Federico Maria Gigli

Digital observations through Structure from Motion photogrammetry reveal impact from sediment load on local corals in Mindelo, Cabo Verde.

UNIVERSIDADE DO ALGARVE

Faculdade de Ciências e Tecnologia

Year 2022

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Mestrado em Biologia Marinha

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Declaração de autoria de trabalho / Statement of Authorship

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(Federico Maria Gigli)

Acknowledgments

First of all, I would like to thank my associated supervisors Guilherme Mascarenhas and Rui Freitas. Thanks to their help and their relentless work ethic we were able to accomplish such a demanding work with limited resources

I also want to thank my supervisors Aschwin Engelen and Ester Serrão, who gave me the opportunity to delve into a subject that is very dear to me, collecting important information on the status of coral in Cabo Verde. Thanks to this opportunity, I spent a fantastic time in Cabo Verde, a genuine and friendly place where I had the opportunity to work together with fantastic people and learn about the creole culture.

Furthermore, I would like to thank my family who supported me emotionally and financially during these years of study. Their help and generosity allowed me to spend two unforgettable years in Portugal, establishing important friendships that I will treasure for the rest of my life. In these two years, I have had the opportunity to experience fantastic moments and collect experiences that will enrich me forever. In particular, I want to thank my sister Beatrice, who has been a pillar of strength during this past year. Without her help, and the countless hours spent together correcting and improving my manuscripts, I would not have been able to finish many school assignments on time. I also want to thank my brother-in-law Davide, and my sister-in-law Victoria, who have also helped me a lot in many different tasks.

My heartfelt thanks also go to Teresa Correia, whose generosity was crucial to the success of this project. Thanks to her knowledge and her fantastic way of working, we were able to develop a truly interesting and unique project

Finally, I want to thank all my friends and all the people I have met along my life's path. Their affection has made me who I am today. Without them, my life would have been completely different, and my decisions would definitely not have been the same.

Thanks to all and single of you, you made this possible!

Resumo

O impacto do homem na natureza tem sido cada vez mais drástico nos últimos anos. Como os habitats marinhos pouco profundos estão a ser especialmente ameaçados ao longo das últimas décadas. Fenómenos como a construção intensiva perto das zonas costeiras, assim como a libertação descontrolada de sedimentos nas águas costeiras, podem levar a danos muito graves com um impacto directo em todos os organismos que vivem perto dessas zonas. Os recifes de coral, para além de representarem um dos mais diversos habitats do nosso planeta, são também locais chave para a conservação e preservação de outras formas de vida. Os grandes peixes pelágicos, muitas vezes essenciais tanto para a economia local como para a subsistência de muitas populações que vivem perto do mar, dependem diretamente do bem-estar destes ecossistemas. Para além disso, as águas pouco profundas representam também um importante local de segurança onde os organismos aquáticos passam muito frequentemente as fases iniciais das suas vidas antes de se deslocarem para maiores profundidades. A conservação destas zonas deve ser considerada um requisito fundamental, especialmente para os países menos desenvolvidos próximos do mar, cujas economias dependem estritamente do bem-estar das águas que os rodeiam. A monitorização destas áreas, bem como a criação de áreas marinhas protegidas que englobam a linha costeira, deve ser levada a sério para que as gerações futuras possam usufruir dos benefícios trazidos pelo mar.

Este estudo aborda o problema geral da perturbação de habitats marinhos como os corais tropicais devido a gestão terrestre que causa acumulação de sedimentos sobre os habitats marinhos. Para estudar esta questão foi considerada uma pequena área chamada 'Enseada de Coral' (16° 53' 48" N; 24° 59' 34") localizada ao longo das costas do Mindelo, São Vicente, Cabo Verde.

A área deste estudo é de especial importância não só do ponto de vista turístico, sendo as suas águas tranquilas visitadas diariamente por banhistas locais, mas também do ponto de vista da biodiversidade, uma vez que uma grande quantidade e variedade de organismos vive nas suas águas. Até à data, foram contadas mais de 500 espécies diferentes de organismos na Enseada, muitas delas endémicas de Cabo Verde ou apenas dessa área. Esta zona, bem como a praia da Laginha que a rodeia, sofreram nos últimos anos transformações substanciais derivadas da área da construção, sendo uma das últimas o derrame de um tubo de drenagem de águas pluviais que, durante a estação das chuvas, liberta uma grande quantidade de sedimentos sobre os organismos que vivem perto dela.

Neste estudo, quisemos mostrar como, os corais duros que estão mais próximos desta drenagem estão mais ameaçados. Em particular, foram tidos em consideração dois parâmetros de medição, a

percentagem de cobertura de coral e o número de colónias presentes. Para realizar o estudo, a área acima mencionada foi dividida em três áreas diferentes mais pequenas, de 10x50 m cada, sendo a primeira a mais próxima da fonte de perturbação e a terceira a mais distante. Estas áreas foram então subdivididas em 5 sub-áreas diferentes de 10x10 m cada. Neste estudo, foi utilizada uma técnica inovadora de monitorização chamada estrutura a partir do movimento, que envolve a criação de mapas bidimensionais, e se desejado modelos tridimensionais, do fundo do mar a partir de imagens individuais. Para o sucesso do estudo, foram recolhidas inúmeras imagens subaquáticas e depois, com a ajuda de um software chamado Agisoft Metashape, estas imagens foram fundidas para criar estes mapas. No total foram criados quinze mapas diferentes, um para cada um dos quadrados 10x10 em cada uma das três áreas. Para a criação de cada mapa, foram geralmente recolhidas entre 2000-3000 fotografias. Os dados necessários para realizar os testes estatísticos foram então extraídos utilizando o software TagLab, que, através da utilização dos seus comandos, permitiu a extrapolação de dados importantes, tais como o número de colónias de coral presentes dentro dos quadrados e a área superficial de cada coral individual.

Os resultados deste estudo mostraram que a percentagem de cobertura de coral aumenta à medida que nos afastamos da perturbação. Por conseguinte, as áreas de controlo, mais afastadas da perturbação, mostraram uma maior percentagem de cobertura de corais do que a zona mais afetada pela sedimentação. Além disso, o número de colónias também aumentou com o afastamento da fonte de perturbação. Tanto o número de colónias como o tamanho dos corais aumentam com o afastamento da fonte de perturbação, mesmo dentro da própria primeira área junto à fonte de sedimentos. Isto pode significar que à medida que a profundidade aumenta, a percentagem de danos nos corais diminui, provavelmente devido a uma maior taxa de dispersão de sedimentos. Os corais *Siderastrea* representaram o coral mais resistente a estas condições, pois as suas colónias foram as maiores e mais numerosas, sugerindo que este coral tem mais capacidade adaptativa a estas condições de sedimentação do que os outros. Finalmente, os resultados também mostraram que a segunda área parece ser a "mais saudável". De facto, esta área, apesar de ter menos colónias, tem, em média, corais maiores e a percentagem de cobertura de coral é maior do que em qualquer outra área. As causas da maior cobertura de corais e do maior tamanho dos corais nesta área central relativamente à outra área longe das perturbações pelos sedimentos são desconhecidas.

A comunidade de coral que vive nas águas que circundam o arquipélago de Cabo Verde ´e muito rica, mas existe pouca informação científica publicada relacionada com este tema. Este estudo representa o primeiro do seu género realizado nas águas deste arquipélago e procura salientar a importância e utilidade da monitorização de através de cartografia digital, para zonas com habitats rochosos cobertos de povoamentos biológicos que podem ser cartografados por fotografia digital. Cabo Verde é um hotspot de corais marinhos para esta costa Atlântica de África. A riqueza da biodiversidade marinha que se encontra nestas ilhas torna esta uma área importante a preservar, e a sua monitorização ativa é crucial para enriquecer o nosso conhecimento sobre os organismos que nelas vivem. Este estudo pioneiro cria uma linha de base cartográfica detalhada que dá início a uma possível série de futuras atividades de monitorização. Espera-se que as informações recolhidas de forma continuada ao longo do tempo a larga escala ajudarão a preservar o recife de coral, fornecendo e enriquecendo o conhecimento científico que guie as decisões de gestão e conservação sobre este lugar especial. Em particular, procura-sesensibilizar para a riqueza desta baía apesar de estar numa zona muito urbana, tendo em vista a criação de uma área marinha protegida no futuro.

Abstract

Land-based pollution and unregulated construction practices are two of the major threats to shallow water ecosystems. In most coral communities, the percentage of scleractinian coral has dropped dramatically in recent years. Although many nations are undertaking large-scale monitoring programs, in many developing countries, the damage to these habitats is often ignored due to either a lack of information or lack of resources needed to monitor these ecosystems. This study aimed to assess the effects of sediment loads on coral communities, by comparing coral community structure across areas with different degrees of impact. For this purpose, an innovative technique called 'Structure from Motion' was used, to verify the level of damage induced by a rainwater pipe pouring sediment onto a small coral community adjacent to it, in Mindelo, São Vicente, Cabo Verde. Through the use of this technique, it was possible to obtain large photomosaics of three different areas, divided in a total of 15 different plots, each covering 100 m^2 of the benthic habitat. 4223 coral colonies were identified, mapped and classified, successfully delimiting their surface areas. The findings revealed that, in the areas closest to the source of disturbance, coral show a lower size and lower colonies number. However, this tendency seems to lessen as one moves further away from the source, not only in distance but also in depth, indicating that the sediments disperse more easily with depth. This study represents one of the first attempts to monitor the benthic community in Cape Verde and the only one of its kind as a methodology in this area. It is necessary for these studies to be carried out consistently, to ensure the proper preservation of marine ecosystems, which are essential for the wellbeing of the people living in their vicinity.

Keywords: Coral, Monitoring, Structure from Motion, Cabe Verde, Pollution

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List of Abbreviations, Acronyms and Symbols

AI	Artificial Intelligence
CPV	Costal protection value
DEM	Digital Elevation Model
GBR	Great Barrier Reef
GCC	Global Climate Change
GCRMN	Global Coral Reef Monitoring Network
ICRI	International Coral Reef Initiative
MPA	Marine Protected Area
ppMV	Parts Per Million Volume
SfM	Structure from Motion
SSTs	Sea Surface Temperatures
USD	United Nation Dollar
UV	Ultraviolet

General Introduction

Coral life cycle

Among the most spectacular of all ocean's ecosystems are coral reefs. These structures originated, over thousands of years, through the accumulation of seawater minerals conducted by certain reef-building coral. The rocky formations thus created can be extremely thick and stretching for hundreds of kilometres. However, the organism originating this structure, only consists of a small cylindrical-body polyp with catching tentacles. A wide range of reproductive strategies have been developed by different coral species to strive in their dynamic environment. Coral reproduction can occur in two forms: asexual and sexual. Each of them is divided into subcategories. The main types of reproduction strategies will be described in the following paragraphs.

Asexual reproduction

About three-quarters of coral species reproduce by releasing male or female gametes into the water. However, a good amount of them reproduce through asexual reproduction, e.g., by fragmentation, budding or by producing asexual larvae (Highsmith 1982; Tunnicliffe 1981). Fragmentation is usually induced by external physical disturbance to coral reefs, such as severe storms or fish grazing which can accidentally cause the fragmentation of coral branches. This phenomenon is mostly common in coral such as *Acroporidae* (Baums, Miller, and Hellberg 2006), *Pavona* (Willis and Ayre 1985) or *Porites* (Hunter 1993). Fragments bigger than others have a higher chance to survive (Lirman 2000) and with time they can extend for metres (Neigel and Avise 1983; Baums, Miller, and Hellberg 2006). Other coral species reproduce by releasing asexual larvae, called planulae, into the water column. Planulae have an identical genotype to the one of their mothers' and will form identical colonies (Stoddart 1983; Brazeau, Gleason, and Morgan 1998). The dispersal potential of asexually produced larvae is similar to the sexually produced ones and, as such, they can be transported further away than fragmented branches (Stoddart 1983). In Hawaii, for example, different clones of *Pocillopora damicornis* were found spread over eight different reefs (Stoddart 1983). Asexual reproduction is usually a safe strategy and has a fast rate of growth. For this reason, it is widely used in many restoration programs worldwide. However, its main disadvantage is that it does not promote the same level of genetic diversity as the sexual reproduction.

Sexual reproduction

Reproduction, for the majority of ocean animals, occurs when sex cells are spread into the water column and fertilisation happens haphazardly. Coral reproduction happens through spawning. In this event, sperm-releasing and egg-releasing coral of the same species must be synchronised to make sure fertilisation occurs (Fig. 1). Favourable circumstances for long-range dispersal of larvae can be provided by sexual reproduction as well as genetic recombination (Neely et al. 2018). Stony-building coral usually reproduce as either gonochoric (separate male and female polyps), or hermaphroditic (producing both eggs and sperm bundles) (Neely et al. 2018). For the for former, egg or sperm cells are discharged synchronously in the water, and fertilisation occurs. For the latter, on the other hand, bundles containing either sperm or egg cells are released from the coral, slowly reaching the water surface. At this point, bundles open up and fertilisation initiate (Neely et al. 2018). Being several coral species self-incompatible, to successfully fertilise, they necessitate interaction with different coral's gametes (Babcock et al. 1986).

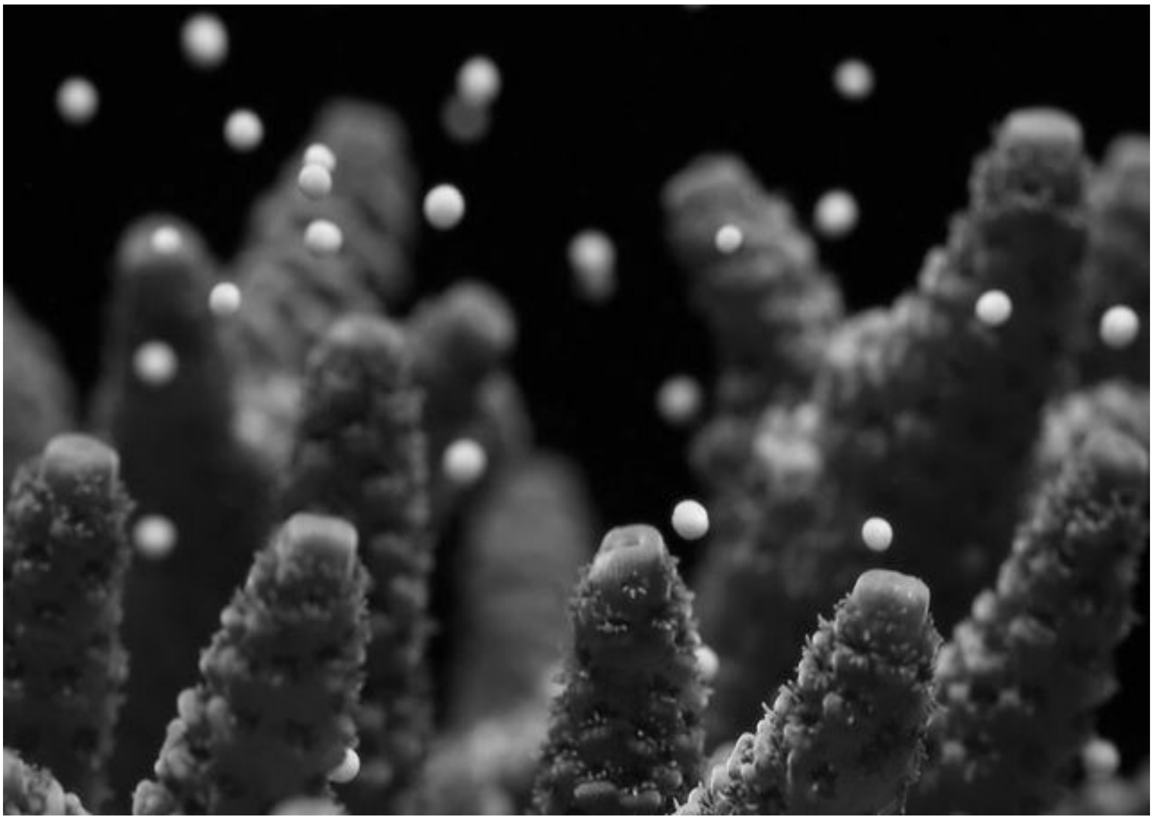

Figure 1: Acropora coral releasing bundles during spawning season. Image source: https://www.coralspawninglab.org

From larvae to coral

The sedimentary polyp is the main actor in the life cycle of coral and related anemones. To maximise the probability of sexual reproductivity, polyps' gametes are synchronically discharged in bundles. From the fertilised egg, a planula larva originates and mixes into the water currents. If it manages to survive predators, the larvae slowly reaches the safe environment of the seabed to settle, turns into a polyp, and gradually develop a new coral colony (Fig. 2). The life stages of a coral can be divided into main episodes. During the first stage, reproduction, polyps living inside the calcium carbonate structure release large amounts of egg-sperm cells which, once they meet, initiate fertilisation (Ball et al., 2002). The second stage is also referred to as the egg-growth stage. During this step, which normally occurs a few hours after fertilisation, the cell begins to divide and grow, eventually giving rise to a planula larva (Ball et al., 2002). The larva, before meeting the specific place in which to attach, spends days, even months floating in the water and being carried along by the currents. During this time the larva feeds on symbiotic algae that will help it grow. In the next stage the larva has finally met the right place where to settle. During this process, the larva becomes stationary, and its pelagic period ends. At this stage, the larva will go through a process called metamorphosis in which it will develop into a polyp (Ball et al., 2002). Finally, the polyp will grow, divide, and create a true colony. This stage is the longest and is the one in which the polyp grows its tentacles and gives rise to symbiosis with the zooxanthellae algae (Schwarz et al., 2008).

