mycetophyllia lamarckiana	LC ¿?	X		X
Orbicella annularis	EN ↓ (A2bce)	X	X	X
Orbicella faveolata	EN ↓ (A2bce)	X	X	X
Orbicella franksi	NT ↓ (A2bce)	X	X	X
Porites astreoides	LC ¿?	X	X	X
Porites colonensis	VU ↓ (B2ab iii)	X[†]		X[†]
Porites divaricata	LC ¿?	X	X	X[†]
Porites porites	LC ¿?	X	X	X
Pseudodiploria clivosa	NT ↓ (A2bce)	X	X	X
Pseudodiploria strigosa	CR ↓ (A3c)	X	X	X
Scolymia spp.	CR ↓ (A3c)			X
Siderastrea radians	LC ¿?	X	X	X[†]
Siderastrea siderea	CR ↓ (A3c)	X	X	X
Solenastrea bournoni	LC →			X[†]
Stephanocoenia intersepta	NT ↓ (A2bce)	X	X	X
Stylaster roseus	Not evaluated			X

Abbreviations: X (presence); X[†] (new record for the reef complex). IUCN categories: critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT); least concern (LC), decreasing population trend (↓), unknown (?), stable (→).

Coral health

In the three reef complexes, nine signs associated with seven coral diseases were identified [White Band Disease (WBD); White Plague Disease (WPD); Yellow Band Disease (YBD); Dark Spots Disease (DSD); Black Band Disease (BBD); Aspergillosis (ASP) and bleaching] (Gil-Agudelo *et al.,* 2009). In addition, four of these signs are associated with Stony Coral Tissue Loss Disease (SCTLD). Of the total number of colonies evaluated (17 379), the signs found affected 4 genera, 14 species and 11.4 % of the colonies. The highest prevalence of signs was recorded in Bajo Nuevo (23.5 %), followed by Alburquerque (3.3 %) and Bolívar (1.8 %). The sign associated with BBD was only recorded in the southern cays, while neighborhoods affected by signs associated with SCTLD accounted for 63 % in Bolívar and 84.9 % in Bajo Nuevo.

Diseases have been an important source of coral mortality in recent decades on Colombian reefs (Garzón-Ferreira, Gil-Agudelo, Barrios, & Zea*,* 2001). The results of the expeditions confirm that coral deterioration linked to mixed epizootics is differential between reef complexes, and that the reefs of Bajo Nuevo are the most deteriorated, despite the fact that in the 1990s they were classified as the best preserved in the Colombian Caribbean (Bruckner, 2012).

Algal turf assemblages in interaction with living coral tissue

At the edges of interaction between living coral tissue and turf algae, 15 morphofunctional groups were identified, 14 of them present in the samples collected in Alburquerque, 10 in Bajo Nuevo and 9 in Bolívar (Table 3). These assemblages were made up of 50 morphotypes, belonging to 33 genera, 12 orders and 23 families. Assemblages with morphologies based on thin non-calcareous filaments, with erect and/or prostrate thalluses were the most recurrent in the interaction edges evaluated. By contrast, turfs with vesicular shapes and calcareous thalli were unique to Alburquerque.

In Bolívar and Bajo Nuevo, the assemblages were dominated by groups of prostrate uniseriate and multiserial algae, corticated, of smaller size and laminar with forked thalli, which together form short, dense mats with tangled thalli. In contrast, in Alburquerque the assemblages were, for the most part, of smaller and larger corticated algae, and complex non-filamentous functional groups, such as non-calcareous crusty algae, foliar and vesicular. These differences may be a response to the combination of local environmental factors such as the availability of nutrients, light, grazing, among others (López, Rodríguez, & Silva*,* 2004). However, the presence of less morphologically complex algae also suggests primary processes of colonization of the new available substrate, assuming that the disturbance linked to the loss of tissue and exposure of the coral skeleton, possibly epizootics, was operating recently, as observed in the reefs of Bajo Nuevo (Gómez-Cubillos *et al.,* in press). These findings suggest that the structural complexity of turf algae interacting with living coral tissue provides clues about the chronology of disturbance.

Table 3. Proposal of morphofunctional groups of algal grasses that interact with remaining living coral tissue in reefs of the Seaflower BR.

Growth form	Morphofunctional group	Description	Genus	Edge	Reef complex		
					Alburquerque	Bajo Nuevo	Bolívar
Filamentous	Cianobacteria	Filaments generally epiphytic, with a thallus less than 1 mm, intertwined or attached to the host. Organized in clusters like bouquets.	*Lyngbya* spp. Oscillatoriaceae *Spirocoleus* spp	Cyanobacteriota	X	X	X
Filamentous	Uniseriate prostrate	Filaments in corticated, uniserial, branched or no. With or without rhizoids. Without stolons.	*Cladophora* spp. *Chaetomorpha* spp. *Ectocarpus* spp. *Hincksia* spp.	Chlorophyta	X	X	X
		Filaments in corticated, uniserial, branched. Prostrate thallus, without rhizoids, with or without thick stolons.		Ochrophyta	X	X	
Filamentous	Uniserials and multiserials erect	Non-cortical filaments, thin (up to 2 µm wide), with one or more series of cells. Thallus erect with or without stolons, with or without rhizoids.	*Aglaothamnion spp.* *Bostrychia spp.* *Ceramium spp.* *Centroceras spp* *Heterosiphonia spp.*	Rhodophyta	X	X	X
Filamentous	Smaller multi-series	Multi-seriate uncorticated filaments, less than 2 µm wide. Unbranched and rhizoid-containing stolons.	*Sphacelaria* spp.	Ochrophyta	X		
Filamentous	Pluriseriate Prostrate	Fine filaments (up to 2 mm wide) not cortified, with an extensive prostrate system from which erect shafts emerge, branched or not. With or without rhizoids or stolons.	*Herposiphonia* spp. *Polisiphonia* spp	Rhodophyta	X X	X X	X X
Filamentous	Cortical Hollow Stalk	Erect thalluses, formed by hollow tubes of few layers, branched or not, with or without rhizoids or stolons.	*Champia* spp. *Griffithsia* spp.	Rhodophyta	X	X	
Filamentous	Cortical smaller size	Filaments erect, cortical, branched, with thin axes (up to 2 µm wide). No stolons, no rhizoids.	*Chondria* spp. *Dasya* spp.	Rhodophyta	X	X	X

Growth form	Morphofunctional group	Description	Genus	Edge	Reef complex		
					Alburquerque	Bajo Nuevo	Bolívar
Filamentous	Cortical larger size	Filaments erect, corticate, branched, with thick (more than 2 µm wide) and polysiphonic axes. With one or more apical cells. With rhizoids, without stolons.	*Gellidiela* spp. *Gellidium* spp. *Gelidiopsis* spp. *Hypnea* spp. *Pterocladiella* spp.	Rhodophyta	X	X	X
Vesicular	Siphonic with vesicular thallus	Single-celled vesicles with a rounded or elongated shape.	*Valonia* spp.	Chlorophyta	X		
Vesicular	Siphonic with hollow vesicular thallus	Stem hollow, erect, Uniseriate, without branches or stolons. Rounded vesicles.	*Enteromorpha* spp.	Chlorophyta	X		
Crustose	Crustose Non-chalky	Flattened cortical thalluses adhered to the substrate, but not strictly adherent. With or without branches. No stolons or rhizoids.	*Peyssonnelia* spp.	Rhodophyta	X		
Foliate	Foliaceous with cenocytic filaments	Cortical thalluses, with variable growth, forming sheets of one to a few layers of thick polychotomous cells of interlaced cenocytic filaments. With rhizoids.	*Anadyomene* spp.	Chlorophyta	X		
Foliate	Laminar with forked thallus	Laminar thallus, flattened, with dichotomous bifurcations, branched with rounded and bilobed apices. With rhizoids.	*Dictyota* spp.	Ochrophyta	X	X	X
Foliate	Laminar corticated	Flat, erect laminar thallus, with cortical area with 2 to 3 rows of cells.	*Cryptonemia* spp.	Rhodophyta		X	
Articulate	Coral articulated smaller size	CaCO3-impregnated cell walls, dichotomous ramifications with articulated regions, and connections between adjacent filaments.	*Amphiroa* spp.	Rhodophyta	X	X	X

Richness and abundance of herbivores

In Bolívar, 20 herbivorous species were recorded with a total abundance of 3,171 individuals. This diversity was represented by 14 species of fish belonging to 3 families (Acanthuridae = 3 spp.; Labridae = 9 spp. and Kyphosidae = 2 spp.), 4 species of sea urchins (*Diadema antillarum*, *Echinometra lucunter*, *Echinometra viridis*, *Eucidaris tribuloides*) and 2 species of crustaceans (*Percnon gibbesi* and *Maguimithrax spinosissimus*) (Table 4).

The average richness was 15.8 ± 2.8 species, with the lagoon terrace (19 spp.) and the pre-reef terrace (18 spp.) being the most diverse environments. The highest total average abundance was recorded in the lagoon and in the lagoonal terrace (85.05 ± 78.3 and 40.3 ± 88.6 individuals, respectively). The most representative family in number of species was Labridae (parrots and wrasses) with 9 species and with the greatest abundance in the lagoon and the leeward terrace. In the other environments, the most abundant family was Acanthuridae (surgeonfishes), with 1 367 individuals. The abundances for this family in descending order were the blue surgeon *Acanthurus coeruleus* (832 individuals), the brown surgeon *Acanthurus tractus* (471) and the striped parrot *Scarus iseri* (380) (Figure 5).

In general, several studies from the Caribbean confirm that the Acanthuridae and Labridae are the most abundant families in reef fish assemblages. This is because surgeons are very abundant given their high biomass, herbivorous diet, food availability, and ability to form aggregations of massive schools for feeding (Bellwood *et al.,* 2003). Parrotfish, on the other hand, have been described as generalist habitat species, capable of persisting in a wide range of environmental conditions and conspicuous in reef environments (Cheal, Emslie, Miller, y Sweatman*,* 2012).

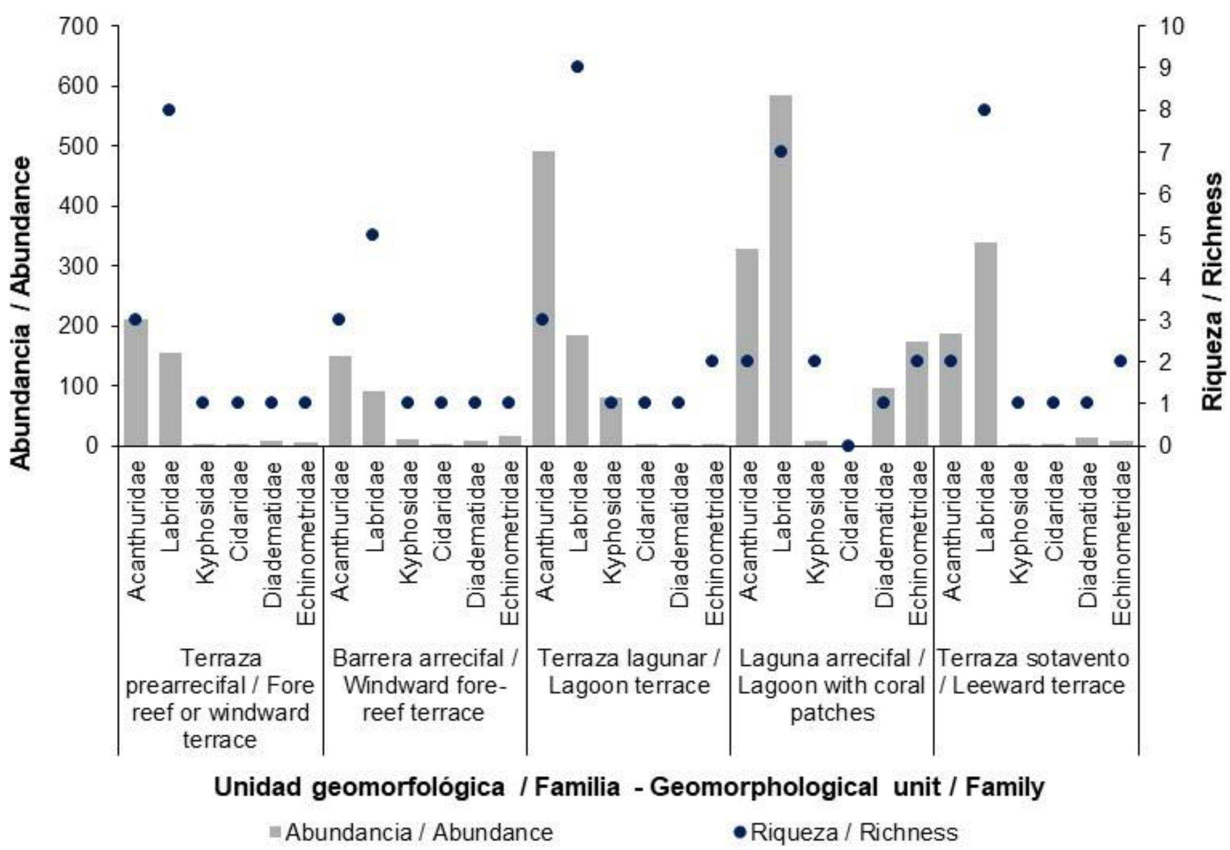

Figure 5. Abundance and richness of herbivorous species families in Bolívar Atoll.

