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Coral reef monitoring : Using structure from motion photogrammetry to evaluate reef complexity, coral cover and coral diversity at D'Arros Island and Saint Joseph atoll in Seychelles.

Faculdade de Ciências e Tecnologia

Year 2023

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Mestrado em Biologia Marinha

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I hereby declare to be the author of this work, which is original and unpublished. Authors and works consulted are properly cited in the text and included in the reference list.

(Victor Gautier)

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Acknowledgements

I want to thank Dr Aswchin Engelen and Dr Robert Bullock for their invaluable help throughout this project.

Aswchin, thanks for your expert advice and the time you gave me to complete this project.

Rob, thank you for the wonderful opportunity to do my master's thesis on a subject that is close to my heart, and for the time you have given me to prepare my fieldwork and process my data.

I would like to thank the whole team at D'Arros Research Centre for their warm welcome and for showing me the various monitoring programmes.

I would like to thank the Save Our Seas Foundation for this opportunity.

Finally, I would like to thank my family and friends who have helped me in one way or another in this adventure.

Resumo

Apesar de ocuparem menos de 0,2% da superfície oceânica mundial, os recifes de coral são o lar de mais de 25% das espécies marinhas. Representam um ecossistema crucial, servindo como habitat, refúgio e fonte de alimento para uma vasta gama de organismos marinhos. Contudo, os recifes de coral estão sob ameaça crescente a uma escala global, agravada pelo branqueamento dos corais, frequentemente associado às atividades humanas. Esta situação é alarmante, dada a importância dos corais na defesa contra a erosão costeira, na sustentabilidade económica de milhões de pessoas, onde se inclui o turismo e a pesca e na contribuição para os ciclos globais de carbono e azoto. Nos últimos 30 anos, as ameaças resultaram numa diminuição notável na cobertura de coral, na diversidade de espécies e na complexidade estrutural dos recifes. Embora não tenha sido claramente estabelecida uma relação direta entre estes três parâmetros, são necessários mais estudos de investigação. A monitorização contínua e aprofundada dos corais é, portanto, essencial para desenvolver conhecimento e identificar soluções eficazes para a sua conservação.

O campo da monitorização de recifes de coral tem avançado de forma significativa. Desde técnicas tradicionais como o transecto de interceção de linha ou a técnica de quadratura, para

métodos mais inovadores como a fotogrametria Structure from Motion (SfM). A fotogrametria Sfm envolve a modelação 3D dos recifes de coral, permitindo a análise de muitos parâmetros à distância. Esta técnica, que surgiu há cerca de dez anos, ainda se encontra num processo evolutivo e parece promissora. A SfM desempenha assim, um papel importante nos programas de monitorização, uma vez que o método pode ser repetido em qualquer intervalo de tempo para monitorizar as alterações ambientais.

Este estudo tem como objetivo avaliar a complexidade dos recifes, a cobertura de corais, a diversidade e a forma como interagem, utilizando a fotogrametria Sfm na Ilha D'Arros e no Atol de Saint Joseph nas Seychelles.

Explora-se a hipótese de que existem variações na cobertura bentónica, na diversidade de corais e na complexidade estrutural dos recifes, influenciadas pela diversidade dos parâmetros ambientais. A cobertura de corais e a diversidade de corais estão correlacionadas com a complexidade do recife. A técnica de fotogrametria Sfm fornece dados eficientes e precisos.

Utilizam-se amostras recolhidas aleatoriamente em locais de pesquisa pré-determinados, selecionados com base no tipo de habitat e orientação geográfica.

O protocolo de investigação abrange seis zonas distintas à volta das ilhas, três à volta de D'Arros e três à volta de São José, cada uma caracterizada por parâmetros ambientais variáveis. As zonas C e D estão viradas para sul, com condições de ondulação e correntes sólidas, tal como a zona E. As zonas A, F e B estão viradas para norte com mares mais calmos. A zona F é mais profunda do que as outras zonas.

Estabeleceram-se cinco transectos de 100 m^2 (10x10 metros quadrados) dentro destas zonas, para a monotorização em profundidades pouco profundas com variações entre 5 e 12 metros, através de mergulho. A aquisição de dados, envolveu a utilização de uma configuração de câmara dupla, com o objetivo de atingir a melhor sobreposição possível e alargar o campo de visão com fotografias diferentes da mesma área. Foram tiradas fotografias automaticamente a cada segundo, para obter uma sobreposição substancial entre as imagens, tanto para a frente (>80%) como para o lado (>60%). Foram produzidas entre 400 e 800 fotografias durante o decorrer dos protocolos, dependendo do transecto. Foram utilizados vários programas: O Agisoft Metashape, para construir o modelo 3D, o Coral Point Count com extensões Excel para

avaliar a cobertura e a diversidade dos corais, e o Gwyddion para analisar a complexidade dos recifes. O Primer e o Excel foram utilizados para as estatísticas.

