Contributions of the academy for a better understanding of the oceans in Costa Rica

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Resumen

El lanzamiento de la Década de los Océanos en el año 2017 estableció nuevas visiones entre la ciencia y política, para fortalecer la investigación y la gestión de los océanos y las costas. Con un 92% de superficie marina, Costa Rica es una nación de mar, que posee una gran diversidad marina, y que realiza esfuerzos para conocer mejor sus recursos costeros y marinos. En los últimos 20 años, se han desarrollado políticas para promover la gestión integrada de nuestras zonas costeras y la creación de áreas marinas protegidas. Mediante la investigación de las universidades públicas, conocemos mejor, aunque de manera incompleta, cómo se encuentran nuestros recursos pesqueros y acuicultura, los impactos de la contaminación marina y sus efectos sobre organismos y ecosistemas, los impactos del cambio climático, así como los esfuerzos para impulsar la conservación marina y la restauración de los ecosistemas marino-costeros y sus servicios. Del análisis de estas áreas de estudios, es evidente, que existen vacíos de información que deben ser abordados para generar más información científica que permita la toma de decisiones adecuadas y basadas en la ciencia, con el objeto de mejorar las políticas púbicas relacionadas a las zonas costeras, sus recursos, los servicios ecosistémicos, la gestión de las numerosas fuentes de contaminación continental que llegan a la costa y la adaptación al cambio climático.

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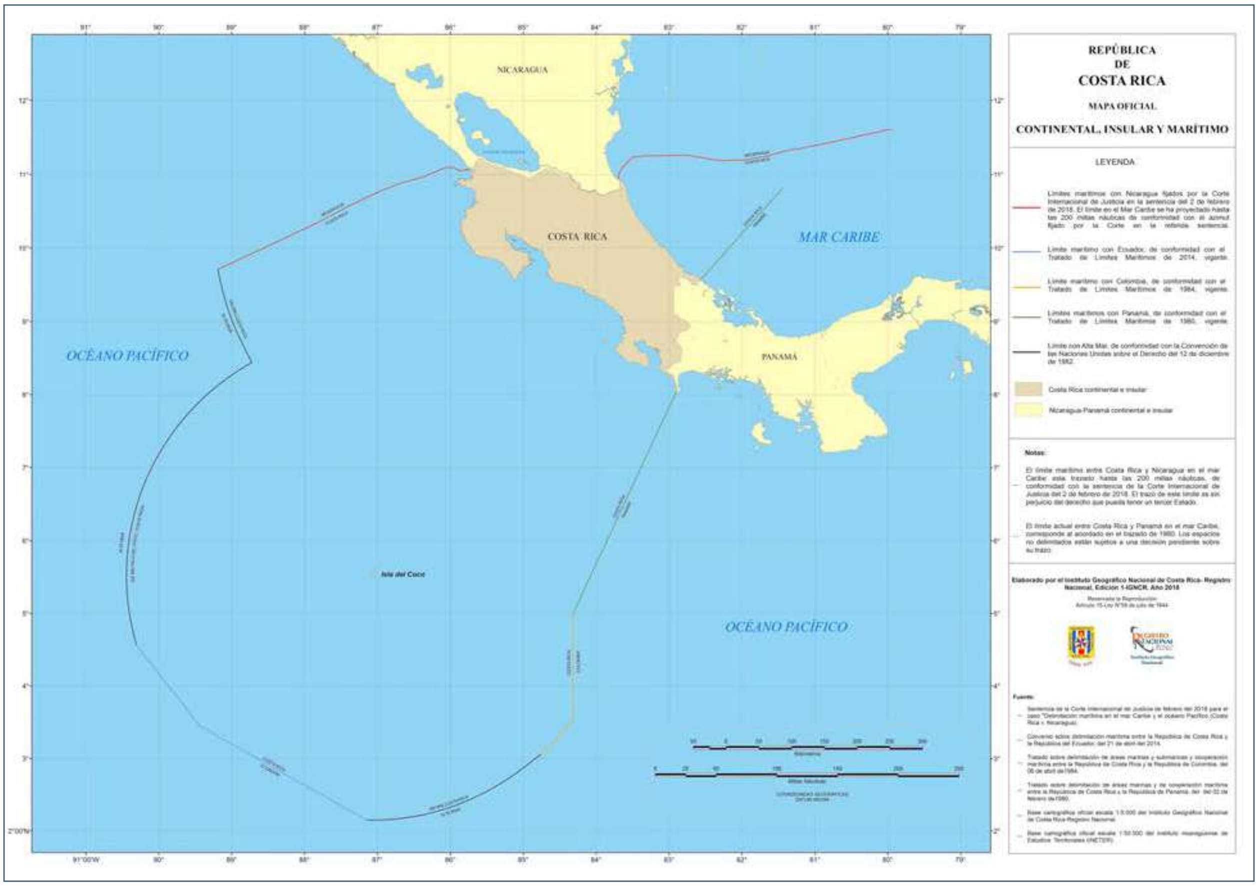


1. Introduction

The ocean covers more than 70% of the Earth's surface. Of this vast area, more than 80% consists of depths greater than 2,000 m. Throughout human history, the oceans have been a means of transportation, recreation, food, oil and mineral extraction, and more recently, a source of substances of medical value. However, many parts of oceanic waters suffer from some type of pollution. The degradation of marine and coastal habitats is notorious, with a significant loss of marine diversity. There has also been marked contamination from solid waste and fishing nets, which have formed large "islands" of plastic in the ocean gyres with an enormous impact on marine life (NOAA, 2020). On the other hand, climate change is causing gradual but very significant changes in the acidity of oceanic waters, with serious economic and environmental consequences. Also linked to climate change, the increase in sea level due to warming of the waters, along with other factors such extraordinary tides and waves, extraordinary waves, and El Niño-Southern Oscillation, have caused significant coastal erosion, loss of mangrove forests, and coral reef bleaching. In response to this situation, June 8th was declared as World Oceans Day by the United Nations in 2008, highlighting that the ocean is not just another resource, but it is the resource that makes all other resources possible. Likewise, the United Nations declared the Decade of Ocean Science for Sustainable Development 2021-2031 (https://oceandecade.org/es/) on December 2017, with the aim of establishing a common framework to support the scientific understanding needed for the sustainable development of the world´s oceans. The Ocean Decade also supports the efforts of countries to achieve the sustainable development goals (SDGs) of the 2030 Agenda for Sustainable Development, in particular SDG 14 on health and life in the oceans.