These results are similar to other studies at Seaflower. The 14 species richness of herbivorous fish reported in 2022 was slightly lower than those in the southern cays (17 spp.), San Andres Island (19 spp.), and Old Providence (18 spp.), where the presence of *Scarus guacamaia*, *Scarus coeruleus*, *Sparisoma radians, Kyphosus sectatrix*, *Kyphosus cinerascens* and *Cryptotomus roseus* was recorded (Bolaños-Cubillos, Abril-Howard, Hooker, Caldas and Acero, 2015); but it was greater than that found in the northern cays (Alice Shoal: 6 spp., Serranilla: 11 spp., Bajo Nuevo: 13 spp.) (Vega-Sequeda *et al.*, 2015). When comparing between expeditions in which other researchers conducted fish censuses on the other atolls, 15 species of herbivorous fish were recorded in Alburquerque, including *S. coeruleus* and *S. radians* (Rivas, Acero, Tavera, Abril-Howard, d Bolaños-Cubillos, 2020), while in Bajo Nuevo, in 100 m^2, of the 20 most abundant fish taxa, 6 were herbivorous (Santos-Martinez, Gavio, Prato, Dorado, d Macaris, 2023)(Table 4).

Table 4. Species of fish and herbivorous invertebrates recorded in expeditions scientists from Alburquerque 2018; Bajo Nuevo 2021 and Bolívar 2022.

Species	Reef complex		
	Alburquerque	**Bajo Nuevo**	**Bolívar Cay**
Acanthurus chirurgus	X	X	64
Acanthurus coeruleus	X	38	832
Acanthurus tractus	X	8	471
Diadema antillarum			128
Echinometra lucunter		51*	88
Echinometra viridis		4*	117
Eucidaris tribuloides			9
Kyphosus spp.			97
Kyphosus vaigiensis	X		5
Maguimithrax spinossisimus			2
Percnon gibbesi			4
Scarus coelestinus	X		3
Scarus coeruleus	X		
Scarus iseri	X	11	380
Scarus taeniopterus	X	4	247
Scarus vetula	X		91
Sparisoma atomarium	X	X	25
Sparisoma aurofrenatum	X	7	226
Sparisoma chrysopterum	X		27
Sparisoma radians	X		
Sparisoma rubripinne	X	X	130
Sparisoma viride	X	4	225

Note: Alburquerque: presence (X) reported by Rivas *et al*. (2020). Bajo Nuevo: Presence and density of individuals in 100 m^2 reported by Santos-Martínez *et al*. (2023). Bolívar: total abundance (# individuals censused). * Total abundance data taken by the authors in 2021.

In relation to sea urchins, despite the fact that 31 species of echinoids have been recorded in the RB Seaflower, the 4 species found in 2022 are the same as those reported most commonly in shallow waters, which are abundant and are officially recorded for San Andres Island, Bolívar, Old Providence, Bajo Nuevo and Serranilla (Borrero-Pérez *et al.,* 2019). Only in Alice Shoal there was a low abundance of *D. antillarum* (Vega-Sequeda *et al.,* 2015), and in the common regime area with Jamaica only *E. tribuloides* and *D. antillarum* were reported (Borrero-Pérez *et al.,* 2019).

Considering the habitat preference by species, it was confirmed that certain families and species registered higher abundances in some geomorphological units compared to others (Table 5). In general, the factors that seem to have the greatest influence on the abundance of herbivores are the degree of exposure to waves, the water-column depth, and the characteristics of the substrate (Alevizon, Richardson, Pitts and Serviss*,* 1985; McGehee, 1994 — Brazil). When comparing the results of 2022 with the study of Mejía and Garzón-Ferreira (2000) it is possible to affirm that *S. iseri*, *S. taeniopterus*, *S. aurofrenatum, A. coeruleus*, *A. tractus* and the youth of *Sparisoma* spp. and *Scarus* spp. are characteristic species of the lagoon basin and the windward and leeward terraces, environments where the depth of the water column reduces exposure to waves; whereas *Kyphosus* spp. *Acanthurus* spp. and *Scarus* spp., prefer shallow environments where high light irradiance favors macroalgae blooms.

Functional redundancy of herbivores

Functional redundancy is the potential ability of a species to replace the ecological function of another in the event of its disappearance, and is measured from the richness of genera and species within the same functional group (Johansson *et al.,* 2013). According to this definition, in Bolívar, the functional groups macroalgae-browser (4 genera and 5 species) and bioeroding grazers (5 genera and 6 species) had the highest capacity for functional redundancy. On the contrary, the groups of cutters, grazers, scrapers and sediment suckers each registered a genus and 1 to 3 species (Table 5). In general, all groups recorded the highest abundances in the reef lagoon, except for the sediment suckers that were more abundant in the windward lagoon and fore reef terrace.

In the context of surgeonfish taking into account all genera and species globally, six functional groups are categorized (macroalgae browsers, cutters, sediment suckers, brushers, hidden cutters, and water column feeders) (Tebbet *et al.,* 2022). According to this, the 2022 records correspond to only 33.3 % of the total functional groups for this family. The small number of genera, species and therefore functional groups in the Caribbean is a consequence of several factors, including the biogeographic origin of fish diversity, which represents one of the reasons why these environments have been less resilient to changes from coral to macroalgae dominance (Roff and Mumby, 2012; Burkepile, Rasher, Adam, Hoey, & Hay, 2018).

The macroalgae browsers were the most diverse group with the greatest functional redundancy in Bolívar (fish: 2 genera and 6 species; invertebrates: 2 genera and 2 species). In the Indo-Pacific this group is composed of 21 species from 5 genera, of which only the genus *Calotomus* (5 species) and *Leptoscarus vaigiensis* are parrots. In the Atlantic, this functional group corresponds almost exclusively to the genus *Sparisoma* and contains the most dominant consumers of macroalgae on reefs and seagrasses (Burkepile and Hay, 2010; Adam, Burkepile, Ruttenberg, & Paddack*,* 2015).

For bioeroding-grazers, 2 genera of parrotfish and 3 of echinoderms are included. In terms of fish, these species are a low record compared to what was reported for the Indo- Pacific (5 species) (Cheal *et al.,* 2012). This is because large parrotfish have declined in the Caribbean due to pronounced herbivore fishing, depleting populations that fulfill this function (Burkepile *et al.,* 2018; Rivas *et al.,* 2020). A limited functional redundancy in this group indicates that these environments are highly vulnerable to the loss of any of these species and that, consequently, bioerosion rates are likely to decrease. For scrapers, 3 species of the genus *Scarus* were recorded. This richness is low compared to the Indo-Pacific (17 species and 2 genera).

In addition, other large scraper species such as *S. coeruleus* were not observed in Bolívar, despite being reported for Seaflower (Bolaños-Cubillos *et al.,* 2015). Apparently, these species are more resilient to the negative effect of fishing, possibly due to their size and greater reproductive capacity, so they may be safeguarding this function and providing greater functional redundancy.

Burkepile and Hay (2010) showed that complementarity among parrotfish improves reef resilience. The joint presence of *S. taeniopterus* and *S. aurofrenatum* causes unique and complementary changes in the algal community. *S. taeniopterus* prevents the establishment of macroalgae and promotes the settlement of crustose coralline algae in the new available substrate; but its impact is low on already established macroalgae occupying an old substrate. On the other hand, *S. aurofrenatum* reduces the abundance of already established leafy macroalgae, but feeds to a lesser extent on filamentous algae. Therefore, this effect taken together is critical for coral recovery after a disturbance.

Considering that there are differences in the spatial distribution of species and, therefore, of functional groups, in response to factors such as food availability, habitat preference, among others (Burkepile *et al.,* 2018), it was shown that the sediment sucking group was more abundant in the fore reef terrace and in the lagoonal terrace, since their habitat preference is around and in the sandy areas of the reefs, where there is a greater presence of sediments and mats of turf algae (Tebbet *et al.,* 2022). On the other hand, cutter species and browsers which feed on the body and stem of filamentous and leafy macroalgae, were more abundant in the lagoonal basin and in the windward peripheral reef. Finally, bioeroders and scrapers that feed on endolithic and epilithic algae were more frequent in exposed environments, such as the windward peripheral reef and the leeward terrace, although they were also recorded in the lagoonal basin (Burkepile *et al.,* 2018).

Generally speaking, Bolívar reefs are defined by low functional redundancy, regardless of diversity (Micheli and Halpern, 2005). The differences between the complementarity between the Caribbean and the Indo-Pacific are a consequence of evolutionary history, over and above differences in the herbivory process. Through this perspective, it is corroborated that the Caribbean has a high degree of vulnerability to the loss of any herbivorous species or worse, of an entire functional group. The richness of herbivorous species is critical to maintaining the structure and function of coral reefs, which is why it is vitally important to maintain and safeguard the richness of genera and species. The foregoing, understanding that the complementarity provided by the different modes of feeding produces an indirect but positive effect on the settlement, maintenance and recovery of corals and therefore of the entire reef ecosystem (Burkepile and Hay, 2010).

Table 5. Habitat preference, functional groups and ecosystem function performed by herbivore species in the coral reefs of the Bolívar Atoll.

Family	Species	Preference of habitat	Functional group	Ecosystem function
Acanthuridae	*Acanthurus chirurgus*	Lagoonal terrace	Sediment sucker	They consume microalgae films and particulate matter from the surface of the soft substrate (sand around corals or mixed substrate with gravel and sand).
	Acanthurus tractus	Fore reef terrace		
	Acanthurus coeruleus	Lagoonal terrace and lagoonal basin	Cutter	They consume usually filamentous algae by cutting them above the substrate.
Diadematidae	*Diadema antillarum*			
Echinometridae	*Echinometra lucunter*	Lagoonal basin	Bioeroding grazerer	They feed on the algal epilithic matrix and endolithic turfs of algae, by disturbing or deeper excavation of the substrate.
	Echinometra viridis	Fore reef terrace and leeward terrace		
Cidaridae	*Eucidaris tribuloides*			
Kyphosidae	*Kyphosus spp.*	Lagoonal terrace		
	Kyphosus vaigiensis	Lagoonal terrace and fore reef terrace	Macroalgae browser	They select individual components of the algae and remove only the algae and the epilithic material.
Mithracidae	*Maguimithrax spinosissimus*			
Percnidae	*Percnon gibbesi*	Lagoonal terrace		
Labridae	*Scarus coelestinus*			They feed on the algal epilithic matrix and endolithic turfs of algae by disturbing or digging deeper into the substrate.
	Sparisoma viride	Lagoonal basin and fore reef terrace		
	Scarus iseri		Bioeroding grazer	They feed on the algal epilithic matrix and endolithic turfs of algae, but only disturb the surface.
	Scarus taeniopterus	Lagoonal terrace		
	Sparisoma aurofrenatum	Lagoonal basin and leeward terrace	Scrapers	
	Sparisoma atomarium	Lagoonal basin		
	Sparisoma chrysopterum	Fore reef terrace and lagoonal terrace	Macroalgae browser	They select individual components of the algae and remove only the algae and the epilithic material.
	Sparisoma rubripinne	Outlying Reef windward		

Conclusions

In the reef complexes of Alburquerque, Bolívar and Bajo Nuevo, the benthic cover was dominated by non-reef-building organisms, with algal turfs being the dominant community; while reef-building organisms accounted for less than 26%. This trend is partly due to low richness, abundance, and functional redundancy of herbivores, which reduces natural control over macroalgae. Additionally, disease outbreaks induce significant losses of coral cover, favoring the proliferation of turf algae on the exposed skeleton. These results show that in these reefs the coral domain is changing to the macroalgae domain, a trajectory already described in other Caribbean reefs.

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Authors' contribution

Conceptualization: C.G. and C.D.; methodology: C.G., C.D., and S.Z.; analysis: C.G., C.D., L.F., M.B., and R.D.; research: C.G., C.D., L.F., M.B., R.D., and S.Z.; drafting - preparation of original draft: C.G., C.D., L.F., M.B., R.D., and S.Z.; drafting - revision and editing: C.G., C.D. and S.Z.; supervision: S. Z.; project management: S. Z. All authors have read and accepted the published version of the manuscript.

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RESEARCH ARTICLE

Marine and Coastal Management: Maritime Authority Vision in island areas. Archipelago of San Andrés, Providencia y Santa Catalina, Colombian Caribbean

Ordenamiento Marino Costero: Visión de Autoridad Marítima en zonas insulares del archipiélago de San Andrés, Providencia y Santa Catalina, Caribe colombiano

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ABSTRACT

Island territories hold significant importance due to their environmental, economic, and social characteristics, making it necessary to plan and manage their marine and terrestrial spaces. In Colombia, the Archipelago of San Andrés, Providencia y Santa Catalina stands as a primary tourist destination, hosting various maritime activities that have the potential to generate conflicts and impact diverse natural environments. The purpose of this research was to apply the methodology of Marine and Coastal Management: Maritime Authority Vision (MCM:MAV), to analyze the current and future conditions of marine-coastal uses and activities within the islands, as a tool for decision making. Results from this research reveal that the primary contributors to conflict include restricted areas, the Marine Protected Area, the artisanal fishing zone, and the coral reefs. Furthermore, the most suitable zones for the development of maritime activities and their compatibility were defined on the basis of the Allocation and Co-location Model (MAYC in Spanish). The study established the percentages of suitable areas for aquaculture (61.24%), offshore wind farms (48.02%), and submarine cables (48.32%). Finally, through the implementation of the Prioritization Index for Decision Making (IPTD in Spanish) which determined the degree of development trend and representativeness of each use/activity in the area, aquaculture emerges as the sector with the highest growth potential when compared to offshore wind farms and submarine cables.

KEYWORDS: coastal zone management, maritime activities, conflicts, allocation, co-location, future development scenarios, Geographic Information Systems.