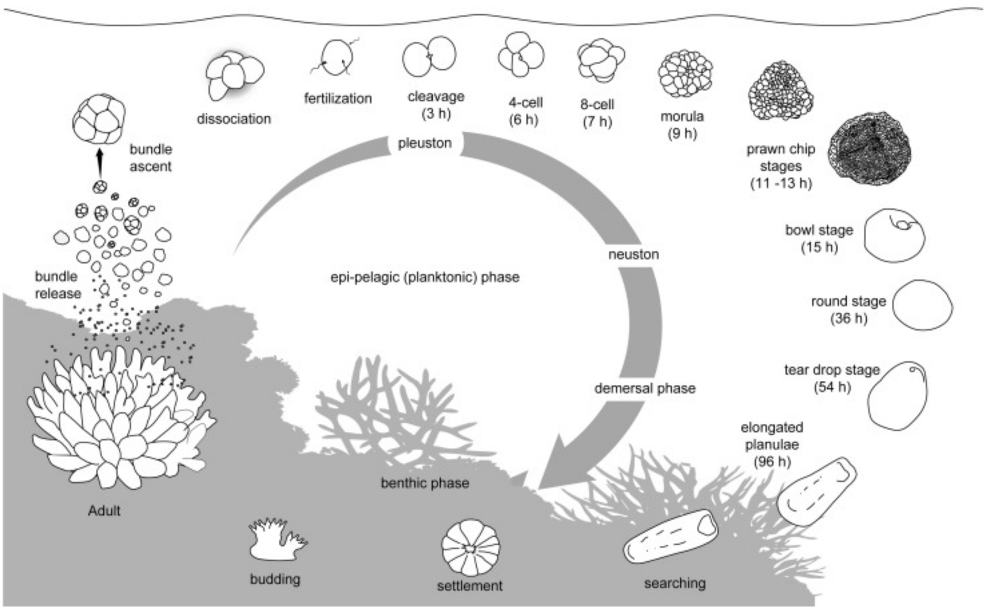

Figure 2: Example of the reproductive cycle of the broadcast spawner Acropora species from bundle to coral, with demonstrating timings (Jones, Ricardo and Negri, 2015).

Coral distribution around the world and types of coral reefs

Coral species exist in all world's oceans (Fig. 3). However, scleractinian coral are predominantly found in shallow tropical and subtropical waters. As their distribution is mainly associated with requirements of temperature, salinity, and illuminated substrate, they are usually found in shallow waters. However, when warm water currents extend poleward, coral is given the possibility to extend in regions outside tropical areas. At the same time, when cold currents extend in tropical areas (generated by upwelling events for instance), they restrict the distribution of coral reefs, such as in the case of the West African coast (Sheppard, Davy, et al. 2017).

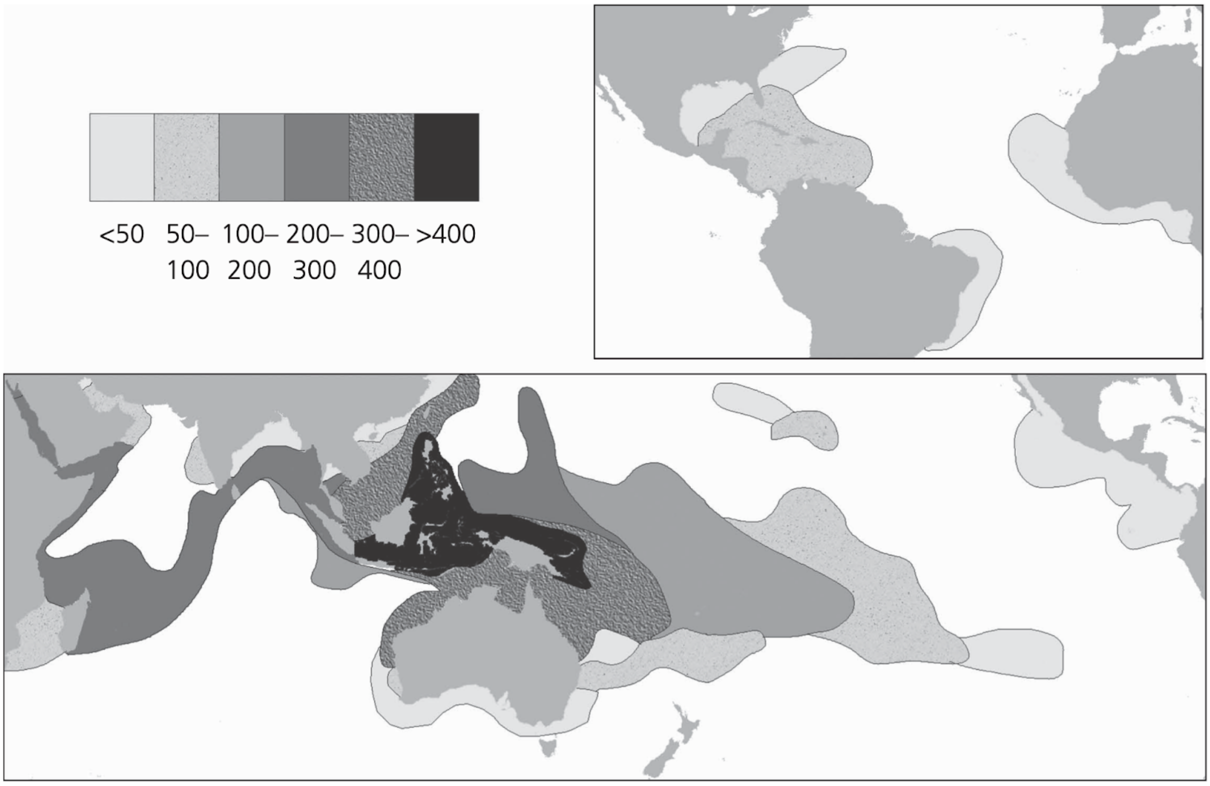

Figure 3:Map of the global distribution of coral reefs with the annexed legend of reef-building coral species diversity (Sheppard et al., 2017)

It is difficult to estimate the total area covered by coral reefs since mapping methods can be very different. However, rough estimates from different methods such as satellite images or depth sounding, revealed different estimates of coral reefs extension (Sheppard, Davy, et al. 2017). Spalding (2001) estimates that the total area covered by coral reefs around the world is 284.330 square kilometres and, of these, 91% is only present in the Indo-Pacific region (Tab. 1) (Spalding et al. 2001).

Table 1: Areas covered by coral reefs in different part of the world (Spalding et al., 2001).

Rank	Country	Area (Km²)	Per cent of world total cover
1	Indonesia	51,02	17,95
2	Australia	48,96	17,22
3	Philippines	25,06	8,81
4	France, including territories	14,28	5,02
5	Papua New Guinea	13,84	4,87
6	Fiji	10,02	3,52
7	Maldives	8,92	3,14
8	Saudi Arabia	6,66	2,34
9	Marshall Islands	6,11	2,15
10	India	5,79	2,04
11	Solomon Islands	5,75	2,02
12	United Kingdom and territories	5,51	1,94
13	Micronesia	4,34	1,53
14	Vanuatu	4,11	1,45
15	Egypt	3,8	1,34
16	USA and territories	3,77	1,33
17	Malaysia	3,6	1,27
18	Tanzania	3,58	1,26
19	Eritrea	3,26	1,15
20	Bahamas	3,15	1,11
21	Cuba	3,02	1,06
22	Kiribati	2,94	1,03
23	Japan	2,9	1,02
24	Sudan	2,72	0,96

However, different estimates revealed different numbers. This is caused not only by the different methods used, but also by the different ideas of what an associated habitat that constitutes coral reefs should be (Sheppard, Davy, et al. 2017).

Biodiversity of coral reefs

No other habitat on Earth includes as many phyla as coral reefs (Porter and Tougas 2001). Out of 34 phyla described worldwide, 32 were found in coral reefs, reflecting not only a high species' diversity, but also a significant productivity in terms of biomass. The estimation of the total number of species found in coral reefs ranges from 600.000 to 9 million globally (Knowlton 2001). However, the exact number is probably impossible to assess, as it is believed that many species are yet to be found, with only around 10% of total species having been classified. In the Indo-Pacific region, the total number of species present in coral reefs is much higher than in any other coral habitats, making it the top spot in the world for marine species biodiversity (Tab. 2). This vast area is home to at least ten times more coral and fish species than the ones found in sites such as the Galapagos Islands (Briggs 1999). Within this area, the species hotspot is located in the Indonesian-Philippines region, in an area called the "Coral Triangle". The pattern of high diversity in the Coral Triangle of South-East Asia, and the decline in diversity with increasing distance from it, has long been recognized (Stehli and Wells 1971).

Table 2: Pattern of species diversity in a different part of the world highlighting the species richness in the Indo-Pacific region (Spalding et al., 2001).

Taxonomic group	**Indo-West Pacific**	**Eastern Pacific**	**Western Atlantic**	**Eastern Atlantic**
Stony corals	719	34	62	
Soft corals	690+	0	6	
Sponges	244		117	
Gastropods				
Cowries	178	24	6	9
Cone shells	316	30	57	22
Bivalve molluscs	2.000	564	378	427
Crustaceans				
Mantis shrimps	249	50	77	30
True shrimps	91	28	41	
Echinoderms	1,2	208	148	
Fish	4.000	650	1.400	450
Seagrasses	34	7	9	2
Mangroves	59	13	11	7

Types of reefs

Mainly three types of reefs exist: fringing reef, barrier reef and atoll reef (Fig. 4). When coral fringes an island, they create a fringing reef. Coral reefs in the open ocean are the result of reef organisms building a fringing reef around the perimeter of newly emerged volcanic islands. After volcanic activity ends, the island recedes in the water due to a combination of plate movement and erosion (Sheppard, Davy, et al., 2017). Initially, the newly formed reef, continues to grow around the island perimeter, thus becoming a barrier reef. Afterwards, the island sinks, leading to the creation of an atoll, a circular band of coral islands without a central landmass, as in the case of the Maldives Islands. These are the three classical forms, which integrate according to their stage of development (Sheppard, Davy, et al., 2017).

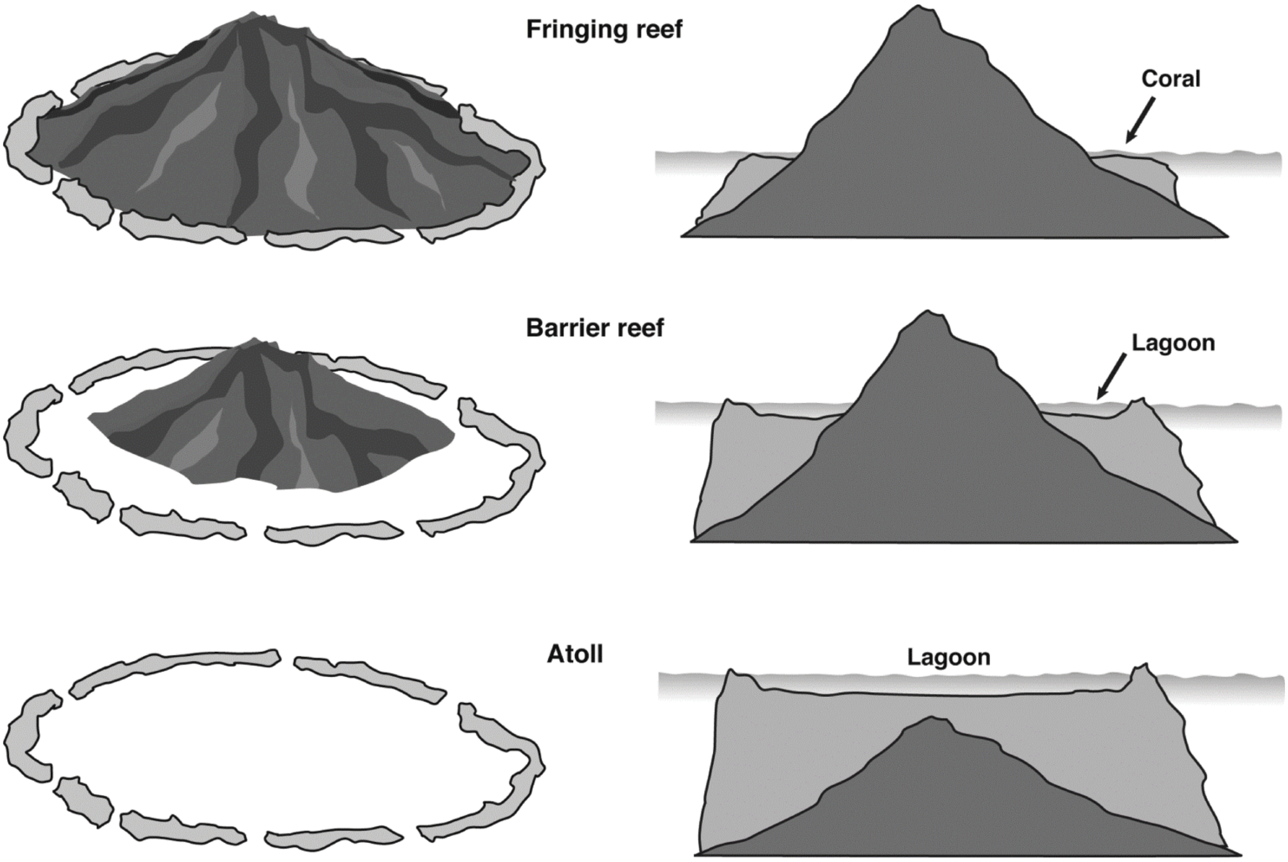

Figure 4:The three main different types of coral reefs formation. Source: http://www.insightsonindia.com

Outlines and reefs' sectors

Despite their different nomenclatures, coral reefs tend to have elements in common with one another. To broadly divide the sections of a reef, it can be said that reefs have three different main sections: 1) the flat reef, 2) the reef crest and 3) the reef slope. Almost every reef that reaches the surface includes a reef flat, which usually extends for approximately ten metres from the beach. In some cases, however, these flats can extend for several metres from the shoreline. Normally this area is no deeper than 1-2 metres, but some areas within it may have a greater depth than others. Reef flats are characterised by higher water temperatures (compared to other areas of the reef), being remarkably shallow and, normally, these characteristics make it a very challenging area to live in (Bellwood et al., 2018). The high-water temperature, in fact, decreases the level of dissolved oxygen in the water and, favouring the evaporation of the water, greatly increases the salinity level. For these reasons, the concentration of organisms present in these areas is significantly lower than in other parts of the reef. The second part is called "reef crest". This area determines the point at which the reef begins to gradually descend. Normally coral boulders and coral colonies can be encountered. The angle that is created between the reef flat and the reef crest can be more or less acute and generally represents the point most affected by wave breaking. For this reason, not many coral colonies are encountered in this area (Sheppard, Davy, et al., 2017). Generally, this area is dominated by calcareous red algae which are remarkably resistant to wave action, and which deposit a form of limestone called high-magnesium calcite. The last part of the reef is the so-called reef slope. This part is also named the "heart of the reef" and is in fact the area where most coral is concentrated. In some reefs of the Red Sea and the Caribbean, these slopes can ensure the presence of coral up to 50 metres deep. Generally, in this zone, as depth increases, the force generated by wave breaking and the percentage of solar irradiation decrease while the percentage of sedimentation increases. Due to its particularly favourable location, it is possible to find the highest rate of biodiversity (Sheppard, Davy, et al., 2017).

Importance of coral reef ecosystems

Coral reefs are among the most biologically prolific and varied ecosystems on Earth. Even though they only cover 0.1-0.5 % of the ocean floor, their importance in the balance of marine ecosystems is crucial and many different species rely on them for their existence (census of marine life, n.d. Raeka-Kudla and Wilson 1997). Coral reefs influence our everyday life in many ways, each one essential to us by some means. Worldwide, many different populations depend on healthy coral reefs to provide coastal protection from aggressive swells which, otherwise, would lead to coastal erosion; others, depend on the food security they provide. It was demonstrated that approximately 10% of the fish consumed by humans derives from coral reefs (Hatcher, Imberger, and Smith 1987) and that at least tens of millions of people depend on these ecosystems for their protein intake or for their livelihood (Salvat 1992). Their importance also extends to different areas, impacting ecological and cultural spheres. The main benefits provided by coral reefs will be described and evaluated in greater detail in the following sections.