Located on the frontier between the Caribbean Sea and the Pacific Ocean, Costa Rica is undoubtedly a "blue" nation (Fig. 1). The total area of this "small" country in Central America is composed of only 8% landmass while 92% of its total surface is marine. Costa Rica´s marine areas are highly diverse, serving as a home to 3.5% of the world's marine biodiversity (Wehrtmann & Cortes, 2009). The largest mountain range in the country is the Coco Submarine Volcanic Range, which extends 780 km submerged in the Pacific Ocean and includes a key island for the country, Isla del Coco. About 60% of Costa Rica´s oceans are deeper than 2000m, of which only a small portion have been explored, offering enormous opportunities for scientific studies through international collaborations (Cortés & Cambronero, this volume). Costa Rica has a wide variety of marine and coastal habitats (Nielsen & Quesada, 2006; Cortés, 2016 a,b). However, many of these habitats are degraded and overexploited, contaminated by (micro-) plastics, emerging contaminants, organic matter, and trace metals (see below: Marine Pollution) (Ambientico, 2013). In addition, overfishing of many marine resources is a problem and despite of this situation there are constant efforts by the Costa Rican Government to continue bottom-trawl fishing, which has been virtually banned in Costa Rica since 2013.

Despite these challenges, Costa Rica has produced a wealth of scientific information about its oceans, mostly generated by public universities. Here, we present a brief overview of key efforts by academics thus far towards understanding marine habitats and resources in Costa Rica.

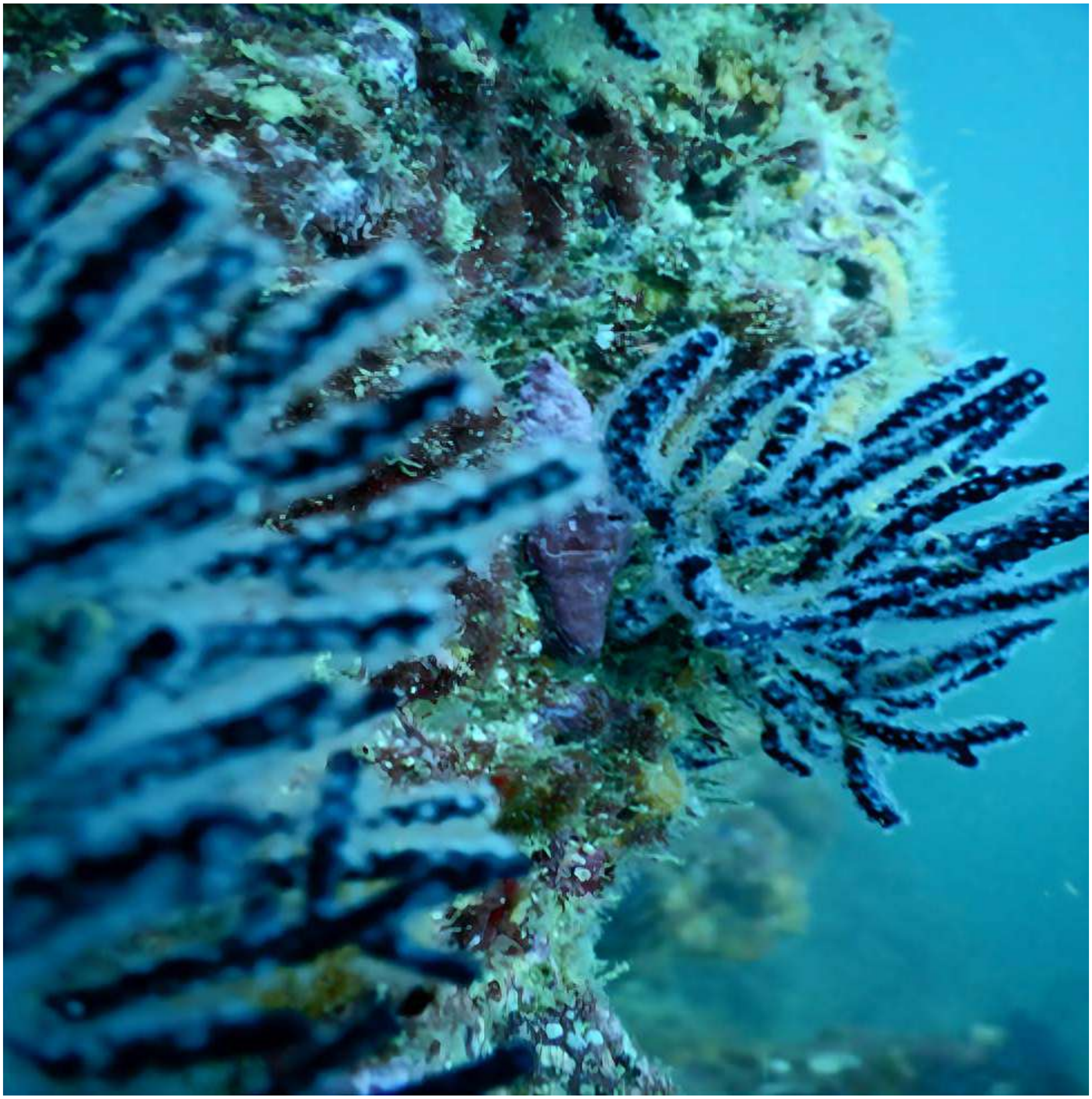
2. Integrated coastal management

During the United Nations Conference on Environment and Development, 175 countries adopted the Agenda 21 by consensus. This Agenda provides guidance on the various aspects of positive human interaction with the environment (Olsen *et al.*, 1995), and its Chapter 17 addressed the international call for an integrated coastal management approach. Integrated Coastal Management (ICM) has been considered worldwide as an appropriate approach to implement comprehensive programs for the protection or development of coastal regions (Cuadrado-Quesada al., 2018). Costa Rica has been highlighted as the first developing country to initiate an ICM program (Sorensen, 1990, 2000), linked to the creation of the Maritime-Terrestrial Zone Law at the end of the 1970s (Decree No. 6043, March 2, 1977). This Law established that the maritime terrestrial zone (ZMT) corresponds to the 200 m horizontal strip inland of the high tide line or the upper limit of estuarine or coastal wetlands (i.e. mangroves) and is of a public nature belonging to the State. Academic efforts in integrated management of its coastal zones began in 1993 with the seminar "Integrated Management of Coastal Zones in Central America", organized by the University of Costa Rica (UCR). This seminar included the participation of several researchers from European and North American universities and concluded the need for the region to develop human resources trained in ICM. In 1997, the UCR joined the ALFA-COSTA International Network (ALFA Program of the European Union), coordinated by the University of Bremen, Germany, from which the Postgraduate Program in Integrated Management of Tropical Coastal Areas (GIACT) at the UCR was born. Also, the GIACT started in