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Resumen

Los territorios insulares presentan una gran importancia debido a sus características ambientales, económicas y sociales, por lo que es necesario la planificación y gestión de sus espacios marinos y terrestres. En Colombia, el Archipiélago de San Andrés, Providencia y Santa Catalina es uno de los principales destinos turísticos y en donde se desarrollan varias actividades marítimas que podrían generar conflicto entre ellas y afectar los diferentes ambientes naturales. El propósito de esta investigación fue aplicar la metodología del Ordenamiento Marino Costero: Visión de Autoridad Marítima (OMC:VAM), con el fin de analizar las etapas de condiciones actuales y futuras entre usos/actividades marino-costeras presentes en las islas, como una herramienta para la toma de decisiones. Los resultados indicaron que los usos que más contribuyen al conflicto son las áreas restringidas: el área marina protegida, la zona de pesca artesanal y los corales. Adicionalmente, se definieron las zonas más adecuadas para el desarrollo de actividades marítimas y su compatibilidad a partir del Modelo de Asignación y Colocalización (MAyC), y se establecieron los porcentajes de zonas aptas para los usos de acuicultura (61.24 %), parques eólicos (48.02 %) y cables submarinos (48.32 %). Finalmente, con el establecimiento del Índice de Priorización para la Toma de Decisiones (IPTD), que determinó el grado de tendencia de desarrollo y representatividad de cada uso/actividad en el área, se consideró que la acuicultura es el sector con mayor tendencia de crecimiento con respecto a parques eólicos y cables submarinos.

Palabras clave: *ordenamiento marino costero, actividades marítimas, conflictos, asignación, colocalización, escenarios de desarrollo futuro, sistemas de información geográfica.*

Introduction

In island areas, the growth of sectors related to tourism, fishing, trade and agriculture, among others, as well as urban development, have generated pressure on marine resources. In addition to the above, the lack of management plans that involve both marine and terrestrial components has caused incompatibilities between maritime activities, ecosystems and the different actors (Aldana and Hernández, 2016; Gallego-Cosme, 2014).

The Archipelago of San Andrés, Providencia y Santa Catalina, located in Colombia, is not exempt from this problem, since multiple activities have been carried out in its marine-coastal areas in a disorganized manner, mainly due to the fact that its Land Use Planning (POT in Spanish) took around 15 years (1989-2003) to be approved (Ramírez-Charry, 2019). In turn, the increase in population, which according to the National Administrative Department of Statistics (DANE) was 2.86% between 2005 and 2018 (Government Department of the Archipelago of San Andrés, Providencia and Santa Catalina, 2021), has led to greater conflicts of use for space (Christie, Smyth, Barnes, & Elliott, 2014).

That is why the General Maritime Directorate (Dimar), as the National Maritime Authority, is responsible for the execution of the Colombian State policy in this topic, through the regulation and coordination of maritime activities (Decree Law No. 2324, 1984), the mission, the vision, the institutional principles, the maritime interests, the institutional development strategies projected towards the year 2042 (Dimar, 2022); and the provisions of Conpes 3990 (DNP, 2020a) have addressed the "Marine and Coastal Management: Maritime Authority Vision (MCM:MAV)", which seeks:

> "[...] analyze and assign temporal and spatial distributions of human activities in Colombian jurisdictional waters and coastal areas, in order to achieve the consolidation of the country as a biooceanic power under a holistic approach and comprehensive maritime, river and port security; as well as a national maritime strategy and structure, guaranteeing ecological, economic, and social principles" (Afanador-Franco, Molina-Jiménez, Pusquin-Ospina, Escobar-Olaya, & Castro-Mercado, 2019).

Likewise, due to the COVID-19 contingency that affected the world economy, the MCM:MAV considered the future development trend of marine-coastal activities based on the analysis of global growth under scenarios with and without a pandemic, to facilitate decision-making focused on improving the current and future conditions of the maritime space (Ehler and Douvere, 2009; McGowan, Jay, & Kidd, 2019; Scenario Introduction, 2021).

Taking into account the above, the Caribbean Oceanographic and Hydrographic Research Center (CIOH) carried out the application of the MCM:MAV methodology in the Archipelago of San Andrés, Providencia y Santa Catalina, as a contribution that facilitates the management of the territory for decision-makers, as it is an area with great environmental importance and a high offer of tourism plans.

According to the Colombian Association of Travel and Tourism (Anato, 2023), the Archipelago is the sixth department with the highest number of tourist arrivals, both national and international, and it is considered the most dependent on tourism in the country, since it is estimated that 70% of its economy revolves around this activity (Government Department of the Archipelago of San Andrés, Providencia and Santa Catalina, 2019). Fishing is also an important economic activity. However, it is not enough to supply the needs of the community, therefore, the implementation of aquaculture projects could be an option with which fishermen agree to improve their conditions and those of the environment (Government of the Archipelago of San Andrés, Providencia and Santa Catalina, n.d.; Sarmiento-Guerrero & Pérez-Walteros, 2021). In terms of energy generation, the aim is to change the use of fossil fuels for renewable energies that meet the needs of the islanders, help reduce costs and dependence on diesel (Arias and Duffis, 2017; Más Comunidad, 2023). Additionally, due to their geographical location, submarine cables are an important tool for establishing the necessary telecommunications for connectivity and access to information, and to deal with any situation that arises on the islands (Asomovil, 2021).

In this research, the MCM:MAV methodology was applied based on the provisions of the publications entitled: 'Conflictos de Uso en el Proceso de Ordenamiento Marino Costero: Visión de Autoridad Marítima. Departamento de Bolívar-Colombia' (Afanador-Franco *et al.,* 2019), 'Ordenamiento Marino Costero: Visión de Autoridad Marítima. Departamento de Bolívar - Colombia' (Afanador-Franco *et al.,* 2021), 'Modelo de asignación y colocalización de actividades marítimas para el ordenamiento marino costero en el Departamento de Bolívar, Colombia' (Afanador-Franco *et al.,* 2022), 'Zonificación de actividades marítimas bajo escenarios de desarrollo futuro en los departamentos de Bolívar, Sucre y Córdoba, Colombia' (Afanador-Franco, Molina-Jiménez, Pusquin- Ospina, Barrientos, Banda-Lepesquer, & Castro-Mercado, 2023).

Study Area

The Archipelago of San Andrés, Providencia y Santa Catalina is located in the Caribbean Sea, northwest of Colombia, between 12º and 16º North latitude and between 78º and 82º West longitude (Fig. 1), occupying an area of 180,000 km^2. It was declared by the United Nations Educational, Scientific and Cultural Organization (UNESCO), in 2000, as a Seaflower Biosphere Reserve, due to its importance for marine and coastal ecosystems. It includes the islands of San Andrés, Providencia and Santa Catalina, the islands of Courtown Cays, Serranilla Bank, Southwest Cays, Roncador Bank, Queena Reef, Serrana Bank, Alice Shoal and Bajo Nuevo Bank (Carvajal, 2009; CCO, 2015; CCO, n.d.; Decree 1946 of 2013; Díaz, 2005).

It has a great wealth of marine biodiversity and important ecosystems such as mangroves, coral reefs and seagrasses, among others. It is characterized by a humid climate from May to November, and a dry climate from December to April, influenced by the NE trade winds; with an average temperature of 28ºC and high humidity during most of the year (Dagua, Torres, & Monroy, 2018). Additionally, it is located within the Caribbean hurricane belt, which is evident with the passage of several of these events throughout history, with an occurrence until 2010 of approximately 0.54 events/year, of which only some have reached the coast (CIOH, 2010; Ortiz-Royero, 2012; Ortiz-Royero, Plazas, & Lizano, 2015; Rey *et al.,* 2019; Rey *et al.,* 2021).

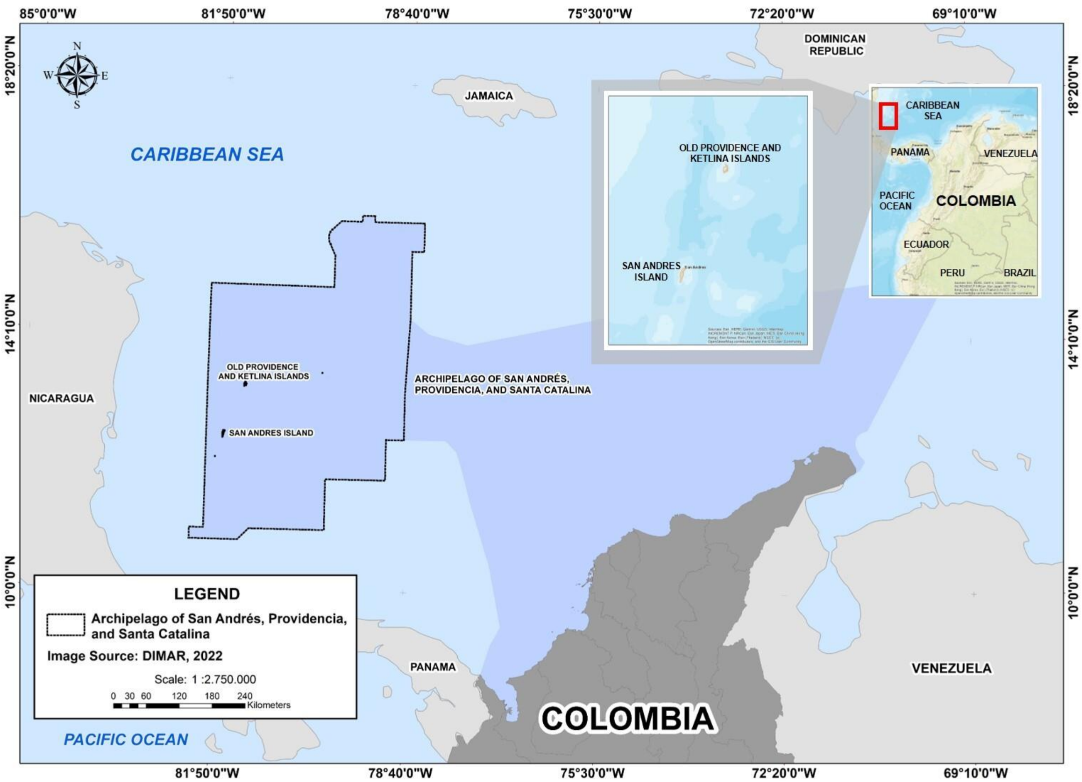

Figure 1. Location of the Archipelago of San Andrés, Providencia y Santa Catalina.

The Archipelago of San Andrés, Providencia y Santa Catalina is located in the upper part of Nicaragua, northwest of the Colombia basin, and it presents a NNE-SSW trend with a volcanic origin in the early Cenozoic, represented by lava flows and pyroclastic and epiclastic deposits. Subsequently, the subsidence of these volcanoes and the deposition of reef limestones defined the geomorphological features observed so far (Carvajal, 2009; Case *et al.,* 1990 in Idárraga-García, García-Varón, & León-Rincón, 2021; Dimar-CIOH, 2013; Geister & Díaz, 2007; Idárraga-García & León-Rincón, 2019; Milliman and Supko, 1968, in Díaz, 2005).

According to Idárraga-García *et al.* (2021), the Archipelago of San Andrés, Providencia y Santa Catalina corresponds to the geomorphological province called the Volcanic Province of the Western Caribbean, which is represented by geoforms of volcanic and structural origin, such as seamounts, guyots, spurs, volcanic peaks, basins limited by faults, and structural columns. Regarding coastal geomorphology, there are units associated with low coasts and high coasts, such as beaches, coastal lagoons, coastal bars, reef bars, dunes, floodplains, hill systems, and elevated abrasion platforms and coral terraces (Carvajal, 2009; Dimar-CIOH, 2013).

Methodology

The MCM:MAV in the Archipelago of San Andrés, Providencia y Santa Catalina, was applied following the methodology proposed by Dimar in Afanador-Franco *et al*. (2019, 2021, 2022 and 2023), which consists of the following stages:

Establishing the elements of governance

Turning the country into a biooceanic power was established as a strategic objective, in alignment with the National Development Plan - Colombia World Power of Life 2022-2026, in its axes of transformation of water management, productive transformation, internationalization and climate action. In addition, a series of technical aspects were defined, such as the scales of representation, the different types of uses/activities, cartographic conformation and spatial documentation.

Pre-planning stage

In this phase, through secondary information, primary direct users of the resources who can contribute to the conflicts were identified, followed by secondary actors, corresponding to the different entities that regulate the activities present in the Archipelago. They answered the following questions: Who should be involved in the process? When should they be summoned to the process? How should they be involved? (Maguire, Potts, & Fletcher, 2012; Afanador-Franco *et al.,* 2019; 2021).

Analysis of current conflict-related conditions

The spatial and photographic documentation of marine-coastal activities was carried out, through fieldwork, by means of surveys using the ArcGIS Survey 123 tool, in which the categories of use/activity were defined, taking into account the provisions of Decree Law 2324/84.

According to the above information and through the judgment of experts, the multicriteria analysis based on the Analytic Hierarchy Process (AHP) was applied, which consists of establishing comparisons between pairs of uses through relative values using an importance scale (Malczewski, 1999; Afanador-Franco *et al.,* 2019, 2021). These were presented in a cross-matrix of pair compensation, in which the crossovers between the uses in the study area were analyzed and the overlapping conflicts were defined.

In addition, three matrices were made corresponding to: *i)* Justification matrix, in which the reason for the assignment of the important values was briefly explained, *ii)* Normalized matrix of compensation by pairs, in which, based on a mathematical process, the values assigned in the first matrix were adjusted to a range between 0 and 1, and *iii*) Matrix of weights, in which the weights of each use were calculated, averaging their respective conflicts and identifying the uses that contribute most to the conflict.

Then, using geographic information systems (GIS) tools, two approaches were made to visualize and present the spatial distribution of the conflicts. The first consisted of quantifying the index of conflict between pairs of uses, taking into account the weights of each one; and the second analyzed the amount of overlap between the uses that have the most conflicts.