Ecological benefits

Coral reefs are directly or indirectly connected to many different ecosystems. When this relationship is balanced and both ecosystems are healthy, they both thrive. Seagrass meadows and mangroves, for example, are natural carbon sinks and they are fundamental to provide coral ecosystems with clear water that is poor in nutrients (Kuhlmann 1988). In addition, they stop freshwater discharge, and fish that grow within the safety of mangroves and seagrass meadows are then attracted by the abundance provided by coral reefs. Many fish, in fact, migrate from coral reefs to seagrass meadows or mangroves and use these areas as nursery ground (Ogden and Gladfelter 1983). In exchange, coral reefs play an important role in buffering the water from strong waves and aggressive swells, providing a calm and suitable living environment for mangroves and seagrass meadows (Moberg and Folke 1999). The result of this behaviour, which by fact links different ecosystems between them, is a constant transfer of energy, essential for the reciprocal well-functioning (Ogden and Gladfelter 1983).

Sustenance-related benefits

The economic and nutritional added value provided by healthy coral reefs and reef fisheries is crucial to many poorer and underdeveloped countries (Whittingham, Campbell, and Townsley 2003; Yvonne Sadovy and Domeier 2005). It is estimated that more than 400 million people live within 100 Km from coral reefs and directly rely on them (Donner and Potere 2007). Every year the economic value of coral reefs amounts to over 30 billion USD, 5.7 of which comes from reef fisheries (Cesar, Burke, and Pet-Soede 2003). Tropical reefs also have an enormous commercial value when it comes to moving organisms that live within them to aquaria around the world (Y Sadovy et al. 2003; Wabnitz 2003).

Physical structure benefits

Beyond their beauty and their importance as a food resource, coral reefs provide a key function to ecosystems as they protect shorelines from aggressive swells, avoiding coastal erosion. The basic principle of this action comes from their 3-dimensional structure, which plays an important role in dissipating wave energy, meaning that waves reach the shorelines less intensively (Gourlay 1996). This extra layer of protection is essential to shelter human populations living on coasts, their economic activities, and physical properties (Barbier et al. 2011). By serving as environmental barriers, coral structures have an immense “hidden” economic value. This kind of value is hardly noticeable in everyday life but is quantifiable by the money that would otherwise be spent to protect coastlines (van Zanten, van Beukering, and Wagtendonk 2014). Different studies have tried to evaluate this hidden value of coral reefs around the world by trying to identify the benefits that these ecosystems provide to coastal populations (Burke and Maidens 2004; Cesar, Burke, and Pet-Soede 2003). It was estimated that the CPV (coastal protection value) of coral reefs amounts to over 9 billion dollars worldwide (Cesar, Burke, and Pet-Soede 2003). A more local study, trying to evaluate the CPV of coral reefs on the Caribbean coastline, was conducted by Burke in Maidens (2004). The result showed that the coastal economic value of coral reefs in that specific area amounted to 750 million USD to 2.2 billion USD every year (Burke and Maidens 2004).

Biotic benefits

The beauty of tropical reefs mostly relies on their stunning coral and their fascinating 3-dimensional structures. These characteristics not only bestow a spectacular beauty upon these ecosystems, but they also enable the creation of a rich and diverse environment for other species to thrive in (Birkeland 1997; Paulay 1997). Their diverse 3-dimensional structures create shelters and provide protection to many different organisms, and, because of this, they are among the richest environments (species-wise) in the world, they are fundamental to maintain a wide genetic diversity and serve as a genetic pool for future generations (Benzie 1999). The abundance of species is also crucial in guaranteeing different keystone processes that regulate the ecosystem balance, such as predation and grazing (Terence P Hughes 1994; Timothy R McClanahan 1994). Many other species that would not seem to have keystone processes at first, might take over one if one of the key species is lost (McClanahan in press).

Scientific information benefits

Coral skeletons can serve as important testimonials of the level of pollution in the ocean. By studying their skeleton structure and chemical composition it is in fact possible to detect long-term chemical recorders of metal levels in seawater (Dodge and Gilbert 1984) and track past changes in the world's oceans salinity and sea surface temperature (de Villiers, Nelson, and Chivas 1995; Swart and Dodge 1997). Given that coral reefs are very sensitive ecosystems, they play an important role in monitoring the stress levels that the anthropogenic pressure is leaving behind (C. R. Wilkinson 1999; Eakin, Lough, and Heron 2009). Also, the structure of the coral, such as branches' width and density, is very important to understand the history of the world's oceans by revealing the environmental condition that characterised a moment in the coral development (Barnes and Lough 1996). Finally, also the chemical composition of their skeleton can be very important to track.

Tourism-related benefits

Coral reefs also play a very important role in generating income from leisure activities (Moberg and Folke 1999), creating an immense economical value for many people to rely on. The economic benefits that derive from coral reefs vary greatly from site to site (Burke et al. 2011) mainly due to the size of the tourism market, and their economic value is usually associated with the amount of money that is spent by tourists (Burke et al. 2011). The variation of values between countries is also mainly due to the differences in accessibility to the places (Burke et al. 2011). In recent years, a summary of 29 different papers tried to create a global census on what is the total economic value of coral reefs provided by tourism. The findings suggested that a total of 11.5 billion dollars worldwide is spent every year for tourism purposes related to coral.

Threats to coral reefs

Coral reefs around the world are facing a period of great decay and their future is wistfully uncertain. Despite all the efforts that are being made to preserve coral reefs, the world's hard coral cover is rapidly declining, and this trend seems to get worse year by year. After major tragic events involving coral ecosystems, in the late '80s world leaders finally called for global action to understand and study their future. After initial warnings, the "Coral Reef Initiative" was launched in 1994 (Crosby et al. 1995) and threats to coral reefs finally became more evident, as research and management programs were promoted. Coral reefs are extremely fragile ecosystems whose biological conditions and health are easily endangered in different ways. The threats affecting them are usually divided into two big categories: 1) Natural threats to coral reefs; 2) Anthropogenic threats to coral reefs, further divided into two sub-categories: direct and indirect.

Natural threats to coral reefs

Earth has always been affected by major natural threats. A destabilised ecosystem usually has the capacity to recover from those threats (C. R. Wilkinson 1999). However, in recent years especially, this resilience seems to have diminished, probably as a result of natural threats' increased frequency and impact (C. R. Wilkinson 1999). Nowadays, in fact, it is becoming more and more complicated to understand the role and reach that anthropogenic stress plays in natural events. The main natural menaces to coral reefs will be described in the following sections.

Geological disturbances and extreme events

Coral reefs, as well as many other ecosystems, have been subject to severe climate changes, such as glaciations, extreme heat, changes in the ocean floor, etc. The glaciation that occurred during the Pleistocene, for example, drastically changed the sea water level, which dropped as much as 100 metres compared to normal levels (C. R. Wilkinson 1999). Only 6000 years ago, during the Holocene, the oceans finally returned to normal levels and the coral populations had the possibility to re-colonize much of the space they had lost (C. R. Wilkinson 1999). Imminent geological events such as tsunamis, earthquakes or volcano explosions can also cause significant damage to coral reefs and alter their condition for long periods (C. R.

Wilkinson 1999). Finally, also an extended time of exposure to air, usually caused by extreme tide events, can cause severe damage to coral reefs. An example of the latter is provided by the Red Sea coral, which are exposed to extreme low tides that can extend from hours to days. In this case, the synergistic effect of tides and strong winds can cause massive coral mortalities (Fadlallah, Allen, and Estudillo 1995).

Inundations

Coral situated near freshwater outlets or lagoons can be significantly altered by heavy rainfalls. High amounts of fresh water can modify the salinity of the ocean water for extended periods of time, causing many coral species to die (C. R. Wilkinson 1999). In Kaneohe Bay, Hawaii, coral is usually subject to these kinds of events. These circumstances usually occur once every 20-50 years and lead to extended periods during which the ocean's salinity drops significantly, thus affecting coral organisms living in the proximity (Bahr, Jokiel, and Rodgers 2015). However, the sensibility of coral to salinity has been demonstrated to vary from different species (Berkelmans, Jones, and Schaffelke 2012). Species like *S.pistillata* for example, have been demonstrated to be very sensible to changes in salinity (Ferrier-Pages, Gattuso, and Jaubert 1999) while other species such as *S.radians* show very good levels of resistance to it (Lirman and Manzello 2009). In recent years, probably as a consequence of human activity, the amount of freshwater responsible for these inundations is increasing (C. R. Wilkinson 1999).

Predators and diseases

Like many other organisms, coral is affected by predation. Different organisms (such as fishes, annelids, crustaceans, echinoderms, and molluscs) are known to consume living coral (Rotjan and Lewis 2008). Most of the time, these organisms do not constitute a serious threat, while other times they can induce extreme damage (Rotjan and Lewis 2008). The most blatant example is provided by the crown-of-thorn starfish (*Acanthaster planci*) in the Great Barrier Reef (GBR). In recent years, the presence of this starfish increased exponentially in the GBR, spreading beyond its geographical borders. Crown-of-thorn starfish outbreaks remain one of the main causes of mortality of coral in the GBR and elsewhere in the Indo-Pacific, and significantly contribute to the deterioration of coral reefs ecosystems (reviewed by (Rivera-Posada, Caballes, and Pratchett 2014). From field observations, it was revealed that these outbreaks account for the second largest contributor to coral reef decline in the GBR, for a total loss of 1.24%$^{year-1}$ in the last 28 years (De'Ath et al. 2012).

The development of new diseases is also a serious cause of coral reef decline. Coral diseases have always been present; however, it seems that their intensity is increasing with time (Weil, Smith, and Gil-Agudelo 2006). Caribbean waters are renowned to be the hotspot of coral reef diseases, which are becoming a serious threat all over the world. The main example of coral reef disease is the white pox disease of the stag-horn coral (*Acropora palmata*) in the Caribbean, which has been accounted as one of the most aggressive in the history of coral reefs. In the Florida Keys National Marine Sanctuary, *Acropora palmata* has suffered a decline of over 88% (Sutherland and Ritchie 2004). This coral plays a very important role in coral reef ecosystems, as it is one of the major calcium carbonate depositors, as well as an important contributor to the 3-dimensional complexity of coral reefs (Rogers, Suchanek, and Pecora 1982). The onset of new aggressive diseases as well as predator outbreaks are considered to be natural events, which can be initiated or accentuated by anthropogenic activities (C. R. Wilkinson 1999). Coral diseases, for example, can originate from different mechanisms triggered by thermal stress. First, elevated sea surface temperatures (SSTs) can intensify the virulence and growth rate of pathogens, increasing their density and their rates of infectivity (Kushmaro et al. 1998). Secondly, elevated SSTs can jeopardise coral immune systems, thus increasing the number of susceptible hosts (Ritchie 2006; Lesser 2006). Thirdly, (Ward et al. 2006)warm waters can increase the survival rates of the pathogens, leading to longer and more severe diseases. Finally, elevated temperatures can also compromise the relation between coral and the dinoflagellates, causing them to abandon the coral structure and leading to a higher probability of coral disease and death (Glynn 1984; Muller et al. 2008). Chiefly for these reasons, it is believed that predator and disease outbreaks will get stronger in the future.

Anthropogenic threats to coral reefs

Direct anthropogenic stress to coral reefs

The natural world is heavily suffering from anthropogenic stress, as human action is leaving a more and more pronounced, and in some cases irreversible, mark on natural balance. Anthropogenic stresses are usually divided into two different sub-categories: direct and indirect. Direct stresses are represented by all actions that leave their mark instantly, while indirect stresses are generated as a consequence of previous human behaviour. A clear example of the former is the release of sediment loads on reefs, while an example of the latter is the warming of the sea surface temperature. The main stresses to coral reefs will be described and evaluated in greater detail in the following sections.

Sediment loads

Globally, nearly 2.5 billion (Burke et al. 2011) people dwell within 100 Km of the coast. The coastal development generated by this enormous population can have both direct and indirect impacts on the marine ecosystem nearby. Direct sediment load damage to coral reefs is usually caused by construction and is mainly associated with dredging or landfilling actions (Burke et al. 2011). During these stages, large amounts of sediments can reach the water, permanently changing the balance of the ecosystem. Great quantities of sediment can deposit on top of living coral, interfering with their natural processes, bringing them slowly to die (Dubinsky and Stambler 1996). Usually, sediment loads enrich the water with nutrients, favouring the growth of algae (Reopanichkul et al. 2009) which compete with coral for space (Burke et al. 2011). This trend represents the first source of coral deterioration in nearby land masses (Dubinsky and Stambler 1996). Bozec et al. (2008) demonstrated that the increase of coastal development in the northern part of the Yucatan Peninsula in Mexico resulted in an algal-dominated state with a very low coral cover (Bozec et al. 2008). Coastal development has also a direct effect on other ecosystems which are connected to coral reefs such as mangroves and seagrass beds (Duarte and Cebrián 1996). Both these ecosystems are essential for the correct functioning of coral reefs and their well-being. The impact of coastal development can be largely attributed to scarce regulation and building planning. Actions to be taken should focus on the preservation of important areas, such as mangroves and seagrass beds (Burke et al. 2011). Also, efficient construction planning should avoid coastal development in areas that are nearby reefs. In the Barbados archipelago, for example, it was regulated that any new coastal development should be at least 30 metres away from the high tide mark. These measures should be able to prevent the excessive proximity of future building allocations, also taking into account higher future sea levels (Clark 1997).

Organic and inorganic pollution

Increased urbanisation near coastal areas also has effects on organic and inorganic pollution (Dubinsky and Stambler 1996). The main source of pollution is usually the cause of direct discharge of sewage into the ocean (through pipes or rivers), which tends to contaminate water and reefs and promote algal growth. In such conditions, planktonic and large benthic algae thrive together with animal competitors of coral (Hunter and Evans 1995). Coral reefs inhabiting areas close to river mouths are particularly exposed since they are continuously overrun by high volumes of freshwater and sediments (Bryant et al. 1998). The increase of pollutants in coastal waters has also been recognized as a direct cause of reef bioerosion, reducing the structural strength of coral (Glynn and Morales 1997). In 2017 Prouty *et al.* demonstrated that nutrient-rich and pH-low submarine groundwater that is discharged onto coral reefs close to the shore off west Maui, decreases the pH of seawater, exposing coral to high nitrate concentrations. The water discharged decreases the rates of coral calcification while increasing the rates of coral bioerosion (Prouty et al. 2017). It is forecasted that nutrient levels in coral reefs waters will increase in future years if these rates of deforestation, irresponsible construction and aggressive agriculture will endure (C. R. Wilkinson 1999). The most destructive effects will be witnessed when important organisms such as algae grazers will gradually disappear from the waters due to human action (C. R. Wilkinson 1999). In this case, coral cover will be rapidly substituted by an algal-dominated state.

Overexploitation

The overexploitation of fish and natural resources from coral reefs can have extreme negative impacts on these ecosystems. The term overexploitation refers to the practice by which the harvest of natural resources exceeds their reproduction. The effects can be observed both during and after the depletion of these resources (Clive Wilkinson 2000). One of the most severe impacts is caused by the repercussions of overfishing on herbivorous fish. The latter are fundamental to maintain a balance in these ecosystems by eating algae that are deposited on reefs. In fact, when algae accumulate on top of coral surface, they tend to block the sunlight and consume the oxygen coral needs for respiration (Clive Wilkinson 2000). Also, the excess of algae can lead to the growth of new microorganisms, like bacteria and fungi, that can be pathogenic to coral. The North coast of Jamaica witnessed an exemplary type of collapse after major overfishing events and hurricane phases (Terence P Hughes 1994). Similar records were observed in Eastern Africa (Tim R McClanahan and Kaunda-Arara 1996) and in the southern islands of Japan (CR Wilkinson et al. 1996). Furthermore, fishing practices including the use of dynamite or cyanide poison can be greatly detrimental to coral reefs (Johannes and Riepen 1995), in that they can destroy large parts of reefs as well as poisoning the animals living within them, ultimately affecting the ecosystem balance. Finally, the overfishing of key species, such as sharks and groupers facilitates macroalgae colonisation of coral reefs by leading to a physical breakdown of the coral reef system (Hodgson 1999). It has been forecasted that in future years the cumulative effects of overexploitation will greatly increase the pressure on coral reefs, reducing the populations of fish and increasing the percentage of algae cover (Clive Wilkinson 2000). Also, the exploitation of coral reefs fisheries in many non-protected coral reefs around the world, will slowly bring these ecosystems to collapse (Clive Wilkinson 2000).