2002 at the UCR within the framework of a second international Network: the ALFA-GIACT. On the other hand, during the first half of the 2000s, the Costa Rican government, public universities and various non-governmental organizations (NGOs) came together and prepared the National Strategy for Integrated Management of Marine-Coastal Resources (CZEE, 2008), which was evaluated very positively by Caviedes (2011). At the beginning of the second decade of the 21 century, the academy was part of another important effort in Costa Rica to generate the first National Policy for the Sea, which included the vision of governance and ICM. In addition, a presidential commission issued a report on marine governance and highlighted the importance of Costa Rica working more on this aspect to improve its public policies related to its coasts and resources. In 2009, the UCR, the National University (UNA) and the Ministry of the Environment (MINAE) joined the Iberoamerican Network for ICM (IBERMAR), which worked on diagnoses and proposals regarding the 10 principles of the decalogue of the GIAL group of the University of Cádiz, Spain (Morales-Ramírez *et al.*, 2009, 2011). Similarly, both the UCR and the UNA, together with the MINAE and the French cooperation, formed part of the Cousteau Observatory for the Coasts and Seas of Central America (OCCA), which defined key action areas, including integrated environmental management (Quirós *et al.*, 2017). Positive experiences with integrated coastal management processes have been carried out in different areas of Costa Rica including in the northern Pacific coast (Sánchez *et al.*, 2014), at Cabo Blanco in the central Pacific (Morales-Ramírez *et al.*, 2014), and in the southern Pacific (Silva & Carrillo, 2004). A review of the progress of these initiatives in the country has been detailed in Samper-Villarreal *et al.* (2020). Despite strengths such as the existence of national strategies, policies, instruments for ICM, and, the existence of a Vice Ministry of Waters, Seas, Coasts and Wetlands for a limited time (Morales-Ramírez & Mora, 2015), as well as the existence of postgraduate programs in public universities on ICM, Costa Rica still needs to strengthen its public policy with concrete application of ICM principles (Morales-Ramírez, 2013). In particular, Costa Rica´s coastal zones are characterized by the lowest human development indices (Atlas Desarrollo Humano Cantonal, 2021). In a comprehensive analysis of ICM in Latin America and the Caribbean, Barragan (2020) placed again Costa Rica as a country in transition on its path to development of the ICM, a condition that has not changed between 2001 and 2019. Recently, the UCR took over the general coordination of the IBERMAR network and will organize the IV Ibero-American Congress of Integrated Coastal Zone Management in 2027, which will take place in Costa Rica.

3. Marine Conservation

Costa Rica is a country that is globally respected for its natural resource and habitat conservation initiatives. The National System of Protected Areas (Sistema Nacional de Áreas de Conservación - SINAC), as part of the MINAE, is a robust and autonomous governmental institution that was conceived and designed to manage protected areas, as well as to promote the development of the regional economy and culture (CIZEE-CR, 2008). The first protected wilderness area that included a marine surface in Costa Rica was the Cabo Blanco Absolute Natural Reserve created in 1963, being a pioneer in the Central American region. Currently, Costa Rica has reached the global goal of protecting 30% of its national waters, thanks to the National Statute No. 43368-MINAE published in 2022.



Octocorales Reserva Natural Absoluta Cabo Blanco, Pacífico de Costa Rica.
Foto cortesía Karol Ulate

Currently, Costa Rica has 13 marine protected areas, of which four are no-take zones and the remaining areas have a management plan that allows the use of marine resources under controlled conditions. However, the country does not have sufficient financial support to enforce its conservation initiatives in full and is believed that there are many illegal activities around and within these areas (López-Garro *et al.*, 2016; Sánchez-Jiménez *et al.*, 2014). The impact of these illegal activities on the organisms that inhabit these areas is unknown. SINAC and public universities have formed alliances to create monitoring protocols to assess the impacts of illegal activities on these marine ecosystems.

A key turning point was reached in 2016 with the formalization at the national level of various ecological monitoring protocols focused on marine coastal ecosystems, with the aim of obtaining robust and comparable information over time and between protected areas. This work was supported by local academics and covered ecosystems such as sandy beaches, rocky beaches, coral reefs, and marine organisms such as cetaceans and sea turtles. In subsequent years, the academic sector supported the training of park rangers, who oversaw the field monitoring efforts in some areas. In later years, the academic sector identified other priority ecosystems and organisms to be assessed and proposed applicable methodologies in mangroves, rocky reefs, and pelagic fish. Each of these new methodological techniques was evaluated by experts at the national level, and a major effort was made by the universities to train government personnel, not only in field implementation, but also in data processing and their interpretation.

This monitoring capacity building of SINAC staff is motivated by the scientific community and the ultimate goal of these monitoring protocols is to have scientifically valid data that can provide insight into condition of the habitat and population. This will ultimately allow science-based decision-making options for local and national conservation decision makers. In Costa Rica's marine and coastal areas, there are unique management models within the Central American region, where local communities, NGOs, tourism companies, and the fishing sector, as well as scientific representatives from state universities can actively participate in the decision-making process. These management structures, created by law, aim to give ownership and active participation to those directly involved in these areas, in order to motivate the conservation of marine resources (Ley de Biodiversidad No.7788, 1998).

4. Climate change

Temperature increase and ocean acidification

According to Castellanos *et al.* (2022), there is "high confidence" that ocean and coastal ecosystems in Central America, such as coral reefs, estuaries, mangroves, and sandy beaches, are highly sensitive and negatively affected by climate change, especially in relation to global and regional increases in surface sea and air temperature (e.g., Almazroui *et al.*, 2021) and ocean acidification. Ocean acidification in particular has led to the creation of a regional network to better understand its impacts and management[12]. Some of these impacts include a reduction in coral abundance and an increase in the number of coral bleaching events. Impacts may be amplified in conjunction with natural climate variability such as the El Niño-Southern Oscillation or ENSO (e.g., Alvarado *et al.*, 2020). Other impacts include changes in salinity, plankton communities, and ocean and coastal food web structures, loss of vegetated wetlands, and changes in seafloor communities. This highlights that climate change is also affecting activities in the Exclusive Economic Zones of Central America (Castellanos *et al.*, 2022).

