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Outreach and citizen science for coral reef conservation and restoration

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Abstract

Coral reefs are among the most biodiverse ecosystems on Earth and provide essential ecosystem services to millions of people. However, they face escalating local and global disturbances that threaten their existence, with scleractinian corals, the primary reef builders, among the most endangered marine organisms. Addressing this environmental crisis requires multidisciplinary and innovative approaches that integrate top-down conservation strategies with meaningful public engagement. Despite its potential, the role of non-professionals in advancing coral reef science and conservation remains partly untapped. On one hand, citizen science can help answer scientific questions when the scale, timeframe, or remoteness of the research make it impossible for experts to gather data themselves, whilst also providing an opportunity for fostering ocean knowledge. On the other hand, scientists can reduce the gap between science and society through outreach to connect with the global community and help the general public make informed decisions that can influence the sustainable development of the planet for future generations

This PhD thesis developed and evaluated two novel public-engagement initiatives through citizen science and outreach to address an understudied scientific question and to test an innovative approach to fostering environmental awareness.

The first project, Map the Giants, was designed from the ground up as a global citizen science initiative to identify exceptionally large coral colonies (>5 m linear length), defined as giant corals. These may represent centennial, ecologically valuable organisms, serving as living archives of historical oceanic conditions and, from a cultural standpoint, functioning as symbols of resistance and conservation. The open nature of the repository is intended to enable scientists across different fields to conduct independent and multidisciplinary studies and represents an outreach tool to connect with non-professionals. From its launch, the project reached a global diffusion, receiving 195 submissions from 22 countries, of which 133 were validated and included in a publicly accessible database. Structure from Motion photogrammetry was employed to generate 14 three-dimensional models of coral colonies, extract morphological features, and create a high-definition archive for research and dissemination. These results demonstrate the feasibility and scientific value of citizen science for documenting rare organisms over large-scale.

The second project, Playing with Corals, aimed to foster environmental awareness by integrating coral reef restoration with football-based activities. By leveraging the popularity of football, the project engaged and formed local trainers and about 100 students between 10 and 14 through play to enhance ocean connectedness and promote stewardship of the marine environment. Football training sessions were designed to support children's personal development, while reef restoration served as a tool to bridge the gap between participants and the ocean through a place-based experience that would help children gain greater confidence in the water, foster a sense of responsibility toward reefs, and expose them to potential future careers. The pilot study identified key challenges and opportunities to support the development of a replicable model suitable for expansion within the Maldives and other Small Island States. Together, these projects demonstrate that public participation can effectively contribute to both coral reef research and conservation-oriented education, highlighting its potential as a foundational component of future marine conservation strategies.

Chapter 1

1.1 Introduction

1.1.1 Coral reefs' status and threats

Warm water coral reefs are found throughout the tropical coastal areas of the world, located in a narrow band within the tropics, they cover less than 0.1% of the ocean's surface (Spalding et al., 2001; Spalding & Grenfell, 1997), corresponding to an estimated 348,361 km^2 of shallow coral reefs. About one quarter of this surface is suitable for supporting a significant amount of corals, providing hard substrate for their settlement (Lyons et al., 2024). There are two main regions where corals are distributed: the Atlantic (the wider Caribbean) and the Indo-Pacific, which extends from the Red Sea to the Central Pacific Ocean.

Coral reefs are among the most biodiverse ecosystems on Earth (Fisher et al., 2015; Heywood et al., 1995; Hoeksema, 2017), with invertebrates making up the majority of reef biodiversity (Stella et al., 2011). Estimates of the global number of coral reef species report around 830,000 (95% credible limits: 550,000-1,330,000) multi-cellular species, with the exclusion of fungi. Over one quarter of the known and named marine species are found on reefs, but less than 10% of all multi-cellular species on coral reefs have been named, and many still await to be discovered (Fisher et al., 2015). In fact the research, and species description tend to focus on the most conspicuous groups: vertebrates (fish, mammals, reptiles) and corals, with fewer studies on cryptic organisms (Stella et al., 2011).

Scleractinian corals represent reefs' main building blocks. Among over 1,300 different species of hard corals (Cairns, 1999), the majority of biodiversity is found in the Indo-Pacific region, with fewer in the Atlantic. Numerous forms of symbioses occur between corals and many other organisms, playing an important role in the ecology and evolution of both hosts and symbionts (Blackall et al., 2015). From organisms such as crabs, sponges, algae, fish, seastars, worms living in proximity, above or within corals, to microscopic ecto-, epi-, and endo-symbionts often playing a role in the biology and physiology of the coral colony (Blackall et al., 2015). The numerous associations can have direct consequences for the positive and negative fates of coral colonies, often influencing responses to external factors such as disease, resilience (Blackall et al., 2015; Montano et al., 2017; Montano, 2020), or predation (Glynn & Enochs, 2011).

Most scleractinian corals are reef-building organisms, capable of generating structures visible from satellites and land masses, suitable for people's lives (Yamano et al., 2005). Around 200 million people live in close proximity to the reefs within 10m of elevation and 50km of distance (Ferrario et al., 2014), depending on this ecosystem for various aspects. Studies have estimated that the global economic value of reefs is around US$10 trillion per year (Costanza et al., 2014), as they provide numerous ecosystem services arising from the interactions between people and reefs. Coral reefs deliver supporting, provisioning, regulating, and cultural ecosystem services (Millennium Ecosystem Assessment; Woodhead et al. 2019), including fisheries that sustain approximately 6 million people and generate nearly $7 billion while providing a primary protein source (Cisneros-Montemayor et al. 2016), supplementary resources such as the aquarium trade and sand extraction (Wabnitz et al. 2003), coastal protection through wave attenuation (Beck et al. 2018), biogeochemical regulation including nutrient cycling and calcium balance (Moberg & Folke 1999), and substantial cultural and economic contributions via tourism estimated at $35.8 billion per year (Spalding et al. 2017). Additionally, they serve as a resource for research. Among others, corals function as archives and climate records. Through their skeletons, researchers can reconstruct historical levels of salinity, water temperature (Thompson, 2022) and rainfall (Isdale, 1984). Reefs provide important "supporting services" as breeding, spawning, feeding and sheltering grounds for a multitude of organisms. Their connection to other ecosystems, such as mangroves and seagrass beds, represents an additional value for their interdependence (Moberg & Folke, 1999).

Coral reefs are degrading at an unprecedented rate due to global and local pressures (Hoegh-Guldberg et al., 2017; IPCC, 2023), which often combine to produce unpredictable and more detrimental effects. To date, due to global impacts, it is estimated that the capacity of coral reefs to provide ecosystem services has halved globally (Eddy et al., 2021). The continued decline of coral reefs and other habitats is raising global alarms about the future survival of this ecosystem. Overall, historical coral coverage in reef systems worldwide was estimated to be between 58% and 70%, but declined by about 50% between 1957 and 2007 (Eddy et al., 2018). The 2023 IPCC Report stated that coral reefs are among the ecosystems already facing intolerable risks and irreversible losses, even under optimistic scenarios. There is high confidence that, with 1.5 °C of global warming above pre-industrial levels, coral reefs will decline by a further 70-90%, and by 99% with 2 °C of warming. Near-term risks of terrestrial, coastal, and marine biodiversity loss are high to very high, with very high confidence, and certain regions bear the greatest consequences, among them Small Island Developing States (IPCC, 2023). Scleractinian corals, the foundation of reefs, are among the organisms whose conservation raises the most concern, with over 44% of warm-water coral species threatened (IUCN, 2025).

In 2024, the Fourth Global Bleaching event has been officially confirmed by the National Oceanic and Atmospheric Administration (NOAA) and the International Coral Reef Initiative (ICRI) (https://icriforum.org/4gbe/). If the first global bleaching event, in 1998, and the second, in 2010, resulted from peaks of El Niño–Southern Oscillation (ENSO), the two most recent ones, 2014-2017, and 2024, were amplified by the effects of climate change and produced the greatest damage (Reimer et al., 2024).
Coral cover on tropical reefs has deteriorated, with virtually no colony unaffected (Riegl et al., 2009, Tebbett et al., 2023). Aside from bleaching events, global warming has triggered a change in ocean chemistry, disease outbreaks (Burke et al., 2023), and biodiversity loss.
The world's coral reefs have been reported as the first Earth System to exceed the central estimated thermal tipping point of 1.2 °C of global warming above pre-industrial levels (Lenton et al., 2025). With the continuous increase in temperature, it is expected that coral reefs will be virtually certain (>99%) to tip, even if local and global responses limit the temperature increase to 1.5 °C over the next 10 years (Bevacqua et al., 2025).
Locally, in certain areas, overfishing has altered reefs' balance, affected functional biodiversity, and caused phase shifts (Graham et al., 2013; Ling et al., 2009; Pal & Bhattacharyya, 2020). Unsustainable fishing practices are still being used, with catches exceeding reefs' recovery capacity and the adoption of physically damaging techniques that result in bycatch and damage to untargeted organisms and habitats (Andrello et al., 2022; Fenner, 2012).
The loss of three-dimensionality, typical of complex reefs, combined with severe weather events and sea-level rise, may compromise coastal protection and affect populations in low-lying countries. The increase in global population and tourism causes pollution, further coastal development, habitat destruction, and the overuse of resources (Knowlton, 2001; Riegl & Glynn, 2020). All these impacts will not only affect the reefs' integrity but also threaten the livelihoods of millions of people dependent on them (Chaijaroen, 2023).
Many of the world's coral reefs will continue to degrade without their decline being recorded. In fact, in numerous locations, there's a paucity of baseline data (Darling et al., 2019; Gouezo et al., 2019; Rodriguez-Ramirez et al., 2020) and opportunities to conduct coordinated, standardised surveys during peak events (Rivera-Sosa et al., 2025). Furthermore, scientists have been calling for decades for the inclusion of additional parameters in reef monitoring to better understand the demographic dynamics on reefs (Edmunds & Riegl, 2020; Pisapia et al., 2020). As such vital information has not been recorded for many years and locations. Reefs are also too vast, spanning numerous remote locations and often found in low- to middle-income nations with limited funding, presenting various challenges (Roch et al., 2025).

1.1.2 Challenges and opportunities for preserving coral reefs

To protect coral reefs for future generations, multiple strategies have been proposed and must be implemented promptly. A combination of sustainable governance, rapid and effective actions to address climate change and local stressors, and a holistic approach is required to secure a future for the oceans, particularly coral reefs. Both top-down and bottom-up strategies must be implemented with governments and society acting synergically.

On an international level, the Sustainable Development Goals, adopted in 2015 by the United Nations (UN) General Assembly through the 2030 Agenda (United Nations, 2015), aim to eradicate poverty, safeguard the environment, and promote peace and prosperity worldwide by 2030 (https://sdgs.un.org/2030agenda). Amongst the 17 goals, many are particularly relevant for ocean conservation: Goal 4 "Quality Education" (Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all); Goal 13 "Climate Action" (Take urgent action to combat climate change and its impacts"; Goal 14 "Life Below Water" (Conserve and sustainably use the oceans, seas and marine resources for sustainable development). Five years from the deadline, many of the targets of the aforementioned goals remain far from being achieved (United Nations Department of Economic and Social Affairs, 2025).

Originated in 2012 during the United Nations Conference on Sustainable Development, the concept of Blue Economy has been introduced and increasingly used to ensure a "sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem"(World Bank, 2017). The idea is to have two seemingly contrasting concepts work hand in hand: on one side, growth and development; on the other, the protection of threatened and vulnerable ecosystems. This can be achieved only through multistakeholder engagement and sustainable development (Sarangi, 2023). In support of this, the United Nations designated the years 2021 to 2030 as the "Decade of Ocean Science for Sustainable Development" with the objective of reversing the decline in ocean health and ensuring that ocean science contributes effectively to the sustainable development of marine environments. The goal is to fill existing knowledge gaps and strengthen governments' and communities' efforts in support of global conservation.

Particularly challenging is securing both human development and nature conservation in tropical countries. In fact, these iconic locations, considered tourism hotspots, bear the highest costs in terms of direct impacts and pressures on sensitive ecosystems (Skarakis et al., 2023) or threatened organisms (Papafitsoros et al., 2021).

Given the complexity and intertwined issues, holistic and interdisciplinary approaches are needed in ocean governance for coral reef ecosystems. Mitigation of local stressors and active coral reef restoration to buy time are two of the management strategies proposed (Reimer et al., 2024). These should be complemented by traditional passive conservation management practices of protection, together with an increase in global awareness (Veysel & Yasemin, 2020), local capacity (Susskind & Kim, 2022), and environmental stewardship (Peachey, 2008).

1.1.3 Passive conservation strategies

To address the environmental concerns, over the years, not without challenges, passive conservation strategies have been adopted and often preferred, with various goals in mind, including protecting species, areas, and habitats; managing fisheries; reducing pollution; and proposing regulations and laws to mitigate the effects of climate change.

Many of these strategies are particularly successful. For example, thanks to the protection of endangered species, many populations that were once at risk have recovered over time (e.g., Ashe et al., 2013; Mazaris et al., 2017). The initiatives implemented often include various areas of focus, such as the control of trade through the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), international hunting and harvesting bans, and the introduction of preventative measures for the reduction of unintentional harm to marine life (e.g., control of fishing gear, reduction of pollution).

Additionally, non-governmental organisations are playing a crucial role in ocean governance and conservation efforts, helping raise awareness on various environmental-related issues and engaging in various conservation activities, including advocacy, scientific research, management, empowerment, and enforcement (Vance & Rangeley, 2019). Activists within these groups can act as intermediaries between indigenous communities, authorities, and various other stakeholders.

These organisations often focus on protecting charismatic species and engaging with the media and the public, informing the global community. They help advance the conservation cause by raising awareness and thus influencing people’s perceptions of specific organisms and challenges (Grip, 2017). They can also play a key role in shaping industry choices by promoting initiatives encouraging responsible practices across supply chains, including the use of selective, low-impact fishing techniques (Jacquet & Pauly, 2007). These efforts help reduce ecosystem disruption, as unsustainable fishing can alter fish communities and contribute to coral–algal phase shifts after disturbances (McManus, 2000). Additionally, NGOs strongly advocate for pollution and plastic reduction. Plastic debris, chemicals, and wastewater continue to cause widespread ecological harm and pose risks to human health through bioaccumulation of pollutants. Over 5.25 trillion plastic particles are already present in the oceans (Eriksen et al., 2014), with 4.8–12.7 million metric tons added annually (Haward, 2018). NGOs therefore emphasise prevention at the source, targeting industries, consumers, and land-based inputs, while highlighting the growing threat of both macro- and microplastics to marine ecosystems and food chains (Thiagarajan & Devarajan, 2025). Plastic pollution is the focus of many citizen science (CS) initiatives designed to collect data on types, abundance, and distribution. These initiatives aim to raise awareness and actively involve people in finding solutions and preventing the problem (Nelms et al., 2022), creating a shared sense of responsibility.

Area-based conservation measures represent one of the most prominent passive conservation tools. This type of measure, with its numerous forms and levels of jurisdiction, is widely used in many countries and across different habitats to preserve highly valuable sites, reduce the degradation of sensitive locations and promote the recovery of damaged areas. Area-based conservation strategies include both traditional "marine protected areas" (MPAs) and also "other effective area-based conservation measures" (OECMs). The global commitment to protect 30% of land by 2030, as defined by Parties to the Convention on Biological Diversity in 2022, has spurred numerous initiatives to ensure widespread protection and halt biodiversity loss, although as of 2024, the global coverage of protected and conserved areas remained limited accounting for 8.4% of marine and coastal waters (UNEP-WCMC and IUCN, 2024). Protected areas are primarily designated for biodiversity conservation and, when effectively managed, can yield positive ecological and economic outcomes (Ban et al. 2019; Grorud-Colvert et al. 2021; Lester et al. 2009; Zupan et al. 2018), yet Marine Protected Areas often generate stakeholder tensions and variable results due to differing management levels, underscoring the need for their continued implementation to safeguard vulnerable and biodiverse sites and benefit adjacent areas (Maestro et al. 2019), alongside improved monitoring of effectiveness and management quality rather than solely tracking spatial expansion (Chen et al. 2023; Geldmann et al. 2021).

Alongside formal protected areas, Other Effective Area-Based Conservation Measures (OECMs) provide a complementary approach by conserving biodiversity and associated ecosystem services within defined areas through sustained long-term and effective governance and management (Convention on Biological Diversity, 2018) that do not rely solely on traditional authorities but can use alternative instruments. Private individuals, organisations, groups of entities, and indigenous and local communities can act as guardians and promoters of these areas, ensuring that their management supports biodiversity conservation. The involvement of various stakeholders in the designation and management of OECMs is a valuable tool for conservation, ensuring that different needs are addressed and that management practices are more inclusive. Examples include locally managed marine areas in Mozambique where, following successful examples in Madagascar (Benbow et al., 2014) temporary closures of certain areas were agreed with the local community to produce tangible results (Diz et al., 2018) in fisheries. These new forms of area-based conservation measures complement traditional Protected Areas with their various levels of protection and traditional management tools.

1.1.4 Active strategies

Alongside passive conservation measures, active restoration has become a major tool to counteract degradation, biodiversity loss and the effects of climate change on various ecosystems. It is also used to advance people's awareness and engagement through various projects that involve the general public (e.g., Blanco-Pimentel et al., 2022; Hesley et al., 2017). Ecological restoration is defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (Clewell et al., 2004).

The United Nations (UN) declared 2021-2030 as the Decade of Ecosystem Restoration with the aim of "supporting and scaling up efforts to prevent, halt and reverse the degradation of ecosystems worldwide and raise awareness of the importance of successful ecosystem restoration" (United Nations General Assembly, 2019).

In recent years, for the same reasons stated by the UN, coral reefs have seen a surge in restoration activities, given that the time required and even the likelihood of natural reef recovery remain uncertain, and that strategies to improve their resilience are still being researched. This offers a valuable opportunity to mitigate and reverse the negative impacts on reefs, reduce coral loss, and accelerate reef recovery, buying time before the positive effects of any global action on climate change begin to benefit reefs. While many scientists contend that interventions like coral gardening are necessary to kickstart and boost reef recovery, counteract the increasing impacts of climate change and facilitate the long-term rehabilitation of coral reefs (Anthony et al., 2017), others argue that these measures should remain a last resort intervention, especially considering the high-costs and limited extension of most interventions (Bellwood et al., 2019; Mulà et al., 2025) and the challenges in alleviating the stressors causing the degradation (Streit et al., 2024).

Over the years, research and practical applications have enhanced outplanting success, diversified the range of species used, selected more resistant corals, lowered costs, and promoted the widespread adoption of asexual propagation to increase genetic diversity (Hesley et al., 2023). One of the most common methods used in coral reef restoration is coral gardening, an asexual-based restoration technique that involves a two-step process: growing coral fragments derived from the wild in ex-situ or in-situ nurseries and then outplanting them on degraded reefs (Rinkevich, 2006) using various techniques and materials. These nurseries rear corals in more favourable or controlled environments, thereby promoting faster growth (Rinkevich, 2006) and potentially enabling managers to select the most resistant genotypes (Baums, 2008). Coral gardening can also include the use of microfragments generally derived from slow-growing corals and cultivated in intermediate in-situ or ex-situ phases before being outplanted on the reef (Boström-Einarsson et al., 2020; Forsman et al., 2015)

Alongside coral gardening, restoration practitioners have more recently begun researching and adopting techniques based on sexual reproduction requiring highly trained practitioners and facilities (Guest et al., 2023). This technique can improve genetic diversity (Carne et al., 2016), especially in locations where populations of certain coral species have significantly declined over the past few decades (e.g., Jackson et al., 2014; Vardi et al., 2021). Genetic diversity is crucial to species conservation (Baums 2008), and restoration based on assisted and non-assisted sexual reproduction may also allow for the selection of the most resistant individuals (van Oppen et al. 2017).

Additionally, in the last years, the use of a new technique based on simple, low-cost modular iron frames (e.g., reef stars) has become widespread and adopted also with the aid of local reefs and consolidate rubble, thus having a multidimensional role (Williams et al., 2019).

An increasing number of studies suggest including a social component in the assessment of coral reef restoration projects to evaluate their success beyond ecological metrics (Hein et al., 2017, 2019; Sebastian et al., 2024). Where restoration projects have involved the community, this has often led to lower costs and increased environmental knowledge, awareness, and stewardship (Cruz et al., 2014). The direct involvement of people (indigenous communities or tourists) in restoration activities increases understanding of reefs' status and problems and encourages them to reduce direct anthropogenic damage and to engage in finding solutions (Hein et al., 2019). In some instances, involving the local community in reef restoration has not only developed stewardship but also built a skilled workforce, boosted local capacity and created jobs (Kittinger et al., 2016).

There is a growing recognition that the relationship between society and the environment plays an important role in the success of restoration efforts (Fischer et al., 2021). By including local knowledge and community support, projects are more likely to be viable in the long-term (McAfee et al., 2022). Through targeted communication strategies, social research, and participatory community engagement, restoration initiatives foster awareness, motivate support, and cultivate long-term commitment to ocean stewardship—occasionally even inspiring new community-led initiatives (McAfee et al., 2022). Restoration involving the society offers an opportunity to enhance people's connection to the sea, inspiring, engaging, and educating participants through experiential ocean literacy. In some cases, restoration initiatives have frequently been driven by the tourism industry, with tourists directly being involved or exposed to this practice (Hein et al., 2018, 2019). It has been shown that conservation education and stewardship are maximised when linked to practical "hands-on" experiences (Dean et al., 2018; Hein et al., 2019; Hesley et al., 2017), leading also to a greater acceptance when people involved belong to the local community (Danielsen et al., 2010). However, it often appears that volunteers and participants in restoration projects are visiting tourists rather than members of the local community (Hein et al., 2019), limiting the direct benefits to coastal locations and reefs. On the one hand, involving tourists expands outreach to national and international levels, but on the other hand, there is a missed opportunity to reduce local threats and improve local stewardship.

Of course, working with people outside the science field poses limitations in terms of efficiency, continuity, and expertise, and the potential negative impacts of involving volunteers in restoration activities can include reduced outplantation skills and inadvertent damage to the reefs. Limitations arising from the use of non-trained participants can be effectively managed and anticipated, as the benefits of greater awareness, an enhanced sense of ownership, lower costs, and larger-scale projects outweigh these constraints (Hesley et al., 2017).

Consequently, the involvement of volunteers in restoration endeavours not only can produce a more literate society but can also have direct financial and social benefits (Hein et al., 2019).

1.1.5 Citizen Science

When the scientific world engages with society, it appears to produce multiple benefits.

The inclusion of the general public in research projects is definitely not a new approach and has been adopted both on land and in the marine environment for many decades (Bonney et al., 2009). Although most define "Citizen Science" (CS) as research involving non-professionals willing to contribute to conservation (Theobald et al., 2015) in data collection or analysis at different levels (Bonney et al., 2009), it is also true that volunteers taking part in practical activities (such as reef restoration) with a scientific approach and to support research can be considered citizen scientists (Hesley et al., 2017). Despite the variety of disciplines and situations in which citizen science can be adopted, there are some basic principles that underlie good practices for ensuring an ethical approach to projects involving the general public. The 10 Principles of Citizen Science developed by the European Citizen Science Association (ECSA, 2015) state that citizen science projects actively involve citizens in genuine scientific research that produces new knowledge, benefits science and society, and respects ethical, legal, and data-quality standards. Participants should receive feedback and recognition, data and results should be openly accessible where possible, and projects should be evaluated for scientific quality, participant experience, and societal impact.

In fact, citizen science is also considered a way to bring the public and science together, democratise science, and involve people in decision-making on environmental topics (Bonney et al., 2016). Citizen science projects can involve tourists (Bargnesi et al., 2020; Butler et al., 2023) or local people (Danielsen et al., 2010; Fulton et al., 2018), increasing the legitimacy and acceptance of projects and their effectiveness in generating outcomes (Cigliano et al., 2015).

Citizen science allows scientists to carry out research projects they would not be able to do alone due to spatial, financial, or workforce constraints (Bonney et al., 2009). In fact, citizen science projects are especially valuable for addressing scientific questions that span large areas or periods of time, whilst still providing high-quality data (Finger et al., 2023).

The use of non-professionals requires that the task to be completed relies on basic skills to ensure greater participation, or on higher skills when following a training (Bonney et al., 2009). In fact, many have raised questions about the validity of data collection by amateurs (Aceves-Bueno et al., 2017), but years of scientific research have proven that, with some adjustments, numerous questions can be answered with this approach, providing equally valuable data (Finger et al., 2023; Kosmala et al., 2016).

Marine citizen science projects focus on biological monitoring (Bruce et al., 2014; Bulleri & Benedetti-Cecchi, 2014; Delaney et al., 2008; Pecl et al., 2019; Valsecchi & Gabbiadini, 2024), environmental parameters monitoring (Wright et al., 2016), impacts of climate change such as bleaching through, for example, Coral Watch (Marshall et al., 2012), and pollution, such as plastics on the beach (Nelms et al., 2022; Zettler et al., 2017). Frequently targeted organisms encompass charismatic species that attract tourists and are easily identifiable, such as whale sharks (e.g., Araujo et al., 2017; Norman et al., 2017), manta rays (Armstrong et al., 2019; Blanco-Parra et al., 2022; Ehemann et al., 2022), cetaceans (Bruce et al., 2014; Tonachella et al., 2012) and sea turtles (Casale et al., 2020; Dunbar et al., 2021; Rousso et al., 2024).

Some citizen science projects that have been running for many years have proven the validity of this methodology, resulting in scientific publications and wide engagement.

For example, Redmap Australia was launched in 2009 in Tasmania and then rolled out to all of Australia in 2012. The project has two aims: 1) to provide an early indication of climate-induced range shifts for marine species, and 2) to engage the community on marine climate-change issues using data gathered by them. People contribute with "opportunistic" photos of marine species found outside their known range, and entries are displayed on a website after validation by a team of experts (Pecl et al., 2019). Numerous scientific publications have been derived from the programme (e.g., Lenanton et al., 2017; Robinson et al., 2015; Stuart-Smith et al., 2018), also thanks to the verification process that ensures a robust dataset. In terms of wider engagement, the project has participated in events, created outreach articles and reached people through newsletters (Pecl et al., 2019), revealing a comprehensive approach.

Reef Life Survey (Edgar et al., 2020; Edgar & Stuart-Smith, 2014), has shown that by training recreational SCUBA divers, citizen science projects can produce high-quality, globally relevant marine biodiversity data. Their efforts have resulted in thousands of standardised underwater surveys across more than 3,500 sites in 53 countries, documenting fish, invertebrates, macroalgae and corals. The dataset has become a foundational baseline for global reef biodiversity and conservation, used by scientists and marine-park managers to monitor ecosystem changes, assess impacts of fishing or climate stressors, and inform protection strategies.

CoralWatch was initiated in 2002 and integrates educational aspects and public outreach in global reef monitoring efforts by citizen scientists. Its main tool, a square plastic card, allows participants, regardless of their expertise, to monitor coral bleaching and coral health by comparing coral colours to the card's swatch to then submit them on an online repository (Siebeck et al., 2006). The project has a worldwide diffusion and has involved a variety of participants, including students, divers, tourists, and environmental groups (Marshall et al., 2012). An important feature of this citizen science initiative is its educational component, which provides outreach opportunities, organises reefblitz, workshops and events and offers lesson plans and activities for school teachers and tourists on a variety of topics. Data derived from the surveys conducted with the CoralWatch card are publicly available. This programme represents a striking example of the possible link between public engagement, data collection and scientific outputs.

Citizen science has also been employed to gather data on rare, threatened or enigmatic animals (Andrzejaczek et al., 2016; Fontaine et al., 2022; Valsecchi & Gabbiadini, 2024), specifically on their distribution, behaviour, movements and especially over large geographical areas (Armstrong et al., 2019; Coppari et al., 2024; Norman et al., 2017). Particularly when the targets of the studies are large charismatic organisms, the role of tourists becomes key, with many citizen science projects relying on them for data collection (Butler et al., 2023).

Beyond scientific outputs, citizen science is often promoted for its potential to enhance ocean literacy, stewardship, and public engagement (Kelly et al., 2019), bridging the gap between science, society, and conservation (Cigliano et al., 2015; Dickinson et al., 2012). The extent to which this occurs depends on many factors, including participants' background knowledge. In fact, relying on volunteers, participatory research may attract more knowledgeable and inclined people, with an already high degree of awareness, attitude to activism, and high interest in nature recreation and connection to the environment (Martin et al., 2016). In simple terms, when participating in a marine citizen science project, people can get closer to the ocean, inform themselves and become ambassadors, even if only within their social network. Consequently, it is believed that a better-informed society can promote improved conservation by taking a more active role in influencing local policies and decision-making (Bonney et al., 2009; Haywood et al., 2016). When research projects address scientific questions with significant conservation outcomes, involving citizen scientists can lead to greater recognition, increased engagement, advocacy, and foster a sense of connection and responsibility, potentially extending to enforcement actions (Dosemagen & Parker, 2019). Although rare, there are instances in which citizen-led initiatives have guided policy to address issues identified through research (Warner et al., 2019). In fact, citizen science can offer a spectrum of engagement opportunities beyond the collection of data by non-professionals. These include communities advocating for their own health and environment, informal and formal education opportunities, media campaigns to raise awareness and promote further action, and practical activities to address environmental problems, whether or not complemented by formal regulatory enforcement (Dosemagen & Parker, 2019).

However, although more research is needed, current studies of the effects of citizen science projects on people’s interest in science and the environment, and their motivation to join scientific activities, do not allow for generalisation and do not prove that CS increases interest or motivation, as short-term participation in CS seems to have little effect on attitudes toward science (Finger et al., 2023).

There are examples of increased awareness generated by data collection (Haywood et al., 2016; Kelly et al., 2020), which is not always accompanied by an increase in understanding the nature of the scientific processes (Bonney et al., 2009; Brossard et al., 2005; Jordan et al., 2011; Trumbull et al., 2000). Behaviour change is a particularly challenging outcome to wish for, as the mechanisms driving it are quite complex and people tend to be willing to alter their behaviour when they believe it can have a significant impact (Cornwell & Campbell, 2012; Toomey & Domroese, 2013). In terms of outcomes on people, a straightforward, simple behaviour change and key transferable aspect is advocating the research topic and its wider context through communication with others within one's extensive social network (Dalrymple et al., 2013; Haywood et al., 2016; Johnson et al., 2014). Furthermore, methods that encourage active learning and provide hands-on experiences showing success in achieving conservation goals can effectively influence behaviour change (Jordan et al., 2011).

Regardless of the final outcome, hands-on learning experiences are a valuable tool for people to reflect on new perspectives and generate greater awareness (Zettler et al., 2017), especially when emotions are involved, fostering transformative experiences (D'Amato & Krasny, 2011; Dean et al., 2018).

1.1.6 Ocean Literacy

To ensure "peace and prosperity of our planet" as well as the preservation of our planet and ocean, in 2015, the United Nations formulated the *2030 Agenda for Sustainable Development* with its Sustainable Development Goals (United Nations, 2015). To meet them, it is necessary to combine and integrate activities from both the scientific and governmental sectors, with community-driven actions. Furthermore, to promote ocean science and knowledge creation aimed at reversing the decline of the ocean system and fostering new sustainable development, UNESCO declared 2021-2030 the "Ocean Decade". One of the seven outcomes that describes "the science we need for the ocean we want" is to enhance ocean literacy through 'inspiring and engaging' oceans (UNESCO-IOC, 2021b). Ocean literacy is defined as the understanding of the ocean's influence on us and our influence on the ocean (Cava et al., 2005). Ocean literacy is an "approach for society as a whole that catalyses actions to protect, conserve and sustainably use the ocean" (UNESCO-IOC, 2021a). Citizen science represents a valuable tool, in combination with others, to support ocean conservation in the Ocean Decade (Kelly et al., 2020).

Ocean Literacy has been defined by seven principles to emphasise that there is one interconnected ocean that shapes the planet's geology, climate, and ability to support life, while hosting immense biodiversity. These principles highlight humanity's deep dependence on the ocean and the fact that much of it remains unexplored, underscoring both our responsibility for its health and the opportunities for future discoveries (Santoro et al., 2017).

Ocean literacy is essential for improving people's understanding of and connection to the ocean, both of which can inspire collective actions at various levels and scales to tackle environmental challenges (Treviño et al., 2025). Management strategies can and should include the general public if we seek to ensure a future for the coming generations. Increasing ocean literacy can guide a more sustainable use of the resources and help shape decisions by governmental organisations and by grassroots initiatives. Consequently, enhancing people's connection to the ocean and the environment more generally has the potential to increase the likelihood of a sustainable future.

Ocean literacy is considered as people's ability to understand how the ocean influences society and vice versa (Schoedinger et al., 2010). This results in people's capacity to understand basic concepts about the ocean, communicate effectively about ocean topics, make responsible decisions and adopt sustainable behaviours (Brennan et al., 2019; Cava et al., 2005). Although the responsibility for a sustainable future through ocean literacy should not fall solely on new generations (Kelly et al., 2022), enhancing young people's understanding of climate and ocean science is crucial for enabling them to actively participate in dialogue and decision-making (McCaffrey & Rosenau, 2012).

Ocean literacy is achieved through a range of activities in formal and informal settings. It can take different forms and be adapted to various contexts, including traditional knowledge sharing in schools and practical activities in the field that enhance people's connection to the ocean, foster active participation, and engage a diverse public (Dubickas & Ilich, 2017; McKinley et al., 2023).

Ocean literacy should be encouraged everywhere; in fact, even for people living close to the ocean, the marine environment can feel distant (Fauville et al., 2020), a distance that can be narrowed or closed through direct experiences in the ocean. These are known to shape people's attachment and increase ocean literacy levels (McKinley et al., 2023), whether they are direct physical experiences or indirect experiences taking advantage of technology such as Virtual Reality (Fauville et al., 2020).

To be effective, ocean literacy should encompass various levels. There are various drivers that define the human-ocean relationship and generate ocean literacy: knowledge, awareness, attitude, behaviour, activism, communication, emotional connection, access and experience, adaptive capacity, trust and transparency (McKinley et al., 2023). It is recognised that knowledge alone is not enough to increase environmentally conscious behaviours and enhance people's connectedness to the ocean, rather, practical exposure and experiences in nature (Otto & Pensini, 2017) can empower young people to become environmental stewards within their communities (Browne et al., 2011). Simultaneously, this suggested connection with nature can promote physical and mental well-being as well as personal resilience (Gill, 2014; L. Martin et al., 2020).

Alongside formal education on ocean literacy in schools (UNESCO-IOC, 2021a), which is still struggling to be integrated into formal curricula in many countries (Bastos et al., 2025), young people often acquire ocean knowledge outside schools through hands-on, immersive in-field experiences (Niedoszytko et al., 2019).

Fieldwork and excursions are believed to improve awareness of local environments and their challenges, and strengthen ocean and environmental literacy. Practical experiences are also valuable for applying theoretical knowledge gained through formal education in a range of subjects, including chemical, physical, and biological sciences (O'Brien et al., 2023).

It is globally recognised that protecting ocean resources requires involving multiple stakeholders in decision-making and co-designing solutions that are widely accepted, and this starts with widespread awareness.

To ensure a future for our planet and ocean, science must put the human capital at its centre, bridge a gap with society and ensure that governance is driven both by formal institutions and by informal grassroots initiatives, understood, led and driven by the wider community.

1.2 Aims of the Project

Many unresolved research challenges in marine science can only be effectively addressed through collaborative efforts that extend beyond the academic community. By engaging a broader public in research and conservation, such initiatives can generate results on a global scale while simultaneously fostering widespread awareness that would otherwise be difficult to achieve. In this context, some research projects have the capacity not only to produce valuable scientific outcomes but also to draw attention to conservation issues of critical importance that risk remaining overlooked without public involvement.

The aim of this project was to use outreach and citizen science to foster and spread marine conservation and restoration in coral reef areas. The rationale is to raise attention not only to the specific scientific question but also to the role of non-professionals in addressing knowledge gaps and to the potential to enhance ocean literacy for the sustainable management of marine resources.

Specifically, the thesis aims are:

- Demonstrate the effectiveness of citizen science in addressing a large-scale and underexplored marine research topic that cannot be adequately investigated by professional researchers alone.
- Explore the use of sport and coral reef restoration as tools to foster engagement, environmental awareness, a sense of ownership, and long-term stewardship of marine ecosystems.

We developed two new scientific initiatives that require collaborative efforts, with the objective of raising awareness and establishing a novel narrative for reef conservation.

The first case study, *Map the Giants*, addresses a research topic of global relevance that has received limited attention to date, despite its ecological and conservation significance. This project was developed to test whether a collaborative, citizen-driven approach could generate robust scientific data at a global scale while simultaneously demonstrating the value of non-professional involvement in advancing marine research and filling critical knowledge gaps.

The second case study, *Playing with Corals*, focuses on community engagement and capacity building in island communities in the Maldives. This project aimed to explore how to develop innovative and engaging outreach strategies to improve ocean literacy and promote environmental stewardship among young people, specifically by integrating marine conservation concepts into football training sessions and hands-on reef restoration activities. In this context, reef restoration is not treated as a solution to coral reef degradation, but as a participatory tool to engage local youth, strengthen community connection to marine environments, and promote a conservation attitude.

Overall, this thesis seeks to demonstrate that engaging people outside the professional scientific realm is not only beneficial but often essential for addressing complex and overlooked marine conservation challenges. Furthermore, by engaging non-professionals, this work aims to support collaborative approaches as effective tools for advancing marine knowledge, fostering ocean literacy among new generations.

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Chapter 2 - Map the Giants

2.1 Introduction

2.1.1 Global status of coral reefs and long-lived corals

Coral reefs are known to be one of the most biodiverse ecosystems on Earth (Knowlton et al., 2010; Reaka-Kudla et al., 1997), whilst covering a small portion (0.1%) of the Ocean surface (Spalding et al., 2001; Spalding & Grenfell, 1997). Despite this, they provide ecosystem services to millions of people worldwide (Moberg & Folke, 1999). The global decline of coral reefs, driven by global effects of climate change and direct anthropogenic pressures, is threatening reefs and the livelihoods of people who depend on them (Hoegh-Guldberg, 2019). We are losing biodiversity and jeopardising habitats at an alarming rate, even before we have fully understood the mechanisms that underpin the resistance and resilience of certain species or individuals and with so much more to discover in terms of marine species (Appeltans et al., 2012), and so many unknown areas (Kennedy & Rotjan, 2023). Corals are among the most threatened organisms in our oceans, with over 44% of the known scleractinian coral species being declared “Threatened” by IUCN in a report from 2025 (IUCN, 2025).