Indirect anthropogenic stress to coral reefs

Specific anthropogenic actions can be a trigger to events that ultimately influence the world's ecosystems. The blatant example of our time is the Global Climate Change phenomena (GCC), which is induced by the release of greenhouse gases (CO^2, CH^4 and N_2O) into the atmosphere. This phenomenon is greatly affecting the global climate, exacerbating natural occurrences such as increases in sea surface temperature, droughts, floods, etc. The effect of these changes can already be witnessed and is believed to affect the world’s population by some means. All these effects will have tremendous impacts on all marine organisms, coral included. The main indirect anthropogenic threats to coral reefs will be described in the following sections.

Temperatures and coral bleaching

Elevated seawater temperatures are the main cause of coral bleaching. All over the world, the increase in ocean temperature is affecting, more or less significantly, all marine organisms. Coral, differently from other organisms, do not have the capacity to migrate to colder waters and they can only count on their acclimatisation capacity (Glynn and Morales 1997). However, the pace of current climate changes is believed to be too rapid, and it is uncertain whether coral will have the capacity to acclimatise to intensifying temperatures (Palumbi et al. 2014; Chakravarti, Beltran, and van Oppen 2017). The most important aspect that characterises shallow water coral reefs is their symbiosis with dinoflagellates microalgae (Odum and Odum 1955). Coral and zooxanthellae form a mutualistic symbiosis in which both organisms derive benefits from one another. The coral provides the algae with compounds for photosynthesis and a protected environment; the algae, in return, produces oxygen and supplies the coral with glycerol, glucose, and amino acids. These will be later converted into proteins, fats, and carbohydrates to produce calcium carbonate, the main element making up the coral skeleton (Dennison and Barnes 1988). Coral bleaching is the result of a loss of colour in the coral’s skeleton, originating by a gradual expulsion of the *Symbiodinium* population (Fig. 5). It occurs when elevated SST and strong UV radiation break the symbiosis between coral polyps and the photosynthetic algae (zooxanthellae), causing the coral to expel the algae (Terry P Hughes et al. 2003, 200). With the algae expulsion, coral lose their main food source and slowly begin to starve. If starvation persists for a long time, the coral begins to lose their strength, become weak, and ultimately die. It has been forecasted that these events and the deterioration of large areas of coral reefs will increase greatly in the next decades, as a consequence of the rising atmospheric temperatures (Hoegh-Guldberg 1999).

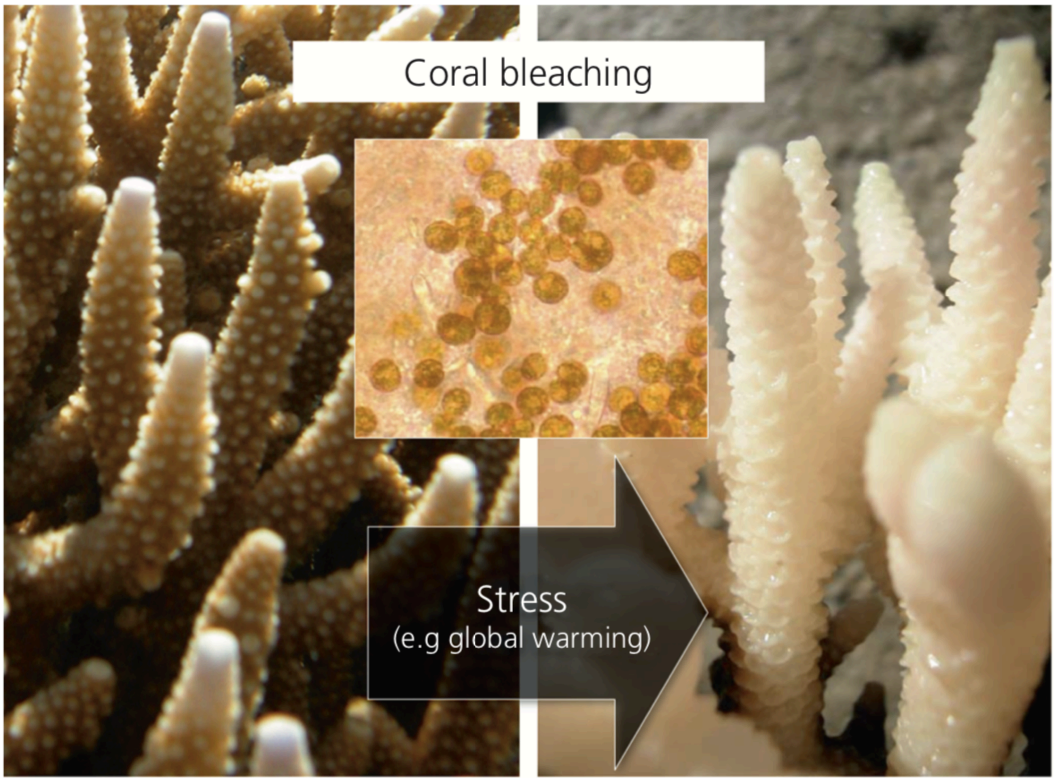

Figure 5: Illustration of coral bleaching in Acropora species. The healthy coral (left) gradually loses its zooxanthellae, converting into a white skeleton (right) (Hoegh-Guldberg, 1999)

Increasing CO_2 concentrations and coral calcification

Ocean and atmosphere are inter-connected as they exchange massive amounts of gases daily. The ocean provides the atmosphere with fresh oxygen, while the atmosphere relies on the ocean to sink the huge amount of carbon dioxide that it could not process by itself. This equilibrium is crucial to maintain and guarantee life on the planet. The concentration of carbon dioxide in the atmosphere has changed significantly during Earth's history. In the past 800.000 years, CO_2 concentration has been stable, amounting to a value of 172-300 parts per million by volume (ppmv) (Lüthi et al. 2008). During the age of industrialisation, this value has started to grow significantly, reaching 412 ppmv in 2021 and is expected to reach 1071 ppmv by the end of 2100 (Plattner et al. 2001). High CO_2 concentrations are not only dangerous when accumulated in the atmosphere, where they significantly destabilise its heat balance, but also when they precipitate in the ocean, affecting its calcium carbonate equilibrium (Kleypas et al. 2005). When high concentrations of CO_2 end up in the water, they trigger a mechanism called ocean acidification. This term refers to a reduction in the pH of the water, mainly caused by the uptake of CO_2 from the atmosphere (Gattuso and Hansson 2011). As shown in the equation below, once dissolved in the water, CO_2 increments the concentration of dissolved inorganic carbon and bicarbonate ions. On the other hand, it decreases the concentration of carbonate ions together with the saturation state of the carbonate minerals forming shells and skeletons (Gattuso and Hansson 2011). With the occurrence of this phenomenon, the balance between carbonate and bicarbonate ions is disturbed (see equation below).

$$CO_2 + H_2O + CO_3^{2-} \rightarrow 2HCO_3^{2-}$$

The above process can be extremely dangerous for marine calcifying organisms as their rate of calcification is drastically reduced when carbonate-ion concentration decreases. This will ultimately accelerate their erosion since the formation of aragonite (the chief crystalline form of calcium carbonate accumulated in coral skeletons) strives in such conditions. Experimental studies have shown that the increase in atmospheric CO_2 lowers coral growth and calcification by up to 40%, impeding aragonite formation, as carbonate concentration diminishes (Kleypas et al. 2005). There is growing concern that ocean acidification will cause significant changes in the biodiversity and functions of marine organisms with significant economical and societal repercussions (Gattuso and Hansson 2011).

The future of coral reefs and coral monitoring

Anthropogenic stress on coral reefs is becoming increasingly evident. Direct stresses can be the consequence of humans' immediate short-term actions. However, they can be easily reversed and fixed by prompt government decisions and informed and judicious human action. CO^2 driven consequences, such as the increasing acidification of oceans and water temperatures, are, on the other hand, very difficult to reverse. These consequences are only observable in the long term, and they can last for much longer. There is a high chance that in future times coral reefs will become the first major ecosystem to be extinct. Scientists believe that one-third of the 845 main reef-building species will face significant risk of extinction in the next future (Green, Edmunds, and Carpenter 2008). Also, one-third of all reefs worldwide have been reported to be irrecoverably damaged and trends seem to worsen every year (Goldberg and Wilkinson 2004). The future of coral reefs is wistfully uncertain, and it is not sure whether these ecosystems will manage to overcome the above-mentioned stresses, partially overcome them, or perish forever (Sheppard et al., 2018). When looking at increasing water temperatures, it is not the annual ocean average temperature that is cause for concern. It is rather the short-term extreme temperature peaks and drops that are causing severe mortalities (Sheppard, Davy, et al. 2017). Forecasts on the future of coral are not reassuring in a time when seawater temperatures are continuing to increase, water pH is dropping rapidly, and continuous pollution and nutrient enrichment in water are becoming more significant.

Possible coral adaptation to stressors

It is not yet certain whether coral will be able to acclimatise to stressors in the future. Some different coral species have shown a higher ability to acclimatise than others, but it is uncertain whether these organisms can deal with the different stressors acting synergistically. Some oceanic coral species perish when water temperatures reach 30° degrees. However, the same species can thrive in bays or lagoons where water temperature is at least two degrees warmer every year (Sheppard, Davy, et al. 2017) (Fig. 6). One possible explanation could be given by the fact that the nature of the zooxanthellae in different coral is diverse, with some clades resisting better than others to changing environments (Buddemeier et al. 2004).

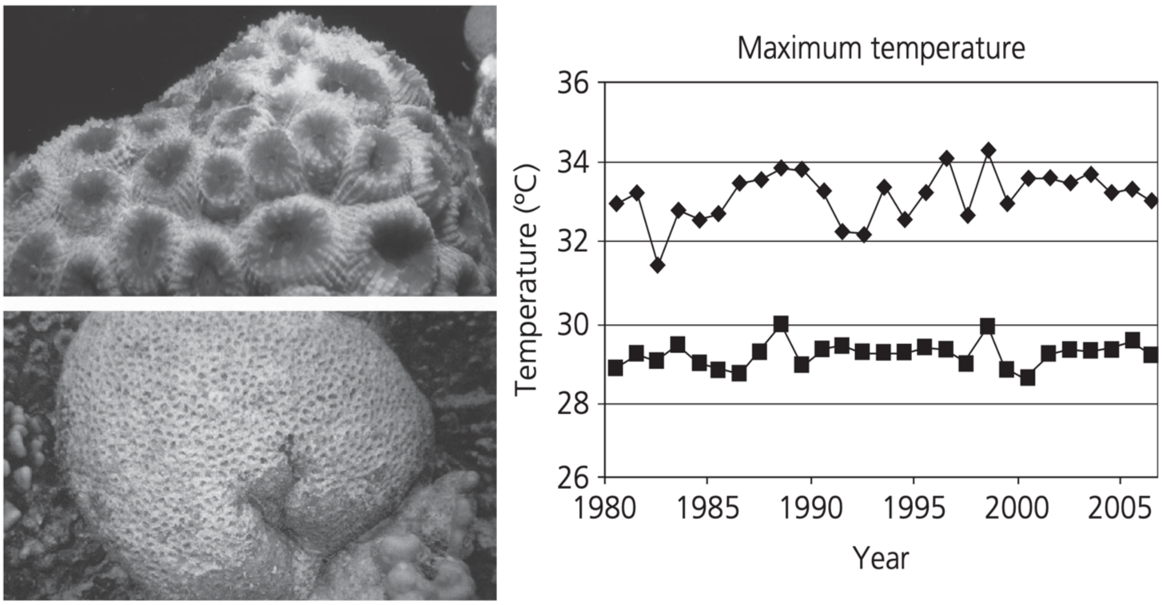

Figure 6: Different examples of coral adaptation. On the right, the table shows the maximum temperatures in the Arabian Gulf (top) and the central Indian Ocean (bottom). The Gulf water temperatures are clearly higher than the ones in the central Indian Ocean. However, the same species (Favia) survives well in the Arabian Gulf with higher temperatures, but struggles in the central Indian Ocean at lower temperatures (Sheppard et al., 2017).

Even though past times have recorded temperatures that are much higher than the ones we are experiencing today, the problem of the current times relies on the speed at which these changes are happening. Coral's acclimatisation capacity in fact, might not keep up with the pace of these stressors.

Monitoring coral

The above-mentioned threats, together with other minor factors (coral diseases, toxic sunscreen chemicals, marine debris accumulation such as plastic, irresponsible tourism, and invasion of new dangerous species), act synergistically against reefs, reducing their lifespan. It was observed that in the period going from 2009 and 2018, the percentage of hard coral cover declined on average 33.3% to 28.8%, representing a loss of 13.5 % of the world's hard coral population (McLeod et al. 2019). Concurrently, the global algal cover grew from 15.4 % to 19.3% from 2011 to 2018, showing an increase of approximately 20%. This positive trend corresponded to the decline of hard coral cover starting in 2009 (Logan et al. 2021). Increasing efforts have been made to protect and restore coral reefs around the world. From 1994, the International Coral Reef Initiative (ICRI) has been promoting the global importance of coral reefs. In 1995, the Global Coral Reef Monitoring Network (GCRMN) was founded as an operational network on ICRI. The main objectives of the GCRMN are to collect data on coral reef health both at regional and global levels, to facilitate coral reefs' reporting locally and nationally, and to increase protecting actions towards coral reefs (McLeod et al. 2019). The purpose of GCRMN is to create a database to evaluate the status, trend, and future of coral reefs and to promote their preservation.

Reef monitoring

Coral reef monitoring is an effective tool through which coral reef managers can answer important specific questions on the status of these ecosystems, by gathering data on coral reefs or on the people that directly or indirectly rely on coral reefs' resources. This process should be carried out on a regular basis over an extended period. Through an effective monitoring program, it is possible to understand dynamics such as: coral reefs health and improvement, effectiveness of management in marine protected areas, coral reefs and other organisms' response to threats and damaging practices, impact on local communities' economies etc. (Hill and Wilkinson 2004). An accurate measurement of different parameters should help the coral reefs managers to map the coral reef habitats to its extensions, understand the status of coral reefs communities, measure the size and the structure of human populations using coral reefs resources, understand government rules and regulations on coral reefs and conservation (Hill and Wilkinson 2004). Wilkinson and Hill (2004) divide coral reef monitoring into two different categories: ecological monitoring and socio-economic monitoring. These two types of monitoring are mostly interconnected, and it is advisable to perform them together to effectively understand the results of a monitoring practice. The main characteristics of these monitoring techniques will be analysed in the following sections (Hill and Wilkinson 2004).

Ecological monitoring

As the name suggests, ecological monitoring is focused on monitoring the organisms living in the coral reef. It analyses the natural environment both in its physical and biological aspects. Biological characteristics offer data on the health trends of coral reef organisms (Hill and Wilkinson 2004) and can assess the level of disturbance and damage to coral reefs caused by human activities and natural phenomena. The most important ecological parameters used to monitor coral reefs are coral species, sponges and algae cover percentages, coral communities' species and composition, percentage or presence of coral juveniles, species composition and size of fish communities, coral bleaching and coral diseases (Hill and Wilkinson 2004). Physical parameters, instead, are analysed to measure the level at which physical events are affecting coral reefs and they mainly focus on water currents and temperature, wind, depth, salinity, and water quality.

Socio-economic monitoring

This monitoring tries to assess and understand the influence and the interaction between human population and coral reefs. Local communities living near coasts are greatly affected by coral reefs health. These parameters are very important to assess whether management actions are functioning successfully. As reported by Hill and Wilkinson (2004), the most important aspects to consider in the socio-economic monitoring are: employment levels and incomes of community populations, size and location of fisheries, reef fisheries catch and prices, perception of coral reefs by local communities and the MPA's relevance for tourism (Hill and Wilkinson 2004).

Monitoring methods

Different monitoring methods are used worldwide to monitor coral reefs. Deciding on which to rely depends mostly on the extension of the area that will be monitored and the type of research that reef managers need to conduct. To date, the most common methods that are used are manta tow, transects and quadrats. However, lately, new innovative techniques have been developed to increase the level of precision of coral monitoring and to facilitate data collection. The main methods of coral monitoring will be discussed in the next sections.

Manta tow

This technique is very effective to obtain a first broad understanding of a reef site. It is usually used when large areas of reef are considered and the question to answer does not require a high level of accuracy. This method consists in towing a snorkeler to a boat at low constant speed using a towing rope (Fig. 7). The snorkeller has the task to record the data when the boat stops. The stops are usually determined before, and they happen every specific amount of time (e.g. 2 minutes) (Hill and Wilkinson 2004). This technique is very efficient when the goal is to analyse the distribution of organisms and the level of disturbance caused by a specific phenomenon in a certain area (e.g. coral bleaching, typhoon damage, destructive fishing techniques, floods damages etc.).