12 Red Latinoamericana de Acidificación del Océano: Plan de Gobernanza. Documento Técnico. Primera Edición, 32 pp. October 2020. DOI: 10.13140/RG.2.2.35544.52486

Sea level rise and coastal erosion

Castellanos *et al.* (2022) also reported that there was "high confidence" that sea-level hazard is affecting coastal areas in Central America. In Costa Rica, there have been several studies reporting observed and projected evidence of coastal flooding (e.g. Lizano Araya & Lizano Rodríguez, 2022; Pérez-Briceño & Lizano Rodríguez, 2021). Coastal flooding affects Costa Rica´s coastal infrastructure, protected areas, agricultural land, and leads to saltwater intrusion into freshwater sources for human and animal consumption. In addition, important socio-economic activities, such as the import and export of goods, and national and international tourism, will be affected by coastal flooding. Furthermore, most of the coastal areas in Costa Rica are among the least developed socioeconomically[13], thereby increasing the vulnerability and exposure. The risks these communities are under have been related to key issues, including water insecurity, systemic risks of surpassing infrastructure and public service systems, coral reef ecosystem degradation due to coral bleaching and coastal socio-ecological systems will be affected due to sea level rise, storm surges, and coastal erosion (Castellanos *et al.*, 2022).

Tropical cyclones

The evidence for the role of human influence on changes in the frequency of occurrence and intensity of tropical cyclones (including tropical storms and hurricanes) has been further strengthened in the latest report from the Intergovernmental Panel on Climate Change (IPCC), published this year, compared with the previous report in 2014. There is "high confidence" that heavy rainfall and an increased proportion of strong winds in tropical cyclones associated with climate change will cause flooding in many regions, including coastal areas and low-lying cities ("medium to high confidence"). The proportion of major (category 3–5 hurricanes) tropical cyclones is likely to have increased over the last four decades (IPCC, 2023).

For Central America, especially the coastal areas of Nicaragua and Costa Rica, it is alarming that since 2016 at least six tropical storms have passed near or impacted the coast: Otto (21-26 November 2016), Eta (31 October to 14 November 2020), Iota (13-18 November 2020), Bonnie (1-9 July 2022), and Julia (7-10 October 2022). These storms had considerable negative impact on communities around Costa Rica. The occurrence of major hurricanes near Central American coasts shows an increasing trend (although not yet significant) from 1970 to 2021 (Martínez *et al.*, 2023). This potentially indicates changes in climate that may have altered the trajectories of storms in recent decades leading to higher flood risks in our coastal regions.

Inland extreme sediment transport to sea

At the global level, there are many studies that suggest a future increase of flooding in the Central American region due to climate change. In Costa Rica, recent work using a pessimistic greenhouse gas concentration scenario associated with climate change showed projected significant future (mid-century) increases in the design stream flows of hydraulic structures in most of the hydrological basins of the Pacific slope (Hidalgo *et al.* 2023). This increase in the frequency of extreme floods could arguably result in

13 https://www.undp.org/es/costa-rica/atlas-de-desarrollo-humano-cantonal; https://www.mideplan.go.cr/indice-desarrollo-social

increased sediment loads to the estuaries and coastal areas, but to our knowledge, the magnitude of this potential impact has not been assessed yet.

Increased aridity

Climatological aridity is a condition that can be related to the balance between precipitation (water supply) and potential evapotranspiration (*PET* or water demand from the atmosphere). Any change in either of these variables can cause increases or decreases in aridity. Note that since *PET* is related to temperature, as temperature increases (for example, due to global warming), the demand for water from the atmosphere increases, and therefore, aridity will increase, unless there is a compensating increase in associated water supply with an increase in precipitation. Increased aridity is associated with drier soils, which adversely affects vegetation (crops and natural), water resource availability for human and environmental systems, increased wildfire risk, higher erosion potential, and other related impacts.

The warmest climatological average temperatures found in Costa Rica are recorded in its coastal areas (Hidalgo *et al.*, 2017). In particular, the lowlands of the Pacific northwest region of the Guanacaste province, which also recorded the lowest national annual rainfall. For this reason, Guanacaste is the area with the greatest relative climatological aridity in the country. The aridity conditions of Guanacaste make it part of the Central American Dry Corridor, a region of generally drier conditions with a well-defined dry season (Quesada-Hernández *et al.*, 2019). The coastal regions of Guanacaste will experience significant increases in temperature along with decreases in precipitation and modeled annual stream flow by the end of the century (Moreno *et al.*, 2019; Hidalgo *et al.*, 2021). Other studies have shown that future large-scale climate features in the surrounding oceans would increase the likelihood of more frequent, severe, and sustained droughts in the future (Pascale *et al.*, 2021).

5. Fisheries and aquaculture

Shrimp bottom-trawl fisheries

There is a relatively large body of literature on shrimp bottom-trawl fisheries produced by various Costa Rican institutions. During the initial phase of trawling in Costa Rica (see Álvarez & Ross, 2010), some scattered reports were made available by government agencies in the 1970s, followed by studies conducted by scientists from the Universidad de Costa Rica and the Universidad Nacional. This early research period included studies analyzing the discarded bycatch in commercial shrimp fisheries in the Golfo de Nicoya and Golfo de Papagayo (Campos, 1983, 1986). There were also studies on the *Penaeus stylirostris* ("camarón blanco") shrimp fishery in the Golfo de Nicoya (Palacios *et al.*, 1996). The first stock assessment of *P. stylirostris* was also done for the Golfo de Nicoya (Tabash & Palacios, 1996). Overall, there have been several published contributions by academic institutions to support our understanding of the ecology of commercially exploited shrimp species (e.g., Alfaro *et al.*, 1993; Palacios *et al.*, 1993; Palacios Villegas & Vargas Barquero, 2000) and about the shrimp bottom-trawl fishery along the Pacific coast (e.g., Tabash Blanco, 2007). Due to declining catches of shallow-water shrimp and a shift to fishing in deeper waters, a more recent focus of fishery research has been on the deep-water shrimp fishery in Costa Rica (for review see Wehrtmann & Nielsen-Muñoz, 2009; Wehrtmann *et al.*, 2012). Important information about decapods associated with this fishery has been made available by Wehrtmann & Echeverría-Sáenz (2007), while Arana *et al.* (2013) compared the bycatch associated to the fishery of two deep-water shrimp species in Chile and Costa Rica. This study concluded that species diversity was considerably higher in Costa Rica and that 5.7 kg of bycatch were caught per kg of shrimp in Costa Rica compared to only 1.1 kg in Chile on average. Currently, the government fishing institute (Instituto Nacional de Pesca y Acuicultura - INCOPESCA) is conducting a new study on the deep-water shrimp trawl fishery along the Pacific coast of Costa Rica.