Despite their slow growth rates, corals are the foundation of reefs, representing the main building blocks of coral islands, and creating an ecosystem where millions of species live in close relationships and symbiosis. Coral reefs are highly productive ecosystems that support immense biodiversity, provide habitat and nursery grounds for countless marine species, sustain complex food webs, protect coastlines from erosion and storm damage, and play a crucial role in nutrient cycling within otherwise nutrient-poor ocean waters (Moberg & Folke, 1999).

Alongside the most important symbiotic relationships between the majority of coral species and zooxanthellae (LaJeunesse, 2020), coral colonies establish various associations with a range of other organisms (Montano, 2020; Stella et al., 2011). The extent, benefits, and harms caused by these relationships vary widely depending on who is involved. In some cases, associations are obligate and lifelong; in others, they are temporary and limited to a specific life stage of the organisms involved.

Associated fauna may include crustaceans inhabiting interstitial spaces within a colony, molluscs boring in the skeleton of corals, sponges overgrowing the corals’ live tissue, and small obligate coral-dwelling cryptobenthic fish species relying on corals for shelter or food throughout their lives (Bellwood et al., 2006; Coker et al., 2014). Drawing a comparison, on land, mature forests have been at the centre of numerous studies (e.g., Pasques & Munné-Bosch, 2024), highlighting the value of the different tree longevities in providing particular niches and different habitat-colonising options for various organisms. No such studies exist on long-lived corals, their life stages, and associated organisms, although they may act as Marine Animal Forests, creating three-dimensional frameworks with structural complexity that provide habitat, refugia, food, or nurseries for other species (Orejas et al., 2022).

With their different evolutionary strategies, some coral species appear to be less vulnerable than others (Van Woesik et al., 2011). If branching species are generally fast-growing, yet particularly sensitive, massive corals are often slow-growing, highly resistant organisms (Loya et al., 2001; Van Woesik et al., 2011). The growth rate (linear extension) varies considerably among species, with fast-growing corals such as Acroporididae reaching 100-150 mm/year (Dullo, 2005), whereas species like *Porites lobata* or *Diploastra heliopora* grow far less, i.e., ~1cm/year and 3-6mm/year, respectively (Bagnato et al., 2004, 2005; D'Olivo et al., 2024; Watanabe et al., 2003). In terms of lifespan, fast-growing corals such as *Pocillopora verrucosa* can reach 3.6-3.9 years, or *Acropora hemprichii* 13-24 years (Bythell et al., 2018). Yet, in particular circumstances, for reasons yet to be fully investigated, and despite global threats, certain coral colonies have, over time, reached remarkable sizes and ages (Montano et al., 2024; Siena et al., 2024), representing unique research opportunities. For example, although the average age of *Porites* spp. from a study in an area of Great Barrier Reef has been assessed 41±12 yr (mean±SD) (Darke & Barnes, 1993), this genus can reach over 1,000 years (Bythell et al., 2018), or colonies of *Diploastrea heliopora* 2.6m in height have been reported to be over 600 years old (D'Olivo et al., 2024).

For these reasons, the calcium carbonate skeletons of long-lived corals are often used by scientists to investigate multiple aspects of the past, using the information contained within them as historical proxy for climate and environmental studies (Lough, 2010). Therefore, slow-growing, large-sized colonies can serve as exceptional archives for yearly or even seasonal studies spanning over centuries (e.g., Canesi et al., 2024; D'Olivo et al., 2024). Thanks to their large sizes and three-dimensionality, numerous micro and macro-organisms can find shelter and establish temporary or lifelong associations within them (Blackall et al., 2015; Coker et al. 2014; Graham & Nash, 2013; van der Schoot & Hoeksema 2025). Additionally, their longevity is likely a testimony to their ability to withstand environmental changes and survive human interventions, demonstrating high resistance and resilience, whether thanks to refugia, enhanced tolerance (Camp et al., 2018) or a series of interconnected factors such as acclimatisation, genotypic differences, adaptation, and epigenetics (Drury, 2020). Their existence could provide important insights into the future capacity of scleractinian corals to survive in a changing environment.

From a cultural perspective, charismatic species in conservation biology are considered those organisms capable of fostering awareness and promoting conservation initiatives. They are, not without criticism (Ducarme et al., 2013), considered powerful symbols of contemporary issues and environmental ambassadors thanks to their appeal and the feelings they can evoke (Heywood et al., 1995). Although commonly represented by endangered large vertebrates (Mazzoldi et al., 2019; Simberloff, 1998), some researchers have proposed that corals may be considered "charismatic megafauna and cultural icons for extinction" due to the emotional attachment they can generate, and that can, in turn, drive conservation initiatives (Schuster, 2019). Indeed, large coral colonies exhibit several characteristics that could qualify them as charismatic organisms, and the most distinctive and valuable among them could be transformed into 'marine monuments' (Montano et al. 2024).

Studies on giant organisms in the ocean have involved various species, including invertebrates such as sponges *Xestospongia muta* (McMurray et al., 2008; Pawlik, 2025), giant jellyfish *Nemopilema nomurai* (Uye, 2008), giant deep-sea tube worms *Riftia pachyptila* (Grassle, 1987), giant squids *Architeuthis dux* (Verril, 1879) and many other vertebrates and invertebrates (McClain et al., 2015). Some are giant organisms presenting short life spans, others, like *Xestospongia muta* (McMurray et al., 2008) or *Tridacna gigas* (Rosewater, 1965), can reach remarkable ages. Yet, even specific studies on giant organisms (McClain et al., 2015) fail to mention the existence of giant corals, despite several colonies already reported in the literature at the time of the publication. In fact, giant coral records have been scattered throughout different scientific papers over the years, sometimes aimed at reporting the presence of exceptionally large colonies (Brown et al., 2009; Potts et al., 1984; Smith et al., 2021; Takeuchi & Yamashiro, 2017; Tokioka, 1968), the anthropogenic threats from overexploitation they faced (Soong, 1993), their reproductive capacity (Mezaki et al., 2014), within paleoclimatology studies (Canesi et al., 2024; D'Olivo et al., 2024; Lough, 2010) and in rare cases considering their size distribution over a certain area as the key research question (Coward et al., 2020; Done & Potts, 1992).

Organisms of similar ecological value and comparable societal roles on land have received greater attention for many years. Redwoods (*Sequoiadendron giganteum)*, Bristlecone Pines, Alerce Trees (*Fitzroya cupressoides)* are some of the most notorious millennial trees and are often regarded for their high ecological, environmental, and cultural value (Blicharska & Mikusiński, 2014; Mattioni et al., 2020).

Large and old trees are extremely valuable for studying the climate sensitivity of forests and dynamics over long periods of time (Pasques & Munné-Bosch, 2024). They also possess ecological, physiological, and evolutionary traits that are beneficial to human health and wider ecosystem services (Gilhen-Baker et al., 2022). They are irreplaceable organisms that have gone through a strong selection process and have survived, yet current pressures put them at risk. With the current multiple threats from direct anthropogenic stressors (forest degradation, fragmentation, defaunation, and forest fires (Leuschner & Homeier, 2022)), if they are lost, the restoration of their functionality within a forest is virtually impossible (Piovesan et al., 2022), and offset policies will be limited in effectiveness. Thus, only official protection and practices widely accepted by communities are effective tools for preserving them. Multiple countries have already started compiling national databases of their presence and passed various forms of legislation to protect them (e.g., Italy, UK, USA) (Piovesan et al., 2022; Sladonja et al., 2023).

For trees, it is suggested that three forms of management action are possible and necessary, though each of them presents various challenges: the protection of individual trees when they are found in locations of limited value; landscape-level actions to preserve locations that constitute refugia (although current refugia may not correspond to suitable locations in the future); protection over large time-frames given their extended lifespan, a task not easy from various technological and jurisdictional perspectives (Lindenmayer & Laurance, 2017). It is also proposed for trees to be allocated a special status, such as for example, using the "UNESCO World Heritage" criteria vii) and x)* (Lindenmayer & Laurance, 2017).

Large, old corals could be considered analogous to monumental trees, yet to the best of our knowledge, no individual marine organism has ever been protected on its own, in a way comparable to that reserved for monumental trees on land. While the idea of monumental trees is well established, the concept of monumental corals is only beginning to be introduced in marine science (Montano et al., 2024; Siena et al., 2024; Strona & Montano, 2025).

In the ocean, organisms threatened with extinction (e.g., Dulvy et al., 2016; Goble et al., 1999; Hoekstra et al., 2002; IUCN/SSC, 2008; Schwartz, 2008) or endangered charismatic species (Hammerschlag & Gallagher, 2017; Sergio et al., 2006) are often at the centre of conservation strategies through for example the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), or the risk assessments performed by IUCN through their Red List of Endangered Species, or the Convention on Biological Diversity that guides global policies for protecting life at all levels (ecosystems, species, genes). Additionally, conservation strategies are often directed to specific areas, whether protecting them through traditional formal Marine Protected Areas, or Other Effective Area-based Conservation Measures, or by non-traditional yet innovative strategies. One of these informal management tools is the designation of highly valuable areas, critical to the health of the ocean, as “Hope Spots”, which are not automatically supported by binding regulations, but receive international recognition and advocacy by non-governmental organisations (https://missionblue.org/hope-spots/).

Within this gap of knowledge and conservation strategies, giant corals provide, therefore, unique understudied opportunities for science, marine conservation and global awareness.

*Criteria vii) “to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance”; criterion x) “to contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.” (https://whc.unesco.org/en/criteria/).

2.1.2 Finding millennia-old 'monumental' corals could unlock secrets of climate resilience

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Large, ancient ‘monumental’ trees are important ambassadors for nature conservation. Besides their symbolic value, they have overcome more ecological challenges than most of their younger relatives, and so might hide evolutionary secrets to mitigate the impacts of climate change (Pasques & Munné-Bosch, 2024).

Finding analogues of monumental trees in the animal kingdom is hard. Various species can survive for centuries, but only a few individuals — such as Jonathan, a Seychelles giant tortoise (*Aldabrachelys gigantea hololissa*) that hatched in 1832 — have been monitored.

A citizen science initiative, Map the Giants, launched by the Marine Research and High Education centre at the University of Milano-Bicocca, Italy, aims to raise awareness of monumental corals. Some coral colonies still produce clones of larvae that settled millennia ago, and they could hold precious evidence of adaptation.

The first records, including colonies with circumferences that exceed 50 metres, have already been uploaded to the database. With reefs threatened across the globe, and Australia’s Great Barrier Reef experiencing one of its most severe ‘bleaching’ events, finding the giants will be a race against the clock. With a coordinated global effort, we stand a better chance of protecting them.

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2.2 Aims of the project

To address a multilayered gap, acknowledging the many values of giant corals, their currently overlooked role in ecology and society, and the lack of knowledge about their global abundance and distribution, Map the Giants project was created and launched.

The project has three overarching objectives:

1. Setting up a citizen science project aimed at discovering the largest coral colonies in the world (>5m) and advancing ocean literacy
2. Studying identified giant corals through various scientific disciplines, to reveal ecological patterns and unique characteristics that allowed them to reach such unusual lifespans
3. Explore the legal basis to create a new conservation concept for governmental recognition and for a greater awareness: Monumental Corals.

The present work aimed to address the first two goals and provide sufficient evidence for the third goal to be pursued with.

We aimed to:

- Build an instrument to reach worldwide coverage of reports of giants and define the effectiveness of the citizen initiative (Section 2.3);
- Assess the main ecological patterns of the validated entries (Section 2.4);
- Reconstruct some of the giants through Structure from Motion photogrammetry (Section 2.5).

2.3 Global Citizen Science Portal Development and Engagement

This section is inserted as submitted to Nature Conservation

Map the Giants: a new citizen science portal to map, study, and protect the largest coral colonies

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Abstract

Coral reefs are rapidly degrading under escalating local and global pressures and some centennial coral colonies may disappear before they are even documented. These giant colonies embody resistance and resilience in a changing ocean, can archive long-term environmental histories and may hold valuable clues to the traits that have enabled their survival. Yet, coordinated, large-scale information on their distribution, condition and ecology is still lacking. Map the Giants is a global citizen-science initiative launched in 2024 to locate, document and help protect giant coral colonies. This paper has two main aims: first, to synthesise the scientific and practical motivations for focusing on giant corals as both research targets and conservation symbols; and second, to present the design, protocol and operational workflow of Map the Giants. We describe how the project integrates citizen-science principles, user-centred website design, standardised reporting methods and multi-expert validation into a coherent framework, with a public, interactive map and dedicated learning materials to support ocean literacy.

Preliminary outcomes from the first 18 months: 195 submissions from 22 countries, of which 133 entries have been validated and added to the public database, demonstrate the feasibility and scientific value of this approach. Contributors routinely exceeded minimum data requirements and high validation rates indicate strong data quality despite heterogeneous participant backgrounds. Together, these elements show that Map the Giants can generate robust, scalable data on giant coral colonies while simultaneously engaging the public, providing a methodological reference for future studies and similar large-scale monitoring initiatives.

Keywords: climate change, coral reef monitoring, giant coral colonies, marine conservation, ocean literacy

2.3.1 Marine citizen science, ocean literacy and the need for large-scale data

Citizen science has been described as a research methodology in which large numbers of individuals, including non-scientists, collect, categorise, transcribe and even analyse scientific data (Bonney et al., 2014). In recent years, this approach has proved instrumental in overcoming key research constraints by mobilising non-trained people willing to contribute to conservation efforts (Theobald et al., 2015). This approach enables the collection of data that researchers alone would not be able to gather because of large spatial or temporal scales and financial limitations (Edgar & Stuart-Smith, 2014; Garcia-Soto et al., 2017) and offers opportunities for responsiveness (Mayfield, 2025). Citizen science represents not only a resource for data collection, but also a tool to bridge the gap between science, society and conservation (Dickinson et al., 2012). Active participation can spark pro-environmental behaviour by increasing public awareness (Haywood et al., 2016; Wyles & Ghilardi-Lopes, 2023) and may even mitigate some of the negative effects of growing tourism pressure on marine environments (Branchini et al., 2015; Skarakis et al., 2023).

Despite this considerable potential, the engagement of non-professionals in marine initiatives remains largely underutilised (Butler et al., 2023). In ocean research, scuba divers tend to be positively disposed towards participatory projects (Lucrezi et al., 2018), yet recruiting and retaining volunteers, especially over the long term and across large spatial scales, remains challenging (Pecl et al., 2019).

Nevertheless, population studies of specific marine organisms are often carried out with the support of volunteer observers, covering areas that would otherwise be impossible to monitor (e.g. Beeden et al., 2014; Edgar & Stuart-Smith, 2014). Frequently targeted organisms include charismatic species that are attractive to tourists and easy to identify, such as whale sharks (e.g. Araujo et al., 2017; Norman et al., 2017), manta rays (e.g. Ehemann et al., 2022) and sea turtles (e.g. Dunbar et al., 2021). Although species identification was once considered a potential obstacle in marine citizen-science projects (Martin et al., 2016) recent tools, such as *iNaturalist,* have demonstrated that quality-checked data can also support more complex studies (DiBattista et al., 2021; Di Cecco et al., 2021). In recent years, the integration of citizen science with Artificial Intelligence (AI) has shown a promising avenue for expediting data collection and analysis (Chen et al., 2024), overcoming traditional limitations on data accuracy and cost efficiency (Fortson et al., 2024; McClure et al., 2020). Projects such as the Great Reef Census, which have successfully combined citizen science with deep-learning, have already demonstrated that they can produce accurate results (Lawson et al., 2025).

The recent widespread availability of relatively inexpensive yet high-quality photo and video equipment has created further opportunities for both active (Andrachuk et al., 2019; Azzurro et al., 2013; Raoult et al., 2016) and passive citizen science (Edwards et al., 2021; Nascimento et al., 2024). While social media mining entails limitations related to data reliability (Daume, 2016), the growing number of wildlife encounter reports represents a valuable source of information, especially when entries are verified individually. In parallel, the increasing use of drones has expanded the scope of citizen-science projects. Despite constraints, such as limited battery life and restricted survey areas (Tmušić et al., 2020), consumer-grade drones have been effectively deployed in citizen-science research (Papakonstantinou et al., 2021; Pucino et al., 2021), enabling various marine surveys through high-resolution imagery and geospatial data.

Several long-running programmes illustrate how marine citizen science can generate robust data while being engaging for contributors. Redmap Australia (https://www.redmap.org.au/), which collects opportunistic data on the occurrence of unusual species, relies on expert validation of entries and provides contributors with an immediate automatic response, a subsequent follow-up after verification and a final publication on the project website. This process simultaneously addresses the need for data robustness and offers formal recognition to participants, both key elements of successful citizen science (Aceves-Bueno et al., 2017; Hunter & Hsu, 2015; Robinson et al., 2018; Rotman et al., 2012). Reef Check is a long-standing citizen-science project (Hodgson & Stepath, 1998) that adopts a standardised monitoring protocol, based on easy-to-identify, high-value indicator organisms to survey coral reefs worldwide. The protocol has been adapted to reflect regional features (Done et al., 2017; Hodgson & Stepath, 1998; Turicchia et al., 2021) and relies on the training of citizen scientists in data collection. Despite the time investment required for training, this initiative has a strong record of engagement and scientific publications (e.g., Done et al., 2017; Isdianto et al., 2025; Pancrazi et al., 2026). Similarly, Reef Life Survey, monitoring shallow rocky areas and coral reefs, requires intensive training and commitment and has produced valuable data over time (Edgar & Stuart-Smith, 2014).

Beyond their research value, citizen-science projects play an increasingly recognised role in fostering ocean literacy and in leading to increased awareness and knowledge amongst participants (Bonney et al., 2016). Citizen science is now viewed as a key tool for bridging the gap between society and the ocean (Parkinson et al., 2025). The growing importance of ocean literacy was highlighted by the United Nations' "Ocean Literacy for All Toolkit" (Santoro et al., 2017), which seeks to help diverse audiences navigate ocean-related issues and build knowledge about the marine environment. Within this framework, project websites and social media channels have become central interfaces where science and the public converge, serving as both communication hubs, outreach and ocean literacy tools. Environmental organisations and research institutions increasingly rely on digital platforms to disseminate their work, with science communication and citizen science emerging as key strategies for connecting research and society, including in coral reef research (Roche et al., 2023).

Despite the recognition of the role of citizen-science projects in generating knowledge (Bonney et al., 2016), influencing attitudes and behaviour (Toomey & Domroese, 2013), there is a growing need to investigate the breadth of these impacts (Baechler et al., 2024; Pateman & West, 2023; Wehn et al., 2025).

2.3.2 Coral reefs, knowledge gaps, and giant colonies as overlooked assets

Coral reefs are globally threatened by both natural and anthropogenic drivers (Hughes, Barnes, et al., 2017; Hughes, Kerry, et al., 2017). Their degradation poses risks to millions of people who depend on them (Morrison et al., 2020; Woodhead et al., 2019) and raises serious concerns regarding biodiversity loss (Cardinale et al., 2012). Although reef ecosystems are amongst the most biodiverse on Earth (Fisher et al., 2015; Hoeksema, 2017), they occupy less than 0.1% of the ocean surface (Spalding et al., 2001; Spalding & Grenfell, 1997). Scleractinian corals, the framework-building organisms of coral reefs, are particularly threatened: over 44% of warm-water coral species are currently considered at risk (IUCN, 2025). Climate change, pollution, disease outbreaks, destructive fishing practices and coastal and marine development all exert major pressures on reefs. These impacts can affect virtually every coral colony and its associated fauna worldwide (Hoegh-Guldberg et al., 2007; Riegl et al., 2009), including both fast- and slow-growing species.

Globally, more than 800 species of tropical, shallow-water scleractinian corals (Dietzel et al., 2021) exhibit diverse morphologies and growth rates, shaped by species-specific traits and environmental conditions (Darling et al., 2012; Veron, 2000). Linear extension varies markedly amongst taxa: fast-growing Acroporidae can reach 100–150 mm year^{-1} (Dullo, 2005), whereas massive species, such as *Porites lobata* and *Diploastrea heliopora,* grow at a much slower rate, at about 10 mm year^{-1} and 3–6 mm year^{-1}, respectively (Bagnato et al., 2004, 2005; Watanabe et al., 2003). Lifespans also differ considerably: fast-growing *Pocillopora verrucosa* may reach 3.6–3.9 years and *Acropora hemprichii* can live 13–24 years (Bythell et al., 2018). Yet, under specific circumstances, some colonies have attained exceptional sizes and ages that remain only partially understood (Montano et al., 2024; Siena et al., 2025; Strona & Montano, 2025).

For instance, although the mean age of *Porites* spp. in one Great Barrier Reef study was estimated at 41 ± 12 years (Darke & Barnes, 1993), some colonies of this genus can exceed 1000 years (Bythell et al., 2018) and *Diploastrea heliopora* colonies 2.6 m in height have been dated at over 600 years (D'Olivo et al., 2024).

Despite their scientific and conservation relevance, exceptionally large coral colonies have received limited dedicated attention. A few notable examples include a giant *Porites* sp. reported off Taiwan, 31 m in circumference and 12 m in height (Soong et al., 1999), another *Porites* sp. documented off Australia measuring 10.4 m in circumference and 5.3 m in height (Smith et al., 2021) and a giant *Pavona decussata* studied in Japan for its reproductive capacity and measuring 50.9 m in length (Mezaki et al., 2014). The reefs surrounding Ta'U Island in American Samoa represent one of the few areas where a systematic effort has been made to classify large coral colonies following the discovery of what was thought to be one of the largest corals known at the time (Brown et al., 2009), measuring 7 m in height, 17 m in diameter and 41 m in circumference. Subsequent surveys around Ta'U (Coward et al., 2020) highlighted the potential of focused research: around 400 colonies over 5 m in diameter were identified, including a *Porites* sp. 22.4 m in diameter, 8 m in height and 69.2 m in circumference. Although such colonies are highly conspicuous, they may often go unreported when they are not the explicit focus of research. In American Samoa, they had been mentioned in technical reef assessment reports (Green, 2002), but the broader scientific community had little indication that the area would later be dubbed the "Valley of Giants" by NOAA.

Long-lived corals provide high-resolution archives of past climate and environmental conditions through their skeletons (Canesi et al., 2024; D'Olivo et al., 2024; Lough, 2010; Lough & Barnes, 1997) and their large, three-dimensional structures support diverse associated organisms (Blackall et al., 2015; Coker et al., 2014; Graham & Nash, 2013; Van Der Schoot & Hoeksema, 2025). Their longevity may also reflect strong resistance and resilience to environmental changes via refugia, tolerance, acclimatisation, genotypic differences, adaptation or epigenetics (Camp et al., 2018; Drury, 2020). Culturally, these very large corals may act as charismatic organisms (Ducarme et al., 2013; Schuster, 2019), analogous to monumental trees, valued and protected for ecological and symbolic reasons (Mattioni et al., 2020; Sladonja et al., 2023), yet no individual marine organism has received comparable protection. Exceptionally large corals, therefore, offer unique opportunities for science, conservation and public awareness.

These considerations underscore both the ecological and symbolic value of these unique colonies despite the current lack of coordinated, large-scale information about them. Their monumentality, longevity and potential resistance traits make them unique research targets as well as compelling ambassadors for reef conservation. At the same time, their detection and monitoring require observational coverage across vast and remote reef areas, a task that surpasses the capacity of conventional scientific surveys alone. The combination of growing awareness of the potential of citizen science, the availability of low-cost and essential tools, such as underwater cameras and drones, the value of exceptionally large coral colonies and the recognition of what dedicated studies can achieve (Coward et al., 2020), collectively provided the motivation to establish a global database for their identification and mapping.

For these reasons, we launched *Map the Giants*, a global framework for the systematic identification and mapping of these coral colonies.

Therefore, the present work has two overarching aims. First, it synthesises the scientific and practical motivations for establishing a global initiative dedicated to identifying and documenting these unique coral colonies, highlighting why these organisms represent both valuable research targets and important conservation symbols. Second, it presents the design, protocol and operational workflow of Map the Giants, detailing how the project integrates citizen-science principles, standardised reporting methods, expert validation and open-data practices to build a reliable global database. By outlining this framework, we aim to provide a transparent methodological reference that can support future studies on giant corals and provide information for similar large-scale monitoring initiatives.

2.3.3 Mapping giant coral colonies via citizen science: discovery, monitoring, and open data

Map the Giants is a global citizen-science initiative launched in January 2024 to locate, study and safeguard giant coral colonies (corals over 5 m in two-dimensional linear length, defined as the straight-line projection of the longest dimension; see below for full definition). The project has three linked aims: (1) to crowd-source reports of potential giant colonies from divers, citizens and researchers (according to definitional criteria described below); (2) to validate and prioritise verified colonies for targeted, multidisciplinary field studies; and (3) to collaborate with various stakeholders to explore protection measures for colonies of outstanding value.

Citizen participation is essential to achieve global spatial coverage at feasible costs (Goffredo et al., 2010; Pecl et al., 2019). To ensure data robustness despite heterogeneous contributor backgrounds, the project uses a clear reporting protocol, standardised metadata fields and a multi-expert validation workflow.

The project is designed and managed in line with the ten European Citizen Science Association (ECSA) principles (ECSA - European Citizen Science Association, 2015). It actively involves people from diverse backgrounds — divers, researchers and ocean enthusiasts — who may submit one-off reports or act as long-term stewards of specific colonies by providing periodic photo and video updates. The project produces genuine scientific outcomes: it generates new biogeographic knowledge on giant corals and creates a validated sampling frame that supports peer-reviewed studies. Benefits are reciprocal. Scientists gain scalable, otherwise unattainable data and access to rare colonies; contributors gain skills, recognition and a deeper understanding of reef vulnerability. Citizens can participate at multiple stages, from discovery to longitudinal monitoring and, where appropriate, co-producing local stewardship actions.

Participants receive timely feedback: an instant confirmation, a unique entry ID and, when needed, follow-up requests. Validated records appear on the interactive map, making contributors' impact visible and concrete (Fig. 1), an essential motivational lever in citizen science (Land-Zandstra et al., 2021; Tiago et al., 2017) and resulting publications and reports are shared in free-to-read online versions. Contributors are acknowledged and images are credited. Finally, the project complies with European legal and ethical standards — including privacy, copyright and intellectual property, data-sharing agreements and environmental care — using Creative Commons licensing and non-extractive protocols to minimise impact.

The dedicated website (https://www.mapthegiants.com) serves both as the submission repository and as an educational hub, sharing validated data, guidance and open-access outputs with the wider community.

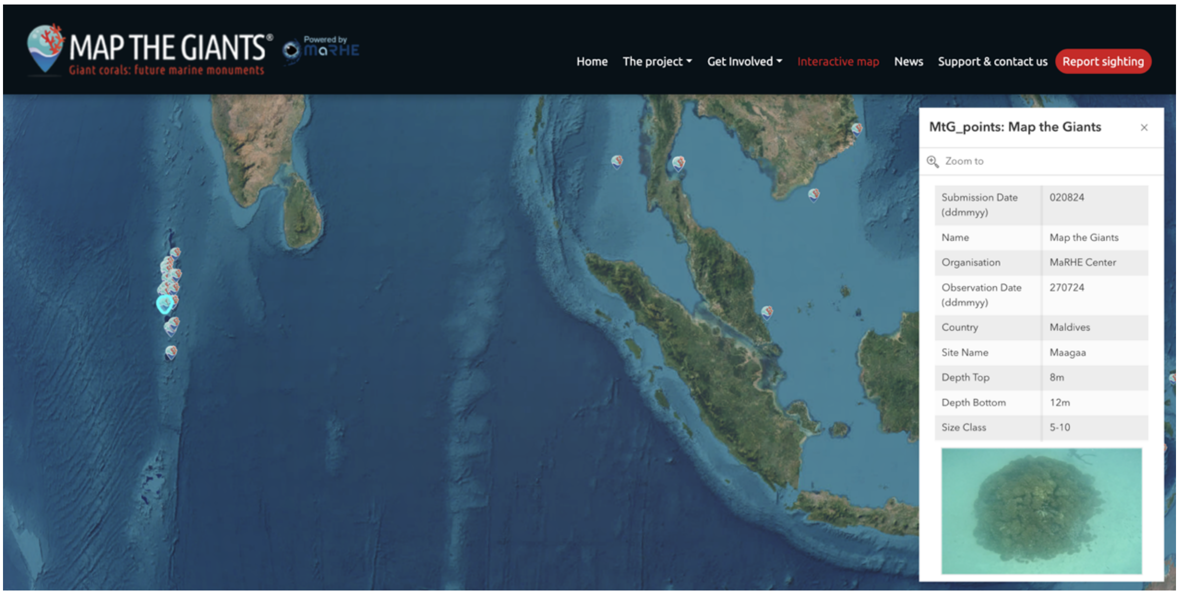

Figure 1. Landing view of the interactive map on https://www.mapthegiants.com, which serves as the central interface for visualising the curated archive of validated giant coral colonies reported to date. The map is hosted on ESRI ArcGIS Online.

2.3.4 Website design and information architecture

Recognising the central role of communication and usability in citizen-science initiatives, Map the Giants was conceived as a user-centred web ecosystem that reduces friction from initial interest to action. Grounded in user-centred design (UCD) principles — clarity, progressive disclosure, error prevention, accessibility and timely feedback — the site guides users through a gradual journey: learning the basics, preparing a report and finally visualising validated sightings.

This sequence is reflected in the top-level navigation: The Project (About, Aims, Partners/Team), Get Involved (Learn, How to Monitor, Share), Interactive Map, News and Support and Contact. Each section has a clear purpose: first orientation (plain-language explanations and visuals), then step-by-step, task-focused guidance (what to observe, what to record and how) and, finally, submission and feedback.

To reduce cognitive load, the reporting workflow uses plain language, sensible defaults and field-level cues (e.g. examples and validation prompts), while keeping a prominent, persistent Report Sighting call-to-action for fast entry. Consistent labelling and layout strengthen predictability. Mobile-responsive pages, legible typography and accessible contrasts support use in real-world conditions (e.g. on boats or beaches). Immediate confirmations and follow-up requests provide closure and build trust, while the interactive georeferenced map closes the loop by rendering contributors' efforts visible.

Overall, the information architecture aligns navigation, content and forms with users' tasks, contexts and constraints, so that both researchers and non-experts (e.g. divers or tourists) can contribute confidently and efficiently.

2.3.5 Building ocean literacy: the Map the Giants "Learn" page and outreach

One of the objectives of Map the Giants is to promote understanding of scientific concepts amongst general audiences. Special care has, therefore, been devoted to the Learn page within the Get Involved section. From the title onward, the aim is to maximise public engagement with the data-collection and scientific activities that underpin the monitoring programme, guiding contributors through a gradual, task-orientated pathway that culminates in data submission. This section represents an educational component designed to advance ocean literacy. Here, readers find concise explanations and practical cues for reporting a giant coral: an accessible overview of coral reef ecology, followed by clear descriptions of the ecological parameters required in the submission form. References to relevant scientific literature are included to support deeper exploration by interested participants. The introductory materials define the project's focal taxa (i.e. tropical, reef-building scleractinian corals) and situate them within the broader reef ecosystem in which Map the Giants operates.

The page then outlines the main coral growth forms, providing examples of coral species within each category, citing some linear growth rates and clarifying the rationale for including or excluding specific forms from the database. In particular, branching coral colonies are currently excluded, as this growth form often develops into monospecific thickets that cover extensive areas via fragmentation and ramet dispersion (Highsmith, 1982; Lirman, 2000). As a result, it is difficult to determine whether a reported structure represents a single connected genotype without specific genetic studies.

To strengthen field capacity and improve data quality, the page also includes a paragraph on coral health conditions. Given the increasing threats to coral reefs, particularly the rise in coral disease (Burke et al., 2023), more frequent bleaching events (Hughes, Barnes, et al., 2017; Hughes, Kerry, et al., 2017; Reimer et al., 2024) and outbreaks of predators (Meekan et al., 2025; Zhang et al., 2024), the global need for diffused and long-term monitoring has been recognised as essential to better inform science, management and policy (Obura et al., 2019). This section provides a basic toolkit for recognising and reporting selected health parameters in the field. Contributors are introduced to key distinctions, such as those between bleached and dead corals, to help track the fate of giant colonies over time. In addition, photographs and descriptions of common potentially harmful organisms are provided, along with basic information on growth anomalies and some of the most frequent coral diseases. The goal is not to enable participants to diagnose diseases, something that would require specific training, but to help them notice unusual conditions and report them.

To further enhance Ocean Literacy, the project's social media channels are managed through an editorial plan that disseminates information on the research protocol, results and outreach activities, while also covering topics related to coral reef ecosystems.

Beyond online communication, outreach events have played a central role in advancing ocean literacy and engaging potential citizen scientists. Activities have included online presentations for diving groups, in-person events at scuba exhibitions and participation in public science events in urban or virtual settings (e.g. podcasts, radio interviews). Through immersive 360° VR videos, giant colonies can be showcased to wider audiences in emotionally impactful ways, with potential benefits for awareness and environmental engagement (Thoma et al., 2023).

2.3.6 Standardising reports: eligibility criteria and monitoring methods

Another central element of the website is the How to Monitor page, which introduces and explains the monitoring protocol to prospective contributors. The first paragraph outlines best practices to avoid damaging giant colonies and the reef in general. These guidelines were developed in recognition of the importance of pre-dive and snorkelling briefings in mitigating the negative impacts of tourism on coral reefs (Krieger & Chadwick, 2013; R. C. Roche et al., 2016) and in light of documented damage to giant colonies in the past (Soong et al., 1999). The Green-Fins Code of Conduct (Hunt et al., 2013) served as a key reference for these recommendations.

The page then clarifies what is meant by "giant corals" within the project. This definition is based on two main components. First, it adopts Done's (2011) description of a coral colony as "the limestone skeleton plus the living polyp tissue, produced by replication of the primary zooid and all its descendants". Second, it sets a size threshold. Accordingly, a colony qualifies as a giant coral if it meets multiple criteria: (1) it measures at least 5 m in one of its two-dimensional projected linear lengths; and (2) it presents continuous live tissue and/or (3) a continuous skeleton (Figs. 2A-D). While relying on continuous skeleton rather than tissue alone may introduce some inaccuracies and while only genetic analysis would confirm the colony is of one single genotype, this trade-off was considered necessary to facilitate data collection by non-experts.

The chosen minimum size ensures inclusion of both colonies with particularly slow linear extension (for example, *Diploastrea heliopora* growing a few millimetres per year (Canesi et al., 2024)) and fast-growing corals that have reached unusual sizes (e.g. tabular Acroporids). In the latter case, reports may be especially important given the short life-span (Bythell et al., 2018) and susceptibility of certain fast-growing species (McClanahan et al., 2009).

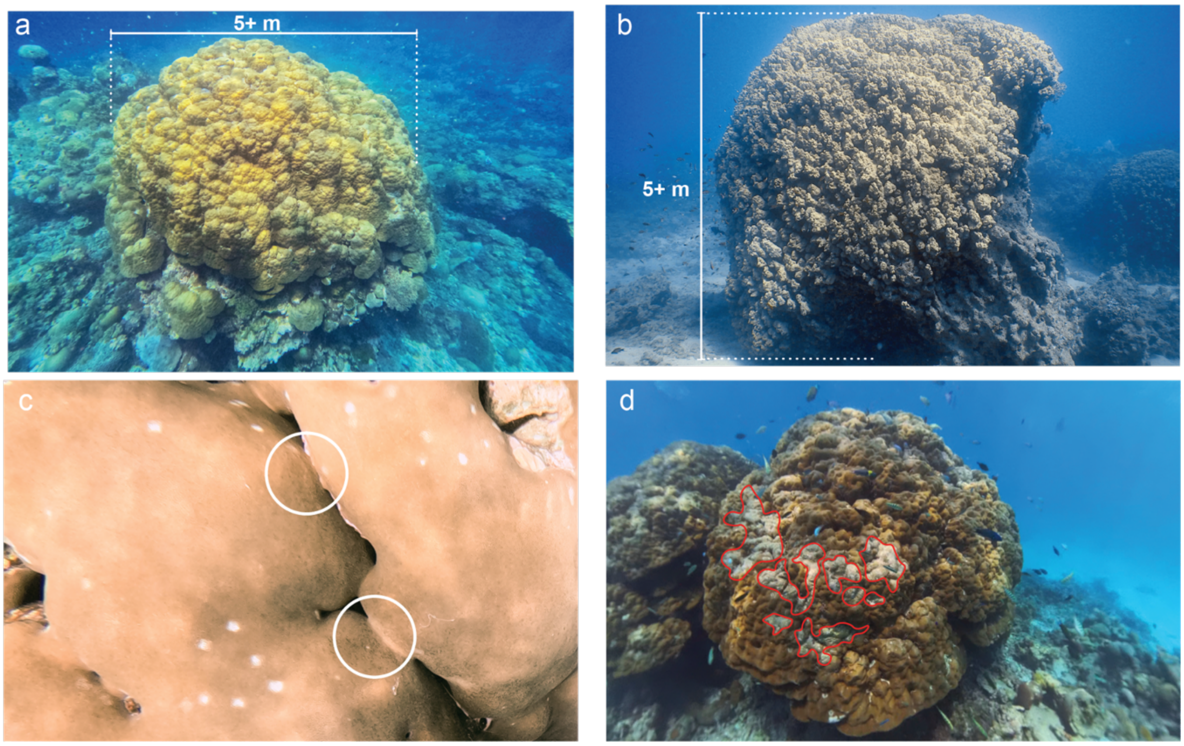

Figure 2. Criteria for the inclusion of giant coral colonies within the database. A. Colonies with a straight projected linear length of 5 m or greater; or B. Colonies with a height of 5 m or greater; and C. Continuous tissue (circles mark areas of tissue fusion); and/or D. Continuous skeleton (areas in red mark partial mortality of the colony).