Finally, the maps corresponding to each of the approaches were generated and the free areas in which there were no uses or conflicts were defined, thus they may be suitable for the development of future maritime activities. The detailed process of this stage is described in Afanador-Franco *et al.,* 2019, 2021 (Fig. 2).

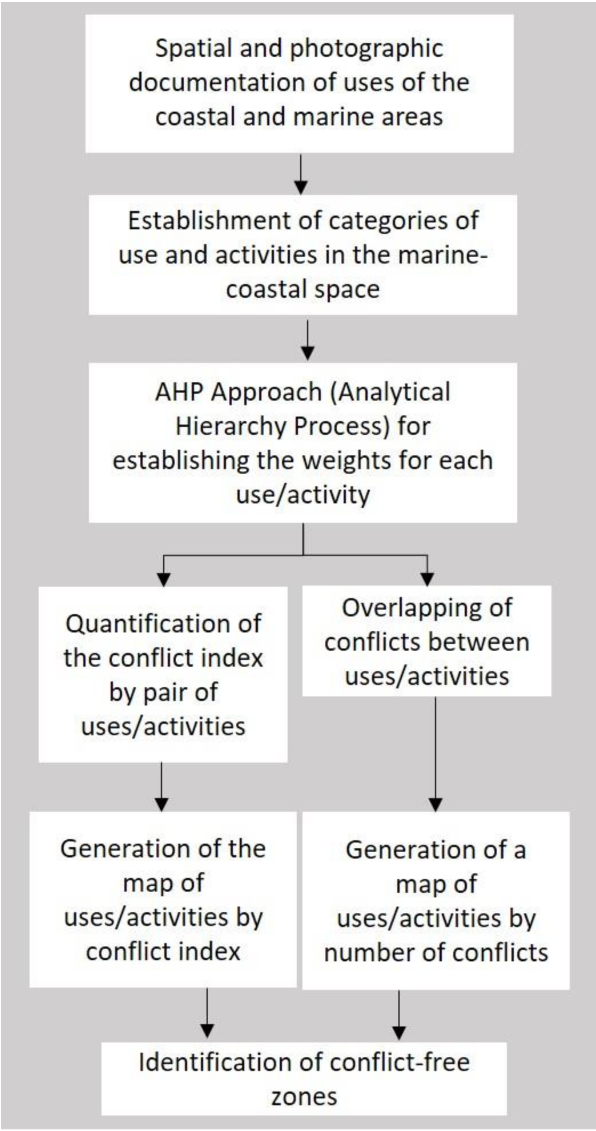

Figure 2. Methodological process for the analysis of current conflict-related conditions.

Analysis of future conditions

In this stage (Fig. 3), the Assignment and Co-location Model (MAYC) was implemented, seeking to spatially establish the best location of uses with a tendency to development, in places that meet certain technical and environmental criteria. Based on this, scenarios are proposed that allow the identification of opportunities, conflicts and compatibilities to guide decision-making (Afanador-Franco *et al.,* 2021).

In this case, the scenarios before and after the COVID-19 pandemic were considered, and the characteristics of future growth and development for the uses of aquaculture, wind farms and submarine cables were evaluated (Afanador-Franco *et al.,* 2022, 2023).

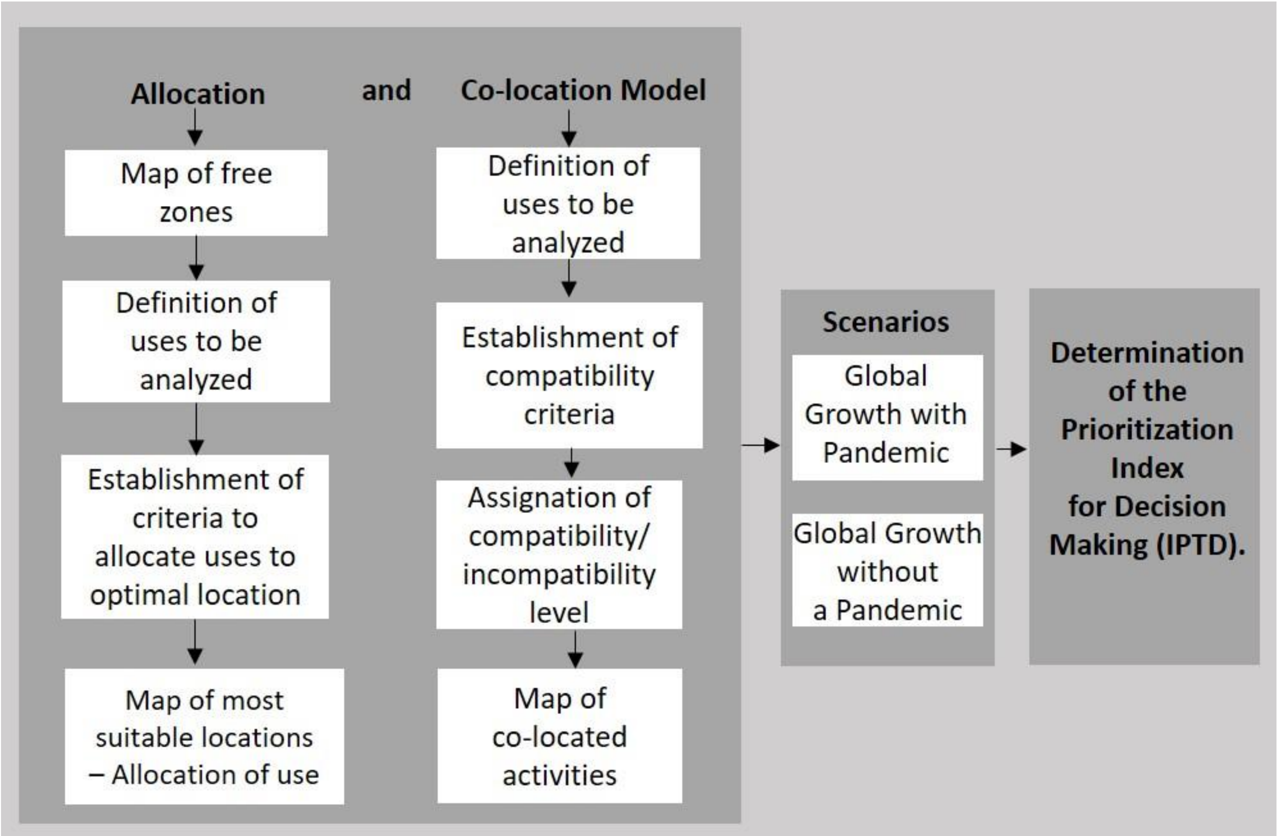

Figure 3. Methodological process for the analysis of future conditions.

Allocation analysis. The technical and environmental criteria (depth, type of bottom, currents, waves, among others) were established through bibliographic information, expert judgment and availability of data. They were subdivided into sub-criteria of suitable, moderately suitable and unsuitable conditions; then they were cross-referenced through GIS tools to determine the location of possible suitable areas for the future development of a use in areas free of maritime activities, as it is today. The detailed process of this stage is described in Afanador-Franco *et al.,* 2022.

Co-location analysis. This stage concentrated on the development of uses in the same geographical space, minimizing their conflicts by means of a compatibility scale between pairs of uses that evaluates the positive and/or adverse effects. A matrix was built with the criteria established in the allocation analysis and with variables of efficiency and effectiveness (proximity to the coast, tourist vocation, water quality, among others) defined for each use. The detailed process of this stage is described in Afanador-Franco *et al.,* 2022.

Future development scenarios and percentage of future trend. The following scenarios were defined: *i)* Global Growth without a Pandemic, in which it is assumed that the COVID-19 pandemic did not occur and that the growth trends of maritime activities will continue until 2030. *(ii)* Global Growth with Pandemic, which estimated the recovery of future maritime development trends during COVID-19 until 2030. For each activity, the percentage of future trend under each scenario was established through bibliographic information (Afanador-Franco, Molina-Jiménez, Pusquin-Ospina, Barrientos, Banda-Lepesquer, & Castro-Mercado, 2023).

Determination of the Prioritization Index for Decision Making (IPTD). Taking into account the MAYC analysis and the scenarios defined for each activity, the IPTD was calculated, based on the development trend and the relationship between the area of the suitable area and the total study area, which allows defining, among several activities, which one should be given priority in the event that several requests for the space are submitted to be developed at the same time (Afanador-Franco *et al.,* 2023).

To calculate the IPTD between several uses, a normalization was performed, in which values close to 1 indicate which use should be prioritized, since it has a greater growth and representativity tendency. The detailed process of this stage is described in Afanador-Franco *et al.,* 2023.

Results

Governance elements

In the MCM:MAV, national and international decrees, policies, conventions and/or agreements were identified as:

- Decree Law 2324 of 1984, which establishes that the General Maritime Directorate has as its purpose the regulation, direction, coordination and control of maritime activities.
- Decree 5057 of 2009, which defines the functions of the Director General of Maritime Affairs, specifying the responsibility of planning, directing, coordinating and evaluating the regulations for the development, control and surveillance of maritime activities.
- Dimar's Strategic Plan 2042 (Dimar, 2022), which defines the strategic objectives corresponding to "directing the promotion and safe and sustainable development of maritime activities" and "influencing the national and international sphere to consolidate maritime interests."
- The General Policy of Land Use (PGOT) (DNP, 2020b), which aims to "guide the physical, socio-spatial and political-administrative organization of the national territory."
- The National Ocean and Coastal Spaces Policy (Pnoec) (CCO, 2018) and the National Council for Economic and Social Policy Conpes-3990 (DNP, 2020a) that stipulate the inter-institutional objective of turning Colombia into a biooceanic power, through the connection of the continental territory to the oceanic territory.
- The National Development Plan 2022- 2026 (DNP, 2023), which establishes the axes of transformation related to land use planning around water (functional approach to land use) and productive transformation, internationalization and climate action (use of clean energy).
- The 1974 International Convention for the Safety of Life at Sea and the 1978 SOLAS 74/78 protocol, related to the standards that merchant ships must comply with to carry out safe navigation.
- The International Convention for the Prevention of Pollution from Ships, which focuses on issues of oil pollution, the handling of harmful liquid substances, the transport of harmful substances, and sewage and garbage from ships: MARPOL 73/78.

In addition, information on maritime activities was compiled from data available from different entities at the national level related to the management and planning of coastal marine spaces, and for an adequate representation of the uses/activities identified between the limit of public use assets and 200 nautical miles, scales between: 1:1 750 and 1:820 000, under the MAGNA-SIRGAS coordinate system with single origin (CTM12) (Afanador-Franco *et al.,* 2019, 2021).

Pre-planning

For the purposes of the development of coastal marine planning, in the study area of the Archipelago of San Andrés, Providencia y Santa Catalina, 517 primary actors were identified related to activities such as fishing (1), tour operators (3), hotels (188), restaurants (161), water sports (29), commercial sector (74), marinas (8), institutional sector (49), cooperatives (1), submarine cables (3), in addition to 32 secondary actors from different sectors such as defense, environment, tourism, fisheries and telecommunications. The results obtained during the MCM:MAV will be shared with all of them in order to provide feedback on the process (Afanador-Franco *et al.,* 2019, 2021).

Current conflict-related conditions

The categories of uses/activities were established in accordance with Decree Law 2324 of 1984, corresponding to maritime activities in which Dimar has interference, such as land uses and a natural base classified by ecosystem function, according to the definition of De Groot, Wilson and Boumans (2002) and Portman (2016). 38 uses/activities were identified, which correspond to 32 uses categorized into 11 maritime activities and 6 uses included in the classification of land uses.

The information was compiled from available databases provided by different entities such as Dimar, the National Hydrocarbons Agency (ANH), the Providencia Territorial Land Use Plan, Tremarctos Colombia 3.0, National Natural Parks of Colombia, the Information System for the Management of Mangroves of Colombia (SIGMA), the Institute of Marine and Coastal Research "José Benito Vives de Andréis" (Invemar), the Colombian Institute of Rural Development (Incoder) and the University of Bogotá "Jorge Tadeo Lozano" (Table 1).

Table 1. Categories of uses/activities for the coastal marine zone of the Archipelago of San Andrés, Providencia y Santa Catalina.

Item	Maritime activities (Decree-Law 2324/84)	Use/Activity
1	Maritime Signaling	Buoys & Lighthouses
2	Maritime traffic control	Anchoring areas
3		Navigation channels
4	Construction, operation and management of port facilities	Port concessions
5	Administration and development of the coastal zone	Maritime concession for submarine outfalls
6		Hotel maritime concession
7		Maritime concession restaurants
8		Marine Maritime Concession - Marinas
9	Placement of any type of structure, fixed or semi-fixed works on the marine ground or subsoil	Submarine cables
10		Underwater pipeline
11	Conservation, preservation and protection of the marine environment	Threatened species
12		Concentration of birds
13		Concentration of mammals
14		Reptile concentration
15		Regional National Parks
16		National Natural Parks
17		Marine protected area
18		Seagrasses
19		Corals
20		Artisanal fishing area
21		White fishing area

Item	Maritime activities (Decree-Law 2324/84)	Use/Activity
22	Use, protection and preservation of coastlines	Public use goods - beaches
23		Public use goods - low tide
24		Mangrove
25	Search and extraction/retrieval of antiques or shipwrecked treasures	Shipwrecks
26	Recreation and marine nautical sports	Diving
27		Water sports area
28	Dredged fills and ocean engineering works	Coastal protection works
29		Dredged fills and ocean engineering works
30	Other marine uses and/or exploitation	Restricted areas
31		White fishing route
32		Artificial reefs
33	Land uses	Urban area
34		Tourism
35		Institutional
36		Animal husbandry
37		Agriculture
38		Beaches with a tourist vocation

According to what was obtained through the AHP approach, the uses that contribute the most to the conflict correspond to restricted areas, marine protected areas, artisanal fishing areas, beaches with a tourist vocation and corals (Table 2, Fig. 4). On the other hand, the maritime activities with the highest number of conflicts identified from the overlaps for the Archipelago of San Andrés, Providencia y Santa Catalina correspond to the artisanal fishing zone, restricted areas, marine protected area, seagrasses and corals (Table 3, Fig. 5).