Collaboration of students, invited researcher from Brazil and the crew members of the commercial shrimp trawler "Onuva" as part of a Public-Private-Partnership Project lead by the Unidad de Investigación Pesquera y Acuicultura (UNIP) of the Centro de Investigación en Ciencias del Mar y Limnología (CIMAR), Universidad de Costa Rica (Credit: Ingo Wehrtmann).

Mollusks

Mollusks are another example of the importance of research carried out by public universities in Costa Rica. Over the years, numerous studies have been carried out on these organisms, which include several commercially important species. The focus of these studies has varied considerably, from bacteriological studies to the use of a hydrocarbon contamination index, from the evaluation of different sampling methods for the "chucheca" (*Grandiarca grandis*) and "piangüa" (*Anadara tuberculosa*) to population and distribution studies, including ecological characteristics and their conservation and management (see Appendix for additional references). Another study on the fishery potential of "piangüas" concluded that conservation measures are urgently needed to avoid local extinction, as happened to the formerly abundant and larger sister species the "chucheca" (Stern-Pirlot & Wolff, 2006) Moreover, the results of some of these studies served as input for the 2018-2023 management plan of "piangüas" (*A. tuberculosa* and *Anadara similis*) in the mangroves of Bahía Golfito, on the southern Pacific coast of Costa Rica (SINAC-ACOSA, 2018).

Sharks

Our knowledge of sharks in Costa Rican waters has been shaped by studies led by scientists from public universities in the country with important contributions from researchers from national and regional non-governmental organizations (NGOs), often in collaboration with national park rangers (e.g., Zanella *et al.*, 2016). Research has focused on four geographic regions: (1) Isla del Coco; (2) coastal areas of the northern Pacific; (3) Golfo Dulce and coastal areas of the southern Pacific; and (4) seamounts connecting the offshore island Isla del Coco with the Galapagos Islands (see Appendix for additional references). Important information on the vulnerability of sharks and other elasmobranchs to bottom trawl fishery in Costa Rica has been provided by studies conducted by the UCR (Clarke *et al.*, 2016, 2018), while several studies have analyzed shark catches in various artisanal fisheries along the Pacific coast of Costa Rica (López-Garro *et al.*, 2009; Zanella *et al.*, 2009), including in Golfo Dulce (López-Garro & Zanella, 2015, Zanella & López-Garro, 2015). The results of these and other studies have provided valuable input to management and conservation issues. An evaluation of the available information of chondrichthyan fishes (sharks, rays, and chimaeras) in Costa Rica was carried out to identify knowledge gaps, to discuss fishery-related threats, and to highlight management challenges and research needs (Espinoza *et al.*, 2018). It is also important to note that current research on these threatened species in Costa Rica is conducted using non-lethal methods and is based on acoustic telemetry (Zanella *et al.*, 2019; Matley *et al.*, 2022) and baited remote underwater video – BRUVs (Cambra *et al.*, 2021). Finally, international collaborations of Costa Rican researchers from the UCR allowed for a better understanding of the feeding ecology of common demersal elasmobranch species using modern techniques such as stable isotope analysis (Espinoza *et al.*, 2015).

Artisanal fisheries in the Golfo de Nicoya

The Golfo de Nicoya is one of the most important areas for small-scale artisanal fishing in Costa Rica (Castro-Campos & Jiménez-Ramón, 2021). The UNA has conducted most of the studies on biological aspects of the species targeted by artisanal fishers in the Golfo de Nicoya. Although not the only species of commercial interest, the spotted rose snapper (*Lutjanus guttatus*) has received the most attention, including studies on its reproductive biology, growth, feeding habits, and key aspects of its fishery biology, among others (see Appendix for additional references). "Corvinas" (*Cynoscion* spp.; Sciaenidae) are another group of fishes commercially exploited by artisanal fishers. Their size at maturity has been reported for the Golfo de Nicoya, which is crucial information for the proper management of these resources (Campos, 1992). More recent studies on commercially important fishery stocks in the area include the stock assessment of the genus *Opisthonema* as part of sardine fishery (Corrales, 2010), species composition and sizes in bottom line fishery (Villarreal-Bogarín, 2001), fish abundance and diversity (Bartels *et al.*, 2016), identification of ecosystem services in communities (Umaña-Blanco & Arroyo-Zeledón, 2021), species identification through analysis of mitochondrial DNA sequences (Umaña-Castro *et al.*, 2021).

Likewise, the Golfo de Nicoya has also received special attention from researchers at public universities as it is one of the most important areas of employment opportunities for coastal communities. These efforts have led to the publication of information on stock assessments (Corrales, 2010), the current state of fisheries (Vega Corrales *et al.*, 2013), species composition and sizes in bottom line fishing (Villarreal-Bogarín, 2001), fish abundance and diversity (León, 1973; Bartels *et al.*, 2016), species biology (Rojas, 1997b; Vásquez-Arias 1999), identification of ecosystem services in communities (Umaña-Blanco & Arroyo-Zeledón, 2021), species identification (Peterson, 1956; Umaña-Castro *et al.*, 2021).

Other fisheries

Other important contributions of the public universities to fishery resources in Costa Rica are related to the blue crab fishery. In the 1980s and 1990s, the UCR published several papers on the biology and ecology of "jaibas" *Callinecetes arcuatus* (e.g., DeVries *et al.*, 1983; Dittel *et al.*, 1985, Dittel, 1993). As part of a collaboration between the Centro de Investigación en Ciencias del Mar y Limnología (CIMAR) of the UCR and the Leibniz Centre for Tropical Marine Research of the University of Bremen, Germany, the blue crab fishery in the Golfo de Nicoya was evaluated, concluding that the maximum effort of 1600 traps recommended by the Instituto Costarricense de Pesca y Acuicultura (INCOPESCA), is unlikely to be sustainable for the crab population (Fischer & Wolff, (2006).

Finally, another valuable contribution of public universities to the management of artisanal fisheries was provided by (Bystrom *et al.* (2017). These authors used socio-ecological perceptions of the fishers in Bejuco, on the Pacific coast of Costa Rica, as well as seven years of catch data of spotted rose snappers (*Lutjanus guttatus*) to evaluate the performance of these fisheries. Based on the results obtained, the authors were able to develop a series of useful management recommendations.