To accommodate contributors with different levels of experience and time availability, the protocol offers two complementary methodologies, simple and advanced, that can also be combined. Both are explained and illustrated to provide clear visual references, particularly for less experienced users.

The simple methodology is designed for participants who encounter a giant coral opportunistically during recreational activities and may lack specific expertise or equipment. A simple survey (see Supporting File 1) includes the minimum set of data required for a submission to be valid: an estimate of colony size, growth form, location, depth and photographs. Colony size is assigned to one of three classes (5-10 m, 10-20 m, > 20 m) based on its longest straight dimension. Growth form options include massive, submassive, encrusting, tabular, foliose, columnar, branching or other. For georeferencing, contributors provide the country and site name, as well as estimated depth. Including GPS coordinates is optional, but strongly recommended to improve accuracy.

The advanced methodology, described in more detail in Supporting File 2, targets more experienced contributors with greater time availability and access to specific tools. In addition to the information required in a simple survey, participants may provide further optional data. These include a more detailed taxonomic identification (to genus or species where possible), environmental parameters, such as depth at the lower and upper colony limits and water temperature and a structured assessment of colony health. Health-related fields encompass the proportion of live tissue (classified into percentage classes), bleaching status, the presence of growth anomalies and observations of nearby competing or potentially harmful organisms (e.g. Crown-of-Thorns Seastar, Pin-Cushion Seastar, corallivorous snails *Drupella* sp., *Terpios hoshinota* sponge, *Dendropoma* sp. mollusc and overgrowing algae).

Contributors can also submit reports derived from drone surveys. Drones have proven valuable for shallow-water benthic surveys (Fallati et al., 2017), generating high-resolution images from which measurements of potential giant colonies can be extracted. Although the information gained from drone surveys is limited, this methodology is useful for locating potential giant coral colonies over larger areas, followed by dedicated in-water surveys for completeness. The methodology for acquiring and processing these images is briefly outlined to support consistent data collection within the How to Monitor section.

To facilitate reporting, a dedicated submission page is accessible from various sections of the website, including the Share subsection. Here, users can upload their data through a straightforward form that combines open questions, dropdown menus and multiple-choice fields. The page clearly explains the terms and conditions under which coral and user data are stored and used for.

Upon submission, contributors receive an automatic email thanking them for their entry and providing a summary of the information they submitted. To address common criticisms of citizen science, particularly concerns about inaccuracy and unreliability (Burgess et al., 2017), all data are manually filtered: photos are checked and entries are assessed for compliance with the project's definition of giant corals by multiple researchers individually. Independently, two to three researchers analyse all the photos received and the correspondence with the data provided and provide feedback on whether the coral is compliant, non-compliant or whether additional proof is required. When initial assessments differ, validators discuss the case and reach consensus, ensuring that borderline cases are resolved consistently rather than by a single rater. Within a few days, a personalised follow-up email assigns the report an ID number, provides feedback and may request additional information, photos or videos if needed to confirm the validity of the submission. This one-to-one approach has proven valuable for formally recognising citizen-scientists' contributions and supporting participant retention in other citizen-science programmes (Nursey-Bray et al., 2018).

Once validated, submissions are displayed on the Interactive Map section of the website. Each giant coral is represented by a Map the Giants pin and accompanied by the associated data (excluding the email address), a selection of photos and the specific licence under which data and images can be reused. The map is hosted on the ESRI ArcGIS Online platform and is manually updated as entries are verified (Fig. 1). Although publicly accessible, the dataset cannot be bulk-downloaded from the website.

2.3.7 Privacy, transparency, and features of the platform

While most contributors are willing to share information, some may be concerned about the public display of entries on a map (Pecl et al., 2019), particularly due to potential risks associated with over-tourism or tensions amongst stakeholder groups (Soong et al., 1999; Wolf et al., 2019). To respect contributors' privacy and address these sensitivities, personal data as well as GPS coordinates are handled with particular consideration. In fact, while precise GPS coordinates are essential for data quality and follow-up monitoring, public-facing coordinates are rounded to two decimal places (reducing spatial precision) by default, with full-precision data available upon request.

The website is updated regularly so that contributors can clearly see that the project is active, follow its progress and access the latest findings. Key features include:

- *Up-to-date data*: submissions are reviewed and incorporated on a rolling basis, leading to a constantly evolving and comprehensive map;
- *Accessible language*: the platform is designed for a wide audience, including non-scientists; clear and simple language is used and technical jargon is avoided to foster engagement, including amongst younger users;
- *Downloadable guidance*: the monitoring methodology is available as downloadable flyers, enabling participants to bring concise instructions into the field and follow the protocol easily;

- *User-friendly submission form*: data can be entered through straightforward dropdown menus and open-ended fields; the form is accessible from several sections of the website to facilitate quick reporting;
- *Automated confirmation*: automatic, real-time email responses give contributors a record of their report and allow them to verify the accuracy of the information submitted;
- *Visibility for partners*: a dedicated sponsors and supporters page acknowledges collaborators and provides visitors with a set of potentially useful contacts.

2.3.8 Preliminary Outcomes and Engagement Metrics

In 2025, global coral reefs were reported as the first Earth system to exceed the central estimated thermal tipping point of 1.2°C above pre-industrial levels (Lenton et al., 2025). With continued warming, coral reefs are considered virtually certain (> 99%) to cross critical thresholds even if temperatures stabilise at 1.5°C within the next decade (Bevacqua et al., 2025). Emerging evidence indicates increased thermal tolerance in some taxa (Lachs et al., 2023), suggesting that giant colonies may represent particularly promising targets for further investigation. Against this backdrop, projects such as Map the Giants acquire heightened relevance and urgency (Strona & Montano, 2025).

2.3.9 Participation and validation outcomes

During the first 18 months, Map the Giants received a total of 195 submissions, of which 146 were contributed by citizen scientists and 49 originated from dedicated expeditions conducted by the project team. After multi-expert review, 92 citizen-science entries and 44 expedition entries were validated and incorporated into the online database (e.g. Figs. 3A and B). The overall validation rate of 69.3% underscores the importance of expert assessment in ensuring data robustness and filtering out submissions that do not meet the project's criteria.
The responsiveness of contributors to follow-up questions was generally high, with only a small number of cases lacking sufficient supplementary material for validation. Consistent with other large-scale citizen-science programmes — such as Redmap Australia, which relies heavily on expert verification — this multi-step process strengthens confidence in the resulting dataset while offering recognition and feedback to contributors (Pecl et al., 2019).

Out of all the entries, only 10 (5.1%) were received by private individuals; the remaining contributions came from 44 different organisations (excluding the Map the Giants team), involving 58 individuals. Notably, one group submitted 28 entries, of which 19 were validated. Although this group significantly enriched the dataset, the proportion of invalid reports highlights the essential role of the validation workflow. To date, no contributor has requested for the data to be kept private.

Figure 3. Examples of validated giants. **A** *Turbinaria* sp. reported by MaRHE Center team from the Maldives measuring 11 m in diameter; **B** *Porites* sp. reported from the Seychelles measuring 5.3 m in diameter (Photo credit Daniel Bichsel).

2.3.10 Patterns in metadata submission

Analysing entries made by each contributor, in practice, no submission provided only the mandatory data. Most reports combined elements from both approaches, with contributors frequently opting to provide more detail than minimally required.

For example, although GPS coordinates are categorised as advanced data, all validated entries eventually included them, either at submission or after follow-up. Only 39 of 195 submissions relied solely on size-class estimates; the remaining 80% provided at least one specific measurement (length, width, diameter or height), whether estimated in situ or obtained through underwater tape measurements or Structure from Motion photogrammetry. Beyond the datasets collected by the project team, only four contributors shared photogrammetry products, which is unsurprising given the specialised expertise, hardware and time required.

Regarding colony health, almost all fields were consistently completed: bleaching status was reported for 157 entries, health condition for all, but 14 and water temperature for 124 submissions (Fig. 4). Information on potentially harmful or competitive organisms was more variable and represented the least consistently reported category.

These patterns suggest that, while flexibility in data requirements facilitates broad participation, certain currently optional fields, particularly GPS coordinates, could be made mandatory without deterring contributors.

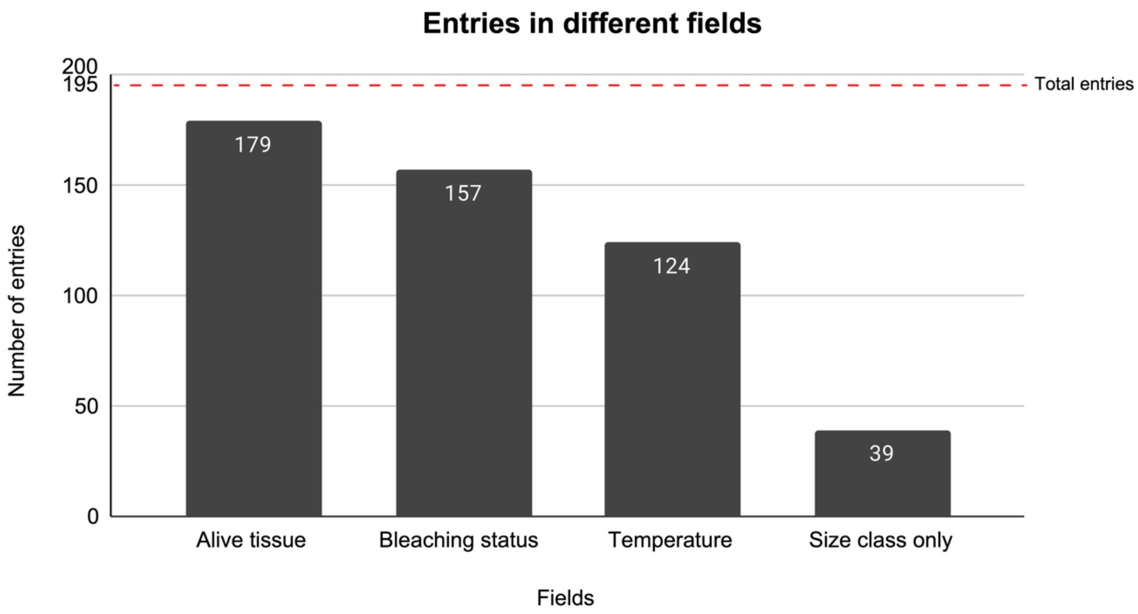

Figure 4. Number of entries in some of the advanced fields.

2.3.11 Geographical distribution and future expansion needs

To date, submissions have been received from 22 countries, with no reports from the Atlantic Ocean. Strengthening social-media strategies or establishing local ambassadors could increase geographic coverage and improve representation across ocean basins. The absence of Atlantic records indicates a need to expand outreach strategies or increase efforts in regions where giant colonies may be less common as a result of long-standing pressures (Connell, 1997; Gardner et al., 2003; Hughes, 1994; Miloslavich et al., 2010; Mumby et al., 2007; Papke et al., 2024;

Weil, 2004). Although initial analyses of the geographical distribution of a subset of giant coral colonies have shown that many are located in thermal refugia, some have already experienced and survived several instances of thermal stress over time (Strona & Montano, 2025), generating hopes to discover giant corals even in highly degraded areas.

2.3.12 Implications and future directions

The first 18 months of Map the Giants demonstrate the feasibility and scientific value of a global citizen-science initiative for documenting giant coral colonies. Although the project is still in its infancy, it has already produced a consolidated and rapidly expanding public database of validated giant coral records. The volume and quality of early submissions indicate strong engagement, with contributors consistently exceeding the minimum data requirements, an encouraging signal for the long-term sustainability of the initiative. Current high validation rates, along with broad participation, point to the emergence of a community of practice capable of supporting systematic monitoring efforts.

With this in mind, we will trial transforming some discretionary parameters into mandatory ones, such as the GPS coordinates, as this will significantly contribute to more complete data and reduce the need for follow-up emails. Additionally, although not applied in the present study, machine learning could be a natural extension of our approach to reduce observer bias during validation and extract additional features. As a necessary future step, it is paramount to expand the project into currently unreached areas and to conduct research that updates historical data in literature with current information.

As data are regularly uploaded, reports will become obsolete over time, requiring updates from the field. This would also be necessary following possible large-scale disturbances. The website will be periodically updated to include information on the current status of the reports. Each validated record is, in fact, associated with a persistent identifier that allows it to be updated through follow-up submissions linked to the original entry (e.g. health status after disturbance events, updated photos and re-measurements). The open nature of the portal's data will also allow managers and practitioners to access giants' locations and assess, on a voluntary basis, their fate over time. The continued involvement of regional ambassadors, despite not ensuring consistent commitment, appears to be the most feasible approach for long-term monitoring, at least until governmental protocols include giant corals into regular demographic studies (Edmunds & Riegl, 2020; Pisapia et al., 2020).

Looking ahead, the project's growth prospects are substantial. To facilitate participation and improve accessibility, the development and release of a dedicated native mobile application, freely available on major app stores, could be considered. Such a tool would offer a more immediate and user-friendly reporting interface, enabling contributors to submit sightings, upload photographs and videos and access guidance materials directly from the field.

As the database expands, Map the Giants will also be able to support increasingly robust ecological analyses, enhance comparisons across regions and provide information for conservation planning and potential heritage-orientated protection measures for exceptional colonies. Future developments may include strengthening collaborations with marine managers, integrating drone-based or photogrammetric workflows more systematically and broadening training and outreach activities to enable contributors to participate not only in discovery, but also in the long-term stewardship of giant coral colonies. Collectively, these advances will reinforce the project's role as a scalable, data-rich and community-driven framework for understanding and protecting some of the ocean's most remarkable organisms.

2.3.13 Conclusions

Given the urgent need to improve the management of coral reef ecosystems and prevent further loss, current research is increasingly focused on strategies that can overcome spatial, temporal and economic constraints. Centennial coral colonies remain largely understudied, despite their potential vulnerability to unprecedented pressures, their importance as archives of the past conditions of the ocean and as conservation ambassadors. The lack of comprehensive global data on these organisms represents a critical knowledge gap that must be addressed.

In Siena et al. (2025), we analysed the first ecological results of the project, while this paper is protocol- and workflow-focused. Here, we outlined the rationale behind the development and implementation of a novel research initiative specifically designed to fill a knowledge gap and to broaden the concept of which organisms are considered worth protecting. The project builds on a citizen-science framework that employs a robust yet adaptable protocol and is supported by a comprehensive communication strategy, including a dedicated website, social media channels and outreach events. Together, these elements provide an essential tool for advancing knowledge of giant corals at scales that would otherwise be unattainable.

This framework also embeds key principles of participatory research and Ocean Literacy, thereby enhancing both scientific understanding and public engagement. Giant corals not only serve as archives of ocean history, but they may also reveal mechanisms of resistance and resilience, becoming powerful symbols for marine conservation. The present project illustrates the potential of citizen science to generate valuable scientific data while simultaneously fostering ocean literacy and raising global awareness of the fate of these exceptional organisms.

2.3.14 References

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Zhang, F., Jia, X., Lin, Z., Jiang, Y., & Qu, M. (2024). The outbreak of *Drupella* snails and its catastrophic effects on coral reefs: A comprehensive review. *Frontiers in Marine Science, 10*, 1290001. https://doi.org/10.3389/fmars.2023.1290001

2.3.15 Supporting file 1: Simple Survey Method

Map the Giants: a new citizen science portal to map, study, and protect the largest coral colonies

Federica Marialuisa Siena[1,2,3*], Alessandro Gabbiadini[4], Luca Fallati[1,2] , Paolo Galli[1,2,3], Simone Montano[1,2,3]
[1]Depatment of Earth and Environmental Sciences, University of Milano-Bicocca, Italy; [2]MaRHE Center (Marine Research and High Education Center), Faafu Atoll, Maldives; [3]NBFC (National Biodiversity Future Center), Palermo, Italy; [4]Department of Psychology, University of Milano-Bicocca, Italy

MAP THE GIANTS

HOW TO SURVEY CORAL COLONIES

Help us locate a Giant Coral!

Please choose the type of survey that best suits you: simple, advanced or with a drone.

SIMPLE SURVEY. Diving or snorkelling
This can be undertaken during any excursion and without any dedicated equipment.

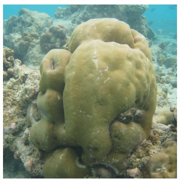
! Remember that GIANTS are corals OVER 5 METERS in diameter presenting continuous skeleton and/or continuos tissue

Steps to take:

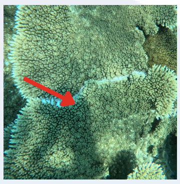
- **Grab** your diving or snorkelling equipment and any safety tool you may require. If you have a waterproof camera, we highly recommend you to carry it along;
- **Head out** to the chosen reef;
  Look out for any large coral colony;

WHAT IS A GIANT CORAL COLONY?

Colonies **over 5 metres in diameter** and presenting a **continuous tissue or skeleton.**



This colony originates from a single polyp and can grow in size indefinitely.
This is ONE colony.



The white mark is a scar, typical of two different colonies fighting and **growing side by side. This is NOT a colony but two.**

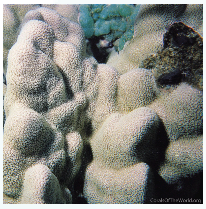
- Estimate the **size** of the **diameter** or **longest dimension** based on these size classes:
  5-10 meters
  10-20 meters
  >20 meters

GIANT CORALS.
FUTURE MARINE MONUMENTS.

- **Growth form:** **massive, submassive, encrusting, foliose, tabular, and columnar** are the **most likely growth forms for GIANT.**

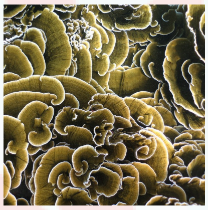
Massive

Submassive



Tabular

Foliose



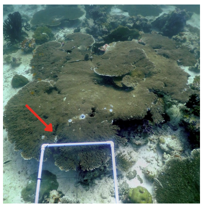
Encrusting

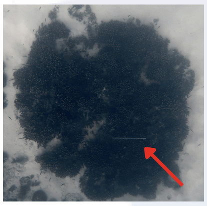
Columnar

Branching

Digitate

- **Site**. Indicate the Island /Atoll, name of the reef and provide us with the
- **GPS coordinates.** Provide them with the best approximation; Not mandatory but suggested
- **Depth:** Estimate the depth at which the coral was sitting and of its upper part (meters);
- **Photo.** When taking photos, please include an object of known size such as a person (as close as possible to the colony without physical contact). This helps us validate your entry.
- **Videos** are very useful for a complete overview. Please send them to mapthegiants@unimib.it





Please try to take a few pictures of the entire colony Include an object of known size and let us know the size in the note section. Also include dead portions.

Photos are mandatory and required for the entry to be validated and included in our database.

- Add any **note** on the colony.

MAKE AN ENTRY

Submit your data by scanning the **QR code** on the right or navigating to **www.mapthegiants.com** under the section **Get Involved → Share**

Get in touch:

mapthegiants@unimib.it

MAP THE GIANTS Powered by MaRHE

2.3.16 Supporting file 2: Advanced Survey Method

Map the Giants: a new citizen science portal to map, study, and protect the largest coral colonies

Federica Marialuisa Siena[1,2,3*], Alessandro Gabbiadini [4], Luca Fallati[1,2] , Paolo Galli[1,2,3], Simone Montano[1,2,3]
[1]Depatment of Earth and Environmental Sciences, University of Milano-Bicocca, Italy; [2]MaRHE Center (Marine Research and High Education Center), Faafu Atoll, Maldives; [3]NBFC (National Biodiversity Future Center), Palermo, Italy; [4]Department of Psychology, University of Milano-Bicocca, Italy

MAP THE GIANTS

HOW TO SURVEY CORAL COLONIES

Help us locate a Giant Coral!

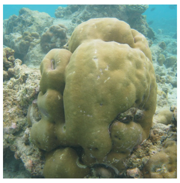
Please choose the type of survey that best suits you: simple, advanced or with a drone.

ADVANCED SURVEY. Diving or snorkelling

This type of survey is advisable for more experienced participants and can also be used to provide additional information on colonies which have been identified with a simple survey.

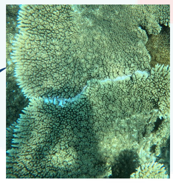
Steps to take:

- **Grab** your diving or snorkelling equipment and any safety tool you may require. If you have a waterproof camera, we highly recommend you to carry it along;
- **Head out** to the chosen reef;
- **Look out** for any large coral colony. Remember: a giant coral is considered a colony **over 5 metres in size and presenting a continuous living tissue and/or continuous skeleton.**



This colony originates from a single polyp and can grow in size indefinitely.
This is ONE colony.

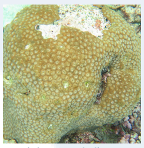
The white mark is a scar, typical of two different colonies fighting and **growing side by side**. This is **NOT a colony but two**.



- **Identify the genus** or species or take wide-angle and close-up photos (possibly with a scale bar within the photo) and send it to us. Please see below the most likely genera:

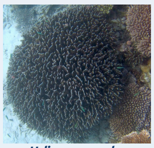
Porites sp.

Goniopora sp.



Diploastrea heliopora

Turbinaria spp.

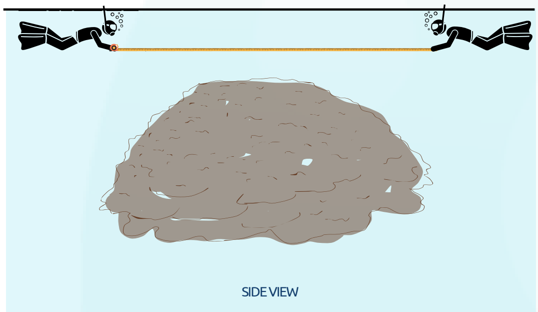


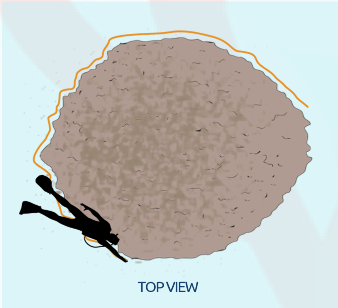
Heliopora coerulea

GIANT CORALS.
FUTURE MARINE MONUMENTS.

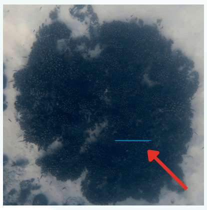
- Collect **measurements** following the preferred methodology:

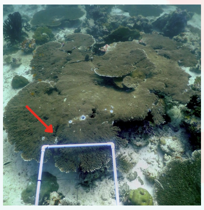
  Measuring tapes: measure length, width or diameter, and height perpendicular to the colony in its largest points, and circumference in the widest spot (see side view image). For colonies with a **circular shape,** the diameter can be calculated by measuring the perimeter and dividing by 3.14 (see top view image).



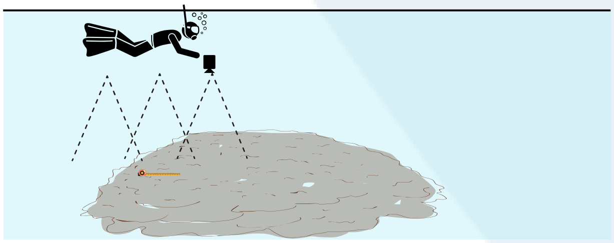


  Scalable photos: take one or multiple photos that include an object of known size (as close as possible to the colony without physical contact) such as a diver, a SCUBA tank, or a scaled bar to allow for size extrapolation;





  Photogrammetry: shoot a photo every 2 seconds or set the camera with a self-timer of 2 seconds to cover the entire surface. Photos should have a 70% horizontal and vertical overlap. Shoot then photos at 45° angle to capture all the features of the colony and prevent gaps in the final model. Try to cover the whole colony or at least the widest side of the colony. Please remember to **include an object of known size** to extrapolate the measurements of the colony. For a complete guide please visit our website.



- **Videos** are very useful for a complete overview. Please send them to mapthegiants@unimib.it

MAP THE GIANTS Powered by MaRHE

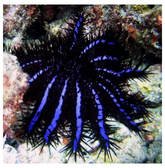
- **Site:** Indicate the Atoll, island, and site name of the reef and provide us with the
- **GPS coordinates:** define the location with the best approximation;
- **Depth:** Estimate the depth at which the coral was sitting and of its upper part (meters);
- What was the **water temperature?** (degrees Celsius)

- **Health conditions:** Estimate the percentage of live coral tissue based on these size classes:
  - 0% → dead colony
  - <25% alive tissue;
  - 26–50% alive tissue;
  - 51–75% alive tissue;
  - 76–99% alive tissue;
  - 100% alive tissue (alive);
- Did the colony present any sign of **bleaching?**
- Did you see any **abnormality on the tissue?**

Bleached coral


Tissue abnormalities

- **Competing organisms**: did you see any of these organism on or near the colony?


Crown of Thorns


Cushion Seastar


Drupella sp.


Terpios hoshinota


Dendropoma sp.

- Add any **note** on the colony or the surrounding environment.

MAKE AN ENTRY

Submit your data by scanning the **QR code** on the right or navigating to **www.mapthegiants.com** under the section **Get Involved → Share**

Get in touch:

mapthegiants@unimib.it

MAP THE GIANTS Powered by MaRHE

2.4 Assessing the ecological patterns of giant corals through citizen science

This section presents the ecological results from the collected data.
Part of the results were included in an article published in Coral Reefs

Mapping monumental corals through citizen science

Siena, F.M., Galli, P., Fallati, L., Dehnert, I., Gobbato, J., Afzal, M.S., Strona, G. and Montano, S., (2025). *https://dx.doi.org/10.1007/s00338-025-02688-9*

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2.4.1 Introduction

Coral reefs are recognised as one of the most biodiverse marine ecosystems (Fisher et al., 2015), and provide livelihood, food, and socio-cultural services to hundreds of millions of people across the globe (Woodhead et al., 2019). Unfortunately, they are threatened worldwide by human impacts, pollution, and climate change, with rising sea temperature responsible for the majority of mass mortality events (Hoegh-Guldberg et al., 2017; Hughes et al., 2017; Oliver et al., 2018). On April 14, 2024, the Fourth Global Coral Bleaching Event was officially confirmed by the National Oceanic and Atmospheric Administration (NOAA) and the International Coral Reef Initiative (ICRI) (ICRI, 2024), with a coordinated call to action to address the consequences of climate change. Indeed, certain carbon emissions scenarios have highlighted a significant risk of near-term losses in coral reef biodiversity, up to 99% following a 2 °C increase in global temperature (van Hooidonk et al., 2016; IPCC, 2023). This will have direct repercussions on reef structures (Alvarez-Filip et al., 2009; Wilson et al., 2019), fish biodiversity (Strona et al. 2021a, b), and ecological functions (Bellwood et al., 2019), as well as substantial economic impacts (Hoegh-Guldberg et al., 2015; Hughes et al., 2003). These are therefore challenging times for coral reef science, and there is an imperative need to develop novel and effective conservation strategies (Reimer et al., 2024), alongside greenhouse gas reductions (Hoegh-Guldberg et al., 2019). In this scenario, coral reefs might lose, among others, also the most resistant and ancient coral colonies. The average life span of most scleractinian species is limited (Devlin-Durante et al., 2016) (for instance, 13–24 years for *Acropora hemprichii* (Guzner et al., 2007)) as a combination of age-dependent mortality and other disturbances. However, some coral colonies demonstrated exceptional longevity and growth capacity, reaching impressive ages and sizes (Bythell et al., 2018). During their extended lives, these colonies might have endured a broad array of different disturbances, and especially in the last few decades when the severity and frequency of impacts, particularly in terms of temperature increase, have reached unprecedented levels compared to the past 2000 years (Mann, 2007). The longevity of giant corals might be due to species and individual (genetic) traits or to local conditions. In fact, certain colonies might exhibit genetic resistance (Drury, 2020), conferring them exceptional tolerance to anthropogenic stresses (Sweet & Brown, 2016), or to climate change impacts (Mellin et al., 2024), as well as an increased resilience to a changing environment (Coward et al., 2020), permitting them to recover after impacts. Additionally (or alternatively), their existence might be owed to local and regional environmental conditions. That is, giant colonies might have benefitted from inhabiting remote locations, or refugia habitat which, so far, have been spared by destructive global change impacts (Hoegh-Guldberg & Bruno, 2010; Keppel et al., 2012; Limmon et al. 2023; Strona et al. 2021a, b;). Giant coral colonies are most likely very rare, and characterised by slow growth rates, thus losing them might have dire consequences at multiple levels (Muir et al., 2022). In fact, they might be extremely important both for ecosystems and for scientific knowledge. Long-lived corals preserve unique information from a biological, genetic, and paleoclimatic point of view as they have resisted many environmental perturbations for hundreds of years (Lough, 2010; Thompson, 2022), and demonstrated exceptional capacity of survival. Thus, their identification, study, and protection could open novel avenues to help reefs withstand unprecedented environmental changes, and help increase marine conservation efforts (Oktan & Atar, 2023; Pasques & Munné-Bosch, 2024). For instance, in the terrestrial environment, monumental and ancient trees are considered exceptional enough to deserve special protection and occupy unique places in human culture and imagination (Zapponi et al., 2017). The same consideration should be granted to large, long-lived corals since their study has the potential to help mitigate the impacts of global change (Oktan & Atar, 2023), and serve the marine environment conservation cause (Montano et al., 2024). In the past years, some very large and old coral colonies have been reported in the literature, but not systematically. Several of them have been identified in American Samoa, with the first recorded giant being a *Porites* cf. *lutea*, measuring 7 m in height, 41 m in perimeter, and presenting a maximum straight-line length of 17 m (Brown et al., 2009). Following that discovery and those of several other giant coral colonies in the area, a dedicated study was conducted around the same island of Ta'U (Coward et al., 2020), measuring five additional Porites spp. with straight diameter over 5 m. The largest of them was eight meters high and over 69.2 m in circumference (22.4 m in diameter). The authors dated the two biggest corals between 368 and 652 years, depending on the approach adopted. In a different study and location, Mezaki et al. (2014) documented a spawning event from a large (50.9 m long, 30.6 m wide), 150-year-old *Pavona decussata* in Japan in 2011 and 2012, which might support the ecosystem importance of giant corals as a reliable, massive source of gametes for local coral recruitment. Despite their ecological and socio-cultural significance, giant coral colonies remain unidentified and understudied. Citizen science, defined as the engagement of non-professional volunteers in generating scientific knowledge (Bonney et al., 2009), presents a valuable opportunity to fill in this gap. Over the past decade, citizen science has gained recognition within the scientific community due to its cost-effectiveness and impactful approach, which facilitates the collection of extensive amounts of data while fostering environmental awareness and public education (Conrad & Hilchey 2011;

Dickinson et al., 2010; Goffredo et al., 2004, 2010; Schmeller et al., 2009). Advancements in technology have expanded its application globally and across several challenging fields of marine research, including climate change impacts, species distribution, ecosystem monitoring, and data collection on elusive or rare species and behaviours (Coppari et al., 2024; Dickinson et al., 2012; Edgar & Stuart-Smith, 2014; Garrabou et al., 2022; Gobbato et al. 2024; Kobori et al., 2016; Magson et al., 2022). While potential limitations may be associated with contributions from non-experts, these data, following verification and validation by professional scientists, are increasingly utilised in research across diverse geographic regions (Kelly et al., 2020). Additionally, citizen science may have some intrinsic geographical bias, with data being received increasingly from dive tourism hotspots and lacking in remote areas (Johnston et al., 2020). However, data from citizen science projects have informed conservation initiatives and policy developments, such as the design of marine protected areas (Hyder et al., 2015), real-time monitoring (e.g., Redmap Australia), and the creation of large-scale datasets (e.g., the Australasian Fishes Project). These collective efforts enhance resource management and address the United Nations Sustainable Development Goals, while fostering connections between communities and their local environments, promoting social capital and marine stewardship (Cigliano et al., 2015; Kobori et al., 2016).

Large coral colonies are an invaluable resource (Montano et al., 2024), and given their potential charisma (Schuster, 2019), they could help the coral reef cause by narrowing the gap between society and the ocean and further raising attention to this ecosystem, thus potentially contributing to reducing large-scale reef decline.

Here, we present the results of a citizen-science project aimed at discovering long-lived, large, monumental corals one year after its launch. By reporting on the data collected and lessons learnt so far, we provide an in-depth discussion on the opportunities giant corals offer for scientific research, conservation strategies, and the promotion of marine awareness.

2.4.2 Materials and Methods

The citizen science initiative was launched in January 2024 by the Marine Research and High Education (MaRHE) Center of the University of Milan-Bicocca to report the presence of exceptionally large coral colonies. Both citizens and scientists have been encouraged to report sightings and information on these iconic colonies through an open portal, Map the Giants (https://www.mapthegiants.com/). The criteria for the inclusion of giant corals in the database are multiple and coexisting: 1- colonies must exceed five meters in linear length (measured as the longest straight two-dimensional projection), and 2- the tissue or 3- the skeleton must be connected. Observations have to be made in-situ using various methods, including snorkelling, SCUBA diving, or drones. The website includes a section with guidelines to help par-participants fill out the survey and familiarize themselves with the different parameters and stressors to be recorded. The section also serves as a tool for ocean literacy. The website describes a simplified survey option for participants with limited data availability or knowledge, focusing on more essential information, and an advanced survey option including additional fields for more expert participants (see Paragraph 2.4) ; Supplementary Materials S1). The minimum amount of information for a valid submission includes contributors' name and email address, date, country, and location of the sighting, colony size class (considering the longest linear length: 5–10 m, 10–20 m, > 20 m), and a number of photos with a reference scale as a proof of the colony size. Optional information includes the submitter affiliation, if any, GPS coordinates, colony depth, water temperature, further measurements such as height, perimeter/circumference, linear length/diameter, specifying the measurement technique used (estimation, tape, photo, or Structure from Motion (SfM) photogrammetry (Burns et al., 2015; Figueira et al., 2015)). Given the nature of the observations, the expected accuracy is in the order of decimetres when colonies are measured and size class when estimated. Submissions also require technical details about the height, perimeter/circumference, length/diameter, specifying the measurement technique used (estimation, tape, photo, or SfM photogrammetry). Additional fields are the growth morphology of the colony (massive, sub-massive, encrusting, tabular, foliose, branching, and other) and the identification at genus or species level, along with the health status of the colony, evaluated as the percentage of alive tissue (0%, 1–25%, 26–50%, 51–75%, 76–99%, 100%), presence or absence of signs of bleaching and tissue abnormalities, and the presence of "potentially harmful organisms" such as Crown of Thorns (*Acanthaster planci*), Pin-Cushion Sea Star (*Culcita* sp.), *Drupella* sp., *Terpios hoshinota*, *Dendropoma* spp., or over- growing algae. The participant is asked to include images of the colony, and, in the case of drone footage, to specify the height of the flight and provide details of the equipment used. Moreover, a note section allows the inclusion of any additional information that might be relevant (such as signs of disease, long-term observations, or local value/use of the colony).

All data are reviewed and validated by experts, and submissions/records failing to meet the inclusion criteria are excluded from the database, but still considered in the statistics regarding the overall submissions received. The database presently, does not include large coral colonies described in the literature or reports backdated to ensure data are current.

2.4.3 Results and Discussion

Since January 1, 2024, the "Map the Giants" project has started a systematic collection of records to document features and distribution of some of the world's oldest and largest coral colonies, leveraging a citizen-science approach involving both researchers and the general public. The project received 195 entries from 22 different countries, with an average of around eight entries per month and the highest number of submissions (35) in June 2024. After quality checks, 67.7% (n = 132) of the entries were deemed valid, while 32.3% (n = 63) were excluded due to insufficient photo quality, unclear tissue or skeleton connection, lack of reference objects, or measurements below the minimum threshold. Overall, the Republic of Maldives stands out as the major contributor of entries (55.4%, n = 108) followed by Thailand (n=28) and Indonesia (n=27) (Fig. 1, Fig. 2a,b,c).

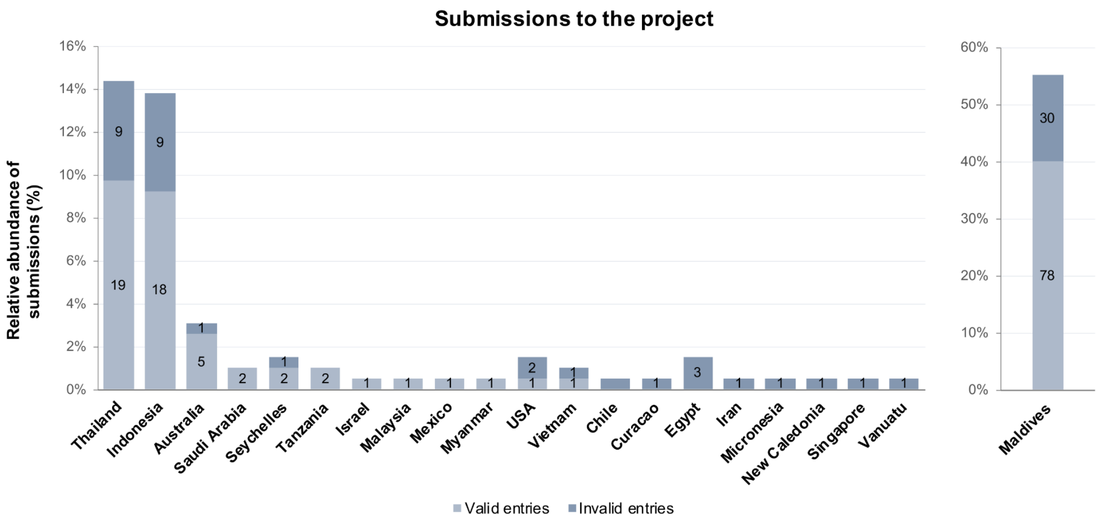

Figure 1. Submissions to the project by country and validity. The numbers in the bar represent the absolute abundance of corals

With the exclusion of reports by the Map the Giants team - 48 entries, 42 valid entries, all the contributions from Thailand come from a single organization in Koh Tao (Fig. 2c), followed by Indonesia (n = 27). These results are obviously driven by the fact that the project was launched in the Maldives, with an initial high and localized effort within the country by the Map the Giants' team and their collaborators. Still, they clearly demonstrate the effectiveness and potential globe-wide extension of the project, which is gaining momentum and promoting awareness for the conservation of giant corals and the coral reefs they inhabit.