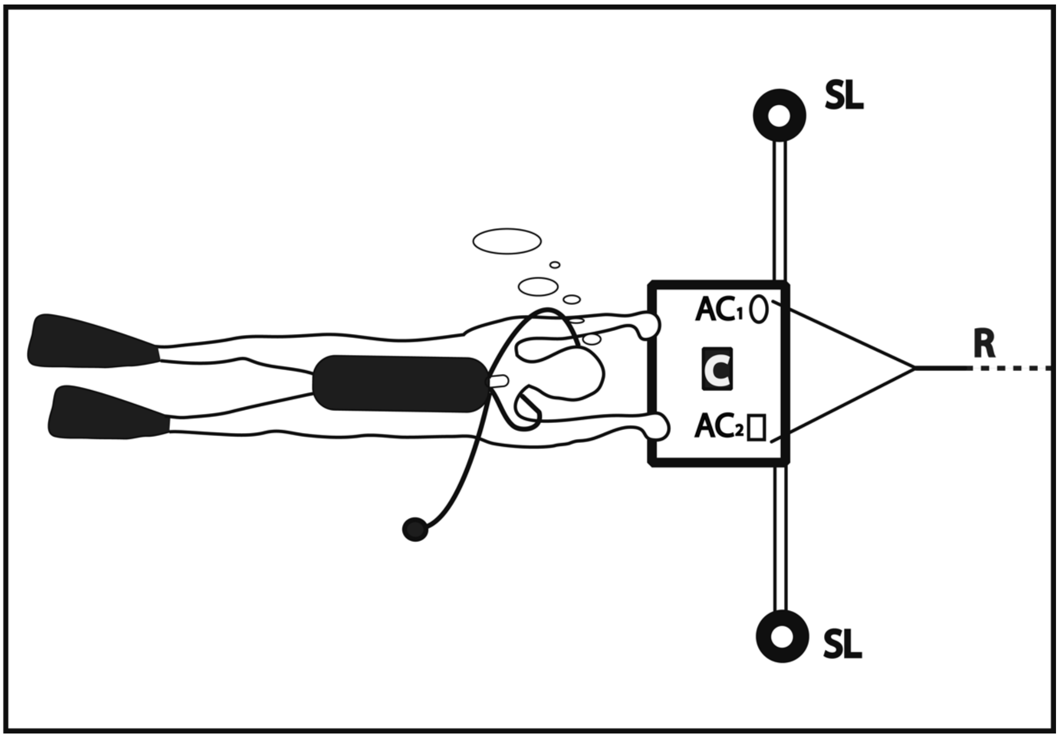

Figure 7: Manta tow illustration. Image source: (Chancerelle et al., 2008)

The main advantages of this technique is the facility to be used and that there's no need for strong field training. It provides a large amount of data in a short period of time, the equipment to use has very low prices, it can be done in any location with minimum equipment. However, as all methods, it also has limitations. This technique is very dependent on the boat driver towing routes, for this reason it may cover large areas of sand or deep reef slopes may be covered too, the variables usually included are few because the diver must remember a lot of information in the towing period. Also, the area to monitor must be shallow and a good visibility is required. Coral cover can only be assessed in large percentages and the accuracy is very limited when assessing organisms' distribution (Hill and Wilkinson 2004). To increase the level of accuracy, this method can also be performed using a video device. Information can be post-processed and analysed in the studio.

Transects

Transects are lines that can vary in length, usually distributed on the ocean floor. They can be used to count coral or other organisms such as fishes or clams (Fig. 8). The main advantage of this method is that it can easily provide medium scale information. It is also a non-destructive method, and, with enough replicates, it can provide valuable and precise information. Among the disadvantages are the fact that it is time consuming and, especially in the case of moving organisms such as fish, the results can vary greatly depending on the time of the day or season in which the surveys are conducted. The length of the transect should be decided depending on the abundance and spatial distribution of the subject to be monitored as well as the spatial heterogeneity of the site (Hill and Wilkinson 2004).

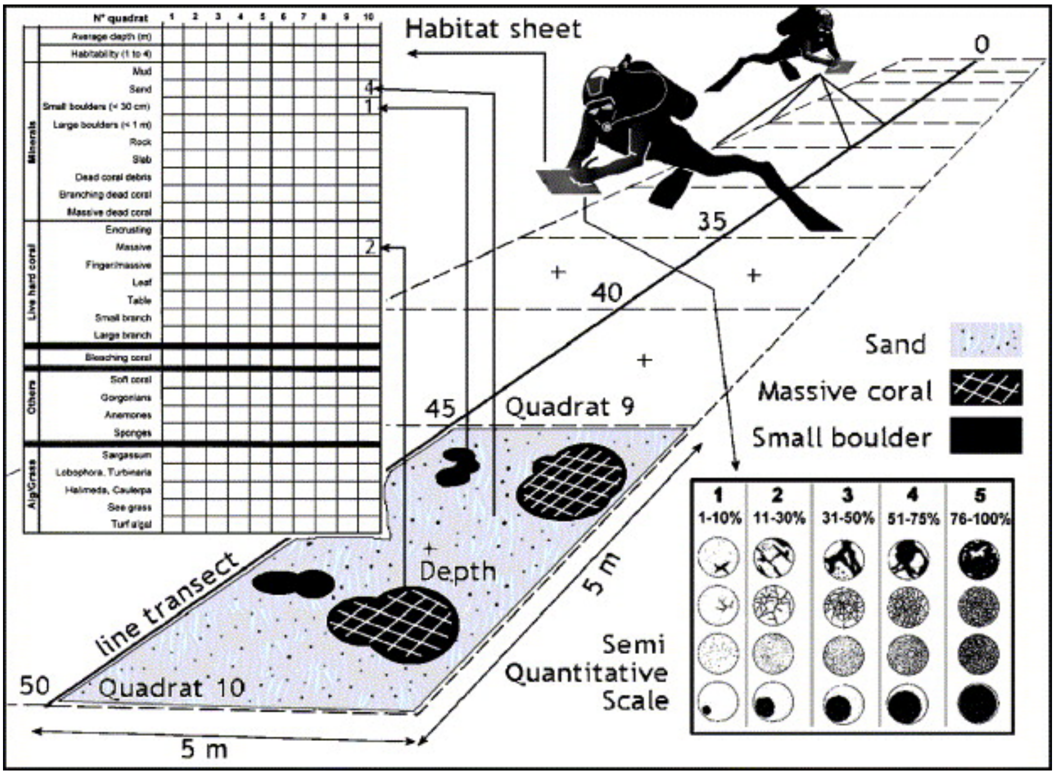

Figure 8: Illustration of a coral monitoring using a 50m transects line. During the monitoring, different aspects are taken into consideration Transect lines can vary in length and material. Image source: (Clua, 2004)

Quadrats

Quadrats are square or rectangular sampling units in which it is possible to count or measure organisms. They usually measure 0.5-1 m^2, but they can also be larger, depending on the organisms needing to be counted/measured (Fig. 9). Quadrats can be analysed in three different ways: 1) visual estimation, 2) visual point sampling, and 3) photo quadrats. The main advantage of the quadrats is that they are usually non-destructive, they can provide valuable information when randomly sampling an area, and they are easily repeatable over time. Among the disadvantages are the fact that, to obtain a very precise estimation on the taxa and amount of a certain organism present inside the quadrat, their use requires prepared observers that have an extended taxonomic knowledge. Also, quadrats can only be used to count organisms with limited mobility only, preferably algae, coral, sea urchins, starfishes etc. (Hill and Wilkinson, 2004).

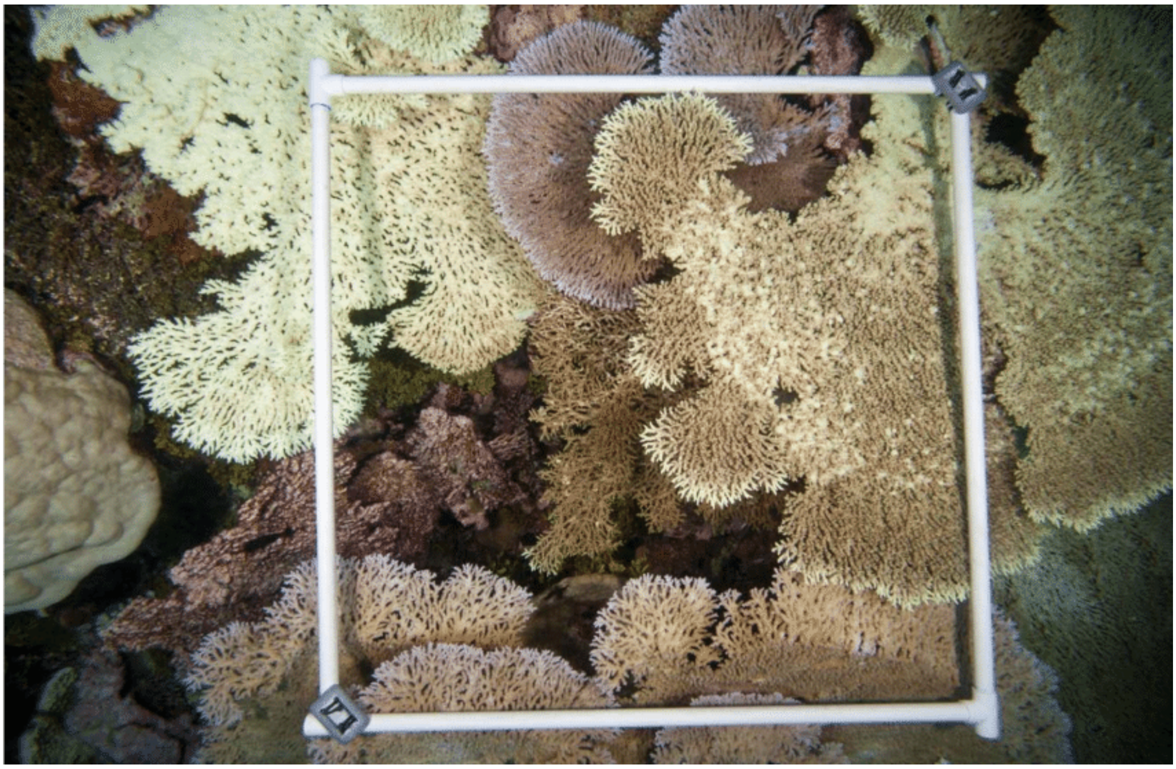

Figure 9: Example of monitoring using quadrats. Quadrats can be used to study different aspects such as: coral cover percentage, diseases percentage etc. Image source: (Sheppard, Sheppard, et al., 2017).

New techniques

Coral reefs' monitoring techniques are rapidly evolving. Every year new solutions are being developed in order to facilitate data collection, while increasing its accuracy. The dependency of digital information is becoming more and more essential for two main reasons: accuracy of data collection and creation of data banks. Digital techniques allow for images to be processed in a way that makes it possible to obtain the highest quality of information. Images' data banks are very useful as they can always be re-evaluated to assess changes in the coral communities. A new technology called structure from motion (SfM) (or photogrammetry) is revolutionising coral monitoring. SfM permits to obtain 3-dimensional images that enhance precision of monitoring and create a permanent record of the reef (Fig. 10). This method uses 2-dimensional overlapping photos to create a 3-dimensional dense cloud of points. From this

3 dimensional cloud it is possible to obtain a 2-dimensional ortho-projection of the dense cloud (Couch et al., 2021). When pictures are collected using high quality photo cameras, it is possible to study the reef from the coral polyp to the reef-scale. To date, different studies using SfM have been able to quantify structural complexity, disease and bleaching, study spatial clustering of corals, analyse coral growth, and size frequency distribution (Couch et al., 2021).

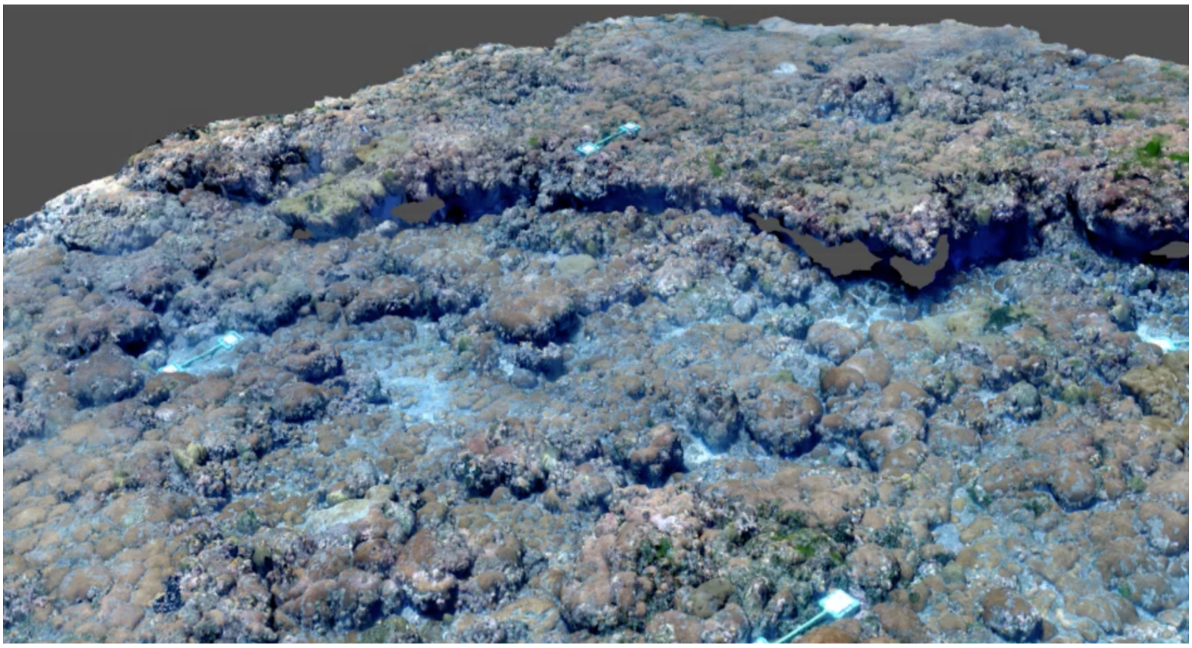

Figure 10: Example of Structure-from-Motion model from Area 3-Sq. 2

However, SfM has some limitations. In certain cases, in fact, it is complicated to capture every surface and colony angle that can otherwise be obtained by in-water assessments. Also, the fact that this technique requires long post processing may impede prompt data generation when needed (Couch et al., 2021). Long processing times are somewhat being improved by the fast-learning artificial intelligence (AI). AI tools are revolutionary in this field; however, human interaction is still needed to make sure all annotations are correctly conducted.

Conclusion

Multiple global threats are affecting coral reefs around the world. Global climate change, together with other local factors such as overfishing and pollution, are endangering these fascinating ecosystems, reducing coral cover, and impoverishing their biodiversity. It is essential to do the best that we can to preserve these ecosystems in order to avoid future economic and social disasters. As the threats to coral reefs increase every day, reef managers and scientists around the world continue to search for effective and innovative tools to increase the capacity, scale, and efficiency of coral reefs monitoring. Monitoring techniques provide valuable information to track changes in coral reefs communities around the world. This information is essential to efficiently develop preservation and restoring plans to help protect coral reefs globally.

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Digital observations through Structure from Motion photogrammetry reveal impact from sediment load on local corals in Mindelo, Cabo Verde.

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Keywords: Corals, Monitoring, Cabo Verde, Anthropogenic impact

Abstract

Land-based sediment loads are one of the major threats to shallow water ecosystems worldwide. In most coral communities, the percentage of scleractinian corals has dropped dramatically in recent years. Although many nations are undertaking large-scale monitoring programs, in many developing countries, the damage to these habitats is often ignored due either to lack of information or lack of resources needed to monitor these ecosystems. This study aimed to assess the effects of sediment loads on coral communities, by comparing coral community structure across areas with different degrees of impact. For this purpose, an innovative technique called 'Structure from Motion' was used, to verify the level of damage induced by a rainwater pipe pouring sediment onto a small coral community adjacent to it, in Mindelo, São Vicente, Cape Verde. Using this technique, it was possible to obtain large photomosaics of three different areas, divided in a total of 15 different plots, each covering 100 m^2 of the benthic habitat. In total, 4223 coral colonies were identified, mapped and classified, successfully delimiting their surface areas. The findings revealed that, in the areas closest to the source of disturbance, corals showed a lower coral abundance and colony size. However, this tendency seems to lessen as one moves further away from the source, not only in distance but also in depth, indicating that the sediments disperse more easily with depth. This study represents one of the first digital baselines to monitor the marine benthic community in Cape Verde islands. This method is useful for future consistent and comparable surveying of the area, and to provide information for land management aiming at conservation of marine ecosystems, which are important for the wellbeing of the people living in their vicinity.

