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CIENCIA CIUDADANA PARA LA RESTAURACIÓN ECOSISTÉMICA Y MONITOREO BIOLÓGICO DEL ARRECIFE CORALINO DE OCOTAL, GOLFO DE PAPAGAYO, COSTA RICA

CITIZEN SCIENCE FOR THE ECOSYSTEMIC RESTORATION AND BIOLOGICAL MONITORING OF THE OCOTAL CORAL REEF, GULF OF PAPAGAYO, COSTA RICA

Tesis sometida a la consideración de la Comisión del Programa de Posgrado en Gestión Integrada de Áreas Costeras Tropicales para optar al grado y título de Maestría Académica en Gestión Integrada de Áreas Costeras Tropicales

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DEDICATORIA

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Capítulo 1: Ciudadanos del mar: evaluación de la participación de científicos ciudadanos en la investigación de biología marina. La ciencia ciudadana (CC), en ambientes marinos, provee a diversos actores con datos valiosos para la conservación y la gestión costera integrada. Para revisar los componentes de los proyectos de CC en biología marina, los temas de investigación y la participación ciudadana, revisamos artículos científicos publicados entre el 2009 y agosto del 2023. Se analizaron un total de 445 documentos de literatura científica. Se identificó un aumento en la publicación a través de los años, en regiones y países que tienen un contexto favorable, incluyendo soporte financiero, institucional y social, para apoyar tales programas. El 75 % de los estudios duraron un máximo de ocho años, con grupos que varían entre 1 y 19 843 ciudadanos, apoyado por académicos y plataformas digitales. El capital humano hace posible realizar proyectos principalmente relacionados con patrones espaciotemporales de grupos biológicos; sin embargo, otros temas fueron estudiados. El acceso y atractivo de los ecosistemas puede estar influenciado los ambientes estudiados, ya que las zonas costeras y arrecifes fueron los sitios más estudiados. Los científicos ciudadanos principalmente realizaron trabajo de campo; sin embargo otras funciones fueron menos frecuentes, pero relevantes. En todos los casos, los autores destacaron la relevancia de la investigación de CC en resultados de conservación. Las iniciativas de CC deberían considerarse como un complemento de metodologías tradicionales, no un reemplazo. Los programas de CC marina ofrecen ventajas que sobrepasan la reducción de costos para la recolección de datos, es una forma de saldar la deuda histórica que la ciencia tiene con las comunidades locales, al mismo tiempo que se fomenta una plataforma de participación ciudadana en temáticas ambientales.

Capítulo 2: Ciencia ciudadana: una ruta para la restauración de arrecifes coralinos en Bahía Ocotal, Pacífico Norte de Costa Rica. Los arrecifes coralinos están afrontando una crisis mundial. Para promover la participación pública en los esfuerzos de restauración, establecimos un programa de CC en Bahía Ocotal, en el Pacífico Norte de Costa Rica, con el objetivo de restaurar y monitorear el arrecife degradado. Este estudio evalúa la efectividad de un acercamiento de CC, usando parámetros biológicos y el entendimiento social como indicadores. Estructuras artificiales llenas de fragmentos de *Pocillopora* spp. fueron colocadas. Los voluntarios y académicos monitorearon la composición del sustrato y la comunidad de peces. Encuestas fueron llevadas a cabo para perfilar los valores sociales de los voluntarios. En dos años se llevaron a cabo 63 actividades. Los voluntarios reportaron siete sustratos, con diferencias significativas en la composición del sustrato, comparándolo con las evaluaciones hechas por académicos. Reportaron 12 de 20 de las especies de peces de peces documentadas para la zona de restauración, la cual mostró cambios debido a la restauración activa. El repaso de protocolos y la participación continua parecen estar influenciando la eficiencia del monitoreo. A pesar del blanqueamiento causado por el aumento de la temperatura superficial del océano, la cobertura coralina sana duplicó su área a lo largo del estudio. Los voluntarios están motivados por incentivos idealistas y los servicios ecosistémicos culturales que proveen los arrecifes de coral. Garantizar la sostenibilidad a largo plazo requiere abordar otros aspectos. El conocimiento estuvo positivamente correlacionado con la experiencia en deportes marinos y el compromiso con el proyecto, sugiriendo que la habilidad de los voluntarios hace que sea más probable que se lleven a cabo los protocolos de forma correcta. Los conceptos de restauración coralina y ciencia ciudadana son comprendidos, pero está restringido a sus experiencias. Involucrar a las comunidades en los esfuerzos de conservación de arrecifes coralinos es necesario para contribuir con arrecifes resilientes que son capaces de sobrellevar las condiciones actuales y futuras.

ABSTRACT

Chapter 1: Sea-citizens: assessing the participation of citizen scientists in marine biology research. Citizen science (CS), in marine environments, provides stakeholders with valuable data for conservation and integrated coastal management. To overview components of marine biology CS projects, research topics and citizens participation— we review peer-reviewed articles published from 2009 to August 2023. A total of 445 scientific papers were analyzed. This review identified an increase in the publication through the years, in regions and countries who have a favorable context— including financial, institutional, and social involvement—to support such programs. 75 % of the studies lasted a maximum of eight years, with groups that range between 1 to 19 843 citizens, supported by academics and digital platforms. The human capital makes possible to conduct projects predominantly related to spatiotemporal patterns of biological groups; however, other research topics were addressed. The access and attractiveness of the ecosystems may have influenced the surveyed ecosystems, since coastal areas and reefs were the most extensively studied. Citizen scientists predominantly conducted fieldwork, yet other roles were less frequent, but still relevant. In all cases, authors pointed to the relevance of CS research in conservation outcomes. CS initiatives should be seen as a complement to traditional surveys, not a replacement. Marine CS programs present perks that exceed the cost reduction of data collection, it is a way of repaying the historical debt that science has with local communities while encouraging a framework of social participation in environmental issues.

Chapter 2: Citizen science: pathway for coral reef restoration in Ocotal Bay, Costa-Rican north pacific. Coral reefs are facing a worldwide crisis. To promote public participation in restoration efforts, we established a citizen science program in Ocotal Bay, North Pacific of Costa Rica— aimed to restore and monitor the degraded reef. This study evaluates the effectiveness of a citizen science approach, using the biological parameters and volunteers' social insight as indicators. Artificial structures filled with *Pocillopora* spp. fragments were placed. Volunteers and academics monitored the substrate composition and fish community. Surveys were conducted to profile the volunteers' social values. In two years, 63 activities were carried out. Volunteers reported seven substrates, with significant differences in the substrate composition, compared to academic evaluations. They recorded 12 out of 20 fish species documented in the restoration area, which showed changes due to the active restoration. Protocols refreshment and sustained participation seem to be influencing the monitoring efficiency. Despite the bleaching event caused by the increase in the sea surface temperature, healthy coral cover almost duplicated its area throughout the study. Volunteers are motivated by idealistic incentives and cultural ecosystem services from coral reefs. Ensuring long-term sustainability requires addressing other values. Volunteers' knowledge was positively correlated with marine sports experience and commitment to the project, suggesting that skilled volunteers are more likely to properly apply protocols. The concepts of coral restoration and citizen science are well understood, but their knowledge is restricted to their experience. Engaging communities in coral reef conservation efforts is necessary to contribute with resilient reefs that are able to overcome current and future conditions.

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LISTA DE ABREVIACIONES

CC: Ciencia ciudadana

CS: Citizen science

PIT: Point of Intercept Transects

PIT: Puntos de Intersección de Transecto

INTRODUCCIÓN

La ciencia ciudadana (CC) se refiere a procesos en los cuales personas no-científicas se involucran en diferentes pasos de las investigaciones científicas. A este involucramiento se le han reportado ventajas como una mayor capacidad espacio temporal, la reducción de costos de investigación, la creación de plataformas de educación ambiental y gestión integrada de recursos costeros, promoviendo la democratización y acceso a la ciencia. A su vez, retos como sesgos espaciales, subjetividad en la toma de datos y aplicación incorrecta de protocolos de investigación se han destacado para estos proyectos. En ambientes marinos, estos procesos se han realizado en múltiples ecosistemas, entre los que se encuentran los arrecifes coralinos. En estos ambientes, se han estudiado realizado monitoreos puntuales y de largo plazo que permiten identificar patrones espacio-temporales, reproductivos y poblacionales, de organismos que los habitan y la respuesta ante eventos de estrés. Datos obtenidos de proyectos de este tipo se han traducido a la generación de políticas públicas que promueven la conservación de estos ecosistemas.

Los arrecifes coralinos son ecosistemas altamente diversos que sustentan gran cantidad de servicios ecosistémicos. Sin embargo, debido a estresores globales como el aumento en la temperatura del océano y cambio climático, y locales, como sobrepesca, contaminación y mal manejo de recursos han generado el colapso de arrecifes enteros y una alta vulnerabilidad en los que persisten. Herramientas de manejo como iniciativas de restauración coralina, han surgido en todo el mundo para tratar contrarrestar esta crisis y recuperar los arrecifes coralinos. Estos proyectos involucran a diferentes actores involucrados en la conservación de estos espacios; entre estos se encuentran la academia, instituciones gubernamentales, organizaciones no-gubernamentales y comunidades locales. La CC ha sido un acercamiento ejecutado para escalar los procesos de restauración coralina a través del involucramiento comunitario. La participación de científicos ciudadanos ha ido desde la siembra de corales y el mantenimiento de sitios de restauración, hasta la implementación de nuevas metodologías.

Es por esto que esta tesis tiene como objetivo general evaluar desde un enfoque teórico y práctico la implementación de proyectos de ciencia ciudadana en ecosistemas marinos, haciendo un énfasis una iniciativa de restauración de un arrecife coralino degradado. Dos objetivos específicos se derivan de este. El primero es actualizar el estado de conocimiento de la ciencia ciudadana marina, al analizar descriptores de los proyectos y de las investigaciones, y realizando una caracterización de la participación de científicos ciudadanos en estos programas; es abordado por el capítulo 1. El segundo objetivo específico, desarrollado en el segundo capítulo, es evaluar la efectividad de un acercamiento de ciencia ciudadana en un proceso de restauración de un arrecife coralino degradado en Bahía Ocotal, en el Pacífico Norte de Costa Rica, usando cambios en la comunidad biológica y en las percepciones sociales de los voluntarios como indicadores.

En el Capítulo 1, para poder entender el estado actual de la ciencia ciudadana en biología marina, se realizó una revisión bibliográfica sistemática. En esta se buscaron dilucidar patrones de los proyectos que los ejecutan, de la investigación biológica, y se generó una caracterización de la participación que los ciudadanos estaban teniendo dentro de cada programa. Esta revisión se realizó modificando la metodología PRISMA. Trece combinaciones de palabras clave, que incluían el término “ciencia ciudadana” y algún ecosistema o grupo de organismos marinos, fueron colocadas en la base de datos científica Scopus (https://www.scopus.com/).

Una lista final de 445 artículos fueron escrutados para identificar los descriptores requeridos. Para caracterizar los patrones de los proyectos se obtuvo información del año de publicación del artículo, delimitación espacial (países y región biogeográfica), duración, y número de participantes del proyecto, el acompañamiento de miembros de la academia, el uso de plataformas digitales, y metodologías de verificación de resultados. Los descriptores de investigación incluyeron el grupo biológico, tema y ecosistema de estudio. Finalmente, la caracterización de la ciencia ciudadana abordó los roles que los voluntarios tenían dentro los proyectos y las implicaciones en conservación que los autores destacaban de la participación de científicos ciudadanos.

Un incremento en la publicación entre el 2009 y agosto del 2023 fue observada. Estos estudios fueron realizados mayoritariamente en el Atlántico Templado Norte (n = 169), el Indo-Pacífico Central (n = 63); en particular, los países de Australia y Estados Unidos acumularon la mayor cantidad de publicaciones, con 60 cada uno. El 75 % de los documentos reportaron un máximo de ocho años de duración de los proyectos, con reportes de grupos que variaron entre 1 y > 19000 voluntarios, un consistente apoyo de la academia (64.94 %, n = 289), un uso constante de plataformas digitales (56.63 %, n = 252) y de metodologías de verificación de resultados (57.30 %, n = 255).

La mayoría de proyectos abordó temáticas estrictamente biológicas (84.3 %), mientras que el porcentaje restante estudió tópicos que tienen implicaciones en patrones biológicos (geociencias y contaminación). Los grupos más estudiados fueron invertebrados (24.06 %) y peces óseos (23.46 %). Los patrones espacio temporales de grupos biológicos fue la temática más abordada (51.01 %). Los ambientes más estudiados fueron cercanos a la línea de costa (36.18 %) y los arrecifes coralinos (35.51 %).

Los científicos ciudadanos realizaron principalmente trabajo de campo para la recolección de muestras y datos (95.73 %); sin embargo, a lo largo de los años, se incrementaron los roles en los que se involucraron los participantes, incluyendo procesamiento de información, planificación y comunicación. Finalmente, toda la literatura coincidió que la participación de los voluntarios en la investigación promueve la conservación. Otros roles fueron destacados como el manejo de recursos, movilizaciones sociales y cambios de políticas.

Con todo este marco conceptual, procedimos a ejecutar un programa de ciencia ciudadana. El capítulo 2 presenta el caso aplicado de la implementación de un programa de ciencia ciudadana para la restauración y monitoreo del arrecife coralino de Ocotal, ubicado en el Pacífico Norte de Costa Rica. Esta región ha sobrellevado diferentes estresores que condujeron a un colapso de sus arrecifes, con una caída en su cobertura de coral vivo de ~40 a 1-4 % en un periodo de 20 años. Previo a la intervención, la matriz arrecifal de Bahía Ocotal estaba altamente degradada con colonias solitarias dispersas. Estructuras artificiales de acero con ~20 fragmentos (10-15 cm cada uno) fueron colocadas en esta matriz, siguiendo experiencias previas de restauración en la región.

En colaboración con la Alianza Mar y Tierra se reclutaron voluntarios que fueron entrenados en técnicas de monitoreo biológico y estrategias de restauración. A lo largo de este proceso se llevaron a cabo 63 actividades que incluían siembras de coral, mantenimiento de estructuras, entrenamientos de colecta de datos, monitoreos para la recolección de datos biológicos, encuestas para recolección de datos sociales y talleres comunitarios. Los monitoreos biológicos incluyeron análisis de la composición del sustrato (empleando la metodología de puntos de intersección de transecto), la comunidad de peces arrecifales (con transectos en túnel de 5 x 5 x 10 m) y densidad de invertebrados móviles (estudiadas con transectos en banda de 1x10 m). Además, se le dio un seguimiento a través de fotografías a las estructuras. Además, se realizó una encuesta que buscaba entender aspectos sociales relacionados con demografía, la apropiación cultural de los ecosistemas marinos, percepciones y conceptualización de los procesos de ciencia ciudadana y restauración coralina.

Los voluntarios lograron identificar siete de los nueve tipos de sustratos observados en el arrecife de Bahía Ocotal; sin embargo, la composición del sustrato varió entre los monitoreos realizados por científicos ciudadanos y academia. Los voluntarios lograron documentar 12 de las 20 especies de peces observadas en la zona de restauración. De estas especies ocho fueron documentadas por ambos grupos; las especies *Diodon holocanthus, Halichoeres dispilus, Serranus psittacinus* and *Sufflamen verres* fueron únicamente reportados por los voluntarios, y *Acanthurus xanthopterus*, *Arothron meleagris*, *Chaetodon humeralis*, *Halichoeres* spp (Juveniles), *Haemulon* spp., *Johnrandallia nigrirostris*, *Lutjanus guttatus* and *Zanclus cornutus* fueron documentados solo por el grupo académico. A lo largo del tiempo, los datos de los voluntarios fueron irregulares, en algunos casos ejecutando inapropiadamente los protocolos o estimando incorrectamente las abundancias.

A lo largo del periodo de estudio, la cobertura de coral por estructura artificial prácticamente se duplicó. Durante el primer monitoreo (mayo 2023), la cobertura promedio por estructura fue de 469.74 ± 34.57 cm^2, y para el final del estudio (julio 2024) fue de 869.46 ± 46.57 cm^2. Es importante acotar que durante el periodo estudiado, un evento de blanqueamiento tuvo lugar entre los meses de setiembre y diciembre de 2023. Durante este periodo un descenso significativo en la cobertura de coral sano fue observada, con un punto máximo en octubre de 2023, cuando el 87.29 ± 11.54 % (542.34 ± 51.95 cm^2) del tejido de coral en cada estructura se encontraba blanqueado. Posterior a este evento, inicialmente hubo un descenso en el área de coral total y progresivamente un aumento en el tejido sano, llegando a su máximo en julio de 2023.

Un total de 16 voluntarios accedieron a completar la encuesta. La edad media de los participantes es de 39.6 ± 9.1 años, sin diferencias entre sexos. La mayoría de los participantes fueron costarricenses, que residen a más de 25 minutos de distancia de Bahía Ocotal y poseen un nivel académico universitario. Para la fecha de la encuesta, estos habían participado en el proyecto 7.6 ± 0.5 meses y la mitad contaban con experiencias previas en otros proyectos de restauración. Los voluntarios mencionan diferentes tipos de motivaciones para participar en proyectos de este tipo, siendo “conservación de arrecifes” el factor más recurrente y las motivaciones de tipo idealistas las más frecuentes. Además, los participantes declararon percibir principalmente servicios ecosistémicos de tipo cultural. Se encontró una correlación fuerte positiva entre las habilidades percibidas en deportes marinos, el compromiso declarado con el proyecto de Ocotal y el conocimiento autopercibido de los voluntarios. Además, se encontró otra correlación fuerte positiva entre el compromiso y las habilidades de buceo. Los voluntarios identificaron la restauración coralina como un proceso de intervención humana que impulsa la recuperación de los arrecifes coralinos y la ciencia ciudadana como un proceso de participación ciudadana en el que colaboran comunidades con científicos que requiere entrenamiento para la una apropiada recolección de datos.

INTRODUCTION

Citizen science (CS) refers to processes in which non-scientists are involved in different steps of scientific research. This involvement has been reported to offer advantages such as increased spatiotemporal capacity, reduced research costs, the creation of environmental education, and integrated management of coastal resources platforms, promoting the democratization of and access to science. At the same time, challenges such as spatial bias, subjectivity in data collection, and incorrect application of research protocols have been highlighted in these projects. In marine environments, these processes have been carried out in multiple ecosystems, including coral reefs. In these environments, punctual and long-term monitoring have been conducted, allowing for the identification of spatiotemporal, reproductive, and population patterns of the organisms that inhabit them, as well as their response to stress events. Data obtained from projects of this type have been translated into the development of public policies that promote the conservation of these ecosystems.

Coral reefs are highly diverse ecosystems that support a multitude of ecosystem services. However, global stressors— such as rising ocean temperatures and climate change—, as well as local stressors —like overfishing, pollution, and inadequate resource management, have led to the collapse of entire reefs and left those that persist highly vulnerable. Management tools such as coral restoration initiatives have emerged worldwide to face this crisis and recover coral reefs. These projects involve various stakeholders involved in the conservation of these spaces; among those are academia, government institutions, non-governmental organizations, and local communities. CS has been an approach implemented to scale up coral restoration processes through community engagement. The participation of citizen scientists has ranged from coral outplants, and maintaining restoration sites to implementing new methodologies.

Therefore, the general objective of this thesis is to evaluate, from a theoretical and practical perspective, the implementation of citizen science projects in marine ecosystems, with an emphasis on a restoration initiative for a degraded coral reef. Two specific objectives are derived from this one. The first is to update the state of knowledge of marine citizen science by analyzing project and research descriptors, and characterizing the participation of citizen scientists in these programs; this objective is addressed in Chapter 1. The second specific objective, covered in the second chapter, is to evaluate the effectiveness of a citizen science approach in a restoration process for a degraded coral reef in Ocotal Bay, in the North Pacific of Costa Rica, using changes in the biological community and the social perceptions of volunteers as indicators.

In Chapter 1, a systematic literature review was conducted to understand the current state of citizen science in marine biology. This review sought to elucidate patterns in the projects that implement them and in biological research, and to characterize citizen participation within each program. This review was conducted by modifying the PRISMA methodology. Thirteen keyword combinations, which included the term "citizen science" and a specific ecosystem or group of marine organisms, were entered into the scientific database Scopus (https://www.scopus.com/).

A final list of 445 articles was reviewed to identify the required information. To characterize project patterns, data was obtained regardless of the year of publication, spatial delimitation (countries and biogeographic region), duration, and number of project participants, the support of academics, the use of digital platforms, and methodologies for verifying results. Research descriptors included the biological group, topic, and ecosystem studied. Finally, the characterization of citizen science addressed the roles volunteers played within the projects and the conservation implications highlighted by the authors of the participation of citizen scientists.

An increase in publications was observed between 2009 and August 2023. These studies were mostly conducted in the North Temperate Atlantic (n = 169) and the Indo-Central Pacific (n = 63); in particular, Australia and the United States accumulated the largest number of publications, with 60 each. Seventy-five percent of the documents reported a maximum of eight years of project duration, with records of groups ranging from 1 to > 19,000 volunteers, consistent academic support (64.94 %, n = 289), constant use of digital platforms (56.63 %, n = 252), and results verification methodologies (57.30 %, n = 255).

Citizen scientists primarily performed fieldwork to collect samples and data (95.73 %); however, over the years, the roles in which participants were involved increased, including information processing, planning, and communication. Finally, the literature all agreed that volunteer participation in research promotes conservation. Other roles highlighted included resource management, social mobilization, and policy change.

With this state of the art in place, we proceeded to execute a citizen science program. Chapter 2 presents the case study of the implementation of a citizen science program for the restoration and monitoring of the Ocotal coral reef, located in the North Pacific of Costa Rica. This region has endured various stressors that led to reef collapse, with a decline in live coral cover from ~40 % to 1-4 % over a 20-year period. Prior to the intervention, the Ocotal Bay reef framework was highly degraded, with scattered solitary colonies. Artificial steel structures with ~20 fragments (10-15 cm each) were placed in this matrix, following previous restoration experiences in the region.

In collaboration with the Alianza Mar & Tierra, volunteers were recruited and trained in biological monitoring techniques and restoration strategies. Throughout this process, 63 activities were carried out, including coral outplants, structure maintenance, data collection training, biological data collection monitoring, social data collection surveys, and community workshops. Biological monitoring protocols included analyses of substrate composition (using the Point of Intercept Transects (PIT) methodology), the reef fish community (with 5 x 5 x 10 m belt transects), and mobile invertebrate density (studied with 1 x 10 m band transects). Structures were also monitored through photographs. A survey was also conducted to understand social aspects related to demographics, the cultural appropriation of marine ecosystems, perceptions and conceptualization of citizen science and coral restoration processes.

Volunteers were able to identify seven of the nine substrate types observed on the Ocotal Bay reef; however, substrate composition varied between the surveys conducted by citizen scientists and academics. Volunteers were able to document 12 of the 20 fish species observed in the restoration area. Of these, eight were documented by both groups; *Diodon holocanthus*, *Halichoeres dispilus*, *Serrranus psittacinus*, and *Sufflamen verres* were reported only by the volunteers, and *Acanthurus xanthopterus*, *Arothron meleagris*, *Chaetodon humeralis*, *Halichoeres* spp. (juveniles), *Haemulon* spp., *Johnrandallia nigrirostris*, *Lutjanus guttatus*, and *Zanclus cornutus* were documented only by the academic group. Over time, volunteer data were inconsistent, in some cases resulting in improper execution of protocols or incorrect estimates of abundance.

Throughout the study period, coral cover per artificial structure practically doubled. During the first monitoring period (May-2023), the average cover per structure was 469.74 ± 34.57 cm^2, and by the end of the study (July-2024) it was 869.46 ± 46.57 cm^2. It is important to note that during the study period, a bleaching event occurred between the months of September and December-2023. During this period, a significant decrease in healthy coral cover was observed, with a peak in October-2023, when 87.29 ± 11.54 % (542.34 ± 51.95 cm^2) of the coral tissue in each structure was bleached. Following this event, there was an initial decline in the total coral area and a progressive increase in healthy tissue, reaching its peak in July-2023.

A total of 16 volunteers agreed to complete the survey. The mean age of participants was 39.6 ± 9.1 years, with no differences between sexes. The majority of participants were Costa Ricans, residing more than 25 minutes from Ocotal Bay and holding a university degree. At the time of the survey, they had participated in the project for 7.6 ± 0.5 months, and half had previous experience in other restoration projects. Volunteers mentioned different motivations for participating in projects of this one, with "reef conservation" being the most common factor and idealistic motivations the most frequent category. Furthermore, participants reported primarily perceiving cultural ecosystem services. A strong positive correlation was found between perceived marine sports skills, the stated commitment to the Ocotal project, and volunteers' self-perceived knowledge. Another strong positive correlation was found between commitment and diving skills. Volunteers identified coral restoration as a human-involved process that drives coral reef recovery, and citizen science as a participatory process in which communities collaborate with scientists and requires training for proper data collection.

CAPÍTULO 1

SEA-CITIZENS: ASSESSING THE PARTICIPATION OF CITIZEN SCIENTISTS IN MARINE BIOLOGY RESEARCH

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1. Introduction

Citizen science (CS) has been conceptualized as the public's participation in research processes (Cigliano et al. 2015, McKinley et al. 2017). Data recorded under these programs can and should be used by stakeholders— such as scientists, and decision makers; their results should have the same peer-review requirements as Non-CS research (McKinley et al. 2017). Modern CS differs from its origins, initially as an activity for wealthy and privileged groups; now being more accessible to communities (Silvertown 2009). In this continuous evolution, it should be addressed on how CS can respond to the current global scenario. CS is a tool that should be considered for achieving and assessing the sustainable development goals (Fritz et al. 2019, Ryabinin et al. 2019, Ballerini & Bergh 2021), since over the years, CS has been involved in conservation and ecological studies of natural resources (McKinley et al. 2017, Fraisl et al. 2022).

CS initiatives have been applied in marine ecosystems for decades (Thiel et al. 2014). That said, marine CS holds multiple benefits, but it also has challenges that need to be addressed. Among the outstanding advantages is the capacity to study bigger areas, with a lower economic cost (Aylesworth et al. 2017), the possibility to enable data collection platforms in areas where there is an incipient or absent academic structure (Gouraguine et al. 2019) or during worldwide lockdowns (Licuanan & Mordeno 2021, Díaz-Mendoza et al. 2023, Nijman 2023), and reduction of research's carbon footprint (Paradinas et al. 2021). Information obtained from marine CS data has been used for an integrated coastal management (Turicchia et al. 2021), enabling quick responses to environmental stressors (Jones et al. 2017), and policy development (Crabbe 2012). CS can address the historical barriers that traditional science has held with local communities (Iporac et al. 2022), while at the same time is a platform for social interaction (Hann et al. 2018).

On the other hand, marine CS initiatives have to actively work to address challenges as the data quality (e.g. species misidentification, geographical biases) (Aceves-Bueno et al. 2017), being able to understand the motivations of citizens (Cerrano et al. 2017, Blanco-Parra et al. 2022), and to keep the long–term engagement among the participants (Martin 2013). Also, due to the nature of marine science, logistical concerns also arise, such as limited access to offshore and remote areas, specialized training requirements (e.g. scuba diving), higher operating costs and increased safety considerations (Cigliano et al. 2015). It is important to recognize the limitations each program has, to work towards more sustainable CS efforts (Abreo et al. 2019, Johansen et al. 2021, Pirotta et al. 2022).

Among the research subjects that had been reviewed in marine CS are the participation of citizens in marine litter evaluations (Kawabe et al. 2022), biological invasions (Encarnação et al. 2021), the cetaceans populations in Kenya (Mwango'mbe et al. 2021), the elasmobranch communities in Palau (Hari et al. 2021) and current trends in European CS initiatives (Garcia-Soto et al. 2021). Globally, Thiel et al. (2014) did a comprehensive study about the citizens profiles, research topics and biological groups studied, and Kelly et al. (2020) analyzed study cases, both highlighting the importance of public participation in conservation outcomes. This review aims to update the existing knowledge on marine CS, by overviewing project and biological research descriptors, but also providing a citizen scientist role characterization. By synthesizing this information, we seek to contribute to the planification of future and current CS initiatives.

2. Materials and methods

A systematic bibliographic review of scientific literature was carried out modifying the PRISMA method (Page et al. 2021). The search was carried out in the scientific database Scopus (https://www.scopus.com/) using as syntax different combinations of the keywords (Table 1) and the booleans AND and OR (Table 1). The total number of documents (n = 1 289) were downloaded during August 2023 with no restriction of a specific language or year of publication. In cases where the download was unsuccessful in Scopus platform, authors were contacted via ResearchGate (https://www.researchgate.net/). If by December 2023 there was no answer, those documents were not considered. Documents were manually filtered by MS, to remove the duplicates. Also, the literature that did not meet the selection criteria (explained below) was removed (Fig. 1).

Table 1. Search results in the Scopus database for each syntax of keywords, used to evaluate the marine citizen science initiatives.

Syntax		**Number of hits**
Citizen science AND	coast	290
	reef	155
	mangrove	14
	marshes	17
	seagrass	23
	beach	172
	benthos	20

	elasmobranchs OR sharks OR rays	142
	marine AND mammals OR fish	174
	marine AND plants	14
	marine AND invertebrate	23
	algae	53
	coastal AND management	192

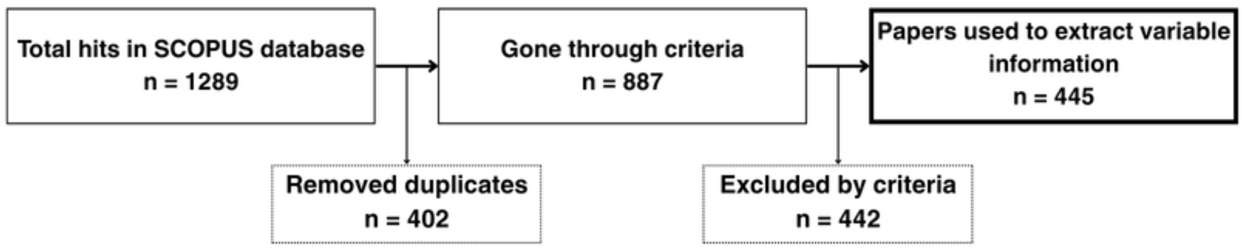

Fig. 1. Flowchart used for filtering documents obtained from the SCOPUS database.

A total of 887 documents were scrutinized (Fig. 1), following four selection criteria to identify the documents used for the present review: (1) Only scientific articles were included; (2) All articles should be performed exclusively in natural marine environments. Exceptions for freshwater ecosystems were included if the river mouth or the estuary were also sampled. Articles that included terrestrial ecosystems or aquarium-based research were not included; (3) The study had to be related to biological research or have implications in biological processes (e.g. pollution topics that quantify marine debris that might affect the biological community, or oceanographic themes that analyse currents or coastal erosion); (4) Citizen scientists should participate in some part of the research (planification, fieldwork, processing, communication, and local ecological knowledge). Articles that only recommend implementation of CS initiatives were dismissed.

The final database included 445 sources (Fig. 1; Table S1). To categorize them, a complete review of the abstract, objective, methodology, results, and discussion was individually carried out. The categories of information were designed as follows: project descriptors, biological research descriptors, citizen science characterization. The variables and data treatment used are detailed in Table 2. One article can fit in more than one description (e.g. if a study included different biological groups). In most of the sections, only information explicitly stated in the documents was included (Table 2 footnote).

Table 2. Variable description of the information categories obtained from CS scientific literature review.

Information category	Variable	Data treatment
Project descriptors	Year	Publication year of the article
	Spatial delimitation	**Biogeographical realm:** according to Spalding et al. (2007). If there was more than one realm it was determined as "multiple". **Country:** in which the studies were conducted. If there was more than one country, it was classified as "multiple".
	Project duration	Duration of the project (in months). In cases where it was not clarified the months, a year-round time frame was assumed.
	Number of citizens	Number of citizen scientists involved in the research process.
	Contact with academics *	It was determined if any kind of contact with academics somehow ensured a training process, clarification of questions or a structured research protocol.
	Use of digital platforms *	It was determined if it mentioned the use of any kind of digital platform or social media, including communication apps.
	Verification methods *	It was considered a verification method whenever there was evidence (photographs, videos…) or a methodology implemented to verify CS results' accuracy.
Biological research descriptors	Biological groups	In case there were biological groups studied, they were classified in: algae, angiosperms, invertebrates, reptiles, birds, bony fish, elasmobranchs, and mammals.
	Research topics	A singular article can have more than one research topic. The research topics were classified in: **Spatiotemporal patterns:** distribution reports, migration, habitat use or natural aggregations. **Ecosystemic stressors:** ecosystem degradation, effects of climate change, pollution, diversity loss, fishing pressure or anthropogenic stress. **Diversity descriptions:** individuals' characterization, population or community structure, ecosystemic monitoring or phenology. **Behaviors:** Reports of behaviors or inter/intraspecific interactions. **Molecular profiling:** environmental DNA or genetic descriptions. **Management:** governance or marine spatial planning.

		Conservation attributes: ecosystem or population restoration, environmental education, resources conservation. **Methodology test:** model training or artificial intelligence, refinement of methodologies. **Geosciences:** Oceanography or geomorphology.
	Surveyed ecosystems	The ecosystems were classified in: reefs (coral, rocky, artificial, and algae-based), coastal ecosystems (sandy, rocky, intertidal, and dunes), seagrass meadows, mangroves, sea marshes, and estuaries. If there was not a clear description of the surveyed ecosystem, it was classified as other.
Citizen science characterization	Citizen scientists' role	The participation of the citizens was broken down in: planification, fieldwork, processing (of data or sample), communication of results and local ecological knowledge (LEK) (modified from Bonney et al. (2009); Table S2).
	Implications for conservation	The implications for conservation were categorized in: policy change, social implications (including education and community), management (of species and sites) and research outcomes (modified from Cigliano et al. (2015); look Table S3).

* In these sections, non-mentioned of the element was inferred as non-use, even if it was not explicitly reported (e.g. use of digital platforms).

We acknowledge that this review has certain limitations. Among these, we can point using only peer-reviewed articles obtained from a single database. Regardless of this limitation, we are confident the results we are presenting are representative of the reality established in scientific literature since we're analyzing a large volume of documents. For future reviews, including other types of documents could help to cover the CS projects that never reach publication (Conrad & Hilchey 2011, Zhang et al. 2023). Another aspect that might have influenced our results is only using explicit information. We preferred doing it instead of assuming information; however, this might encourage a broader description of CS aspects in scientific articles

All visualizations were programmed in R Studio software (R Core Team, 2023), using the packages ggplot2 (Wickham 2016), sf (Pebesma & Bivand 2023), dplyr (Wickham et al. 2023), forcats (Wickham 2023), tidyverse (Wickham et al. 2019), ggridges (Wilke 2024b), cowplot (Wilke 2024a) and rnaturalearth (Massicotte & South 2023).