Finally, the map of conflict-free zones and the map of use-free zones were generated, as a result of a process with GIS tools in which the areas occupied by conflicts and by the different uses/activities, respectively, are extracted (figures 6 and 7).

Table 2. Uses that contribute most to conflict in the marine coastal area of the Archipelago of San Andrés, Providencia y Santa Catalina.

Use/Activity	Weight
Restricted areas	0.1221
Marine protected area	0.0988
Artisanal fishing area	0.0833
Beaches with a tourist vocation	0.0553
Corals	0.0459

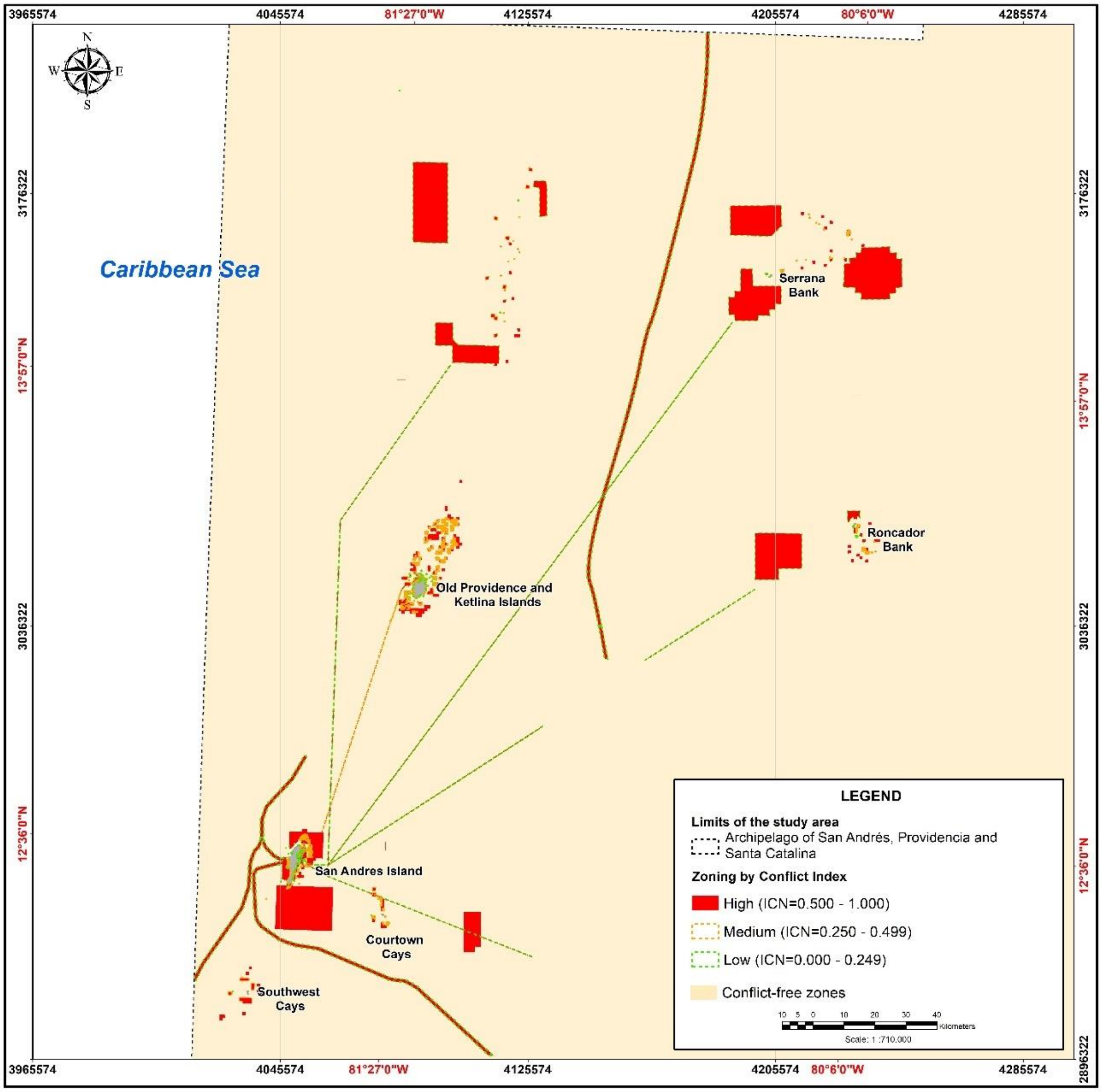

Figure 4. Zoning map by conflict index in the Archipelago of San Andrés, Providencia y Santa Catalina.

Table 3. Uses with more overlaps in the coastal marine area of the Archipelago of San Andrés, Providencia y Santa Catalina.

Use/Activity	Conflicts
Artisanal fishing area	19
Restricted areas	19
Marine protected area	17
Seagrasses	15
Corals	15

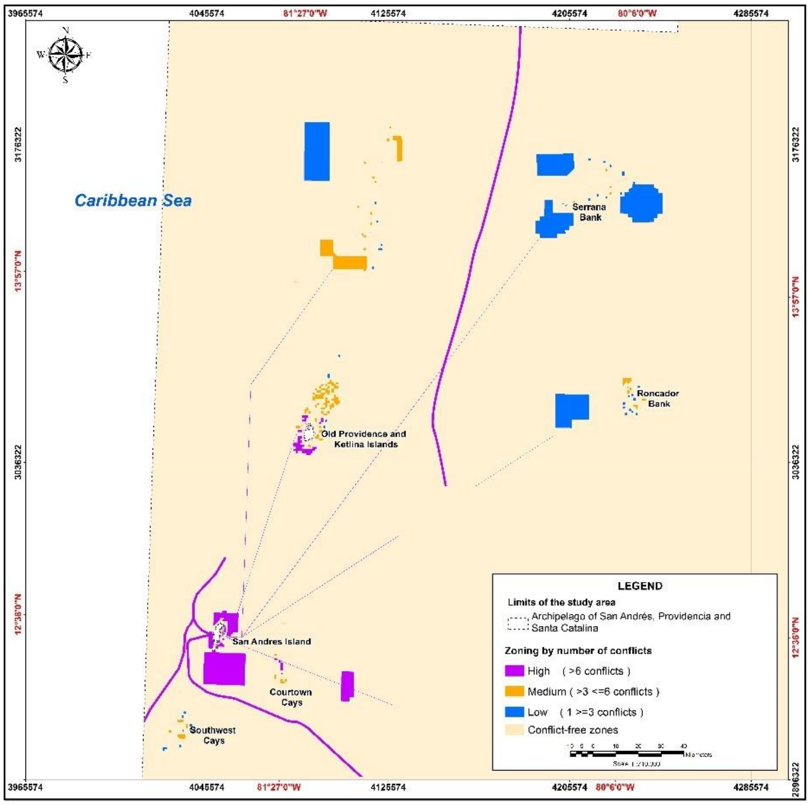

Figure 5. Zoning map by number of conflicts in the Archipelago of San Andrés, Providencia y Santa Catalina.

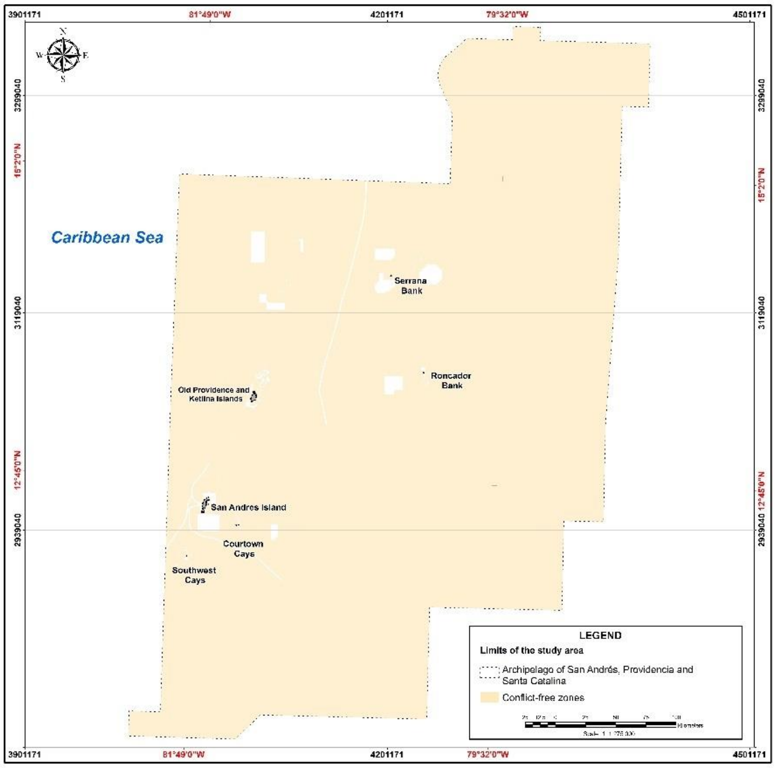

Figure 6. Map of conflict-free zones in the Archipelago of San Andrés, Providencia y Santa Catalina.

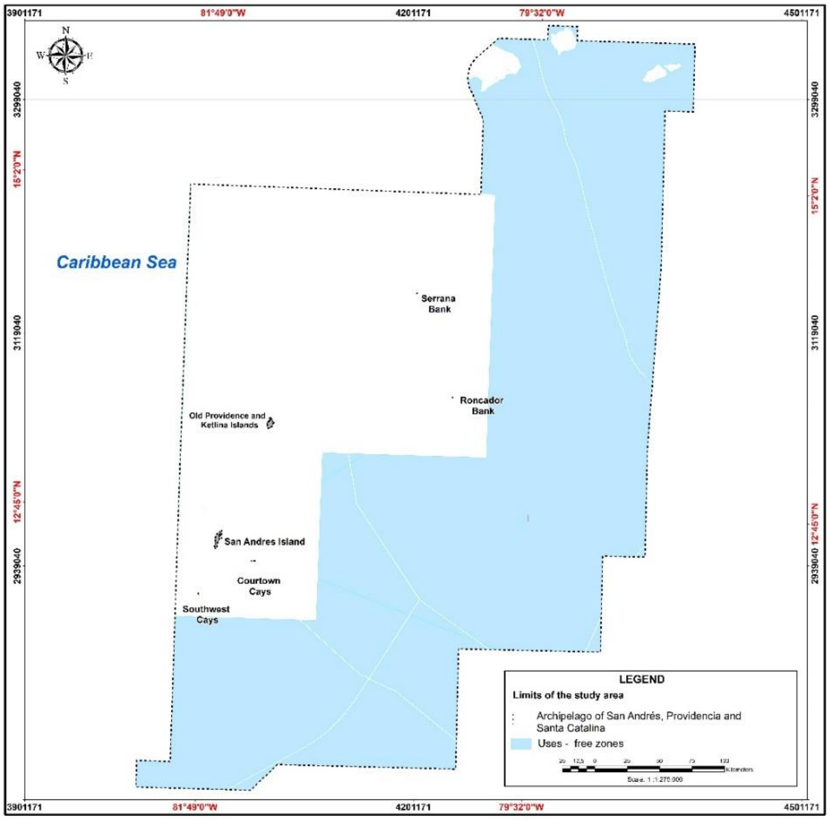

Figure 7. Map of free use zones in the Archipelago of San Andrés, Providencia y Santa Catalina.

Future conditions

Allocation. Aquaculture, wind farms, and submarine cable activities were selected because they present a greater trend of future development in both economic and social terms, thus the most suitable areas for their location and development in the study area were established (Afanador-Franco *et al.,* 2022).

Aquaculture. The determination of areas suitable for future aquaculture development was defined using the available oceanographic criteria and data: seabed type, swell period, significant wave height, currents and possible effects on sediments. In this case, depth was not taken into account, because it varies depending on the species to be grown (Table 4; Fig. 8).

Table 4. Technical and environmental criteria used in the establishment of the most suitable areas for the development of aquaculture.