1. Introduction

Land occupation, transformation and management practices do not only change terrestrial biodiversity, but they are also a main cause of impacts on marine biodiversity. However, this fundamental dependence and connection between terrestrial management and the health of marine ecosystems is insufficiently demonstrated with empirical data specifically designed to test this hypothesis. Such missing evidence weakens efforts for consideration of marine impacts on land management planning. This is particularly striking for filter-feeding sessile invertebrates which dependent on clean rocky habitat for settlement, especially coral. Coral reefs are widely mentioned and studied for effects of anthropogenic threats dependent on climate changes, but the effects of land runoff is much less emphasized, despite widespread occurrence.

Conservation of coral facing anthropogenic pressure from land inputs is particularly important in Capo Verde, where coral communities are poorly studied but form rare and rich communities in comparison with the mainland. Cape Verde Islands, situated in the Eastern Atlantic, is one of the many archipelagos supporting a great number of endemic species, both marine and terrestrial (Peters et al. 2016). These islands are located approximately 450km away off the coast of Senegal and, together with the Azores, Madeira, and the Canary Islands, form the biogeographical region of Macaronesia. Although the islands are particularly arid and biodiversity on land is scarce, the waters surrounding them are incredibly rich in life. Darwin himself, passing through these islands, noted how the waters embracing them were incredibly rich in biodiversity (Darwin 1845). In 2002 Roberts, conducting a study on the distribution of geographically restricted species to identify various centres of endemism, identified the Cape Verde Islands as the eleventh among eighteen of the richest centres of endemism in the world, remarking it as a major biodiversity hotspot (Roberts et al. 2002). In the same study, he also conducted a parallel analysis on the level of threat to habitat loss to these hotspots, placing the Cape Verde Islands eighth out of eighteen (Roberts et al. 2002). The islands, in fact, are developing very rapidly, and their tourism-based economy foresees booms in infrastructure development that very often coincide with direct damage to the shallow-water habitats, coral communities included (Peters et al. 2016). All possible measures must be taken to ensure absolute protection to these unique biodiversity heritage islands.

Between all shallow-water habitats, coral reefs are among the most multifaceted, varied, and prolific ecosystems in the world (Porter and Tougas 2001). Their richness and diversity not only support a wide range of biodiversity, but they are also fundamental to the livelihood of millions of people (Clive Wilkinson 2000). Coral reefs are found especially in tropical areas where water temperatures range between 18°C and 30°C. In equatorial areas affected by the presence of cold currents, on the other hand, their development is scarce. Throughout the Atlantic Ocean, warm-water coral reef communities extend from Florida to the northern regions of Brazil. However, also on the West Coast of Africa, different communities have been identified in Cape Verde, São Tome, Senegal, Cameroon, Ivory Coast and Gabon (Laborel 1974). Coral in this area tend to form large colonies (Monteiro et al. 2008) but fail to create coral reef structures, differently from the ones found on the Eastern African Coast and in the Caribbean, which tend to form fringing tropical reefs (Medina-Valmaseda et al. 2020). The reason comes from the fact that these organisms are particularly sensitive, especially to salinity, nutrients and temperature conditions (Monteiro et al. 2008). The World's west coasts are remarkably characterised by upwelling events, which favours nutrient rich water and cold-water temperatures. These conditions, favour the creation of large fisheries areas but are not favourable for coral growth (Sheppard, Davy, et al. 2017).

Although their extent is considerably smaller than that of larger coral reefs such as the Great Barrier Reef, coral communities living in colder and more dynamic environments are exceptionally interesting. The scleractinian group, for example, is smaller in number (eighteen different hard coral species have been detected up to now) (Wirtz 2021) than the one in the neighbouring coast of the Caribbean (around seventy species discovered) (Cortés and Reyes-Bonilla 2017). However, for certain species such as *S. radians*, the colony size is significantly larger, as large as ten metres (Moses et al. 2003), when compared to the colonies that can be found on the Caribbean coast, reported to be as large as 60 cm maximum (Lewis 1989). Although the presence of coral in the West Coast of Africa is documented (Monteiro et al. 2008)(Moses et al. 2003)(Laborel 1974), it is believed that many more species are yet to be discovered (Wirtz 2021). A more comprehensive study on the relations between western and eastern Atlantic coral should be conducted to make clearance on the biogeography of coral in the Atlantic Ocean.

Despite their long history and their key importance in the balance of the world's oceans, these ecosystems are extremely vulnerable to stress. Their richness has rapidly declined during recent history, mainly because of human pressure (Harvell et al. 1999; Hoegh-Guldberg et al. 2007). Overextended threats such as ocean warming, overfishing, pollution, diseases, and severe storms have pushed coral reefs ecosystems to a critical point in the last years (Couch et al. 2021; Hoegh-Guldberg et al. 2007; Sandin et al. 2008). The cumulative effect of these threats has resulted in a constant degradation of coral reef habitats (Bruno and Selig 2007; Miller et al. 2009) and a pronounced variation in coral reef communities (Hughes et al. 2018). Solid management and monitoring practices are needed to avoid an imminent global degradation of coral habitats. Coral reef monitoring is a crucial tool that can help preserve these ecosystems by providing important information for effective management (Hill and Wilkinson 2004). Through this practice, it is possible to obtain valuable information on the biological and physical parameters that interest coral reefs (Hill and Wilkinson

2004). Important knowledge such as size-frequency distribution, colony density, partial mortality, colony health and variety can provide key information about the capacity of coral to recover, the reaction to acute and chronic disturbance circumstances and the variation in communities (Baskett, Fabina, and Gross 2014; Riegl and Purkis 2015; Edmunds and Riegl 2020). To date, there are no records confirming the existence of any coral monitoring programs in West Africa thus far. Therefore, it is essential to implement monitoring routines of the coral communities to build baseline data records to access future changes in the communities.

In recent years, the methods used in coral monitoring have improved significantly allowing the collection of more data at higher resolution. New monitoring techniques have revolutionised the way reefs are monitored by enabling the collection of long-term digital data that can be examined in future. A new technology called Structure from Motion (SfM), completely changed the coral monitoring approach. This new technique uses photogrammetry, which enables the extraction of 3-dimensional information from photographs, to create a 3-dimensional map of the underwater world. Based on the quality collection of the photographs, these models can be used to study reef parameters such as coral polyp density and reef structure both in 2-D and 3-D forms. To date, many different studies have begun to use this technique to unveil and clarify various aspects of the reef, such as the structural complexity (Burns et al. 2015; Figueira et al. 2015), coral bleaching and diseases (Fox et al. 2019; Voss et al. 2019), coral growth (Lange and Perry 2020), and size-frequency distributions (Hernández-Landa, Barrera-Falcon, and Rioja-Nieto 2020). SfM could permanently change the way coral monitoring is developed, opening interesting new possibilities for data collection, creating digital image banks that can be examined over time to track reef changes and allowing images to be re-analysed and future monitoring surveys to be compared with past ones.

In this study, we aim to assess the effects of sedimentation from urban rainwater discharge on a tropical coral ecosystem in West Africa, and to evaluate the utility of the method "Structure from Motion (SfM)" as an efficient monitoring approach for this purpose. In particular, for this study only the scleractinian coral *Favia fragum, Porites astreoides, Porites porites and Siderastrea radians* were taken into consideration, being the most abundant in the area. We provide a baseline of the state of 'in town' coral communities along a depth gradient and distance to breakwater and rainwater output by digitally mapped 1500 m^2 of shallow coral reef, consisting of fifteen 100 m^2 plots. We hypothesise that the corals closest to the disturbance source will be present in smaller numbers, will have smaller average sizes and will cover a smaller surface area than the others present in the two areas more distant from the disturbance. These hypotheses were tested by examining different coral parameters such as coral percentage cover, coral population density (number of colonies present in each quadrat), and coral average size, using the photogrammetry technique. In addition to this hypothesis testing, this research represents also a first step in describing a baseline of information on coral ecosystem status in the Enseada de Coral which can hopefully be continued in future monitoring surveys.

2 Materials and Methods

2.1 Study Area

The study was conducted in the "Enseada de Coral" (16° 53' 48" N; 24° 59' 34"), a small reef strip adjacent to the town of Mindelo, São Vicente, Cape Verde (Fig 2.1). The region extends for approximately 200 metres and its depth varies from 1.5 to 5 metres. This small reef is in an exceptional location and is situated in front of one of the city's most iconic restaurant. This unique location means that the reef is visited daily by many people who enjoy its clear waters and the unique marine biodiversity that inhabits it. However, this exceptional position can also have negative consequences. Indeed, the Enseada is often endangered, mainly due to irresponsible tourism, local fishing and the release of sediment into the water. All these factors, over time, could cause substantial damage and endanger the biodiversity that inhabits its waters.

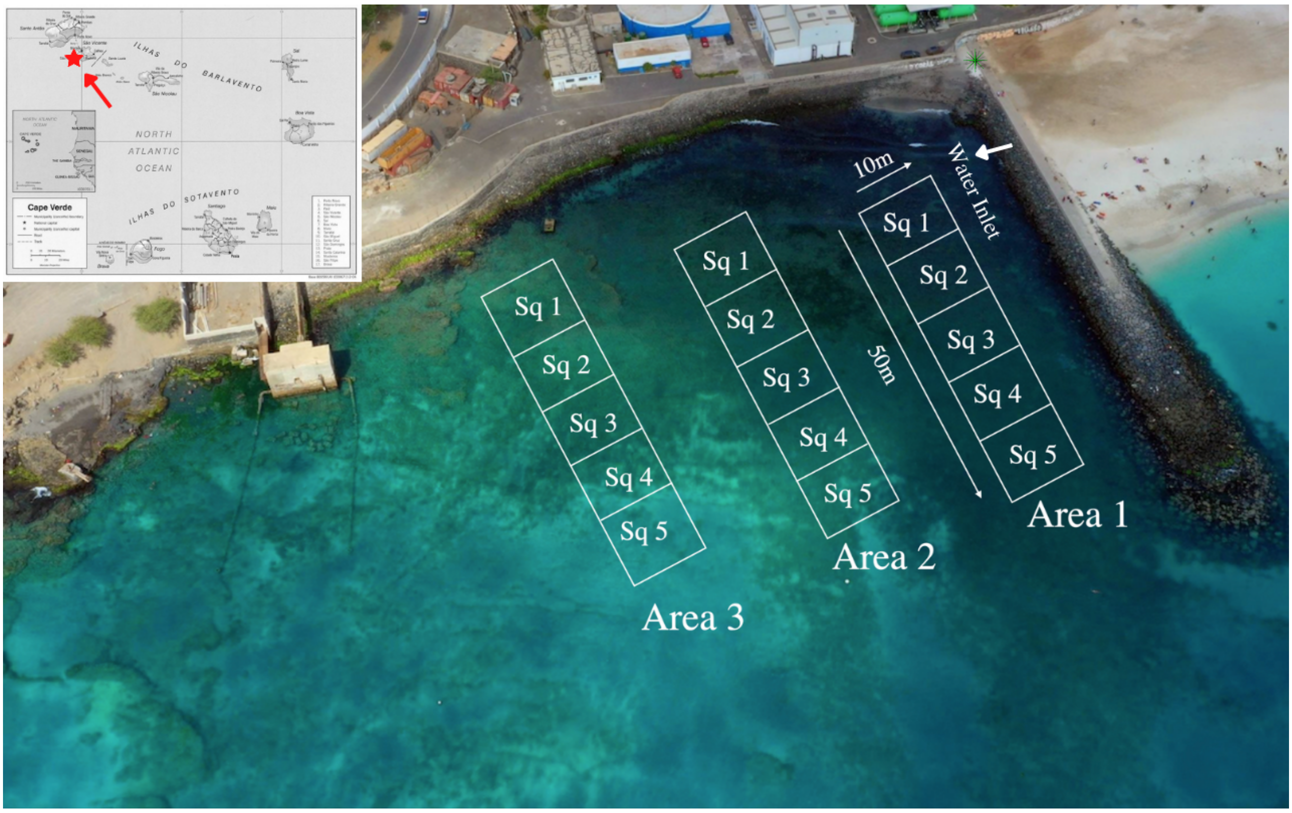

Figure 11: Aerial view of the Enseada de Coral with the Areas and squares used for the study

As the benthic community greatly differs in the Enseada, for the purpose of this study three different rectangles of 10x50 metres were arranged inside the area. Each rectangle was later divided into five 10x10 metres squares, named Square-1, Square-2, Square-3, Square-4, Square-5 (being Square-1 the shallower one) adding up to fifteen squares located at different depths. A total of 1500 square metres were covered by the survey, 500 square metres for each area (Fig. 1). The size of each area was sufficiently wide enough to collect solid information and to consider numerous coral colonies. The four extremities of each area were marked with permanent steel bars threaded into the seafloor, and the coordinates of each corner were noted down to assist future surveys.

2.2 Collecting Imagery

All the images were collected using an Olympus TG-6 camera, mounted on top of the supporter handle, (12 megapixel) with a focal length of 25 mm. For the purpose of the study, the images were collected using a grid-like swim pattern. This kind of technique requires passing over each part of the surveyed area, thus allowing a substantial overlap between images, both forward (>80%) and sidewise (>60%). During each dive, a 10x10m square was photographed and thus a total of 100 m^2. This decision was made to avoid overloading the camera and allowed us not to handle huge amounts of data all at once. An intervalometer of one second was used between each image to help obtain a good overlap and to avoid over-relying on the shutter. The total time to collect the data for each square varied between 75-90 minutes, while the total of images varied between 3000-4000. All the images were later analysed, and all the out-of-focus and blurry images were removed before uploading them to *Agisoft Metashape*. The images were all saved into a 2T hard disk. During the dives, different size scale bars were used to later scale the model (four 50 cm and four 25 cm scale bar per survey) to improve the scaling result of the model, and each corner of the square was marked with a buoy and the depth was noted down. It was decided to use a high number of scale bars to maximise the scaling quality of the model.

2.3 Technical processing of mosaic imagery

After the data collection, all the images were photogrammetrically processed in *Agisoft Metashape*LCC to create ortho-images. The functions of this software have been already widely discussed in many studies (Suka *et al*., 2019; Million and Kenkel, 2020). The software leads to the creation of three-dimensional models or two-dimensional ortho images from previously collected photographs. These maps can then be processed to gather very important information about the state of the world's barriers anywhere in the world. To obtain the final ortho-images we followed the steps suggested by '*Large Area Imagery Collection and Processing Standard operating*

Procedures'(Scripps institute of Oceanography UC San Diego). The images were initially uploaded in chunks to the software which later aligned them by matching them based on the number of points in common between one image and the next. After the alignment, a three-dimensional sparse point cloud was created. Subsequently from this, a dense point cloud was generated which led to the creation of a Digital elevation model (DEM). This final ortho-image was then created by merging all the photographs of each individual 10x10m square. A total of 15 ortho images were then obtained in the study, one for each square in each area. Once the images were obtained, they were saved and transferred to other two software: *Qgis* and *TagLab*, from which the data was subsequently derived.

2.4 Post-processing of images

The images of each square were subsequently uploaded to *Qgis* software to verify the correct scaling of the model and to manually create 1x1 metre sub-areas, named Subsq-1,Subsq-2, Subsq-3, Subsq-4, Subsq-5 for each Square of each area, in the form of shape files, within each photograph. This process was necessary as it would have been too time consuming to fully analyse the photograph on Tag Lab. By obtaining sub-squares of 1x1 metre instead, it was possible to reduce the amount of work but still obtain a large amount of data in order to carry out statistically relevant tests later on. The sub-squares within each photograph were arranged in the middle and were all divided by one metre each. Once this process was completed, the images and their shapefiles were uploaded to *TagLab*. The software is an AI-powered segmentation software created to assist with the analysis of large orthographic images generated through the photogrammetric device. It is also gifted with a semi-automatic and an automatic modality to annotate images, helping the efficiency and time consuming of the study. Recent studies have shown that the capacity of the automatic mode to correctly outline the corals is as high as 90 percent, preserving the labelling accuracy. However, for the purpose of this study, it was not necessary to use the artificial intelligence mode. In addition to this functionality, the software has other tools, through which the contours of each coral colony can be delimited. The most frequently used tools for the purpose of this study were manual segmentation and positive/negative segmentation. Once the areas of the colonies have been delimited, the software gives the possibility of assigning a class to the colonies, which are indicated by different colours. Once the segmentation of each individual coral colony in the 1x1 metre areas of each square is complete, the software generates Excel files in which it defines the species of coral, and the size of the delimited area. When a part of the corals was outside the square created through *Qgis*, only corals with more than 50% of their surface inside the square were considered in the study. Once all this data had been obtained, the spreadsheets relating to each square were combined into a single file from which statistical tests were carried out (see Fig 2.2).