Aquaculture

Research on marine aquaculture in Costa Rica has focused mainly on three groups: fish, bivalves, and shrimps. The species that have received the most attention are the shrimps *Litopenaeus vannamei, L. stylirostris* and *L. occidentalis.* At the beginning of the 21st century, efforts were focused on understanding the reproductive biology of shrimp (see reference link for relevant publications). In addition, and thanks to the results of studies carried out by the Universidad Nacional, it has been possible to define the role of neurotransmitters on the male reproductive mechanism (Alfaro *et al.*, 2007), models of male sexual maturation (Alfaro-Montoya *et al.*, 2017), and locate the gland that controls masculinity in crustaceans (Alfaro-Montoya & Hernández, 2012). One of the main concerns in shrimp farming is infectious diseases, which cause deformities and reduced growth, among other problems. Various studies have focused on these issues (Parajeles Mora *et al.*, 2021, Peña Navarro *et al.* 2020) and analyzed the prevalence of the main infectious diseases in *L. vannamei* (Peña-Navarro & Varela-Mejías, 2016). Biotechnological advances for mariculture in Costa Rica have been summarized by the Universidad Nacional (Rojas-Alfaro *et al.*, 2017). Finally, public universities conducted several studies to establish the culture of white shrimp *L. vannamei* in floating cages in the Golfo de Nicoya as a productive alternative in responsible fishing areas.

The challenges associated with poverty and overexploitation of resources along the coasts of Costa Rica have led to studies on the mariculture potential of native fish and bivalve species. Since the 1990s, research on seed production, growth (Boza-Abarca *et al.*, 2008), reproduction (Boza-Abarca *et al.*, 2011), feeding (Carvajal-Oses, 2013), and culture of the spotted rose snapper (*L. guttatus*) have provided information on fundamental aspects of its behavior as well as valuable data on its potential for reproduction in captivity and culture (Olivares & Boza-Abarca, 1998; Chacón-Guzmán, 2010, Herrera-Ulloa *et al.*, 2010; Chacón-Guzmán *et al.*, 2021). In 2002, a floating cage culture project was developed to promote sustainable development, equity, and the resilience of the link between social and ecological systems (Herrera-Ulloa *et al.*, 2010). This project was developed by the Parque Marino del Pacífico, an organization of MINAET, with the support of UNA, later joined by INCOPESCA (Herrera-Ulloa *et al.*, 2009). An evaluation of the environmental perception of *L. guttatus* juvenile releases as an educational and awareness-raising tool for the conservation of the marine resources in the Golfo de Nicoya concluded that the active participation of the population increases awareness of the conservation of coastal marine resources (Chacón-Guzmán *et al.*, 2019). On the other hand, studies of public universities about bivalve aquaculture have focused mainly on the development of oyster mariculture in the Costa Rican Pacific (Arias *et al.*, 1998-1999; Quesada-Céspedes *et al.*, 2019) and to a lesser extent on other species such as mussels (Ureña-Juárez & Peralta, 2020).

6. Restoration of marine-coastal ecosystems

Climate Change Mitigation – Blue carbon

Mangrove forests and seagrass meadows are habitats that act as sinks for organic carbon, thereby contributing to climate change mitigation (Mcleod *et al.*, 2011). Quantifying the carbon stored in these habitats is based on estimates of their total area, the organic carbon (OC) in their biomass and associated sediment, and their active sequestration rates per year. In Costa Rica, 99% of mangrove forests are located on the Pacific coast (Cortés, 2016). The spatial distribution of mangroves has been assessed at the national level through the National Forest Inventory (REDD/CCAD-GIZ - SINAC, 2015). In February 2023, the national Map of Mangrove Ecosystems 2021 was officially released by the Costa Rican government with an estimated 52,802 ha of mangroves (SINAC & CATIE, 2023). Published studies on the carbon content of Costa Rican mangrove forests have reported 70-225 Mg OC ha^{-1} stored in mangrove trees (Manrow-Villalobos & Vilchez-Alvarado, 2012; Taylor *et al.*, 2015) and 410-654 Mg OC ha^{-1} in their associated sediment measured to a total depth of 3 m (Boone Kauffman *et al.*, 2017). The conversion of mangrove forests to shrimp aquaculture ponds in the central Pacific coast of Costa Rica has been shown to cause a drastic loss of carbon in their biomass and sediment (Boone Kauffman *et al.*, 2017). OC sequestration rates in mangroves of Costa Rica have not been reported to date. The carbon content of sediment from Costa Rican mangroves has also been included in global modeling studies (Ouyang & Lee, 2020; Rovai *et al.*, 2018), while other efforts to quantify OC in Costa Rican mangrove forests have been reported in theses and grey literature (see Appendix for additional references). Mapping of Costa Rican seagrasses has only been conducted by the Universidad de Costa Rica, which reported the spatial distribution of seagrass meadows on the Pacific and Caribbean coasts and an estimated area of 133 ha (Samper-Villarreal *et al.*, 2018). Seagrass meadows in Costa Rica store 0.02-3.7 Mg OC ha^{-1}in their biomass (Samper-Villarreal *et al.*, 2022) and 160-358 Mg OC ha^{-1} in their associated sediment standardized to 1 m depth (Samper Villarreal *et al.*, 2020, 2022). The sources of carbon stored in seagrass sediment have been studied at several meadows throughout the country using carbon and nitrogen stable isotopes, with percentage contributions of seagrass carbon ranging from 12% to 51% (Samper-Villarreal *et al.*, 2020, 2020). Studies in Costa Rican meadows have also shown that more OC is stored in their biomass when the meadows are composed of larger species, such as the turtle grass *Thalassia testudinum* (Samper-Villarreal *et al.*, 2022). Other studies on carbon storage in Caribbean meadows revealed that OC stored in biomass and associated sediment increased when seagrasses were protected from excessive grazing by sea turtles, allowing leaves to become longer and wider (Samper Villarreal *et al.*, 2022). An increase of up to 4 cm in relative sediment level was found when meadows were protected from grazing over a 13-month time period (Samper Villarreal *et al.*, 2022). Despite ^{210}Pb dating of sediment profiles along the Caribbean coast, the carbon sequestration and sediment accumulation rates in seagrasses have yet to be reported for Costa Rica, due to challenges associated with sediment bioturbation and mixing (Samper-Villarreal *et al.*, 2022).