3. Results

Here we are presenting information from 445 peer-reviewed scientific articles related to marine biology studies that fit the selection criteria. This means that roughly one of every three documents that were obtained from the syntax of keywords were used to elucidate patterns in the project and research attributes of CS initiatives, the participation that citizen scientists are having in these projects, and potential conservation outcomes.

3.1. Project descriptors

Data shows an increase in the publication of scientific articles from 2009 to 2023, with a peak maximum in 2022 (Fig 2). During 2010 no articles that fit the established criteria were obtained. Finally, it is important to highlight that the articles referring to the year 2023 do not correspond to the entire year, since the download of documents was carried out in August. (Fig. 2). Regardless of the spatial distribution, the biogeographic realm with the major record of published articles was the Temperate Northern Atlantic (n = 169), followed by the Central Indo-Pacific (n = 63) and the Temperate Northern Pacific (n = 49); and contrastingly, the Southern Ocean did not register any (Fig. 3; Table S4). A total of 33 studies were conducted in two or more biogeographic realms. The analyzed studies were conducted in 63 different countries (Table S5), with Australia and USA as the most representatives (each with 60 scientific articles) (Fig. 4). Conversely, 40 countries only were represented by three or less papers (Table S5). Also, 68 studies cover two or more countries.

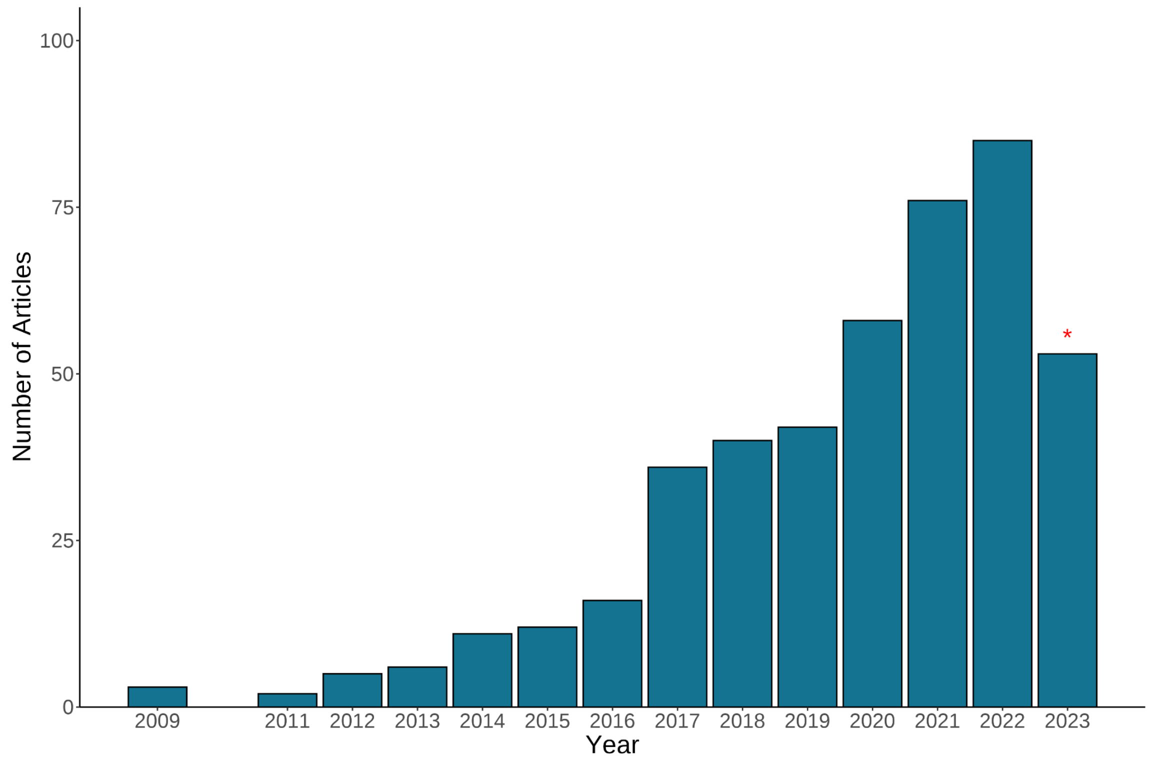

Fig. 2. Number of articles related to marine CS research obtained from the Scopus database. (*) Articles corresponding to the year 2023 include those obtained up to August.

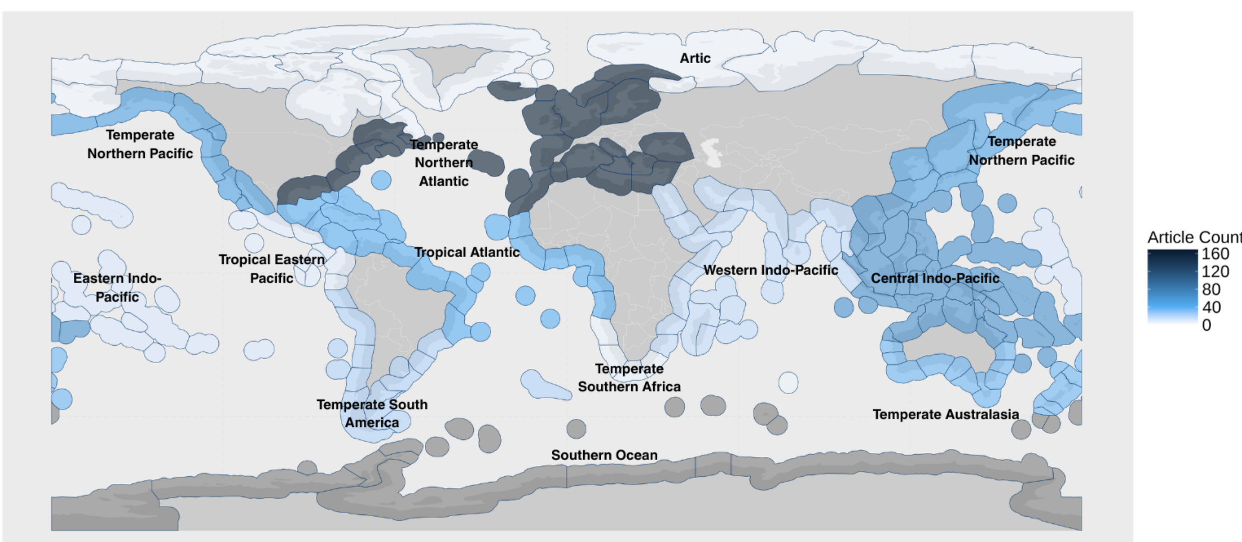

Fig. 3. Heatmap of the biogeographical realms reported in the analyzed articles. Darker colors indicate more reports. Gray color indicates the absence of reports. Articles with multiple biogeographical realms are not represented in the graphic.

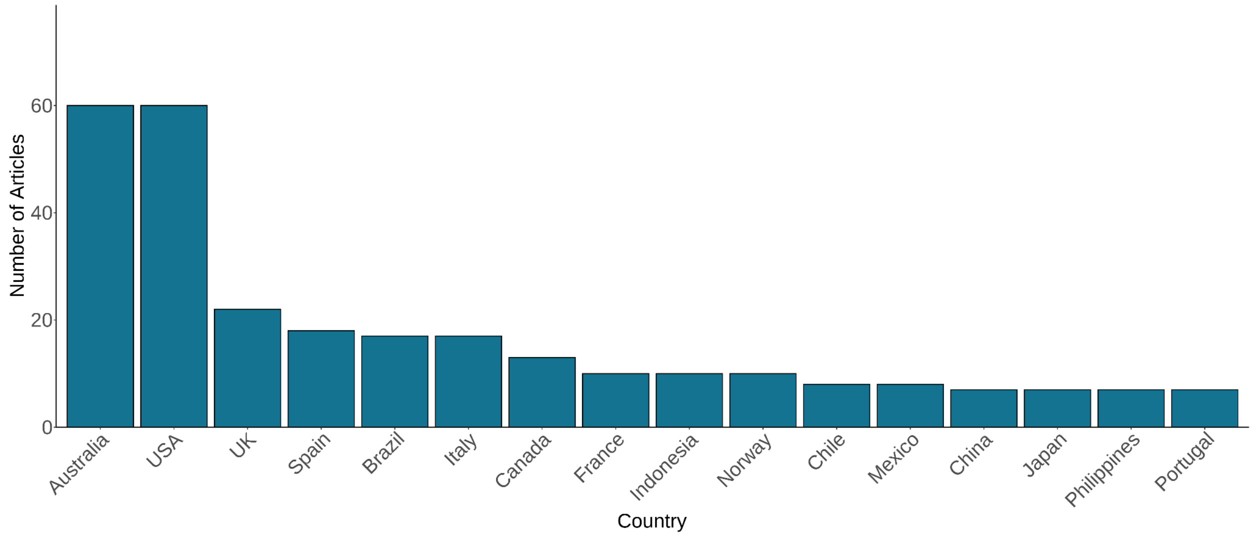

Fig. 4. Top sixteen countries with the largest amount of marine biology citizen science research obtained from the Scopus database.

Regarding the duration of the projects, 73.48 % reported a project length from >30 days up to almost 50 years; however ~26 % (n = 118) did not provide this information. Out of these records, 75 % lasted at least eight years (Table 3). Also contrasting data on the number of citizens was recorded, since most of the analyzed publications did not report the specific sum of citizens involved in the CS programs (67.94 %, n = 303). Among those studies that did report, the group sizes range between 1 and ≥19 000 individuals (Table 3). These groups were supported by academics in most of the cases (64.94 %, n = 289) and commonly used digital platforms for multiple purposes (56.63 %, n = 252). Methods that allow verification of the obtained results were used in more than half of the studies (57.30 %, n = 255).

Table 3. Reported length duration and number of citizens of marine biology citizen science research.

	Minimal	1st quartile	Median	3rd quartile	Maximum
Project duration (months)	Less than a month	9	36	96	594
Number of citizens	1	20	71	281	19 843

3.2. Biological research descriptors

The largest number of articles had themes related to biological groups (Fig. 5A), with only 15.7 % addressing topics such as pollution, geosciences and management. Of those who directly studied biological species, the most scrutinized groups were invertebrates and bony fishes, with 24.06 % and 23.46 % respectively; and among the most representatives per year in most cases (Table S6). In 2020 algae research had its peak, before studies involving algaes were reduced; after this year, they were constantly observed. Elasmobranchs had little to no representation at the beginning of the time series, but starting in 2017, the studies began to increase through the years. With marine mammals, an increase in the publications was also observed after 2018 (Table S6, Fig 5B). Finally, angiosperm studies are limited (4.37 %); however, they are consistent since 2020. Marine birds (3.98 %) and reptiles (4.37 %) appear, constantly, but with no huge rise in the publication

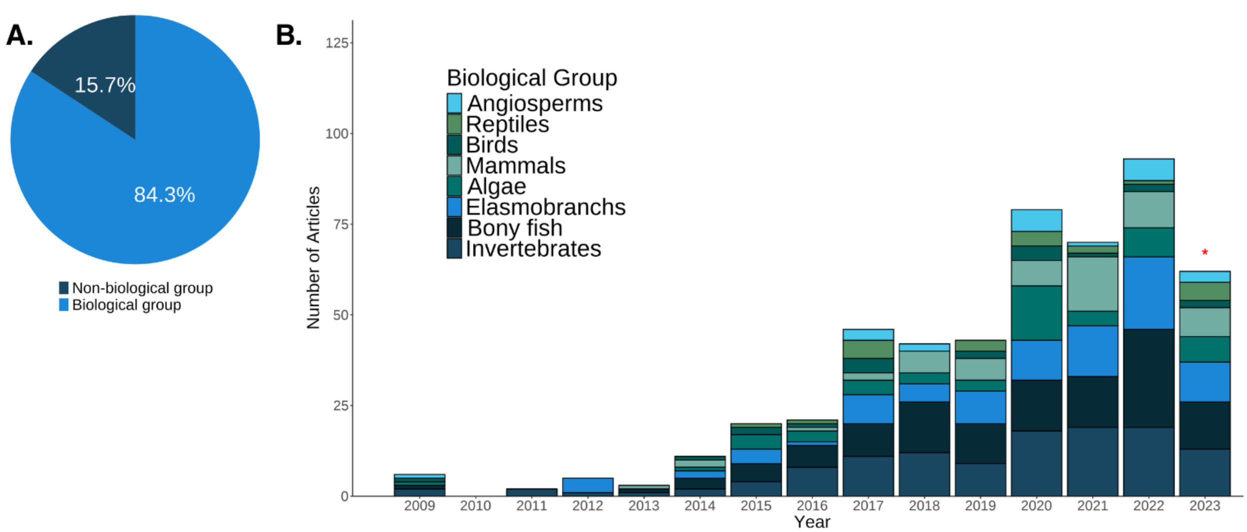

Fig. 5. A. Proportion of articles related (or not) to biological groups and **B.** biological groups studied in the marine biology citizen science-based articles analyzed, over different years. One singular article might've studied more than one biological group. (*) Articles corresponding to the year 2023 include those obtained up to August.

More than half (51.01 %) of the articles had topics related to the spatiotemporal patterns of biological groups (Fig. 6). This topic and ecosystemic stressors headed the research focus in the decade of 2013-2023, with the exception of 2015. Before 2013, the most common topic was diversity descriptors. Overall, behavior studies were low during the years, having their peak in 2022 (n = 9). Regardless of management topics, the first records were in 2014 (n = 2) and a continuous growth of publications through the years (excepting 2021, with no records at all) was observed. From 2017 to 2023, research on conservation attributes was common; however it maintained few publications over that period. Data showed that methodology testing had also a small representation through the analyzed documentation (Table S7). The least evaluated topics in all the years analyzed were molecular profiling, and geosciences, with 4.27 % and 2.25 %, respectively (Fig. 6; Table S7).

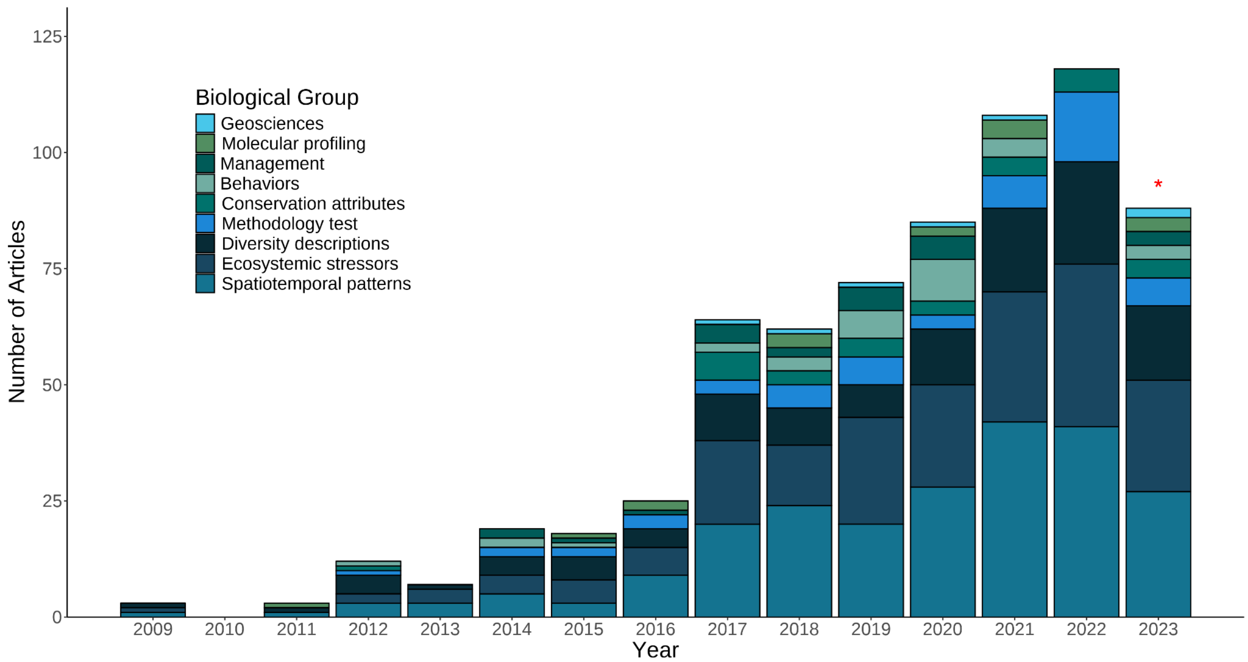

Fig. 6. Research topics in marine biology citizen science-based articles through the years. One singular paper can have different research topics. (*) Articles corresponding to the year 2023 include those obtained up to August.

Most studied ecosystems were those located along the coastline (including sandy and rocky shores, intertidal pools, or dunes) (36.18 %), followed by different types of reefs (35.51 %). With the exceptions of 2012 and 2016, these two classifications cover most of the publications per year throughout the study period (Table S8). Estuaries started to be represented in marine CS literature in 2015 and remained low in numbers for the rest of the surveyed time, with a slight peak in 2022 (n = 14). Overall, angiosperm-based ecosystems were the least represented study areas, including seagrass meadows (6.52 %), mangroves (3.60 %) and sea marshes (0.67 %). It is important to point out that 33.26 % of the analyzed records did not provide an optimal description of the ecosystems studied, so they were classified as "others" (Fig. 7). These values were constantly high over the years; this classification in some years (2023, 2018, and 2015) even represented the most frequently surveyed ecosystem.

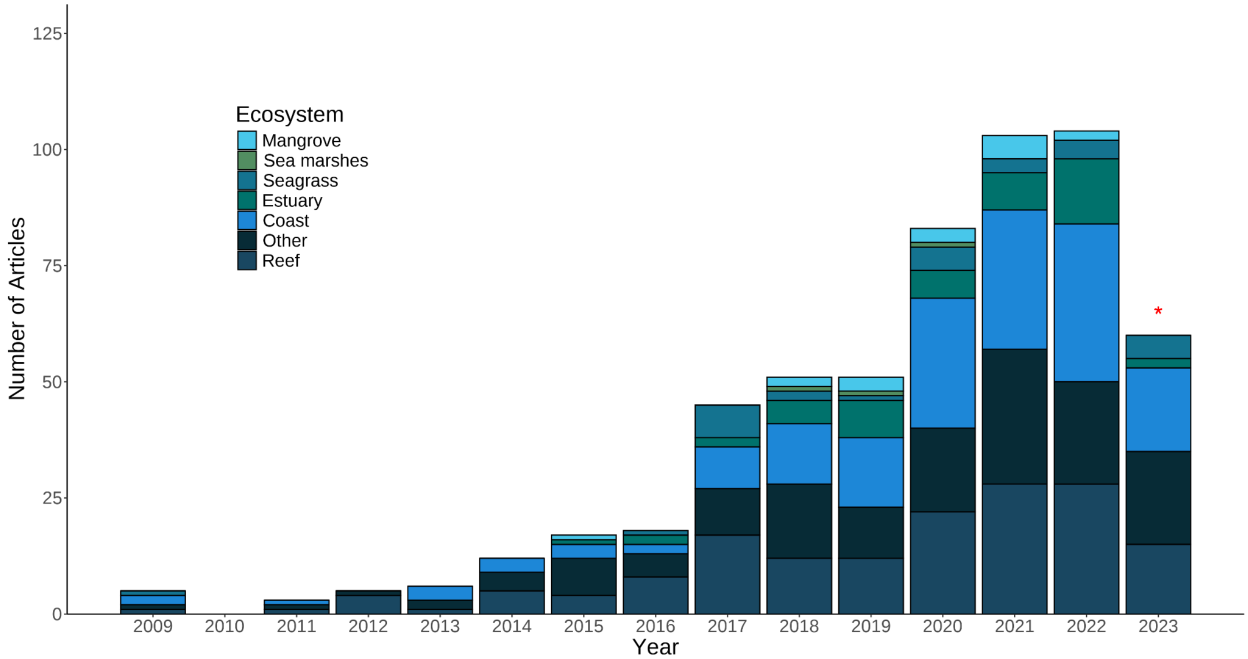

Fig. 7. Ecosystems studied in marine biology citizen science-based articles through the years. One singular paper can be conducted in different ecosystems. (*) Articles corresponding to the year 2023 include those obtained up to August.

3.3. Citizen science characterization

Overall, fieldwork was the most frequently reported role performed by citizen scientists (95.73 %), consistently heading the list of activities across every year analyzed. Data and sample processing, and planification were uncommon at the beginning of the analyzed time; however after 2013, citizens enrollment in these activities was more frequently reported. The use of Local Ecological Knowledge was included from the beginning (2009), and it increased over time, yet it remained with a low representation. Communication duties were the least performed activities (1.57 %); however, it is important to point out that since 2016 it is possible to observe reports of citizen scientists being involved (Fig. 8, Table S9).

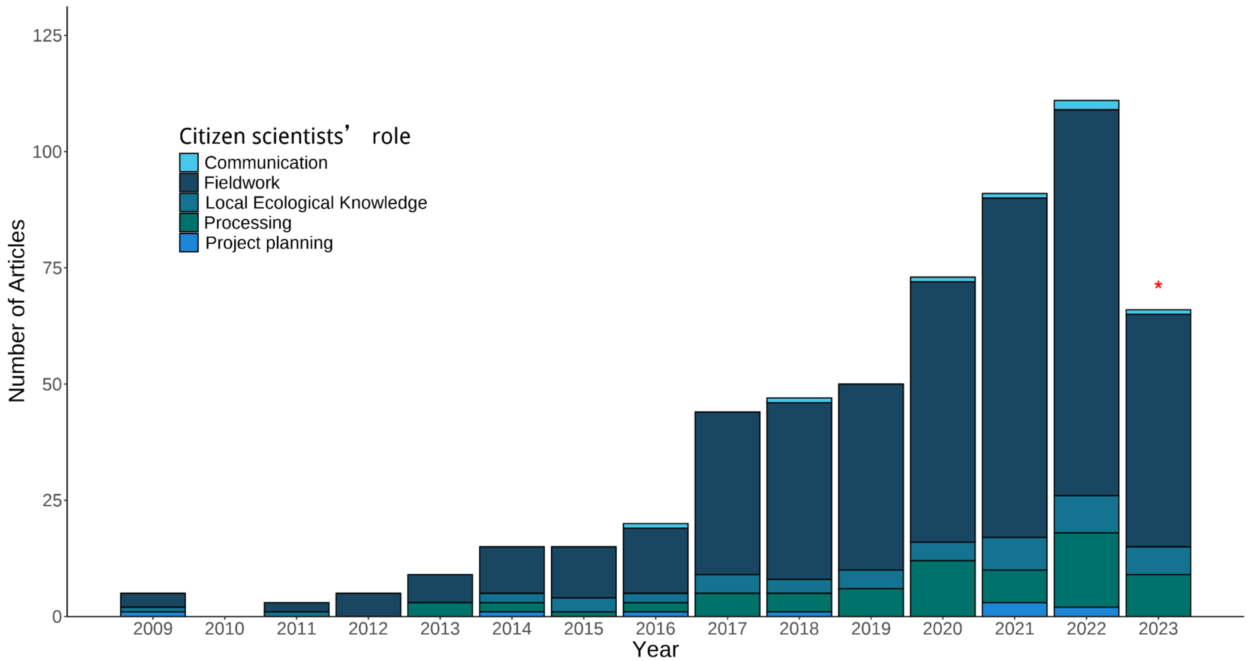

Fig. 8. Reported role performed by citizen scientists in marine biology citizen science-based articles through the years. Different roles could be covered in the same article. (*) Articles corresponding to the year 2023 include those obtained up to August.

All four implications—research, management, social, and policy change— were reported in the analyzed documentation. The relevance of research in the conservation efforts was mentioned across all studies. Throughout the years, this order (research, management, social, and policy change) was almost consistently preserved (Fig. 9; Table S10).

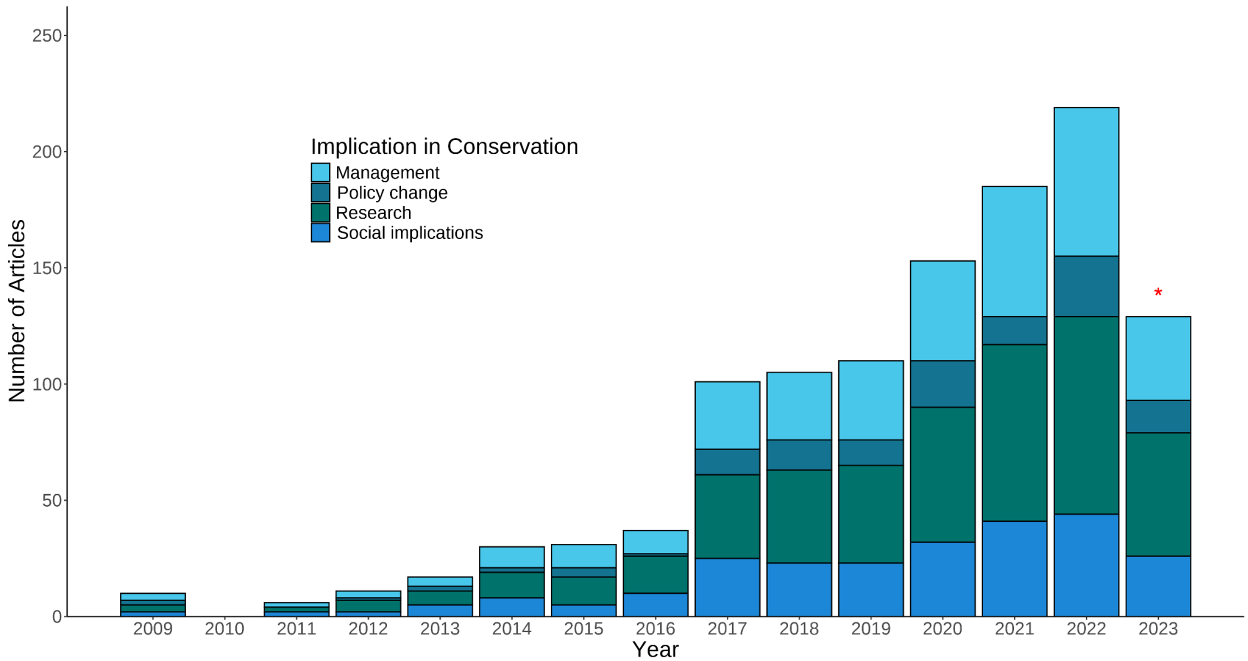

Fig. 9. Implications for conservation discussed in marine biology citizen science-based articles through the years. Authors might have highlighted more than one implication in the same article. (*) Articles corresponding to the year 2023 include those obtained up to August.

4. Discussion

4.1. Project descriptors

There is an increase in the number of publications through the years (Fig. 2), following the pattern shown by Thiel et al. (2014). This increase in CS programs has been attributed to a better awareness of the ecosystemic stressors implicated in human life, a widespread environmental education and an increase in NGOs participation (Conrad & Hilchey 2011). It is also due to a greater understanding by the academy of the benefits of citizen participation in research (Aceves-Bueno et al. 2017).

CS projects can be designed to cover different scales that go from local to global extensions (Thiel et al. 2014, McKinley et al. 2017), while also giving the chance of surveying very distant locations in a small-time frame (Paradinas et al. 2021). One of the features that might limit the area coverage is how easy to deploy and light to carry equipment is, especially in remote areas (Ershova et al. 2021). We found that the biogeographical realms that hold the higher number of published articles are the Temperate Northern Atlantic, followed by the Central Indo-Pacific and the Temperate Northern Pacific (Fig. 3). These spaces overlap with the Global North, the favorable context that this region has, including countries that have the highest Gross Domestic Product (The World Bank 2023b) and per-capita income (GDP per capita) (The World Bank 2023a), and a bigger scientific infrastructure (Collyer 2018), might modulate the willingness of stakeholders such as communities, governments, NGOs, and academia to invest in marine CS projects (Conrad & Hilchey 2011). Public participation in marine CS initiatives might be catalyzed by the presence of local communities near to the coast, since these areas are densely populated (Cosby et al. 2024). It should also be addressed that biodiversity hotspots are in these regions, like the Coral Triangle in the Central Indo-Pacific, and the Caribbean Sea in the Tropical Atlantic (Roberts et al. 2002, Ramírez et al. 2017).

A similar pattern of what was reported in scientific literature was found related to the marine CS country project distribution (Fig. 4), as the USA, Australia, the United Kingdom and Canada top the list of CS programs. In marine and non-marine environments, some of these countries have a long history of CS initiatives (Conrad & Hilchey 2011, Thiel et al. 2014). Thiel et al. (2014) reported 59 countries, while we are reporting 63 countries, which represents an increase in these processes. It is worth noting that, in most of the cases, the representation was low. Importantly, 68 of the articles we analyzed were conducted in two or more countries, reinforcing the importance of transboundary approaches for research and conservation efforts. CS initiatives boost the possibility of sharing data and experiences while responding to the fact that species and environmental stressors distribution are not dependent on countries boundaries (Potts et al. 2021).

We found that marine CS programs had a time frame that mainly goes up to eight years (Table 3). The ability to continue with long term programs it's constricted by funding (Hamburger et al. 2018, Allison et al. 2022, Ward et al. 2023). This economic instability has led to time periods when it was impossible to conduct surveys and a reduction of the applied protocols (Hamburger et al. 2018). CS programs have been noted for the reduction in the research costs (Aylesworth et al. 2017, Heres et al. 2021, Parretti et al. 2023). However, especially in marine environments (Cigliano et al. 2015), they require monetary investment, especially in the first steps of each program (Heres et al. 2021) and to keep a long-term engagement of the volunteers (Cottam et al. 2021).

Overall, marine CS studies were conducted by a small number of volunteers (Table 3). A reduced-controlled group of volunteers gives the possibility to improve the training quality and to correct mistakes of the applied methodologies (Abesamis et al. 2022). On the other hand, crowdsourcing data can be a useful way of acquiring large volumes of data; however, this might imply a reduction of the quality of this information, since it's almost impossible to track down all the volunteers to ensure the proper application of the protocols (McKinley et al. 2017). To actively look for ways of recruiting and maintaining long term volunteers it's crucial, since the citizen scientists working worldwide have contributed to millions of research hours in marine environments (Conrad & Hilchey 2011, Martin & Studer 2022)

Over 65 % of the articles reported contact with academics. We are considering contact with academics as a way of ensuring a certain degree of training, protocol control or mistake fixing. These aspects are fundamental since constant training has been associated with an increase in the data quality and the ability of volunteers to properly identify species (Aceves-Bueno et al. 2017, Abreo et al. 2019, Encarnação et al. 2021).

More than half of the articles described the use of digital forms for different purposes. Encarnação et al. (2021) was able to document a similar proportion in the reports of marine invasive species. An increase in the peer-reviewed publication using data from digital platforms has been observed (McKinley et al. 2017). Different technologies have been explored to improve data collection, such as smartphone apps and social media (Gundelund et al. 2021, Heres et al. 2021, Abesamis et al. 2022). Digital platforms, like social media, are extraordinaries tools to enhance the impact of CS programs (Tiralongo et al. 2020). On one hand they provide an avenue to obtain opportunistic data with a minimal cost (Beck et al. 2014), and on the other it is a way of keeping the engagement with the volunteers (Lazic et al. 2022). While the widespread access to smartphones and the internet is now common, it should be considered that in low-income or remote areas these technologies might not be useful. Therefore, in this context other methodologies could be encouraged.

More than half of the analyzed articles applied verification methods. As mentioned before, one of the challenges faced by CS programs is the ability to prove that the collected data can face the peer-reviewed standards of traditional science (Silvertown 2009). This is why proactively creating mechanisms that will enable the validation or even a reanalysis of the data is needed (Kržel j et al. 2020, Valani et al. 2020). At the same time as these verification methods are used, aspects such as training and support from experts must be implemented (Thiel et al. 2014, Encarnação et al. 2021). In an ultimate way, regardless of the concerns about CS data quality, observations made by the volunteers can be used as a starting point from traditional research questions (Matear et al. 2019, Séguigne et al. 2023). Lastly, having backup material to review can also benefit scientists, since their data can also hold errors (Aceves-Bueno et al. 2017).

4.2. Biological research descriptors

A small proportion of the analyzed documents were not related to the direct study of biological groups (Fig. 5A). However, most of these studies' topics were related to ecosystemic stressors, like pollution (Koly et al. 2021, Yen et al. 2022, Meyer et al. 2023), or environmental patterns, such as oceanography (Harley et al. 2019, Ortigosa et al. 2022); that had implications in biological groups (check research topics section). Most of our reviewed articles were related to the study of biological groups features (Fig. 5A). This pattern was also found by Thiel et al. (2014) and Aceves-Bueno et al. (2017). In both these cases, the authors also found a predilection for animals than other groups, as botany-studied species.

Invertebrates and bony fishes were the most studied groups (Fig. 5B). Thiel et al. (2014) found that bony fishes were the most represented group; however, invertebrates were not as relevant in their analysis. Even if invertebrates are not considered as “charismatic” as other groups (Machado et al. 2021), if they are easy to identify or have an “added value” in terms of attractiveness, like nudibranchs or corals (Nimbs et al. 2016, Pert et al. 2020), studies can be easily conducted. Groups that had a good representation in Thiel et al. (2014) review, still have a relevant number of articles. These being elasmobranchs, reptiles (mostly sea turtles) and sea mammals that have in our review 90, 58 and 22 records, respectively (Fig. 5B). Elasmobranch publications increased throughout the years (Fig 5B, Table S6), which can be a response to the raising alarm due to the ecological consequences by-product of the violent decrease that sharks and rays populations are facing (Roff et al. 2018); but also the reshape of the public perspective of these animals and the rise of an animal observation-based eco-tourist industry (Bargnesi et al. 2019).

With megafauna, like elasmobranchs, sea turtles and marine mammals, another factor that might influence public participation is the accessibility and cost reduction of technologies required to provide a register of distribution or behaviors such as cameras (Roberts et al. 2022). This is particularly important since a lot of CS methodologies rely on photo-identification (Whitney et al. 2012, Andrzejaczek et al. 2016, Gibson et al. 2020). Some of these species are emblematic, so even if the possibility of encounter is low, it should be acknowledged that they might be much easier to observe than cryptic organisms (Chin 2014, Weinstein et al. 2014, Vieira et al. 2020). Lastly, marine bird investigation was barely represented in our review; and this might be a result of the exclusion process, since birds tend to overlap with multiple non marine ecosystems.