Criterion	Weight of the criterion	Sub-criteria	Weight of the sub-criterion	Category	* Weighted weight	Source
Type of seabed	0.20	a) Sandy	0.5	Suitable	0.100	Meindl, 1996; Rojo, 2016; Cardia, Ciattaglia, & Corner, 2017; Ivars, 2017; Queensland Government, 2019
		b) Rocky	0.35	Moderately suitable	0.070	
Swell period (T)	0.12	a) 1.9 s < T ≤ 359 s	0.5	Suitable	0.060	Munk, 1950 in Palomino, Almazán, & Arrayás, 2001; Rubino, 2008; Cavia del Olmo, 2009; Kapetsky, Aguilar, & Jenness, 2013; COWI & Ernst, 2013; López and Ruiz, 2015

Criterion	Weight of the criterion	Sub-criteria	Weight of the sub-criterion	Category	* Weighted weight	Source
Significant wave height (Hs)	0.13	a) 0.59 m < Hs ≤ 6.9 m	0.5	Suitable	0.065	Munk, 1950 in Palomino, *et al.,* 2001; Rubino, 2008; Cavia del Olmo, 2009; Kapetsky *et al.,* 2013; COWI & Ernst, 2013; López and Ruiz, 2015
Current speed (Wc)	0.25	a) 0.13 m/s < Wc ≤ 1 m/s (Average)	0.5	Suitable	0.125	Milne, 1976; Carroll, Cochrane, Fieler, Velvin, & White, 2003; Stigebrandt, 2011; Kapetsky *et al.,* 2013; COWI & Ernst, 2013; López & Ruiz, 2015
		b) 0 m/s ≤ Wc ≤ 0.13 m/s (Slow)	0.35	Moderately suitable	0.087	
Direct destruction	0.30	a) Sediments	0.4	Suitable	0.120	Handy & Poxton, 1993; Boyd, 1995; FAO, 2006; Pérez, García, Invers, & Ruiz, 2008; Herbeck, Unger, Wu, & Jennerjahn, 2013; Rabasso, 2016

**weighted weight = criterion weight x subcriterion weight*

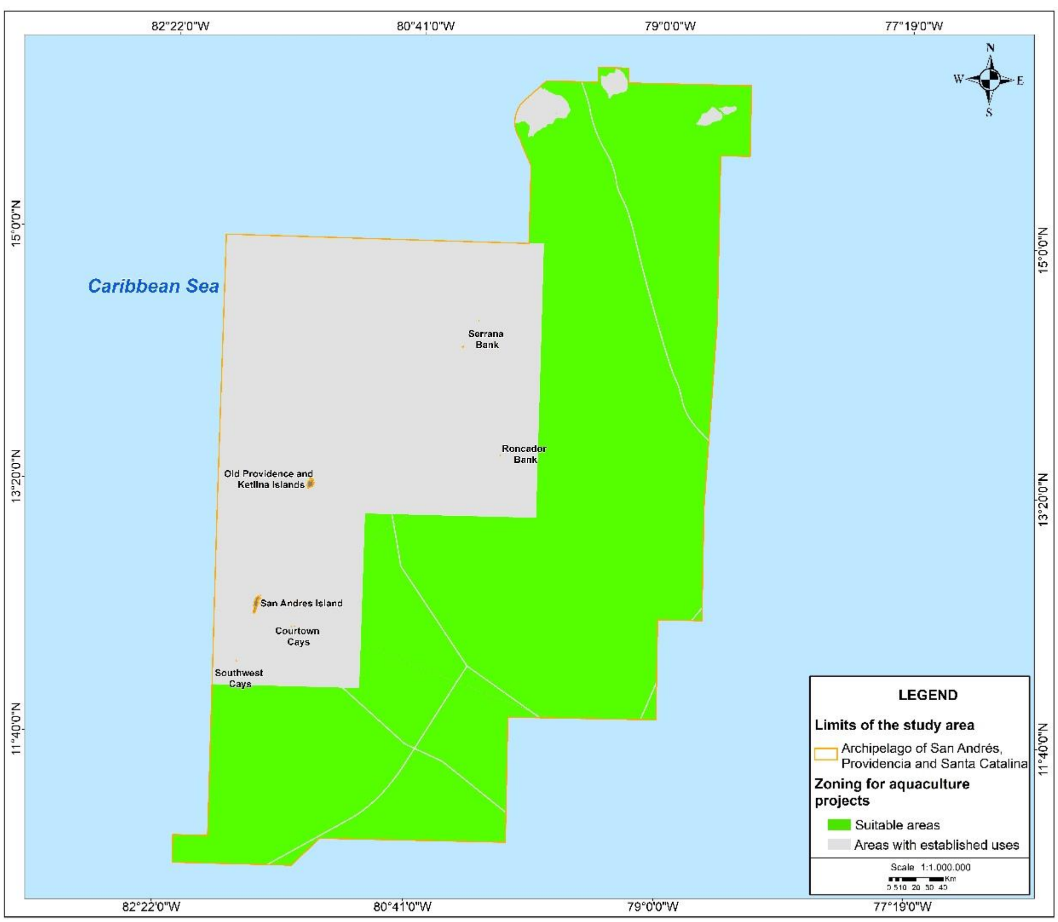

Figure 8. Map of the location of areas suitable for the development of aquaculture projects in the jurisdiction of the Archipelago of San Andrés, Providencia y Santa Catalina.

Wind farms. The criteria used for the optimal location of wind farms were: depth, currents, significant wave height, wind speed at an altitude of 150 m with respect to sea level, type and slope of the bottom, in addition to the possible effects on sediments (Table 5; Fig. 9).

Table 5. Technical and environmental criteria used in the establishment of the most suitable areas for the development of wind farms.

Criteria	Weight of the criterion	Sub-criteria	Weight of the sub-criterion	Category	*Weighted weight	Source
Depth (P)	0.25	a) 0 m – 60 m	0.7	Suitable	0.175	Usón, 2014; Fugro Marine Geoservices Inc., 2017; Vagiona and Kamilakis, 2018
		b) > 60 m	0.3	Moderately suitable	0.075	
Type of seabed	0.12	a) Sandy	0.5	Suitable	0.060	Boehlert & Gill, 2010; Prado, 2018; Xu *et al.*, 2020
		b) Mud and silt	0.35	Moderately suitable	0.042	
Seabed slope (Pf)	0.11	a) 0 % - 3 %	0.5	Suitable	0.055	Malhotra, 2010; Xu *et al.,* 2020
		b) 3 % < x ≤12 %	0.35	Moderately suitable	0.038	
Current speed (Wc)	0.03	a) 0 – 1.75 m/s	0.7	Suitable	0.021	Kapetsky *et al.,* 2013; González, 2007; Esteban, 2009; Loughney, Wang, Bashir, Armin, & Yang, 2021
		b) > 1.75 m/s	0.3	Moderately suitable	0.009	
Significant wave height (Hs)	0.04	a) 0 – 5 m	0.5	Suitable	0.020	Loughney *et al.,* 2021
		b) 5 m < Hs ≤ 8 m	0.35	Moderately suitable	0.014	
Wind speed (V)	0.28	a) >8 m/s	0.8	Suitable	0.224	Baban & Parry, 2001; Sesma, 2020
Direct destruction	0.09	a) Sediments	0.5	Suitable	0.045	Mariyasu, Allain, Benhalima, & Claytor, 2004; Inger *et al.*, 2009; Wilhelmsson *et al.*, 2010
Sediment plume generation	0.08	a) Sands	0.6	Suitable	0.048	NOAA, 2007; Vaselli, Bertocci, Maggi, & Benedetti-Cecchi, 2008

**weighted weight = criterion weight x subcriterion weight*

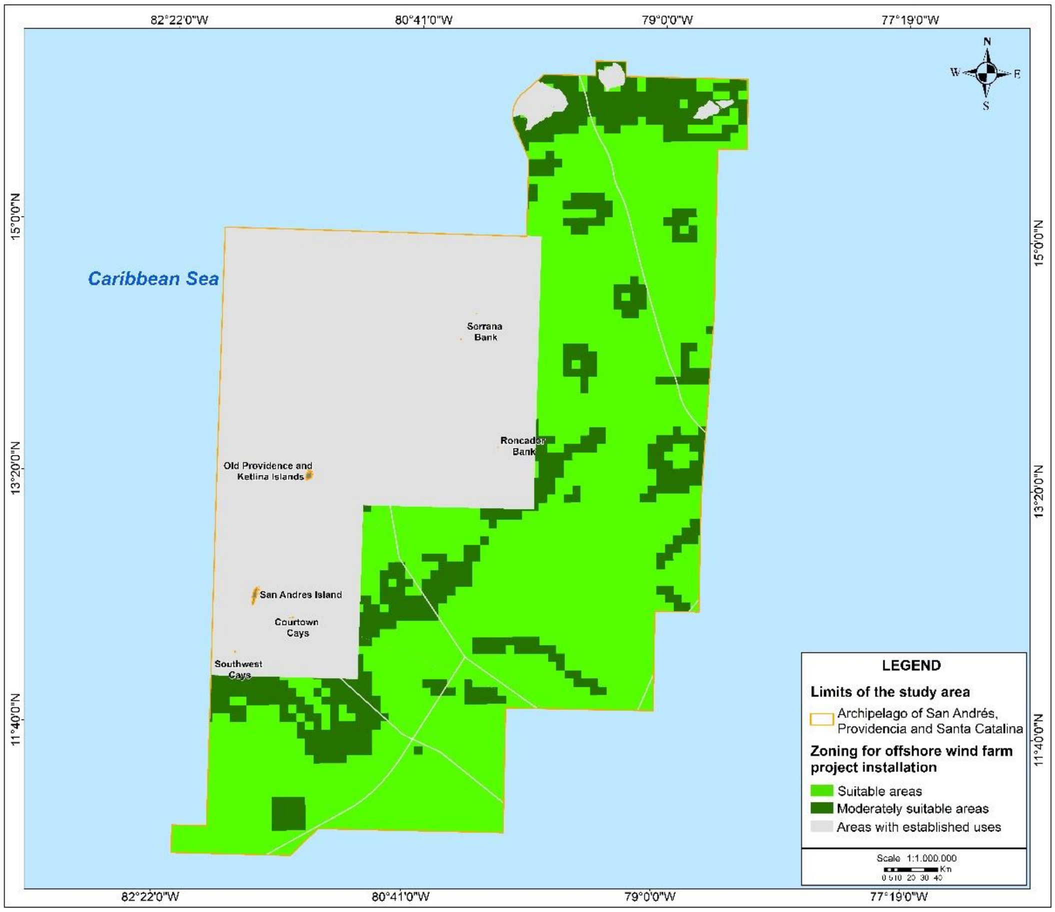

Figure 9. Map of the location of suitable and moderately suitable areas for the development of wind farms in the Archipelago of San Andrés, Providencia y Santa Catalina.

Submarine cables. The determination of the areas suitable for the future development of submarine cables was defined using criteria and available oceanographic data, slope and type of seabed, swell period, significant wave height, currents, possible effects on coastal marine ecosystems and the generation of sediment plumes (Table 6; Fig. 10).

Table 6. Technical and environmental criteria used in the establishment of the areas most suitable for the development of submarine cables.

Criteria	Weight of the criterion	Sub-criteria	Weight of the sub-criterion	Category	*Weighted weight	Source
Seafloor slope (Pf)	0.25	a) Pf ≤ 3 % b) 3 % of < Pf ≤ 12 %	0.5 0.35	Suitable Moderately suitable	0.125 0.0875	Carter *et al.* (2009), Álvarez (2017); Taormina *et al.*, (2018).
Type of seabed	0.20	a) Sandy b) Mud and silt	0.5 0.35	Suitable Moderately suitable	0.1 0.07	Almazán, Palomino and García, (200); Carter *et al.* (2009); Worzyk (2009); Álvarez (2017)
Deep currents (Wc)	0.10	a) 0 m/s ≤ Wc ≤ 1.75 m/s b) Wc > 1.75	0.6 0.4	Suitable Moderately	0.06 0.04	Carter *et al.* (2009); Cavia del Olmo (2009); Guande, Yancong Peng, Chengkai, Xiaoli, and Yang,

		m/s		suitable		(2013)

Criteria	Weight of the criterion	Sub-criteria	Weight of the sub-criterion	Category	*Weighted weight	Source
Swell period (T)	0.05	a) T ≤ 1.9 s b) 1.9 s < T ≤ 359 s	0.5 0.35	Suitable Moderately suitable	0.025 0.0175	Munk (1950) en Palomino, *et al.*, (2001); Carter, *et al.* (2009), and Cavia del Olmo (2009).
Significant wave height (Hs)	0.07	a) Hs ≤ 0.59 m b) 0.59 m < Hs ≤ 6.9 m	0.5 0.035	Suitable Moderately suitable	0.035 0.0245	Carter et al., (2009) y Cavia del Olmo (2009)
Direct destruction	0.18	a) Sediments	0.5	Suitable	0.09	Carter *et al.* (2009); Andrulewicz, Napierska y Otremba (2002); Taormina *et al.* (2018)
Sediment plume generation	0.15	a) Sands	0.6	Suitable	0.09	Taormina *et al.* (2018); OSPAR (2009); ESSO (2008); Newcombe and MacDonald (1991); Pinilla, Gutiérrez, & Ulloa-Delgado (2007)