Ecological Restoration of Coastal Ecosystems

In Costa Rica, a country that is 92% marine, there is a great variety of marine and coastal ecosystems. However, these habitats have been severely degraded, mainly due to anthropogenic pressures. As a country with a history of successful terrestrial reforestation, there has been an increasing focus on marine habitat restoration initiatives in recent years. Coral reef restoration in particular made progress, with a focus on assessing the feasibility of "coral gardening", a process that involves collecting fragments of living corals and attaching them to various hard structures such as disks or pegs, monitoring their survival rates and growth in "nurseries" using different materials and shapes, carefully "weeding" them by removing the growth of unwanted organisms and protecting them from grazers, and then "planting" them in areas or coral reef degradation once they have grown to a certain size. Studies on the survival of coral fragments of differing sizes, during different seasons and using various structures of different materials and shapes have been conducted on the Pacific coast of Costa Rica at Bahía Culebra and Golfo Dulce (Chomitz *et al.*, 2023b; Combillet *et al.*, 2022; Fabregat-Malé *et al.*, 2023; Vargas Ugalde *et al.*, 2020). There have also been studies on the changes in associated fauna during coral restoration (Chomitz *et al.*, 2023a). Studies have also highlighted the importance of understanding local community perceptions and the socioeconomic context as key components of coral reef restoration efforts (Palou Zúniga *et al.*, 2023; Villalobos-Cubero *et al.*, 2023). Coral reef restoration initiatives have also been developed along the Pacific coast of Costa Rica by NGOs, local associations, and students from local universities (see Appendix for additional references).

Restoration structures type "araña" in Playa Blanca, Bahía Culebra, Pacific coast of Costa Rica, with fragments of the coral *Pocillopora* spp. as part of a research project of the Centro de Investigación en Ciencias del Mar y Limnología (CIMAR), Universidad de Costa Rica (Credit: Juan José Alvarado).

Mangrove restoration has focused on the Pacific coast, where most of the country's mangroves are located. Mangrove areas that have been cleared for agriculture, ponds for shrimp aquaculture and salt production, and for coastal development are key sites for restoration projects. An abandoned shrimp pond on the Pacific coast of Costa Rica at an unspecified location was reported to have undergone a hydrological restoration ten years ago, and the results were a 64% increase in total basal area of mangrove species compared to a control site, yet other sites did not show this level of improvement (Lewis *et al.*, 2019). A study in the Golfo de Nicoya, Pacific coast, of mangrove regeneration in shrimp ponds that had been inactive for 1-10 yr and 11-20 years showed slow and unpredictable recolonization and development of mangroves and carbon content in the ponds compared to controls (Cordero-Murillo *et al.*, 2023). This highlights the need for active restoration of hydrological dynamics as part of mangrove restoration initiatives. Carbon stored in mangrove forests has also been known to decrease drastically in Costa Rica (Boone Kauffman *et al.*, 2017), highlighting the benefits of their restoration for climate change mitigation. Many mangrove restoration initiatives in Costa Rica include propagule growth in "nurseries" and planting of seedlings by community associations and NGOs, the government, and student thesis projects (see Appendix for additional references).

Seagrass meadows in Costa Rica have been degraded and disappeared at several sites in Costa Rica and are thus in need for ecological restoration efforts. On the Pacific coast of Costa Rica, seagrass meadows have disappeared from two sites in association with strong storms (Cortés, 2001) and possible nutrient overloading (Samper-Villarreal *et al.*, 2020). In the Caribbean, long-term monitoring has shown a decline in seagrass meadows (Cortés *et al.*, 2010; Loría-Naranjo *et al.*, 2018), similar to other meadows in the Caribbean (van Tussenbroek *et al.*, 2014). The degradation of Caribbean meadows has been linked to excessive grazing by sea turtles (Samper-Villarreal *et al.*, 2022). Despite the degradation of Costa Rican meadows, there is only one seagrass restoration initiative currently underway in Bahía Culebra on the Pacific coast, where a baseline study of current seagrass distribution and environmental conditions is currently underway.

7. Marine Pollution

The government of Costa Rica has made efforts to reduce and manage its solid waste generated by daily activities. The country, however, does not have the infrastructure that allows it to provide adequate waste management (Ministerio de Salud & Ministerio de Ambiente y Energía, 2021). The amount of waste in Costa Rica's territorial seas is unknown (CENIGA, 2020), but it has been estimated that approximately 3,732 tons/day are generated in the country, of which only 3% is recycled or co-processed. Therefore, it can be assumed that a lot of waste ends up in our oceans either accidentally or intentionally. The sectors most affected by marine pollution are tourism and fishing, which account for more than 217,000 jobs, or 9% of Costa Rica's working population. Therefore, the cost of inadequate waste management will have an economic impact not only in these sectors, but also at the national level (Ministerio de Salud & Ministerio de Ambiente y Energía, 2021).

The connectivity of riparian ecosystems directly affects the health of coastal marine ecosystems. Costa Rica has abundant and diverse water resources, which not only support a high biodiversity of organisms, but are also essential for the social and economic well-being of the country. Accelerated industrial and urban development, however, has degraded the quality of the main hydrographic basins of the Greater Metropolitan Area. At the national level, poor solid waste management, mismanagement of land use around watersheds, and unplanned urban development have been identified as the main factors threatening the health status of both terrestrial and marine ecosystems (Rodríguez & Sáenz 2020).

Poor wastewater management is one of the main threats to coastal water quality in Costa Rica (Badilla-Aguilar & Mora-Alvarado, 2019; Laureano-Rosario *et al.*, 2021). The results of studies conducted by Costa Rican researchers from public universities, in collaboration with international colleagues, showed that the presence of fecal coliforms is very common on beaches near population centers (Laureano-Rosario *et al.*, 2021, Montiel Mora & Gómez Ramírez, 2023). Another problem associated with poor wastewater management is the presence of emerging contaminants, which include components of pharmaceutical and personal care products (PPCPs) and antibiotics. Important contributions to these issues have been published by Costa Rican researchers as part of international collaborative projects that detected PPCPs in coastal surface waters collected along the Pacific and Caribbean coasts (Spongberg *et al.*, 2011) and the presence of 70 pharmaceutical compounds in wastewater treatment plants (Ramírez-Morales *et al.*, 2020).