Spatiotemporal patterns of biological groups harbor most of the published documentation, followed by ecosystemic stressors (Fig. 6; Table S7). The human capital that is available in CS initiatives allows a constant on-field presence to monitor the ecosystems (Silvertown 2009). The status of several marine ecosystems (discussed below) might inspire programs of marine CS to address environmental stressors, like contaminants (Souto & Batalhão 2022, Mishra et al. 2023), ghost fishing (Thorbjørnsen et al. 2023), massive population proliferation (Iporac et al. 2022), touristic activities (So et al. 2023) or natural disasters (Carter et al. 2022). The research topics trends seem to have slightly changed from the assessment done by Thiel et al. (2014); while the majority of the thematics are still related to ecological features of the studied species, we also found a variety of emerging topics as ethology studies, molecular profiling, and management (Fig. 6), but with a smaller representation. The reduced volume in the behavior category may reflect the nature of opportunist observations, which rely on the phenomenon itself being observed, recorded, analyzed and finally published (Whitehead & Gayford, 2023). Molecular profiling techniques constantly require extensive training and equipment (Guindon et al. 2015, de Virgilio et al. 2020) that could discourage public participation. Management studies increased over time, which may be a mobilization to an integrated coastal management framework that is nourished in public participation and holds social interactions through the involvement of citizens in research efforts (Furukawa et al. 2019, Lau et al. 2019). Themes such as geosciences and methodology testing might have been underrepresented, as search syntax was focused on biological groups. To obtain more accurate representation, reorienting the keywords syntax to address these thematics should be considered.

Easy to access ecosystems, like those located in the shores, and reefs were the most studied ecosystems (Fig. 7), which follow the described pattern by Thiel et al. (2014). Shore ecosystems, in general, are easier to access compared to other ecosystems, since in some cases marine transportation is not required (Cigliano et al. 2015) and are relatively close to densely populated areas (Neumann et al. 2015, Cosby et al. 2024). All these facilitate the logistics of marine CS operations.

Reefs are accessible with scuba diving and have a touristic industry associated (Lucrezi et al. 2018, Vieira et al. 2020), possess iconic and endangered species (Chin 2014, Paxton et al. 2018, Hanna et al. 2021, Osgood et al. 2021) and are strongly affected by disturbances (Reimer et al. 2024). They have been so studied that not only monitoring (Forrester et al. 2015), but also the presence of invasive species (Dumas et al. 2020), restoration efforts (Hesley et al. 2017) management (Voorberg & Van der Veer 2020) and even the aesthetic values perceived by volunteers (Pert et al. 2020). While this volume of information is extremely valuable, other ecosystems barely have representation in the literature (Fig. 7, Table S8). Plant-built ecosystems like mangroves, sea marshes and seagrass meadows did not receive the same attention, which is concerning due to the threat these environments are facing (Orth et al. 2006, Thomas et al. 2017), but also the lack of public knowledge of the ecosystem services they provide (Mtwana Nordlund et al. 2016, Friess et al. 2020, Smeaton et al. 2022). An important aspect that must be highlighted is the remarkable number of articles that did not describe in depth the research area. We're encouraging a better description of the ecosystems studied for future research.

4.3. Citizen science characterization

Over the years, we found that the most represented role is fieldwork data collection, while other roles became more frequently mentioned in recent years (Fig. 8). The extensive representation of fieldwork in the analyzed articles can be attributed to one of the often-highlighted benefits of monitoring large spatial areas (Armstrong et al. 2019). While this aspect it's important to enforce, others should be considered and encouraged. The degree of participation of citizens must consider the reality of each initiative, the research scope (McKinley et al. 2017), the availability to participate in the different steps of research and the knowledge each individual holds (Weinstein et al. 2014). Therefore, to achieve a broader spectrum of participation, different methodologies can be considered (Becken et al. 2019). One of those is local ecological knowledge to obtain historical data of species dynamics and ecological baselines in areas where no previous research was conducted (Blanco-Parra et al. 2022).

The communication of the results role was the least represented (Fig. 8). We know that this low number reported might result from only considering explicit information stated in the analyzed documents. Nevertheless, future publications should consider a more in-depth description of the participation of the citizens. Since it has been emphasized that involving the community in the communication process enhances flow of information to decision makers and a broader public (Izquierdo-Gómez 2022). From an integrated coastal management perspective, the widespread use of CS projects has positive implications since citizens can potentially be involved in different steps beyond data acquisition; including policy development and quick response to emergent crises (McKinley et al. 2017).

Unsurprisingly, research implications were mentioned in all the documents (Fig. 9), this might be a reaction to only using scientific articles. In the future, reviewing gray literature might elucidate this pattern. The data recorded in CS programs can be used to establish new lines of scientific research, management, and governance of nature resources (Owens et al. 2022). If analyzing sites and species management, even if CS data sources cannot be comparable between each different protocol, the results created can give a starting point for management regulations (Hernan et al. 2022), restrictions for invasive species (Grason et al. 2018), uncommon presences or behaviors (Tiralongo et al. 2022) or better methodologies for scaling up restoration efforts (Hesley et al. 2017, Unsworth et al. 2021).

Effective management cannot be successful without involving community's dynamics (Redpath et al. 2013). More than half of the analyzed articles noted the social implications of marine CS (Fig. 9). CS, due to its nature as a participatory process, has a remarkable potential in environmental education and social components (Guindon et al. 2015, Kiessling et al. 2017, Eberhardt et al. 2022). Involving different stakeholders in this kind of process it is indispensable to face the challenges, like lack of funding and volunteer recruitment, faced by CS initiatives (Potts et al. 2021, Martin & Studer 2022).

To achieve a greater impact, marine CS can contribute to the development of policies that contribute to the protection of the studied ecosystems (Conrad & Hilchey 2011, Vann-Sander et al. 2016), even if it’s the least represented implication mentioned in the literature (Fig. 9). In an ultimate perspective, CS can contribute to create and validate policies based in science, the way it has been seen in Jamaica’s coral reef protection (Crabbe 2012) and management of marine debris in India (Owens et al. 2022). CS has been suggested to increase the trust in science-based decision making, due to a more educated community. More educated community also implies more aware citizens facing environmental issues (Conrad & Hilchey 2011).

5. Conclusions

We found that the growing wave of marine CS projects is mainly made from medium-term (less than 8 years) programs that study easy-to-access nearshore ecosystems; most of them are conducted by a small number of volunteers in areas with economic availability (by people and governments). Half of the studies related to biological groups analyzed their presence in space. And while the biological groups that used to hold the greatest representation in literature still have presence, others have gained predominance. Citizens in these programs have performed the data collection; with implications in conservation related to the data acquisition, management and social participation.

CS must be visualized as a complement to traditional science (and other methodologies), not a replacement (Graba-Landry et al. 2023). CS benefits go beyond data collection and data quality; including the chance to engage stakeholders and increase the public knowledge of science (Bonney et al. 2016, Aceves-Bueno et al. 2017). In a very ultimate instance, CS it's a key for environmental and science democratization (Conrad & Hilchey 2011). It's a way of giving the population real access to marine spaces. CS programs require funds, time, peer-reviewed standards and the consideration of the social attributes of the citizens to succeed and have a prevalence in time (McKinley et al. 2017).

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7. Supplementary material

Table S1. Scientific articles of marine biology citizen science-based analyzed in this review

Citation	Article name
Ademantopoulou et al. 2023	Citizen science indicates significant range recovery and defines new conservation priorities for Earth's most endangered pinniped in Greece.
Brodie et al. 2023	The Big Seaweed Search: evaluating a citizen science project for a difficult to identify group of organisms.
Bundone et al. 2023	Investigating rare and endangered species: when a single methodology is not enough—the mediterranean monk seal *Monachus monachus* along the coast of Salento (South Apulia, Italy).
Burel et al. 2023	Range expansion of some non-indigenous seaweeds along the coasts of Brittany - English Channel.
Calatayud Pavía et al. 2023	Seasonal occurrence and environmental drivers of pelagic shark species in Los Cabos, Mexico, assessed using citizen science.
Campbell et al. 2023	Citizen science surveys provide novel nearshore data
Cao et al. 2023	Global population estimate and conservation gap analysis for the Nordmann's Greenshank (*Tringa guttifer*).
Courtin et al. 2023	Site fidelity and population parameters of pantropical spotted dolphins in the Eastern Caribbean through photographic identification.
Díaz-Mendoza et al. 2023	Abundance and distribution of cigarette butts on the sand of five touristic beaches in Latin America during the COVID-19 pandemic.
Dixon et al. 2023	Movement patterns of the iconic giant trevally *Caranx ignobilis* from southern Africa, determined using tag-recapture data.
Dobson et al. 2023	Citizen science effectively monitors biogeographical and phenological patterns of jellyfish.
Ferreto et al. 2023	Optimizing the restoration of the threatened seagrass *Posidonia australis*: plant traits influence restoration success.
Gacutan et al. 2023	Assessing human and physical drivers of macro-plastic debris spatially across Queensland, Australia.
Gole et al. 2023	Herd size dynamics and observations on the natural history of dugongs (*Dugong dugon*) in the Andaman Islands, India.
Gotama et al. 2023	Citizen science approach for monitoring fish and megafauna assemblages in a remote marine protected area.
Graba-Landry et al. 2023	Citizen science aids the quantification of the distribution and prediction of present and future temporal variation in habitat suitability at species' range edges.
Hermawan et al. 2023	Utilization of the hydrodynamic model to determine the movement characteristics of marine debris in Karimata islands compare to data collection from citizen science research.
Hoschke et al. 2023	Population distribution, aggregation sites and seasonal occurrence of Australia's western population of the grey nurse shark *Carcharias taurus*.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Jensen et al. 2023	Reviewing introduction histories, pathways, invasiveness, and impact of non-indigenous species in danish marine waters.
Khamis et al. 2023	Long-term persistence of large dugong groups in a conservation hotspot around Hawar Island, Kingdom of Bahrain.
Kiessling et al. 2023	What potential does the EU Single-Use Plastics Directive have for reducing plastic pollution at coastlines and riversides? An evaluation based on citizen science data.
Lee et al. 2023	Eight years of community structure monitoring through recreational citizen science at the “SS Thistlegorm” wreck (Red Sea).
Malloggi et al. 2023	Accidental discovery of a Tetraodontidae (*Sphoeroides marmoratus*) within a cuttlefish (*Sepia officinalis*) bought in a fish shop in Italy: risk assessment associated with the presence of Tetrodotoxin.
Malloggi et al. 2023	First toxicological analysis of the pufferfish sphoeroides pachygaster collected in italian waters (Strait of Sicily): role of citizens science in monitoring toxic marine species
Marcoux et al. 2023	A first look at whale sharks in Hawaiian waters: Using citizen science to study the world's largest fish, *Rhincodon typus.*
Marshall et al. 2023	Southward range extension and transboundary movements of reef manta rays *Mobula alfredi* along the east African coastline.
Massey et al. 2023	Monitoring green sea turtles in the San Gabriel River of Southern California.
Matsuba et al. 2023	Effectiveness of hierarchical Bayesian models for citizen science data with missing values: A case study on the factors influencing beach litter in Shimane Prefecture, Japan.
Meyer et al. 2023	Where does Arctic beach debris come from? Analyzing debris composition and provenance on Svalbard aided by citizen scientists.
Meyerjürgens et al. 2023	Sources, pathways, and abatement strategies of macroplastic pollution: an interdisciplinary approach for the southern North Sea.
Middleton et al. 2023	Occurrences of tropical, subtropical and rare marine fishes in Aotearoa New Zealand indicate biodiversity change.
Mishra et al. 2023	Assessment of national beach litter composition, sources, and management along the Indian coast - a citizen science approach.
Neves-Ferreira et al. 2023	Photo-identification shows the spatio-temporal distribution of two sea turtle species in a Brazilian developmental foraging ground.
Nijman, 2023	Tourists, selfies and coastal monitoring during COVID-19.
Nyegaard et al. 2023	Rapid physiological colouration change is a challenge - but not a hindrance - to successful photo identification of giant sunfish (*Mola alexandrini*, Molidae).
Parretti et al. 2023	Citizen science and expert judgement: a cost-efficient combination to monitor and assess the invasiveness of non-indigenous fish escapees.
Patterson et al. 2023	Improving certainty in marine ecosystems: A biophysical modelling approach in the remote, data-limited Gulf of Carpentaria.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Pereira-Cabral et al. 2023	The influence of El Niño Southern Oscillation on the population dynamics of oceanic manta rays in the Mexican Pacific.
Putman et al. 2023	Improving satellite monitoring of coastal inundations of pelagic *Sargassum* algae with wind and citizen science data.
Rambahiniarison et al. 2023	Distribution of the reef manta ray *Mobula alfredi* and the oceanic manta ray *Mobula birostris* in the Philippines: a collaborative effort for conservation.
Santos-Fernandez et al. 2023	Increasing trust in new data sources: crowdsourcing image classification for ecology.
Séguigne et al. 2023	Citizen science provides valuable data to evaluate elasmobranch diversity and trends throughout the French Polynesia's shark sanctuary.
So et al. 2023	Underwater impact and intention–behaviour gap of scuba divers on coral communities in Hong Kong SAR, China.
Suzuki-Ohno et al. 2023	Evaluation of community science monitoring with environmental DNA for marine fish species: "Fish survey project using environmental DNA".
Tavares et al. 2023	Tracking marine tetrapod carcasses using a low-cost mixed methodology with GPS trackers, passive drifters and citizen science.
Thorbjørnsen et al. 2023	Hazard and catch composition of ghost fishing gear revealed by a citizen science clean-up initiative.
Urquhart et al. 2023	Generalized additive models for categorical count data: An exploration of the decline of queen triggerfish *Balistes vetula* in the Bahamas and Turks and Caicos.
Vilches et al. 2023	Life histories of satellite-tracked southern right whales through photo-identification and citizen science in patagonia, argentina.
Ward et al. 2023	Spatial variation and antecedent sea surface temperature conditions influence Hawaiian intertidal community structure.
Węgrzyn et al. 2023	The use of social media in assessing the impact of war on cetaceans.
Whitehead & Gayford, 2023	First record of bottom-feeding behaviour in the whale shark (*Rhincodon typus*).
Winton et al. 2023	Harnessing citizen science to tackle urban-sourced ocean plastic pollution: Experiences and lessons learned from implementing city-wide surveys of plastic litter.
Zhang et al. 2023	Citizen science to support coastal research and management: Insights from a seagrass monitoring case study in Hainan, China.
Abesamis et al. 2022	MPA-FishMApp - A citizen science app that simplifies monitoring of coral reef fish density and biomass in marine protected areas.
Agersnap et al. 2022	A national scale "bioblitz" using citizen science and eDNA metabarcoding for monitoring coastal marine fish.
Allison et al. 2022	Simulating the distribution of beached litter on the northwest coast of Scotland.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Arellano-Verdejo et al. 2022	Use of semantic segmentation for mapping *Sargassum* on beaches.
Ashley et al. 2022	Documenting fishes in an inland sea with citizen scientist diver surveys: using taxonomic expertise to inform the observation potential of fish species.
Aximoff et al. 2022	New Occurrences of the Tiger Shark (*Galeocerdo cuvier*) (Carcharhinidae) off the Coast of Rio de Janeiro, Southeastern Brazil: Seasonality Indications.
Bargnesi et al. 2022	New technologies can support data collection on endangered shark species in the Mediterranean Sea.
Bengtsson et al. 2022	Cetacean spatial trends from 2005 to 2019 in Svalbard, Norway.
Berrow & Whooley, 2022	Managing a dynamic North Sea in the light of its ecological dynamics: Increasing occurrence of large baleen whales in the southern North Sea.
Blanco-Murillo et al. 2022	Spatiotemporal trends observed in 20 years of *Posidonia oceanica* monitoring along the Alicante Coast, Spain.
Blanco-Parra et al. 2022	Citizen science as a tool to get baseline ecological and biological data on sharks and rays in a data-poor region.
Bolt et al. 2022	Using the background of fish photographs to quantify habitat composition in marine ecosystems.
Bostrom-Einarsson et al. 2022	An ecological assessment of Australia's first community oyster gardens.
Bouzekry et al. 2022	Addressing the challenge of marine plastic litter in the Moroccan Mediterranean: A citizen science project with schoolchildren.
Cárdenas-Farfán et al. 2022	Citizen science program and contamination by anthropogenic marine debris in the coastal marine zone-Huanchaco.
Carter et al. 2022	Cyclone impacts on coral reef communities in Southwest Madagascar.
Carvalho et al. 2022	Citizen science as a tool for understanding the silent dispersion of toadfish *Opsanus beta* (Goode and Bean, 1880).
Castro-Gutiérrez et al. 2022	Estimation of jellyfish abundance in the south-eastern Spanish coastline by using an explainable artificial intelligence model based on fuzzy logic.
Ćetković et al. 2022	Observations of juvenile sandbar sharks *Carcharhinus plumbeus* (Nardo, 1827) around the Bojana River delta (Southern Adriatic Sea).
Clapis Garla et al. 2022	Mating behavior of the lemon shark, *Negaprion brevirostris* (Carcharhiniformes: Carcharhinidae), as revealed by citizen science in the Equatorial Atlantic Ocean.
Cloyed et al. 2022	Habitat selection and abundance of West Indian manatees *Trichechus manatus* at the margins of their expanding range.
Cranswick et al. 2022	Social media and citizen science records are important for the management of rarely sighted whales.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Davis et al. 2022	Is conscientious beachcombing the key to 'unlock' marine plastic pollution trends through citizen science? A case study from Cockburn Sound, Western Australia.
Des Roches et al. 2022	Shoreline armor removal can restore variability in intertidal ecosystems.
Souto & Batalhão, 2022	Citizen science as a tool for collaborative site-specific oil spill mapping: the case of Brazil.
DiBattista et al. 2022	A comprehensive analysis of all known fishes from Sydney Harbour.
Duan et al. 2022	Comparison of IUCN and species distribution modeling-estimated ranges of shorebirds in Coastal Mainland China.
Duan et al. 2022	Combining bootstrapping procedure and citizen science data to elucidate waterbirds' dependence on coastal wetland.
Eberhardt et al. 2022	Connecting science and community: Volunteer beach profiling to increase coastal resilience.
Eby et al. 2022	Sea otters in a California estuary: Detecting temporal and spatial dynamics with volunteer monitoring.
Edelist et al. 2022	Tracking Jellyfish Swarm Origins Using a Combined Oceanographic-Genetic-Citizen Science Approach.
Ehemann et al. 2022	Manta and devil ray species occurrence and distribution in Venezuela, assessed through fishery landings and citizen science data.
Encarnação et al. 2022	Coastal countercurrents increase propagule pressure of an aquatic invasive species to an area where previous introductions failed.
Eryaşar & Saygu, 2022	Using social media to identify recreational bluefish angling in the Mediterranean and Black Sea.
Foster et al. 2022	Age and Growth of the Cape Knifejaw *Oplegnathus conwayi,* an Endemic South African Teleost.
Freitas et al. 2022	In an octopus's garden in the shade: Underwater image analysis of litter use by benthic octopuses.
Gacutan et al. 2022	Continental patterns in marine debris revealed by a decade of citizen science.
Gan et al. 2022	Identifying marine debris source position using adjoint marginal sensitivity method and stranded beach litter data in Singapore.
Germanov et al. 2022	Residency, movement patterns, behavior and demographics of reef manta rays in Komodo National Park.
Hernan et al. 2022	Measuring the efficiency of alternative biodiversity monitoring sampling strategies.
Hoh et al. 2022	A dataset of sea turtle occurrences around the Taiwan coast.
Hughes et al. 2022	Movement patterns of an iconic recreational fish species, mulloway (*Argyrosomus japonicus*), revealed by cooperative citizen-science tagging programs in coastal eastern Australia.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Iporac et al. 2022	Community-based monitoring reveals spatiotemporal variation of sargasso inundation levels and morphotype dominance across the Caribbean and South Florida.
Izquierdo-Gómez, 2022	Synergistic use of facebook, online questionnaires and local ecological knowledge to detect and reconstruct the bioinvasion of the Iberian Peninsula by *Callinectes sapidus* Rathbun, 1896.
Jones et al. 2022	Microplastic distribution and composition on two Galápagos island beaches, Ecuador: Verifying the use of citizen science derived data in long-term monitoring.
Knochel et al. 2022	Crowdsourced data reveal multinational connectivity, population demographics, and possible nursery ground of endangered oceanic manta rays in the Red Sea.
Koroza & Evans et al. 2022	Bottlenose dolphin responses to boat traffic affected by boat characteristics and degree of compliance to code of conduct.
Kovačic et al. 2022	Identification of Mediterranean marine gobies (Actinopterygii: Gobiidae) of the continental shelf from photographs of in situ individuals.
Lawson et al. 2022	Engaging online citizen scientists and the consensus method to monitor the marine biofouling community.
Lazic et al.2022	Assessing seahorses' distribution along the Italian coasts through citizen science and social media platforms.
Lester et al. 2022	Whale sharks (*Rhincodon typus*) feed on baitfish with other predators at Ningaloo Reef.
Lima-Júnior et al. 2022	Knowledge connections for conservation of the Atlantic Goliath Grouper, *Epinephelus itajara*: records of tropical Brazilian coast.
Magson et al. 2022	Citizen science reveals the population structure and seasonal presence of whale sharks in the Gulf of Thailand.
Martin & Studer, 2022	Citizen science on the beach: grunion greeters in California.
Maxwell, 2022	The first record of *Neodilatilabrum* Dekkers, 2008 (Stromboidea, Neostromboidae, Strombidae) in Australia.
McCluskey et al. 2022	On the seasonal dynamics of phytoplankton chlorophyll-a concentration in nearshore and offshore waters of plymouth, in the english channel: enlisting the help of a surfer.
McCosker et al. 2022	Sea temperature and habitat effects on juvenile reef fishes along a tropicalizing coastline.
Merten et al. 2022	A citizen science approach to enhance dolphinfish (*Coryphaena hippurus*) data collection to improve species management.
Micaroni et al. 2022	Project "Biodiversity MARE Tricase": A species inventory of the coastal area of southeastern Salento (Ionian Sea, Italy).
Miya et al. 2022	The use of citizen science in fish eDNA metabarcoding for evaluating regional biodiversity in a coastal marine region: A pilot study.
Mungia-Vega et al. 2022	Social-ecological networks and connectivity within and between two communities of small-scale fishers in Mexico.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Natoli et al. 2022	Citizen science data of cetaceans in the Arabian/Persian Gulf: Occurrence and habitat preferences of the three most reported species.
Nguyen et al. 2022	Baseline marine litter surveys along vietnam coasts using citizen science approach.
Öndes et al. 2022	Spatial distribution and density of the invasive sea urchin *Diadema setosum* in Turkey (eastern Mediterranean).
Ortigosa et al. 2022	Barcelona coastal monitoring with the “Patí a Vela”, a traditional sailboat turned into an oceanographic platform.
Owens et al. 2022	Empowering local practitioners to collect and report on anthropogenic riverine and marine debris using inexpensive methods in India
Perez-Jiménez et al. 2022	Inferring ecosystem impacts of a small-scale snapper fishery through citizen science data, productivity and susceptibility analysis, and ecosystem modelling.
Pirotta et al. 2022	Drone Observations of Marine Life and Human–Wildlife Interactions off Sydney, Australia.
Pulido Mantas et al. 2022	Mediterranean sea shelters for the gold coral *Savalia savagli*a (Bertoloni, 1819): An assessment of potential distribution of a rare parasitic species.
Roberts et al. 2022	Many cameras make light work: opportunistic photographs of rare species in iNaturalist complement structured surveys of reef fish to better understand species richness.
Ross Robertson et al. 2022	An updated, illustrated inventory of the marine fishes of the US Virgin Islands.
Schneider et al. 2022	Volume-based assessment of coastal litter reveals a significant underestimation of marine litter from ocean-based activities in East Asia.
Serranito et al. 2022	Small- and large-scale processes including anthropogenic pressures as drivers of gastropod communities in the NE Atlantic coast: A citizen science based approach.
Setyawan et al. 2022	Population estimates of photo-identified individuals using a modified POPAN model reveal that Raja Ampat’s reef manta rays are thriving.
Simons et al. 2022	Determining the effects of artificial light at night on the distributions of western snowy plovers (*Charadrius nivosus nivosus)* and california grunion (*Leuresthes tenuis*) in Southern California.
Smith et al. 2022	Quantifying catch rates, shark abundance and depredation rate at a spearfishing competition on the Great Barrier Reef, Australia
Smith et al. 2022	Removal of macroalgae from degraded reefs enhances coral recruitment.
Tiralongo et al. 2022	From the Strait of Sicily to the Sicilian Ionian Sea: the expansion of *Hemiramphus far* (Forsskål, 1775) in Italian waters.
Wambiji et al. 2022	Integrating long-term citizen science data and contemporary artisanal fishery survey data to investigate recreational and small-scale shark fisheries in Kenya.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Ward-Paige et al. 2022	Community-driven shark monitoring for informed decision making: a case study from Fiji.
Willis et al. 2022	Using long-term citizen science data to distinguish zones of debris accumulation.
Wosnik et al. 2022	Global assessment of shark strandings.
Yen et al. 2022	Quantity and type of coastal debris pollution in Taiwan: A rapid assessment with trained citizen scientists using a visual estimation method.
Zava et al. 2022	Records of the critically endangered *Squatina aculeata* and *Squatina oculata* (Elasmobranchii: Squatiniformes: Squatinidae) from the Mediterranean Sea.
Zimmermann et al. 2022	Inclusion of recreational fishing in data-limited stocks: a case study on Norway lobster (*Nephrops norvegicus*) in Norway.
Al Mabruk et al. 2021	New record of *Epinephelus areolatus* in the mediterranean sea: first record from Syria.
Armitage et al. 2021	Effects of mangrove encroachment on tidal wetland plant, nekton, and bird communities in the Western Gulf of Mexico.
Baird et al. 2021	Site fidelity, spatial use, and behavior of dwarf sperm whales in Hawaiian waters: using small-boat surveys, photo-identification, and unmanned aerial systems to study a difficult-to-study species.
Bucair et al. 2021	Sightings trends and behaviour of manta rays in Fernando de Noronha Archipelago, Brazil.
Bustamante et al. 2021	Observations of coastal aggregations of the broadnose sevengill shark (*Notorynchus cepedianus*) in Chilean waters.
Castriota & Falautano, 2021	Reviewing the invasion history of the blue crab *Callinectes sapidus* (portunidae) in sicily (central mediterranean): An underestimated alien species.
Castro et al. 2021	A new signal of tropicalization in the northeast atlantic: The spread of the spotfin burrfish *Chilomycterus reticulatus* in madeira archipelago and its invasion risk.
Castro-Azofeifa, 2021	Sightings of *Orcinus orca* (Linnaeus, 1758) (Cetartiodactyla: Odontoceti: Delphinidae) in the Costa Rican Pacific (1990-2020).
Christensen et al. 2021	Population ecology, growth, and physico-chemical habitat of anadromous European perch *Perca fluviatilis*.
Coché et al. 2021	Kakila database: Towards a FAIR community approved database of cetacean presence in the waters of the Guadeloupe Archipelago, based on citizen science.
Cottam et al. 2021	Drain detectives: lessons learned from citizen science monitoring of beach drains.
Cuevas et al. 2021	First evidence of regional migration of the copper shark *Carcharhinus brachyurus* (Günther, 1870) in the Southwest Atlantic.
de Virgilio et al. 2021	Citizen science in the monitoring of *Ostreopsis ovata* blooms in southern Italy: A five-year study.
De Weerdt et al. 2021	Cetacean strandings along the Pacific and Caribbean coasts of Nicaragua from 2014 to 2021.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Encarnação et al. 2021	Low-cost citizen science effectively monitors the rapid expansion of a marine invasive species
Ershova et al. 2021	Combining citizen and conventional science for microplastics monitoring in the White Sea basin (Russian Arctic).
Esenkulova et al. 2021	Harmful algae and oceanographic conditions in the strait of georgia, canada based on citizen science monitoring.
Fonseca Rech et al. 2021	Species with insufficient data and red lists: The dilemma of the beach trigonal clam *Tivela mactroides*.
Garcés-Ordóñez et al. 2021	Marine litter pollution in mangrove forests from Providencia and Santa Catalina islands, after Hurricane IOTA path in the Colombian Caribbean.
Garcia-Cegarra et al. 2021	Citizen science as a tool to assess cetacean diversity in the Atacama Desert coast.
García-Gómez et al. 2021	Monitoring extreme impacts of *Rugulopteryx okamurae* (Dictyotales, Ochrophyta) in El Estrecho Natural Park (Biosphere Reserve). Showing radical changes in the underwater seascape.
Gassett et al. 2021	Community science for coastal acidification monitoring and research.
Giovos et al. 2021	Integrating literature, biodiversity databases, and citizen-science to reconstruct the checklist of chondrichthyans in cyprus (Eastern mediterranean sea).
Gundelund et al. 2021	Evaluation of a citizen science platform for collecting fisheries data from coastal sea trout anglers.
Gutiérrez-Estrada et al. 2021	Integrating local environmental data and information from non-driven citizen science to estimate jellyfish abundance in Costa del Sol (southern Spain).
Gutiérrez-Muñoz et al. 2021	Patterns and trends in cetacean occurrence revealed by shorewatch, a land-based citizen science program in Scotland (United Kingdom).
Hanna et al. 2021	Citizen-sourced sightings and underwater photography reveal novel insights about green sea turtle distribution and ecology in southern California.
Hari et al. 2021	The sharks and rays of Palau: Biological diversity, status, and social and cultural dimensions.
Heres et al. 2021	Using citizen science to track population trends in the american horseshoe crab (*Limulus polyphemus*) in Florida.
Huseyinoglu et al. 2021	Spatio-temporal distribution of lionfish, *Pterois miles* (Bennett, 1828) in Kas-Kekova Special Environmental Protected Area, Turkey.
Jambura et al. 2021	Using historical and citizen science data to improve knowledge about the occurrence of the elusive sandbar shark *Carcharhinus plumbeus* (Chondrichthyes – Carcharhinidae) in the Adriatic Sea.
Jesus et al. 2021	Can citizen science help delimit the geographical distribution of a species? The case of the *Callistoctopus* sp. ("eastern octopus") on the Brazilian coast.
Johansen et al. 2021	Assessing the value of a citizen science approach for ctenophore identification.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Johnson & Davoren, 2021	Distributional patterns of humpback whales (*Megaptera novaeangliae*) along the Newfoundland East Coast reflect their main prey, capelin (*Mallotus villosus*).
Jones et al. 2021	Long-term patterns of mass stranding of the colonial cnidarian *Velella velella*: influence of environmental forcing.
Kabasakal & Bayri, 2021	Great white sharks, *Carcharodon carcharias*, hidden in the past: three unpublished records of the species from turkish waters.
Keen et al. 2021	Fin whales of the Great Bear Rainforest: *Balaenoptera physalus velifera* in a Canadian Pacific fjord system.
Keeping et al. 2021	Trends in sightings of the stingrays of southern Mozambique.
Koly et al. 2021	Marine litter composition and density in Alor Island.
Laporta et al. 2021	Citizen science recording the shifting distribution of subtropical species in the Southwestern Atlantic: the southernmost records of *Orthopristis ruber* (Haemulidae, Lutjaniformes).
Licuanan & Mordeno, 2021	Citizen science reveals the prevalence of the 2020 mass coral bleaching in one town.
Machado et al. 2021	Participatory monitoring of marine biological invaders: a novel program to include citizen scientists.
Marambio et al. 2021	Unfolding jellyfish bloom dynamics along the mediterranean basin by transnational citizen science initiatives.
Martin et al. 2021	Population trends of beach-spawning California grunion *Leuresthes tenuis* monitored by citizen scientists.
McCann et al. 2021	The shortfin devilray (*Mobula kuhlii*) aggregates at Pulau Si Amil, Sabah, Malaysia.
Merlino et al. 2021	Citizen science for marine litter detection and classification on unmanned aerial vehicle images.
Middleton et al. 2021	Introduced alien, range extension or just visiting? Combining citizen science observations and expert knowledge to classify range dynamics of marine fishes.
Milankovic et al. 2021	Seasonal occurrence and sexual segregation of great white sharks *Carcharodon carcharias* in Mossel Bay, South Africa.
Morais et al. 2021	Harnessing the power of social media to obtain biodiversity data about cetaceans in a poorly monitored area.
Murphy et al. 2021	Identifying possible drivers of the abrupt and persistent delay in capelin spawning timing following the 1991 stock collapse in Newfoundland, Canada.
Mwango'mbe et al. 2021	Cetacean research and citizen science in Kenya.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Noviello et al. 2021	Modelling Critically Endangered marine species: Bias-corrected citizen science data inform habitat suitability for the angelshark (*Squatina squatina*).
Osgood et al. 2021	Effects of climate-change-driven gradual and acute temperature changes on shark and ray species.
Paradinas et al. 2021	A new collection tool-kit to sample microplastics from the marine environment (sediment, seawater, and biota) using citizen science.
Phillips & Kotrschal, 2021	Where are they now? Tracking the Mediterranean lionfish invasion via local dive centers.
Pirotta & Harcourt, 2021	Opportunistic sightings of blue whales off Sydney, Australia.
Pottie et al. 2021	Quantifying the distribution and site fidelity of a rare, non-commercial elasmobranch using local ecological knowledge.
Pucino et al. 2021	Citizen science for monitoring seasonal-scale beach erosion and behaviour with aerial drones.
Ragkousis et al. 2021	Rarely reported cryptobenthic fish in marine caves of the eastern Mediterranean sea.
Régnier et al. 2021	Age and growth of the Critically Endangered flapper skate, *Dipturus intermedius*.
Requilme et al. 2021	Using citizen science and survey data to determine the recruitment envelope of the giant clam, *Tridacna gigas* (Cardiidae: Tridacninae).
Ribeiro et al. 2021	Marine litter on a highly urbanized beach at Southeast Brazil: A contribution to the development of litter monitoring programs.
Ringvold et al. 2021	In situ recordings of large gelatinous spheres from NE Atlantic, and the first genetic confirmation of egg mass of *Illex coindetii* (Vérany, 1839) (Cephalopoda, Mollusca).
Rodriguez et al. 2021	Spatial and temporal variation in the occurrence of bottlenose dolphins in the Chesapeake Bay, USA, using citizen science sighting data.
Ross Robertson et al. 2021	*Acanthurus mata* (Cuvier, 1829), Elongate Surgeonfish (Acanthuridae), newly recorded in the Tropical Eastern Pacific.
Ross Robertson et al. 2021	*Lutjanus inermis* (Peters, 1869), Golden Snapper, range extension to the Galapagos Islands.
Schneider et al. 2021	Rapid-survey methodology to assess litter volumes along large river systems—a case study of the tamsui river in taiwan.
Smith et al. 2021	Field measurements of a massive *Porites* coral at Goolboodi (Orpheus Island), Great Barrier Reef.
Tirelli et al. 2021	Citizens' eyes on mnemiopsis: How to multiply sightings with a click!
Turicchia et al. 2021	The Reef Check med dataset on key mediterranean marine species 2001–2020
Turner et al. 2021	Transport, weathering and pollution of plastic from container losses at sea: Observations from a spillage of inkjet cartridges in the North Atlantic Ocean.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Unsworth et al. 2021	Outplanting optimized: developing a more efficient coral attachment technique using Portland cement.
Van Cise et al. 2021	Mark–recapture estimates suggest declines in abundance of common bottlenose dolphin stocks in the Main Hawaiian Islands.
van der Molen et al. 2021	Potential micro-plastics dispersal and accumulation in the north sea, with application to the msc zoe incident.
Ver Hoef et al. 2021	Species density models from opportunistic citizen science data.
Zorzo et al. 2021	An approach to the integration of beach litter data from official monitoring programmes and citizen science.
Araujo et al. 2020	Citizen science sheds light on the cryptic ornate eagle ray *Aetomylaeus vespertilio*.
Arellano-Verdejo & Lazcano-Hernandez, 2020	Crowdsourcing for *Sargassum* monitoring along the beaches in Quintana Roo.
Armstrong et al. 2020	Satellite tagging and photographic identification reveal connectivity between two UNESCO World Heritage Areas for reef manta rays
Armstrong et al. 2020	The geographic distribution of reef and oceanic manta rays (*Mobula alfredi* and *Mobula birostris*) in Australian coastal waters.
Assis et al. 2020	A fine-tuned global distribution dataset of marine forests.
Balaguera-Reina et al. 2020	Individual identification patterns as a monitoring strategy for American crocodiles: Tayrona national natural park as a study case.
Barton et al. 2020	Observations of 'pseudoparasitism' involving snake eels (Teleostei: Ophichthidae) in commercially important black jewfish *Protonibea diacanthus* (Sciaenidae) and other teleost species.
Bellido et al. 2020	Atmospheric indices allow anticipating the incidence of jellyfish coastal swarms.
Botero-Acosta et al. 2020	First record of a Fin whale (*Balaenoptera physalus*) in the Rosario and San Bernardo Corals National Natural Park, Colombian Caribbean.
Camins et al. 2020	Paddle surfing for science on microplastic pollution.
Changeux et al. 2020	The use of citizen science for marine biodiversity surveys: from species identification to ecologically relevant observations.
Chen et al. 2020	A nationwide assessment of litter on China's beaches using citizen science data.
Consoli et al. 2020	Characterization of seafloor litter on Mediterranean shallow coastal waters: Evidence from Dive Against Debris®, a citizen science monitoring approach.
de Virgilio et al. 2020	A first attempt of citizen science in the genetic monitoring of a *Posidonia oceanica* meadow in the Italian Southern Adriatic Sea.
Díaz-Tapia et al. 2020	Discovery of *Flabellia petiolata* (Halimedaceae, Chlorophyta) in the southern British Isles: A relict population or a new introduction?