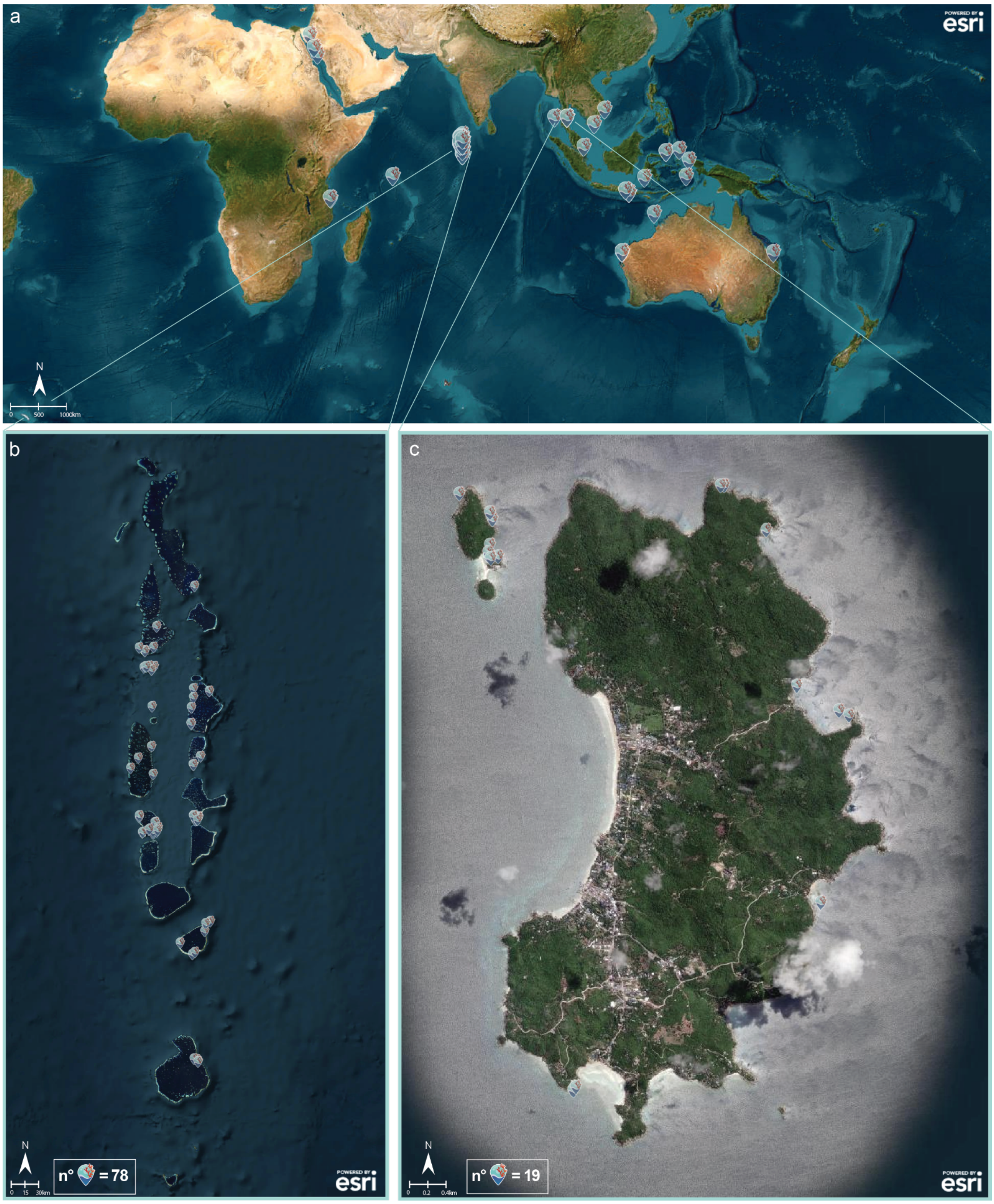

Figure 2. Geographical area covered through Map the Giants valid reports: **a)** Central Indo-Pacific area; **b)** Republic of Maldives; **c)** Koh Tao, Thailand. To date, no reports have been received from the Caribbean.

The giant colonies recorded so far have been discovered through different survey methods, mainly by SCUBA diving and snorkelling, but also using drones. Measurements have also been acquired with various approaches, with size assessed using: underwater tapes for most colonies (n = 124); visual estimation of the size class (n = 40), visual estimation of the size (n=8); a-posteriori from photos including a size reference objects (n = 16), and SfM photogrammetry using Agisoft Metashape® (n = 7) (Fig. 3).

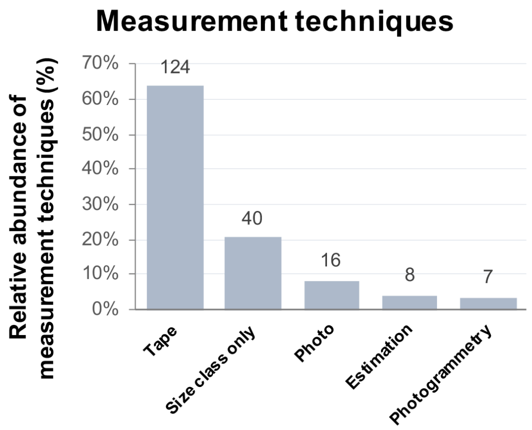

Figure 3. Measurement techniques used for all entries. The numbers in the bar represent the absolute abundance of corals

Independently of its function for data gathering, SfM photogrammetry reconstruction was performed for a total of 21 colonies in three instances (e.g. for colony shown in Fig. 8f), the reconstruction was carried out independently by contributing researchers. In the other cases, SfM processing was conducted by the authors using either images they collected themselves (15 colonies; e.g., for corals shown in Fig. 5a, b) or images provided by contributors (two colonies).

Most of the valid entries (78.8%, n = 104) (Fig. 4) were giant corals belonging to the 5–10 m size class, while the 14.4% (n = 19) were within the size class 10–20 m (e.g., Fig. 5a) and the 6.8% (n=9) were over 20 m (Fig. 5b).

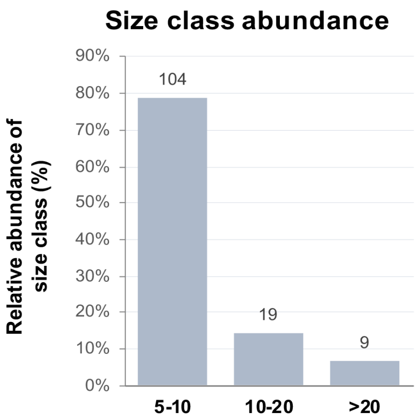

Figure 4. Size class abundance of valid entries. The numbers in the bar represent the absolute abundance of corals

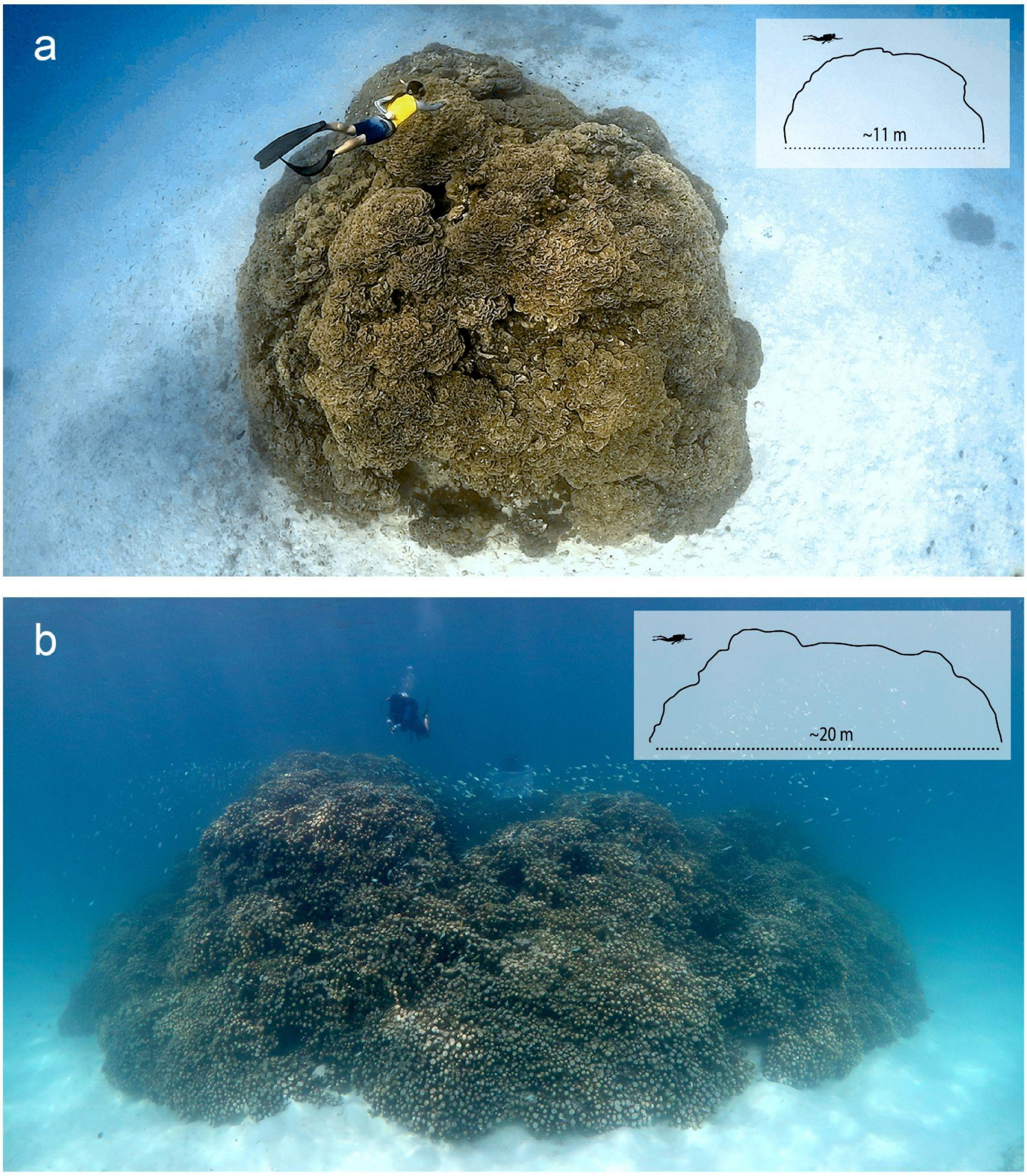

Figure 5. Examples of giant corals found in Faafu Atoll, Republic of Maldives: **a)** *Turbinaria* sp.; and **b)** *Pavona clavus*

Among the largest colonies (over 20 m in linear length), 3 were identified as *Galaxea* cf. *astreata*, and 3 as *Pavona* sp., and the remaining across various genera. The largest coral is a *Galaxea* cf. *astreata* from Tanzania, measuring 95 m x 47 m; the other two are from Indonesia, measuring 45.7 m x 18.6 m and 71m x 38 m, respectively. The three colonies of *Pavona* sp.

were reported from Saudi Arabia, Vietnam and Maldives and measured respectively 22.5m x 15.9 m, 56 m x 32 m and the last one 20m in diameter (Fig. 5b). Most giant colonies exhibited massive growth forms (66.7%, n = 88), followed by columnar (10.6%, n=14), submassive (9.1%, n=12) (Fig. 6a). The most frequent genus of giant corals was *Porites* (52.3% of giant colonies, n = 69), followed by colonies belonging to the genus *Goniopora* (9.8%, n=13), *Pavona* (9.1%, n=12), *Diploastrea* (8.3%, n = 11), *Psammocora* (8.3%, n = 11), *Galaxea* (13.8%, n=5), *Turbinaria, Acropora* and *Heliopora* (2.3%, n=3 each), *Pocillopora* and *Montipora* (0.8%, n=1 each).; (Fig. 6b, Table 1).

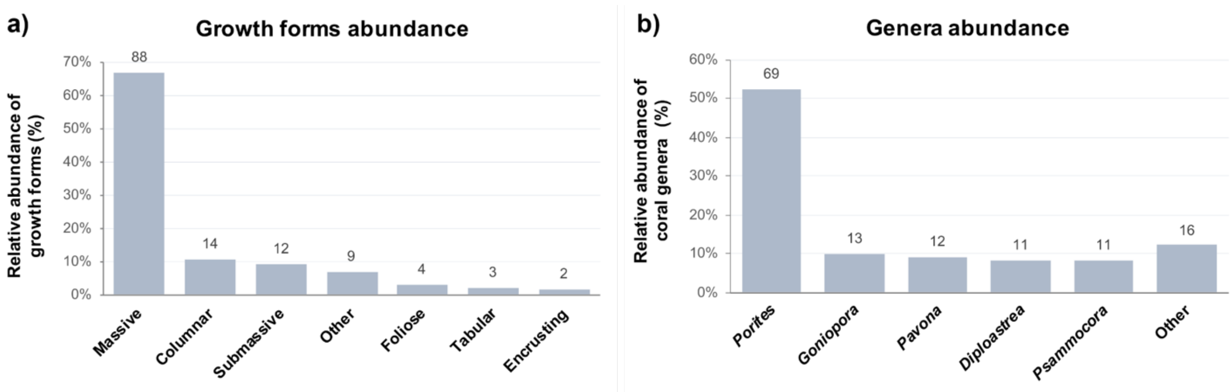

Figure 6. Valid submissions by **a)** growth form and **b)** genera. The numbers in the bar represent the absolute abundance of corals

In accordance with literature (Alvarez-Filip et al., 2009; Alvarez-Filip et al. 2011a, b), these results suggest that massive corals, as well as *Porites* (Fig. 6a-b) might be more likely to adapt and survive the challenges posed by environmental fluctuations. On the one hand, the predominance of massive growth forms is not surprising, as certain growth forms and genera are less likely to grow to monumental sizes due to evolutionary strategies and higher structural fragility (e.g., branching) and/or life history traits (which, from an evolutionary perspective, might not be independent from growth forms). On the other hand, the relatively modest threshold size adopted for the project allows for the inclusion in the dataset of colonies from genera and growth forms that, although currently underrepresented, are still present, such as tabular corals (e.g., Fig. 6a, Fig. 8c). In general, contributors reported the alive tissue estimates for their reports, only 15 entries out of 195 did not filled in this field. Giant colonies were mostly located in the healthiest classes at the time of observations. Specifically, 71.2% (n = 94) of the giants exhibited between 76 and 99% live tissue, with five colonies described as 100% alive. A small number of colonies (18.2%, n = 24) displayed signs of moderate tissue loss, with

51–75% live tissue, while five colonies presented less than 50% alive tissue. Participants did not specify the field for four colonies (Fig.7, Fig. 8a-h).

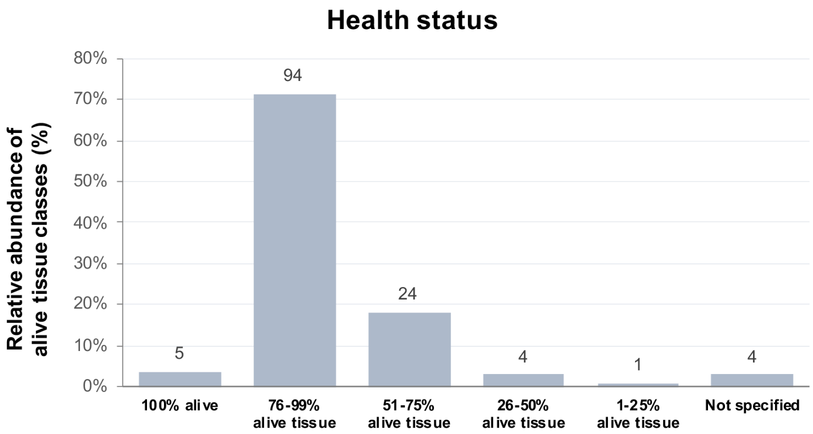

Figure 7. Health status of valid submissions. The numbers in the bar represent the absolute abundance of corals

Bleaching was reported for 18 coral colonies as the project was launched at the time of the fourth global bleaching event. No mortality was reported as a result of the 2024 mass bleaching event. Notably, the 10 m *Porites* sp. colony found in Australia experienced severe bleaching (Fig. 8h) in April 2024 but recovered by the end of June 2024, suggesting an exceptional resilience in the giant colony. Likewise, another *Porites* sp. from the Maldives was reported bleaching and then recovering. At least one of the pre-selected "potentially harmful organisms" was observed on 42 colonies, with overgrowing algae being the most common, followed by *Dendropoma* spp. and *Drupella* sp., while *Terpios hoshinota* was reported from three colonies. The inclusion of data on the presence of *Dendropoma* spp. and *Terpios hoshinota* in future submissions is encouraged as these are well known to be detrimental to corals. Vermetid snails cause damage both to the structure of the coral and affect its metabolism (Barton et al., 2020). The sponge *Terpios hoshinota* also known as the "Coral-Killing Sponge", displays an aggressive behavior competing for space and overgrowing corals' live tissue (De Voogd et al., 2013; Montano et al., 2015; Reimer et al., 2011; Rützler & Muzik, 1993). It needs to be highlighted that the pre-selected categories proposed in the survey are limited to some of the most common potentially harmful ecological interactions readily observable on coral colonies. More in-depth studies might assess if different maturity stages of the giant colonies are characterized by specific ecological interactions, as it has been observed in the case of large, old trees (Courbaud et al., 2022). No disease was reported in the "Note" section, either because of their absence or of lack of identification by contributors. Nonetheless, the inclusion of this field contributes to global monitoring of disease distribution.

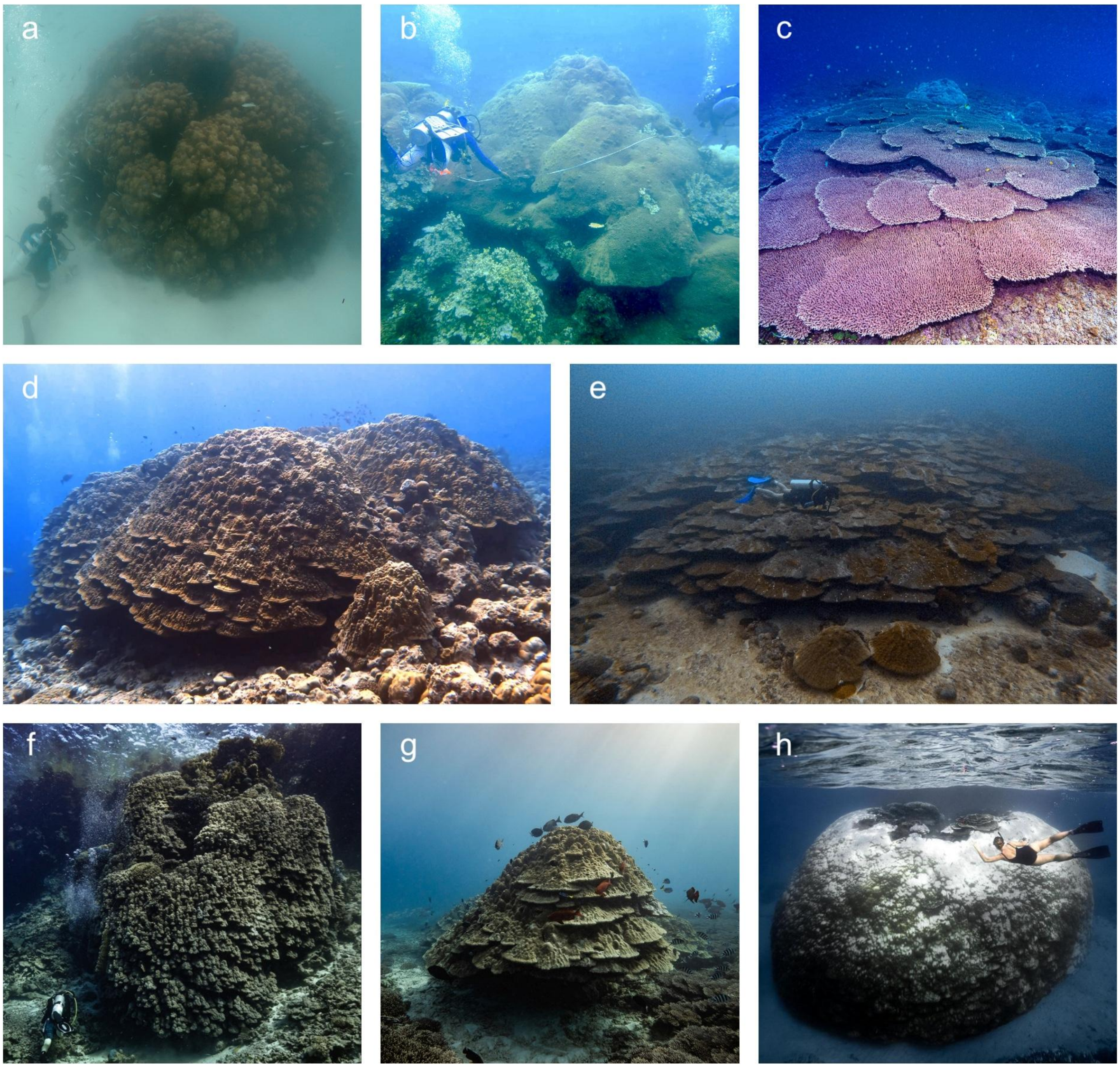

Figure 8. Overview of some of the notable observations received from around the world: **a)** *Porites* sp. of 7 m in linear length found in Faafu Atoll, Republic of Maldives; **b)** *Diploastrea heliopora* of 7.2 m in linear length found in Thailand (Gavin Miller—Global Reef); **c)** *Acropora* sp. of 5.7 m in linear length found in Indonesia (Vincent Chalias - Ocean Gardener); **d)** *Porites* sp. of 8 m in linear length found in Noonu Atoll, Republic of Maldives (Cecilia Maccanti); **e)** *Porites* sp. estimated > 10 m in linear length in Gaafu Alif Atoll, Republic of Maldives (Ocean Tribe); **f)** *Porites* sp. of 7.9 m in height found in Saudi Arabia (Luis Silva - Red Sea Global); **g)** *Porites* sp. of 8.1 m in linear length found in Fregate Island, Seychelles (Daniel Bichsel - Oceans Hope); **h)** *Porites* sp. of 10 m in linear length found in Australia (Sheree Jeldosev)

Among the data collected, it is important to specify that 48 reports have been included in the database following dedicated expeditions in search of giant coral colonies by the project's team. Of all the reported corals, 44 have been identified as giant coral colonies following independent validation. Expeditions have been conducted in four atolls in the Maldives, Faafu Atoll, Goidhoo Atoll, Vaavu Atoll, Vattaru Atoll and the island of Thoddoo. Goidhoo and Vattaru have been explored following a specific methodology that required validation and could maximise efforts. Following the placement of several giant corals on the Interactive Map, we recognised that some of the giants were visible in the satellite images and exhibited a peculiar shape and colouration. Following the selection of an area to be explored, satellite images freely available online have been examined, specifically Google Maps, Google Earth Pro, Bing Maps, and Apple Maps, looking for monochromatic circular shapes. The comparison between different basemaps and different historical times allowed us to narrow the findings. Whenever feasible, a customer-grade DJI-Mini 4 Pro drone was then employed to survey the areas more closely and narrow down the selection, resulting in higher-definition images. These images, depending on water conditions and the depth of potential colonies, helped identyifying the location of possible giants, which then underwater surveys confirmed (Fig. 9 a-e).

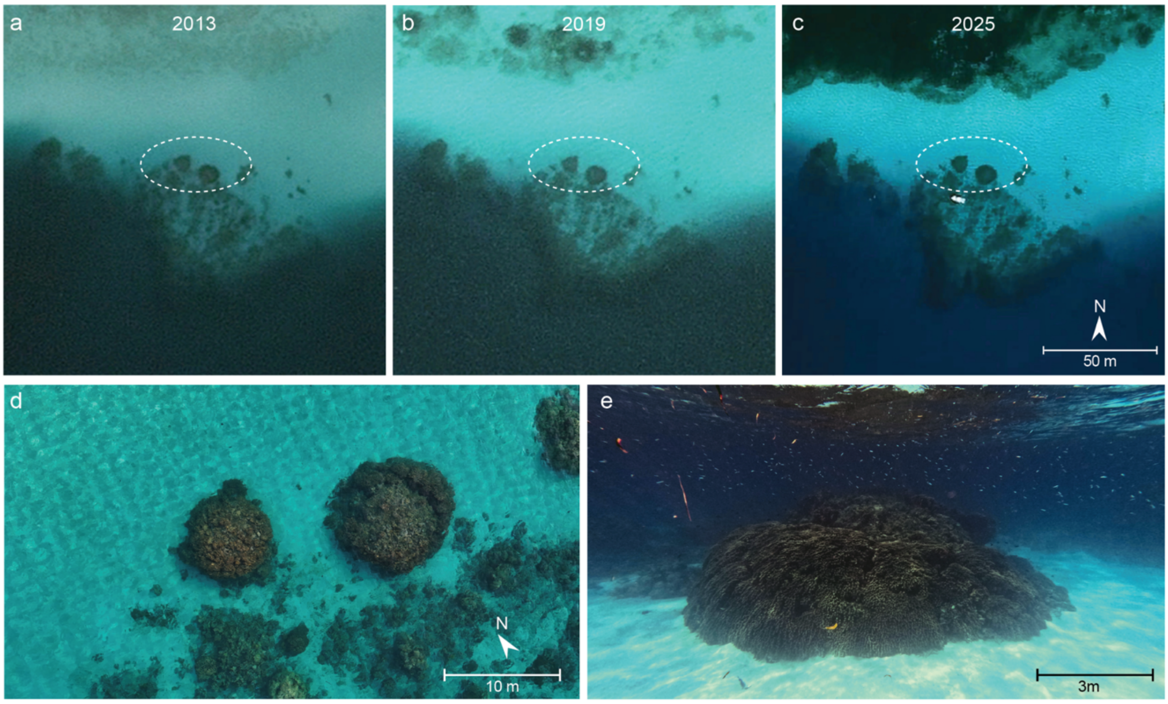

Figure 9. Images showing the process for locating two giants in Goidhoo Atoll, Maldives from satellite photos from Google Earth Pro from **a)** 2013; **b)** 2019; **c)** 2025; **d)** to drone photos; and confirmation through **e)** underwater surveys

Each area was surveyed over four days producing a total of 42 confirmed giants. Out of all the reported colonies, one giant was over 20m in linear length, 7 between 10 and 20 m and the majority (34) between 5 and 10 m (Fig 10a). The most represented genus was *Porites* with 12 colonies (29%), followed by *Psammocora* with 10 colonies (24%), *Goniopora* with 9 colonies

(21%), *Pavona* with 6 colonies (14%), *Heliopora* with 3 colonies (7%), and *Turbinaria* with 2 colonies (5%) (Fig. 10b).

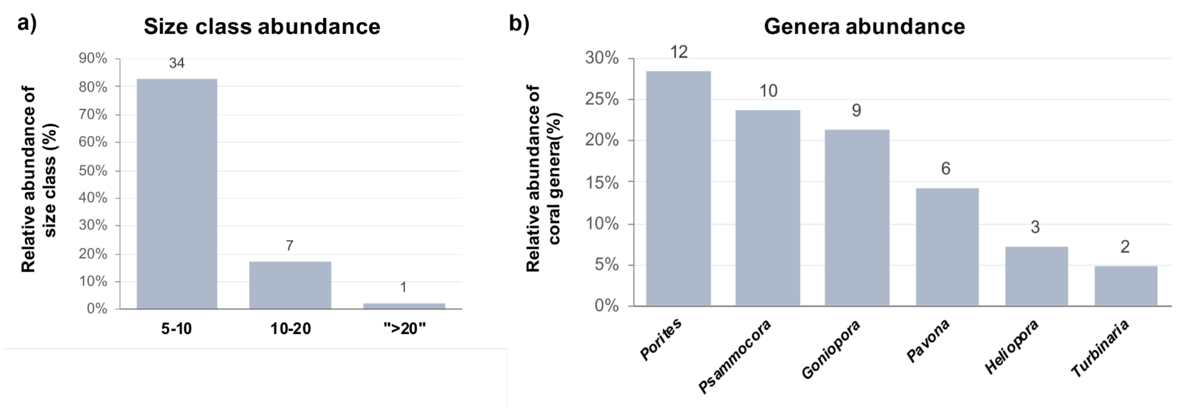

Figure 10. Expeditions reports by **a)** size class and **b)** genera. The numbers in the bar represent the absolute abundance of corals

Most of the colonies reported presented over 75% of alive tissue (27 colonies were reported 76-99% alive and 2 colonies 100% alive).

The largest coral found is a *Pavona* cf. *clavus* from Faafu Atoll, sitting at a depth of 14m, measuring 20 m in diameter and presenting an alive tissue of 76-99% alive (Fig. 5b), although presenting a doughnut-shape with an empty central portion. Results stemming from the identification of giant coral colonies from satellite images, whether or not followed by drone surveys and subsequent underwater surveys, demonstrate that with dedicated efforts, a number of giant colonies can be identified in a reasonable amount of time. As for the study conducted around the island Ta'U in American Samoa (Coward et al., 2020), the majority of large coral colonies belong to the 5-10 m size class, although it is remarkable the presence of one colony over 20 m in linear length in such a small sample.

Although the estimated age of corals ranges from a few years (Richards et al., 2015) to over 1000 years (Devlin-Durante et al., 2016; Soong et al. 1999;), the presence of the latter remains unique, rare, and enigmatic, calling for further studies with particular attention to the reasons of their long survival. Corals are not immune to senescence, as demonstrated by studies on the aging mechanisms (Irikawa et al., 2011), with larger colonies presenting higher partial mortality, decreased lesion regeneration, and lower calcification rate (Bythell et al., 2018). Moreover, despite a report describing the reproduction of a very large coral (Mezaki et al., 2014), it is still unclear if large colonies undergo reproductive decline. Nonetheless, massive corals such as *Porites* sp. that were highly represented in our study seem to present an indeterminate growth (Bythell et al., 2018). The exceptional longevity of certain colonies seems to defy the typical limits of coral survival and warrants future studies. Further investigations could focus, among others, on intracolonial or intraspecific genetic diversity, genetic traits of coral resilience and resistance to environmental stressors, senescence, reproductive capacity, microbiome, symbioses, environmental parameters of the surrounding areas, and changes in growth rate over time. The extended longevity and long-term growth to gigantic size may be the result of a combination of biological, ecological, and environmental factors (Lough & Cantin, 2014). For instance, an area subjected to strong water flow may mitigate the thermal stress induced by increased sea temperatures during bleaching events, allowing some corals to survive (Nakamura & van Woesik, 2001). Similarly, this condition may be helpful in terms of nutrient availability and reduction of disease susceptibility (Maynard et al., 2015). Moreover, pristine coral reefs with a diverse and structured fish community may also play a role by limiting competition with opportunistic organisms such as algae (Raymundo et al., 2009). Or, again, the remoteness of some reefs or colonies from human activities may provide conditions leading to corals' unusual growth, having shown net positive carbonate budgets (Perry et al., 2015). Interestingly, the data collected so far by Map the Giants showed diversified results. In fact, the reported giants belonged to different genera, exhibited different growth morphologies and potential adaptation to environmental stress. From an initial evaluation of the satellite images, it was intriguing to note that some of the largest colonies were found in sandy lagoons. Enclosed, sandy lagoons, although more protected from wave action, are characterized by warmer temperatures and reduced hydrodynamics, higher nutrient loads, and greater sedimentation, which are generally and historically considered more challenging environments (Kleypas et al., 1999). In addition, from an analysis of the coordinates, colonies did not appear to be significantly affected by anthropic disturbances, despite some of them were found in localities close to human settlements and areas with intense recreational activities (e.g., diving, snorkelling), which can pose potential threats (Abidin & Mohamed 2014; Soong et al., 1999). This variability in size, location, and taxonomy calls for in-depth studies to determine which factors might enable these corals to thrive under conditions that have proved fatal to many others. The rapidly growing Map the Giants dataset offers an invaluable resource to create models to shed light on the distribution of large corals and help conservation managers forecast their vulnerability in the face of climate change. Old monumental colonies hold invaluable ecological and biological significance and should also become culturally valuable (Montano et al., 2024). In fact, their terrestrial counterparts, monumental trees, have remarkable socio-cultural importance (Blicharska & Mikusiński, 2014), being targets of ecotourism (Asan, 2017), and benefitting from various forms of protection (Lisa, 2011; Sladonja et al., 2023). Additionally, giant colonies might provide unique contributions to paleoclimatic studies. In fact, their skeleton preserves information of past climate and oceanographic conditions, which might provide important insights into the history of environmental changes. For instance, a recent study of a single 600-year-old *Diploastrea heliopora* colony from Fiji revealed how the Pacific Ocean has changed since 1370 CE (D'olivo et al., 2024). Even more importantly, understanding the mechanisms at the basis of their long-term survival might lead to breakthroughs in coral reef conservation. Giant colonies could be a reservoir of genetic material and information, symbionts, or biomolecules that could enhance effective interventions for maintaining coral reefs functional in the face of ongoing and future environmental changes. This may boost the performance and enhance the efficiency and scalability of these actions (Peixoto et al., 2024). The success of the project demonstrates the importance and effectiveness of the citizen-science approach, similar to other studies (Kelly et al., 2020), as a powerful, cost-effective tool to collect essential ecological data at a large geographical scale, while also fostering public engagement in marine conservation (Earp & Liconti, 2020). By mobilizing divers, snorkellers, and local communities, the project has demonstrated how giant coral colonies, despite being rare, can be effectively detected and mapped. Notably the efforts of a single conservation organization (Global Reef) over a year reinforced the power of systematic surveys, documenting nine colonies within an area measuring about a hectare (Fig. 1c). Finally, from a conservation perspective, identifying and protecting these unique and rare colonies would also increase the ecological value of their habitats and reefs, turning these locations inhabited by giants into priority areas of conservation. Giant colonies, seen as ancient guardians of a unique resistance to climate change, could thus become powerful symbols of resilience against biodiversity loss and climate change. Their iconic status may also promote a deeper connection between people and coral reef ecosystems, similar to the reverence for ancient trees in the terrestrial environment (Pasques & Munné-Bosch, 2024). Raising awareness about these extraordinary organisms could inspire admiration and increase conservation efforts, encouraging the protection of this fragile yet fundamental ecosystem and contributing to the identification of sensitive areas worth protection. In conclusion, the preliminary results of this ongoing project offer a beacon of hope for coral reefs to survive the dramatic challenges posed by climate change and human pressures. By laying the basis for a global, collaborative effort, Map the Giants represents a crucial starting point to tackle many exciting scientific questions surrounding the existence and survival of the world's largest corals. At the same time, by integrating scientific research and public engagement, Map the Giants promises to enhance ocean awareness, contribute to the protection of sensitive habitats, and support the long-term preservation of critical marine ecosystems.

Table 1. Number of valid giant coral entries by genus, growth form, size class and maximum linear length (m)

Species ID	Growth form	Size class				
		>20 m	10-20 m	5-10 m	# of colonies	MAX LENGTH (m)
Acropora	tabular			3	3	6.9
tot					**3**	**6.9**
Diploastrea	encrusting			2	2	6.3
	massive			9	9	7.5
tot					**11**	**7.5**
Galaxea	columnar	1			1	45.7
	massive		1		1	-
	submassive	2	1		3	95.0
tot					**5**	95.0
Goniopora	columnar		1	7	8	15.2
	massive			1	1	9.0
	submassive	2	2		4	28.0
tot					**13**	**28.0**
Heliopora	other			3	3	9.0
tot					**3**	**9.0**
Montipora	foliose			1	1	-
tot					**1**	-
Pavona	columnar	1	2	2	5	20.0
	massive	1	2		3	34.1
	other		1	1	2	5.6
	submassive	1	1		2	5,0
tot					**12**	**56.0**
Pocillopora	other			1	1	4.5
tot					**1**	**4.5**
Porites	massive		5	60	65	17.5

	other			2	2	7.0
	submassive	1		1	2	27.0
tot					**69**	**27.0**
Psammocora	massive			8	8	9.4
	other			1	1	5.0
	submassive			2	2	-
tot					**11**	**9.4**
Turbinaria	foliose		3		3	11.0
tot					**3**	**11.0**

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2.4.5 Supplementary material 1

Mapping monumental corals through citizen science

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Table S1 - Survey fields present in the online submission form (https://www.mapthegiants.com/giant-corals-share-your-sighting/). Mandatory fields are marked with an asterisk.

	SIMPLE SURVEY	ADVANCED SURVEY
Name	✓*	✓*
Surname	✓*	✓*
Your email address	✓*	✓*
Sighting Date	✓*	✓*
Country	✓*	✓*
Site name	✓	✓
GPS location	✓	✓
Size class (5-10 m; 10-20m; >20m)	✓*	✓*
Growth-form	✓	✓
Measurement technique (Tape; Photo; Photogrammetry; Estimation)	✓*	✓*
Photos	✓*	✓*

Depth (Top)		✓
Depth (bottom)	✓	✓
Coral ID (genus or species)		✓
Colony linear length		✓
Colony width		✓
Colony height		✓
Colony diameter		✓
Colony perimeter / circumference		✓
Colony health condition (0-dead; 1-25% alive tissue; 26-50% alive tissue; 51-75% alive tissue; 76-99% alive tissue; 100% alive)		✓
Bleaching		✓
Tissue abnormalities		✓
Potentially harmful interactions (*Acanthaster planci*; *Culcita* sp.) *Drupella* sp. *Terpios hoshinota* *Dendropoma* sp. Algae, other)		✓
Water temperature (°C)		✓
Drone model		✓
Height of the flight		✓
Notes	✓	✓

Table S2 - Number of valid giant coral entries by genus, growth form, and recorded maximum linear length (m)

Coral genera	Growth form	Number of colonies	Max length
Acropora	tabular	2	6,1
	tot	**2**	**6,1**
Diploastrea	massive	6	7,2
	tot	**6**	**7,2**
Galaxea	massive	1	> 10
	tot	**1**	**> 10**
Goniopora	massive	2	9
	other	1	9,4
	tot	**3**	**9,4**
Heliopora	other	3	9
	tot	**3**	**9**
Montipora	foliose	1	5-10
	tot	**1**	**5-10**
Pavona	massive	1	16
	other	3	20
	submassive	1	26
	tot	**5**	**26**
Pocillopora	other	1	7,5
	tot	**1**	**7,5**
Porites	massive	43	13
	other	1	5
	submassive	1	5,2
	tot	**45**	**13**
Psammocora	other	1	5
	tot	**1**	**5**
Turbinaria	foliose	1	11
	tot	**1**	**11**
Not identified		1	>10

2.5 Photogrammetry as a conservation tool: documenting giant corals in 3D

2.5.1 Introduction

The current status of coral reefs

The worldwide decline of coral reefs has been widely documented as a result of local and global threats (Hoegh-Guldberg et al., 2017, 2023; IPCC, 2023). This process is causing habitat loss (Munday, 2004), affecting the three-dimensional complexity of coral reefs (Alvarez-Filip et al., 2009; Bozec et al., 2015; Pisapia et al., 2020), and the abundance and biodiversity of organisms (Hughes et al., 2018; Tebbett et al., 2023). Many species that rely on structural complexity and are associated with coral colonies may decrease as they lose their source of food and shelter (Alvarez-Filip et al., 2015; Kochan et al., 2023), moreover colony surface complexity seems to play a role in facilitating larval recruitment (Hata et al., 2017).