The quantification of PPCPs in coastal waters is rare, in part because there are no regulations regarding their presence in coastal waters, and because the laboratory techniques required for their analysis are usually expensive and sophisticated. However, a profile of substances used in aquaculture in coastal areas need to be included in future monitoring programs. For example, antibiotics of the tetracycline group have been reported to be widely used in shrimp production (de la Cruz *et al.*, 2014), and there are many inconsistencies between labeling and actual concentration in animal feed (including shrimp aquaculture) in Costa Rica (Granados-Chinchilla *et al.*, 2012; Leiva *et al.*, 2019). Antibiotics are of particular concern for human health and aquaculture due to the development of antibiotic resistance in pathogenic bacterial species.

Pesticides can reach coastal ecosystems via rivers that drain agricultural areas, but sampling in marine areas is rare in Costa Rica. Chemical pollution is expected to be relevant to Costa Rican coasts because the country ranks high in the world for pesticide use per hectare, where intensive monocultures occupy slopes where large rivers that drain into the sea transport toxic concentrations of pesticides (Echeverría-Sáenz *et al.*, 2021).

Other less studied contaminants are metals. Recently, the concentration of a number of metal elements (Cd, Cu, Cr, Mn, Ni, Pb Zn and total Hg) in sediment and biota was compared between the northern Caribbean coast, which is more affected by agriculture and port activities, and the southern Caribbean coast for reference (Méndez *et al.*, 2021). Although a tendency towards higher concentrations of metals was found on the northern Caribbean coast, these two coasts did not show differences overall. However, the analysis of biota, including macroalgae and sponges, showed that sediment metals are bioavailable and can be bioaccumulated in these organisms and higher concentrations of Mn were detected compared to previous studies (Méndez *et al.*, 2021). Further research is needed to determine if there is a relationship between the regular aerial application of fungicides and Mn in the Caribbean slopes or if this is the result of natural conditions.

Another source of contamination is microplastics, which are small particles typically created by the fragmentation of larger plastic pieces (Gillibert *et al.*, 2019). This process, however, is not the only source, as there are microplastics created from a primary source, which is mainly used for cleaning products and to improve their abrasive power (Auta *et al.*, 2017). Microplastics are considered a hazardous pollutant of global concern because scientists worldwide have found that they are omnipresent, with pathways of dispersion through the water cycle as well as airborne (Allen *et al.*, 2019; Zhang *et al.*, 2021; Surendran *et al.*, 2023). In Costa Rica, research groups from public universities have detected these particles in seawater and sediment (Johnson *et al.*, 2018; Sagot Valverde, 2022), as well as in organisms such as fish and crustaceans, both marine and freshwater, as well as in marine mollusks (Bermúdez-Guzmán *et al.*, 2020; Astorga *et al.*, 2022; Astorga-Peréz *et al.*, 2022; Rojas-Jimenez *et al.*, 2022). The presence of microplastics in Costa Rica is consistent with results from similar studies worldwide for marine environments (see Coyle *et al.*, 2020; Yang *et al.*, 2021). However, it is alarming that these particles have also been detected in aquatic organisms of the remote offshore island Isla de Coco (Astorga *et al.*, 2022). Recently, the national academic sector has studied the effects of this pollutant in aquatic organisms (Guillén-Watson *et al.*, 2023), as well as the implications for the human health of the consumption of microplastics and plasticizers by marine species (Montero *et al.*, 2023).

8. Conclusions and recommendations

In the last 20 years, Costa Rica has developed a series of policies that have allowed it to seek, with clear objectives, a development model for its coastal areas, based on the concept of integrated management of its coasts. Efforts must continue to ensure the proper management of marine protected areas. This is why the role of universities has taken on a unique value by getting involved not only in the evaluation of ecosystems and the organisms that inhabit them, but also in supporting government institutions in their decision-making.

As shown by this certainly incomplete overview, the research carried out by the public universities is very important for your understanding of the various aspects related to fisheries and aquaculture in Costa Rica. The national and international networks developed by these universities have been fundamental in the scientific progress of our knowledge of these aquatic resources. However, our knowledge of Costa Rican fisheries and aquaculture resources is far from complete. For example, basic information for management purposes, such as legal catch sizes, is lacking for the majority of commercially important species. In addition, there are no biomass estimates for the main species fished in the country, and there are resource management plans are available that include, among other things, on-board monitoring on fishery vessels, estimation and updating of catch quotas, and control of illegal and unregulated fishing.

In the other hand, the high vulnerability to climate impacts and the level of emissions in Central America, forces the need for a greater focus on adaptation measures within existing public policy instruments, strengthening the role of the Climate Change Office (Dirección de Cambio Climático de Costa Rica in Spanish) within the Ministry of the Environment (MINAE in Spanish). There is an urgent call for adaptation action to improve the climate monitoring network of surface and aerial weather stations in the region, including coastal areas. There are significant opportunities to strengthen collaboration in these areas between academic institutions, such as the UCR, and government agencies responsible for systematic Earth observation and meteorological and hydrological monitoring, normally assigned to the National Meteorological and Hydrological Services.

A key to mitigating climate change is knowing the rates of carbon sequestration and sediment accumulation rates. Despite efforts made in seagrass meadows Costa Rica does not know these rates in mangroves and seagrasses, and further funding and focus on research in this area is urgently needed. As marine wetlands, both mangroves and seagrasses have been in Costa Rica since 1992 under the Ramsar Convention on Wetlands. The conservation of mangroves and seagrasses in Costa Rica is also supported by the National Strategy of Blue Carbon and the National Wetlands Policy (2019-2030) recently presented in February 2023, which is currently the United Nations Decade of Ecosystem Restoration (2021-2030). A regional network on mangrove and seagrass restoration (Tropical Restoration Network - TRN), based at the Universidad de Costa Rica, has recently been developed to increase scientific collaboration, exchange of experiences and capacity building on this topic in the region. In particular, mangrove restoration in Costa Rica has been developed through the collaboration of the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the NGO Conservation International and the Sistema Nacional de Áreas de Conservación (SINAC) of the Costa Rican government. Finally, research on contamination in coastal-marine zones is costly, and additional studies are urgently needed to assess the presence, distribution, and impact of these hazardous contaminants in the environment and for the public health. Antibiotics must be included in such monitoring because of the development of microbial resistance in humans and aquaculture pathogens. Furthermore, the results of the studies conducted by public universities must have a greater incidence in national policies, since the last two national development plans did not even mention universities as relevant actors when referring to pollution issues (MIDEPLAN, 2014, 2018).

Ver bibliografía exhaustiva en Apéndice al final de la Revista.