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Dumas et al. 2020	Citizen Science, a promising tool for detecting and monitoring outbreaks of the crown-of-thorns starfish *Acanthaster* spp.
Either et al. 2020	Twenty years of coastal waterbird trends suggest regional patterns of environmental pressure in British Columbia, Canada.
Gibson et al. 2020	Using social media as a cost-effective resource in the photo-identification of a coastal bottlenose dolphin community.
Gizzi et al. 2020	Before and after a disease outbreak: Tracking a keystone species recovery from a mass mortality event.
Grol et al. 2020	Conservation value of a subtropical reef in south-eastern Queensland, Australia, highlighted by citizen-science efforts.
Gudka et al. 2020	Participatory reporting of the 2016 bleaching event in the Western Indian Ocean.
Harr et al. 2020	Citizen science data indicate a reduction in beach litter in the Lofoten archipelago in the Norwegian Sea.
Holland et al. 2020	Latitudinal patterns in trophic structure of temperate reef-associated fishes and predicted consequences of climate change.
Jiménez-Alvarado et al. 2020	Investigation of juvenile angelshark (*Squatina squatina*) habitat in the Canary Islands with recommended measures for protection and management.
Johnson et al. 2020	Community marine monitoring toolkit: A tool developed in the Pacific to inform community-based marine resource management.
Kagawa et al. 2020	Citizen science via social media revealed conditions of symbiosis between a marine gastropod and an epibiotic alga.
Katsanevakis et al. 2020	Unpublished mediterranean records of marine alien and cryptogenic species.
Krželj et al. 2020	Enhancing diversity knowledge through marine citizen science and social platforms: The case of *Hermodice carunculata* (Annelida, Polycheta).
Lehtiniemi et al. 2020	Citizen science provides added value in the monitoring for coastal non-indigenous species.
Lim et al. 2020	Diversity and distribution of intertidal marine species in singapore.
Naasan Aga Spyridopoulou et al. 2020	Filling the gap of data-limited fish species in the eastern Mediterranean Sea: A contribution by citizen science.
Nel et al. 2020	Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom.
Nelms et al. 2020	Investigating the distribution and regional occurrence of anthropogenic litter in English marine protected areas using 25 years of citizen-science beach clean data.
Nimbs et al. 2020	The heterobranch sea slugs of lord howe Island, NSW, Australia (Mollusca: Gastropoda).

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Noble et al. 2020	Identifying spatial conservation priorities using Traditional and Local Ecological Knowledge of iconic marine species and ecosystem threats.
Pert et al. 2020	Beauty and the reef: Evaluating the use of non-expert ratings for monitoring aesthetic values of coral reefs.
Peterson et al. 2020	Monitoring through many eyes: integrating disparate datasets to improve monitoring of the Great Barrier Reef.
Petit et al. 2020	Resting dynamics and diel activity of the green turtle (*Chelonia mydas*) in Rapa Nui, Chile.
Ringvold et al. 2020	Encounters with the rare genus *Helicosalpa* (Chordata, Thaliacea, Salpida), using citizen science data.
Robbins et al. 2020	Citizen science in the marine environment: Estimating common dolphin densities in the north-east Atlantic.
Schoneich-Argent & Freund, 2020	Trashing our own "backyard" – Investigating dispersal and accumulation of floating litter from coastal, riverine, and offshore sources in the German Bight using a citizen science-based wooden drifter recapture approach.
Siano et al. 2020	Citizen participation in monitoring phytoplankton seawater discolorations.
Silva Santos et al. 2020	Transatlantic movement of domestic pigeons *Columba livia domestica*.
Skukan et al. 2020	Find invasive seaweed: An outdoor game to engage children in science activities that detect marine biological invasion.
Slager, 2020	Seasonal and directional dispersal behavior in an ongoing dove invasion.
Taklis et al. 2020	Social media: a valuable tool to inform shark conservation in Greece.
Tanduo et al. 2020	Citizen-science detects the arrival and establishment of *Branchiomma luctuosum* (Grube, 1870) (annelida: Polychaeta: Sabellidae) in Albania.
Thomson et al. 2020	Population status of the black skimmer (*Rynchops niger*) in Chile.
Tiralongo et al. 2020	Snapshot of rare, exotic and overlooked fish species in the Italian seas: A citizen science survey.
Tunnell et al. 2020	Measuring plastic pellet (nurdle) abundance on shorelines throughout the Gulf of Mexico using citizen scientists: Establishing a platform for policy-relevant research.
Uhrin et al. 2020	Temporal trends and potential drivers of stranded marine debris on beaches within two US National Marine Sanctuaries using citizen science data.
Valani et al. 2020	Presence and movement of humpback whale (*Megaptera novaeangliae*) mother-calf pairs in the Gold Coast, Australia.
Vieira et al. 2020	Diving into science and conservation: recreational divers can monitor reef assemblages.
Voorberg & Van der Veer, 2020	Co-management as a successful strategy for marine conservation.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Vye et al. 2020	Patterns of abundance across geographical ranges as a predictor for responses to climate change: Evidence from UK rocky shores.
Weir & Stanworth, 2020	The Falkland Islands (Malvinas) as sub-Antarctic foraging, migratory and wintering habitat for southern right whales.
Zangaro et al. 2020	A new extralimital sighting of *Monachus monachus* (Hermann, 1779) in the Aquatina di Frigole NATURA 2000 site (IT9150003) beach (Salento peninsula, Apulia Region, Italy) after two decades: Strategies for conservation are needed.
Zubak Čižmek et al. 2020	Fast, not furious - adaptation of the species list and fish size classes for fish assemblage survey technique (FAST) for the Adriatic Sea .
Abreo et al. 2019	Social media as a novel source of data on the impact of marine litter on megafauna: The Philippines as a case study.
Ambrose et al. 2019	Spatial trends and drivers of marine debris accumulation on shorelines in South Eleuthera, The Bahamas using citizen science.
Anderson et al. 2019	Oyster reef enhancement utilizing gardened oysters in a subtropical estuary.
Armstrong et al. 2019	Photographic identification and citizen science combine to reveal long distance movements of individual reef manta rays *Mobula alfredi* along Australia's east coast.
Austin et al. 2019	Predicting habitat suitability for basking sharks (*Cetorhinus maximus*) in UK waters using ensemble ecological niche modelling.
Beale et al. 2019	Population dynamics of oceanic manta rays (*Mobula birostris*) in the Raja Ampat Archipelago, West Papua, Indonesia, and the impacts of the El Niño–Southern Oscillation on their movement ecology.
Becken et al. 2019	A hybrid is born: Integrating collective sensing, citizen science and professional monitoring of the environment.
Begossi et al. 2019	Fishers and groupers (*Epinephelus marginatus* and *E. morio*) in the coast of Brazil: Integrating information for conservation.
Brown et al. 2019	Potential encounters between humpback whales (*Megaptera novaeangliae*) and vessels in the New York Bight apex, USA.
Carpentier et al. 2019	Preliminary insights into the population characteristics and distribution of reef (*Mobula alfredi*) and oceanic (*M. birostris*) manta rays in French Polynesia.
Cloyed et al. 2019	Linking use of ship channels by West Indian manatees (*Trichechus manatus*) to seasonal migration and habitat use.
Donnelly-Greenan et al. 2019	Entangled seabird and marine mammal reports from citizen science surveys from coastal California (1997–2017).
Doyen et al. 2019	Occurrence and identification of microplastics in beach sediments from the Hauts-de-France region.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Ellul et al. 2019	Invasion alert: Rapid range expansion of *Caulerpa taxifolia var. distichophylla* in maltese waters (central mediterranean).
Falk-Andersson et al. 2019	Citizen science for better management: Lessons learned from three norwegian beach litter data sets.
Furukawa et al. 2019	Importance of citizen science application for integrated coastal management - change of gobies' survival strategies in Tokyo Bay, Japan.
Germanov et al. 2019	Contrasting habitat use and population dynamics of reef manta rays within the Nusa Penida Marine Protected Area, Indonesia.
Gibson et al. 2019	Utility of citizen science data: A case study in land-based shark fishing.
Giovos et al. 2019	Integrating local ecological knowledge, citizen science and long-term historical data for endangered species conservation: Additional records of angel sharks (Chondrichthyes: Squatinidae) in the Mediterranean Sea.
Gorta et al. 2019	Pelagic citizen science data reveal declines of seabirds off south-eastern Australia.
Gouraguine et al. 2019	Citizen science in data and resource-limited areas: A tool to detect long-term ecosystem changes.
Guerrero et al. 2019	First record of beaching events for a calycophoran siphonophore: *Abylopsis tetragona* (Otto, 1823) at the Strait of Gibraltar.
Harley et al. 2019	Shoreline change mapping using crowd-sourced smartphone images.
Honorato-Zimmer et al. 2019	Inter-hemispherical shoreline surveys of anthropogenic marine debris – A binational citizen science project with schoolchildren.
Lau et al. 2019	Tracing coral reefs: a citizen science approach in mapping coral reefs to enhance marine park management strategies.
Lee et al. 2019	Rapid assessment of marine debris in coastal areas using a visual scoring indicator.
Martin et al. 2019	Comparing quantity of marine debris to loggerhead sea turtle (*Caretta caretta*) nesting and non-nesting emergence activity on Jekyll Island, Georgia, USA.
Mat Zauki et al. 2019	Citizen science frontiers horseshoe crab population regain at their spawning beach in East Peninsular Malaysia.
Matear et al. 2019	Cetacean biodiversity in the Bay of Biscay: Suggestions for environmental protection derived from citizen science data.
Nordstrom et al. 2019	Tracking jellyfish and leatherback sea turtle seasonality through citizen science observers.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
O'Neil et al. 2019	Sudden seasonal occurrence of humpback whales *Megaptera novaeangliae* in the Firth of Forth, Scotland and first confirmed movement between high-latitude feeding grounds and United Kingdom waters.
Pasternak et al. 2019	Nearshore survey and cleanup of benthic marine debris using citizen science divers along the Mediterranean coast of Israel.
Potts et al. 2019	Can long-term content analysis of print media be used to examine species composition, population demography and changes in distributional range of recreational fishery species?
Rizgalla et al. 2019	First record of *Aplysia dactylomela* rang, 1828 (Mollusca: Gastropoda) in Libyan coastal waters.
Schofield & Akins, 2019	Non-native marine fishes in florida: Updated checklist, population status and early detection/rapid response.
Snyder et al. 2019	Citizen science observations reveal rapid, multi-decadal ecosystem changes in eastern Long Island Sound.
Stanev et al. 2019	Extreme westward surface drift in the North Sea: Public reports of stranded drifters and Lagrangian tracking.
Tiralongo et al. 2019	From scuba diving to social networks: A curious association between two small fish species, *Lepadogaster candolii* Risso, 1810 and *Parablennius rouxi* (Cocco, 1833), and *Muraena helena* (Linnaeus, 1758) coming from citizen science.
Tiralongo, 2019	Is the mangrove red snapper *Lutjanus argentimaculatus* (Forsskål, 1775) established in the eastern mediterranean sea? first records from Greece through a citizen science project.
Turrell, 2019	Spatial distribution of foreshore litter on the northwest European continental shelf.
Verlaque & Breton, 2019	Biological invasion: Long term monitoring of the macroalgal flora of a major European harbor complex.
Wilson et al. 2019	Atlantic tarpon (*Megalops atlanticus*) nursery habitats: evaluation of habitat quality and broad-scale habitat identification.
Adelir-Alves et al. 2018	Non-native reef fishes in the Southwest Atlantic Ocean: A recent record of *Heniochus acuminatus* (Linnaeus, 1758) (Perciformes, Chaetodontidae) and biological aspects of *Chromis limbata* (Valenciennes, 1833) (Perciformes, Pomacentridae).
Bariche et al. 2018	First confirmed record of the white-spotted puffer *Arothron hispidus* (Linnaeus, 1758) in the Mediterranean sea.
Bauer-Civiello et al. 2018	Using citizen science data to assess the difference in marine debris loads on reefs in Queensland, Australia.
Benjamins et al. 2018	Evaluating the potential of photo-identification as a monitoring tool for flapper skate (*Dipturus intermedius*).
Champion et al. 2018	Rapid shifts in distribution and high-latitude persistence of oceanographic habitat revealed using citizen science data from a climate change hotspot.
Currie et al. 2018	Conservation and education through ecotourism: Using citizen science to monitor cetaceans in the four-island region of Maui, Hawaii.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Di Camillo et al. 2018	Building a baseline for habitat-forming corals by a multi-source approach, including Web Ecological Knowledge.
Enolsen & Reiss, 2018	Diet of Norwegian coastal cod (*Gadus morhua*) studied by using citizen science.
Florisson et al. 2018	Reef vision: A citizen science program for monitoring the fish faunas of artificial reefs.
Garrone-Neto & Rodrigues, 2018	*Megalops atlanticus* Valenciennes, 1847 (Elopiformes, Megalopidae): New records for the state of São Paulo, with comments on its occurrence in the southeastern coast of Brazil, Southwest Atlantic.
Gatt et al. 2018	Is citizen science a valid tool to monitor the occurrence of jellyfish? The spot the jellyfish case study from the Maltese Islands.
Giovos et al. 2018	First records of the fish *Abudefduf sexfasciatus* (Lacepède, 1801) and *Acanthurus sohal* (Forsskål, 1775) in the Mediterranean Sea.
Grason et al. 2018	Citizen science program detects range expansion of the globally invasive European green crab in Washington State (USA).
Hamburger et al. 2018	Volunteer algae monitoring program (VAMP) in the Indian River Lagoon.
Hann et al. 2018	Obstacles and opportunities of using a mobile app for marine mammal research.
Harvey et al. 2018	Comparing citizen science reports and systematic surveys of marine mammal distributions and densities.
Hidalgo-Ruz et al. 2018	Spatio-temporal variation of anthropogenic marine debris on Chilean beaches.
Khoo & Sivasothi, 2018	Population structure, distribution, and habitat use of smooth-coated otters *Lutrogale perspicillata* in Singapore.
Kienberger & Prieto, 2018	The jellyfish *Rhizostoma luteum* (Quoy & Gaimard, 1827): not such a rare species after all.
Kumangai et al. 2018	High-resolution modeling of thermal thresholds and environmental influences on coral bleaching for local and regional reef management.
Lamine et al. 2018	Can citizen science contribute to fish assemblages monitoring in understudied areas? The case study of Tunisian marine protected areas.
Lodi & Tardin, 2018	Citizen science contributes to the understanding of the occurrence and distribution of cetaceans in southeastern Brazil – A case study.
Loizidou et al. 2018	Persistent marine litter: small plastics and cigarette butts remain on beaches after organized beach cleanups.
Mannino & Balistreri, 2018	Citizen science: a successful tool for monitoring invasive alien species (IAS) in Marine Protected Areas. The case study of the Egadi Islands MPA (Tyrrhenian Sea, Italy).
McCoy et al. 2018	Long-term photo-identification reveals the population dynamics and strong site fidelity of adult whale sharks to the coastal waters of Donsol, Philippines.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
McNelly & Souto, 2018	Utilizing citizen science as a tool for muck mapping in the Indian River Lagoon.
Paxton et al. 2018	Citizen science reveals female sand tiger sharks (*Carcharias taurus*) exhibit signs of site fidelity on shipwrecks.
Pires et al. 2018	Untangling *Velella velella* (Cnidaria: Anthoathecatae) transport: A citizen science and oceanographic approach.
Porter, 2018	Exploring stakeholder groups through a testimony analysis on the Hawaiian aquarium trade.
Rosenberg, 2018	New record and range extension of the fiddler crab *Uca princeps* (Smith, 1870) (Brachyura, Ocypodidae) from California, USA.
Shertzer et al. 2018	Release mortality of endangered Warsaw grouper *Hyporthodus nigritus*: A state-space model applied to capture-recapture data.
Smale et al. 2018	Spatiotemporal variability in the structure of seagrass meadows and associated macrofaunal assemblages in southwest England (UK): Using citizen science to benchmark ecological pattern.
Smith et al. 2018	Tracing the source of marine debris on the beaches of northern New South Wales, Australia: The Bottles on Beaches program.
Storrie et al. 2018	Determining the species assemblage and habitat use of cetaceans in the Svalbard Archipelago, based on observations from 2002 to 2014.
Støttrup et al. 2018	Harvesting geo-spatial data on coastal fish assemblages through coordinated citizen science.
Van der Stocken et al. 2018	Caught in transit: offshore interception of seafaring propagules from seven mangrove species.
Walther et al. 2018	Type and quantity of coastal debris pollution in Taiwan: A 12-year nationwide assessment using citizen science data.
Ward-Paige et al. 2018	Using eOceans diver data to describe contemporary patterns of marine animal populations: A case study of sharks in Thailand.
Weaver et al. 2018	The living dock: A study of benthic recruitment to oyster substrates affixed to a dock in the Indian River Lagoon.
Wonham & Hart, 2018	El Niño Range Extensions of Pacific Sand Crab (*Emerita analoga*) in the Northeastern Pacific.
Agarwal, 2017	First record of *Dendronotus orientalis* (Baba, 1932) (Nudibranchia: Dendronotidae) in the temperate Eastern Pacific.
Alelio et al. 2017	Plankton food for benthic fish: De visu evidence of trophic interaction between rainbow wrasse (*Coris julis*) and pelagic tunicates (*Pegea confoederata*).
Anderson et al. 2017	The role of conservation volunteers in the detection, monitoring and management of invasive alien lionfish.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Araujo et al. 2017	Population structure, residency patterns and movements of whale sharks in Southern Leyte, Philippines: results from dedicated photo-ID and citizen science.
Aylesworth et al. 2017	Generating spatial data for marine conservation and management.
Bergmann et al. 2017	Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wildlife.
Bosker et al. 2017	Determining global distribution of microplastics by combining citizen science and in-depth case studies.
Cerrano et al. 2017	Diving for science - science for diving: volunteer scuba divers support science and conservation in the Mediterranean Sea.
Clauson-Kass et al. 2017	Species-specific environmental preferences associated with a hump-shaped diversity/temperature relationship across tropical marine fish assemblages.
Colmenero et al. 2017	Plastic debris straps on threatened blue shark *Prionace glauca*.
Deidun et al. 2017	The first record of the white-spotted Australian jellyfish *Phyllorhiza punctata* von Lendenfeld, 1884 from maltese waters (Western mediterranean) and from the Ionian coast of Italy.
Edgar et al. 2017	New opportunities for conservation of handfishes (Family Brachionichthyidae) and other inconspicuous and threatened marine species through citizen science.
Hesley et al. 2017	Citizen science benefits coral reef restoration activities.
Hieb et al. 2017	Sighting demographics of the West Indian manatee *Trichechus manatus* in the north-central Gulf of Mexico supported by citizen-sourced data.
Hof et al. 2017	First citizen-science population abundance and growth rate estimates for green sea turtles *Chelonia mydas* foraging in the northern Great Barrier Reef, Australia.
Holcer & Lazar, 2017	New data on the occurrence of the critically endangered common angelshark, *Squatina squatina*, in the Croatian adriatic sea.
Hylton et al. 2017	The sharks and rays of the Solomon Islands: A synthesis of their biological diversity, values and conservation status.
Jones et al. 2017	Mass mortality of marine birds in the Northeast Pacific caused by *Akashiwo sanguinea*.
Kelly et al. 2017	Marine turtles are not fussy nesters: A novel test of small-scale nest site selection using structure from motion beach terrain information.
Kiessling et al. 2017	Who cares about dirty beaches? Evaluating environmental awareness and action on coastal litter in Chile.
Lenanton et al. 2017	Potential influence of a marine heatwave on range extensions of tropical fishes in the eastern Indian Ocean—Invaluable contributions from amateur observers.
Long & Azmi, 2017	Using photographic identification to monitor sea turtle populations at Perhentian Islands Marine Park in Malaysia.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Lots et al. 2017	A large-scale investigation of microplastic contamination: Abundance and characteristics of microplastics in European beach sediment.
Meyers et al. 2017	Population structure, distribution and habitat use of the Critically Endangered Angelshark, *Squatina squatina*, in the Canary Islands.
Miyazaki et al. 2017	Adding fish images taken in other countries to the biodiversity database of a Japanese public museum, with report of range extension of *Labrisomus jenkinsi* from the Pacific coast of Costa Rica.
Moles et al. 2017	As fast as a hare: Colonization of the heterobranch *Aplysia dactylomela* (Mollusca: Gastropoda: Anaspidea) into the western Mediterranean Sea.
Muurmans et al. 2017	Dunewatch: Launching citizen science for sandy dunes on the gold coast, Queensland, Australia.
Nelms et al. 2017	Marine anthropogenic litter on British beaches: A 10-year nationwide assessment using citizen science data.
Nimbs & Smith, 2017	Revision of the southern distribution limit for the tropical marine herbivore *Syphonota geographica* (A. Adams & Reeve, 1850) (Heterobranchia: Aplysiidae) in a global climate change hot-spot.
Norman et al. 2017	Undersea constellations: The global biology of an endangered marine megavertebrate further informed through citizen science.
Savage et al. 2017	Effectiveness of community and volunteer based coral reef monitoring in Cambodia.
Stuart-Smith et al. 2017	Assessing national biodiversity trends for rocky and coral reefs through the integration of citizen science and scientific monitoring programs.
Suazo et al. 2017	Emerging platforms to monitor the occurrence and threats to critically endangered seabirds: The waved albatross in Chile and the Southeast Pacific.
Toh et al. 2017	A cost-effective approach to enhance scleractinian diversity on artificial shorelines.
Ward-Paige & Worm,2017	Global evaluation of shark sanctuaries.
Williams et al. 2017	Spatial distribution and residency of green and loggerhead sea turtles using coastal reef habitats in Southern Mozambique.
Andrzejaczek et al. 2016	The ecological connectivity of Whale Shark aggregations in the Indian ocean: A photo-identification approach.
Burham et al. 2016	The combined use of visual and acoustic data collection techniques for winter killer whale (*Orcinus orca*) observations.
Chatzigeorgiou et al. 2016	Testing the robustness of Citizen Science projects: Evaluating the results of pilot project COMBER.
Ehmke et al. 2016	An obligate beach bird selects sub-, inter- and supra-tidal habitat elements.
Johnson et al. 2016	Genetic diversity affects the strength of population regulation in a marine fish.

Table S1 (continued). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Liboiron et al. 2016	Low plastic ingestion rate in Atlantic cod (*Gadus morhua*) from Newfoundland destined for human consumption collected through citizen science methods.
Mandigo et al. 2016	Chemical contamination of soils in the New York City area following Hurricane Sandy.
Miralles et al. 2016	Controlling populations of invasive pygmy mussel (*Xenostrobus securis*) through citizen science and environmental DNA.
Morais et al. 2016	The transatlantic introduction of weakfish *Cynoscion regalis* (Bloch & Schneider, 1801) (Sciaenidae, Pisces) into Europe.
Nimbs et al. 2016	Southern range extensions for twelve heterobranch sea slugs (Gastropoda: Heterobranchia) on the eastern coast of Australia.
Parkinson et al. 2016	A citizen science approach to monitoring bleaching in the zoantharian *Palythoa tuberculosa*.
Pikesley et al. 2016	Pink sea fans (*Eunicella verrucosa*) as indicators of the spatial efficacy of Marine Protected Areas in southwest UK coastal waters.
Raoult et al. 2016	GoProsTM as an underwater photogrammetry tool for citizen science.
Roelfsema et al. 2016	A citizen science approach: A detailed ecological assessment of subtropical reefs at point lookout, Australia.
Schultz et al. 2016	Evidence for a trophic cascade on rocky reefs following sea star mass mortality in British Columbia.
Vandendriessche et al. 2016	Jellyfish jelly press and jelly perception.
Bai et al. 2015	Identification of coastal wetlands of international importance for waterbirds: A review of China Coastal Waterbird Surveys 2005-2013.
Branchini et al. 2015	Using a citizen science program to monitor coral reef biodiversity through space and time.
Callaghan et al. 2015	Efficacy of eBird data as an aid in conservation planning and monitoring.
Couturier et al. 2015	First photographic records of the giant manta ray manta birostris off eastern Australia.
Davies II & Murphy, 2015	Plastic in surface waters of the Inside Passage and beaches of the Salish Sea in Washington State.
Forrester et al. 2015	Comparing monitoring data collected by volunteers and professionals shows that citizen scientists can detect long-term change on coral reefs.
Guindon et al. 2015	An overview of the tarpon genetic recapture study in Florida – a citizen science success story.
Jarvis et al. 2015	Citizen science and the power of public participation in marine spatial planning.
Robinson et al. 2015	Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions.
Scyphers et al. 2015	The role of citizens in detecting and responding to a rapid marine invasion.

Table S1 (continued and finished). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Smith & Robinson, 2015	Horseshoe crab spawning activity in delaware bay, usa, after harvest reduction: a mixed-model analysis.
White et al. 2015	Shifting elasmobranch community assemblage at Cocos Island-an isolated marine protected area.
Beck et al. 2014	Using opportunistic photo-identifications to detect a population decline of killer whales (*Orcinus orca*) in British and Irish waters.
Beeden et al. 2014	Rapid survey protocol that provides dynamic information on reef condition to managers of the Great Barrier Reef.
Bruce et al. 2014	Distribution patterns of migrating humpback whales (*Megaptera novaeangliae*) in Jervis Bay, Australia: A spatial analysis using geographical citizen science data.
Chin, 2014	Hunting porcupines: citizen scientists contribute new knowledge about rare coral reef species.
Fairclough et al. 2014	Breathing life into fisheries stock assessments with citizen science.
Pikesley et al. 2014	Cnidaria in UK coastal waters: Description of spatio-temporal patterns and inter-annual variability.
Shamir et al. 2014	Classification of large acoustic datasets using machine learning and crowdsourcing: Application to whale calls.
Smith et al. 2014	Patterns of marine debris distribution on the beaches of Rottnest Island, Western Australia.
Thorson et al. 2014	Demographic modeling of citizen science data informs habitat preferences and population dynamics of recovering fishes.
Vianna et al. 2014	Acoustic telemetry validates a citizen science approach for monitoring sharks on coral reefs.
Weinstein et al. 2014	A first population assessment of black Oystercatcher *Haematopus bachmani* in California.
Azzurro et al. 2013	Citizen science detects the undetected: The case of *Abudefduf saxatilis* from the mediterranean sea.
Boero et al. 2013	A salp bloom (Tunicata, Thaliacea) along the Apulian coast and in the Otranto Channel between March-May 2013.
Cheney et al. 2013	Integrating multiple data sources to assess the distribution and abundance of bottlenose dolphins *Tursiops truncatus* in Scottish waters.
Hidalgo-Ruz & Thiel, 2013	Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): A study supported by a citizen science project.
Martin, 2013	Marine debris removal: one year of effort by the Georgia Sea Turtle-Center-Marine Debris Initiative.
Rosevelt et al. 2013	Marine debris in central California: Quantifying type and abundance of beach litter in Monterey Bay, CA.
Crabbe, 2012	From citizen science to policy development on the coral reefs of Jamaica.

Table S1 (continued and finished). Scientific articles of marine biology citizen science analyzed in this review.

Citation	Article name
Davies et al. 2012	Can citizen science monitor whale-shark aggregations? Investigating bias in mark-recapture modelling using identification photographs sourced from the public.
Jaine et al. 2012	When giants turn up: sighting trends, environmental influences and habitat use of the manta ray *Manta alfredi* at a coral reef.
Whitney et al. 2012	Movements, reproductive seasonality, and fisheries interactions in the whitetip reef shark (*Triaenodon obesus*) from community-contributed photographs.
Witt et al. 2012	Basking sharks in the northeast Atlantic: Spatio-temporal trends from sightings in UK waters.
Cohen et al. 2011	Discovery and significance of the colonial tunicate *Didemnum vexillum* in Alaska.
Lorenzo et al. 2011	Involvement of recreational scuba divers in emblematic species monitoring: The case of Mediterranean red coral (*Corallium rubrum*).
Boero et al. 2009	First records of *Mnemiopsis leidyi* (Ctenophora) from the ligurian, Thyrrhenian and ionian seas (Western Mediterranean) and first record of *Phyllorhiza punctata* (Cnidaria) from the Western Mediterranean.
Hamel et al. 2009	Bycatch and beached birds: Assessing mortality impacts in coastal net fisheries using marine bird strandings.
Koss et al. 2009	An evaluation of Sea Search as a citizen science programme in Marine Protected Areas.

Table S2. Description of the different roles performed by volunteers in marine biology citizen science-based articles, based in Bonney et al. (2009).

Role	Aspects covered
Planification	Observations that led to research, defining scientific question information gathering, hypothesis developed, search for methodologies, fieldwork preparation
Fieldwork	Monitoring, data collection, sample collection.
Processing	Data or sample processing, result analysis, discussion of results, create conclusions.
Communication	Communication of results, turning plans into action
Local Ecological Knowledge (LEK)	Local knowledge, historical knowledge, interviews, narrated baselines. * It was not differentiated between LEK and TEK (Traditional Ecological Knowledge). Consult Thiel et al. 2014.

Table S3. Detailed conservation implications aspects reported in marine biology citizen science-based articles, based in Cigliano et al. (2015).

Conservation-related outcomes		**Description**
Policy change		Greater participation in politics spaces, political pressure, communication channels between academia, communities and policy makers, politics addressing environmental agendas, data created in citizen science used for policy making, evaluation of policies, governance, more aware voters.
Social implications	**Educational**	Awareness and inspiration, individual behavior change, science literacy and critical thinking, emotional links, individual experiences, decision making in daily activities, local involvement, civic engagement, local leaders to communicate information, ownership and co management of resources, increase the scientific literacy, use of marketing strategies in order to change behaviors.
	Community	Increase of the community capacity to address environmental problems, collaborative meetings, mobilization of groups towards some goal, integration of multiple knowledge sources, reduction of resource management conflicts, traditional knowledge included in research.
Management	**Site management**	Long term monitoring data collection for management, rapid detection and response to environmental crisis, monitoring sustainable in time.
	Species management	Charismatic megafauna, umbrella conservation species, proxy species for environmental quality, data for species management (fisheries. invasive species, illness, bleaching), management of endangered species, fill information data voids for species.
Research		Address a scientific objective or question, improve data quality, cost reduction, increase the research funds, improve scientific procedures, increase collaboration among disciplines, create or adapt new methodologies, establish new scientific questions, demystifying science, democratization of science, recruit new scientists, inspire future scientists.

Table S4. Records of citizen science initiatives by biogeographic realm according to Spalding et al. (2007).

Biogeographic realm	**Count**
Artic	4
Central Indo-Pacific	63
Eastern Indo-Pacific	10
Southern Ocean	0
Temperate Australasia	38
Temperate Northern Atlantic	169
Temperate Northern Pacific	49
Temperate South America	20
Temperate Southern Africa	5
Tropical Atlantic	39
Tropical Eastern Pacific	8
Western Indo-Pacific	16
Multiple	33

Table S5. Records of citizen science initiatives by country.

Country	**Count**	**Country**	**Count**
Albania	1	Malta	2
Argentina	2	México	8
Australia	60	Morocco	1
Bahrain	1	Mozambique	3
Belize	1	New Zealand	4
Brazil	17	Nicaragua	1
Cambodia	1	Norway	10
Canada	13	Palau	2
Chile	8	Perú	1
China	7	Philippines	7
Colombia	3	Portugal	7
Costa Rica	4	Russia	1
Croatia	2	Scotland	2
Cyprus	3	Singapore	4
Denmark	5	Solomon Islands	1
Ecuador	3	South Africa	3
Egypt	1	South Korea	1
Fiji	1	Spain	18
Finland	1	Syria	1
France	10	Taiwan	4
Germany	1	Thailand	3
Greece	5	Tunisia	1
India	3	Turkey	4
Indonesia	10	United Kingdom	22
Ireland	2	United States of America	60
Israel	2	Uruguay	1
Italy	17	Vanuatu	1
Jamaica	1	Venezuela	1
Japan	7	Vietnam	1
Kenya	3	Multiple	68
Libya	1		
Madagascar	1		
Malaysia	4		
Maldives	1		

Table S6. Biological groups studied by citizen science initiatives, per year of publication.