Através de um teste de pares, executou-se PERMANOVAs no Primer 7 para cada variável, a fim de determinar diferenças significativas entre zonas e transectos.

Para complementar às PERMANOVAs, efectuou-se PERMDISPs deviation from centroid para comparação de pares para entender-se as diferenças de dispersão entre zonas e um teste de Kruskall Wallis com Mann Whitney de pares para a complexidade do recife.

Os resultados obtidos revelam diferenças significativas entre as zonas e dentro dos transectos de cada zona para as três variáveis. De forma notável, as diferenças inter-zonas foram mais pronunciadas do que as variações intra-zonas, particularmente em algumas zonas que variam entre as variáveis. Curiosamente, não foi identificada qualquer correlação significativa entre a cobertura de corais, a diversidade e a complexidade dos recifes, com coeficientes de correlação próximos de zero. 0,07 entre a cobertura de corais e a diversidade, -0,03 entre a cobertura de corais e a complexidade dos recifes e 0,05 entre a complexidade dos recifes e a diversidade.

As diferenças observadas na complexidade dos recifes são complexas e parecem resultar de uma vasta gama de parâmetros abióticos e biológicos. Os resultados adquiridos ressaltam a necessidade de estudos anuais contínuos para acompanhar a evolução e dinâmicas dos recifes. Além disso, a aplicação de soluções de software alternativas, como o Taglab apoiados pela Inteligência Artificial, podem oferecer insights mais profundos para a construção de soluções e avaliar a complexidade do recife.

Abstract

Despite covering less than 0.2% of the world's oceans, coral reefs harbour over 25% of marine species. They are vital in offering countless marine organisms habitats, nursery grounds, and sustenance. Unfortunately, coral reefs worldwide face escalating threats, with coral bleaching linked to human activities. These threats have resulted in the loss of coral cover, species diversity, and reef complexity, although no direct link has been clearly established between these 3 parameters. Thus, continuous coral monitoring is imperative, offering insights and solutions for conservation.

The field of coral reef monitoring has evolved significantly, leveraging advanced technologies like Structure from Motion (SfM) photogrammetry. This study aims to assess reef complexity, coral cover, and diversity and how they interact using the SfM photogrammetry at D'Arros Island and Saint Joseph Atoll in Seychelles.

The research protocol encompasses six distinct zones around the islands, three around D'Arros and three around Saint Joseph, each characterized by varying environmental parameters. We established five 100 m^2 transects within these zones, monitoring shallow depths ranging from 5 to 12 meters through scuba diving. Our data acquisition involved using a dual-camera setup, with subsequent data processing employing multiple software tools. Agisoft Metashape was employed to construct 3D models, for coral cover and diversity assessments, and Gwyddion for analyzing reef complexity.

Our findings reveal significant differences among the zones and within transects of each zone for all three variables. Notably, inter-zone differences were more pronounced than intra-zone variations, particularly in some zones. Intriguingly, our analysis did not identify any significant correlation between coral cover, diversity, and reef complexity, with correlation coefficients near zero.

This research underscores the importance of annual studies to track reef evolution. Additionally, exploring alternative software solutions, such as the AI-powered Taglab, may offer enhanced capabilities for assessing reef complexity.

Keywords : Coral monitoring, photogrammetry, reef complexity, coral coverage, Seychelles

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List of abbreviation

CPCe : Coral count point with Excel extensions

GB : Gigabyte

m : meters

AI : Artificial intelligence

General introduction

Coral reefs are among our planet's most diverse and ecologically significant ecosystems, providing critical habitats for an astonishing array of marine life. These remarkable formations are constructed by tiny organisms called coral polyps, and they play a vital role in maintaining the health and balance of aquatic environments. (Baker, 2003) The study of corals encompasses various fields of science, including biology, ecology, geology, and climatology, as these organisms and their ecosystems are intricately linked to the complex web of life in the ocean.

Coral refers to many marine animals from the phylum Cnidaria, characterized by their hard skeletons. In a restricted sense, coral designates the order Scleractinia, the reef-building hard corals. In a broader sense, the term represents many other fixed cnidarians, such as gorgonians belonging to the Octocorallia.

There are many different types of coral on the planet. They come in all shapes and colors, soft and hard. Thanks to their incredible diversity, corals can be found in every ocean, at every latitude: the cold-water corals of the deep sea, under the Antarctic ice cap, the corals of temperate environments, and the best-known shallow tropical corals.