These processes have unavoidable consequences on multiple levels, including the human dimension, even if the extent and timeline are unclear (Hoegh-Guldberg et al., 2019). The livelihoods of millions of people worldwide are at risk as the ecosystem services provided by coral reefs may degrade (Woodhead et al., 2019). In this scenario, and considering current trends, future generations might never witness coral reefs in their present conditions (IPCC, 2023).

Many strategies are being implemented by a variety of organisations, authorities, practitioners and non-professionals, including coral restoration at different scales and involving different stages (Peixoto et al., 2024; Suggett et al., 2024). Simultaneously, countries are setting and agreeing on official limits not to exceed and objectives to reach trhough for example the Paris Agreement (United Nations, 2015) or through the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022). Additionally, awareness-raising activities, campaigns, and ocean literacy programmes aim to share knowledge among the general public to promote bottom-up drivers of positive change (Treviño et al., 2025).

In this context, the value of certain unique organisms is multifaceted and irreplaceable, and only conservation strategies can preserve them. Among these are giant coral colonies, which are rare, likely highly resistant, and resilient organisms (Montano et al., 2024). They can be considered time-machines containing information about the past of the ocean (Siena et al., 2025), and their extraordinary three-dimensional extensive size might represent a unique habitat for various associated organisms. Due to their location, sometimes in the middle of enclosed sandy lagoons (Siena et al., 2025), they could be biodiversity hotspots, forming very large 3D carbonate structures. Furthermore, they could become a symbol of resilience, much like charismatic organisms close to extinction, which are considered true threatened survivors (Courchamp et al., 2018).

However, research on their distribution and abundance has only recently begun, with the aim of increasing scientific knowledge and making them more widely available and known to the general public (Siena et al., 2025).

One of the tools used for large-area monitoring above and below water, and also, for example, in coral restoration to assess projects' success, is Structure from Motion (SfM) photogrammetry, introduced in coral reef studies since the early 2000s (Bythell et al., 2001). This technique allows the three-dimensional reconstruction of elements from the size of a coral polyp to a landscape. The technique involves taking a series of overlapping photos at different angles around an object. SfM software then aligns the photos by identifying common points between them and reconstructs a digital, true-to-scale 3D model that serves as a permanent record of the element at the time of reconstruction (Luhmann et al., 2013).

Since its development, underwater photogrammetry has demonstrated high accuracy in measuring surface area, volume, and rugosity at the scale of coral colonies (Aston et al., 2022; Burns et al., 2015; Ferrari et al., 2017; Figueira et al., 2015). The technique has also been adopted for detecting changes in the external structure of single coral colonies of various growth morphologies with an accuracy of <2mm (Figueira et al., 2015). Research suggests that 3D reconstructions provide more robust metrics for detecting changes, including the development and evolution of coral disease (Burns et al., 2016). Studies have also shown that consumer-grade tools such as GoPro provide an adequate resolution for performing benthic studies (Raoult et al., 2016)

The need for a virtual archive of giant corals as an outreach tool

Research is suggesting that nature connectedness seems to encourage pro-environmental behaviours, reducing the likelihood that people cause harm to it (Ibáñez-Rueda et al., 2020; Martin et al., 2020). In recent years, Virtual Reality (VR) has served as a tool to reduce temporal and spatial distance (Attanasi et al. 2025), a concept that appears to have an influence on awareness and behaviour (Trope & Liberman, 2010). Thus, VR may bring people closer to distant topics and places, and it also allows for visualising the effects of events that would otherwise take years to unfold (e.g., the effects of climate change on a glacier) (Thoma et al., 2023). These technologies can help people connect with the ocean, regardless of whether they live by the coast, or what abilities they have (McKinley et al., 2023), offering inclusive opportunities in a world where access to experiences in the ocean, and ocean literacy are still not equitable (Worm et al., 2021). For example, landlocked regions or low-income countries could benefit from the use of VR to enable people to access virtual experiences at reduced cost (Santoro et al., 2017).

VR has also been widely used in many disciplines, such as geological studies, to supplement field trips and allow people (particularly students) to experience complex geological sites that, due to high costs and logistical reasons, would not be able to access otherwise (Giles et al., 2020). Virtual field trips have been included in geology curricula for many years (Hurst, 1998). Using SfM surveys to generate high-resolution 3D reconstruction can further enhance the value of VR, replacing or complementing, when necessary, real-life experiences. The increased distribution and affordability of VR headsets offer promising venues to explore virtual environments in immersive ways at contained costs (Harknett et al., 2022).

The concept of 'dry diving' is used to refer to diving experiences outside the ocean that allow non-divers to virtually access the underwater world, enhancing, for example, the fruibility of submerged cultural heritage sites (Liestøl et al., 2021) or cold-water coral reefs and deep-water habitats (de Oliveira et al., 2022). These technologies can allow different groups of people to experience the ocean in inclusive and innovative ways, otherwise impossible (Santoro et al., 2017)

Immersive VR is fun and engaging, enabling people to express their thoughts about natural sites. This fosters outreach, helping scientists understand society's needs and opinions and non-professionals access opportunities they would otherwise not have access to (Tibaldi et al., 2020).

These technologies represent a valuable tool to freeze in space and time natural and cultural heritage, not only to raise awareness among the present generation but also as a repository for future generations. Considering the vulnerability of coral reefs worldwide, and despite the centennial resistance of giant coral colonies, we now face the reality that organisms that have been around for hundred years risk disappearing before we have begun documenting their existence (Siena et al., 2026).

The aim of this study was thus to collect high-resolution images of giant coral colonies and reconstruct them through SfM Photogrammetry to achieve two goals:

1. Extract morphological parameters of the colonies

2. Create an archive of these reconstructed organisms for outreach and as the foundation for a future virtual museum.

2.5.2 Materials and Methods

The study was conducted over the course of several expeditions in the Republic of Maldives between November 2024 and May 2025. Giant coral colonies were identified and surveyed in Faafu Atoll, Goidhoo Atoll, Vaavu Atoll, Vattaru Atoll and the island of Thoddoo.

A total of 15 colonies have been photographed and measured on site to ensure compliance with the giant coral colonies criteria (see 2.3.6 for the full definition).

Morphological parameters for the colonies that were measured in situ included height (averaged across at least 2 diving computers), length (for some colonies), and perimeter (measured with underwater measuring tapes), whereas alive tissue was visually estimated.

Photos were taken with multiple cameras, according to the surveyor, specifically a Sony Alpha 7 ILCE-M2 and a GoPro Hero 11 Black.

The Sony Alpha 7 ILCE-M2, a mirrorless Full-frame camera, was set to High resolution, capturing images of 6000x4000 pixels at an interval of 2 seconds. The GoPro Hero 11 was capturing photos every second with a resolution of 5568x4872 pixels and was set to linear mode to avoid lateral distortion. The total number of photos varied according to the dimension of the colony, the visibility and complexity of the structure. Photos were taken both parallel and/or perpendicular to the ocean surface and at an angle to maximise the surface captured in the photos.

An underwater measuring tape was placed on the corals, associated, at times, with Ground Control Points (GCPs), downloaded from Agisoft Metashape software. These allow for more accurate photo alignment by providing common reference points and for scaling the model to real-world dimensions.

From the dataset, blurred and moved photos or photos presenting non-target organisms, such as when they included schools of fish covering most of the coral structure, were manually removed to avoid visual noise in the final model.

Images were then enhanced and uniformed using CLAHE (Contrast-Limited Adaptive Histogram Equalisation) algorithm through MATLAB to enhance contrast by partitioning the images into segments and making automatic changes more accurately (Fig. 1).

Photos were then imported into Agisoft Metashape Professional 2.2.1 and aligned with the highest setting to then create scaled colour 3D textured models, Digital Elevation Models (DEM), and orthomosaics. The steps of the workflow were as follows: 1) alignment of the photos, 2) creation of the depth maps (model) in high quality, moderate filtering, 3) creation of the texture, 4) scaling of the models using at least 5 scale bars in different areas of the colony,

5) creation of a copy of the model where parts not pertaining to the colony were removed, 6) creation of a copy of the model and closure of the holes, 7) creation of the point cloud in high quality, 8) creation of the DEM, 9) creation of the orthomosaics, and 10) extraction of morphometrics on the model, the DEM or the orthomosaic.

All the parts not pertaining to the main coral model were manually cropped (e.g., substrate) to be able to extrapolate morphological metrics of the coral colonies such as length, height, perimeter, total surface area, planar surface. To assess the volume, the models were closed using the Metashape "close hole" tool set to "highest". The height was measured on the DEM, whereas the perimeter, length and planar area were measured on the orthomosaic, drawing, respectively, a line that intercepted the lowest and highest points of the colony, a line at the widest section, and a polygon following the largest contour, independently of the points depth. Finally, to calculate surface complexity, we used the 3D-to-2D surface ratio (Urbina-Barreto, Garnier, et al., 2021).

The final stage of the workflow involved the conversion of the 3D textured model into files compatible with a head-mounted display (HMD), and that could be integrated into the main online project platform.

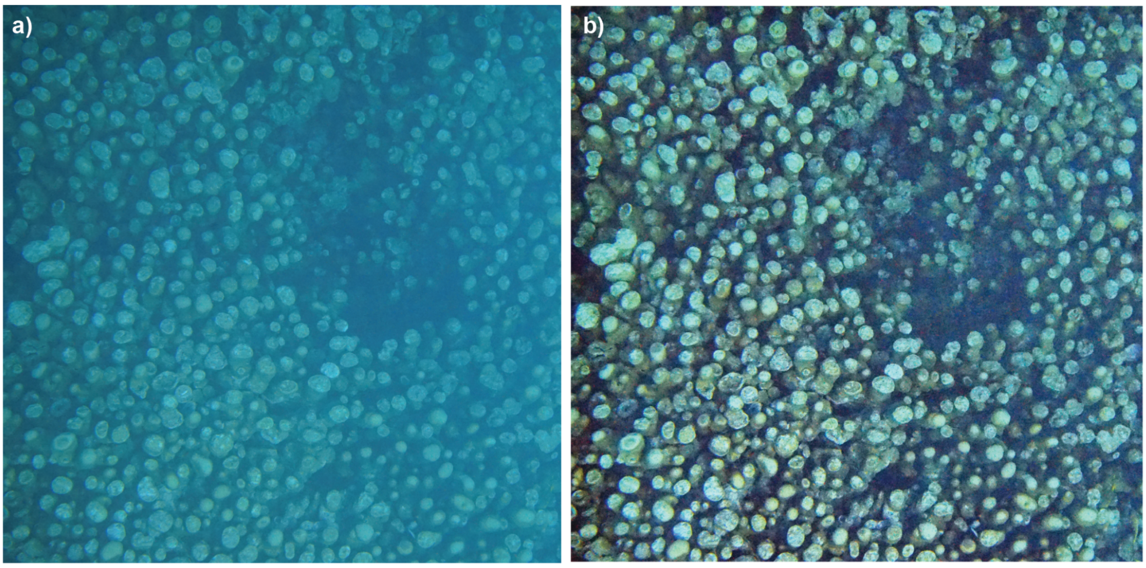

Figure 1. Comparison of images **a)** original photo; and **b)** edited photo using CLAHE algorithm.

2.5.3 Results and Discussion

A total of 15 coral colonies have been surveyed by the MaRHE Center team, and 14 were successfully reconstructed through SfM photogrammetry (Table 1, Fig. 2). For one colony, a *Goniopora* cf. *columna* alignment was not successful and subsequent dives were not possible. Additionally, participants in the citizen science initiative contributed with either full 3D models or photo libraries for 4 coral colonies (not included in the present analysis).

Table 1. Giant coral colonies reconstructed through 3D photogrammetry by the MaRHE Center team.

ID	Date	Coral genus	Atoll	GPS X	GPS Y
78	13/11/24	*Turbinaria*	Faafu Atoll	72.929278	3.125056
103	14/11/24	*Pavona*	Faafu Atoll	73.018132	3.117464
129	01/04/25	*Psammocora*	Goidhoo	72.9824892	4.8724088
132	28/03/25	*Turbinaria*	Goidhoo	72.8871156	4.8745224
138	30/03/25	*Porites*	Goidhoo	72.954775	4.8392601
139	30/03/25	*Porites*	Goidhoo	72.9544960	4.8394071
141	02/04/25	*Porites*	Thodoo	72.96299	4.446153
145	04/05/25	*Porites*	Vaavu	73.401442	3.817459
146	04/05/25	*Goniopora*	Vaavu	73.404782	3.817231
147	05/05/25	*Psammocora*	Vattaru	73.446734	3.229104
148	05/05/25	*Psammocora*	Vattaru	73.4389291	3.2258250
149	06/05/25	*Pavona*	Vattaru	73.459987	3.259033
152	07/05/25	*Psammocora*	Vattaru	73.407294	3.272932
153	07/05/25	*Porites*	Vattaru	73.406676	3.271330

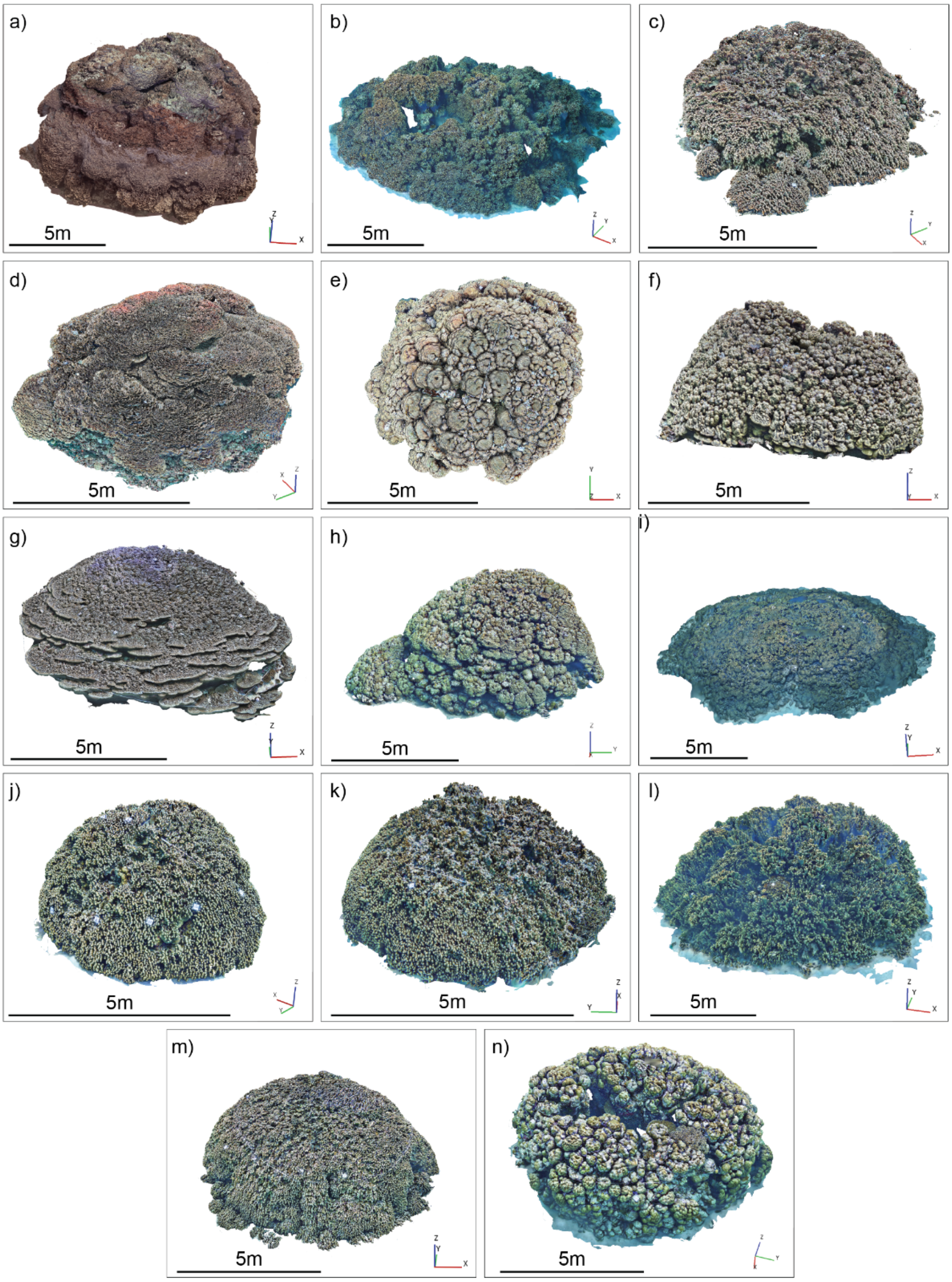

Figure 2. 3D models: **a)** *Turbinaria* sp. from Faafu Atoll, 38.5 m in perimeter (ID #78) ; **b)** *Pavona* sp. from Faafu Atoll, 66 m in perimeter (ID #103); **c)** *Psammocora* sp. from Goidhoo Atoll, 26.6 m in perimeter (ID #129); **d)** *Turbinaria* sp. from Goidhoo Atoll, 39 m in perimeter (ID #132); **e)** *Porites* sp. from Goidhoo Atoll, 21.5 m in perimeter (ID #138); **f)** *Porites* sp. from Goidhoo Atoll, 23.8 m in perimeter (ID #139); **g)** *Porites* sp. from Thodoo island, 27.9 m in perimeter (ID #141); **h)** *Porites* sp. from Vaavu Atoll, 31,9 m in perimeter (ID #145); **i)** *Goniopora* sp. from Vaavu Atoll, 41.8 m in perimeter (ID #146); **j)** *Psammocora* sp. from Vattaru Atoll 15.5 m in perimeter (ID #147); **k)** *Psammocora* sp. from Vattaru Atoll, 19,2 m in perimeter (ID #148); **l)***Pavona* sp. from Vattaru Atoll, 41.7 m in perimeter (ID #149); **m)** *Psammocora* sp. from Vattaru Atoll, 24.5 m in perimeter (ID #152); **n)***Porites* sp. from Vattaru Atoll, 23.2 m in perimeter (ID #153).

All of the models were realised using the same parameters, alignment set to High, Depth Maps realized with High Quality Moderate filtering, 3D models in High quality, and Point Cloud in high quality. Models realised using CLAHE algorithm resulted much better in details and clarity (Fig. 3).

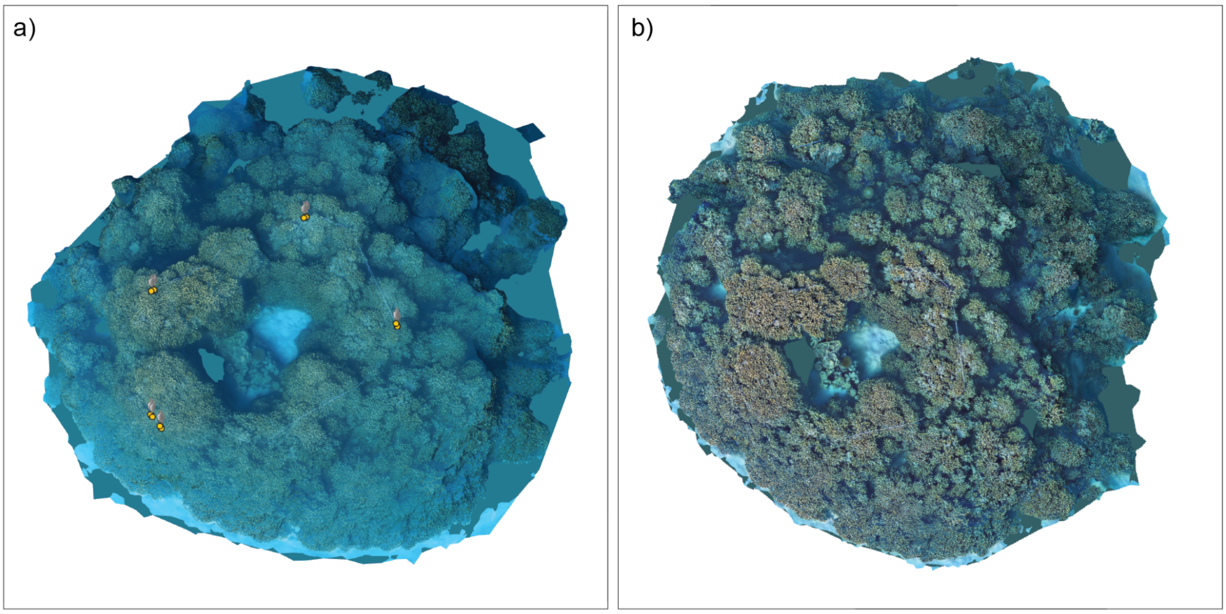

Figure 3. Example of models resulting from **a)** original non-edited images and; **b)** images processed through CLAHE algorithm.

Results from manual measurements and measurements derived from photogrammetry differ to a certain extent (Table 2). Height and perimeter values taken on site (through diving computers and tape measures, respectively) and through photogrammetry were compared statistically to assess significance in differences of methods. Analysing q-q plots, measurements of the differences for both parameters resulted normally distributed, thus paired t-test was used. Analyses of the height suggested no statistically significant difference between tape (M=4, SD=1.5) and photogrammetry (M=3.9, SD=1.6), ($t(13)=0.8$, $p=.463$.). However, photogrammetry measurements for perimeter (M=30.7, SD=13) were significantly higher than tape measurements (M=28.8, SD=12.3), ($t(14) = 4$, $p = .001$.
These results may be due to several factors: length and perimeter on the reconstructed models are measured on a 2D image, extending to the widest point possible, regardless of its depth, something that can not be performed precisely in the field.
For the length, the number of field measurements was much lower than the number of measurements derived from photogrammetry and the significance test was not performed.

Table 2. Ecological parameters derived from photogrammetry compared to parameters measured in the field

ID	Genus	Height		Length		Perimeter	
		Tape	Photogr.	Tape	Photogr.	Tape	Photogr.
78	*Turbinaria*	6	6	11	12.5	35	38.5
103	*Pavona*	6.3	6	20	19.7	63	66
129	*Psammocora*	3	2.1	-	8.1	23.7	26.6
132	*Turbinaria*	6.8	6.9	-	13	32.4 largest 18.3 base	39 largest 19 base
138	*Porites*	4	4.8	-	7	21.5	21.5
139	*Porites*	4	3.3	-	8	23.5	23.8
141	*Porites*	2.5	3.9	-	9	25	27.9
145	*Porites*	4.4	5	10.6	10.7	29.2	31.9
146	*Goniopora*	3.7	3	15.2	13.8	42	41.8
147	*Psammocora*	2.1	2.1	5	5	15.5	15.5
148	*Psammocora*	2.7	2	6.9	5.9	19	19.2
149	*Pavona*	4.4	4	14	12.7	40	41.7
152	*Psammocora*	3.4	2.9	8.2	8.1	22.2	24.5
153	*Porites*	2.8	2.2	8	7.5	21.6	23.2

As coral colonies with more complex shapes may offer larger and more diverse shelter for various organisms (Darling et al., 2017; Urbina-Barreto, Chiroleu, et al., 2021), influencing associated biodiversity (Graham & Nash, 2013), a metric worth analysing was "surface complexity" (surface area / planar area). Certain colonies, located in the middle of sandy lagoons, may act as hotspots of biodiversity, attracting numerous organisms seeking shelter and food among their large, three-dimensional structures. Additionally, this parameter could eventually be linked to future in situ studies on associated organisms or predictive models of coral reef fish density, diversity, and biomass (Wedding et al., 2019). Although the results of these analyses can not be considered representative of the genera, they provide important information on the complexity of each colony studied and to compare them amongst each other. Surface area to planar area ratio varied between 5.76 and 1.98 with the most complex coral being a *Turbinaria* and a *Porites* (Fig 4). If *Turbinaria* corals can be commonly quite complex in shape, this is less expected by massive growth forms such as *Porites* (Urbina-Barreto, Chiroleu, et al., 2021). Yet, the large sizes of the colonies may influence how a colony develops threedimensionally as corals body size may increase and reduce over time through asexual reproduction counteracted by partial mortality (Buddemeier & Kinzie, 1976). The limited sample size for each genus did not allow to perform statistical analysis and correlate the surface complexity to the genera.

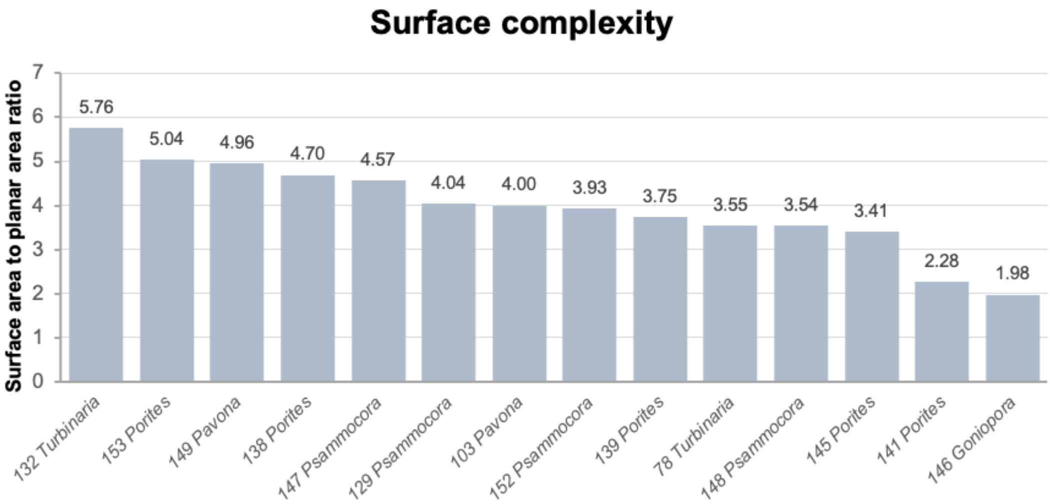

Figure 4. Surface complexity of corals calculated as surface area (m^2) to planar area (m^2) ratio.

Both the models that adopted GCPs and those that only used measuring tape, and those that adopted the professional Sony Alpha 7 ILCE-M2 and those using GoPro images provided good results. Each dive lasted between 40 minutes and 1 hour, and the number of photos collected depended on the prior experience of the surveyor and the possibility of eventually performing a second scan, rather than being directly proportional to the dimensions of the colonies or the features of the camera. Aligned photos (not photos collected) ranged between 352 and 2,945. For example, the elevated number of photos for *Turbinaria* 132 (2,945) (Table 3) resulted from two separate photo collections one day apart, after recognising, during photo alignment, that certain sections of the colony were missing. Inevitably, smaller colonies such as *Psammocora* 147 and *Psammocora* 148 (19.9 m^3 and 34.6 m^3, respectively) required fewer photos.

The collection of photos for 3D reconstruction certainly requires some technical experience, starting from SCUBA diving equipment and the use of UW cameras. As such, this technique should be carefully planned to ensure safety and effective results. As shown in Fig. 5a-c, some practical challenges in realising photogrammetry of giant corals may include, for example, limited visibility around the colonies, shadowed areas, or reduced coral depth. The software might struggle to find matching points during the alignment process, or the operator might struggle to ensure enough photos are taken to achieve sufficient overlap. Despite the collection of photos with tilted camera (Bayley et al., 2019), the presence of fish schools, dark overhangs and small inaccessible crevices could not be avoided at times leaving gaps in the generated models (Fig. 5d) as shown in other projects (Remmers et al., 2024).

Table 3. Volume and number of photos for each reconstructed colony

ID#	Genus	Volume (m^3)	Number of photos
132	*Turbinaria*	301.54	2,945
138	*Porites*	63.77	1,730
139	*Porites*	94	1,666
78	*Turbinaria*	298.37	1,378
145	*Porites*	190.2	1,285
141	*Porites*	54.9	1,241
149	*Pavona*	213.14	1,194
129	*Psammocora*	55.95	962
146	*Goniopora*	173.68	757
153	*Porites*	57.48	757
152	*Psammocora*	68.32	631
147	*Psammocora*	19.9	558
103	*Pavona*	593.58	576
148	*Psammocora*	34.6	352

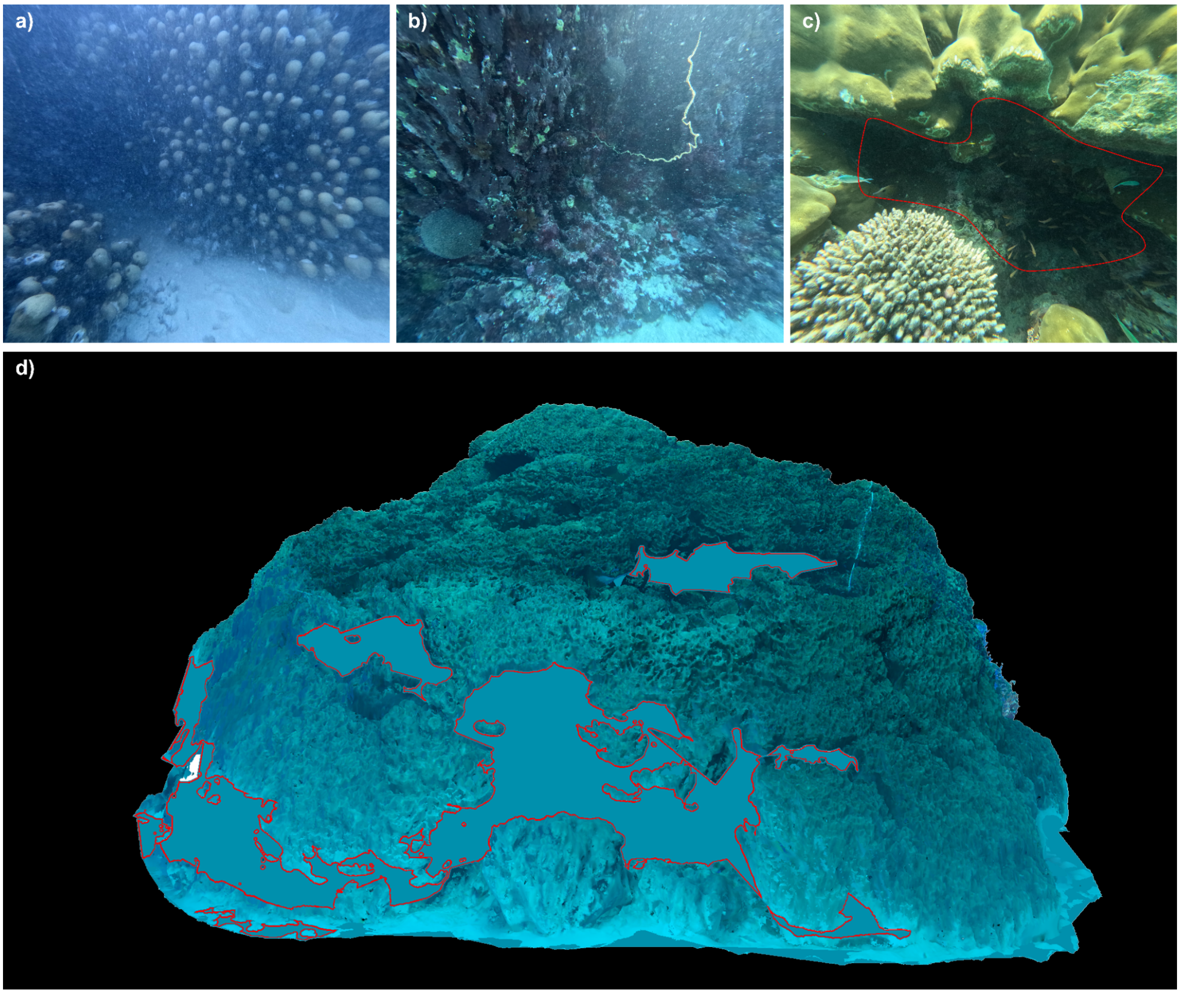

Figure 5. Examples of images of areas where alignment of images resulted challenging for the software producing in gaps in the models: **a)** high sedimentation; **b)** areas with uneven light presenting highly bright areas and dark parts; **c)** image showing a darker area (red path) where details are not visible in the final model; **d)** 3D model showing areas (red paths) where missing parts -holes- were closed with the software.

Given the affordability and popularity of high-resolution action cameras it is not impossible to envision receiving this type of contribution even in a citizen science project, as it has already happened (see 2.4.3). Since SfM photogrammetry requires careful planning and a dedicated dive, contributors providing this data are likely to be based close to the colony for which they are submitting. It is therefore envisionable that if citizen scientists don't have the software for generating the model, images are sent to the project managing team and processed promptly to request additional photos when alignment fails, or the model shows large gaps. Since creating 3D models requires specific software (some free and some subscription-based), and understanding the necessary steps and workflow, we expect a higher likelihood that contributors might choose to share a photo library for us to process, rather than expecting to receive a complete reconstruction.

Moreover, given the elevated number of giant coral entries from single organisations that are permanently based in a specific location (Siena et al., 2025), there is great potential for long-term collaborations yielding valuable data. Yearly 3D models or models realised following specific events (e.g., bleaching or disease outbreaks (Meiling et al., 2020)) could provide important insights into the evolution of coral colonies and their response to these circumstances (Ferrari et al., 2017). Although the time scale of these surveys is short compared to the life span of most colonies, climate change and direct local anthropogenic threats pose greater threats to these organisms nowadays than in past centuries. One of the aims of the project's interactive map is to support long-term monitoring of coral colonies. By publicly sharing information about each giant, the goal is to make the communities surrounding the colonies aware of their existence and potentially involve multiple stakeholders in monitoring them and collectively expanding knowledge. Therefore, in some locations, a tourist's opportunistic encounter with a giant coral and subsequent submission to the database may lead a more experienced contributor or organisation to provide more detailed data, including collecting photos for generating 3D models.

Despite the specific tools and experience required for SfM photogrammetry, the results from models and orthomosaics are of such detail and value to science and outreach that this technique is especially encouraged for more trained contributors.

2.5.4 Conclusions

The use of 3D models for environmental studies has been validated by various disciplines both as a research tool and as an outreach means. In coral reef studies, SfM photogrammetry is used both at landscape scales and at the coral level, allowing for the extraction of various morphological metrics useful to monitor reefs and coral in great detail. In association with other software and even machine learning models, it can help monitor, among others, the diffusion of disease lesions, the growth and loss of tissue and skeleton, the shelter capacity of corals and the effects of bleaching or outbreak events. The complexity and dimension of giant coral colonies, however, require not only experience in photo collection and processing, but also a long time and powerful computers. Giant corals provide shelter to numerous mobile organisms, such as schools of fish, that have been identified as one of the possible cause of artifacts within models. The three-dimensionality and rugosity of the organisms, as well as the presence of overhangs and crevices, are reflected in the uneven brightness and colouration of photos that require processing with specific algorithms to achieve uniformity. Despite these measures, given their large size, models may present holes, leaving gaps in the data that can be collected. However, SfM photogrammetry appears suitable for data collection on giant coral colonies, especially when adequate precautions are taken to overcome practical challenges. The differences between in-situ and ex-post measurements need to be accounted for when dealing with entries received in the database and the level of precision be considered in reports. Further studies on the correlation of morphological parameters with associated organisms and health status of the giant coral colonies may produce valuable insights on these still overlooked organisms and enhance our understanding of them.

Including 3D models of giant coral colonies in VR headsets can narrow the gap between society and the ocean. Considering that most of the giant coral colonies may require SCUBA diving to be fully experienced and that these may be found in areas challenging to reach, this tool may be particularly beneficial to ensure inclusiveness in ocean literacy. Making the 3D models freely downloadable from the website may further enhance this aspect.

Given the specific software and workflow necessary to realise 3D models, it is likely that most of the contributions to Map the Giants will continue to include at most measurements taken in-situ, despite the immense value of 3D models.

The diversity of coral genera and sizes of the current models provides a solid foundation for developing a public database of giant corals in 3D. These have the potential to be shared on Map the Giants website and reach a wide audience, as well as acting as a repository for high-definition baseline data on these organisms, in light of the continuous decline of coral reefs, which may impact even these centennial corals.

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2.6 Map the Giants: discussion and conclusions

2.6.1. Discussion and Conclusions

The importance of giant coral colonies from a multitude of points of view has been underestimated for many years. Despite any study mentioning the presence of a large coral colony recognising its value either in terms of longevity, genetic resilience, historical archives (e.g., Canesi et al., 2024; D'Olivo et al., 2024; Mezaki et al., 2014; Smith et al., 2021), or uniqueness (Brown et al., 2009), efforts have never been made before to identify these organisms on a global scale. In reality, we still lack a global picture of their distribution and ecological traits as well as a global recognition of the value they have.

The project Map the Giants stems from a multidisciplinary knowledge gap and aims to fill it by providing a global repository to assess the distribution of giant corals, using a standardised methodology to monitor morphological and ecological parameters, and laying the groundwork to initiate discussions on their conservation. The value of the project extends beyond ecological outcomes, recognising the importance of these centennial organisms to the communities where they are found, as well as their role in raising awareness of the resilience and vulnerability of coral reefs.