Year	Group	Count	Year	Group	Count	Year	Group	Count
2023*	**Bony fish**	**13**	**2020**	**Invertebrates**	**18**	**2017**	**Invertebrates**	**11**
	Invertebrates	**13**		Algae	15		Bony fish	9
	Elasmobranchs	11		Bony fish	14		Elasmobranchs	8
	Mammals	8		Elasmobranchs	11		Reptiles	5
	Algae	7		Mammals	7		Algae	4
	Reptiles	5		Angiosperms	6		Birds	4
	Angiosperms	3		Birds	4		Angiosperms	3
	Birds	2		Reptiles	4		Mammals	2
2022	**Bony fish**	**27**	**2019**	**Bony fish**	**11**	**2016**	**Invertebrates**	**8**
	Elasmobranchs	20		Elasmobranchs	9		Bony fish	6
	Invertebrates	19		Invertebrates	9		Algae	3
	Mammals	10		Mammals	6		Birds	1
	Algae	8		Algae	3		Elasmobranchs	1
	Angiosperms	6		Reptiles	3		Mammals	1
	Birds	2		Birds	2		Reptiles	1
	Reptiles	1		Angiosperms	0		Angiosperms	0
2021	**Invertebrates**	**19**	**2018**	**Bony fish**	**14**	**2015**	**Bony fish**	**5**
	Mammals	15		Invertebrates	12		Algae	4
	Bony fish	14		Mammals	6		Elasmobranchs	4
	Elasmobranchs	14		Elasmobranchs	5		Invertebrates	4
	Algae	4		Algae	3		Birds	2
	Reptiles	2		Angiosperms	2		Reptiles	1
	Angiosperms	1		Birds	0		Angiosperms	0
	Birds	1		Reptiles	0		Mammals	0

Table S6 (continued and finished). Biological groups studied by citizen science initiatives, per year of publication.

Year	Group	Count	Year	Group	Count	Year	Group	Count
2014	**Bony fish**	**3**	**2012**	**Elasmobranchs**	**4**	**2010**	Algae	0
	Elasmobranchs	2		Invertebrates	1		Angiosperms	0
	Invertebrates	2		Algae	0		Birds	0
	Mammals	2		Angiosperms	0		Bony fish	0
	Algae	1		Birds	0		Elasmobranchs	0
	Birds	1		Bony fish	0		Invertebrates	0
	Angiosperms	0		Mammals	0		Mammals	0
	Reptiles	0		Reptiles	0		Reptiles	0
2013	**Bony fish**	**1**	**2011**	**Invertebrates**	**2**	**2009**	**Invertebrates**	**2**
	Invertebrates	1		Algae	0		Algae	1
	Mammals	1		Angiosperms	0		Angiosperms	1
	Algae	0		Birds	0		Birds	1
	Angiosperms	0		Bony fish	0		Bony fish	1
	Birds	0		Elasmobranchs	0		Elasmobranchs	0
	Elasmobranchs	0		Mammals	0		Mammals	0
	Reptiles	0		Reptiles	0		Reptiles	0

Table S7. Research topics studied by citizen science initiatives, per year of publication.

Year	Research topic	Count	Year	Research topic	Count	Year	Research topic	Count
	Spatiotemporal patterns	27		Spatiotemporal patterns	28		Spatiotemporal patterns	20
	Ecosystemic stressors	24		Ecosystemic stressors	22		Ecosystemic stressors	18
	Diversity descriptions	16		Diversity descriptions	12		Diversity descriptions	10
	Methodology test	6		Behaviors	9		Conservation attributes	6
2023*	Conservation attributes	4	**2020**	Management	5	**2017**	Management	4
	Molecular profiling	3		Conservation attributes	3		Methodology test	3
	Behaviors	3		Methodology test	3		Behaviors	2
	Management	3		Molecular profiling	2		Geosciences	1
	Geosciences	2		Geosciences	1		Molecular profiling	0
	Spatiotemporal patterns	41		Ecosystemic stressors	23		Spatiotemporal patterns	9
	Ecosystemic stressors	35		Spatiotemporal patterns	20		Ecosystemic stressors	6
	Diversity descriptions	22		Diversity descriptions	7		Diversity descriptions	4
	Methodology test	15		Behaviors	6		Methodology test	3
2022	Management	10	**2019**	Methodology test	6	**2016**	Molecular profiling	2
	Behaviors	9		Management	5		Management	1
	Conservation attributes	5		Conservation attributes	4		Conservation attributes	0
	Molecular profiling	3		Geosciences	1		Behaviors	0
	Geosciences	3		Molecular profiling	0		Geosciences	0
	Spatiotemporal patterns	42		Spatiotemporal patterns	24		Diversity descriptions	5
	Ecosystemic stressors	28		Ecosystemic stressors	13		Ecosystemic stressors	5
	Diversity descriptions	18		Diversity descriptions	8		Spatiotemporal patterns	3
	Methodology test	7		Methodology test	5		Methodology test	2
2021	Conservation attributes	4	**2018**	Conservation attributes	3	**2015**	Molecular profiling	1
	Molecular profiling	4		Molecular profiling	3		Behaviors	1
	Behaviors	4		Behaviors	3		Management	1
	Geosciences	1		Management	2		Conservation attributes	0
	Management	0		Geosciences	1		Geosciences	0

Table S7 (continued and finished). Research topics studied by citizen science initiatives, per year of publication.

Year	Research topic	Count	Year	Research topic	Count	Year	Research topic	Count
	Spatiotemporal patterns	5		Diversity descriptions	4		Behaviors	0
	Diversity descriptions	4		Spatiotemporal patterns	3		Conservation attributes	0
	Ecosystemic stressors	4		Ecosystemic stressors	2		Diversity descriptions	0
	Behaviors	2		Conservation attributes	1		Ecosystemic stressors	0
2014	Management	2	**2012**	Behaviors	1	**2010**	Geosciences	0
	Methodology test	2		Methodology test	1		Management	0
	Conservation attributes	0		Molecular profiling	0		Methodology test	0
	Molecular profiling	0		Management	0		Molecular profiling	0
	Geosciences	0		Geosciences	0		Spatiotemporal patterns	0
	Ecosystemic stressors	3		Diversity descriptions	1		Diversity descriptions	1
	Spatiotemporal patterns	3		Molecular profiling	1		Ecosystemic stressors	1
	Diversity descriptions	1		Spatiotemporal patterns	1		Spatiotemporal patterns	1
	Conservation attributes	0		Conservation attributes	0		Conservation attributes	0
2013	Molecular profiling	0	**2011**	Ecosystemic stressors	0	**2009**	Molecular profiling	0
	Behaviors	0		Behaviors	0		Behaviors	0
	Management	0		Management	0		Management	0
	Methodology test	0		Methodology test	0		Methodology test	0
	Geosciences	0		Geosciences	0		Geosciences	0

Table S8. Surveyed ecosystem studied by citizen science initiatives, per year of publication.

Year	Ecosystem	Count	Year	Ecosystem	Count	Year	Ecosystem	Count	Year	Ecosystem	Count
2023	Other	20	**2020**	Coast	28	**2017**	Reef	17	**2014**	Reef	5
	Coast	18		Reef	22		Other	10		Other	4
	Reef	15		Other	18		Coast	9		Coast	3
	Seagrass	5		Estuary	6		Seagrass	7		Estuary	0
	Estuary	2		Seagrass	5		Estuary	2		Mangrove	0
	Mangrove	0		Mangrove	3		Mangrove	0		Seagrass	0
	Sea marshes	0		Sea marshes	1		Sea marshes	0		Sea marshes	0
2022	Coast	34	**2019**	Coast	15	**2016**	Reef	8	**2013**	Coast	3
	Reef	28		Reef	12		Other	5		Other	2
	Other	22		Other	11		Estuary	2		Reef	1
	Estuary	14		Estuary	8		Coast	2		Estuary	0
	Seagrass	4		Mangrove	3		Seagrass	1		Mangrove	0
	Mangrove	2		Seagrass	1		Mangrove	0		Seagrass	0
	Sea marshes	0		Sea marshes	1		Sea marshes	0		Sea marshes	0
2021	Coast	30	**2018**	Other	16	**2015**	Other	8	**2012**	Reef	4
	Other	29		Coast	13		Reef	4		Other	1
	Reef	28		Reef	12		Coast	3		Estuary	0
	Estuary	8		Estuary	5		Estuary	1		Mangrove	0
	Mangrove	5		Mangrove	2		Mangrove	1		Seagrass	0
	Seagrass	3		Seagrass	2		Seagrass	0		Sea marshes	0
	Sea marshes	0		Sea marshes	1		Sea marshes	0		Coast	0

Table S8 (continued and finished). Surveyed ecosystem studied by citizen science initiatives, per year of publication.

Year	Ecosystem	Count	Year	Ecosystem	Count	Year	Ecosystem	Count
2011	Other	1	**2010**	Estuary	0	**2009**	Coast	2
	Reef	1		Coast	0		Other	1
	Coast	1		Mangrove	0		Reef	1
	Estuary	0		Reef	0		Seagrass	1
	Mangrove	0		Sea marshes	0		Estuary	0
	Seagrass	0		Seagrass	0		Mangrove	0
	Sea marshes	0		Other	0		Seamarshes	0

Table S9. Citizen’s role carried out in citizen science projects, per year of publication.

Year	Citizen's role	Count	Year	Citizen's role	Count	Year	Citizen's role	Count
2023	Fieldwork	50	**2018**	Fieldwork	38	**2013**	Fieldwork	6
	Processing	9		Processing	4		Processing	3
	LEK	6		LEK	3		Communication	0
	Communication	1		Communication	1		LEK	0
	Planification	0		Planification	1		Planification	0
2022	Fieldwork	83	**2017**	Fieldwork	35	**2012**	Fieldwork	5
	Processing	16		Processing	5		Communication	0
	LEK	8		LEK	4		LEK	0
	Communication	2		Communication	0		Planification	0
	Planification	2		Planification	0		Processing	0
2021	Fieldwork	73	**2016**	Fieldwork	14	**2011**	Fieldwork	2
	LEK	7		LEK	2		LEK	1
	Processing	7		Processing	2		Communication	0
	Planification	3		Communication	1		Planification	0
	Communication	1		Planification	1		Processing	0
2020	Fieldwork	56	**2015**	Fieldwork	11	**2010**	Communication	0
	Processing	12		LEK	3		Fieldwork	0
	LEK	4		Processing	1		LEK	0
	Communication	1		Communication	0		Planification	0
	Planification	0		Planification	0		Processing	0
2019	Fieldwork	40	**2014**	Fieldwork	10	**2009**	Fieldwork	3
	Processing	6		LEK	2		LEK	1
	LEK	4		Processing	2		Planification	1
	Communication	0		Planification	1		Communication	0
	Planification	0		Communication	0		Processing	0

Table S10. Conservation implications reported in citizen science initiatives, per year of publication

Year	Conservation implication	Count	Year	Conservation implication	Count	Year	Conservation implication	Count
2023	Research	53	**2018**	Research	40	**2013**	Research	6
	Management implications	36		Management implications	29		Social implications	5
	Social implications	26		Social implications	23		Management implications	4
	Policy change	14		Policy change	13		Policy change	2
2022	Research	85	**2017**	Research	36	**2012**	Research	5
	Management implications	64		Management implications	29		Management implications	3
	Social implications	44		Social implications	25		Social implications	2
	Policy change	26		Policy change	11		Policy change	1
2021	Research	76	**2016**	Research	16	**2011**	Research	2
	Management implications	56		Management implications	10		Management implications	2
	Social implications	41		Social implications	10		Social implications	2
	Policy change	12		Policy change	1		Policy change	0
2020	Research	58	**2015**	Research	12	**2010**	Research	0
	Management implications	43		Management implications	10		Management implications	0
	Social implications	32		Social implications	5		Social implications	0
	Policy change	20		Policy change	4		Policy change	0
2019	Research	42	**2014**	Research	11	**2009**	Research	3
	Management implications	34		Management implications	9		Management implications	3
	Social implications	23		Social implications	8		Social implications	2
	Policy change	11		Policy change	2		Policy change	2

CAPÍTULO 2

CITIZEN SCIENCE: PATHWAY FOR CORAL REEF RESTORATION IN OCOTAL BAY, COSTA-RICAN NORTH PACIFIC

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1. Introduction

Coral reefs are highly threatened ecosystems by local and global human-related stressors such as over-fishing (Pandolfi et al. 2003, Edwards et al. 2014), unmanaged tourism (Poonian et al. 2010, Musa & Dimmock 2015), un-adequate resource management (Moberg & Folke 1999), climate change and extreme thermal events (Obura & Grimsditch 2009, Reimer et al. 2024). The massive coral mortalities does not only modify the associated community (Stella et al. 2011, Seraphim et al. 2019, Arias-Godínez et al. 2021), but also the diminish of ecosystem services they provide (Woodhead et al. 2019, Eddy et al. 2021). Currently, 75 % of coral reefs worldwide are threatened and projections point to a further decline (Pandolfi et al. 2003).

This current scenario requires adaptable management actions that engage multiple stakeholders involved in ecosystem rehabilitation (Hein et al. 2019, Ng et al. 2023). Citizen science (CS) is a process that involves non-scientists in different steps of academic research (Cigliano et al. 2015, Cvitanovic et al. 2018, Becken et al. 2019), facilitating data creation and an environmental compromise (Thiel et al. 2014). This approach complements and diversifies traditional research methods (Graba-Landry et al. 2023), increasing the spatio-temporal scope (Weinstein et al. 2014), reducing the operational cost (Toh et al. 2017, Becken et al. 2019), even allowing data collection during worldwide lockdowns (Licuanan & Mordeno 2021), in transboundary spaces (Marshall et al. 2023), reducing the carbon footprint (Paradinas et al. 2021), and facilitating the scientific knowledge democratization (Alabri & Hunter 2010, Forrester et al. 2015).

For coral reefs, CS has promoted involvement and training of local people that get involved in long-term monitoring (Branchini et al. 2015, Forrester et al. 2015, Roelfsema et al. 2016) and becoming an alert system even during bleaching events (Gudka et al. 2020). It has also allowed to record new data of spatial distribution (Armstrong et al. 2019, McCann et al. 2021), reproductive patterns (Requilme et al. 2021, Clapis Garla et al. 2022), response to stressors (Osgood et al. 2021), population structure (Magson et al. 2022, Gotama et al. 2023) of species that inhabit these ecosystems. Under an adaptive management perspective, data raised by CS projects has allowed a quick response to emergent situations (Dumas et al. 2020), have been used as input in resource management of areas of interest (Beeden et al. 2014, Lau et al. 2019) and led to policy development (Crabbe 2012, Ambrose et al. 2019, Grason et al. 2018).

Coral reef restoration is a management tool that has been applied in response to the degradation and loss of these ecosystems (Hein et al. 2019, Omori 2019, Seraphim et al. 2019), and to create a social network that could increase the resilience of these ecosystems (Lamont et al. 2022, Hein et al. 2019). CS projects have been part of these efforts in the maintenance of restoration sites and testing new protocols (Hernández-Delgado et al. 2014, Hesley et al. 2017, Toh et al. 2017, Unsworth et al. 2021, Smith et al. 2022). The high human capital involved also addresses one of the main issues in coral reef restoration that is long-term ecological monitoring (Boström-Einarsson et al. 2020, Goergen et al. 2020).

Latin-American countries have joined the global effort to restore coral reefs, engaging local communities as a path to provide environmental education and livelihood opportunities (Bayraktarov et al. 2020). In Costa Rica, reef restoration initiatives have been carried out for over a decade (Alvarado et al. 2025). On those, it has been highlighted the importance of partnership networks that can strengthen the compliance of the established objectives (Palou Zúñiga et al. 2023), and recently, the local communities perceptions towards these ecosystems has been studied (Villalobos-Cubero et al. 2023). Exploring the implementation of alternatives like CS as a route to scale up restoration efforts, but also encouraging the public participation in coral restoration governance, should be considered. This research evaluates the effectiveness of a citizen science approach in a coral restoration project conducted on the degraded reef of Ocotal Bay, in the North Pacific of Costa Rica, using changes in the biological community and in volunteers' social perceptions as parameters. We hypothesize that public participation can contribute to the recovery of Ocotal Bay's coral reef and enhance community comprehension of the restoration process.

2. Materials and methods

2.1. Study site: This study is conducted in the Ocotal Bay coral reef, located in the North Pacific of Costa Rica (10°32'49''N, 85°43'33' W, Fig. 1). Depth ranges between 2.5 and 4 m, depending on the tide. The substrate is composed of a dead coral framework with scattered living coral colonies of *Pocillopora*, *Pavona* and *Pssamocora* sp., and sand patches (Fig. S1). On this site, few investigations have been carried out, studying in the impact of the invasive algae *Caulerpa serturialoides* (Fernandez García 2007, Fernández-García et al. 2012), the fish community (Espinoza & Salas 2005) and very recent descriptions of the substrate condition and associated community (Mena et al. 2025). This region, located in the Gulf of Papagayo, is seasonally influenced by an upwelling system, decreasing the sea surface temperature and increasing the dissolved nutrients and CO_2 (Jiménez 2001, Jiménez & Cortés 2003, Jiménez et al. 2010, Alfaro & Cortés 2012, Alfaro et al. 2012). This area used to harbor an important coral development in Costa Rica (Jimenez 1997, 2001, Jimenez et al. 2010). However, in the last 20 years, local and global stressors worked in synergy to diminish these ecosystems (Morales-Ramírez et al. 2001, Bezy et al. 2006, Cortés 2012, Sánchez-Noguera 2012, Fabregat-Malé & Alvarado, 2025), caused a major decrease up to 40 % of the living coral cover during the '90s (Jimenez 1997, 2001, Jimenez et al. 2010), to an with a drop up to 1 % by mid 2010's decade (Arias-Godínez et al. 2019), making vulnerable the ecosystem and making urgent the application of resource management protocols (Alvarado et al. 2018, Sánchez-Noguera et al. 2018).

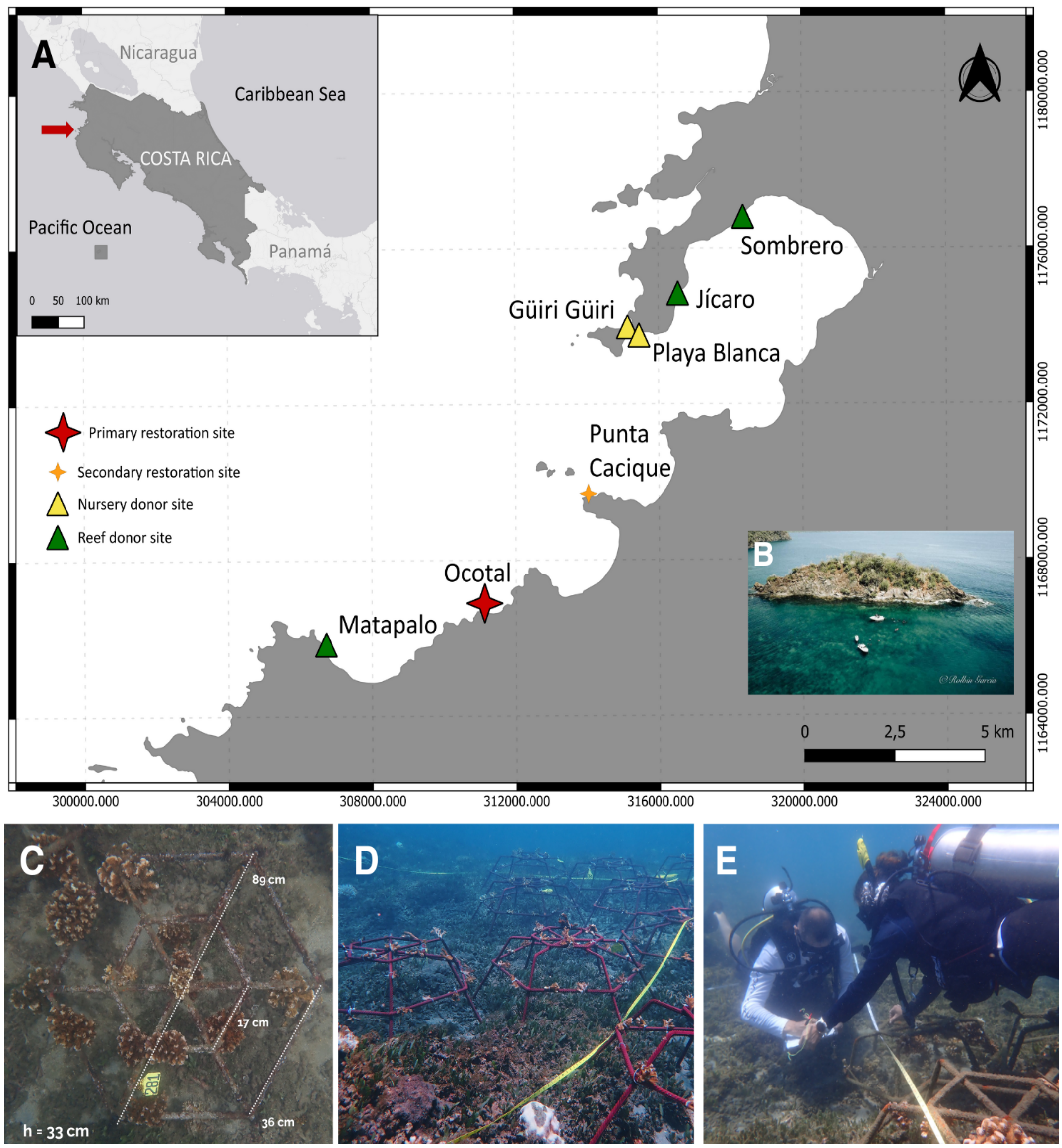

Fig. 1. A. Study site (Ocotal bay) and surrounding areas, Gulf of Papagayo, North Pacific, Costa Rica. **B.** Aerial photograph of the Ocotal Islet (provided by Rolbin Garcia). **C.** Steel spider structures dimensions used to place *Pocillopora* spp. fragments (June, 2024). **D.** Distribution of the spider structures placed on-top of the degraded coral framework of Ocotal reef (August, 2023). **E.** AMT-CS volunteers applying the substrate monitoring protocol following the buddy-pair system (May-2024).

2.2. Restoration protocol: Due to the depletion of the alive coral cover and the absence of a natural recuperation in the region, restoration efforts started in 2019 (Combillet et al. 2022, Fabregat-Malé et al. 2023, 2024, Alvarado et al. 2025). Following this previous experience, artificial hexagonal structures made of steel (modified from the ones used by Combillet et al. 2022), measured 33 cm in height and had a maximum extension of 89 cm (Fig 1B), were placed on top of the dead coral framework, using a distribution that would increase long-term structural complexity (Lamont et al. 2022; Fig. 1D).

Corals were collected from opportunity fragments from nearby natural reefs or other nurseries (Fig. 1A, Table S1). Coral identification was kept at a genus level, since morphological-based *Pocillopora* species identification is challenging due to the phenotypical variability they can exhibit (Pinzon & LaJeunesse 2010). An average of 20 fragments of *Pocillopora* spp. were attached using plastic zip-ties per structure. Fragment size ranges between 10-15 cm. Biweekly, the structures were cleaned, removing the turf, macroalgae or competitors (such as barnacles, ascidians, bryozoans and vermetids) that overgrew the steel structure. Dead colonies were removed from the structures. The intervention covered an approximate area of 300 m^2 (20m x 15m).

2.3. Citizen science approach: A joint effort with the local Non-Governmental Organization "Alianza Mar y Tierra" (AMT-CS) was carried out (see Alvarado et al. 2025). Volunteers were recruited through the AMT-CS; the group was initially composed of 18 volunteers and constantly grew to 65 members (by mid-2025). The recruited volunteers signed an informed consent and willingly participated in the restoration process, monitoring and social surveys. All the volunteers were required to be over 18 years old.

Different types of activities were carried out throughout this program (a full description of each activity is available in Table S1). To develop the abilities required for volunteers to perform biological monitoring, on-land and on-site monitoring training workshops were conducted. Study materials were prepared and sent weeks or months prior to the trainings. These materials included the methodology to-be applied as well as identification photos of the different specimens (Goodson 1988; Fig. S2). Every time that the biological monitoring was conducted, a previous training workshop was conducted, reviewing the methodology. All volunteers must have held at least an PADI Open Water diving license or its equivalent, and had at least 10 dives in the last year. Specific data sheets were designed and validated by the volunteers for data collection (Fig. S2).

2.4. Biological evaluations: To evaluate changes in the biological community, three different biological parameters (substrate composition, fish abundance and sea urchin density) were monitored using SCUBA by the volunteers and the academic team (group affiliation), following the same methodology. In all cases, a buddy-pair system was encouraged to improve the data quality and the safety during the activity (Forrester et al. 2015; Fig 1D). To identify the effect of the restoration effort, the surveyed area was split in three sections: near the rocky reef, the restoration area (where the spider-like structures were placed), and the sandbank closer to the open bay (Fig. S3).

2.4.1. Substrate composition: Using the Point Intercept Transect (PIT) method (Rogers et al. 2001), substrate type was recorded every 20 cm, for a total of 50 points per transect. Three to four 10-meter transects, spaced by at least 1 meter apart, were conducted to assess changes in the substrate within the restoration area (Fig. S3). Transect lines were laid on top of the spider-like structures and the surrounding sea floor (Fig. 1D-E). Volunteers were instructed to classify the substrate type located right beneath the measuring tape in different categories: *Pocillopora* (healthy, bleached, or recently dead), green algae (*Caulerpa sertularioides* or *Halimeda discoidea*), turf, sand, dead coral (rubble) or steel.

2.4.2. Fishes abundance: Volunteers were trained to identify 31 fish species (Table S2); the selected species are conspicuous, have economic and ecological value, and are present in other restoration sites (Turicchia et al. 2021; personal observation MJS, 2022). Underwater visual censuses were carried out to determine the abundance of these species (Table S2), in 5 x 5 x 10 m belt transects, located in the three survey area sections previously indicated (Fig. S3).

2.4.3. Mobile invertebrates presence: Only the long-spined sea urchins *Diadema mexicanum* and *Astropyga pulvinata* were considered, due to the impact in the coral framework erosion they have played in coral reefs of the region (Alvarado et al. 2016a, b) and the abundance observed in other restoration points in the region (Alvarado et al. in prep). All the individuals observed on five belt transects of 1x10 m located in the restoration area (Fig. S3) were counted, and the densities (ind m^{-2}) were calculated.

2.4.4. Coral status: During each visit to the site, photographs of the spiders were taken and the coral cover area (cm^2) was measured using the software Image J (Schneider et al. 2012), using one of the steel bars as a scale (36 cm, Fig 1B). The area was classified between alive, bleached, and dead. For each survey date, the mean area of each category was calculated across the analyzed spider-like structures. Only the corals that were attached to the structures were analyzed. This protocol was only applied by the academic team.

2.5. Social surveys: To assess the influence of the CS program in the volunteers perceptions and motivations, a structured survey was conducted. Four open calls were done in different months to participate in the surveys applied to volunteers (Fig. S3). These volunteers must have completed at least one restoration activity to participate in the social surveys. All surveys were performed face-to-face in Spanish, with two exceptions (the translation of the survey questionnaire it's available in Text S1). Questions were mainly yes-no, short, or Likert scale answers, and three open questions. Volunteers could refuse to answer any of the questions and consent for the use of their data as long as it was kept anonymous. Six interviews were previously conducted to validate the understanding of the survey questions.

Volunteers were asked about demographic information: age, sex, nationality, place of residence (with locals considered as those living within 25 minutes from Ocotal Bay) and economic activities. They were also consulted about their perceived skills on marine sports. In addition, participants reported the activities (recreational, cultural, sports, research, among others) they performed in marine environments, their motivations to participate in restoration efforts, and ecosystem services they perceived from coral reefs. The number of responses on each category was averaged among the participants to provide a global understanding of the volunteers' social profile. Motivations were later categorized under Bayraktarov et al. (2020) framework and the average value of each category was calculated. Finally, they were inquired about their participation in CS and coral restoration projects, as well as their understanding of these concepts.

2.6. Data analysis: All numeric values are reported as mean ± standard error, unless indicated. Data analysis was done using the RStudio Software (R Core Team, 2023). For data transformation and visualization, the packages used were dplyr (Wickham et al. 2023), ggplot2 (Wickham 2016), lubridate (Grolemund & Wickham 2011), patchwork (Pedersen 2024), tidyr (Wickham et al. 2024), and tidyverse (Wickham et al. 2019).

2.6.1. Biological monitoring: Due to the required training time, financial and on-field logistical (mainly sea conditions) constraints, only three survey dates (October-2023, May-2024, and July-2024) were compared for the substrate composition. To differentiate the substrate identification performed by AMT-CS and UCR-Academic, a PERMANOVA and Non-metric multidimensional scaling (NMDS) and ANOSIM analysis were conducted using in a Bray-Curtis dissimilarity matrix — implemented in the vegan package (Oksanen et al. 2024). Prior, the substrate count matrix was $\log_{10}(x+1)$ transformed. PERMANOVA test was applied to analyze overall differences in substrate composition identification among survey dates and affiliations. NMDS was employed to visualize patterns of similarity and dissimilarity among transects. Finally, ANOSIM test was applied to assess if the differences were mainly driven by the survey dates or affiliations.

A qualitative approach was chosen for the fish and sea urchin community, comparing four survey dates (October-2023, March-2024, May-2024, and July-2024). Using data recorded by UCR-academic in six different months a dominance analysis based on the specific occurrence and relative average density was done to classify the fishes into: predominant, common, occasional, and rare (Alvarado et al. 2018).

2.6.2. Coral status: A linear mixed model was applied to identify differences in areas of coral health status (healthy, bleached, or dead) across survey dates. Pairwise comparisons of estimated marginal means (EMS) were performed post-hoc to identify differences (1) in each coral health status across survey dates and (2) in coral health status at each survey date. nlme (Pinheiro et al. 2025), and emmeans (Lenth 2025) were used in these analyses.

2.6.3. Social surveys: A qualitative approach was applied for the social aspects. The declared motivations of the volunteers were classified based on Bayraktarov et al. (2020) framework. To understand possible relations between variables perceived by the volunteers, with the corrplot package (Taiyun &Viliam 2024), a correlation matrix was done with the Likert scale results. Word-clouds were made to explore the conceptualization of the volunteers for the concepts of “coral restoration” and “citizen science”. The most common term was kept in cases where similar words appear (for example, citizen-citizens), the most common term was kept. For this section, tm (Feinerer et al. 2008), SnowballC (Bouchet-Valat 2023), and wordcloud (Fellows 2018) packages were used.

3. Results

3.1. Coral restoration project: Between January 2023 and December 2024, 40 structure maintenance events, six coral outplants, eight monitoring trainings, three monitoring data intake, four social surveys and two community workshops took place (Table S1). A total of 66 steel spider-like structures filled with corals were placed between April and December 2023 in the Ocotal Bay reef (Fig. S4), for a total of 1320 fragments. The month with the greatest addition of structures was August, 2023 (n = 21). During the months of October and November no new corals were placed in structures due to the ongoing bleaching event.

3.2. Biological monitoring results:

3.2.1. Substrate composition: Across surveyed the months, the volunteers were able to identify seven substrate types; while the academic team also identified two others: recently-dead *Pocillopora* in October-2023, and sponge in July-2024. AMT-CS and UCR-academic identification in healthy *Pocillopora* spp. and sand were similar across the three months. Categories like *Caulerpa,* turf, metal and dead coral were observed in the three survey dates, however, values differ in some cases (*Caulerpa* in October-2023). Bleached *Pocillopora* was identified by both affiliations in October-2023, but just by AMT-CS in May-2024 (Fig. 2, Fig. S5).

The PERMANOVA [MS1] analyses showed significant effects of the survey date (strong effect), group affiliation (small effect), and their interaction (Table S3). suggesting that both temporal variation and affiliation influence the substrate identification. The NMDS ordination (stress = 0.165) visualized greater dispersion in May transects (-●-), indicative of higher variability in the substrate type identification; while in October-2023 (-●-) and July-2024 transects (-●-) clustered closely within each survey date, indicating a higher similarity in the substrate composition identification (Fig. 3). The ANOSIM provided an more focused perspective: it detected strong and significant differences among survey dates, but no significant evidence between affiliations (Table S3). Therefore, even if the PERMANOVA detected a minor contribution of the affiliation to the overall variability, temporal changes are explaining most of the substrate identification dissimilarities.

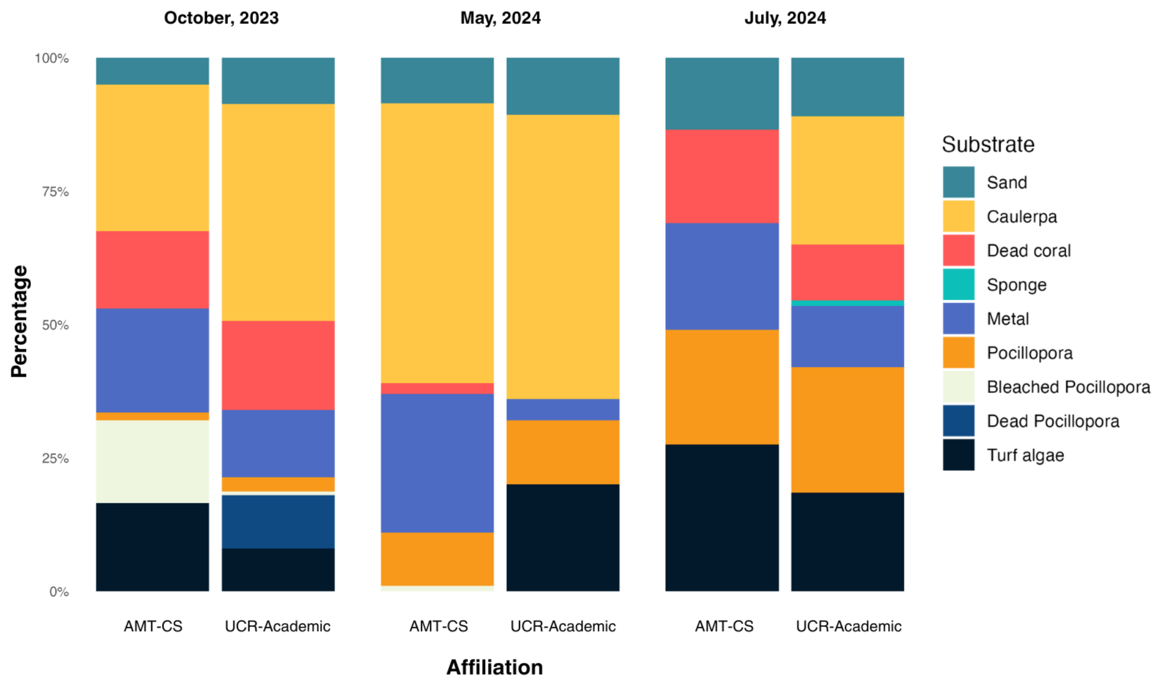

Fig. 2. Coverage percentages of nine substrate types in three survey monitorings done by citizen scientist (AMT-CS) and the academic team (UCR-academic) in the restoration area of Ocotal Bay, North Pacific of Costa Rica.