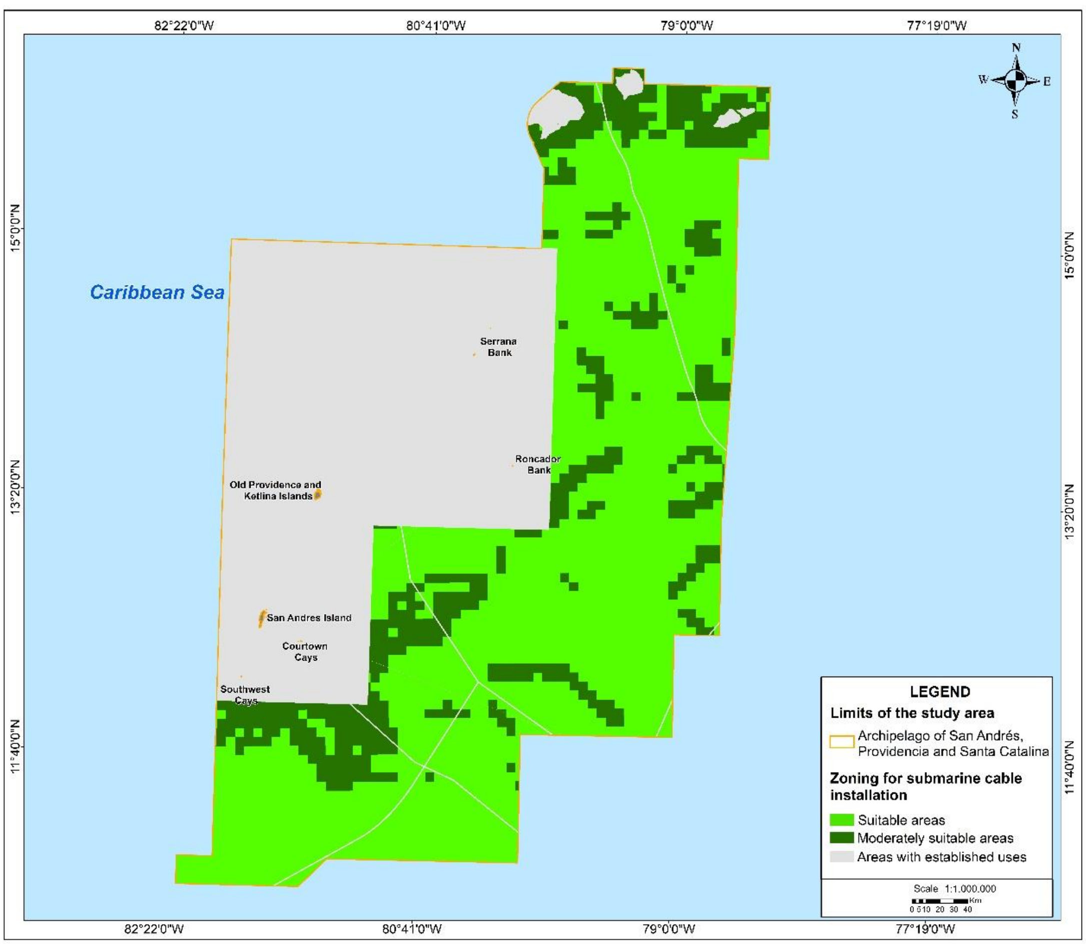

Figure 10. Map of the location of suitable and moderately suitable areas for the installation of submarine cables in the Archipelago of San Andrés, Providencia y Santa Catalina

Co-location

This analysis was based on the elaboration of a cross-matrix between pairs of uses (aquaculture, marine-jetties, submarine cables and wind farms). It took into account the average of the values obtained from the technical/environmental criteria and the efficiency/effectiveness variables established through expert judgment, to determine whether the two uses are mutually improving, do not interfere with each other or negatively affect each other, where values close to 1 indicate greater compatibility between maritime activities (Afanador-Franco *et al.,* 2022) (Table 7).

Table 7. Analysis of the level of compatibility of the uses evaluated.

Uses	Technical and environmental criteria	Efficiency and effectiveness variables	Average	Expression of compatibility/ incompatibility
Aquaculture *vs.* wind farm	0.080	0.750	0.415	Conditionally incompatible
Aquaculture *vs.* submarine cables	0.075	0.750	0.412	Conditionally incompatible
Wind farm *vs.* submarine cables	0.100	1.000	0.550	Conditionally compatible

Additionally, the IPTD was calculated taking into account the two established scenarios. It reflects both the degree of development trend for aquaculture, offshore wind farms and submarine cables, as well as the representativeness between each pair of uses (tables 8 to 10 and figures 11 to 13) (Afanador-Franco *et al.,* 2023; Communications Regulation Commission, 2020; Echeberría, 2020; GWEC, 2019, 2021; FAO, 2016, 2020; Research and Markets, 2020, 2022; TeleGeography, 2022).

Table 8. Prioritization Index for Decision-Making under the non-pandemic and pandemic scenarios for aquaculture uses and offshore wind farms.

Scenario	Use/Activity	Growth trend (%)	Total area of the suitable areas (km^2)	IPTD	IPTD Standardized
No pandemic	Aquaculture suitable areas	46 (FAO 2016, 2020)	101663.8963	0.4597	0.7302
	Offshore wind farms suitable areas	17 (GWEC, 2019)	79717.3333	0.1332	0.2116
	Offshore wind farms moderately suitable areas	17 (GWEC, 2019)	21933.91055	0.0367	0.0582
With a pandemic	Aquaculture Suitable areas	42 (FAO 2020).	101663.8963	0.4197	0.5834
	Offshore wind farms suitable areas	30 (GWEC 2021).	79717.3333	0.2351	0.3267
	Offshore wind farms moderately suitable areas	30 (GWEC 2021).	21933.91055	0.0647	0.0899

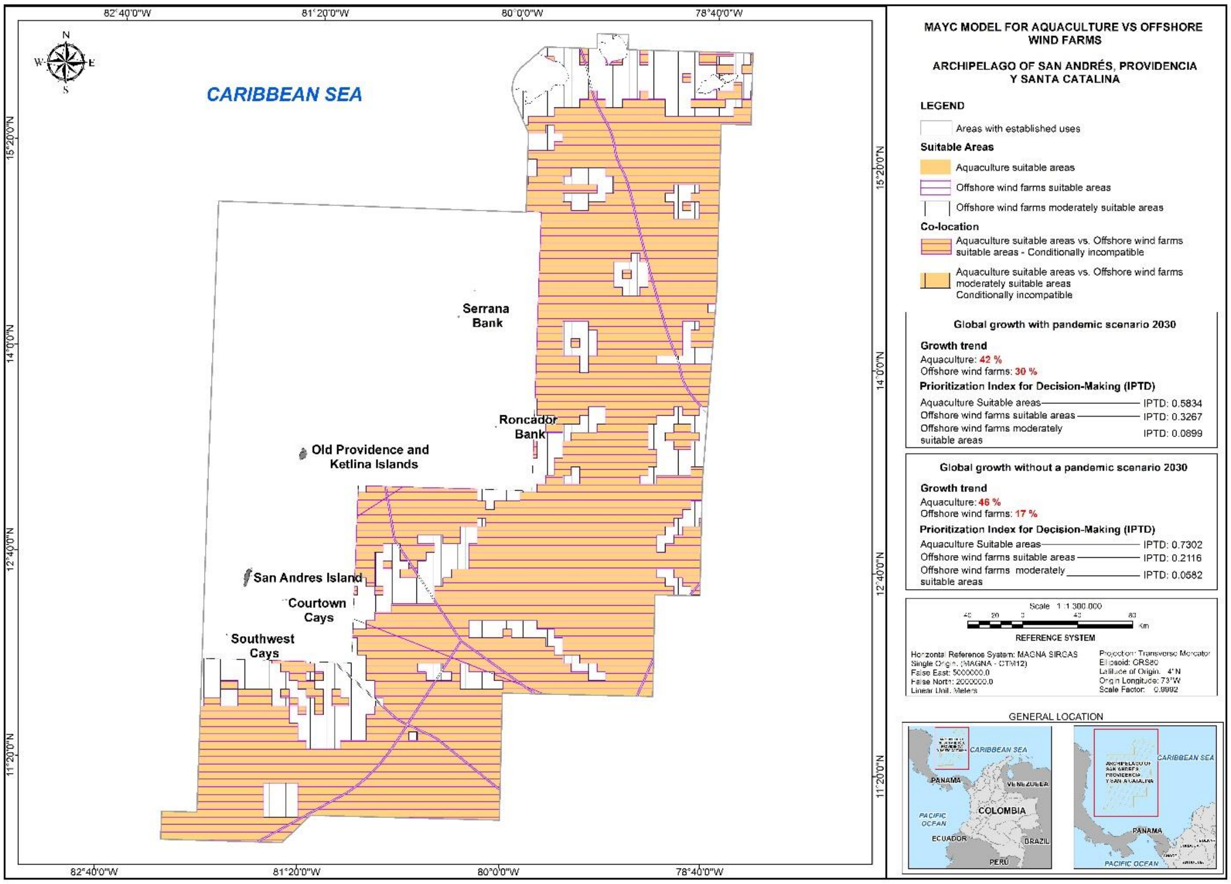

Figure 11. Map of future conditions for aquaculture and offshore wind farms in the scenario with and without pandemic of the Archipelago of San Andrés, Providencia y Santa Catalina.

Table 9. Prioritization Index for Decision-Making under non-pandemic and pandemic scenarios for aquaculture and submarine cable uses.

Scenario	Use/Activity	Growth trend (%)	Total area of the suitable areas (km²)	IPTD	IPTD Standardized
No pandemic	Aquaculture Suitable areas	46 (FAO 2016, 2020).	101663.8963	0.4597	0.9350
	Submarine cables Suitable areas	3.2 (Echeberría, 2020; Research and Markets, 2020).	80219.62134	0.0252	0.0513
	Submarine cables Moderately suitable areas	3.2 (Echeberría, 2020; Research and Markets, 2020).	21433.62719	0.0067	0.0137
With a pandemic	Aquaculture Suitable areas	42 (FAO 2020)	101663.8963	0.4197	0.8607
	Submarine cables Suitable areas	6.8 (Research and Markets, 2022; Tele-Geograp,hy 2022).	80219.62134	0.0536	0.1100
	Submarine cables Moderately suitable areas	6.8 (Research and Markets, 2022; Tele-Geography, 2022).	21433.62719	0.0143	0.0294

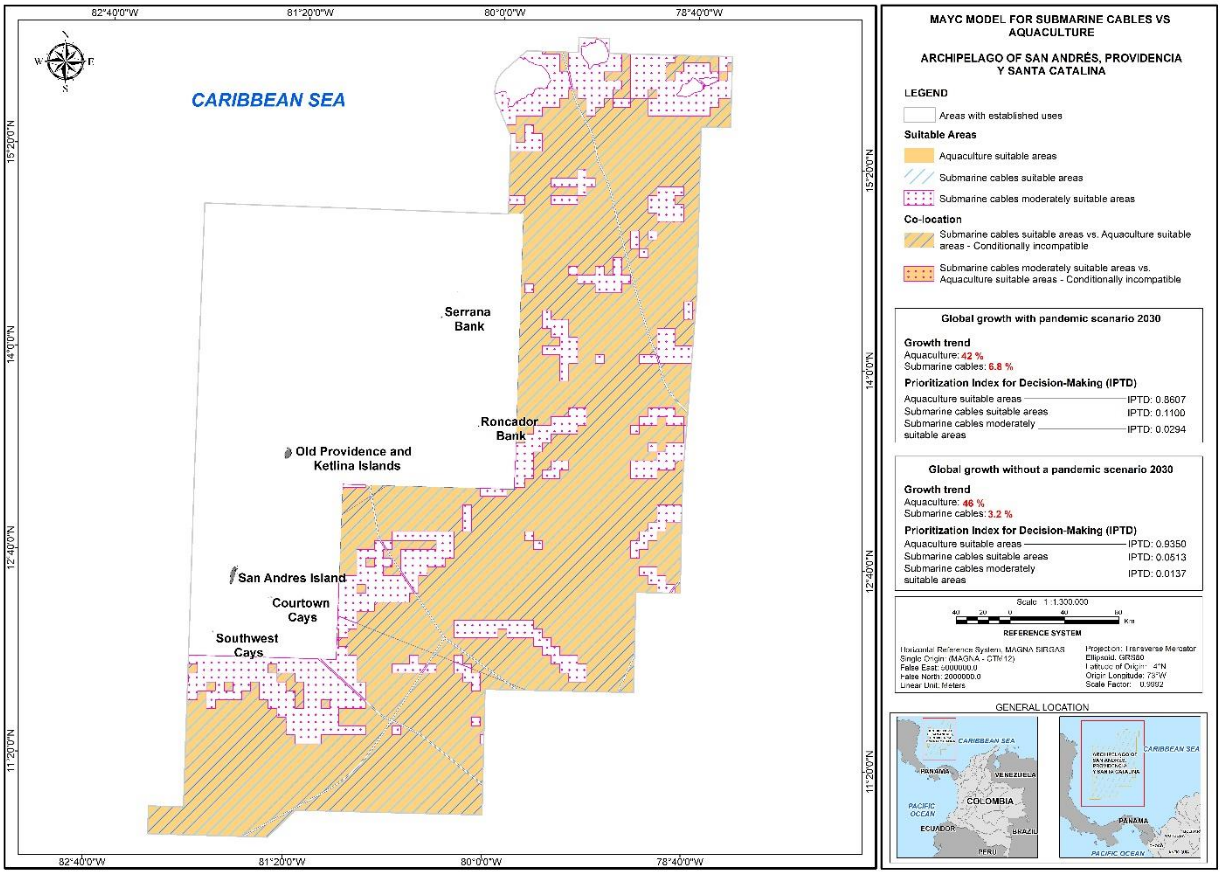

Figure 12. Map of future conditions for aquaculture and submarine cables in the scenario with and without pandemic of the Archipelago of San Andrés, Providencia y Santa Catalina.

Table 10. Prioritization Index for Decision-Making under non-pandemic and pandemic scenarios for the uses of submarine cables and offshore wind farms.