From an ecological perspective, most monitoring efforts currently focus on live coral cover associated with species abundance, but protocols including specific metrics for surveying coral demographics are rare (Edmunds & Riegl, 2020), and thus giant corals are systematically overlooked. Studies on the impacts of bleaching don't mention their presence, and consequently, neither their responses. We are thus failing to understand how these organisms are coping (or perishing) under the current climatic and environmental crisis. Whether these colonies can withstand current environmental pressures remains uncertain, and many may be lost before being documented. In fact, the conditions they are currently facing are more extreme than what they have experienced for the vast majority of their lives, since the first reef-wide bleaching events were recorded starting from 1931 (Yonge & Nicholls, 1928), with human influencing and increasing the chance of compound extreme events since the 1950s (IPCC, 2023). The extent and severity of local and global threats pose risks even to these animals that have existed for hundreds of years, and the urgency to act is paramount for both the scientific community and society.

The study by Strona and Montano (2025) on giant corals' exposure to heat stress, based on reports extracted from the database, indicated that out of 85 colonies examined, most (84.7%) were found in thermal refugia and never faced severe heat stress. However, 13 colonies experienced severe heat stress multiple times, but the lack of historical data on the single colonies doesn't allow us to answer the question of whether these corals showed resilience by bleaching and recovering or whether they possess exceptional resistance features. As the project was launched just before the onset of the fourth global bleaching event, some of the 2024 submissions indicated that even giant coral colonies suffered bleaching. For some of them (2) post-event surveys were conducted, indicating full recovery, and although these are far from being extensive results, they suggest that continued monitoring of colonies and stewardship is possible and that the project has the potential to significantly contribute to answering novel questions. Resistance traits within coral colonies are central to many studies (Grottoli et al. 2006, Loya et al. 2001, Voolstra et al. 2021) because they can address questions about the resilience of future coral reefs. However, giant coral colonies have not yet been examined from this perspective.

Citizen science has already proven to be an effective research method capable of producing significant scientific findings (e.g., Bonney et al., 2016; Done et al. 2017; Edgar & Stuart-Smith, 2014; Isdianto et al. 2025; Pancrazi et al. 2026), and Map the Giants is demonstrating promising results. To date, the project has received almost 200 entries from 22 countries, covering a wide area except for the Atlantic Ocean. The project's reach needs to be extended to cover this region and other heavily impacted areas to determine whether the lack of reports is due to limited awareness of the project, rather than the absence of giants. Reports of very large coral colonies, albeit not reaching the threshold set by Map the Giants, are found in the literature from the Caribbean (Hudson et al., 1994), suggesting that centennial colonies are also present in the area; whether they have resisted more recent disturbances would require further research. Furthermore, the database currently does not include giant corals described in the literature, despite the presence of data on them, as we lack up-to-date information on their status. Since some of them have been described decades ago, locating and monitoring them in the present would provide important insights into their evolution over time and their possible responses to the recent effects of climate change or local impacts.

Not unexpectedly, the most commonly reported coral genus is *Porites,* which is known to grow slowly (Guzman & Cortes, 1989; Morgan & Kench, 2012) and show particular resilience (Levas et al., 2013; van Woesik et al., 2011), yet the largest coral colonies appeared to be from the genera *Pavona* and *Galaxea,* reaching remarkable sizes despite presenting less compact growth forms. The presence of very large tabular *Acropora* corals is also a positive indication of the potential resilience of more vulnerable species. Yet, the limited extension of the database calls for caution in making ecological generalisations and defining global patterns at this stage. The methodology proposed for data collection has allowed a variety of participants to contribute, and in the vast majority of cases, the data reported were not limited to the bare minimum required for a submission to be valid. This suggests possible adaptations to the submission fields to further increase the completeness and robustness of the database.

The adoption of a citizen science-based approach for data collection served a dual purpose: achieving worldwide coverage that would otherwise be unattainable, and engaging a broader audience to raise awareness among non-professionals and thus potentially driving conservation initiatives. By adhering to the principles of citizen science (ECSA - European Citizen Science Association, 2015), the project aims to be ethical, robust and value the contributions of participants. Whilst, on one hand, citizen science principles suggest making results as open as possible, sharing information, such as the location of giant coral colonies, may be a sensitive topic and raise concerns. The impact of tourism on very large colonies has already been reported as an issue in the literature (Soong et al., 1999), as has the broader impact of SCUBA diving on coral reefs (Sumanapala et al., 2023) and the broader impact of overtourism in general (Davenport & Davenport, 2006; Bisht, 2025). Yet the long-term stewardship and monitoring of giant coral colonies are envisioned through shared citizen science responsibility, at least until they are included in official monitoring guidelines of governments and environmental agencies.

The development of a clear and adaptable protocol and an accessible website with regularly updated information, all contribute to the role of the project in advancing ocean literacy and despite this not being part of the present studies, many studies have suggested investigating this aspect of citizen science projects (Bonney et al., 2009), a possible future development of Map the Giants.

The public database, continuously expanding, is set to be used by researchers in various fields to conduct multidisciplinary and interdisciplinary studies, to start unravelling the reasons behind these corals' longevity, which may, in turn, lead to a better understanding of what coral reefs of the future may look like.

In addition to data collected by citizen scientists, the project is generating high-resolution 3D reconstructions of giant corals using SfM photogrammetry, enabling the extraction of detailed ecological and morphological parameters that cannot be captured solely through standard observations. These digital models also serve as a permanent record of the colonies' existence and condition at the time of documentation, while providing an engaging and versatile tool for education, outreach, and future research. With the increased availability of low-cost cameras and the presence of stable, long-term contributors, the aim is to continuously expand this parallel database and build a detailed archive documenting changes in colony structure and condition over time. Given the life spans of these organisms, which exceed those of multiple generations of researchers, such an archive will also serve future scientists by enabling comprehensive tracking of their life histories. Additionally, although not implemented in this study, machine learning could complement the project both in validating submissions and enabling the extraction of additional features.

From a conservation perspective, worldwide, efforts are being made to expand protected areas and safeguard endangered species (Michaelsen et al., 2025). In the same way some organisms are classified in the IUCN Red List of Endangered Species because of their vulnerability to extinction in light of their small population size, or reduction trend, geographic range, or probability of extinction in the wild (IUCN, 2012). Yet protection measures for organisms (not species) that are vulnerable due to their longevity and rarity have not yet been considered, at least in the ocean. On land, this is already happening, with policies for the census and protection of large old trees, which are in place in numerous countries (Nolan et al., 2020; Sladonja et al., 2023). It is recognised that conservation strategies for monumental trees must account for differences from traditional approaches, as it is acknowledged that, with them, it is a life stage might go extinct rather than a species (Lindenmayer et al., 2014). Conservation practices for centennial trees follow both a top-down and bottom-up approaches, with both governments and volunteers playing a role (e.g., Save the Redwoods League, 2025; Nolan et. al, 2020). These examples provide important insights into possible policies for the ocean and giant coral colonies. In driving comparisons with other animals, giant corals possess many features that would allow them to be considered charismatic organisms, serving as symbols to stimulate conservation awareness and action (Ducarme et al. 2013).

Further steps will necessarily need to address methods to explore how giant corals can be recognised by the wider society, using both formal and informal instruments. Drawing inspiration from land-based practices for monumental trees and extending protection concepts currently used for species or areas, new tools must be developed to safeguard these unique organisms. The database will help shed light on their distribution, abundance, species contributions, and size ranges, enabling institutions and non-governmental organisations to identify the most valuable and/or vulnerable individuals.

With the current global environmental crisis, giant coral colonies stand as a beacon of hope, offering a powerful counternarrative to loss and destruction and helping spread a positive message. Giant coral colonies underscore the urgency and feasibility of timely conservation action, reinforcing the scientific consensus that meaningful outcomes are still achievable if decisive measures are implemented.

2.6.2. References

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Chapter 3 - Playing with Corals: football as a gateway toward climate action and marine awareness

3.1 Introduction

3.1.1. Ocean literacy and place-based experience as conservation tools

Coral reefs cover less than 0.1% of the ocean surface (Spalding et al., 2001; Spalding & Grenfell, 1997), yet their high biodiversity and numerous ecosystem services make them vital for millions of people worldwide (Giglio et al., 2024). Almost one billion people live in close proximity to coral reefs : 997 million people live within 100 kilometres and 107 million within 5 km of reefs (Sing Wong et al., 2022) and depend directly and indirectly on the resources they provide for their livelihood (Giglio et al., 2024).

The ever-increasing global and local pressures on coral reefs threaten both the ecosystem's functioning and biodiversity, as well as the people who depend on them (Sing Wong et al., 2022). Anthropogenic threats include coastal development, sand and coral mining, destructive fishing practices (including overfishing), pollution (Burke et al., 2011), and ocean acidification resulting from global carbon emissions (Doney et al., 2020). Natural threats include coral bleaching (Reimer et al., 2024), disease outbreaks (Burke et al., 2023), and storm impacts amplified by climate change (Ferrario et al., 2014). It is estimated that, without immediate actions, 90% of the world's coral reefs might be lost by 2050 (IPCC, 2023).

A total of 591 million people from low- and middle-income countries, including Small Island Developing States (SIDS), live within 100 km of coral reefs, with nearly 50% of the SIDS population in 2020 living within 10 km of reefs (Sing Wong et al., 2022). SIDS comprise 58 UN and non-UN members that share both similar and unique vulnerabilities and characteristics; 54 of these countries are coral reef nations (Sing Wong et al., 2022). They are characterised by small size, remoteness, limited resources, heavy reliance on imports and on natural capital, and exposure to the impacts of climate change and global environmental challenges, and they face inequalities in coral reef science participation (Roch et al., 2025). Many of the SIDS are located predominantly or exclusively in low-lying areas. Here, sea-level rise and other effects of climate change pose a significant threat, potentially endangering their survival (Petzold & Magnan, 2019). Natural habitats, such as mangroves, seagrasses, and coral reefs, can provide coastal protection (Wedding et al., 2022); thus, their conservation should be considered a priority. Since many of these countries rely on biodiversity for livelihood and economies, adapting to climate change by conserving marine and coastal ecosystems could provide multiple benefits. In some cases, more than 20% of their GDP comes from tourism and other ocean-related sectors, thus being also economically vulnerable to the effects of climate change and anthropogenic pressures on the environment (Chaijaroen, 2023). For example, the Republic of the Maldives, heavily reliant on tourism for its GDP, paid one of the highest tolls as a result of the COVID-19 pandemic halt to tourism, with a 33% drop in its GDP in 2020 (Massa et al., 2023).To address the environmental issues our planet faces, many strategies have been proposed at global and local scales. For example, the 2030 Agenda for Sustainable Development (adopted in 2015 by all United Nations Members) delineates common guidelines to achieve peace and prosperity for the current and future generations, whilst addressing climate change and driving efforts to protect and conserve the natural environment (https://sdgs.un.org/2030agenda). The 17 Sustainable Development Goals (SDGs) and 169 targets aim to promote economic, social, and environmental integration and require urgent collective action. Among the 17 goals, some are particularly relevant for coral reef ecosystems, specifically goal 13 (Climate Action) "take urgent action to combat climate change and its impacts" and goal 14 (Life Below Water) "conserve and sustainably use the oceans, seas and marine resources for sustainable development". Their relevance is now even more evident in light of recent global-scale impacts.

In 2024, the fourth global mass bleaching event was declared by NOAA and the International Coral Reef Initiative (ICRI, 2024), with the World Meteorological Organization (WMO) confirming a global average of 1.55 °C above pre-industrial levels (WMO, 2025), and the world's coral reefs have been reported as the first Earth System to exceed the central estimated thermal tipping point of 1.2 °C of global warming above pre-industrial levels (Lenton et al., 2025). Human behaviour is recognised to be one of the drivers of climate change (IPCC, 2023), yet according to the latest SDG report, environmental education and awareness still need improvement. While environmental and sustainability topics are increasingly included in school curricula, climate change content remains low despite global importance, especially in lower grades and in social science subjects (Eilam, 2022; UNESCO, 2026).

Given the urgency to act in light of the threats our planet is facing, there is a vital need to combine traditional top-down formal strategies with grassroots approaches, and this starts by raising the global level of environmental knowledge (McCauley et al., 2021). Target 4.7 of SDG 4 (Quality Education), has a specific focus on developing knowledge to promote sustainable development in all its aspects. In this context, ocean literacy reflects not only what people know about the ocean and our impact on it, but also their attitudes, behaviours towards the ocean, and the capacity to communicate about ocean issues and the sustainable use of its resources (Brennan et al., 2019). The numerous interactions among individuals, society, and the oceans create complex, dynamic, and interconnected networks that influence one another; thus, increasing ocean literacy can lead to broader improvements (Ferreira et al., 2021).

In practice, numerous studies have shown conflicting results on the relationship between knowledge, attitude and behaviour (Brennan et al., 2019). In fact, knowledge on its own does seem to have a limited influence on behaviour change; rather, motivation, attitude (the level of agreement with or concern for a particular position) (Brennan et al., 2019), and environmental values appeared to have an influence on environmental behaviour (Johnson & Činčera, 2015). Instead, connectedness to nature, together with environmental knowledge, is proposed as a tool to drive ecological behaviours (Otto & Pensini, 2017). This relationship with the natural environment can spark place-protective and pro-environmental behaviours (Halpenny, 2010). Moreover, place-based activities and nature-based experiences seem to increase sustainable decision-making (Scott et al., 2014) and contribute to greater theoretical knowledge (Scott et al., 2012) than formal education alone. Finally, exposure to nature appears to have positive effects on personal well-being (Soga et al., 2016). Engagement with children, sharing environmental knowledge outside formal settings, is more likely to foster ocean stewards and create lasting marine citizenship (McCauley et al., 2021). Marine stewardship refers to actions taken by people to sustainably use, protect, and restore the marine environment and apply knowledge to personal sustainable decisions (Bennett et al., 2022). Experiential education can enhance awareness whilst fostering engagement (Mokos et al., 2020) and help people engage in pro-environmental actions (Treviño et al., 2025).

Science education that engages marine scientists in outreach and teaching through "science camps" can positively enhance ocean literacy and advocacy, inspiring interest among younger generations and potentially encouraging them to consider science as a viable career option (Kataržytė et al., 2017; Kelly et al., 2018).

3.1.2 Social value of reef restoration

Coral reef restoration is widely used to kickstart or boost the recovery of reefs (Hein, MCLeod et al., 2020), and global efforts are being spent on finding ways to increase the scale of projects, reduce costs, and innovate on techniques (Boström-Einarsson et al., 2020). Beyond their ecological value, managers are also encouraged to consider the social components of projects (Hein et al., 2017). In fact, projects are often conducted with the practical or financial support of non-professionals, with the aim of providing long-term economic security (Blanco-Pimentel et al., 2022) and raising awareness (Hein et al., 2019; Sebastian et al., 2024). It is recognised

that conservation education and stewardship are maximised when connected to practical experiences and restoration offers this opportunity (Hein et al., 2019). Limitations arising from the use of non-professionals are managed by restoration managers through either adapting the design of their projects, as it happens in some citizen science initiatives (Pocock et al., 2015), or by training volunteers (Hesley et al., 2017). However, most restoration projects open to the general public involve visiting volunteers or tourists and, less commonly, the local population, all of which are equally important and necessary. In fact, local communities can directly benefit from restoration and improve it by incorporating locals' long-term knowledge and supporting practical activities (Hein et al., 2019). In some cases, volunteers (locals and tourists) have also been involved in monitoring coral restoration projects (e.g., Rescue a Reef by the University of Miami-Florida), complementing research at the academic level and gaining, at the same time, educational opportunities from researchers (Hesley et al., 2017). Furthermore, projects involving people can boost scientific literacy in general, foster more positive attitudes toward science and the environment, and increase engagement in decision-making (Bonney et al., 2009, 2016). Additionally, the involvement of the local population can enhance a sense of ownership (Hein et al., 2019; Westoby et al., 2020) and therefore improve the use of the ocean.
Among the numerous restoration techniques, the use of metal frames is common with the help of tourists and local communities, following the design of the 'Mars Assisted Reef Restoration System' (MARRS) reef stars (e.g.,Hein et al., 2018; Williams et al., 2019) or using similar structures. The benefits of this technique are linked to a simple design, the availability of materials also in remote locations and the modularity of the structures allowing to cover large areas (Williams et al., 2019).

3.1.3. Sport for personal and social development

In 1989 UN Convention on the Rights of the Child recognised and highlighted the position of children and adolescents under 18 as a priority group in society. Article 31 remarks the Right to "*rest, play and have proper recreational activities*" (United Nations General Assembly, 1989) emphasising the importance of playing in the evolutionary growing process of every minor.
In recent decades, the role of sport as a tool for social development has gained increasing attention both academically and institutionally. Scientific studies and international programs demonstrate that sport can contribute significantly to preventing juvenile delinquency, building

resilience, and fostering social integration, especially when combined with well-structured educational and psychosocial components (Corvino et al., 2023).

The 2030 Agenda for Sustainable Development identified the role of sport as “an important enabler of sustainable development”, recognising “the growing contribution of sport to the realization of development and peace in its promotion of tolerance and respect and the contributions it makes to the empowerment of women and of young people, individuals and communities as well as to health, education and social inclusion objectives” (United Nations General Assembly, 2015). Governments worldwide made commitments to the Sustainable Development Goals (SDGs) and their achievement, within the structured framework of the 2030 Agenda, aimed at granting the inclusion of the most vulnerable groups with dignity and peace. Sports appear to make a considerable contribution in the achievement of SDGs, particularly SDG 3 (Health and Well-being) and SDG 4 (Quality Education) as they can be valuable tools to address public health and social problems (Campillo-Sánchez et al., 2025; Lindsey & Darby, 2019).

Sport also plays a role in promoting and securing human rights and development, encouraging the adoption of inclusive and accessible sport policies for all (UNESCO, 2017).

Furthermore, well-designed sport-based programs (e.g., Line up and Live up - https://www.unodc.org/dohadeclaration/en/sports/lineupliveup.html), which incorporate quality non-sporting components (Hartmann, 2003) when they are grounded in a credible theory of change (Coalter, 2010) and delivered by well-trained and competent coaches (Sanders & Raptis, 2018) actively engage youth in participatory and empowering ways (Barkley et al., 2019).

On a personal level, sport can help children in difficult situations by building resilience. It can help manage frustration, develop strategies to face challenges, and foster a sense of belonging. When sport is integrated with psychological support, it can promote emotional regulation and provide greater multidimensional benefits, especially alongside strong community networks (Castelli, 2020).

In psychology and education, it appears that sport may strengthen four interconnected areas of personality development: physical, cognitive, emotional, and social. Sport enhances body awareness, motor skills, health, and self-confidence linked to physical competence (Gould et al., 2007).

Participation in sport develops attention, decision-making, problem-solving, and goal-setting skills. Sport provides a structured context for experiencing and regulating emotions such as frustration, fear, joy, and disappointment, fostering emotional intelligence, resilience, self-control, and stress management. Additionally, through teamwork, cooperation, respect for rules, and interaction with peers and adults, sport strengthens communication skills, empathy, leadership, and a sense of belonging within a group or community. When intentionally guided by coaches and educators, sport can become a powerful educational tool that supports holistic personality development, especially in children and adolescents, by integrating learning across all four areas rather than focusing solely on performance (Bailey, 2008).

To assess the effectiveness of the multitude of sport-based educational programs aimed at positive development of participants (from school-based ones, to independent but organised physical activities), various tools have been created, one being the Life Skills through Sports Development Scale, which represents a scientifically grounded instrument designed to assess life skills development through sport (Segrin & Taylor, 2007).

Previous research has outlined the development and validation of this scale, which aims to measure whether and how young people acquire key life skills through sport participation. These life skills include teamwork, goal setting, time management, emotional regulation, interpersonal communication, social skills, leadership, problem-solving, and decision-making. Thus, sport plays a multidimensional role in assisting youth's growth across multiple standpoints and also supporting communities in reaching sustainable development goals.

3.1.4 The Republic of Maldives

The Republic of Maldives is an archipelagic nation built on coral reefs, divided into 20 natural atolls, comprising 1,192 islands: 187 are inhabited by the local population, and over 170 are dedicated to tourism (Ministry of Tourism, 2024), hosting only people and activities related to this service industry. All of the islands in the Maldives are low-lying coral cays with around 80% of the land less than 1 m above sea level (Ministry of Environment and Energy, 2017), and mostly less than 1 km^2 in surface area.

The Maldives are characterised by a distinctive, uneven distribution of population and services. Around 38% of the total population resides in the capital Male in 5.7 km^2, while the remaining population is distributed among the other local islands, with less than 50% of the islands hosting over 1,000 people (Maldives Bureau of Statistics, 2024). This results in an island where population, opportunities, and services are highly concentrated (Male), while the remaining islands face challenges in managing fragmented and overlapping service needs (Malatesta & Schmidt Di Friedberg, 2017). From an administrative point, each island has an island council that manages day-to-day community needs, public services (like waste management, water, health), and development plans. The 20 natural atolls are divided into 21 administrative atolls, each with its own atoll council (which are planned to be phased out as of May 2026) that handles regional planning and resource coordination.

Maldivian coral reefs harbour a vast biodiversity (Galli et al., 2021), but this ecosystem has been facing ever-increasing threats from climate change in the form of mass bleaching events, and from direct anthropogenic pressures deriving from destructive activities such as land reclamation and inadequate waste management (Jaleel, 2013; Perry & Morgan, 2017; Pisapia et al., 2019). The country is highly dependent on its natural resources; in fact, 3.2% of Maldivian GDP derives from fisheries, including fish preparation (0.4%), whereas the tourism industry accounts for 20.3% (Maldives Bureau of Statistics, 2025).

If, on one hand, well-managed tourism may be the driver of economies for small tropical island states (de-Miguel-Molina et al., 2014), on the other, the degradation of the marine ecosystem may lead to a change in tourism from high-end to low-cost, high-volume, potentially impacting tourism (Davenport & Davenport, 2006), further putting reef ecosystems at risk.

The limited land availability has, in recent years, demanded interventions to address current land-use issues through land reclamation projects (van der Pol et al., 2023), both to meet local population needs and to support increased tourism. These activities respond to social needs but raise questions about their environmental impacts (Stevens & Froman, 2019).

The Maldivian population's strong dependence on coral reefs for essential ecosystem services—such as tourism, fisheries, and coastal protection (Jaleel, 2013)—necessitates dedicated efforts to foster environmental sustainability and protection. Coral restoration has been proposed globally as a means to counteract the effects of reef degradation (Boström-Einarsson et al., 2020), and locally, it is often requested as a mitigation measure in Environmental Impact Assessments for the development of new infrastructure (Environmental Regulatory Authority, https://www.era.gov.mv/reports.html.). Although community-driven projects have the potential to enhance reef education and stewardship (Hein et al., 2017), there are still few examples of inclusive restoration projects in practice in the Maldives (e.g., Pancrazi et al., 2025; or https://cordap.org/dipl-team-member/reefseed-a-portable-aquaculture-system/). To date, most restoration projects in the country are carried out outside local islands and in tourist resorts (Dehnert et al., 2022; Hein, Beeden, et al., 2020; Pancrazi et al., 2023).

In SIDS, particularly, environmental awareness is an essential tool for promoting sustainable development and quality education. In the Maldives, a shift from an education based on rote memorisation to participatory place-based education has been proposed as a key strategy to increase resilience of local communities (Di Biase et al., 2022). Although efforts have been made towards a more holistic approach to education, designed to offer rich learning experiences that equally focus on knowledge creation, skill development, and the demonstration of values and positive attitudes (NIE, 2015) challenges still remain (Di Biase et al., 2022). Environmental education has been part of the school curricula since the middle of the twentieth century, but challenges in integrating it with practical experiences still remain (Mohamed & Mohamed, 2021).

At the same time, private funding for environmental awareness programs and conservation activities on local islands is limited (Shareef & Sodique, 2010), although numerous studies have shown the positive effects of bottom-up, community-based marine conservation and outreach initiatives.

Moreover, locally, ocean-based activities such as water sports have mostly been developed and catered to tourists in the Maldives, and although fishing and snorkelling are also common on local islands, football, netball, and volleyball are among the most popular sports amongst the local population (Melli et al., 2024). The drowning prevention report (WHO, 2025) provides details of low drowning mortality in the young population, but also recommends enforcing laws that mandate swimming and water safety in school curricula by scaling up and expanding current localised programmes. In 2025, Learn to Swim programs were included in the official activities for all the schools in the Maldives (https://www.moe.gov.mv/en/activity-calendar) suggesting limited access to the ocean in the young population and a need to address this through official, top-down, large-scale interventions.

This lack of connectedness with the marine environment, the mostly fact-based environmental knowledge, the reduced ocean access, and the high vulnerabilities of the Maldives highlight the need for innovative approaches to enhance ocean literacy and environmental sustainability education among the younger population, aiming to foster marine stewardship and work towards a sustainable future for the country.

To address this, an initiative has been developed by two partners, the Marine Research and High Education Center of the University of Milano-Bicocca and Inter Campus, the CSR (Corporate Social Responsability) branch of the Italian Football Club FC Internazionale Milano. The project 'Playing with Corals: Football as a Gateway towards climate action and marine awareness' stemmed from a desire to promote environmental awareness through an innovative approach that engages children in both football activities and coral restoration.

3.2 Aims of the project

Recognising the role of place-based education in informal settings, the value of non-rote knowledge, and the potential of sports in fostering and strengthening children's personalities, the project "Playing with Corals: Football as a gateway toward climate action and marine awareness" was developed.

The project aims to:

- Use football as educational tool to foster children's resilience, lowering their vulnerabilities and increasing their personal resources;
- Harness the motivational power of sport as an incentive for children to engage in environmental conservation activities;
- Promote an innovative approach to raising environmental awareness on climate change and oceans literacy whilst building local capacity;
- Offer students regular training and reef restoration activities to cultivate a new generation of reef stewards;
- Establish a direct link with the marine environment by fostering a bond through coral reef restoration projects;
- Act as a role model for institutions, other Maldivian atolls, or similar Small Island Developing States in using sport as a linking tool between environmental conservation and a healthy lifestyle.

3.3 Materials and methods

3.3.1 Project area

The project was developed in Faafu Atoll, in the Republic of Maldives. The Atoll is located on the south-western side of the Maldivian chain, about 110-140 km away from the capital Male. The atoll comprises 5 local islands Nilandhoo, the capital, Dharaboodhoo, Magoodhoo, Biledhdhoo, and Feeali and only one resort (Filitheyo) (Fig 1a-c).

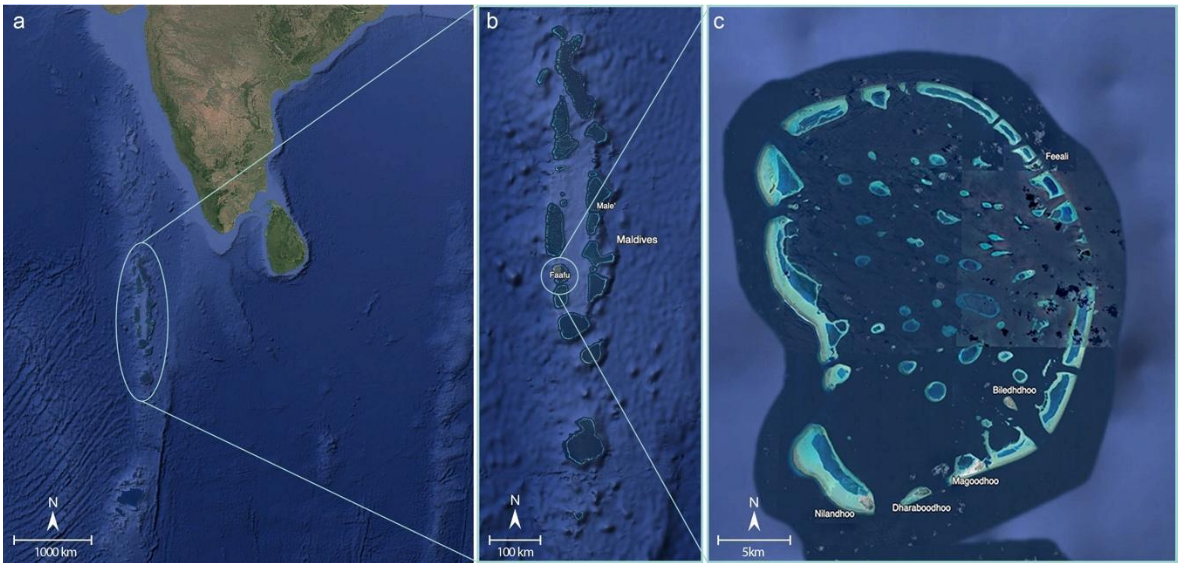


Figure 1. Study area. **a)** Indian Ocean and in the circle the Republic of Maldives; **b)** The Republic of Maldives and in the circle Faafu Atoll; **c)** Faafu Atoll with the 5 inhabited islands

The total resident population of the Atoll is less than 5,000, with around 550 children between 10 and 14 years old (Maldives Bureau of Statistics, 2024). Only Nilandhoo has a population over 1,000 (1,823); the other islands have populations between 455 (Dharaboodhoo) and 967 (Biledhdhoo). All the islands' schools cater for children from kindergarten to grade 10; only Nilandhoo and Biledhdhoo have grade 11 and 12, with a total of around 122 children enrolled in grade 1, and a total of 23 attending grade 11 and 12 in the atoll (Ministry of Education, 2024). Three of the five islands have undergone changes through land reclamation projects (Feeali, Magoodhoo, and Nilandhoo), which have altered the reefs around the islands, covering seagrass meadows (Fig. 2a-b) and limiting access to the ocean.

The Maldives experience two distinct monsoon seasons: the dry northeast monsoon from approximately December to March, and the wet southwest monsoon from May to October (Shankar et al., 2002).

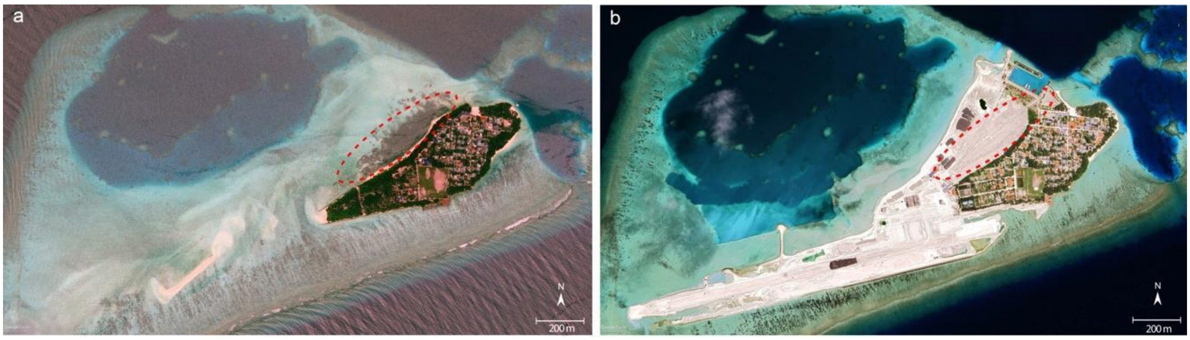


Figure 2. Example of coastal changes derived from land-reclamation (Magoodhoo, Faafu Atoll). In red is highlighted a seagrass meadow that has been covered by the expansion. **a)** 2010; **b)** 2024

3.3.2. Playing with Corals

Playing with Corals (PWC) was developed through a collaboration between the Marine Research and High Education Center (MaRHE) of the University of Milano-Bicocca based in Faafu Atoll, Maldives and Inter Campus, the CSR branch of the Italian Football Club FC Internazionale Milano. The project received financial support from both partners and the UEFA Foundation for Children, as well as logistical support from the Faafu Atoll Council and the councils and schools of each island. The project was born out of consultations with the council of the island of Magoodhoo, which informally requested assistance in providing football trainers. The idea was thus to meet a community need while integrating it with the academic resources of the MaRHE Center. In fact, the center's focus is on environmental science, marine biology, tourism science and human geography with the aim of studying and protecting coral reefs. Consequently, the project was designed to combine football training sessions integrated with environmental games and marine activities using reef restoration as an educational tool.

The MaRHE Centre provided the logistical support for hosting training sessions for trainers through its field station located in F. Magoodhoo, and involved researchers in the field of marine ecology and reef restoration.

Inter Campus provided technical trainers experienced in football training sessions focused on developing children's personality.

To contextualise the project in the local community, a questionnaire was administered to a random sample of adult residents on the islands, selected based on their willingness to participate, to assess their swimming skills, ocean use, and environmental knowledge (see Supplementary Material 1 and 3.3.5).

The project was launched in May 2024 and targeted at least 2 volunteer trainers and 20 students aged 10 to 15 from each of the 5 local islands, and was open to both males and females. The hoped female to male ratio was of at least 25%. Twice a year (4 sessions in total), a team from the MaRHE Center and Inter Campus conducted 'train the trainer' sessions for the local coaches and visited each of the islands to assess progress and meet with the children. The 'train the trainer' sessions lasted between 5 and 7 days and included both theoretical classes and practical experiences, followed by one activity on the football ground and one in the ocean with the children of each island. Each session conducted with the international training team aimed to equip the local coaches with the competencies and tasks they needed to complete independently in the following months. Both football training sessions and marine sessions were scheduled once a week and weekly online coaching sessions were aimed at collating progresses and challenges of the trainers. Participation was not mandatory but highly encouraged.

Additionally, questionnaires were administered to children participating in the programme to assess changes over time (see 3.3.5 and Supplementary Material 2), and to evaluate the continuity of activities, reports on activities conducted on each island were collected on a weekly basis.

3.3.3 Reef restoration for practical ocean literacy

The project aimed to provide trainers with adequate information to independently conduct activities throughout the year and to enhance their ocean literacy. As such, the lectures for trainers included an introduction on safety in marine activities, coral reef ecology and threats (natural and anthropogenic), coral reef restoration techniques, reef stars production, stocking (with the identification of suitable coral genera and selection of suitable fragments of opportunity), maintenance, monitoring, associated fauna, and competing organisms. Each theoretical class was followed by a practical session at sea to apply what had been learnt and visualise concepts in practice. Role-playing activities were conducted among the trainers to help them gain experience in explaining concepts, demonstrating organisms to children, and conducting hands-on restoration.

Reef stars are modular iron frames coated with resin and sand and deployed on a unconsolidate substrate, each hosting 15 fragments of coral attached with cable ties (Fig. 3). These structures have been already used in projects with the assistance of local communities and non-professionals (Williams et al., 2019) and fragments chosen are often corals of opportunities (loose fragments found on the bottom and otherwise likely destined to be covered with sand) (Monty et al. 2006). The deployment of reef stars followed the guidelines used in real restoration projects, but in this case, the safety of the location was prioritised above all other factors. Reef stars had to be accessible from shore, possibly sheltered from both monsoons (Shankar, 2002), and in shallow enough water to be submerged at all times, but also safely reachable by children through freediving (on average, they were placed at 1 to 1.5 m of depth). Apart from preparing the reef stars, which was carried out solely by the trainers for safety reasons, the entire process—from coral collection to fragmentation, attachment, deployment, maintenance, and monitoring—was conducted in collaboration with children.

Figure 3. Reef star coated in resin and sand with corals attached with cable ties, temporarily placedin shallow water by children waiting to be deployed in deeper water with the assistance of trainers

3.3.4 Football for personal and social development

One of the core elements of the football training methodology adopted is the direct on-field work realised through targeted exercises specifically designed to develop certain abilities,based on an initial needs assessment.

The train-the-trainer sessions provided local coaches with the tools to design and carry out weekly activities during the six months following the international trainers' visits.

Each football training session was designed to involve the four areas of personality (motor, cognitive, emotional, and social) through simple yet effective activities, with particular attention paid to interactions, where present, between boys and girls.

Each session was structured into three phases:

- Warm-up or initial phase (15-20 minutes): playful activities to encourage participation;
- Situational phase (20 minutes): activities related to a game-based situation, involving the presence of a goalkeeper, one or more attackers, and one or more defenders;
- Final game: (20 minutes): free experimentation in a real game situation;

The first two phases allowed the integration of environmental games, followed by the traditional final game. To integrate environmental aspects, some activities were also given specific names (such as “sort the garbage” “prey and predators” and “the sharks’ game”) and, when possible, football activities were combined with marine-related content, for example by incorporating theoretical questions about coral reefs: children who answered correctly took on the role of attackers, while those who answered incorrectly or did not respond acted as defenders.

The Life Skills Development through Sports Scale (Cronin, 2015; Cronin & Allen, 2017) was used to evaluate the effectiveness of the training activities on children's development, and to establish the areas that needed improvement. Results allowed to identify the areas of personality that needed greater focus and to structure each subsequent train-the-trainer session, suggesting to local coaches which types of games they needed to concentrate on. The assessment allowed measurement of changes—both positive and negative—in each life skill and developmental area over time. The collected data enabled analysis at island, gender and overall program levels, providing a comprehensive evaluation of the educational and psychosocial impact of the activities on Maldivian children.

3.3.5 Data analysis

To provide a general context, a questionnaire was administered to adults willing to cooperate. The questionnaires were provided either in English or Dhivehi (the local language) according to the participant's preference. The questions gathered anonymous metadata on respondents, included open questions and multiple-choice items, indicating whether the correct answers were single or multiple and offering the option “I don’t know”. Results were analysed with descriptive statistics and no correlation was computed.

For the marine part, we assessed children's closeness to the "Ocean" using the Inclusion of the self in Nature scale adapted from the version of Kleespies et al. (2021), proposing a Venn diagram containing two circles where the overlapping between areas between self and the ocean increased from the first to the last. One circle was labelled "me", the other "ocean", and the "ocean" circle's design was adapted from its original "Other" form to represent the local context, including the ocean, the beach, and a palm tree. Each participant had to choose the pair of circles that best described their relationship with the ocean. The diagrams represent a visual illustration of a Likert scale where the scale ranged from one "other with the ocean" (two separate circles) to seven (two overlapping circles), suggesting "one with the ocean". We calculated and compared the mean and standard deviation of the values at T_0 (November 2024) and at T_1 (May 2025) followed by an analysis of the data through a paired-samples t-test.