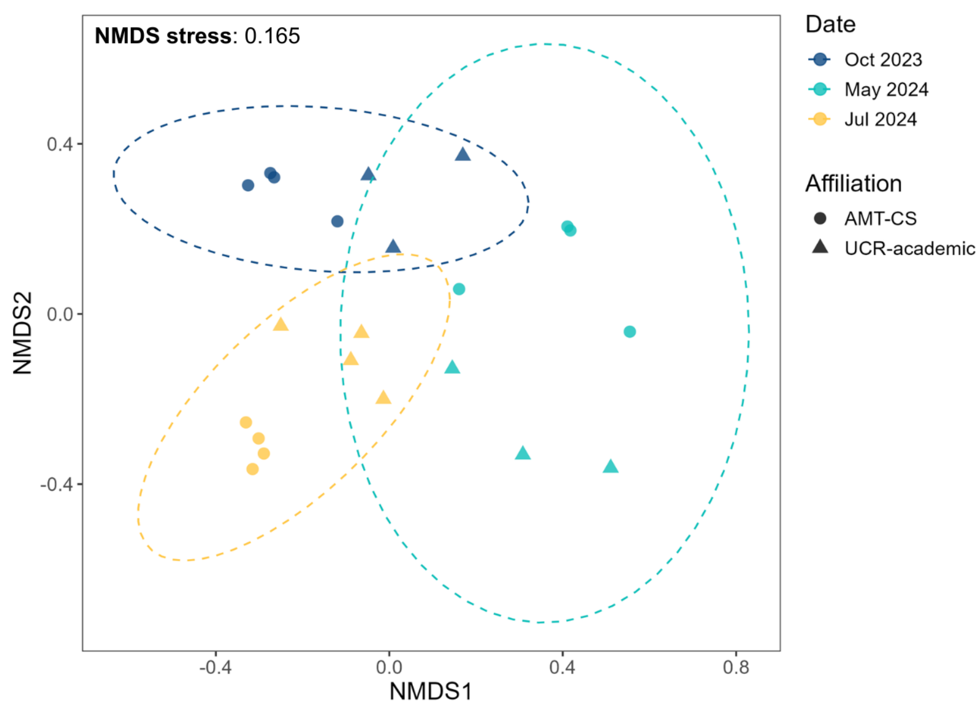

Fig. 3. NMDS of the substrate composition of Point of Intercept Transects (PIT) done in the restoration area for three survey dates on Ocotal Bay, North Pacific of Costa Rica. A $\log_{10}(x+1)$

transformation was applied prior to the analysis, and the NMDS ordination was based on a Bray-Curtis dissimilarity matrix.

3.2.2.Fishes abundance: During the compared months (October-2023, March, May, and July 2024) a total of 22 species were observed in the three surveyed areas. In the rocky reef area (Fig. 4A), 13 fish species were reported. Both affiliations reported the presence of *Arothron hispidus, Canthigaster punctatissima, Scarus* spp.*, Sufflamen verres* and *Thalassoma lucasanum*, and a maximum richness in May-2024 (n = 7). AMT-CS volunteers recorded their exclusively logged the presence of *Arothron meleagris, Fistularia commersonii, Mulloidichthys dentatus* and *Serranus psittacinus*. On the other hand, UCR-academics uniquely documented *Acanthurus xanthopterus, Haemulon* spp.*, Halichoeres chierchiae* and *Stegastes acapulcoensis*.

In the restoration area (Fig. 4B), 20 fish species were documented, with 8 species recorded by both affiliations. AMT-CS reported 12 species, reaching their highest richness per survey date in March 2024 (n = 8), and uniquely reported the presence of *Diodon holocanthus, Halichoeres dispilus, S. psittacinus* and *S. verres*. UCR-academics recorded 16 different species, with a peak richness in May and July 2024 (n = 9), and exclusively recording the presence of *A.xanthopterus, A.meleagris, Chaetodon humeralis, Halichoeres spp* (Juveniles)*, Haemulon* spp., *Johnrandallia nigrirostris, Lutjanus guttatus* and *Zanclus cornutus*.

In the sandbank (Fig 4C), 9 species were observed. Of those, just *C.punctatissima* and *T.lucasanum* were reported by both affiliations. AMT-CS and UCR-academics reported a maximum richness of 4 species in October-2023, and October 2023-July 2024, respectively. AMT-CS exclusively reported the presence of *F. commersonii, Halichoeres* sp. (Juveniles) and *Stegastes flavilatus*; while UCR-academics recorded *A.xanthopterus, A.hispidus, L.guttatus*, and *Scarus* spp. It is relevant to point out that due to boat traffic, May-2024 transects were not performed by both affiliations.

The data recorded by volunteers is highly irregular, with no transects carried out at all (Rocky reef and Sandbank October-2023). Over and under-estimations were observed (Fig. 4). AMT-CS *T.lucassanum* reported abundance in May-2024 restoration transect was more than three times higher than UCR-academics (Fig 4B). In July-2024 sandbank transects, volunteers only reported *T.lucasanum* in low abundances, when other species were also present.

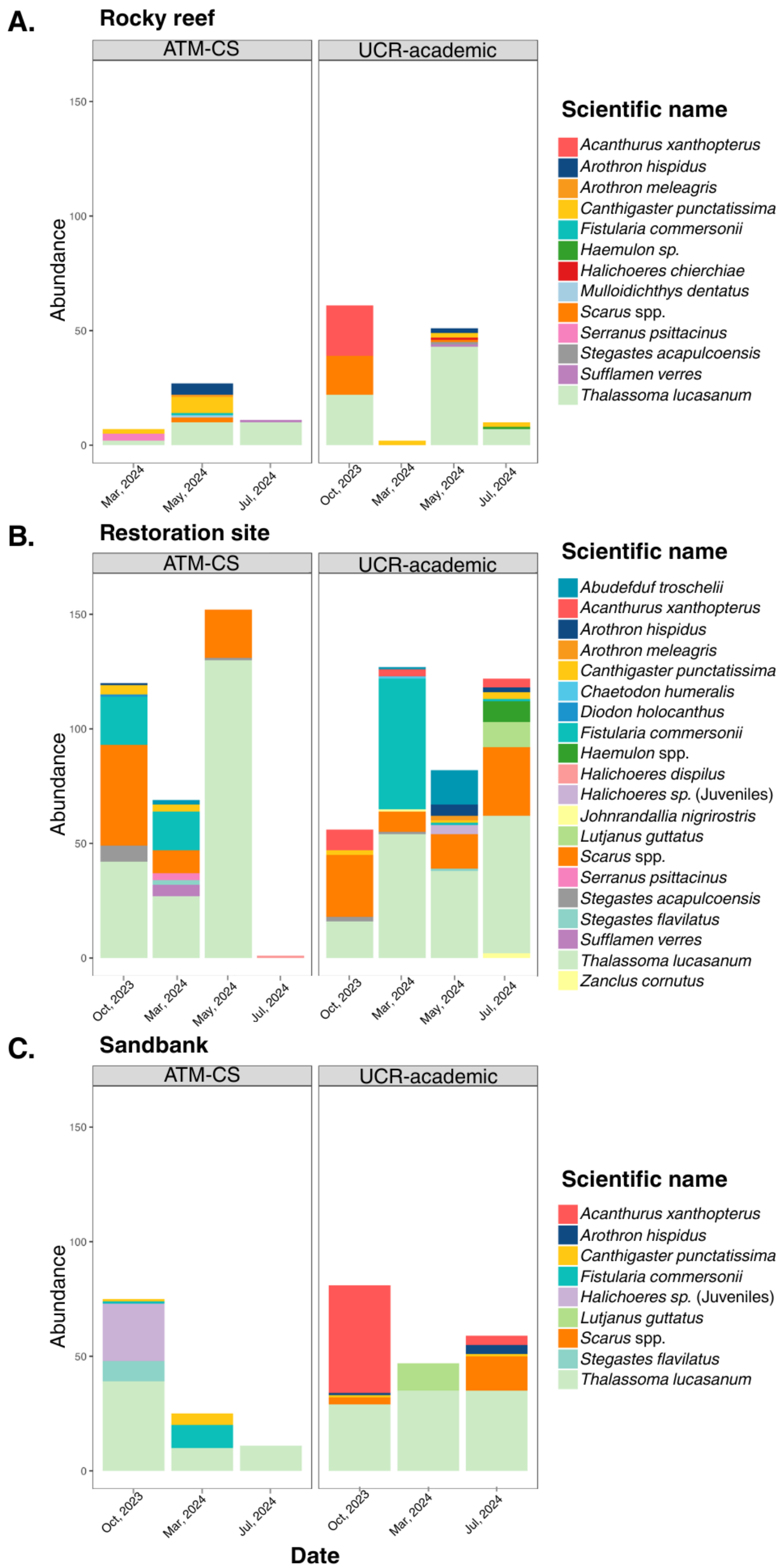
A.
Rocky reef
ATM-CS
UCR-academic
Abundance
Scientific name
Acanthurus xanthopterus
Arothron hispidus
Arothron meleagris
Canthigaster punctatissima
Fistularia commersonii
Haemulon sp.
Halichoeres chierchiae
Mulloidichthys dentatus
Scarus spp.
Serranus psittacinus
Stegastes acapulcoensis
Sufflamen verres
Thalassoma lucasanum
Mar, 2024
May, 2024
Jul, 2024
Oct, 2023
B.
Restoration site
Abudefduf troschelii
Chaetodon humeralis
Diodon holocanthus
Haemulon spp.
Halichoeres dispilus
Halichoeres sp. (Juveniles)
Johnrandallia nigrirostris
Lutjanus guttatus
Stegastes flavilatus
Zanclus cornutus
C.
Sandbank
Date

Fig. 4. Abundances of fish species recorded by volunteers (AMT-CS) and the academic team (UCR-academic) in three surveyed areas. Note: some survey dates lack data, due to on-field logistical difficulties.

With data exclusively recorded by the UCR-academic team, before the intervention of the restoration site (January-2023) the reported richness was of 9 species. The maximum reported richness per survey date was on May-2024 (n = 12). By the last survey date (September-2024), a total of 25 species were documented in the restoration area. Of those, ten species were classified as rare, four as occasional, three as common, and eight predominant, being *T. lucasanum* the only species observed in all the census (Fig. S6, Table S4).

3.2.3. Mobile invertebrates presence: Although the transects were carried out (both by the academic and citizen scientist teams), no individuals were recorded in the five belt transects during the monitoring events. It's relevant to point out that in the nearby area, it was possible to observe individuals of *D. mexicanum*.

3.2.4. Coral status: We found differences in the coral areas based on the coral health status ($F_{(2, 1556)}$ = 504.6368, p =<. 0001), the survey date ($F_{(10, 1556)}$ = 8.9022, p =<. 0001), and the interaction of both variables ($F_{(20, 1556)}$ = 81.8128, p =<. 0001). Coral cover increased from May and August 2023, with the total area composed of healthy tissue. Mean values rose from 469.74 ± 34.57 cm^2 in May to 675.05 ± 62.77 cm^2 in August (Fig. 5, Table S5). However, a decline in the healthy area from September to December 2023 was recorded, with the bleached area remaining similar due to a bleaching event (Fig. 5, Table S6, Fig. S7). Bleached area coverage per spider-like structure peaked in October-2023, reaching 542.34 ± 51.95 cm^2, corresponding to 87.29 ± 11.54 % of the total area (Fig. 5A; Table S5-S8). From February-2024 onward, the bleached area decreased, with percentages not exceeding 6.52 ± 1.38 % of the total area (in February-2024); while total and healthy cover had similar values (Fig. 5, Table S6-S7). Due to the bleaching event, the total area was reduced, from 679.45 ± 63.17 cm^2 in August-2023 to 381.73 ± 28.46 cm^2 in February-2024 (Table S5). This decrease is not visualized as an increase in the dead coral area, since the dead fragments were removed from the spider-like structures; therefore, no significant differences were observed in the dead coral area across the survey dates (Fig. 5B, Table S6). After this date, the total cover increased to a maximum value of 869.46 ± 46.57 cm^2 in July-2024 with a 99.82 ± 7.57 % of healthy coral cover (Fig 5; Table S5-S8).

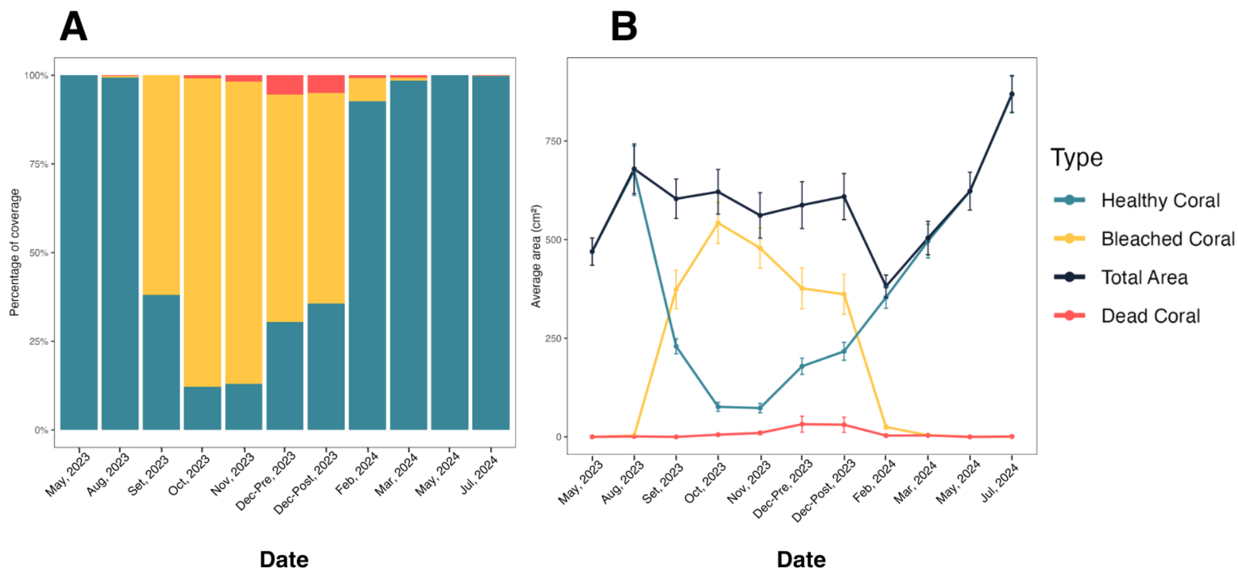

Fig. 5. A. Mean coverage percentages and **B.** average area coverage (±standard error) of healthy, bleached, dead, and total areas of the *Pocillopora* spp. fragments attached to the 66 spider-like structures placed in the restoration site of Ocotal Bay, between May-2023 and July-2024. Two values are associated with December 2023 since there was an outplant as a quick response to the bleaching event.

3.3. Social data:

3.3.1. Demographic general results: A total of 16 participants agree to complete the survey. Of them, six identify as females and 10 as males. The mean age was 39.56 ± 9.13 years, with no difference in age among sexes ($t = 0.58732$, $df = 14$, $p > 0.05$). Most of the participants were Costa Ricans (n = 13), while the rest were foreigners that reside in the area. Six people were locals, while non-locals were the majority (n = 10). Only five of the participants were members of the AMT-CS. The majority (n = 14) of the volunteers highest educational level is university degree. Most of the participants describe themselves as active workers (n = 14), mainly in private enterprises (n = 4) or self-employed (n = 5), with working activities related to data collection (n = 8) and a low economic dependency of marine ecosystems. On average, the volunteers had been part of the project for 7.56 ± 0.45 months and had participated in 8.13 ± 0.82 activities (Text S1, Table S9). Half of the volunteers had previous experience in coral restoration programs and just four declared to have experiences in other CS projects (Table S9).

3.3.2.Marine ecosystem appropriation: Volunteers declare to engage in 5.43 ± 0.54 different marine activities, with snorkeling, scuba diving and recreational use being the most frequently mentioned (Fig. S8). Participants mentioned an average of 10.63 ± 1.14 different motivations for participating in coral restoration projects. Among these, the idealistic motivation type is by far the most common incentive (Fig. 6A), although "reef conservation" (a biotic motivation), was the most constantly mentioned reason for participation (Fig. S9). Additionally, participants perceived an average of 7.31 ± 0.85 different ecosystem services in their life, being cultural services the most mentioned (Fig. 6B, Fig. S10).

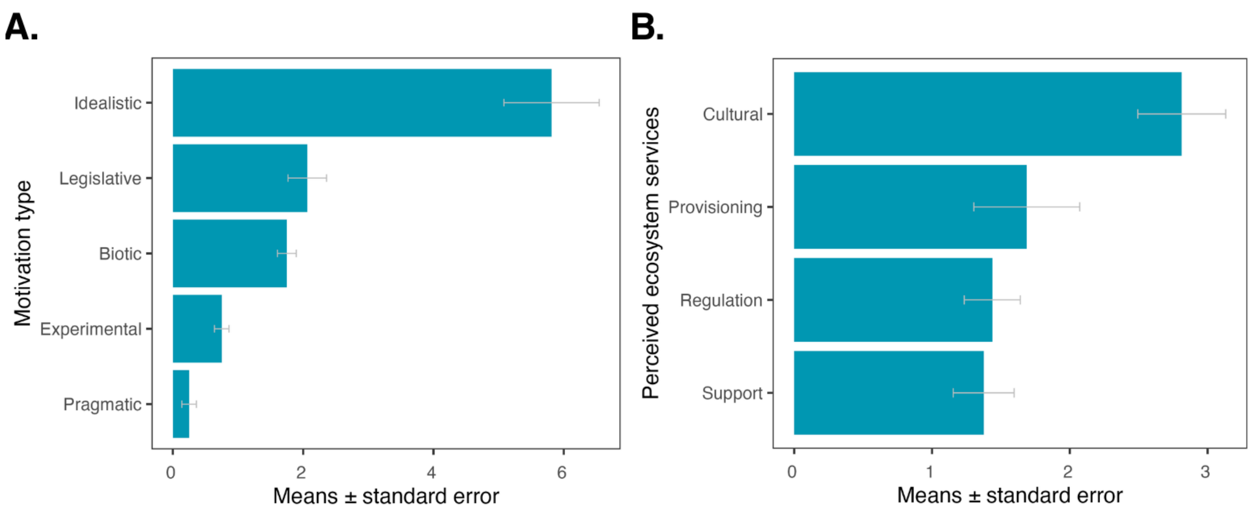

Fig. 6. A. Motivations to participate in coral reef restoration programs and **B.** ecosystem services pointed by volunteers of the Ocotal coral restoration and CS project.

3.3.3.Perceptions: It was possible to observe strong (>0.50) positive correlations between the self-perceived knowledge after the involvement in the Ocotal coral restoration and CS project and different variables: perceived snorkeling skills (0.61), perceived diving skills (0.76) and the declared compromise with the Ocotal's project (0.64). This later also has a strong positive correlation with the perceived diving skills (0.56). No strong negative correlations were highlighted (Fig. 7).

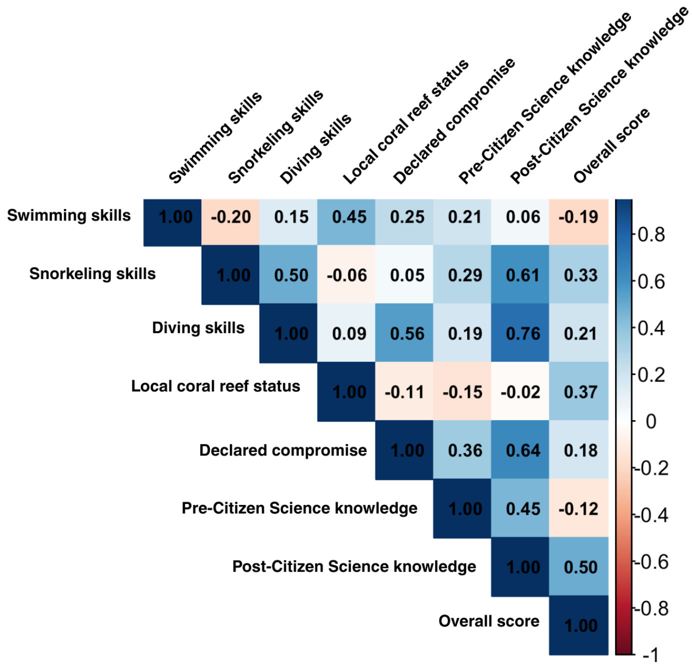

Fig. 7. Correlation matrix between self-perceived social features related to the Ocotal coral reef restoration CS project.

3.3.4. Term conceptualization: For the coral reef concept, the most frequently mentioned words were "boost" (n = 10), "coral" (n = 11) and "recover" (n = 8). On the other hand, for the "citizen science" concept, they were: "citizen" (n = 9), "community" (n = 8) and "training" (n = 7) (Fig. 8, Fig. S11).

Fig. 8. Word-cloud obtained after asking the volunteers what they understood by the terms **A.** "Coral restoration" (n = 16) and **B.** "Citizen science" (n = 14). Minimal frequency = 2.

4. Discussion

This CS project has successfully engaged a diversity of stakeholders involved in the restoration of coral reefs in the North Pacific of Costa Rica, and represents the first documented assessment in the country that involves volunteers as active monitors. Also contributes to the reduced social values´ knowledge in coral reef conservation (Villalobos-Cubero et al. 2023) by profiling the volunteers' perception of these ecosystems and programs.

To safely apply scientific diving protocols, it is required to invest hours in training (Dardeau et al. 2012), developing abilities that include the identification of the studied elements and equipment handling, but also acquiring competencies such as proper buoyancy control and navigation (Féral & Norro 2023). Only a small proportion of the volunteers declared previous experience in CS programs and none of them had previously taken data under a citizen scientific diving platform (Table S9). The process of understanding and properly applying the described data intake protocol was time-consuming; until October-2023 volunteers were able to carry out most of the methodology by themselves. Another factor to consider is the fluctuation in the volunteers' participation. Since the CS platform was created for this project, new recruits joined during the study. This brought the necessity of constantly training them and refreshing the survey protocols for the oldest volunteers, highlighting the importance of investing time, effort, and resources in keeping the volunteers engaged in the project (Martin 2013; Cottam et al. 2021; Lazic et al. 2022). In the future, once the volunteers are properly trained, alternatives such as involving them in the process of apprenticeship of new recruits could be considered (Martin & Studer 2022).

Simultaneous events were taking place at the same time that the citizen scientific diving protocols were learned and implemented. Before and after the bleaching period, the ecosystem effect of the restoration process started, with an increase in the healthy coral cover and changes in the fish community (Opel et al. 2017). On the other hand, the fourth global bleaching event was declared (Reimer et al. 2024), with its effects being perceived in the north-pacific reefs from August to December 2023 (Alvarado et al. 2025), including the one of Ocotal Bay (Fig. 5, Table S5-S8, Fig. S7). These events led to re-evaluation and adaptation of the protocols applied, like the inclusion of new substrate types: bleached and recently dead *Pocillopora* spp. and the addition of fish species to the identification list.

This study presents a preliminary assessment of the restoration process using data taken by community members. Long-term monitoring is required to properly assess ecosystem changes

(Boström-Einarsson et al. 2020). Although substrate composition observations differed between ATM-CS and UCR-academic (Fig. 2-3, Fig S5), volunteers were able to identify seven out of the nine substrate types observed. The remaining two other substrates (recently-dead *Pocillopora* and sponge) were only observed in one monitoring event each; and were included in the training materials after they were observed. In the NMDS ordination, May-2024 transects were more dispersed, suggesting a higher variability in the substrate identification; whereas October-2023 and July-2024 results cluster closely among transects, indicating a greater consistency in the substrate type identification by both affiliations (Fig. 3). Both PERMANOVA and ANOSIM confirmed strong and significant differences among survey dates. On the other hand, regarding the effect of the affiliation, PERMANOVA detected a significant, yet minor contribution; and the ANOSIM did not present enough evidence to support an effect of this variable in understanding the variability in the substrate composition identification (Table S3). Monitors involved in October-2023 substrate identification had been consistently part of training events carried out since April 2023 (Table S1), and those in July-2024 had been enrolled and have constantly contributed to the project since its beginning. Altogether, this pattern suggests that protocol refreshments, longevity, and constant participation in the data collection are key to ensure more reliable data, which aligns with other CS projects (Alabri & Hunter 2010, Branchini et al. 2015, Chatzigeorgiou et al. 2016).

When scrutinizing the fish community data, it's possible to observe overestimations (Fig. 4B, May-2024 *Thalassoma lucasanum* data) and underestimations (Fig. 4B, July 2024 data). Being highly mobile species, identifying and quantifying fishes can be challenging while learning. Nevertheless, it should be acknowledged that between the training and monitoring events, the volunteers identified 19 out of the 25 species observed in the restoration area, including species that were not in the initial training material.

Among the factors that may have influenced the obtained results are the level of experience of the monitors; higher levels of specialization have been associated with better fin positioning, buoyancy control, outcomes in challenging situations (Musa et al. 2010, Ong & Musa 2012) and fish identification skills (Williams et al. 2006). On the other hand, less experienced divers tend to have a poorer control of their breathing; open circuit scuba diving equipment create vibrations, noise and visual disturbances that interferes with fish behavior (Kulbicki, 1998, Lindfield et al. 2014, Lopes et al. 2019). Another aspect to consider is the local visibility, currents, and sedimentation conditions, which are common in the study area and affect the ability to successfully carry out the task. Our demographic group background should also be taken into account, since it was not mainly composed of people whose income was dependent from marine resources (Table S9), such as fishers (Morais & Teodosio 2016, Laporta et al. 2021, Perez-Jiménez et al. 2022, Bundone et al. 2023) and tour-operators (Valani et al. 2020, Osgood et al. 2021, Pavía et al. 2023). People in these jobs have historical knowledge of the presence of local species and are familiarized with their identification, especially since most of the fish species observed have fisheries and aquarism value (Table S2).

The reef fish communities are dynamic and have quick and long-term responses to changes in the coral cover (Booth & Beretta 2002, Garpe et al. 2006, Opel et al. 2017; Arias-Godínez et al. 2019, 2021, Lamont et al. 2022, Mena et al. 2025). The restoration area seems to be influencing the fish community (Fig. 4B) and harboring a greater richness and abundances than the two other survey areas (Fig. 4A, Fig. 4C). This could be attributed to the added tridimensionality obtained from the artificial structures and the coral colonies (Opel et al. 2017, Lamont et al. 2022); but also, due to the strict associations that exist between some fish species and living coral (Öhman & Rajasuriya 1998, Coker et al. 2014). The appearance of new species in all the survey dates and no clear stabilization in the dominance levels (Fig. S6, Table S4) indicates that the fish community is in constant change. Therefore, further analysis requires to be done to have a better understanding of the community dynamics. In nearby long-term restoration sites, a total of 91 fish species have been quantified (Alvarado et al. in prep), so a greater richness could be expected in the Ocotal coral reef.

Among the citizen scientists who apply the monitoring protocols, fish monitoring was the most preferred protocol, followed by the substrate identification (Table S9). It is possible that fish census was the first preference because it has been seen that charismatic species (Weinstein et al. 2014) and ease of identification (Chin 2014, Turicchia et al. 2021) are factors that contribute to these types of studies; the selected list of species had these characteristics. At the same time, the nature of the substrate composition allows more time for the identification and fewer categories are contemplated, which could be why it's the second preference. Unsurprisingly, the least preferred protocol was the mobile invertebrate census (Table S9). The reduced number of observations of the sea urchins contributed to the lack of interest among the volunteers. Nonetheless, it's important to continue this monitoring due to the ecological implications of substrate erosion and herbivory (Alvarado et al. 2016a,b). This information is relevant to designing and adapting the survey protocols in the future. CS protocols should be designed to be highly adaptable, contemplating the data quality improvement through time, an increase in the survey areas and methodologies, and the local demands (Aceves-Bueno et al. 2017, Machado et al. 2021). Once the established species are successfully monitored, an expansion to other groups like conspicuous and commercially relevant invertebrates, like lobsters, sea cucumbers and gastropods should be considered.

Today, more than ever, it's crucial to work with communities to conserve and rehabilitate the coral reefs. CS is a methodology that should be considered to obtain data cost-effectively in moments when it is urgent to obtain data required to quick response to the coral crisis (Reimer et al. 2024). In the Gulf of Papagayo, sea surface temperatures were abnormally high between May and November 2023, in some cases exceeding 30 °C for weeks. These conditions led to widespread coral bleaching the region. In some reefs, coral mortality exceeded 90 % and shifts in the fish community assemblage were documented; that said, in others, a recovery after bleaching was observed (Alvarado et al. in press). In Ocotal Bay coral reef, after the bleaching event, the total coral cover of each spider-like structure was reduced from 609.11 ± 58.4 (EE) cm^2 to 381.73 ± 28.46 (EE) cm^2 (Table S5). The corals that did survive this massive bleaching event have the adaptations required to persist under the extreme temperature conditions that led to the complete or partial loss of reefs in the area (Alvarado et al. in press). Once the conditions were normalized, a continued increase in healthy coral cover is reported due to new outplants and growth (Fig. 5; Table S5-S7). The benefits of involving local communities in rehabilitation extend the biological parameters. Having local communities enrolled in environmental education platforms such as CS projects can improve their environmental compromise (Dean et al. 2018), increase the social resilience of the ecosystem (Cinner et al. 2009), help to unveil how the human activity impacts in marine ecosystems (Zhang et al. 2023), contribute to the policy development of policies for reef protection (Crabbe 2012), improve the ecosystem services provided by coral reefs (Toh et al. 2017) and a reduction in the operative costs of coral restoration (Hesley et al. 2017).

That said, although the AMT-CS volunteers in our project have not yet reached an academic level assessing biological parameters, the results show progress in that direction. More training and the development of study materials based on ludic activities might reduce this gap (Skukan et al. 2020). To ensure long-term engagement, it is essential to implement strategies that encourage citizen participation over time. Advocacy and socialization can support the engagement of citizen scientists toward this initiative, but sustaining their commitment remains a challenge. To address this, securing a long-term financial framework is critical. Funding restraints are common across CS and coral restoration projects (Hamburger et al. 2018, Bayraktarov et al. 2020, Ward et al. 2023), and also were present in ours, restricting our ability to carry out some activities. Providing monetary compensation, or at least securing per diems for the volunteers, could reduce the financial weight and encourage both new and old participants to remain committed to this initiative. Additionally, delivering frequent updates of the project to those involved could serve as a strong motivation tool, giving tangible visualizations of their contribution in local coral restoration outcomes. Finally, recognizing and diversifying the different roles that volunteers of AMT-CS played in this project, not only supporting on-field logistics (Roelfsema et al. 2016), but also organizing events like environmental talks, beach and seafloor clean-ups is part of contributing to community-based conservation efforts.

CS projects offer a valuable opportunity to incorporate socio-ecological dimensions in coral reefs rehabilitation, encouraging community participation (Bellwood et al. 2004, Hein et al. 2019, Hari et al. 2021, Lamont et al. 2022). This is particularly relevant in the North Pacific of Costa Rica, where social indicators such as access to public areas and economic conditions are complex (Navarro-Cerdas 2013, Orias-Arguedas 2015) and there's a significant dependence of the coastal resources (Sánchez-Noguera 2012, Sánchez-Noguera et al. 2018). It is also a way of harnessing local ecological knowledge (Hof et al. 2017), promoting scientific literacy and democratization of scientific knowledge (Alabri & Hunter 2010, Crall et al. 2012, Forrester et al. 2015).

Volunteers engage in multiple activities in marine environments, are motivated to participate in this project by different factors, and perceived different benefits (Fig. S8-S10). Being able to understand the volunteers willingness to participate is essential to properly approach CS (Scyphers et al. 2015, Cerrano et al. 2017, Lucrezi et al. 2018) and coral reef restoration (Bayraktarov et al. 2020). Motivations change in time and vary according to the volunteers' knowledge and experiences (Blanco-Parra et al. 2022). The most commonly reported motivation in coral reef restoration projects is answering scientific questions –an experimental type motivation (Bayraktarov et al. 2019). However, our results differ from that, since the idealistic values are more frequently mentioned by our volunteers and our sample is by far smaller (Fig. 6A). While knowledge creation (experimental) appears in our data and was mentioned by most of the surveyed participants (Fig. S9), it doesn't seem to be a key stimulus. These differences can be attributed to individual preferences instead of project objectives, which are meaningful to address in this context. Lucrezi et al. (2018) found strong motivations among divers related to personal well-being and socialization, which resembles what was observed for this study. Among the cultural ecosystem services associated with coral reefs, recreation and socialization were mentioned more frequently than any other category (Fig. 6B). The social interactions that occur in these spaces are mentioned as factors of maintaining engagement in volunteers (Hari et al. 2021, Spicer et al. 2021, Eberhardt et al. 2022). From an environmental education perspective, a greater effort should be made to design activities that encourage these social behaviours and enhance the community's appropriation of the Ocotal Bay coral reef. Also, it should be appropriate to address the importance of other ecosystem services provided by coral reefs (Woodhead et al. 2019) to increase the pragmatic motivations among the volunteers.

Volunteers participated in several activities, during more than a year (Table S9). To keep the engagement with this process, their self-perceptions should be considered while addressing this public participation scenario. It was observed that volunteers who feel more confident while being in the water are more likely to lean more (Fig. 7). This is likely to be because they already have the non-scientific skills and it's just required for them to learn the scientific protocols (Dardeau et al. 2012). Another interesting finding was that people with better self-perceived diving skills are more involved with the project (Fig. 7). It has been seen that scuba divers with major diving experience are likely to be involved in CS programs (Lucrezi et al. 2018), and are more likely to preserve the ecosystem conditions (Dearden et al. 2006). Also, it has been suggested that CS programs impact environmental knowledge, awareness, and attitude (Srisathan et al. 2024). Altogether, the experience and personal knowledge of each diver may explain why they are compelled to participate in this project.

The way we understand conservation concepts is essential for the expected outcome (Callicott et al. 1999); word-clouds are tools that have been previously used to illustrate community conceptions of conservation issues (Do et al. 2020; Ostrovski et al. 2021; Ternes et al. 2023). An important aspect to highlight is that volunteers understood that both coral restoration and CS are processes (Fig. 8). This notion was constantly expressed through the different activities in order to recognize that these methods demand time, effort and commitment; but also to manage the expectations of the involved volunteers and avoid the loss of commitment if these were not achieved (Massarella et al. 2018).