Scenario	Use/Activity	Growth trend (%)	Total area of the suitable areas (km^2)	IPTD	IPTD Standardized
No pande-mic	Submarine cables Suitable areas	3.2 (Echeberría, 2020; Research and Markets, 2020).	80219.62134	0.0252	0.1250
	Submarine cables Moderately suitable areas	3.2 (Echeberría, 2020; Research and Markets, 2020).	21433.62719	0.0067	0.0334
	Offshore wind farms, suitable areas	17 (GWEC 2019).	79717.3333	0.1332	0.6600
	Offshore wind farms, moderately suitable areas	17 (GWEC 2019).	21933.91055	0.0367	0.1816

Scenario	Use/Activity	Growth trend (%)	Total area of the suitable areas (km^2)	IPTD	IPTD Standardized
With a pandemic	Submarine cables Suitable areas	6.8 (Research and Markets, 2022; TeleGeography, 2022).	80219.62134	0.0536	0.1458
	Submarine cables Moderately suitable areas	6.8 (Research and Markets, 2022; TeleGeography, 2022).	21433.62719	0.0143	0.0390
	Offshore wind farms, suitable areas	30 (GWEC 2021).	79717.3333	0.2351	0.6393
	Offshore wind farms, moderately suitable areas	30	21933.91055	0.0647	0.1759

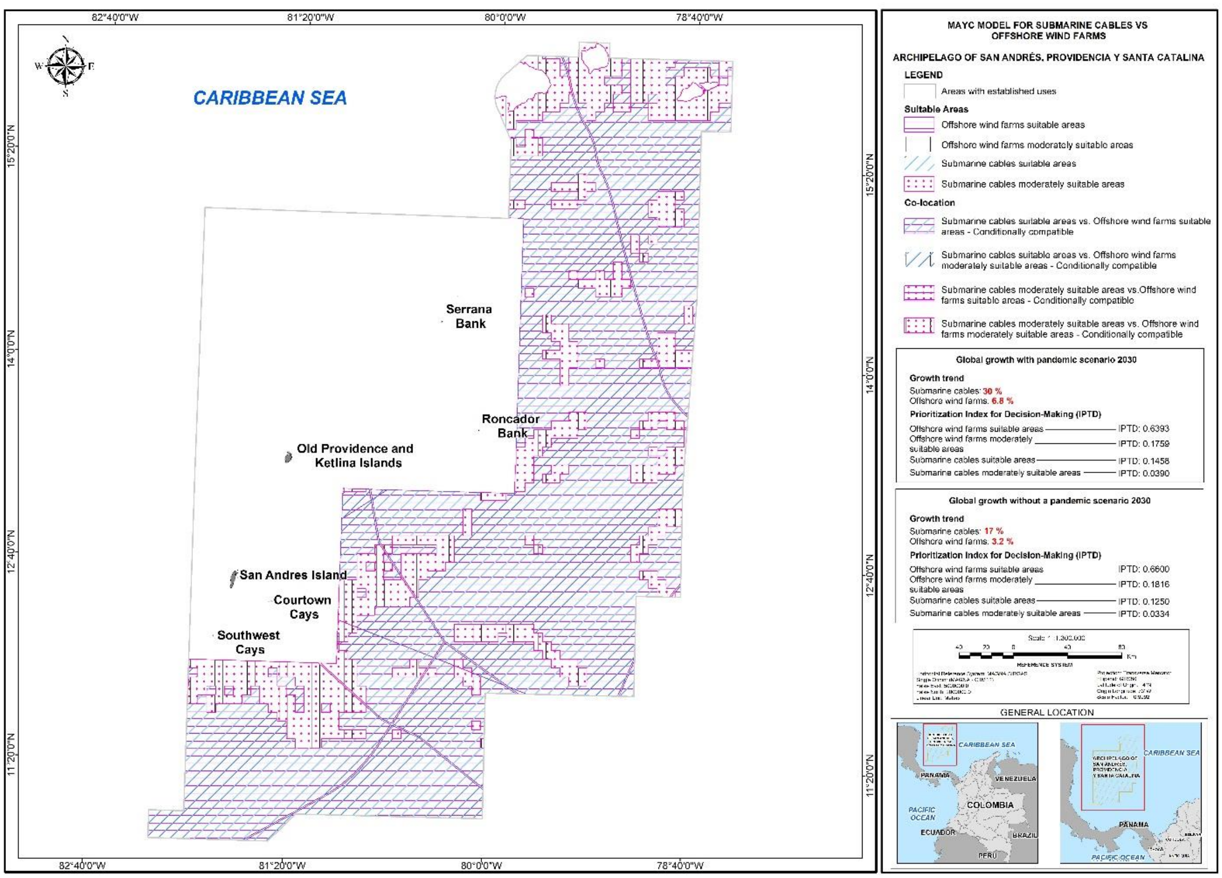

Figure 13. Map of future conditions for submarine cables and offshore wind farms in the scenario with and without a pandemic of the Archipelago of San Andrés, Providencia y Santa Catalina.

Discussion

In the last 20 years, half of the places in the world with marine-coastal areas have implemented Marine Spatial Planning as a tool for the management of these spaces, in order to seek a balance between the conservation of ecosystems and socioeconomic development. In Colombia, DIMAR has implemented its methodology based on the PEM with a quantitative approach in different geographical areas; however, it has been shown that in underdeveloped countries and small islands these processes are affected by factors such as climate change, natural disasters and, mainly, the lack of spatial information related to cultural, economic, ecological and social aspects (Ban, Hansen, Jones, & Vincent, 2009; Ehler, 2021; Mead, 2021). In addition, some island areas may have a much larger marine area than their terrestrial portion, making it difficult to manage marine resources (Jumeau, 2013).

Although progress in the PEM is limited in small islands, due to the different limitations, in some Caribbean islands such as the Dominican Republic, Saint Lucia, the Grenadines, Barbuda, Montserrat, Saint Kitts and Nevis, it has been implemented, with significant progress in the last decade (Flower *et al.,* 2019; Mahadeo, 2022; Pomeroy, Baldwin, & Mc. Conney, 2014; Caribbean Environment Program, 2019; Díaz-Romero, Domínguez-Tejo, & Schill, 2012; The Nature Conservancy, 2012). Likewise, in islands in Asia, French Polynesia and the United Kingdom, among others (André, Van Wynsberge, Chinain, Gatti, Liao, & Andréfouët, 2022; Hardman *et al.,* 2022; Sujadmi & Murtasidin, 2020), these planning instruments have been applied, thus they can become a reference for other island areas.

Globally, economic activities in island areas are mainly related to the tourism and fishing sector (André *et al.,* 2022; Flower *et al.,* 2019; Pratt, 2015). However, due to the limitations of these island spaces, the economy depends on external investments and activities that are mainly carried out in the marine space (André *et al.,* 2022; Flower *et al.,* 2019; Greenhill & Pro, 2018; Pratt, 2015). The Archipelago of San Andrés, Providencia y Santa Catalina is no exception, because it is considered one of the main tourist destinations in Colombia and its economy revolves around this activity, as well as fishing and trade (Aguilera-Díaz, 2016).

Additionally, part of the maritime territory of the Archipelago is protected under the figures of 'marine protected area', 'national natural park' and 'regional national park', with a wide variety of ecosystems that provide services such as food, recreation, coastal protection, among others. However, according to the analysis of the MCM:MAV, it was identified that these areas present a high degree of conflict with uses such as artisanal fishing, beaches with a tourist vocation, landfills, dredging and oceanic engineering works, due to the fact that their regulations limit the development of these activities (Coralina, 2018; Sánchez, 2012).

Despite the maritime activities that are currently being carried out in San Andrés, Providencia y Santa Catalina, one of the challenges of MCM:MAV is to identify the potential for new uses/activities and to establish whether the physical and environmental characteristics of the marine area are adequate for its operation (Afanador-Franco *et al.,* 2022, 2023), contributing to the diversification of the economy and the improvement of the conditions of the population.

Taking into account the above, activities such as aquaculture, wind farms and submarine cables have a high growth trend in the horizon of 2030, due to their importance in terms of food security, clean energy generation and the provision of telecommunications services (Communications Regulation Commission, 2020; Echeberría, 2020; FAO, 2016, 2020; GWEC, 2019, 2021; Research and Markets, 2020, 2022; TeleGeography, 2022). Aquaculture projects are not carried out in the Archipelago (Merino, Bonilla, & Bages, 2013); however, according to Hortúa (2013) and the results corresponding to the suitable areas obtained in this study, it is considered that the area has a high potential for development. Still, it is likely that the current regulations, the lack of research and investment, both from the private and public sectors, added to the costs of transportation, construction, and operation, have not allowed the execution of this activity in these islands (Decree No. 2668 of 2012, Government Department of the Archipelago of San Andrés, Providencia and Santa Catalina, 2020; Greenhill

& Pro, 2018; Merino *et al.,* 2013; Sarmiento-Guerrero, Pérez-Walteros, 2021).

With respect to offshore wind farms, in Colombia, it was only until 2022 that the guidelines for the allocation of areas in the departments of Bolívar and Atlántico were established (Resolution No. 40284 of 2022). Therefore, these types of projects do not exist yet. In the Archipelago, the energy supply has total coverage, but it depends mainly on fossil fuels that produce high air pollution (approximately 134 thousand tons of CO_2 per year). The Archipelago has been making efforts towards the generation of clean energy. Proof of this is the result of this study, which indicates that there is an area of 79,717.33 km^2 of suitable areas (physical and environmental conditions) that correspond to 48.02% of the total area. The studies also point to the potential of wind energy in San Andrés, identifying a possible saving of 8% of the CO_2 emissions currently emitted by the island (IDB, 2016; Grueso-López, 2022).

Likewise, studies have been carried out for the use of wind and solar resources coordinated by the National Learning Service (SENA), highlighting a wind energy proposal that is in the technical feasibility stage (Matiz-Chicacausa *et al.,* 2016; SENA, 2013). However, the construction of these large-scale projects in isolated areas could have very high costs that make their execution difficult (IDB, 2016; Gómez, 2022).

As for submarine cables, before 2020 the Archipelago had only one (San Andrés Isla Tolú Submarine Cable - SAIT), and there were connectivity problems, mainly associated with network saturation and limiting characteristics for the installation of new cables such as geographical location, high infrastructure and transport costs (Martínez, 2017; MinTIC, 2020); however, since 2020, after Hurricane IOTA hit the area, a new submarine cable (America Móvil Submarine Cable System-1, AMX-1) was installed. This generated an advance in telecommunications, increasing the national and international connection that positions it as the second fastest in the country (El Tiempo, 2023). Although the installation of more cables is not planned in the short term, according to the results of the MCM:MAV, the area has 80,219.62 km^2 of areas that meet the physical and environmental conditions for the laying of new submarine cables, which correspond to 48.32% of the Archipelago.

In addition to identifying the activities with the greatest growth potential in the scenarios proposed by Dimar, the MCM:MAV makes it possible to define whether they can be developed in the same geographical space and to establish whether the development of one affects the other, taking into account a co-location analysis, which determines the compatibility/incompatibility between them (Afanador-Franco *et al.,* 2022, 2023). In island areas that have less accessibility due to their geographical location, limited public services, poor food security, among others, the development of large-scale maritime activities can generate high costs, which can limit investment by both the public and private sectors, affecting the quality of life of the population (André *et al.,* 2022; Gómez, 2022; Universidad Distrital "Francisco José de Caldas", 2020). Therefore, it is important to properly manage these spaces, in such a way that it is possible to identify which uses/activities can be more efficient and effective in the same area (Afanador-Franco *et al.,* 2022, 2023).

For the Archipelago, it was identified that aquaculture projects cannot be developed with submarine cables or offshore wind farms, mainly due to the accidental damage that may occur (Afanador-Franco *et al.,* 2022, 2023; Cardia *et al.*, 2017; Meindl, 1996; Queensland Government, 2019; Rojo, 2016). While wind farms, being conditionally compatible with submarine cables, could be executed under certain agreements between the interested parties, since there are common interests such as safety, access, and installation, maintenance, and operations processes on the seabed, their restrictions must be taken into account (Afanador-Franco *et al.,* 2022, 2023; European Commission, n.d.; ESCA, 2016; ICPC, 2013). Additionally, in the event that applications are submitted for these three activities in the same area, according to the value of the IPTD proposed by Dimar, aquaculture should be prioritized with respect to the other two, as it has a greater growth trend and an area suitable for its operation (Afanador-Franco, Molina-Jiménez, Pusquin-Ospina, Barrientos, Banda-Lepesquer and Castro-Mercado, 2023).

Finally, as it is a continuous process and adaptable to the conditions of marine-coastal spaces, the challenge of MCM:MAV is to include climate change in future development scenarios by 2050 in the national territory, recognizing its importance and effects on the planning of maritime activities and natural resources (ECLAC, 2019).

Conclusions

The MCM:MAV is a contribution of DIMAR to the management of marine-coastal activities that take place in the Archipelago of San Andrés, Providencia y Santa Catalina, since their current and future conditions were analyzed, evidencing conflicts, compatibilities and suitable areas for the establishment of new activities.

In the Archipelago area, in the cross-matrix of compensation by pairs, a total of 1,444 crossings were analyzed among the 38 identified uses/activities, of which 288 correspond to areas where there is overlap with conflicts, 180 are areas of overlapping uses, but without conflict, and 976 areas with no overlap between uses/activities.

Likewise, through zoning by conflict index, areas with high, medium and low levels of conflicts were established, depending on the weights assigned from the normalized matrix of compensation by pairs. This indicates that the maritime uses/activities with the highest rate of conflict correspond to restricted areas, marine protected areas, artisanal fishing areas, beaches with a tourist vocation, and corals.

The maritime activities with the most conflicts identified from the overlaps for the Archipelago of San Andrés, Providencia y Santa Catalina correspond to artisanal fishing zones, restricted areas, marine protected areas, seagrasses, and corals.

The application of the MAYC methodology was carried out in the areas free of uses/activities, which represent 61.24 % of the study area, identifying the areas suitable for aquaculture (61.24 %), wind farms (48.02 %), and submarine cables (48.32 %).

The Co-location model made it possible to establish that in areas where aquaculture uses/activities overlap *vs.* wind farms or submarine cables, only one of the two can be developed. Additionally, in cases where proposals for submarine cables with wind farms are submitted and overlap, the interested parties must reach agreements to execute their projects with the minimum number of conflicts.

The IPTD in the two future development scenarios for the Archipelago of San Andrés, Providencia y Santa Catalina suggests that the use of aquaculture should be prioritized over wind farms and submarine cables, due to the fact that it has a greater growth trend.

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