Additionally, to investigate children's pro-environmental concerns, the New Ecological Paradigm (NEP) scale (Dunlap et al., 2000), modified by Manoli et al. (2007) and further reduced to 9-items, was adopted. Respondents were asked to indicate the strength of their agreement or disagreement with several statements through a 5-point Likert scale where "one" stated strong disagreement and "five" strong agreement. These were then clustered into three groups based on the extent to which the question aligned with one of the three facets of an ecological worldview. The group "Rights of Nature" included questions 1,4, and 7, "Eco-crisis" included questions 2, 5, and 8, and "Human exemptionalism" included questions 3, 6, and 9. Values for questions 3, 6, 7, and 9 (anti-environmental) were reverse-scored to obtain comparable results. Changes in responses between T_0 and T_1 were evaluated using the Wilcoxon signed-rank test after having observed their non-normal distribution. The scale was reduced to a 9-items scale for logistical reasons as the questionnaires were administered in the field and needed to be as simple as possible.

Finally, seven multiple-choice questions were asked to assess participants' knowledge of the marine environment, where the option "I don't know was not present". The percentages of correct answers at T_0 and T_1 were calculated and compared to provide descriptive analysis, followed by an analysis of the significance of changes in responses using McNemar's Chi-squared test with continuity correction.

To assess the overall participation and continuity of the project, regular reports of the sessions were collected and recorded. Reef stars number, number of coral fragments and survival rate at the end of the project were documented for each island.

For the football part, the changes in personality development were measured at T_0 and T_1 (November 2024 and May 2025) through the Life Skills Development through Sports Scale

(Cronin, 2015; Cronin & Allen, 2017). The adapted instrument consisted of a 51-item self-report questionnaire structured around six main life skills domains: self-confidence, problem-solving and decision-making, emotion management, friendship building, self-efficacy, and goal setting and playing together. These life skills were further organised according to four core areas of child personality development: motor–technical, cognitive, emotional–affective, and social. This framework generated four parallel self-report perspectives, complemented by two additional cross-area dimensions focusing on socio-emotional and cognitive–social development. Each item was analysed through a 5-point Likert scale, where "one" represented complete disagreement and "five" complete agreement (Supplementary Material 3). Mean and standard deviation of the obtained values were calculated and compared at T_0 and T_1 to descriptively analyse changes in personality development at island level and as a unique group.

3.4 Results and Discussion

3.4.1 The context

Given that the project was implemented in a Small Island Developing State with its own challenges and vulnerabilities, and considering the peculiarities of the geographical dispersion and uneven distribution of opportunities in the Maldives, we first provide a snapshot of the context by looking at the community (adult population). The respondents to the questionnaire administered were a total of 86, despite being very skewed toward the female side, with 16 males and 70 female respondents. Due to the limited number of respondents, especially in the male group, results should be read cautiously, not making generalisations.

The vast majority of the respondents attended only the compulsory school 74.4% (n=64), two reached high school (2.3%), 13 had a bachelor's degree (15.1%), five people had a Master's degree (5.8%), and the remaining (2.3%, n=2) did not specify their level of education.

Looking at swimming abilities, 53.5% (46/86) of respondents declared to be able to swim with at least one proper stroke; 93.7% of males (15/16) and 44.3% of females (31/70) reported proper swimming ability (swim with at least one proper stroke). All participants who had never tried swimming or could not swim at all were female.

Looking at the broader use of the ocean, 70.9% (61/86) of participants have tried snorkelling at least in a sandy area, and only 4.7% have used SCUBA equipment (all male), yet 59% of the respondents have never snorkelled on a reef. These results highlight a modest use of the ocean, especially by females. Considering that the stable population on local islands is often skewed towards females, these results play a role on children's regular access to the ocean. Moreover, this may result in a perceived distance from the ocean and the challenges it faces. The distance between humans and nature may be one of the reasons for the current environmental crisis (Jordan, 2009). In fact, experiences in nature are known to increase personal connection with nature, which in turn can lead to environmentally friendly behaviours (Geng et al., 2015).

We also analysed people's general knowledge about the marine environment (Fig. 4). Overall, 70% of the respondents knew that coral reefs are 'in danger, large areas are threatened by climate change and human actions' (Fig.4, EK7). However, when looking at more knowledge-based concepts, correct responses seldom reached 50%. It thus appears that there is an understanding of the conditions of reefs (EK7), the importance of corals to reefs (EK4), and that bleaching may affect reef biodiversity (EK5). However, when people are asked more theoretical questions on whether corals are animals, plants or rocks (EK6), only 11.6% of the respondents (10/86) knew the correct answer, 16.3% knew that it takes a long time for reefs to grow (EK1), and 29.1% knew what coral bleaching is (EK1). Most people believed that corals are rocks (46.5%), did not know what features characterise reefs (48.8%), and thought that coral bleaching is a disease affecting corals (43%). Despite thinking that coral bleaching is a disease, the association with a process that affects coral reefs is correct, though. The lack of knowledge about corals being living organisms, yet the understanding of bleaching affecting reefs, would require further analysis to investigate the association of a process affecting organisms with something not considered alive. This highlights a gap in theoretical knowledge, but an overall understanding of the status of coral reefs. Despite theoretical concepts being only one of the aspects of environmental awareness and not the only one necessary to develop an environmental consciousness, they form the basis for more complex analyses (Wiek et al., 2011), for example, on the broader effects of local anthropogenic impacts and how to behave in an environmentally friendly way, as a result (Finger, 1994).

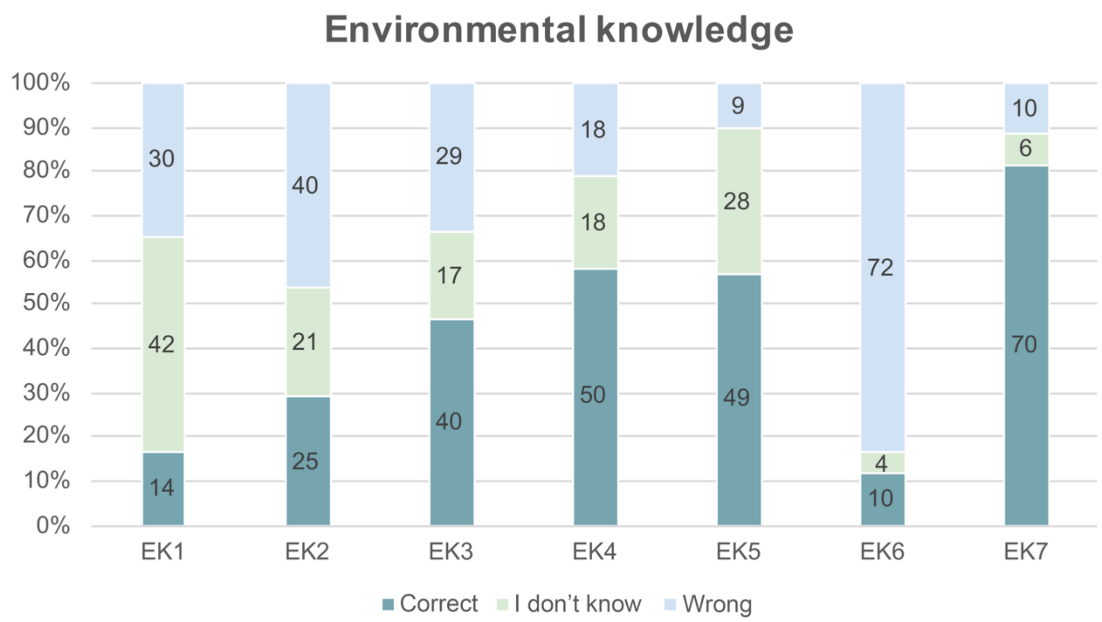


Figure 4. Environmental knowledge. On the Y axis is represented the percentage of answers. Instead, the numbers within the bars represent the absolute number of respondenses. EK1: Which of the following is not a characteristic of coral reefs?; EK2: What is coral bleaching?; EK3: What is the primary cause of coral bleaching?; EK4: What role do corals play in the marine ecosystem?; EK5:How does coral bleaching impact marine biodiversity?; EK6: Corals are?; EK7; Today, the coral reefs conditions are.

The last question (EK8) asked people to choose among some possible threats to reefs: 'Sea water acidification', 'Sea water warming', 'Strong marine currents', 'Big marine predators (sharks)’, ‘Boats anchoring’, ‘Pollution’, ‘Hurricanes’, ‘Land expansion’, and ‘I don’t know’ (Fig. 5). The most common answer was ‘Pollution’ (64%, 55 answers), followed by land expansion (62.8%, 54 answers), sea water warming (60.5%, 52 answers). Pollution is surely a threat the Republic of the Maldives faces daily, with challenges in waste management (Malatesta et al., 2015), anthropogenic marine debris washing up on shores (Fallati et al., 2019), including microplastics (Patti et al., 2020; Saliu et al., 2018) or being trapped on the reef (Jaleel, 2013). Land expansion through land reclamation is a practice commonly used in the Maldives that has been drastically changing islands, including in Faafu Atoll (Fig. 2), and impacting the environment (Duvat, 2020). Boat anchoring is perceived as a threat by 50% of respondents; indeed, anchoring is only prohibited within Marine Protected Areas (Ministry of Environment and Energy, 2021), but elsewhere the practice still occurs, albeit not commonly, both using moorings around large coral heads or anchoring directly onto reefs.

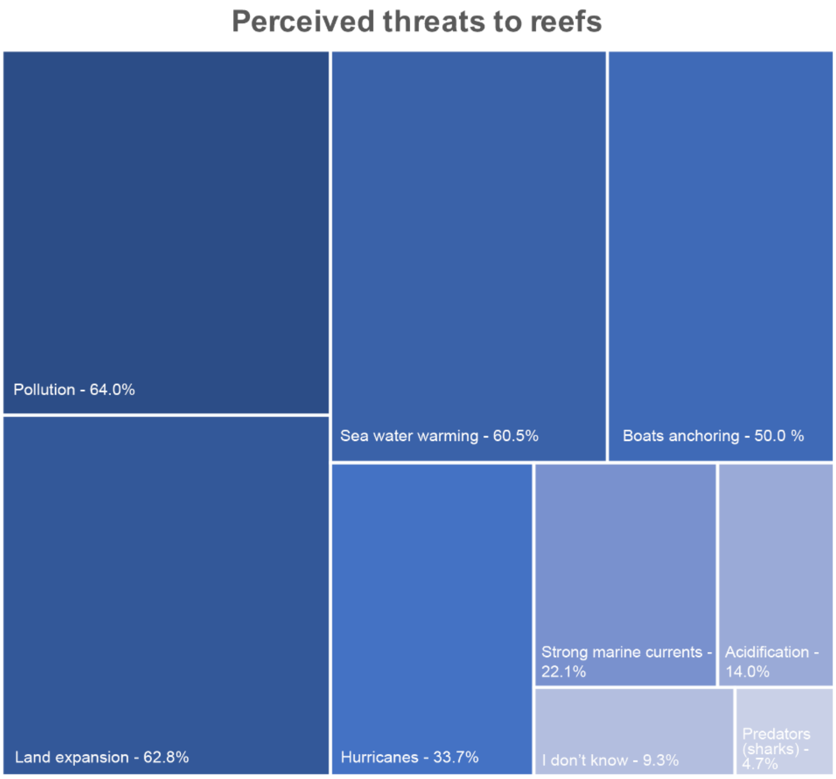


Figure 5. Threats to the reefs perceived by the 86 adult respondents.

3.4.2 Ocean literacy through reef stars

The innovative approach of Playing with Corals was to incorporate environmental topics into football training sessions to build a sense of community among participants and raise environmental awareness, while also using reef restoration to offer practical experience in the ocean and cultivate a sense of ownership and responsibility towards the marine environment by installing and caring for reef stars.

To assess the success and effectiveness of the project, we looked at different metrics. First, the overall participation and continuity of the project, then the change over time in environmental knowledge, and children's closeness to the ocean and pro-environmental concerns. Finally, the number of reef stars and the survival and status of the corals project.

Looking at the demographics of participants, we had an initial number of 96 students, divided between 79 males and 15 females, a bit below the hoped threshold of 25% female participation. Children aged 10 to 14 years during the first session, and some turned 15 at the end of the second year. No new recruits were added after the first year of the project (Fig. 6a-b).

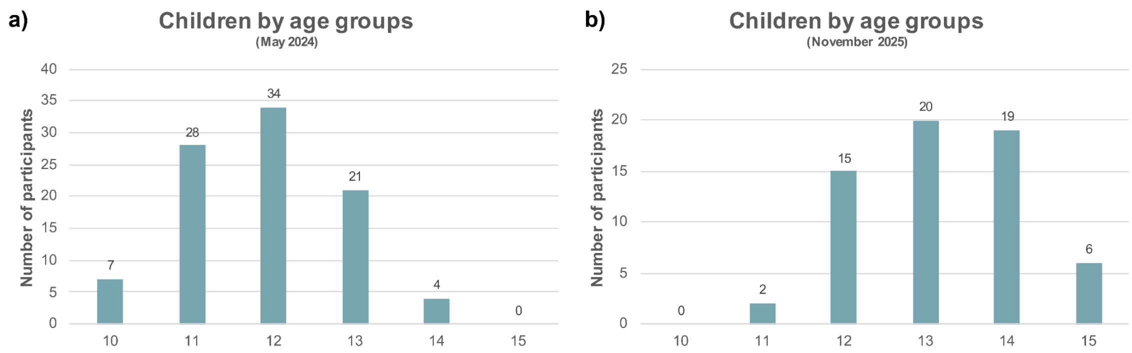


Figure 6. Participants by age group: **a)** May 2024 at the beginning of the project; **b)** November 2025 during the last 'train the trainer' session.

A first analysis focused on the continuity of the project. The number of islands involved decreased; by the first week of training, the objectives and the commitment expected of the trainers were clear to everyone. Unfortunately, one island (Biledhdhoo) decided to drop out, for reasons not disclosed to the organisers or the atoll council. A second trainer from a different island (Feeali) was not present during the last training session, and conducted fewer activities throughout the year (Fig. 7a), thus T_1 questionnaires from this island could not be gathered, drastically reducing the number of responses. Consequently, participants, both trainers and children, decreased over time from 96 children to 62, and from 18 trainers to 7 (Fig. 7b). These results might be driven by several factors. First, the trainers were selected by the island councils through the councils and objectives might not have been fully clear. Although informative sessions were held, more emphasis could have been placed on technical aspects, attracting people interested in developing the technical side of football training, which was only a part of the project. Furthermore, people might not have been fully aware of the commitment required, possibly holding positions that were not entirely compatible with the training activities, or finally, the scattered geography of the Maldives may have led some trainers to travel away from their local islands following job opportunities.

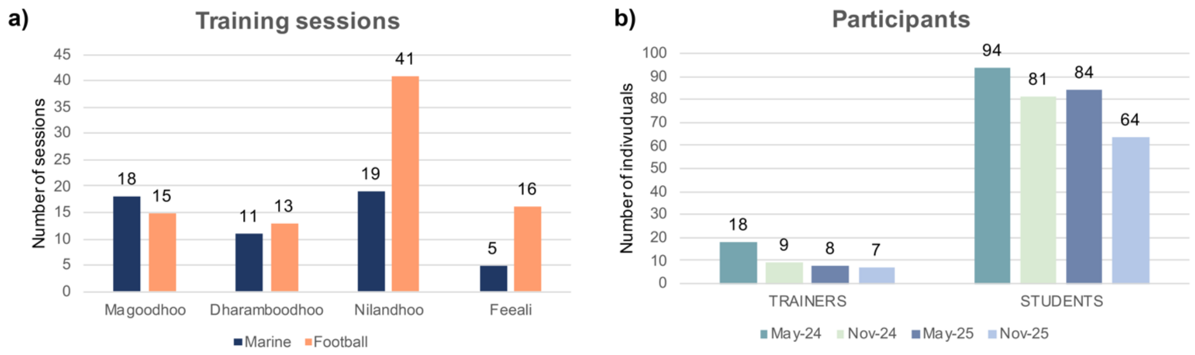


Figure 6. Continuity of activities: **a)** Number of training sessions; **b)** Number of participants over time

The increase in environmental knowledge, the perceived distance from the ocean, and their environmental worldviews, as measured by the NEP scale, were assessed through questionnaires; the results from the first and last sessions are provided. After cleaning the data and removing responses from participants who left fields blank or did not complete both questionnaires at the beginning and the end of the project, we obtained 42 complete responses. Looking at the closeness to the ocean for each participant, we used the Inclusion of the Other in Self (IOS) scale (Aron et al., 1992) as adopted by Kleespies et al. (2021) for a study on the connectedness with nature and adapted for the project (Supplementary Material 2). Descriptive analyses indicated high perceived closeness at baseline (T_0; M = 5.64, Md = 6). At follow-up (T_1), mean IOS scores remained almost stable (M = 5.48, Md = 6), demonstrating no particular change over time. The paired-samples t-test indicated no significant change over time, $t(41) = -0.60$, $p = 0.55$, Cohen's dz = −0.09, but minor individual fluctuations and regression from ceiling, rather than systematic change in closeness. Unchanged values were 17/42 (40%), decreased values (T1 < T0) 14/42 (33%), and increased values (T1 > T0) 11/42 (26%). This could be due to several factors. First, each of the five islands is less than one square kilometre in area (excluding recently reclaimed areas), and this reduces the physical distance to the ocean. Indeed, the ocean, whether or not children access it, plays a pervasive role in the lives of Maldivians. Secondly, children selected for the project were all swimmers, as, for safety reasons, we used this skill as an entry criterion; thus, the sample may have been biased towards children with a stronger connection to the ocean.

We then analysed the frequency distribution of the responses to the pro-environmental concerns through the NEP scale for children at T_0 (May 2024) and T_1 (November 2025) (Table 1).

Table 1. Frequency Distributions of the Responses to the New Ecological Paradigm (NEP) Scale for Children in May 2024 and November 2025 (N = 42)

	Responses (% of students)									
	Strongly disagree		**Disagree**		**Not sure**		**Agree**		**Strongly agree**	
Scale item	T_0	T_1	T_0	T_1	T_0	T_1	T_0	T_1	T_0	T_1
1. Plants and animals have as much right as people to live.	4.8%	2.4%	7.1%	2.4%	9.5%	7.1%	23.8%	38.1%	54.8%	50.0%
2. There are too many (or almost too many) people on earth.	7.1%	11.9%	11.9%	11.9%	33.3%	52.4%	28.6%	16.7%	19.0%	7.1%
3. People are clever enough to keep from ruining the earth.	14.3%	4.8%	4.8%	9.5%	35.7%	35.7%	28.6%	21.4%	16.7%	28.6%
4. People must still obey the laws of nature.	0.0%	0.0%	0.0%	2.4%	16.7%	9.5%	38.1%	31.0%	45.2%	57.1%
5. When people mess with nature it has bad results.	4.8%	2.4%	9.5%	4.8%	21.4%	14.3%	16.7%	23.8%	47.6%	54.8%
6. Nature is strong enough to handle the bad effects of our modern lifestyle.	21.4%	23.8%	21.4%	23.8%	21.4%	33.3%	16.7%	9.5%	19.0%	9.5%
7. People are supposed to rule over the rest of nature.	16.7%	35.7%	28.6%	23.8%	33.3%	23.8%	9.5%	9.5%	11.9%	7.1%
8. People are treating nature badly.	7.1%	4.8%	7.1%	0.0%	19.0%	14.3%	21.4%	21.4%	45.2%	59.5%
9. People will someday know enough about how nature works to be able to control it.	4.8%	4.8%	4.8%	14.3%	40.5%	42.9%	28.6%	23.8%	21.4%	14.3%

The answers were analysed based on the three groups proposed by (Dunlap et al., 2000): Rights of Nature, Eco-Crisis, and Human Exemptionalism. Specifically, items 1, 4, 7 are included in Rights of Nature, items 2, 5, 8 in Eco-Crisis, and items 3, 6, 9 in Human Exemptionalism. Items 3, 6, 7, and 9 were reverse scored (i.e., strongly agree = 1 instead of 5) due to their anti-environmental connotation. We then calculated the mean of the three answers for each participant at T_0 and T_1, computed the means of the values obtained for each factor and their standard deviation. Values were then analysed through the Wilcoxon signed-rank test, as the values were not normally distributed. The results are shown in Table 2 and Figure 7. The factor Rights of Nature does not show a significant difference, though the effect size was small to moderate (r = .27), suggesting a meaningful trend toward change. The remaining two factors did not show a statistically meaningful difference, and the effect size was very small.

Table 2. Comparison of Mean Pre- and Post-test Scores on New Ecological Paradigm for Children (n=42)

	Pre		Post			
Factor	*M*	*SD*	*M*	*SD*	p-value	Effect size
Rights of Nature	3.58	0.66	3.81	0.69	0.08	0.27
Eco Crisis	3.75	0.95	3.83	0.76	0.6	0.08
Human Exemptionalism	3.25	0.84	3.15	0.64	0.54	0.09

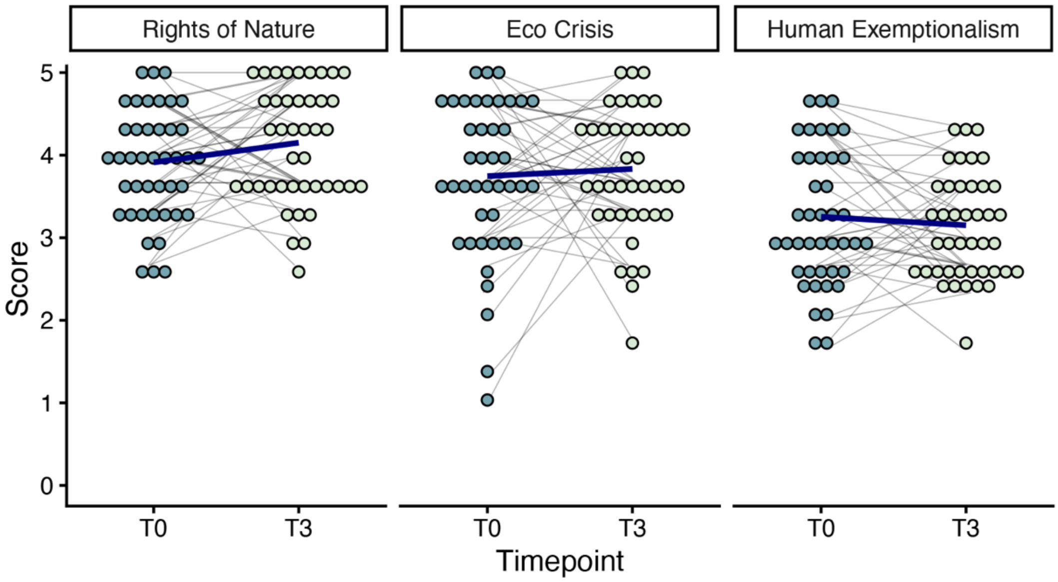


Figure 7. Distributions of the Responses to the New Ecological Paradigm (NEP) Scale for Children at T_0 (May 2024) and T_1 (November 2025) (N = 42)

Results on NEP are not particularly conclusive, and analysing, for example, the answers from Human Exemptionalism NEP7 (People are supposed to rule over the rest of nature), it is possible that children did not perceive the negative connotation of the question, as answers are not clustered on one side but distributed at both extremes (agree and disagree).

Although the project was not aimed solely at providing rote knowledge, trainers were given tools to illustrate theoretical concepts through practical activities, and the increase in environmental knowledge was assessed through pre- and post-surveys.

Environmental knowledge questions were similar to those posed to the adult population, but did not include the option “I don’t know” in the response options, which may have led some responses to be random.

Most values improved, except for question one, ‘which of the following is not a characteristic of coral reefs?’, where the value of correct answers decreased from 66.7% to 54.8%, although not significantly (Fig. 8). The difference between T_0 and T_1 was assessed using a McNemar’s chi-square test with continuity correction to determine whether the proportion of “successes” changed over time, accounting for both errors becoming correct and corrects becoming errors. Only question numbers 2 and 7 resulted significantly different (Table 3).

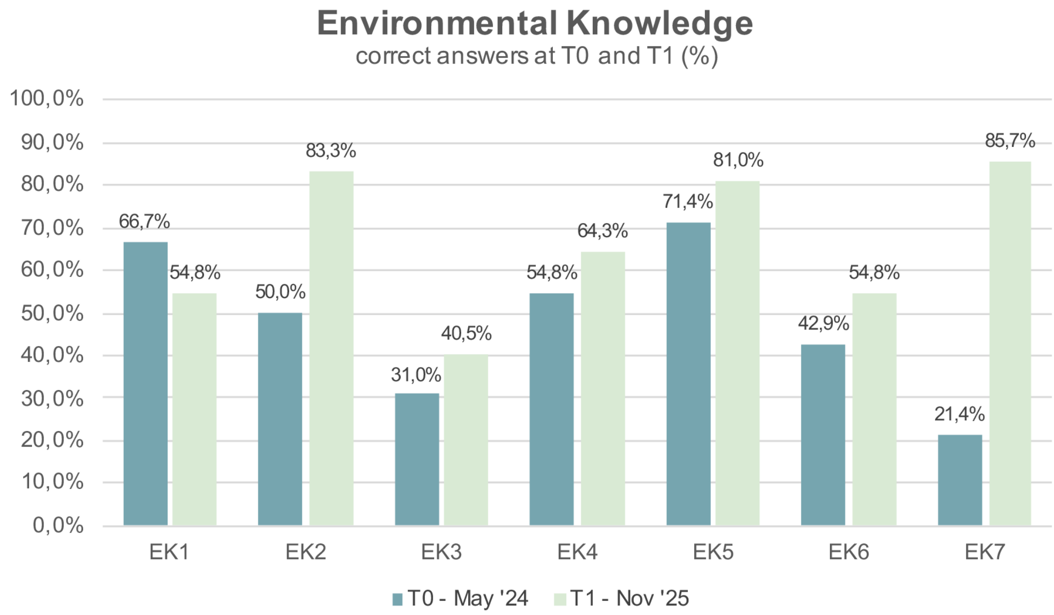


Figure 8. Children’s changes in environmental knowledge from T_0 (May 2024) and T1 (November 2025). EK1: Which of the following is not a characteristic of coral reefs?; EK2: What is coral bleaching?; EK3: What is the primary cause of coral bleaching?; EK4: What role do corals play in the marine ecosystem?; EK5: How does coral bleaching impact marine biodiversity?; EK6: What is the primary function of ocean currents?; EK7: Corals are?.

The environmental knowledge was assessed on general notions rather than focusing on concepts that could have been learned through the practical experiences, making it very similar to a rote-based transfer of knowledge, thus possibly resulting in limited change. It is possible that had questions been more practical, they would have driven a different outcome.

Table 3. Changes in correct response frequencies and statistical significance assessed through McNemar test (significant results are marked with an *)

	T_0 correct (%)	T_1 correct (%)	Change (%)	McNemar p-value
EK1: Which of the following is not a characteristic of coral reefs?	66.7	54.8	-11.9	0.3827
EK2: What is coral bleaching?	50.0	83.3	+33.3	0.005578*
EK 3: What is the primary cause of coral bleaching?	31.0	40.5	+9.5	0.4227
EK 4: What role do corals play in the marine ecosystem?	54.8	64.3	+9.5	0.4227
EK 5: How does coral bleaching impact marine biodiversity?	71.4	81.0	+ 9.5	0.4795
EK 6: What is the primary function of ocean currents?	42.9	54.8	+ 11.9	0.3827
EK 7: Corals are?	21.4	85.7	+ 64.3	3.016e-06*

Aside from the quantitative results on IOS, NEP and environmental knowledge, important results stem from the installation of reef stars, maintenance and survival of corals. Looking at the number of reef stars, the island of Magoodhoo installed a total of 10 reef stars, five during the ‘train the trainer’ sessions and five with the children, whereas Nilandhoo installed a total of 14 reef stars, and Dharaboodhoo installed only five. Furthermore, five reef stars were deployed in Feeali, but the status was checked only after 6 months and not at the end of the project as it was not possible to visit the island during the last training session. A total of 510 fragments were transplanted on the reef stars, which children monitored regularly using simple metrics, replacing dead fragments and removing predators. Children learned through practice to recognise corals of opportunity (loose coral fragments found on the substrate), from the most common genera used in reef stars (*Acropora* and *Pocillopora*) and to tell them apart. Additionally, by conducting regular maintenance, removing dead fragments, and cleaning the structures, they learnt corals’ growth rates, connected them to their vulnerabilities, and understood why some are more suitable than others. At the end of the project, all fragments in the reef stars in Magoodhoo, Dharaboodhoo and Nilandhoo were alive, whether replaced or not over time.

Chosen categories for monitoring included a division between corals of the genera *Acropora, Pocillopora*, and others, and, for health status, they learned to tell healthy fragments apart from bleached and dead ones (e.g., Table 4). In terms of predators, they focused on the presence of *Drupella* sp. shells, recognising molluscs from shells used by hermit crabs, and *Culcita* sp. (Fig. 9d marked by the black arrow). Predators were simply moved away from the reef stars.

Table 4. Example of survey conducted by the children a few months (May 2025) after installation of the reef stars. Categories are simplified

	Acropora Healthy	*Acropora* Bleached	*Acropora* Dead	*Pocillopora* Healthy	*Acropora* Bleached	*Acropora* Dead	Other Healthy	Other Bleached	Other Dead
Frame 1	9	1	1	0	0	0	3	0	0
Frame 2	15	0	0	0	0	0	0	0	0
Frame 3	13	0	1	0	0	0	0	0	0
Frame 4	13	0	1	0	0	0	0	0	0
Frame 5	14	0	0	0	0	0	0	0	0
TOTAL	**64**	**1**	**3**	**0**	**0**	**0**	**3**	**0**	**0**

For Magoodhoo and Dharaboodhoo, it was possible to collect photos in May 2025 and November 2025 to create 3D models and orthomosaics of reef stars through Structure from Motion photogrammetry and assess the survival and status of the project. The resulting images and videos were also used as educational tools for trainers and children, showing them the outcomes of their efforts (Fig. 9a-d). Water visibility in Nilandhoo was always very poor, preventing us from taking photos. The results obtained from reef stars are tangible outcomes of the sense of responsibility felt by children towards corals, recognising the value and fragility of these living creatures, caring for them, and thus fostering the desired sense of personal connection with the marine environment.

The intermittent and varied number of marine sessions conducted by trainers (Fig. 6a) focused more on practical activities (maintenance of reef stars) than on games with an environmental focus, possibly influencing the change (or lack thereof) in knowledge.

The results obtained will help develop the second edition of the project and achieve its last goal to “create a replicable model” for other islands or SIDS. Further to highlighting strengths and challenges of the project, the theoretical background and activities will be formalised into a document accessible to interested parties. During the two years, information has been shared with the trainers formally during the training sessions, and also by adopting tools convenient for field use, such as mobile-friendly worksheets accessible to anyone, also during the project’s weekly activities. A more hands-on approach could have been adopted to ensure the trainers' continued engagement and transfer of knowledge and skills to the children, something that will necessarily be implemented in the future.

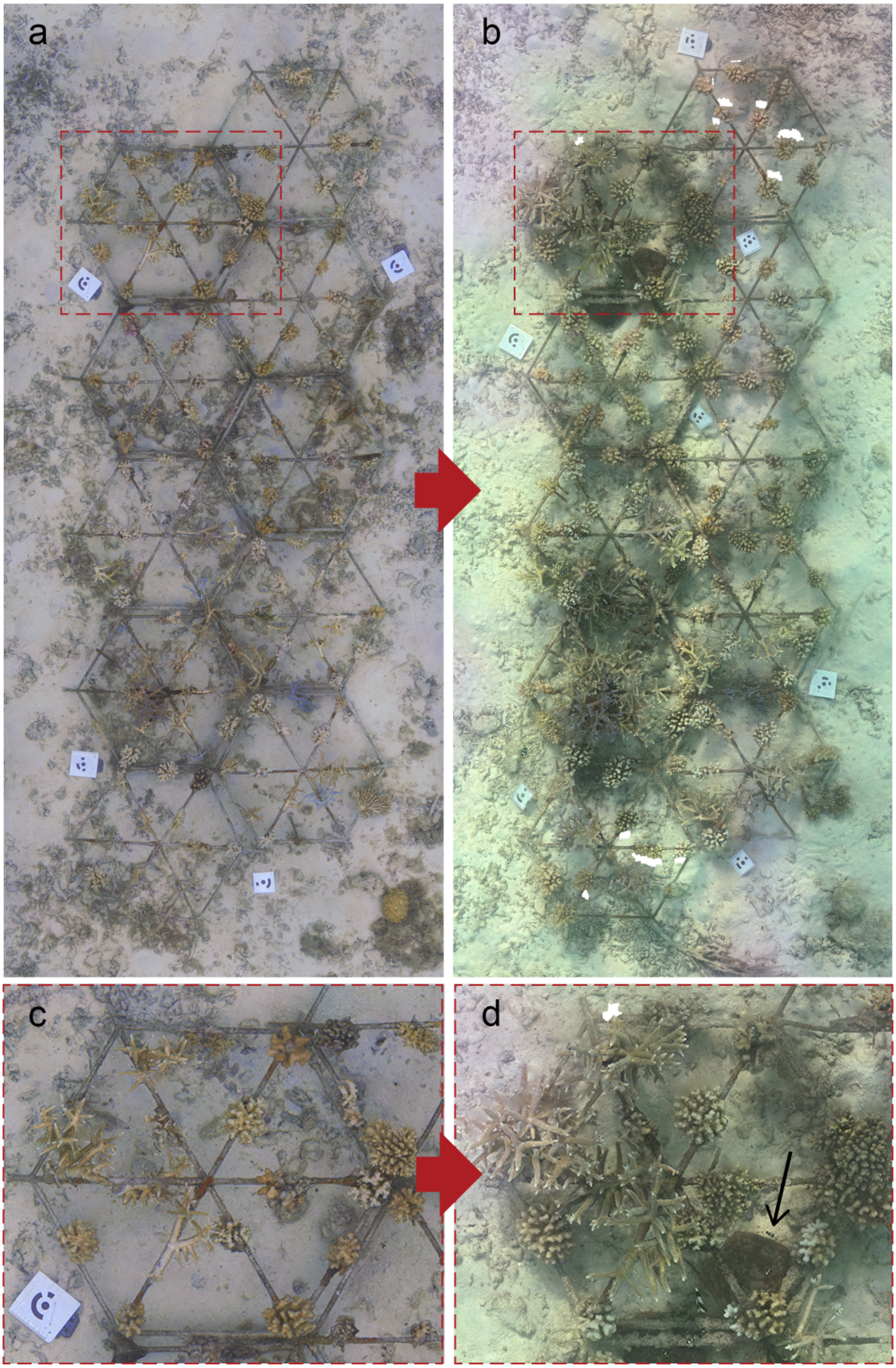


Figure 9. Reef stars in Magoodhoo: **a)** May 2025; **b)** November 2025; c) May 2025 close up of the area marked in red in Fig 9a showing the growth ; **d)** May 2025 close up of the area marked in red in Fig 9b showing the growth of coral colonies.

Although statistical analysis indicates the need to improve in certain areas, the promising outcomes in environmental knowledge, the high connection to the ocean, and the survival and growth of corals on reef stars are encouraging. The limited time available to complete questionnaires, differences in participants' ages, the few respondents, and the perceived willingness of children to provide answers they believed were expected may have influenced the results, limiting the significance of changes over time; however, descriptively, results were trending towards the positive.

Children had numerous opportunities to spend time in the ocean, becoming more comfortable in the water and gaining confidence in completing tasks (such as cleaning and monitoring), being introduced to the ocean as not only a place for leisure but also for achieving tasks. Both children and trainers were exposed to reef restoration, a technique that is commonly practised in the Maldives (Dehnert, 2022; Hein et al., 2018; Pancrazi et al., 2023) and that constitutes a possible employment pathway for them in the future. Our results show that reef stars are a viable restoration technique that can be implemented within local communities, where children participate for learning and engagement purposes under adult supervision, while the restoration outcomes for reefs remain real and measurable. Exposure to role-models and to Science, Technology, Engineering, and Mathematics (STEM), particularly through practical experiences has been shown to play a role in educational and professional career choices (Kelly et al., 2018; Rocker & Dori, 2022; Shin et al., 2016).

3.4.3 Football for personal and social development

The Inter Campus educational–technical methodology is based on practical, field-based interventions through targeted football exercises aimed at fostering the holistic development of children. These activities are designed to enhance not only motor and technical skills, but also cognitive, emotional–affective and social dimensions of personality. At the same time, the methodology places strong emphasis on the training of local coaches, enabling them to autonomously apply educational practices and ensuring continuity and long-term sustainability of the programs. In order to coherently assess the effectiveness of such interventions, it is essential to adopt evaluation and research tools that are aligned with the methodological framework itself. These tools must allow the measurement of program impact in the short, medium and, where possible, long term, both at individual and collective levels.

Within this perspective, the Life Skills through Sports Development Scale represents a scientifically grounded instrument designed to assess life skills development through sport.

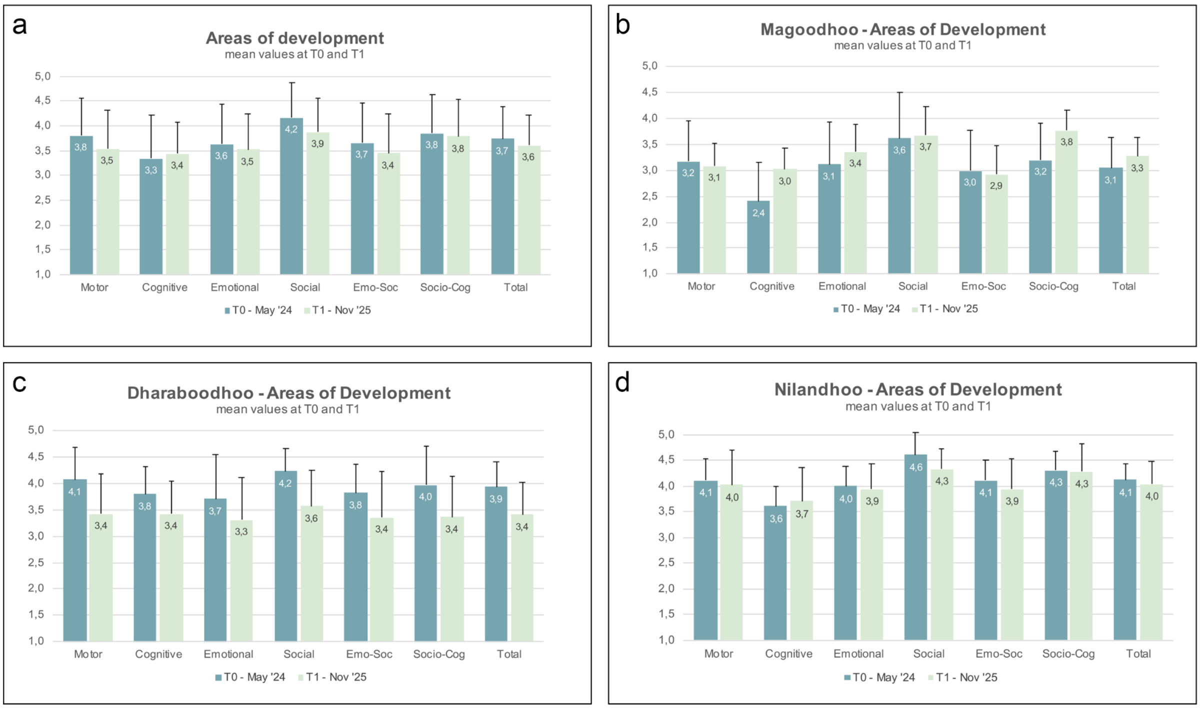
Previous research has outlined the development and validation of this scale, aimed at measuring whether and how young people acquire key life skills through sport participation(Cronin, 2015; Cronin & Allen, 2017) . These life skills include teamwork, goal setting, time management, emotional regulation, interpersonal communication, social skills, leadership, problem solving and decision making.