When asked what volunteers understood by coral restoration, the citizen scientist indicated that it’s an activity that requires human intervention to boost the recovery of corals and coral reefs (Fig. 8A). They’re capturing the essence of the objectives behind the active restoration activities that it’s to promote self-sustained ecosystems that can overcome the future conditions (Hughes et al. 2023). It is also possible to observe that their conceptualization is guided by the methodology that was applied in this project, since the words “nurseries” and “gardening” (Fig. 8A) are also mentioned.

On the other hand, after inquiring about the concept “citizen science”, the volunteers highlighted fundamental aspects: the public participation nature, the collaboration between communities and researchers, and lastly, the demand of training for a proper data collection (Fig. 8B). This concept is being understood as a process in constant adaptation, involving the participation of the involved stakeholders. As before, the conceptualization obtained is modulated by the volunteers’ experience, since only “data collection” was mentioned, without including other tasks that citizen science can execute by participants (Cigliano et al. 2015).

5. Conclusions

The main goal of this project was to encourage stakeholder participation in the local coral reef rehabilitation efforts. Including the local communities in the reef conservation is vital for promoting citizen engagement, advocating for the removal of local stressors contributing to their degradation (Hughes et al. 2023, Srisathan et al. 2024). The stakeholder involvement that resulted from the intervention at the Ocotal Bay coral reef made the implementation of another restoration area- the Punta Cacique coral reef, possible. Altogether these two areas have 112 artificial structures filled with coral fragments that carry the adaptations to survive extreme conditions. Even if the citizen scientist’ monitoring data has not yet reached an academic accuracy, volunteers with no previous knowledge are able to identify several reef species and are more aware of the threats that are facing coral reefs. Encouraging local participation and regularly re-evaluating protocols are key for adaptative programs that respond to current contextual demands. This strategy also responds to the global necessity of obtaining data in a more cost effective way. Knowledge of the volunteers' motivations and perceived ecosystem services is key to properly adapting the CS and reef restoration programs. Acknowledging the role of communities within ecological systems might be the pathway to more resilient reefs.

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7. Supplementary material

Figure S1. Dead coral reef framework with spare coral colonies from different species. Photos taken previous to the restoration and citizen science process in the Ocotal coral reef (January, 2023).

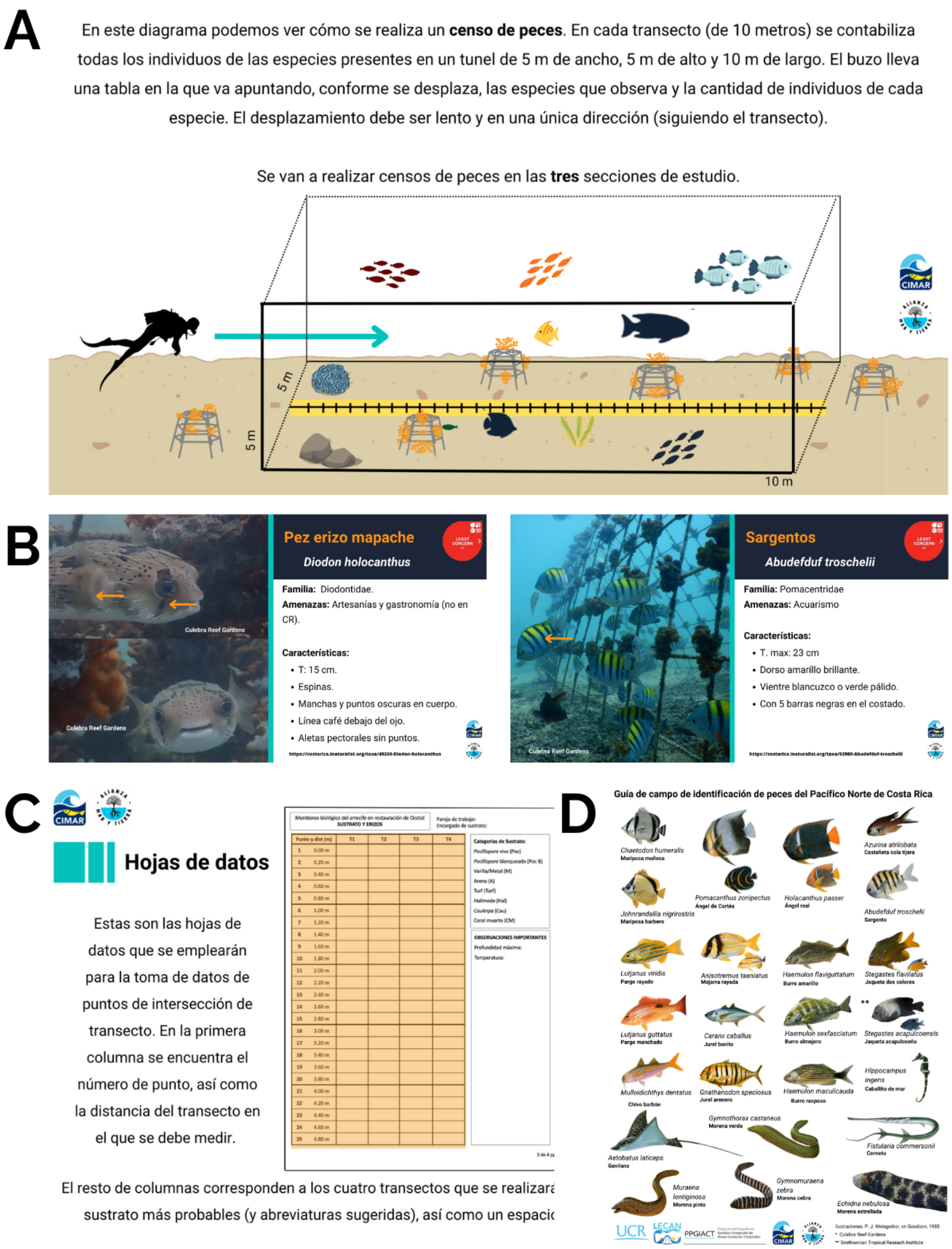

Figure S2. Segments of the materials developed for the training of volunteers in biological monitoring of fishes, substrate and mobile invertebrates. **A.** Fishes census protocol, **B.** Fishes species identification, **C.** Data sheets during the biological monitoring, **D.** Submersible material designed for the identification of fish species (mainly Weisgerber illustrations on Goodson, 1998).

Table S1. Detailed activities performed during the development of a citizen science and coral reef restoration project in Ocotal Bay coral reef.

Activity	**Description**	**Involved stakeholders**	**Months**
Community workshops	Open workshops held to present the restoration project, recruit volunteers and to update results to the community.	AMT-CS, UCR-Academic, Local community, Tourism authority, environmental authority, private sector.	Feb, 23; May, 24; Aug 2025
Coral outplants *[1]	Collection of *Pocillopora* coral fragments from nurseries and natural reefs, and attaching them to steels structures in Ocotal Reef	AMT-CS, UCR-Academic, private sector, local journalists	Apr, Jun-Set, Dec, 23.
Structure maintenance *[1]	Removal of algae and competitors that grow over the structures' steel. Usually, this was done twice a month.	AMT-CS, UCR-Academic	May, 23-Dec, 24.
Training workshops for biological evaluations*[1,2]	Trainings and data collection of biotic parameters done by volunteers and/or academics. On-land and in-situ trainings done to obtain the abilities required for biological monitoring. A refreshment of the protocols was done every time data collection took place	AMT-CS, UCR-Academic	AMT-CS trainings: Apr-May, Aug-Oct 23, Mar, May, Jul, 24. UCR-Academic: Jan, Oct 23; Mar, May, Jul, Set 24 Simultaneous: Oct 23, May, July 24
Social surveys	Surveys applied to the volunteers to understand the social aspects of the citizen science-coral reef restoration project	AMT-CS, UCR-Academic	Feb-Jun, 24.

*[1] To participate in these activities, volunteers must hold at least an Open Water diving license.

*[2] Two types of methodologies were applied for the substrate evaluations.

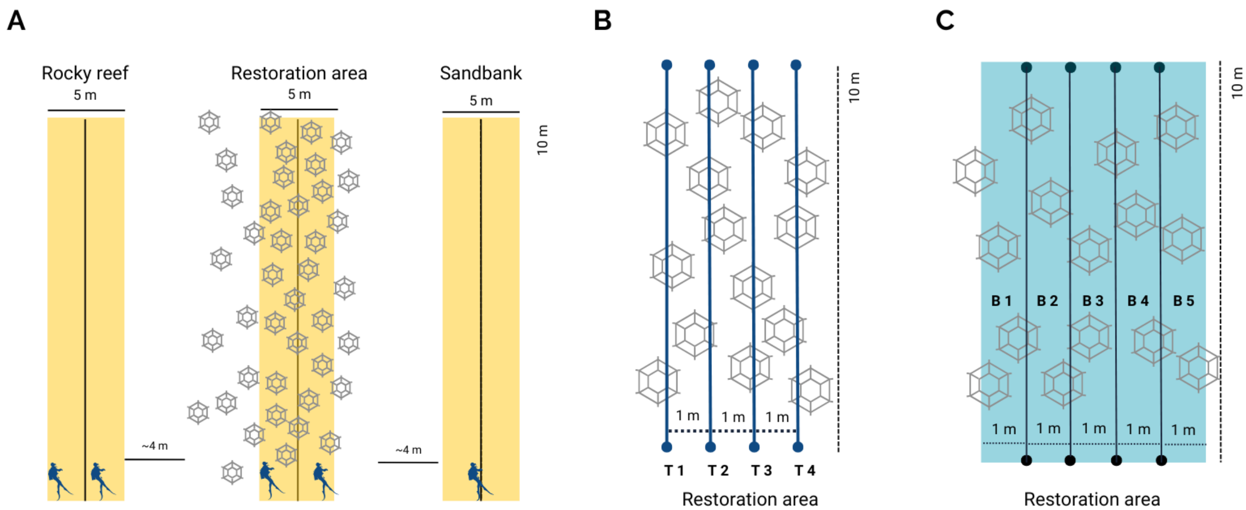

Figure S3. Diagram of the restoration and surrounding areas where the monitoring protocols were applied.

Table S2. Fishes species list considered in the census performed by citizen scientists in Ocotal's coral restoration site.

Family	Species	Conservation status *	Fisheries relevance*	Aquarism *
Balistidae	*Sufflamen verres*	Least Concern		
Carangidae	*Caranx caballus*	Least Concern	x	
	Gnathanodon speciosus	Least Concern	x	x
Chaetodontidae	*Chaetodon humeralis*	Least Concern	x	x
	Johnrandallia nigrirostris	Least Concern		x
Diodontidae	*Diodon holocanthus*	Least Concern	x	x
	Diodon hystrix	Least Concern	x	x
Fistularidae	*Fistularia commersonii*	Least Concern	x	
Haemulidae	*Haemulon* sp.	Least Concern	x	
Labridae	*Halichoeres chierchiae*	Least Concern		x
	Halichoeres dispilus	Least Concern		x
	Halichoeres nicholsi	Least Concern		
	Stethojulis bandanensis	Least Concern		x
	Thalassoma lucasanum	Least Concern		
Lutjanidae	*Lutjanus guttatus*	Least Concern	x	
Mullidae	*Mulloidichthys dentatus*	Least Concern		
Muraenidae	*Echidna nebulosa*	Least Concern		x
Pomacanthidae	*Holacanthus passer*	Least Concern		x
	Pomacanthus zonipectus	Least Concern		x
Pomacentridae	*Abudefduf troschelii*	Least Concern		x
	Azurina atrilobata	Least Concern		x
	Stegastes acapulcoensis	Least Concern		x
	Stegastes flavilatus	Least Concern		x
Serranidae	*Alphestes immaculatus*	Least Concern	x	
	Serranus psittacinus	Least Concern		
Scaridae	*Scarus* sp.	Least Concern	x	
Scorpaenidae	*Scorpaena mystes*	Least Concern	x	
Tetraodontidae	*Arothron hispidus*	Least Concern		
	Arothron meleagris	Least Concern		x
	Canthigaster punctatissima	Least Concern		
	Sphoeroides lobatus	Least Concern		

* According to IUCN

Text S1. Translation of the surveys applied to the volunteers of the Ocotal's coral reef restoration project.

Block 1: Personal information

1. Age
2. Sex
3. Nationality
4. Educational level: ( ) Primary, ( ) Secondary, ( ) Vocational or technical, ( ) Universitary, ( ) Other.
5. Place of residence
6. Daily activities (you can select multiple responses): ( ) Worker, ( ) Student

6.1. In case of being a worker, specify: ( ) Self-employed, ( ) Private company, ( ) Non governmental organization, ( ) Government institution, ( ) Domestic work, ( ) Other.

7. Are you part of the Alianza Mar & Tierra? ( ) Yes, ( ) No.

Block 2: Ocean and reefs

8. Can you swim? ( ) Yes, ( ) No.

8.1. If so, on a scale of 1 to 5, how do you rate your swimming ability? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

9. Have you snorkeled? ( ) Yes, ( ) No.

9.1 If so, on a scale of 1 to 5, how do you rate your snorkeling skills? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

10. Do you know how to dive? ( ) Yes, ( ) No.

10.1 If so, on a scale of 1 to 5, how do you rate your snorkeling skills? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

10.2 Maximum diving level (license):

10.3 In the last year, how many times have you dived? ( ) 0-10, ( ) 10-20, ( ) 20-30, ( ) 30-40, ( ) + 40

10.4 In total, how many times have you dived? ( ) 0-20, ( ) 20-50, ( ) 50-100, ( ) 100-200, ( ) 200-500, ( ) + 500

11. In addition to the above activities (swimming, snorkelling and diving), which other activities do you do in marine environments? ( ) Recreational fishing, ( ) Transport, ( ) Artisanal fishing, ( ) Paddle-surf, ( ) Kayak, ( ) Naturalism, ( ) Surf, ( ) Recreation, ( ) Other
12. What benefits (social, economic, cultural, spiritual, personal, ecological...) do you get from the sea? ( ) Recreation, ( ) Transport, ( ) Spiritual aspects, ( ) Tourism, ( ) Research, ( ) Art, ( ) Food sources, ( ) Species habitat, ( ) Socialization, ( ) Sports, ( ) Material gathering, ( ) Income source, ( ) Other
13. What benefits (social, economic, cultural, spiritual, personal, ecological...) do you get from the reefs? ( ) Food source, ( ) Coastal protection, ( ) Tourism, ( ) Research, ( ) Water quality, ( ) Sports, ( ) Species habitat, ( ) Source of employment, ( ) Spiritual aspects, ( ) Recreation and socialization, ( ) Species diversity, ( ) Material gathering, ( ) Other
14. On a scale of 1 to 5, what condition do you think the coral reefs of Culebra Bay are in? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

Block 3: Work and economy

15. Does your household income depend on sea-related activities? ( ) Yes, ( ) No.
16. Do the people in charge of raising you (mothers/fathers, grandmothers/grandfathers…) have or had jobs related to the sea? ( ) Yes, ( ) No.
17. Your monthly income it's somewhere in the next ranks? ( ) Less than 350 000 colones *, ( ) 350 000 - 500 000 colones, ( ) 500 000 - 750 000 colones, ( ) 750 000 - 1 000 000 colones, 1 000 000 - 1 500 000 colones, 1 500 000 - 2 000 000, ( ) More than 2 000 000 colones

* Colones it's the local currency. 350 000 colones is approximately the minimum wage in Costa Rica.

18. It's your job related to marine ecosystems? ( ) Yes, ( ) No.

19. Does your job involve collecting scientific data? ( ) Yes, ( ) No.

Block 4: Coral restoration

20. What do you understand by "coral restoration"?

21. What motivates you to participate in coral restoration projects? ( ) Reef conservation, ( ) Experiences, ( ) Socialization, ( ) Diving practice, ( ) Personal well-being, ( ) Future implications, ( ) Improved environmental quality, ( ) Source of work, ( ) Knowledge (research and communication), ( ) Recreation, ( ) Environmental commitment, ( ) Fixing environmental problems, ( )Connection with nature, ( ) Material gathering, ( ) Political objectives, ( ) Environmental education, ( ) Other.

22. On a scale of 1 to 5, how necessary do you think it's to implement coral restoration projects?( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

23. Have you participated in other coral reef restoration projects? ( ) Yes, ( ) No.

23.1 If so, in which ones?

Block 5: Citizen science

24. Have you heard of the concept "citizen science"? ( ) Yes, ( ) No.

24.1 If so, the first time you heard the term citizen science was in this project?( ) Yes, ( ) No.

25. What do you understand by "citizen science"?

26. Are you part of other citizen science program? ( ) Yes, ( ) No.

26.1 If so, in which ones?

Block 6: Restoration and citizen science on the Ocotal reef

27. In which of the following activities have you participated in within the Ocotal reef restoration and citizen science project? ( ) Training workshops, ( ) Educational talks, ( ) Coral planting, ( ) Structure maintenance, ( ) Biological monitoring.

28. How many times have you participated in restoration or monitoring activities on the Ocotal reef?

29. In which month did you start participating in restoration or monitoring activities on the Ocotal reef?

30. Of all the activities you have participated in, which ones do you prefer? ( ) Training workshops, ( ) Educational talks, ( ) Coral planting, ( ) Structure maintenance, ( ) Biological monitoring.

31. Besides the activities you have already participated in, what other ones would you like to join? ( ) Educational talks, ( ) Data processing, ( ) Social media management, ( ) Photographing, ( ) Photo analysis, Funding search, ( ) Field trip logistics, ( ) Water sampling, ( )Sensor installation, ( ) Structure maintenance, ( )Biological monitoring, ( ) Training workshops, ( ) Coral planting, ( )Database management, ( ) Methodology search, ( ) Other

32. If you have participated in the biological monitoring, place the order of your preference for carrying out the protocols (1 being the one you feel most comfortable doing and 3 being the one you feel least comfortable doing). ( ) Fish census, ( ) Sea urchin census, ( ) Substrate census, ( ) Without participation

33. On a scale of 1 to 5, how do you consider your level of commitment to the Ocotal reef restoration and citizen science project? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

34. Do you think your level of knowledge regarding coral reefs has changed since you started the Ocotal reef restoration and citizen science project? ( ) Yes, ( ) No.

35. On a scale from 1 to 5, how do you consider your knowledge about coral reefs was before you participated in the Ocotal reef restoration and citizen science project? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

36. On a scale from 1 to 5, how do you consider your knowledge about coral reefs now?( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

37. On a scale of 1 to 5, do you think that diving activities have been carried out safely? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

38. Which aspects do you consider to be priorities for carrying out diving activities safely? ( ) Presence of dive masters, ( ) Use of buoys, ( ) Diving from a boat, ( ) Presence of rescue divers, ( ) Medical check-ups, ( ) First aid courses, ( ) Briefing prior to diving, ( ) Other

39. In general, on a scale of 1 to 5, how do you consider the development of the Ocotal reef restoration and citizen science project? ( ) 1, ( ) 2, ( ) 3, ( ) 4, ( ) 5.

40. Do you have any comments or observations that you would like to make in order to improve the project?

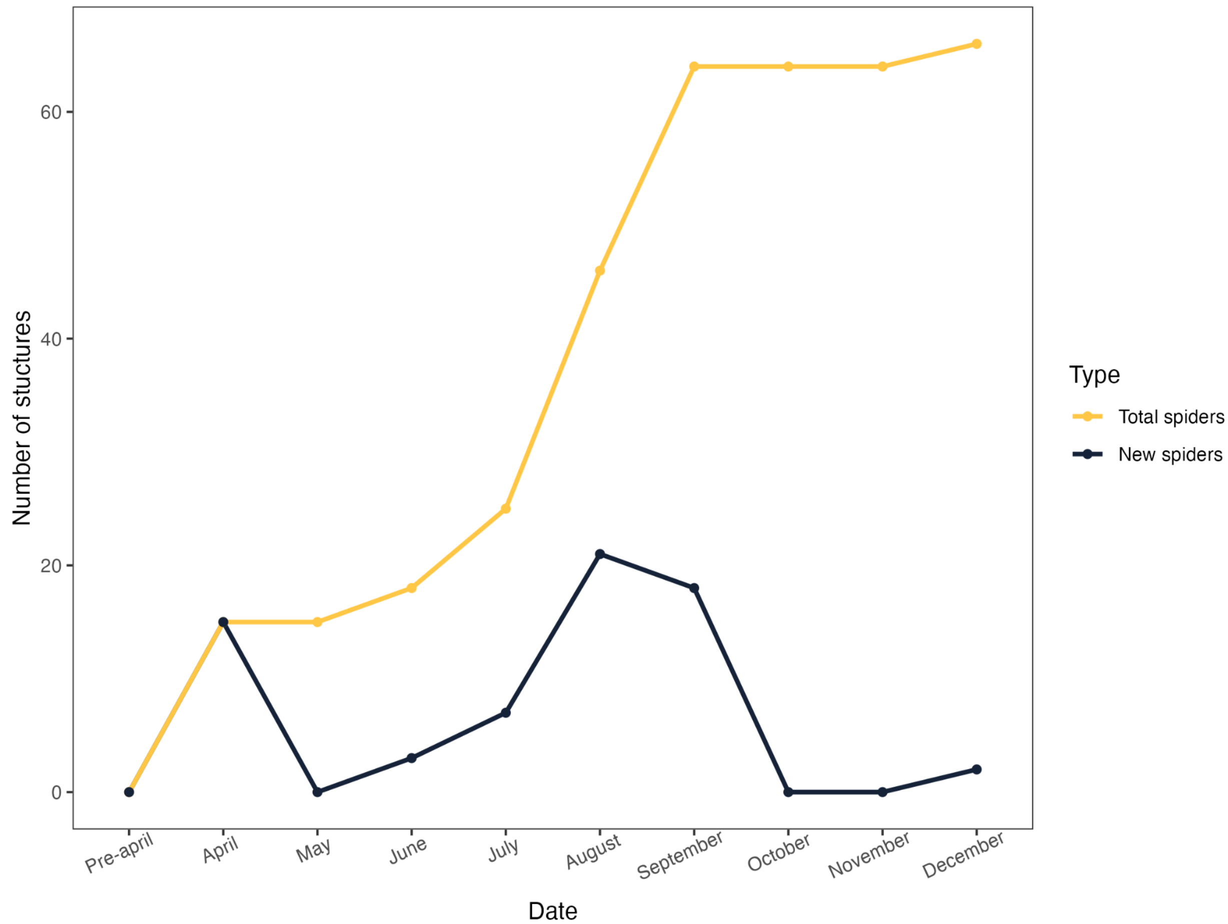

Figure S4. Number of spider-like structures, filled with *Pocillopora* fragments, in the Ocotal restoration site.

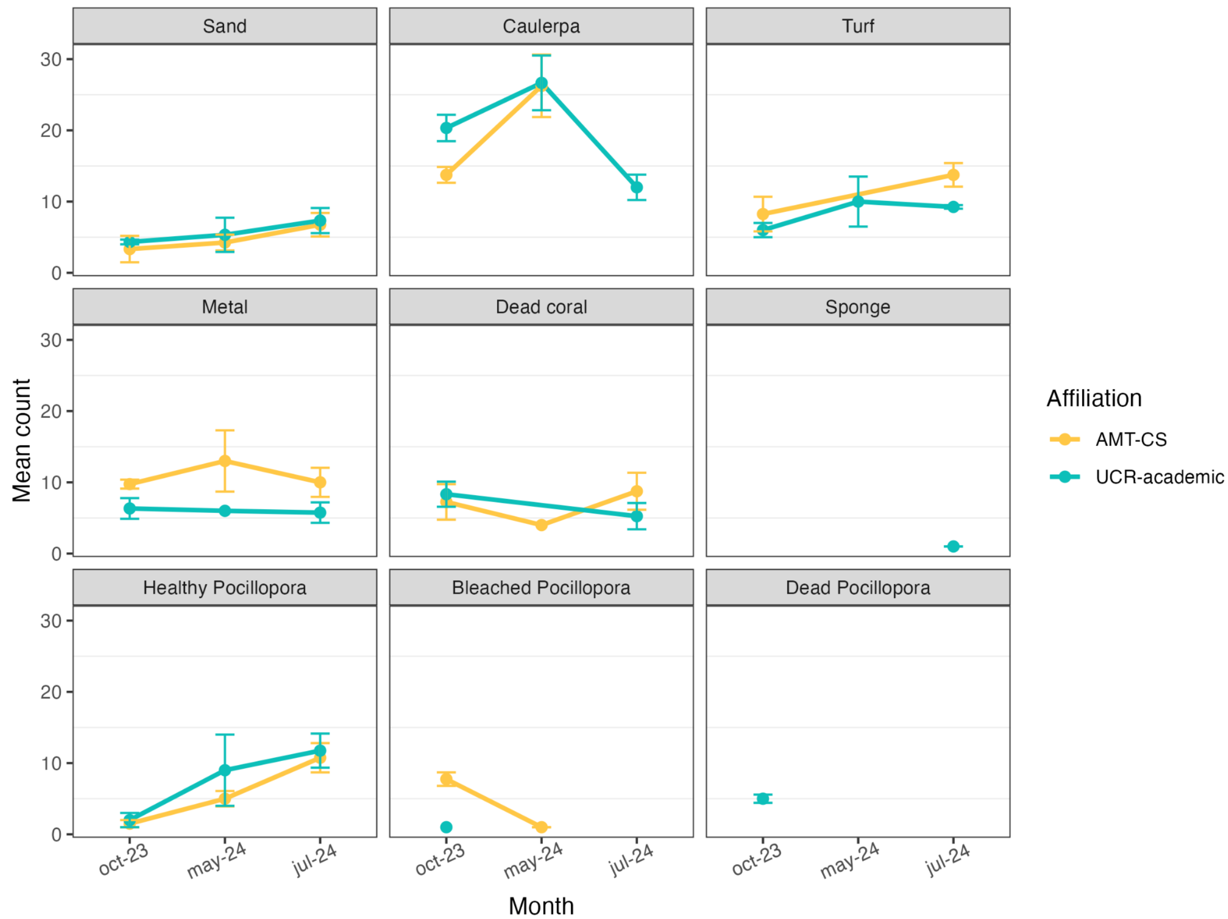

Figure S5. Average counts (±standard error) of nine different substrate types, across three different survey dates, recorded by citizen scientists in the Ocotal Bay coral reef restoration site.

Table S3. Results of the PERMANOVA and ANOSIM test for the substrate composition identification done by citizen and academic scientist in the restoration site of Ocotal Bay.

Statistical test	Evaluated factors	R/R^2 statistics	F-value	p-value
PERMANOVA	Date	$R^2 = 0.518$	F = 20.481	p = 0.001
PERMANOVA	Affiliation	$R^2 = 0.090$	F = 7.100	p = 0.001
PERMANOVA	Date-Affiliation	$R^2 = 0.189$	F = 7.486	p = 0.001
ANOSIM	Date	R = 0.081	-	p = 0.13
ANOSIM	Affiliation	R = 0.700	-	p = 0.001
ANOSIM	Date-Affiliation	R = 0.900		p = 0.001

Bray-Curtis dissimilarity matrix was used and $\log_{10}$ (x+1) transformation were done prior to the test application.

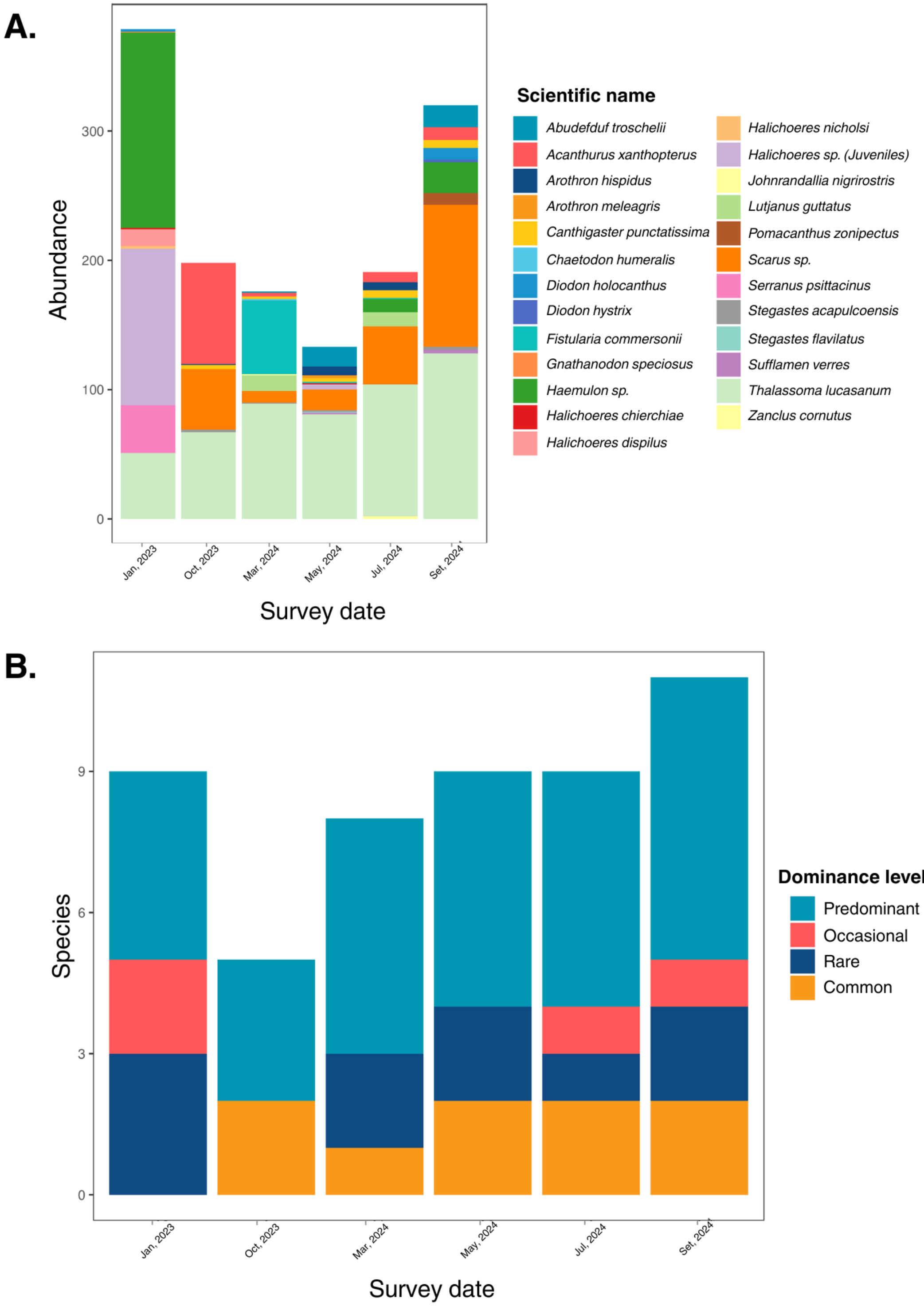

Figure S6. Fish census performed by the academic team in the restoration site on different survey dates. **A.** Total abundance of reef species. **B.** Count of species classified based on specific occurrence and relative average density.

Table S4. Species dominance classification based on the specific occurrence and relative average densities.

Species	**Dominance**	**Frequency**	**Occurrence**
Abudefduf troschelii	Predominant	11	3
Acanthurus xanthopterus	Predominant	6.5	4
Arothron hispidus	Common	3.5	2
Arothron meleagris	Rare	2	1
Canthigaster punctatissima	Common	3	4
Chaetodon humeralis	Rare	1	1
Diodon holocanthus	Predominant	5.5	2
Diodon hystrix	Rare	2	1
Fistularia commersonii	Predominant	19.67	3
Gnathanodon speciosus	Rare	1	1
Haemulon sp.	Predominant	61.3	3
Halichoeres chierchiae	Rare	1	1
Halichoeres dispilus	Occasional	13	1
Halichoeres nicholsi	Rare	2	1
Halichoeres (juveniles)	Predominant	**62.5**	2
Johnrandallia nigrirostris	Rare	1	1
Lutjanus guttatus	Occasional	11	1
Pomacanthus zonipectus	Occasional	9	1
Scarus spp.	Predominant	38.2	5
Serranus psittacinus	Occasional	37	1
Stegastes acapulcoensis	Common	1.67	3
Stegastes flavilatus	Rare	1	1
Sufflamen verres	Rare	3	1
Thalassoma lucasanum	Predominant	57.83	**6**
Zanclus cornutus	Rare	2	1

In bold: The highest value for frequency and occurrence.

Table S5. Average coverage (±standard error) of healthy, bleached, dead and total areas of the *Pocillopora* fragments attached to the 66 spider-like structures placed in the restoration site of Ocotal Bay.

Date	Healthy coral (cm^2)	Bleached coral (cm^2)	Dead coral (cm^2)	Total area (cm^2)
May-23	**469.74 ± 34.57**	0.00 ± 0.00	0.00 ± 0.00	469.74 ± 34.57
Aug-23	**675.05 ± 62.77**	3.18 ± 1.86	1.21 ± 0.78	679.45 ± 63.17
Set-23	229.67 ± 19.01	**373.93 ± 49.11**	0.00 ± 0.00	603.60 ± 50.21
Oct-23	76.09 ± 11.21	**542.34 ± 51.95**	5.42 ± 1.48	621.28 ± 56.66
Nov-23	73.04 ± 12.03	**478.58 ± 51.37**	9.94 ± 4.24	561.56 ± 57.55
Dec.Pre-23	178.98 ± 20.53	**376.56 ± 51.77**	32.03 ± 20.30	587.57 ± 59.52
Dec.Post-23	216.86 ± 22.64	**361.50 ± 50.79**	30.75 ± 19.50	609.11 ± 58.43
Feb-24	**353.65 ± 27.55**	24.90 ± 4.93	3.18 ± 1.51	381.73 ± 28.46
Mar-24	**496.40 ± 42.77**	4.22 ± 1.44	3.61 ± 1.92	504.23 ± 42.48
May-24	**623.12 ± 47.81**	0.00 ± 0.00	0.00 ± 0.00	623.12 ± 47.81
Jul-24	**867.91 ± 46.56**	0.51 ± 0.39	1.04 ± 0.59	869.46 ± 46.57

In bold: Highest values per month. December 2023 has two values since an outplant event took place.

Table S6. Pairwise comparisons of estimated marginal means (EMS) applied to identify differences in each coral health status across survey dates in 66 spider-like structures placed in the restoration site of Ocotal Bay.