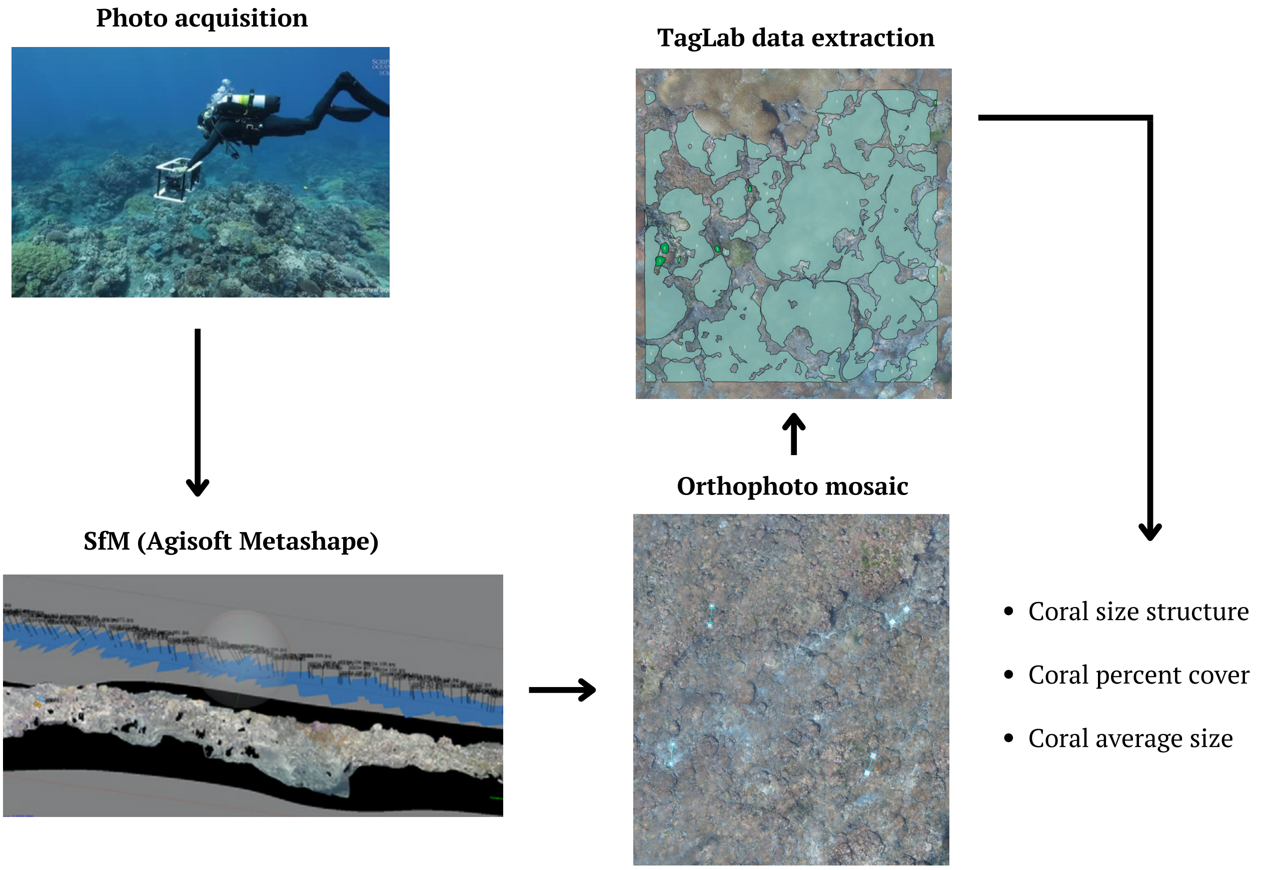

Figure 12: Different step of the study. 1) Photo acquisition, 2) Building of Structure-from-Motion models, 3) Creation of the Ortho-picture, 4) Data extraction through TagLab

2.5 Statistical analysis

Statistical analyses were conducted to determine the impact of the rainwater inlet on the Enseada de Coral. The hypothesis was that, being influenced by the sediment released from the water inlet, the corals closest to the source of disturbance, would comprise smaller colony sizes and lower numbers of coral colonies. In addition, we wanted to check whether coral of different species responded differently to disturbance, and we analyse how the coral cover and coral colonies of the different coral changed with depth and distance from the water inlet.

Before proceeding with the various tests, the distribution of the variable (Tag Lab area) was studied, to check whether the distribution was normal.

Having demonstrated the non-normality of the distribution, statistical analyses were conducted on medians and interquartile ranges, instead of averages. The non-parametric Kruskal-Wallis test was performed to investigate differences in colony size first between the areas and then between the squares inside them. All the results were considered statistically significant when the *p-value* obtained was lower than 0.05, and all values were adjusted according to Bonferroni's correction for multiple tests, being the comparison groups more than two.

Later, a multivariable linear regression test was performed to introduce a logistic causal link between the size of the coral, the area in which they were found and the type of coral. For all the analyses a *p-value* < 0.05 was considered statistically significant.

Finally, to investigate if the distribution of the number of colonies per area was different, a Chi-squared test was performed, being the variable categorical. For the analyses, a *p-value*< 0.05 was considered statistically significant. Statistical analyses were performed using SPSS (Version 28.0.1.1(14)).

3 Results

3.1 Colony size

From a total of 4223 coral species, the results have shown an overall median size of 13.27 cm^2 (4.8 cm^2 - 46.69cm^2). Coral size has shown a substantial difference between Area 1 and Areas 2-3 (Fig 3.1). Of the various areas the second is the one with the highest median coral size (17,33 cm^2) compared to Area 1 (6,98 cm^2) and Area 3 (12,78 cm^2).

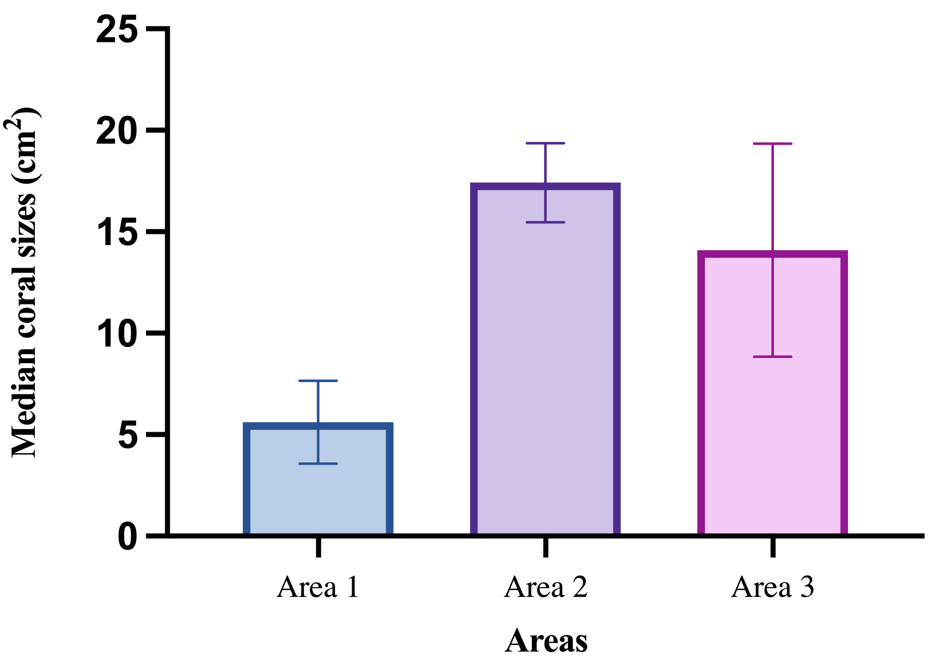

Figure 13: Median coral size across areas. Area 2 shows the higher median coral size, while area 1, the one closer to the disturbance source, shows the lower size.

The Kruskal-Wallis non-parametric test (significance of 0.05) showed a statistically significant difference in coral size between all areas with a *p-value* < 0.001. All the values were adjusted according to Bonferroni's correction for multiple tests.

The test for median coral size in each square gave the following results (Fig 3.2). Showing the larger colony size in Area 3 - Sq 3 (21,13 cm^2) and lower coral size in Area 1 - Sq 2 (3,71 cm^2). The non-parametric Kruskal-Wallis test gave the following results (Table 3.1), showing that, between all areas, the only statistical differences found were inside the squares of Area 1 and Area 3.

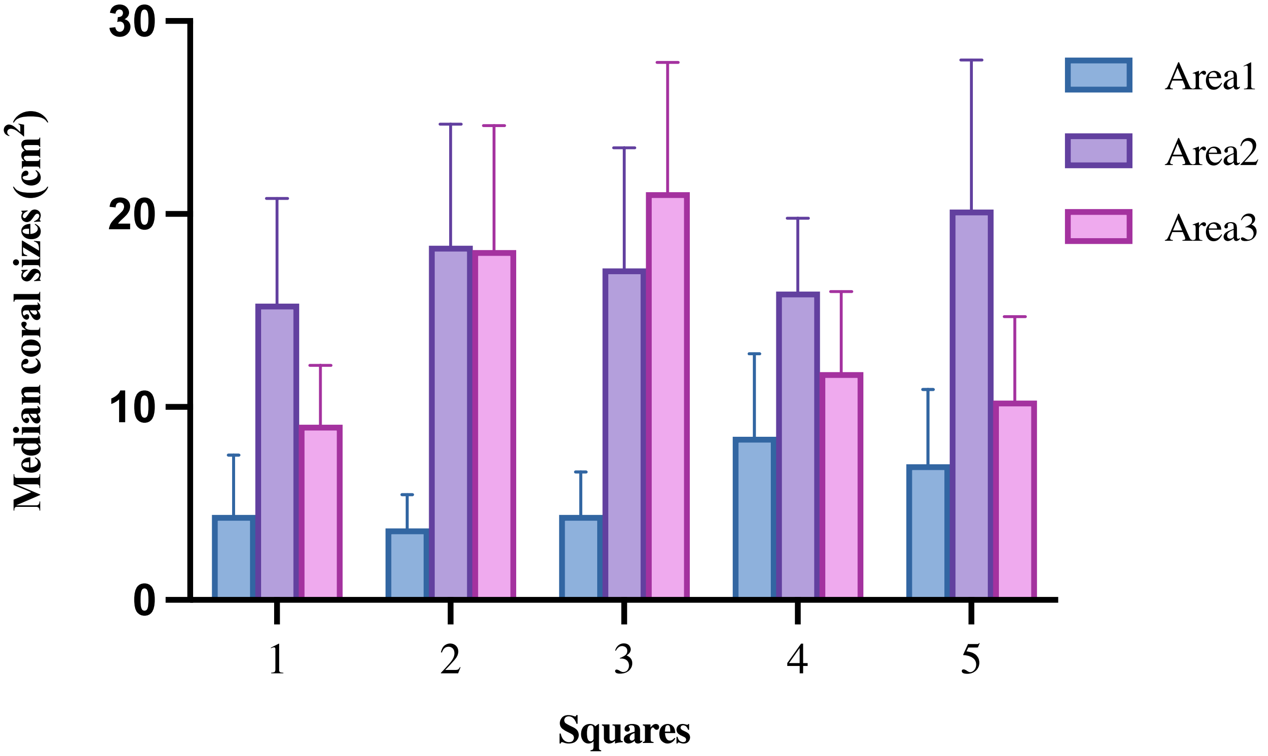

Figure 14: Bar graph showing the median coral size across the different squares of each area. Sq3 in Area 3 shows the highest median number, while Sq2 in Area 1 show the lowest median number.

Table 3.1: Table showing the p-values for multiple comparisons test between the median coral size of the squares of each area. Significance values are shown in bold.

Squares	1-2	1-3	1-5	1-4	2-3	2-5	2-4	3-5	3-4	5-4
Area 1	1.0	1.0	0.409	0.237	1.0	0.064	**0.026**	**0.004**	**0.001**	1.0
Area 2	0.480	0.856	0.154	1.0	1.0	1.0	0.553	1.0	0.992	0.165
Area 3	**<0.001**	**<0.001**	0.539	0.647	1.0	**0.008**	**0.014**	**<0.001**	**<0.001**	1.0

In particular, results show three statistical differences in Area 1, and six statistical differences in Area 3. Within Area 2, no statistical differences in coral size were found between any of the squares. In

Area 1 it is possible to distinguish a statistical difference between the second and third squares with respect to the fifth and fourth squares. In Area 3 instead, although more statistical differences are found, it is not possible to detect a clear pattern in the differences between the median size of the corals in each square.

3.2 Multivariable linear regression

The multivariable linear regression showed that there is a fundamental statistical difference between the different areas and that when moving from the impact area (Area 1) to the control areas (Area 2-3), a significant probability that the corals are on average 57.48 cm^2 larger in the second area and 38.41 cm^2 larger in the third area can be noticed. Also, the test shows that, independently of which area coral are, being a *Porites astreoides* is associated with a significant probability of being 49 cm^2 smaller than *Siderastrea radians*. At the same time, the *Favia fragum* species has a significant probability of being 76 cm^2 smaller than *Siderastrea radians*.

3.3 Colony size per species

Statistical results relating to the differences between the sizes of the various coral species per area showed that, of all the coral, only *Siderastrea radians* shows a statistical difference, with a *p-value* <0.001 when comparing all areas between each other's, while *Porites astreoides* and *Favia fragum* maintain constant sizes. The smaller median size for *Siderastrea* was found in Sq1-Area 1 (4,48cm^2), while the larger median one in Area 2-Sq4 (35,05cm^2) In these tests, it was not possible to ascertain the difference between the various areas with *Porites porites* as, although present in certain squares, the number of colonies counted were too small to be statistically tested.

When comparing the colony size per species across the various squares, *Siderastrea radians* showed a statistically significant difference in Area 1 between Sq4 (11,92 cm^2) and Sq1 (4,80 cm^2), and Sq 4 and Sq 3 (5,32 cm^2), with a *p-value* averaging from 0.01 to 0.028. In Area 1, the size of *Favia fragum* showed statistical difference between Sq2 (4,78 cm^2) and Sq4 (3,83 cm^2), and Sq2 and Sq5 (4,27 cm^2), with a *p-value* averaging from 0.005 to 0.009.

In Area 2 *Siderastrea radians* showed statistically significant difference between Sq1 (19,29 cm^2) and Sq3 (35,04 cm^2), Sq1 and Sq4 (35,05 cm^2), and Sq1 and Sq5 (32,64 cm^2) with a *p-value* averaging from 0.001 to 0.007. In Area 2, *Favia fragum* size showed a statistical difference between Sq4 (2,25 cm^2) and Sq2 (3,55 cm^2), Sq4 and Sq3 (4,68 cm^2), and Sq4 and Sq5 (5,13 cm^2) with a *p-value* averaging from 0.001 to 0.014.

In Area3, *Siderastrea radians* showed statistical differences between Sq1(18,72 cm^2) and Sq2 (28,51 cm^2), and Sq1 and Sq3 (33,35 cm^2); Sq4 (20,0 cm^2) and Sq2 (28,51 cm^2), and Sq4 and Sq 3 (33,35

cm^2); and Sq3 (33,35 cm^2) and Sq5 (19,25 cm^2) with a *p-value* averaging from 0.001 to 0.048. In Area 3, *Favia fragum* showed differences only between Sq1(2,66 cm^2) and Sq5(4,09 cm^2) with a *p-value*= 0.001. For all the areas, multiple comparisons tests for *Porites astreoides* and *Porites porites* were not performed because the overall test did not show significant difference across samples.

From the initial hypothesis, we were expecting a more impactful change between the coral species in the first area. For *Siderastrea radians* it is possible to detect a larger size going to deeper squares, meaning that probably the sediment is less present and thus the coral can growth more easily. However, this is not the case for *Favia Fragum,* which coral size do not show a real changing pattern across the squares. Also, in the second area it is clearly visible that the median size of *Siderastrea radians* changes significantly going from the shallower squares to the deeper ones, while again, for *Favia Fragum* this pattern is not clearly distinguishable. Finally, in the third area, *Siderastra radians'* larger size is in Sq3, and it lowers in the deeper squares. This might mean that, especially in this area, the level of light reaching the deeper squares is not high enough to make this coral grow as in shallower zones. *Favia fragum* instead, shows, in Area 3, differences between the first and fifth square. Although this difference is statistically significant, the gap in size is not really big and would be advisable to repeat the test with more colonies.

From these results, we can assume in general that, compared to *Favia Fragum*, *Siderastrea radians* size suffer more from environmental stresses and so, its size can change more abruptly.