Beyond these transversal life skills, additional dimensions related to technical and motor competencies specific to football were integrated, in order to obtain a more comprehensive overview of children's personality development across multiple domains. The construction of the instrument involved defining each life skill, identifying its core components, and developing specific items capable of assessing each skill and its corresponding developmental area.

Empirical evidence from previous studies has demonstrated that the total number of life skills developed through sport is positively associated with higher levels of self-esteem, positive affect and overall life satisfaction among young people. Furthermore, the scale has shown strong internal consistency and structural reliability. Research findings also highlight the crucial role of the coaching climate in youth development through sport. In particular, an autonomy-supportive coaching climate has been found to be positively related to both life skills development and psychological well-being in youth sport participants.

While coach autonomy support represents a key factor, other contextual variables may also contribute to life skills development through sport, such as peer relationships and the broader social environment. Coaches may foster life skills either directly, through intentional teaching, or indirectly, by using sport as a medium to convey meaningful life lessons (Holt et al., 2008). For this reason, the Life Skills Development Through Sports Scale is considered a reliable and valid tool for evaluating life skills development and for assessing the effectiveness of sport-based educational programs aimed at positive youth development.

Analysis of the responses in the Life Skills Development through Sports Scale scale showed that mean values for all the islands and all the areas of development registered a minimal decrease from 3.7±0.7 to 3.6±0.6 (Fig. 10a). Nilandhoo registered the highest values in all the areas both at T_0 and T_1, whereas Magoodhoo started and finished with the lowest values in all the areas. Average values for all the areas for Magoodhoo were 3.1±0.6 at T_0 and 3.3±0.4 at T_1 (Fig. 10b), for Dharaboodhoo 3.9±0.5 at T_0 and 3.4±0.6 at T_1 (Fig. 10c), and for Nilandhoo at T_0 was 4.1±0.3 and 4.0 ± 0.5 at T_1 (Fig. 10d). Dharaboodhoo registered a consistent decrease in values from T_0 to T_1 with most of the values around the central point between complete disagreement and complete agreement with the statements, especially at T_1. The area with the lowest score is the cognitive area where the average of all respondents at T_0 provided a value of 3.3±0.7 and at T_1 of 3.4±0.6, showing a minimal change in positive from the beginning of the project. Magoodhoo had particularly low values for the cognitive area, starting at 2.4±0.7 at T_0 and reaching 3.0±0.4 at the end of the project. Interpreting the results needs to be conducted with caution, as it is possible that children did not fully understand the concepts in the questionnaires and provided random answers at least at T_0 when questionnaires were administered as the first item in the agenda of the training session, and the number of questions could have been overwhelming. Although English is the language used in all Maldivian schools, some wording might have been more suitable for older students than for younger ones. Additionally, the available time might not have been enough to fully focus on the questions and provide reasoned answers. Results might have also been driven by a non-regular delivery of the activities or activities delivered without following the methodology suggested during the 'train the trainers' sessions. The regular weekly calls only highlighted the results of the previous week and focused on scheduling activities rather than checking with each trainer which types of games were proposed or sharing a detailed plan. Although examples of games were regularly provided, at least during the first months of the programme a more hands-on



approach could have driven more tangible results in the coming months.

Figure 10. Mean and standard deviation of the Life Skills Development Through Sports Scale for each island and for the whole project at T0 (May 2024) and T1 (November 2025). **a)** Aggregated values at T0 and T1 for the whole project; **b)** values for Magoodhoo; **c)** values for Dharaboodhoo; **d)** values for Nilandhoo.

3.5 Conclusions

Playing with Corals is an innovative project designed to engage participants in a fun and appealing way, to raise awareness about the ocean, build local capacity, and enhance ocean literacy. The integration of environmental games into structured football training combines the development of children's personalities alongside the development of their environmental consciousness.

The project was tested over the 2 years in Faafu Atoll, and the results are fundamental to understanding challenges and possible solutions, identifying priority areas and better defining the metrics of success.

Although the quantitative analyses did not detect statistically significant changes, observed trends were generally consistent with the project's intended outcomes. From a marine perspective, the state of the reef stars clearly demonstrates children's sense of responsibility for corals, acknowledging their value and fragility and recognising the processes and challenges they face. This may strengthen a personal connection to the marine environment, leading to positive behaviour changes. The development of place-based activities run in the ocean can increase the connectedness of children with the marine environment and allow their minds to shift from abstract concepts to practical, tangible experiences and effects. Exposure to viable career opportunities for Maldivian children and to reef restoration may inspire their future choices. Our work demonstrates that reef stars are a viable community-based restoration technique, where children participate for educational purposes under adult supervision while delivering tangible restoration outcomes. The overall engagement demonstrates the potential of such a project, but also the striking reliance on the commitment of local trainers to deliver activities on a regular basis. Thus, intermittent sessions may weaken the effectiveness of similar projects.

To foster children's personality development through sports, each training session should follow strict guidelines and a precise program, and this might need to be guided more thoroughly, especially in the first phases of the project. Although reef stars are a valuable tool for fostering a sense of ownership and responsibility, they inherently limit participation to children with swimming skills. This may result in a high baseline connection with the ocean and restrict the benefits of such a project to a broader audience. The results achieved in knowledge gain underscore the need to implement future modifications and adjustments to match questions with topics learnt through practice. In fact, the environmental knowledge was assessed on general notions rather than focusing on practical concepts that could have been learnt through their experiences, making it very similar to a rote-based approach.

Pollution, land expansion, and sea water warming have been perceived by the local adult population as the major threats to coral reefs, and these themes are particularly important and pressing for a country like the Maldives that is threatened by local and global pressures. Therefore, the heart of the second edition of the project will shift more towards these conservation priorities. The proposed activities will focus on both land and the ocean as key areas for implementation, highlighting the interactions between them and enabling us to expand the target group to include also non-swimmers. The format of the football training sessions will also be translated into marine activities to maximise the benefits of both theoretical concepts.

The first edition of Playing with Corals has laid the groundwork for a fully functioning project that will serve as the point of convergence for local environmental challenges and the tool to address them, starting with the younger generation.

The limited positive results call for adaptations to the project, whether on continuity of activities, through more structured sessions or by providing clearer objectives to the trainers. Yet, these findings reinforce the view that experiential connection, rather than knowledge acquisition alone, is critical in promoting stewardship and creating a sense of responsibility.

Finally, exposure to potential career pathways and opportunities in marine conservation may also play an important role in inspiring children and broadening their future aspirations, aspects worth investigating in the future.

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3.7 Supplementary material 1

Questionnaire administered to the adult population- The questionnaire was provided both in english or dhivehi as requested by the respondent.

What is your ISLAND NAME?

How old are you?

You are:
▢ MALE
▢ FEMALE

What is your current job, if any?

Have you ever been working in the tourism sector?
▢ YES
▢ NO

Level of education:
▢ No School
▢ Compulsory School
▢ High School
▢ Bachelor Degree (B.Sc.)
▢ Master Degree (M.Sc.)
▢ Doctorate of Philosophy (Ph.D.)

Just a few questions about you

1. In the water, can you:
▢ Float
▢ Swim (basic)
▢ Swim with at least 1 proper stroke
▢ I can’t do any of this
▢ I’ve never tried

2. If you can swim, how old were you when you learnt?

3. If you can swim, how did you learn to swim?

4. If you have never learnt to swim, why?

5. Have you ever:

▢ Snorkelled with mask, snorkel and fins in shallow water (sandy area)
▢ Snorkelled with mask, snorkel and fins on a reef area
▢ Dived with SCUBA equipment
▢ I have never tried any of these

6. Have you ever played football?

▢ YES
▢ NO

Now, the last part. Let's see how much you know about the ocean!
(For each question, there is only one correct answer!)

1. Which of the following is NOT a characteristic of coral reefs?

▢ High biodiversity
▢ Rapid growth
▢ Sensitivity to temperature changes
▢ I don't know

2. What is coral bleaching?

▢ A process where corals lose their color due to stress
▢ A cleaning method for corals
▢ A disease affecting coral reefs
▢ I don't know

3. What is the primary cause of coral bleaching?

▢ Pollution
▢ Overfishing
▢ Rising ocean temperatures
▢ I don't know

4. What role do corals play in the marine ecosystem?

▢ Providing shelter and food for various marine species
▢ Controlling ocean currents

▢ Regulating the pH levels of seawater
▢ I don’t know

5. How does coral bleaching impact marine biodiversity?
▢ Increases biodiversity by creating new habitats
▢ Decreases biodiversity by destroying coral habitats
▢ It has no impact on marine biodiversity
▢ I don’t know

6.Corals are:
▢ Animals
▢ Plants
▢ Rocks
▢ I don’t know

7. Today, the coral reefs conditions are
▢ Excellent, pristine conditions
▢ Very good, just few areas are suffering
▢ Getting better
▢ In danger, large areas are threatened by climate change and human actions
▢ I don’t know

8. Coral reefs are threatened by (more than 1 answer)
▢ Sea water acidification
▢ Sea water warming
▢ Strong marine currents
▢ Big marine predators (sharks)
▢ Boats anchoring
▢ Pollution
▢ Hurricanes
▢ Land expansion
▢ I don’t know

3.8 Supplementary material 2

Marine and environmental portion of the questionnaire administered to children at T_0 and T_1.

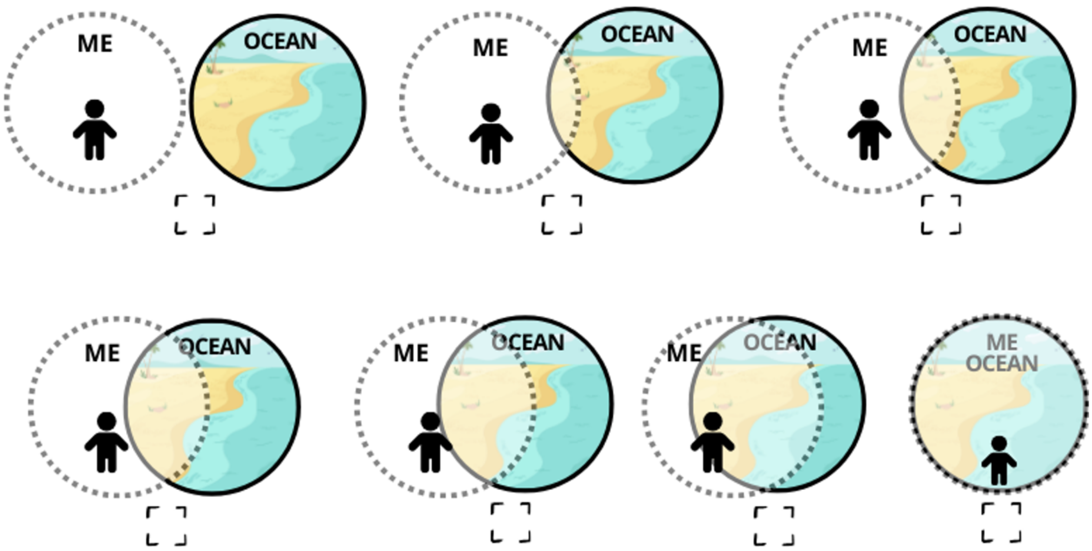
Questionnaire number

What is your ISLAND NAME?
How old are you?
Date:
You are:

- ▢ **MALE**
- ▢ **FEMALE**

Now imagine that the circle on the left represents YOU and the circle on the right represents the NATURAL ENVIRONMENT of the OCEAN

Which picture best describes YOUR RELATIONSHIP with THE NATURAL ENVIRONMENT of the OCEAN?



Please now we ask you to indicate how much you agree or disagree with the following statements. Remember, there are no right or wrong answers but only what you think!

Please note that column 1 (highlighted in grey) was not included in the questionnaire; it is provided here for a visual reference on the subdivision into the three factors for NEP analysis.

		Strongly disagree 1	Disagree 2	Not sure 3	Agree 4	Strongly agree 5
1 Rights of Nature	Plants and animals have as much right as people to live.	○	○	○	○	○
2 Eco crisis	There are too many (or almost too many) people on earth.	○	○	○	○	○
3 Human exemptionalism	People are clever enough to keep from ruining the earth.	○	○	○	○	○
4 Rights of Nature	People must still obey the laws of nature.	○	○	○	○	○
5 Eco crisis	When people mess with nature it has bad results.	○	○	○	○	○
6 Human exemptionalism	Nature is strong enough to handle the bad effects of our modern lifestyle.	○	○	○	○	○
7 Rights of Nature	People are supposed to rule over the rest of nature.	○	○	○	○	○
8 Eco Crisis	People are treating nature badly.	○	○	○	○	○
9 Human exemptionalism	People will someday know enough about how nature works to be able to control it.	○	○	○	○	○

Now, the last part. Let's see how much you know about the ocean!

(For each question, there is only one correct answer!)

Which of the following is NOT a characteristic of coral reefs?

▢ High biodiversity

▢ Rapid growth

▢ Sensitivity to temperature changes

What is coral bleaching?

▢ A process where corals lose their color due to stress

▢ A cleaning method for corals

▢ A disease affecting coral reefs

What is the primary cause of coral bleaching?

▢ Pollution

▢ Overfishing

▢ Rising ocean temperatures

What role do corals play in the marine ecosystem?

▢ Providing shelter and food for various marine species

▢ Controlling ocean currents

▢ Regulating the pH levels of seawater

How does coral bleaching impact marine biodiversity?

▢ Increases biodiversity by creating new habitats

▢ Decreases biodiversity by destroying coral habitats

▢ It has no impact on marine biodiversity

What is the primary function of ocean currents?

▢ Distributing nutrients to marine life

▢ Regulating global temperature

▢ Preventing hurricanes

Corals are:

▢ Animals

▢ Plants

▢ Rocks

3.9 Supplementary material 3

Personality development portion of the questionnaire administered to children at T_0 and T_1-

*Section 1 was used to analyse the **motor** area*
*Section 2 was used to analyse the **cognitive** area*
*Section 3 was used to analyse the **emotional** area*
*Section 4 was used to analyse the **social** area*
*Section 5 was used to analyse the **socio-cognitive** area*
*Section 6 was used to analyse the **socio-emotional** area*

Questionnaire number

Please now we ask you to indicate how much you agree or disagree with the following statements. Remember, there are no right or wrong answers but only what you think!

1. I am able to:

	Completely disagree 1	**Disagree 2**	**Not sure 3**	**Agree 4**	**Completely agree 5**
Driving the ball	○	○	○	○	○
Kicking and shooting the ball	○	○	○	○	○
Receiving and grabbing the ball	○	○	○	○	○
Dribbling and overcome opponents	○	○	○	○	○
Running quickly	○	○	○	○	○
Jumping in different ways	○	○	○	○	○
Passing the ball to my teammates	○	○	○	○	○
Headkicking	○	○	○	○	○
Defending the ball from the opponents	○	○	○	○	○
Scoring goals	○	○	○	○	○

2.I am able to:

	Complete ly disagree 1	Disagre e 2	Not sure 3	Agree 4	Complete ly agree 5
Find a solution to a problem	○	○	○	○	○
Create as many possible solutions to a problem	○	○	○	○	○
Compare each possible solutions in order to find the best one	○	○	○	○	○
Know how to solve problems in day-to-day life	○	○	○	○	○
List my options for solving a problem	○	○	○	○	○
Talk to different people before taking a decision	○	○	○	○	○
Ask other people for possible solutions to a problem	○	○	○	○	○
Assess why my solution to a problem did not work	○	○	○	○	○
Know how to develop a plan to solve a problem	○	○	○	○	○

3.I am able to:

	Complete ly disagree 1	Disagre e 2	Not sure 3	Agree 4	Complete ly agree 5
Control my negative emotions (sadness, anger, aggressiveness)	○	○	○	○	○
Help others to control their emotions	○	○	○	○	○
Use my emotions to get motivated	○	○	○	○	○
Understand other people’s emotions	○	○	○	○	○
Talk about my emotions with others	○	○	○	○	○
Calm down other people when they are angry	○	○	○	○	○
Know how to calm down myself when i get angry	○	○	○	○	○
Know when it’s the right time to speak	○	○	○	○	○
Listen carefully to others	○	○	○	○	○
Think about what i’m going to say before speaking	○	○	○	○	○

4. I am able to:

	Complete ly disagree 1	Disagre e 2	Not sure 3	Agree 4	Complete ly agree 5
Know how to inspire others	○	○	○	○	○
Let others to figure out how they can improve themselves	○	○	○	○	○
Encourage others to work together	○	○	○	○	○
Compliment others for their performance	○	○	○	○	○
Encourage others to put the team/group's interests ahead of theirs own	○	○	○	○	○
Know how to positively influence a group	○	○	○	○	○
Be a good role-model for others	○	○	○	○	○

5. I am able to:

	Complet ely disagree 1	Disagr ee 2	Not sure 3	Agree 4	Completely agree 5
Make friends	○	○	○	○	○
Partecipate in a social group	○	○	○	○	○
Start a conversation	○	○	○	○	○
Ask for help when i need it	○	○	○	○	○
Help others even without them asking for	○	○	○	○	○
Get others to laugh and smile	○	○	○	○	○
Maintain close friendships	○	○	○	○	○

6.I am able to:

	Completely disagree 1	Disagree 2	Not sure 3	Agree 4	Completely agree 5
Cooperate with others	○	○	○	○	○
Help building team-spirit	○	○	○	○	○
Accept suggestions for my improvement from others	○	○	○	○	○
Resolve conflicts with others	○	○	○	○	○
Avoid blaming others for their mistakes	○	○	○	○	○
Understand my role within a team	○	○	○	○	○
Accept different opinions from others	○	○	○	○	○

Chapter 4

4.1 General discussion

With the current global decline of coral reefs (Andrello et al., 2022; Hoegh-Guldberg et al., 2007; Hoegh-Guldberg, Jacob, et al., 2019; Hughes et al., 2017), strategies must be implemented at various levels to halt, if not reverse, this process (Boström-Einarsson et al., 2020; Hoegh-Guldberg et al., 2023; Reimer et al., 2024). Projections estimate that coral reefs will decline by a further 70–90% at 1.5 °C of global warming (IPCC, 2023) if actions are not implemented promptly.

A large portion of the global population lives near coral reef areas (Sing Wong et al., 2022) (Hoegh-Guldberg, Pendleton, et al., 2019) and relies on the resources they provide, in the form of ecosystem services, for their livelihoods (Giglio et al., 2024; Hoegh-Guldberg, Pendleton, et al., 2019); thus, the loss of habitats and biodiversity may have dramatic consequences for them (IPBES, 2019). Small Island Developing States appear to face disproportionate risks and threats from climate change, even at 1.5 °C (Hoegh-Guldberg, Jacob et al., 2019). Globally, scleractinian corals are among the organisms most at risk of extinction, with 44% of species listed as threatened on the IUCN Red List (IUCN, 2025). Among them, we risk losing both fast-growing and slow-growing corals, as well as vulnerable species and rare organisms. As a consequence of bleaching events, certain species have already been declared regionally extinct (Loya et al., 2001), although some have been rediscovered in deeper waters after some time (Yamashiro & Tang, 2024). Moreover, studies indicate local mass extinction risks in native habitats and possible shifts in organisms' geographical ranges (Chaudhary et al., 2023), but unfounded conclusions on the migration of entire reefs to higher latitudes (Hoegh-Guldberg et al., 2017).

From a positive and hopeful perspective, studies show that the benefits of limiting global warming to below 1.5 °C above preindustrial levels outweigh the costs (Hoegh-Guldberg, Jacob et al., 2019). Therefore, actions to safeguard reefs at various levels are essential and imperative (Reimer et al., 2024). In such an urgent scenario, conservation approaches must be diversified (Duarte et al., 2020) to encompass the protection of endangered species, safeguard valuable areas and resources (Michaelsen et al., 2025), whilst also ensuring sustainable development for people and the planet (https://sdgs.un.org/2030agenda).

It is critical to narrow the gap between science and society in order to enable informed, grassroots decision-making alongside official government and international-level policies.

When information is accessible and diffused, the general public can play a meaningful role in shaping what happens on our planet (Bonney et al., 2009). Yet today, ocean literacy, despite ever-increasing efforts, still seems neither inclusive nor sufficiently widespread (Worm et al., 2021).

Ocean literacy can be achieved in various ways, such as by involving people in different processes of scientific research or by providing opportunities to connect with the ocean and have direct and indirect experiences.

The present research work aimed to promote marine conservation through outreach and citizen science. We filled a knowledge gap with the help of non-professional citizen scientists (Map the Giants) and established the foundation to develop an outreach programme (Playing with Corals) to enhance ocean literacy. This second program uniquely combined football and coral reef restoration to effectively engage young Maldivians.

The first project, Map the Giants, was created in recognition that the ocean harbours centennial coral colonies, whose distribution, abundance, and ecology remain poorly studied outside scattered research (e.g., Brown et al., 2009; Coward et al., 2020; Mezaki et al., 2014; Smith et al., 2021). Despite their longevity, rarity, and value for paleoclimatic studies (e.g., D'Olivo et al., 2024; Lough, 2010), their status remains underrecognised. We drew a comparison with monumental trees on land, being recognised for their ecological, cultural and symbolic value (Budău et al., 2025; Asan, 2017;) and the object of numerous studies, often citizen science-based (Moga et al., 2016; Nolan et al., 2020), and protected through various regional and national efforts (Lindenmayer et al., 2014; Sladonja et al., 2023). Building on successful terrestrial and marine citizen science initiatives and inspired by the impressive findings of a dedicated study on the distribution of very large coral colonies around Ta'u (American Samoa), which was initiated following a report of a single enormous *Porites* sp. and a few other sizeable colonies, we selected citizen science as the research methodology to investigate the existence and global distribution of exceptionally large corals (giant corals). Acknowledging the ocean's vastness and the economic, logistical, and temporal challenges of finding these rare organisms, this approach appeared the most feasible for developing a framework for a global database to record the distribution of giant corals.

To face criticisms of citizen science projects connected to the quality and reliability of data, we dedicated extensive attention to the definition, implementation and adaptation of the protocol for data collection to ensure its feasibility (Siena et al., 2026). Examples of mis-identification of species are known to be found in citizen science projects (Bird et al., 2014; Forrester et al., 2015; Kosmala et al., 2016), thus in our project the level of taxonomic identification is set to the highest level of confidence possible and analysis only considered coral genera. Researchers design monitoring protocols that take into account the expertise of contributors and provide, when necessary, dedicated training (Hodgson, 1999; Ratnieks et al., 2016), a process that not all participants may be willing to undertake (Pecl, 2019). If on one hand, data collection taking place during recreational activities and not requiring intensive training is likely more appealing to some contributors (Branchini et al., 2015), on the other hand, some participants are particularly interested in gaining knowledge in the process (Parkinson et al., 2025). Flexible protocols can boost participation rates, as users differ in how much data they can and want to gather and how often they are willing to contribute (Marshall et al., 2012).

The protocol was thus designed with these examples in mind, providing an adaptable tool to include basic yet important submissions by non-specialist volunteers and more detailed data by experienced conservation contributors. The different levels of complexity serve the above-mentioned purpose: to allow the receipt of reports from both opportunistic encounters and dedicated surveys and expeditions. If the protocol is straightforward and participants do not require intensive training, the learning opportunity is offered through the website and social media pages that act as an ocean literacy tool and a means of communicating progress and results to contributors (Siena et al., 2026), thus motivating them (Parkinson et al., 2025). The project's management aligns with key principles of citizen science projects (ECSA, 2015), including sharing results with participants and the wider community and acknowledging contributors also within scientific publications.

From an ecological perspective, the number and distribution of reports received, as well as the percentage of validated entries, show the potential of Map the Giants in achieving its objectives of describing ecological patterns of giant corals. Since the project's launch in January 2024, we received 195 submissions from 22 countries, 133 of which have been validated. Although the majority of reports exceeded the minimum data requirements, the few exceptions that provided only basic data demonstrate that we need to continue offering different levels of complexity, while also suggesting to make additional parameters mandatory to increase the completeness of reports (Siena et al., 2026).

To address the practical question "What is a giant coral?", we utilised various criteria, balancing the need to engage the general public, possibly in the absence of specific monitoring tools, with the need to be as rigorous as possible. The size inclusion criterion (5 m in linear length) has the potential to embrace particularly slow-growing corals, such as *Diploastrea heliopora*, which grows a few millimetres every year and would be hundreds of years old at the 5 m threshold (D'Olivo et al., 2024), as well as faster-growing corals that rarely reach that size because of their vulnerability. Despite the criterion being specific, we are aware that only genetic studies would establish whether an observed coral is indeed a single organism. In fact, examples of intra-colonial genetic heterogeneity (IGH) (i.e., the presence of more than one genotype in a single coral) in the form of mosaicism and chimerism have been reported for scleractinian corals, possibly challenging the notion of a coral colony as an individual (Schweinsberg et al., 2015). With IGH as the major responsible for certain organisms' growth (Chang et al., 2018) and considering the possible evolutionary benefits deriving from it (Oury et al., 2020), genetic analysis on giant coral colonies may help shed some light on these aspects. The potential limitation of not assessing corals' genotype is consistent with the approach used in the literature for reports on other very large coral colonies and is a necessary compromise for the logistical and economic feasibility of a research project on such a large scale and involving non-specialised volunteers. Moreover, the repository's accessibility would allow any researcher or institution to conduct this type of study on the colonies of their interest and answer this and similar questions. For example, Strona & Montano (2025) used repository data to investigate potential drivers of giant coral persistence, including resilience to thermal stress and the occurrence of colonies within thermal refugia.

Currently, the absence of reports from the Atlantic Ocean needs to be investigated. This gap may partly reflect limitations in outreach, communication, and local awareness of the project, but it may also stem from ecological, evolutionary, or anthropogenic factors. While, for example, Hudson et al. (1994) reported the presence of long-lived, centennial coral colonies in the region, these did not reach the threshold size for inclusion in our database. Whether they still exist today, reached the threshold size or have perished due to increasing pressures highlights the need for future research. Indeed, coral reefs in the Caribbean and Western Atlantic have been subjected to multiple and long-standing stressors (Connell, 1997; Gardner et al., 2003; Hughes, 1994; Miloslavich et al., 2010; Mumby et al., 2007; Papke et al., 2024; Weil, 2004), leading to severe population declines and, in some cases, species-level extinction or functional extinction (Manzello et al., 2025). Whether giant corals exist in the Western Atlantic or existed is a question that requires further investigation. Our future efforts should address these still-unsolved questions, among others. Perhaps demographic and dedicated studies may help identify regional trends or highlight the need for geographically adapted size for giant corals to investigate resistance-related traits and how they are locally expressed in coral growth and longevity.

Globally, with the limited number of protocols including studies on the demography or tracking the fate of corals (Edmunds & Riegl, 2020), the project's future goal would be for giant coral colonies to be actively searched for, reported and monitored by governments (Brown et al., 2009; Coward et al., 2020; Hudson et al., 1994) and included in official long-term national monitoring efforts. Although the public availability of data through the Map the Giants website might raise questions about potential negative outcomes of over-tourism (e.g., Soong et al., 1999), it offers an opportunity for long-term collective monitoring, and reporting them represents the first step toward their conservation through public recognition of their existence. Tools such as SfM photogrammetry, already performed by the author's team on 14 coral colonies and from some contributors, have been shown to be feasible with low-cost, consumer-grade underwater action cameras. These can produce high-resolution 3D reconstructions of giant colonies, which are valuable as baseline records of the present status of corals, as time-series records for their long-term monitoring, and as documents to ensure accessibility to the wider society through outreach.

This methodology allows the creation of models useful for extracting morphological metrics a posteriori and for documenting, in a relatively short time and with accessible tools, the full status of giant corals, enabling subsequent ex situ studies. The complexity and threedimensionality of reefs serve as habitat and micro-habitat for other associated organisms (Graham & Nash, 2013; Orejas et al., 2022) and giant corals can be seen as large threedimensional structures. Parameters derived from SfM photogrammetry, such as coral complexity, together with in situ studies, might help understand the ecological role of giant corals in relation to other organisms. Furthermore, from a cultural perspective, the creation of models and their upload within VR headsets, in museum facilities and online might promote ocean literacy inclusiveness, allowing people from any part of the world, regardless of their financial situation, to experience these organisms, even if only remotely. Virtual Reality seems to have a positive role in promoting conservation behaviours and raising climate change awareness (Fauville et al., 2020; Thoma et al., 2023). Despite giant corals having survived for centuries, the impact and extent of current threats pose greater risks to them than they possibly faced in previous centuries, making it imperative to discover, document and communicate their presence before it is too late. The call to action to protect them has been made (Coward et al., 2020; Montano et al., 2024; Siena et al., 2025), the next steps involve promoting a hopeful and action-oriented narrative using these inspiring examples of resilience and finding innovative ways to implement practices and legal frameworks for their protection, either through grassroots efforts or top-level interventions.

To protect the planet and oceans, including giant coral colonies, fostering ocean literacy is an essential effort that can complement national and international strategies and begins by raising environmental knowledge (McCauley et al., 2021). Human behaviours are among the drivers of the environmental crisis (IPCC, 2023), and knowledge alone does not seem to produce the desired behavioural change (Brennan et al., 2019). However, place-based experiences seem to promote connectedness with nature and encourage pro-environmental behaviours, and support health and well-being (Beery et al., 2024; Martin et al., 2020; Otto & Pensini, 2017).

In a country like the Maldives, where less than 1% of the territory is land and the vast majority is ocean (Stevens & Froman, 2019) of which reefs represent a relevant portion (Naseer & Hatcher, 2004) and important direct and indirect economic resource (Maldives Bureau of Statistics, 2025), promoting ocean literacy and experiences on reefs might provide essential benefits. Playing with Corals was developed by the MaRHE Center at the University of Milano-Bicocca in collaboration with Inter Campus, the CSR arm of the Football Club FC Internazionale Milano, and supported by the UEFA Foundation for Children. It aims to promote an innovative approach to foster marine stewardship among young Maldivians by combining one of the most popular sports, football, with coral reef restoration, using it as a means to bring participants closer to the ocean. Sport is recognised for its power to help personality growth by strengthening the four areas of development: motor, social, cognitive and emotional (Gould et al., 2007). The design of football training sessions focused on the areas of development was based on quantitative analyses using questionnaires administered to children to assess changes through the Life Skills Development through Sports Scale (Cronin, 2015; Cronin & Allen, 2017). The integration within the football training sessions of games using environmental and marine evocations was not specifically measured in its ability to transfer knowledge on its own. Rather, questionnaires to analyse children's pro-environmental concerns (Dunlap et al., 2000; Manoli et al., 2007), closeness to the ocean (Kleespies et al., 2021) and general environmental knowledge were administered to look at the effectiveness of the programme as a whole. Results did not show a significant change in closeness to the ocean, which could be due to a high baseline, as participants were all swimmers, or by a physical proximity, as all the islands are so small that the ocean pervades everyday life. Results on pro-environmental concerns also suggest no particular changes, calling for adaptations of the project to be more effective in this sense. Environmental knowledge, instead, showed a positive trend, although it was not significant. The absence of the answer "I don't know" from questionnaires may have led to these inconclusive results.

If, from a scientific standpoint, the project will need some adaptations to be more inclusive, effective, and to drive meaningful change, it appears, though, to have led to a practical sense of ownership and connectedness to the ocean through reef stars. All structures installed on the islands were maintained, and corals were monitored, showing signs of growth and high survival rates throughout the project. With its limitations linked to the need for prior strong swimming skills for the implementation of reef restoration, the project seems, anyway, a valuable tool to promote stewardship and transfer practical knowledge. As the project is set to continue for a further 2 years, the challenges encountered during the first pilot phase will be addressed one by one to create a replicable model that effectively fosters stewardship and increases ocean literacy. The results gained so far demonstrate the potential of place-based experiences but also highlight the need to adopt scientific measurement to assess the effectiveness of activities and ensure resources are used effectively.

4.2 Conclusions

Coral reefs are experiencing rapid and widespread degradation, with climate change and anthropogenic pressures as the main drivers. The future loss of a wide proportion of global reefs within the coming decades threatens biodiversity, ecosystem services, and the livelihoods of millions of people, particularly in Small Island States. In this context, innovative, scalable, and socially inclusive approaches are urgently required to improve both scientific knowledge and conservation outcomes.

The present study shows the potential of citizen science to address critical data gaps in coral reef research, focusing on giant and centennial coral colonies that have, until now, remained poorly documented despite their ecological, paleoclimatic, and symbolic value. Through the development of Map the Giants, a global, open-access platform to locate centennial giant coral colonies on a global scale through citizen science, this work shows that non-professional contributors can generate geographically diverse and scientifically valuable records when supported by well-defined protocols and accessible tools. Early results suggest some possible winners in *Porites, Pavona* and *Galaxea* colonies, although current data limitations preclude broad generalisations. The absence of records from certain regions, notably the Atlantic, points to the need for targeted outreach and region-specific studies.

While genetic confirmation of colony individuality remains beyond the scope of large-scale citizen science, the public availability of the database enables future targeted research, including genetic, physiological, and long-term ecological studies, consequently extending the scientific value of the initiative beyond its currently reached goals. The application of Structure from Motion photogrammetry further improves the utility of these records, delivering high-resolution three-dimensional baselines for monitoring and morphological analyses, whilst offering high-quality material for documentation and outreach purposes. Giant coral colonies offer unique opportunities for research, conservation, and communication. Documenting these organisms can contribute to innovative approaches to reef conservation amid global-scale environmental challenges. Alongside data generation, the project offers also an opportunity for ocean literacy, a complementary tool for conservation.

The widespread need and efforts to advance ocean literacy, despite still limited inclusiveness, call for innovative, place-based engagement strategies to foster stewardship, particularly among young people. Thus, Playing with Corals was created with two main goals: to develop an innovative method for promoting ocean literacy and stewardship by blending an engaging sport, football, with reef restoration efforts, and to measure and share the project's results and challenges to enable adaptations, allowing the creation of a replicable and effective model. Although quantitative measures of change showed limited sensitivity in the Maldivian context, the observed continuity of activities, albeit with temporary intermissions, and the maintenance of reef stars suggested the development of practical ownership and engagement. These findings reinforce the view that practical experiences, rather than knowledge acquisition alone, are critical in promoting personal connectedness. The limited positive results call for adaptations of the project, whether to ensure continuity of activities, or by creating more structured sessions or by providing clearer objectives to the trainers.

Overall, the results of the present work emphasise the importance and potential of combining citizen science, emerging technologies, and experiential approaches to secure a promising future for coral reef conservation, whilst recognising the need to adapt protocols and strategies in due course to reflect the needs of non-professionals and achieve the desired outcomes.

We have now laid the groundwork for two novel projects that will necessarily adapt to remain relevant and continue achieving measurable outcomes. We have shown that citizen science is a fundamental tool for addressing ecological questions, and fostering ocean literacy should not be overlooked in this context and similar projects.

Future developments for Map the Giants should adopt a multidimensional approach. The platform's structure and monitoring protocols should be adapted to enable long-term tracking of the fate of giant coral colonies, allowing changes in their status to be documented over time. The use of machine-learning techniques could enhance multiple stages of the workflow, including data validation, pattern recognition, and automated data extraction. Expanding communication and outreach efforts will be critical to increase the project's global reach, improve data representativeness, and promote long-term stewardship among participating communities. At the same time, future research should address the development of innovative strategies aimed at conserving these exceptional organisms, both through community-led initiatives or through official legislative frameworks. Establishing a coordinated international network of scientists will be key to addressing the many unresolved ecological, evolutionary, and conservation-related questions surrounding giant coral colonies. Ultimately, the creation of innovative, accessible, and engaging tools has the potential to position giant corals as symbols of marine conservation, strengthening public awareness and support for reef protection.

Whilst together with the scientific community, we recognise the value of place-based experiences, including citizen science initiatives, to foster ocean literacy, we also highlight the need for strong measurement tools and a methodical approach to outreach initiatives. The project Playing with Corals has shown that it can produce some of the desired outcomes, albeit with reduced societal impact. We have demonstrated the need for pilot projects to be scientifically measured to highlight challenges and propose adaptations to achieve the desired goals. The open communication of these aspects allows a critical analysis for improvements and to generate change. We have also shown that more practical and tangible goals are just as important and provide opportunities for improvement.

Citizen science and outreach are valuable tools in further advancing scientific knowledge and ocean literacy; their impacts need to be measured systematically to ensure the effectiveness and soundness of the results generated and to include adaptations when required. Ultimately, the long-term conservation of coral reefs will rely on robust, measurable outcomes that use, among other tools, citizen science and outreach as central mechanisms, bridging public engagement, scientific knowledge, and policy action to foster sustainable resource use and ensure the persistence of coral reef ecosystems. These results indicate that public participation offers a scalable opportunity to enhance coral reef research, education, and restoration, reinforcing its relevance for the development of future marine conservation strategies.

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