Healthy coral											
	May 23	Aug 23	Set 23	Oct 23	Nov 23	Dec-pre 23	Dec-post 23	Feb 24	Mar 24	May 24	Jul 24
May 23	*										
Aug 23	-255.269 **0.0006**	*									
Set 23	158.760 0.1399	414.029 **<.0001**	*								
Oct 23	315.864 **<.0001**	571.134 **<.0001**	157.105 **0.0003**	*							
Nov 23	319.838 **<.0001**	575.107 **<.0001**	161.078 **0.0004**	3.973 1.0000	*						
Dec-pre 23	220.449 **0.0057**	475.718 **<.0001**	61.689 0.8501	-95.415 0.2626	-99.389 0.2509	*					
Dec-post 23	179.934 0.0607	435.203 **<.0001**	21.174 1.0000	-135.931 **0.0098**	-139.904 0.0104	-40.515 0.9939	*				
Feb 24	29.493 1.0000	284.762 **<.0001**	-129.267 **0.0078**	-286.372 **<.0001**	-290.345 **<.0001**	-190.956 **<.0001**	-150.441 **0.0018**	*			
Mar 24	-106.149 0.7348	149.120 **0.0082**	-264.909 **<.0001**	-422.013 **<.0001**	-425.986 **<.0001**	-326.598 **<.0001**	-286.082 **<.0001**	-135.641 **0.0077**	*		
May 24	-254.011 **0.0006**	1.258 1.0000	-412.771 **<.0001**	-569.876 **<.0001**	-573.849 **<.0001**	-474.460 **<.0001**	-433.945 **<.0001**	-283.504 **<.0001**	-147.863 **0.0077**	*	
Jul 24	-480.564 **<.0001**	-225.295 **<.0001**	-639.324 **<.0001**	-796.428 **<.0001**	-800.402 **<.0001**	-701.013 **<.0001**	-660.498 **<.0001**	-510.057 **<.0001**	-374.416 **<.0001**	-226.553 **<.0001**	*
Bleached coral											
	May 23	Aug 23	Set 23	Oct 23	Nov 23	Dec-pre 23	Dec-post 23	Feb 24	Mar 24	May 24	Jul 24
May 23	*										
Aug 23	-53.142 0.9979	*									
Set 23	-455.240	-402.098	*								

	<.0001	**<.0001**									
Oct 23	-620.126 **<.0001**	-566.985 **<.0001**	-164.887 **0.0001**	*							
Nov 23	-555.451 **<.0001**	-502.309 **<.0001**	-100.211 0.1614	64.675 0.7826	*						
Dec-pre 23	-446.873 **<.0001**	-393.731 **<.0001**	8.367 1.0000	173.254 **0.0002**	108.578 0.1450	*					
Dec-post 23	-434.444 **<.0001**	-381.302 **<.0001**	20.796 1.0000	185.683 **<.0001**	121.007 0.0546	12.429 1.0000	*				
Feb 24	-111.497 0.6445	-58.355 0.9082	343.743 **<.0001**	508.629 **<.0001**	443.954 **<.0001**	335.376 **<.0001**	322.947 **<.0001**	*			
Mar 24	-83.713 0.9272	-30.572 0.9995	371.526 **<.0001**	536.413 **<.0001**	471.738 **<.0001**	363.159 **<.0001**	350.731 **<.0001**	27.784 0.9995	*		
May 24	-100.635 0.8138	-47.493 0.9870	354.605 **<.0001**	519.492 **<.0001**	454.816 **<.0001**	346.238 **<.0001**	333.809 **<.0001**	10.862 1.0000	-16.921 1.0000	*	
Jul 24	-82.913 0.9257	-29.771 0.9995	372.327 **<.0001**	537.213 **<.0001**	472.538 **<.0001**	363.960 **<.0001**	351.531 **<.0001**	28.584 0.9992	0.800 1.0000	17.721 1.0000	*
Dead coral											
	May 23	Aug 23	Set 23	Oct 23	Nov 23	Dec-pre 23	Dec-post 23	Feb 24	Mar 24	May 24	Jul 24
May 23	*										
Aug 23	-51.174 0.9985	*									
Set 23	-81.310 0.9323	-30.136 0.9994	*								
Oct 23	-83.211 0.9223	-32.037 0.9991	-1.901 1.0000	*							
Nov 23	-86.802 0.9085	-35.628 0.9982	-5.492 1.0000	-3.591 1.0000	*						
Dec-pre 23	-102.337 0.7872	-51.163 0.9745	-21.027 1.0000	-19.126 1.0000	-15.535 1.0000	*					
Dec-post 23	-103.690 0.7682	-52.516 0.9674	-22.380 0.9999	-20.479 1.0000	-16.887 1.0000	-1.353 1.0000	*				

Feb 24	-89.778 0.8758	-38.604 0.9952	-8.468 1.0000	-6.567 1.0000	-2.975 1.0000	12.560 1.0000	13.912 1.0000	*			
Mar 24	-83.109 0.9305	-31.935 0.9993	-1.799 1.0000	0.102 1.0000	3.694 1.0000	19.229 1.0000	20.581 1.0000	6.669 1.0000	*		
May 24	-100.635 0.8138	-49.461 0.9823	-19.325 1.0000	-17.424 1.0000	-13.832 1.0000	1.702 1.0000	3.055 1.0000	-10.857 1.0000	-17.526 1.0000	*	
Jul 24	-83.437 0.9228	-32.263 0.9991	-2.127 1.0000	-0.226 1.0000	3.365 1.0000	18.900 1.0000	20.253 1.0000	6.341 1.0000	-0.328 1.0000	17.198 1.0000	*

Bold indicates statistical differences and the colored squares refer to the consecutives survey dates. December 2023 has two values since an outplant event took place.

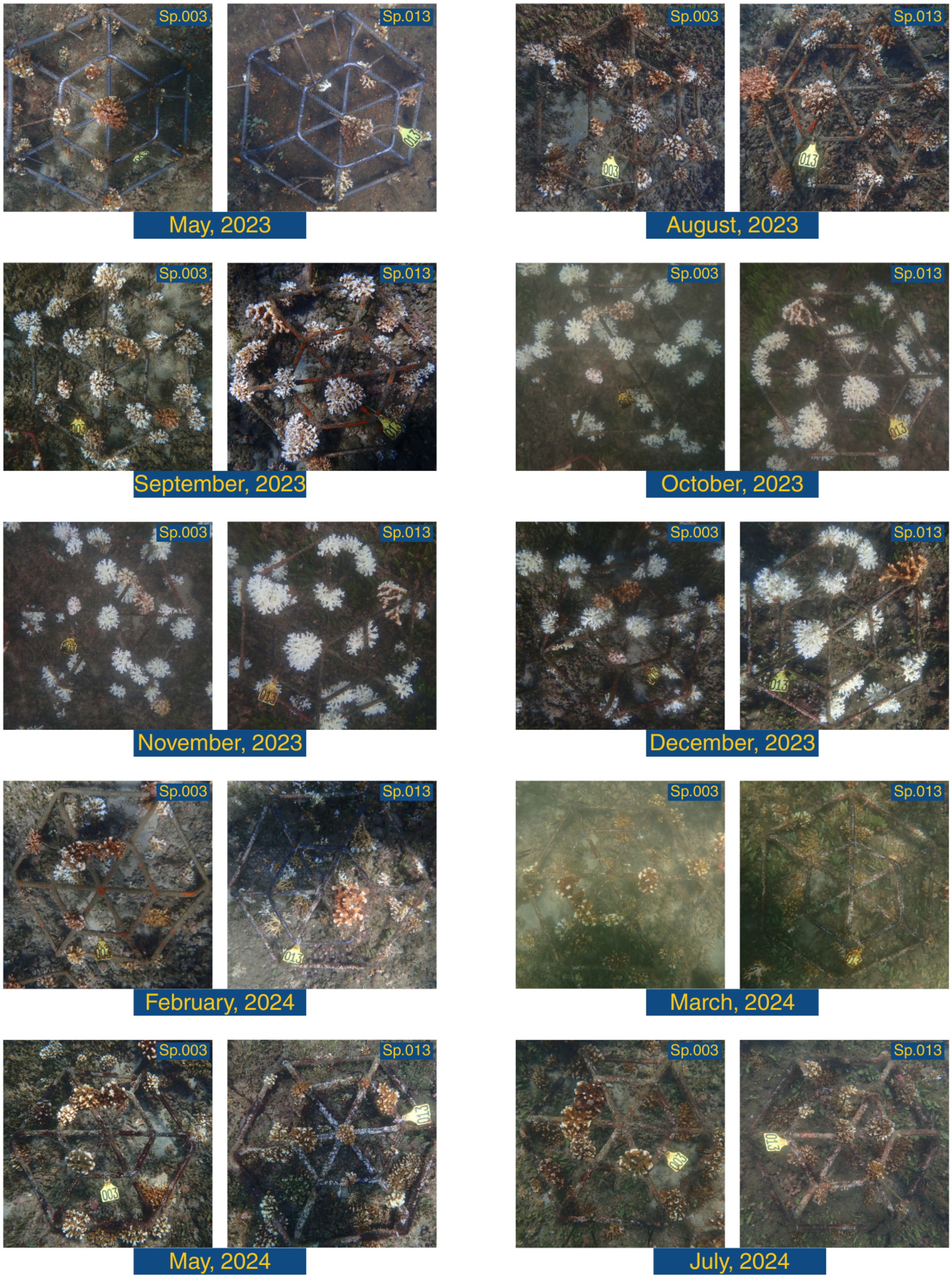

Figure S7. Photographs of the spider-like structures (e.g. 003 and 013) filled with *Pocillopora* fragments, placed in Ocotal's coral reef for its restoration.

Table S7. Coverage percentages (%) (±standard error) determined for the corals attached to spider-like stainless steel structures used for the restoration of the Ocotal's coral reef.

Date	Healthy	Bleached	Dead	Number of structures
May-23	**100.00 (± 10.41)**	0.00 (--)	0.00 (--)	15
Aug-23	**99.35 (± 13.06)**	0.47 (± 0.28)	0.18 (± 0.12)	46
Set-23	38.05 (± 4.46)	**61.95 (± 9.63)**	0.00 (--)	64
Oct-23	12.25 (± 2.12)	**87.29 (± 11.54)**	0.87 (± 0.25)	64
Nov-23	13.01 (± 2.52)	**85.22 (± 12.65)**	1.77 (± 0.78)	64
Dec.Pre-23	30.46 (± 4.66)	**64.09 (± 10.94)**	5.45 (± 3.50)	64
Dec.Post-23	35.60 (± 5.05)	**59.35 (± 10.10)**	5.05 (± 3.24)	66
Feb-24	**92.64 (± 9.99)**	6.52 (± 1.38)	0.83 (± 0.40)	66
Mar-24	**98.45 (± 11.86)**	0.84 (± 0.29)	0.72 (± 0.39)	66
May-24	**100.00 (± 10.85)**	0.00 (--)	0.00 (--)	66
Jul-24	**99.82 (± 7.57)**	0.06 (± 0.04)	0.12 (± 0.07)	66

In bold: Highest values per month. December 2023 has two values since an outplant event took place.
In bold: Highest values per month.

Table S8. Pairwise comparisons of estimated marginal means (EMS) applied to identify differences in the coral health status at each survey date.

	Coral status interactions		
	Healthy - Bleached	**Healthy - Dead**	**Bleached - Dead**
May 23	469.742 **<.0001**	469.742 **<.0001**	0.000 1.0000
Aug 23	671.869 **<.0001**	673.837 **<.0001**	1.968 0.9987
Set 23	-144.257 **0.0001**	229.672 **<.0001**	373.930 **<.0001**
Oct 23	-466.249 **<.0001**	70.667 0.1034	536.915 **<.0001**
Nov 23	-405.546 **<.0001**	63.102 0.2067	468.649 **<.0001**
Dec-pre 23	-197.579 **<.0001**	146.956 **0.0005**	344.536 **<.0001**
Dec-post 23	-144.635 **0.0005**	186.119 **<.0001**	330.754 **<.0001**
Feb 24	328.752 **<.0001**	350.472 **<.0001**	21.719 0.7998
Mar 24	492.177 **<.0001**	492.782 **<.0001**	0.605 0.9999
May 24	623.119 **<.0001**	623.119 **<.0001**	0.000 1.0000
Jul 24	867.393 **<.0001**	866.869 **<.0001**	-0.524 0.9999

In bold: relations with statistical differences.

December 2023 has two values since an outplant event took place.

Table S9. Social features related to economy, water skills and experiences in coral restoration and citizen science of the volunteers of the citizen science program for the biological monitoring and coral reef restoration in Ocotal Bay

Economic features				
Working activities				
Private enterprise		4		
Self-employed		5		
Non-govermental organizations		1		
Domestic labor		1		
Goverment institution		5		
Other		4		
Working activities related to science				
Yes		8		
No		8		
Income **				
~$ 695		1		
~$ 695 – ~$ 955		0		
~$ 955 – ~$ 1485		1		
~$ 1485 – ~$ 1980		1		
~$ 1980 – ~$ 2970		2		
~$ 2970 – ~$ 3960		3		
More than $ 3960		5		
No income		1		
Prefers not to answer		2		
Economic dependency of marine ecosystems				
Main source of income				
	Yes	6		
	No	10		
Secondary source of income				
	Yes	5		
	No	11		
Water skills				
		Perceived skills*		
Swimming (n = 15)		4.53 ± 0.23		
Snorkeling (n = 15)		4.73 ± 0.15		
Scuba diving (n = 14)		4.27 ± 0.21		
	Scuba diving certifications			
	Open water	3		
	Advanced Open Water Diver	4		
	Rescue diver	3		
	Dive master	1		
	Instructor	2		
	Instructor's instructor	1		
Diving immersions				
	Last year	**n**	**Total**	**n**
	0-10	3	0 - 20	1

	20-30	5	20 - 50	4
	30-40	0	50 - 100	2
	More than 40	6	100 - 200	1
			200 - 500	2
			More than 500	4
Coral reef restoration previous experiences				
Participation in other projects			**Number of projects**	
Yes	8		2.4 ± 0.44	
No	8			
			Mean (±SE) *	
Necessity of restoration			4.94 ± 0.06	
Citizen science previous experiences				
Participation in other projects				
Yes		4		
No		0		
Ocotal coral reef-citizen science experience				
Longevity in the project	7.56 ± 0.45 (SE) months			
Min		1		
Max		14		
Number of activities	8.13 ± 0.82 (SE) activities			
Min		1		
Max		27		
Monitoring experience (n = 10)				

	First preference	**Second preference**	**Third preferenc e**
Fish census	9	1	0
Substrate census	1	5	4
Sea urchins census	0	4	6

* Volunteers were asked for their perceived skills or values on a 1 (lower) – to 5 (highest) scale.

** A conversion from costarican colones was applied to USD, the exact value might change based on exchange currency.

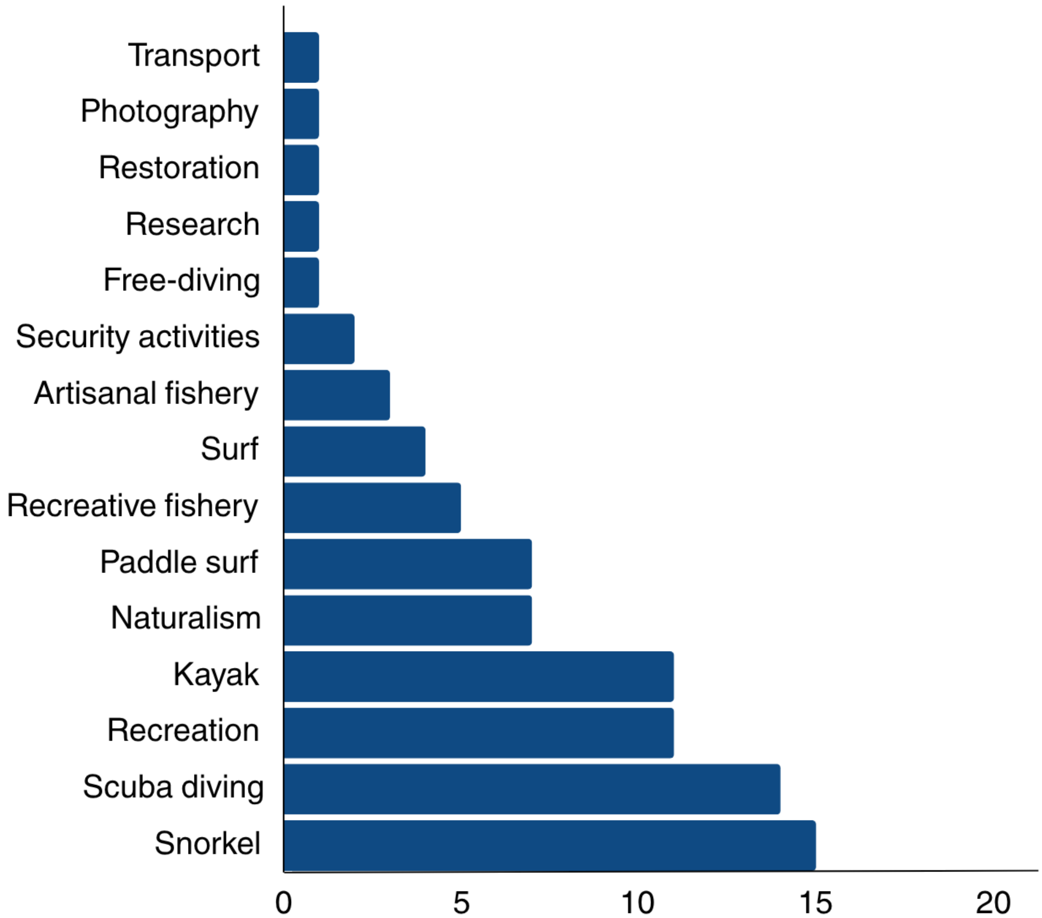

Figure S8. Count of the activities performed in marine environments by volunteers of the citizen science program for the biological monitoring and coral reef restoration in Ocotal Bay.

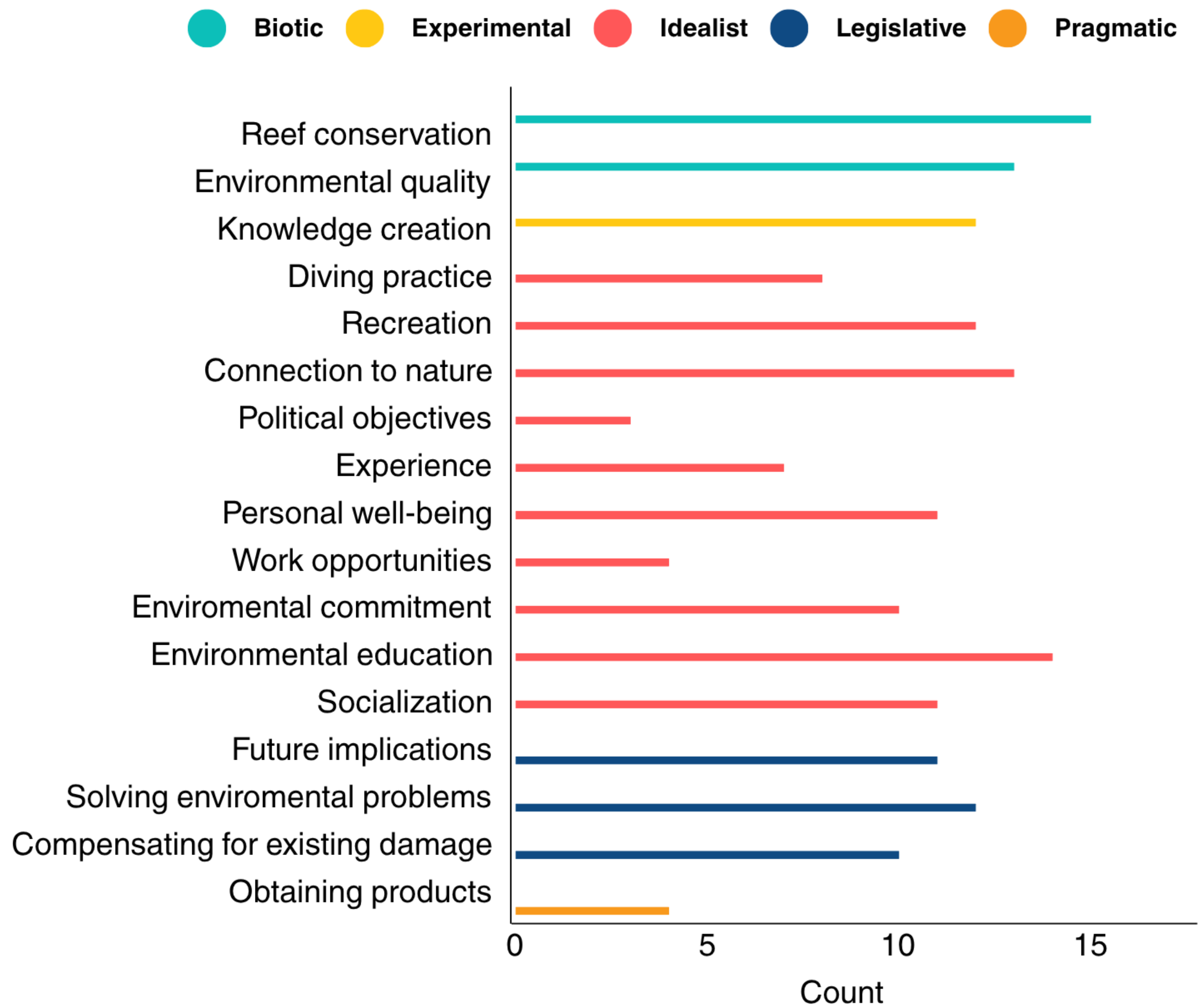

Figure S9. Count of the declared motivations by the volunteers (n = 16) of the citizen science program for the biological monitoring and coral reef restoration in Ocotal Bay, classified based on the Bayraktarov et al. (2020) framework.

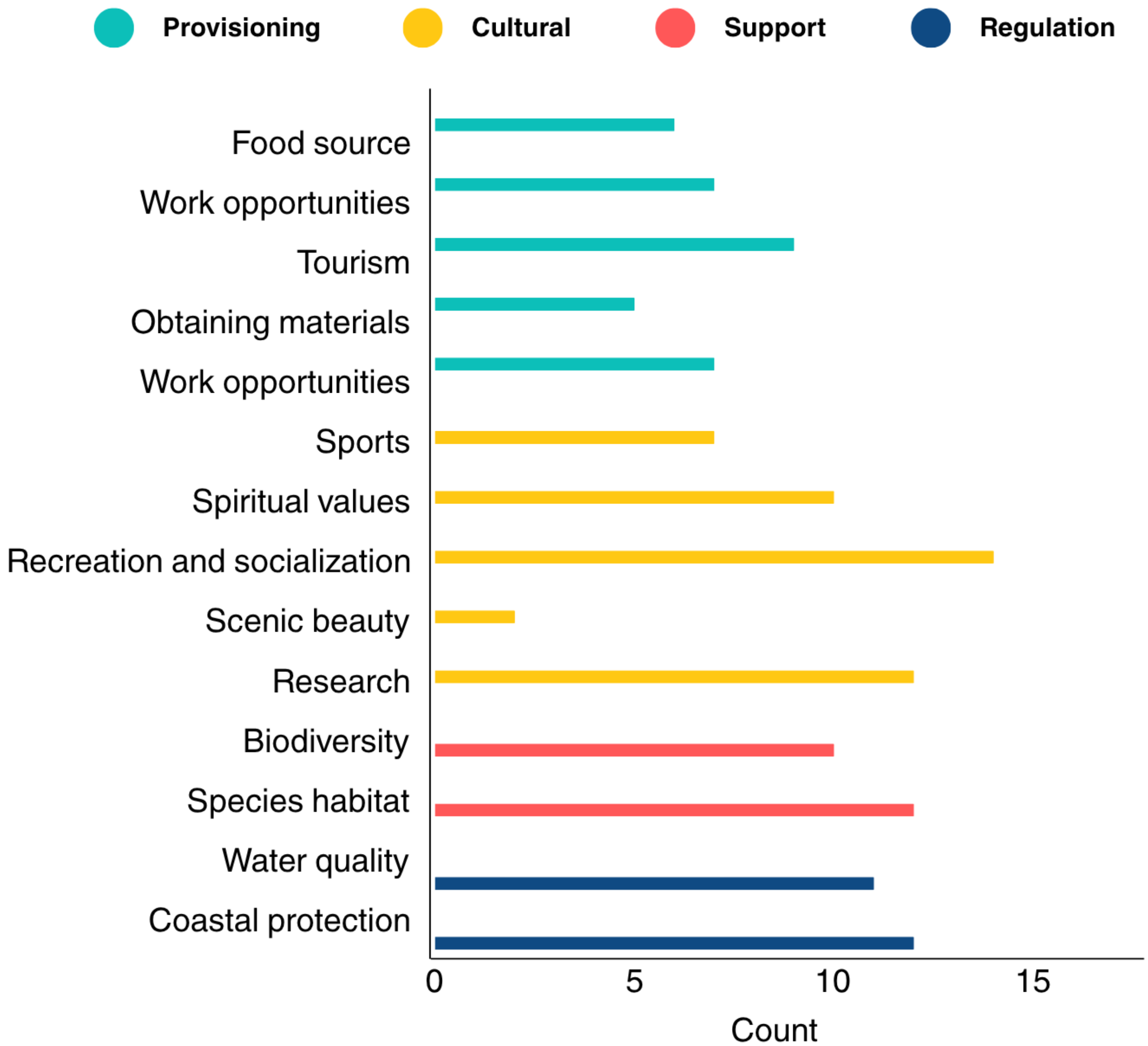

Figure S10. Count of the perceived ecosystemic services by the volunteers (n = 16) of the citizen science program for the biological monitoring and coral reef restoration in Ocotal Bay.

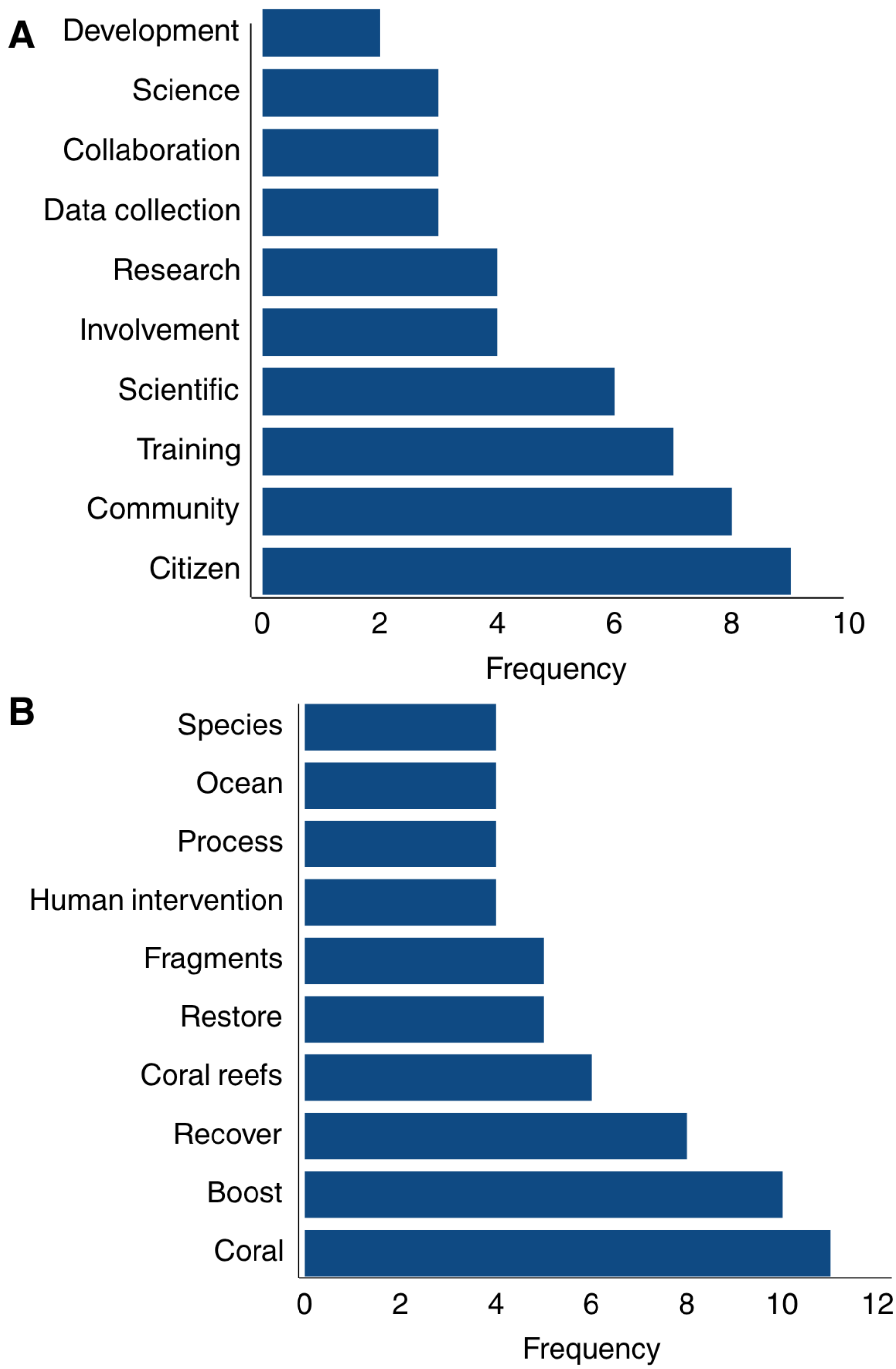

Figure S11. Word frequency of the concepts of A. "citizen science" and B. "coral restoration" described by volunteers of the citizen science program for the biological monitoring and coral reef restoration in Ocotal Bay.

CONCLUSIONES

Esta tesis permitió abordar desde una perspectiva teórica y práctica el uso de la CC como una herramienta para integrar a las comunidades humanas no-científicas en procesos de investigación, los cuales catalizan la gestión integrada de zonas costeras y la conservación de ambientes marinos. El primer capítulo permitió entender patrones en los proyectos, e investigación en CC marina, así como permitir caracterizar la participación que los científicos ciudadanos tuvieron en estos programas. Se ilustró el incremento en la publicación de literatura científica relacionada a la CC marina, movilizada por un mejor entendimiento de los efectos de los estresores ambientales en los ecosistemas y la vida humana, y una mayor intervención de las comunidades y organizaciones no gubernamentales en procesos de este tipo. Las regiones más extensamente estudiadas contaban con sitios de alta diversidad, una estructura científica establecida y un contexto socioeconómico adecuado para sostener este tipo de proyectos. Factores como colaboración entre academia y científicos ciudadanos, uso de tecnologías y metodologías de colaboración contribuyen a mejorar la calidad de los datos obtenidos, permitir un reanálisis de los datos obtenidos y validar el uso de CC en diferentes investigaciones. El atractivo, importancia en los ecosistemas, vulnerabilidad y disponibilidad de tecnologías determinaron los grupos estudiados a lo largo del tiempo. El capital humano y alta presencia en campo movilizaron la mayor cantidad de estudios. Los sitios más altamente estudiados fueron aquellos que contaban con cercanía a sitios urbanos, alto valor estético y facilidad de acceso.

A lo largo del tiempo los roles que cumplen los científicos ciudadanos han incrementado y se han diversificado, indicando un cambio y una mayor apropiación por parte de los ciudadanos de este tipo de investigaciones. El cambio en el reporte de las implicaciones que tiene la CC en la conservación implican una mayor confianza en este tipo de iniciativas para la toma de decisiones basadas en ciencia y mayor involucramiento comunitario, para solventar problemáticas ambientales en ecosistemas marinos. La CC complementa las metodologías tradicionales, brindando una plataforma para la participación social en investigaciones científicas. Garantizar la sostenibilidad de los proyectos es requerido para que perduren en el tiempo.

En el segundo capítulo se desarrolló un estudio de caso de la aplicación de ciencia ciudadana en un proceso de restauración coralina en el arrecife coralino degradado de Ocotal, ubicado en el Pacífico Norte de Costa Rica. El proyecto permitió involucrar diversidad de actores involucrados en la conservación y restauración de arrecifes coralinos. Los corales que actualmente se encuentran en el arrecife de Ocotal fueron capaces de sobrellevar las condiciones extremas de temperatura que se dieron durante el 2023; a pesar del impacto en el estado de los corales, se duplicó el área promedio de las estructuras a lo largo del periodo estudiado. Se identificaron dificultades en la aplicación de los protocolos de monitoreo por parte de los voluntarios; sin embargo, la constancia en la participación de los voluntarios y el refrescamiento de protocolos mejora la habilidad de los voluntarios de ejecutar adecuadamente el monitoreo biológico. El entrenamiento a largo plazo y diversificación de estrategias para mantener el compromiso de los voluntarios deben ser aplicadas. El involucramiento en este proceso alteró el entendimiento de los voluntarios con respecto a valores sociales de los arrecifes coralinos y su rehabilitación. La participación ciudadana en procesos de restauración fortalece los esfuerzos globales de rehabilitar arrecifes resilientes que puedan sobrellevar los escenarios actuales y futuros.

CONCLUSIONS

This thesis addressed, from a theoretical and practical perspective, the use of CS as a tool to integrate non-scientific human communities into research processes that catalyze integrated coastal zone management and the conservation of marine environments. The first chapter shed light on patterns in marine CC projects and research, as well as characterized the participation of citizen scientists in these programs. It illustrated the increase in the publication of scientific literature related to marine CC, driven by a better understanding of the effects of environmental stressors on ecosystems and human life, and greater involvement of communities and non-governmental organizations in these processes. The most extensively studied regions had sites of high diversity, an established scientific infrastructure, and a socioeconomic context suitable for supporting these types of projects. Factors like collaboration between academia and citizen science, use of technology and verifying methods contribute to improving the quality of the data obtained, enabling reanalysis of the obtained data, and validating the use of CC in different research projects. Attractiveness, importance in ecosystems, vulnerability, and availability of technologies determined the groups studied over time. Human capital and high field presence promoted the highest number of studies. The most intensively studied sites were those close to urban sites, with high aesthetic value, and easy access. Over time, citizen scientists roles have increased and diversified, indicating a shift and greater citizen ownership of this type of research. The change in the reports of the implications that CS has on conservation implies greater trust in these types of initiatives for science-based decision-making and greater community involvement, to solve environmental problems in marine ecosystems. CS complements traditional methodologies, providing a platform for social participation in scientific research. Ensuring the sustainability of these projects is essential for their long-term sustainability.

The second chapter presents a case study of the application of citizen science in a coral restoration process on the degraded Ocotal coral reef, located in the North Pacific of Costa Rica. The project enabled the involvement of a variety of stakeholders involved in coral reef conservation and restoration. The corals currently on the Ocotal reef were able to withstand the extreme temperature conditions that occurred during 2023; despite the impact on the corals' health, the average area of the structures doubled over the study period. Difficulties were identified in the application of monitoring protocols by volunteers; however, consistent volunteer participation and protocol refreshers improve their ability to properly perform biological monitoring. Long-term training and diversified strategies to maintain volunteer engagement should be implemented. Involvement in this CS process altered volunteers' understanding of social values of coral reefs and their restoration. Citizen participation in restoration processes strengthens global efforts to rehabilitate resilient reefs that can withstand current and future scenarios.