3.4 Population density (number of colonies)

Of all the 4223 coral colonies, Area 3 showed the highest number (Tot= 1959), Area 2 the second highest (Tot= 1744), while Area 1 showed the lowest number (Tot= 520). To clearly demonstrate the difference in the number between colonies in the various squares of each area, the graphs below were used (Fig 3.3 and 3.4). In both graphs, the difference in the number of coral species between Area 1 and Areas 2-3 decreases, as both the distance from the source of disturbance and the distance from the coastline - and thus the depth at which the colonies are located- increases. The Chi-squared test revealed a global statistical difference between the number of colonies of each area (*p-value* <0.001).

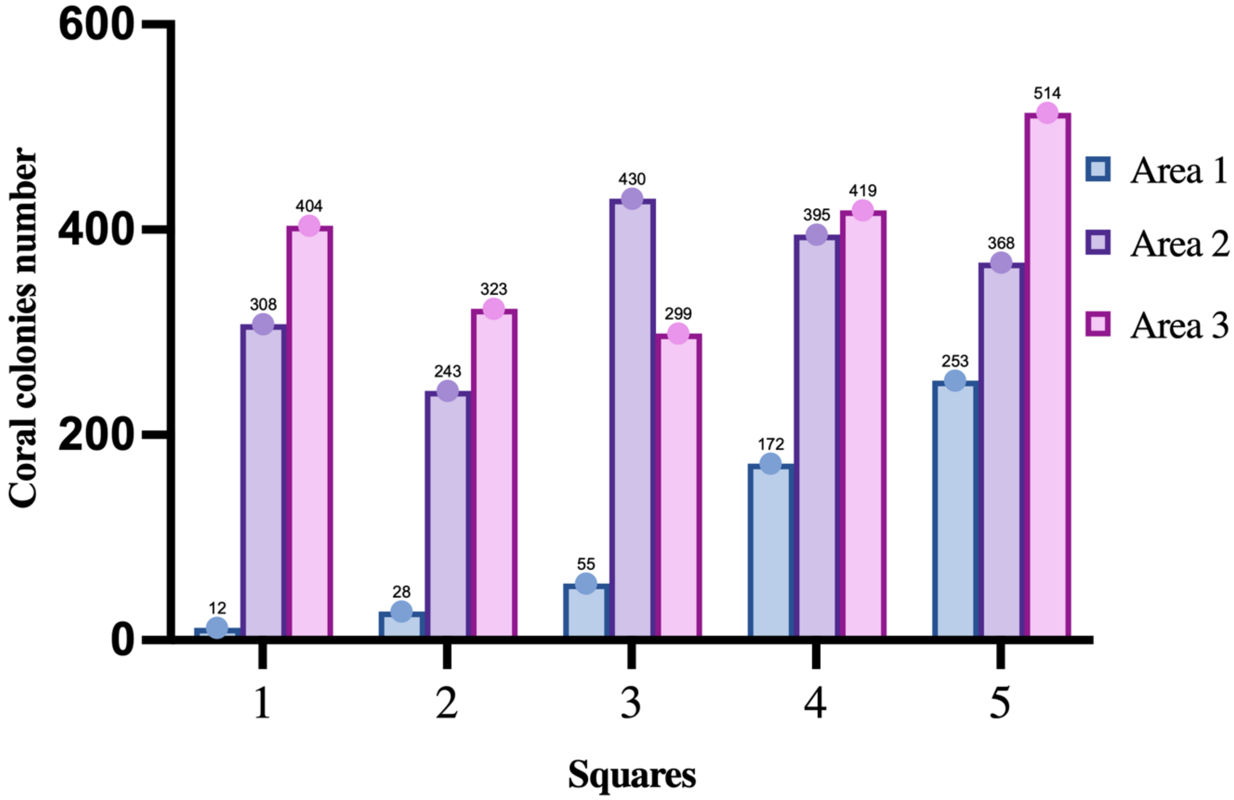

Figure 15: Bar graph showing the population density of corals across the different squares of each area. Sq1 of Area 1 shows the lowest coral number while Sq5 Area 3 the highest.

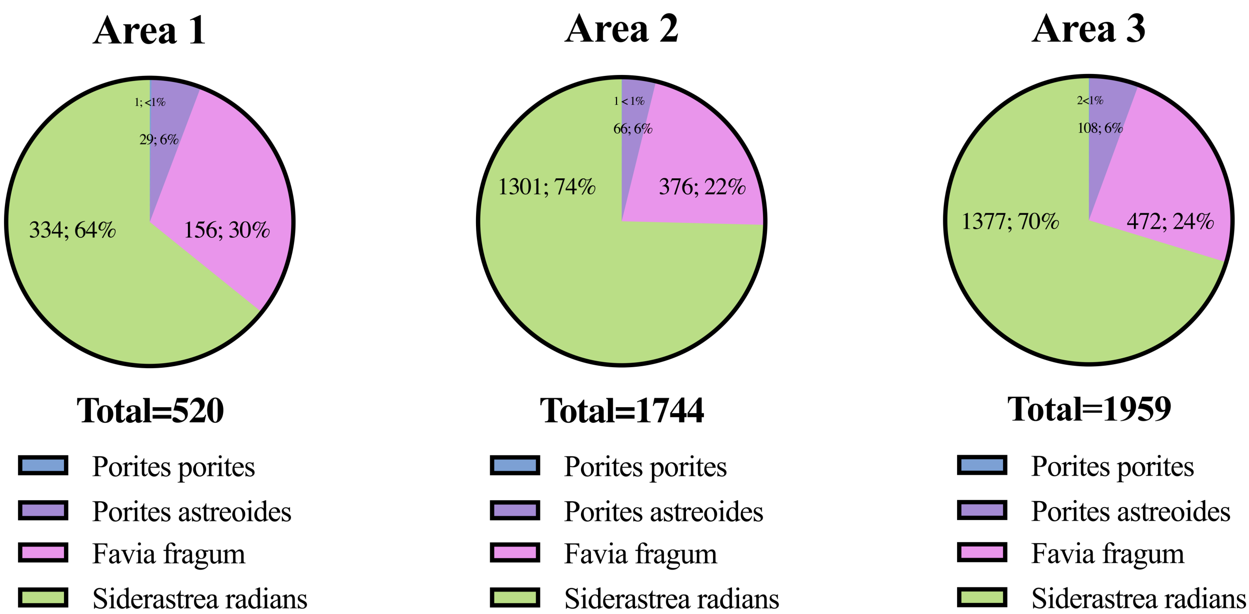

Figure 16: Pie chart showing the total number of colonies for area divided by species. In the graph it is also possible to see the total coral cover in percentage for each species.

4 Discussion

As environmental disorders keep on generating structural changes to reefs all over the world's oceans, efficient ecological monitoring techniques become crucial to document and understand the resulting changes in coral community composition. Sediment load on global reefs is a well renowned source of stress on coral, interfering with their biological functions, baring suitable substrate for coral to settle, reducing hard coral cover species and increasing water turbidity while reducing irradiance (Brown and Howard, 1985) (Van Katwijk et al., 1993).

This study represents the first digital monitoring baseline in Cape Verde and demonstrates that the methods based on a digital map produced from photos are efficient in assessing effects of sediment loads on coral population health.

The number of coral colonies were affected by the disturbance, resulting in the largest number of coral in the area that were more distant to the rain-water inlet, compared with the disturbed area having the fewest. The results also demonstrate a statistically significant difference on median coral size, in which the largest median size in the second area (17.33 cm^2) was more than twice larger than the median coral colony size near the source of sediment disturbance (6.98 cm^2). Finally, the median sizes of the most dominant coral: *Siderastrea radians,* differed between areas, showing smaller sizes next to the disturbance. *Siderastrea* corals close to the outlet (Sq1-Area1) showed to be four times smaller in size compared to the ones at the same depth but in the second area (Sq1-Area2) and significantly lower in number of colonies for the same squares (10 compared to 254). The change in median size of *Siderastrea radians* (4,80 cm^2 in Sq1-Area 1 compared to 19,29 cm^2 in Sq1-Area 2) between areas with a different proximity to the disturbance is important to highlight, being this type of coral one of the most resistant to multiple stress types. (Lirman and Manzello, 2009)□

4.1 Median coral size across areas

The Kruskal-Wallis test showed a statistically significant difference between coral sizes in the different areas. In particular, it reported a significant difference between all three areas, with the second area having the largest median coral size (17,33 cm^2). We can therefore assume that Area 1 is the one most affected by the sediment released from the discharge pipe in terms of coral growth. The coral's response to an increase in sediment in the water can generate different consequences depending on the type of coral. These generally depend on the size of the amount of sediment, the presence of other factors and the original composition of the coral community (Brown, 1997; Dikou and Van Woesik, 2006; Wallace et al., 2014). Some coral can even enhance their growth by ingesting sediment particles, and have therefore adapted to conditions where there is a large percentage of sediment in the water (Anthony and Larcombe, 2000). The coral community present in the Ensenada de Coral has been subject to significant sediment disturbances in the water over the last twenty years for two main reasons, rampant building construction in the surrounding areas, and the presence of the rain-water pipe which, during the rainy season, releases large quantities of sediment into the water. Sediment load, by decreasing the irradiation rate and promoting the growth of algae, which are direct competitors to coral in terms of space, indirectly decreases the size of the coral, causing them to grow smaller and in lower numbers (Sheppard et al., 2017).

4.2 Median coral size across squares

In the Ensenada de Coral, the depth varies significantly within it, reaching its maximum at six metres. In the study, the areas were divided into squares to see if the various parameters (number of colonies and size of coral) changed depending on depth. The results of the tests showed that the median size of the coral present in the impacted area (Area 1) changes significantly between the different quadrants and, therefore, colony size increases with depth. Since the colonies in Square 1- Area 1 are the ones in direct proximity to the water inlet, and therefore to the sediment release, it is expected that this square would also show the smaller coral in size. When released into the water, sediment accumulates either on the existing coral, covering them and slowly killing them, or favouring the growth of algae on top of them (Sheppard et al., 2017). Most of the coral in this square, in fact, showed smaller sizes than those found at the same depth but in different areas (i.e., 4.42cm^2 in Area 1 Sq.1 compared to 15.36 cm^2 in Area 2 Sq. 1), and especially in quadrants of the same area but at greater depths (4.42 cm^2 in Sq.1 compared to 7.04 cm^2 in Sq.5). The explanation for these results could lie in the fact that, when sediment is released from the pipe during rainfall, it precipitates more quickly in the areas adjacent to the pipe and as it moves away, the diffusion increases making the sediment spread more widely.

In a study conducted in the Burdekin watershed in the Great Barrier Reef region, results have shown a decrease in sediment concentration when distance increases from the coast. The results have shown that only small portion of the sediment eroded reach the outer reef, while the biggest particles precipitate very fast (Bartley et al., 2014)

4.3 Multivariable linear regression

During previous tests, it has been shown that coral size decreases as one moves away from the impact area. However, these results do not guarantee with certainty that the reason for the decrease in size is necessarily related to the area in which coral are found. It could also be that the decrease in size is not only related to the area but also to the type of coral, and thus that there are more coral species of a certain type in a certain area, with the difference in size being determined by that. For these reasons, a multivariable linear regression was chosen to answer this question. Results have shown with certainty that the decrease in size is also determined by the area in which coral are found and not only by the type of coral. In particular, the findings tell us that, by moving away from the impact area, coral are associated with a significant probability to be on average 57.48 cm^2 larger in the second area and 38.41 cm^2 larger in the third area. Also, the test shows that, independently in which area you are, being a *Porites astreoides* is associated with a significant probability of being 49 cm^2 smaller than *Siderastrea radians*. While, considering *Favia fragum* is associated with a significant probability of being 76 cm^2 lower than *Siderastrea radians*. These results confirm again our initial hypothesis in which it was postulated that coral species in the impact area are more affected than coral in Area 2 and Area 3 (control areas). Again, the sediment particles released from the pipe, precipitate faster in Area 1, affecting the growth and the colony's number of different types of coral.

4.4 Median coral size per species across areas and squares

Although the Enseada de Coral represents only a small piece of reef, the biodiversity that inhabits its waters is truly rich. To date, more than 500 different species have been identified and photographed and it is thought many more are yet to be discovered (Mascarenhas, 2022). In the Cnidarians' phylum, 36 different species have been counted to date, of which only seven belong to the order Scleractinia. In our study, however, only four species of Scleractinia were identified (*Siderastrea radians, Porites astreoides, Porites porites and Favia fragum*). The reason is that many of these species, although they are present, are very rare (i.e., *Porites porites*). Some others, on the other hand, are not common on flat reefs, they have specific habitats and are therefore difficult to photograph on the benthos (i.e., *Atlantia caboverdiana*).

In our survey, the coral that far outnumbered the others, both in terms of number of colonies and size, were *Siderastrea radians*. In contrast, *Porites porites* was the hardest to find, with only four colonies encountered in the entire area of 1500 m^2. These results are in line with previous studies. Monteiro (2008) in a study on the different coral communities present in Cape Verde revealed that on bedrock patches and boulders *Siderastrea radians* was the coral most abundant (Monteiro et al., 2008).

In this statistical test, we wanted to see whether the median size of different coral species changed depending on the area in which they were found. The results showed that the only coral reported to have a statistically significant difference in size between Area 1 and Area 2 and 3, was *Siderastrea radians*, while for *Porites astreoides* and *Favia Fragum*, the size remained unchanged between the different areas. *Porites porites* was excluded from the statistical tests as the number of colonies were too low to carry out statistical studies.

Although *Siderastrea radians* is a coral that, compared to many others, has an incredible ability to adapt to stressful conditions (Lirman and Manzello, 2009), in this case, its colonies, although present, showed a significant decrease in both numbers and size in Area 1. The high rate of sediment present in the water either covered its colonies, causing them to die, or favoured the appearance and growth of a mantle of algae on top of it.

4.5 Population density

A total of 4223 colonies of four different coral species were identified in the study. As expected from the initial hypothesis, the number of colonies present in Area 1 is largely minor compared to Area 2 and 3. Also, the numbers showed that in each square of Area 1, coral colonies' numbers are smaller when compared to the same squares in Area 2 and 3. As in the case of coral size, the sediments released into the water, present in greater quantities in Area 1, greatly influenced the growth of coral colonies. The sediments, in fact, covered many colonies, leading to their death or promoting the growth of algae that compete for substrate with the coral.

However, results showed something very peculiar. In the bar graph, it is clearly visible how the difference in the number of coral colonies between Area 1 and Area 2 and 3 decreases significantly as one moves away from the coast and thus with increasing depth. This result suggests that the sediment, when released from the water inlet, precipitates very quickly in the areas most adjacent to it, while, moving away from the coast, it spreads more evenly and is therefore less present. The almost total absence of coral in Sq1-Area 1 (12), compared with Sq1-Area 2 (308), and Sq1-Area 3 (404) can therefore be confirmed by the proximity of this area to the water inlet.

This means that, as there is less sediment precipitated in the deeper areas (i.e., Square 4 and 5), the coral will find a healthier environment with less disturbance in which to establish colonies.

5 Conclusion

The coral reef area directly impacted by sediment runoff differed from the control areas both in population density and coral median size. Coral species living in the impact area were significantly smaller compared to the control areas, and their number significantly lower. The average size of the specific coral species changed only for *Siderastrea radians*, which measures were remarkably smaller in Area 1 compared to Area 2 and 3. Also, from the various photographs it is well detectable a high concentration of invasive algae in the impact area. It would be important to conduct future studies to detect the percentage cover of the algae compared to the one of the coral species.

In conclusion, we can say that this novel method was efficient to test the hypothesis raised. The results showed that the sediment released from the rain-water inlet negatively influenced the growth and the number of coral colonies. As for future recommendations, it is important to continue monitoring the condition of these colonies through effective monitoring techniques to better understand the health trends of these coral species in the long-term.

Given the results of this study demonstrating a high level of stress on these colonies, it would be important to implement an engineering plan to divert the course of the rainwater pipe and move its outlet to deeper areas, further away from the coast. In order to prevent human sediment to reach coral reefs, a better awareness of the features, causes and processes generating it is needed. Only in this way, successful watershed management tactics can be employed.

The Enseada de Coral represents an important biodiversity patrimony for Mindelo and it is in the best interest of all to preserve it as best as possible to ensure that the future human generations in Mindelo can enjoy having a healthy coral reef in a privileged location downtown.

This would be of benefit to the increased value of these marine resources in ecosystem services, for tourism and for natural recreational benefits for local residents, among many other services.

6 Acknowledgments

We gratefully acknowledge the support of NVIDIA corporation with the donation of the GPU used for this research.

We also acknowledge the support and kindness of TagLab and Agisoft Metashape teams, which helped for the realisation of these studies.

Financial support for field activities using SCUBA-diving equipment was provided by project MARAFRICA project MARAFRICA: AGA-KHAN/540316524/2019.-

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