Corals are generally colonies of polyps that live together to form superorganisms sharing a calcareous skeleton. By accumulating these mineral skeletons, "reef-building" hard corals form coral reefs, creating the most extensive known structures by living organisms, The Great Barrier Reef in Australia, visible from space. (Baird et al., 2015)

Coral reefs are intricate ecosystems that harbor diverse marine life and provide crucial ecological services. Corals are the primary builders of these reefs, belonging to the phylum Cnidaria and class Anthozoa. (Figure 1.) They are colonial organisms composed of numerous interconnected polyps that work collectively to form expansive reef structures (Hughes et al., 2019).

In this general introduction, we focus on shallow tropical coral reefs.

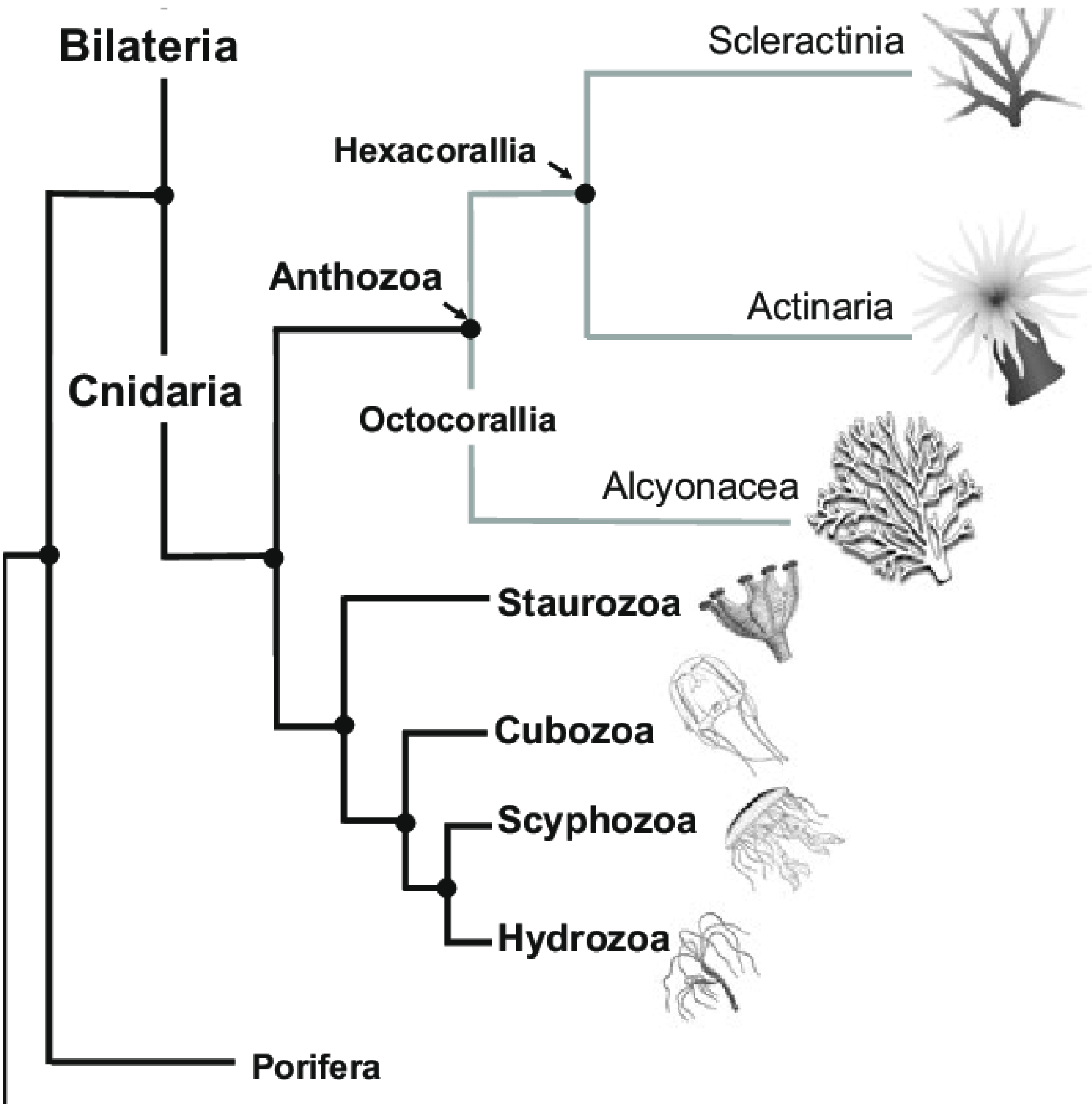


Figure 1. Phylogenetic tree showing the place of coral in the Cnidaria. (Black arrows) (Palmer and Traylor-Knowles, 2018)

1.Coral Biology

Corals are invertebrate animals with a unique relationship with photosynthetic algae called zooxanthellae, residing within their tissues. This symbiotic association allows corals to thrive in nutrient-poor waters, as the algae provide essential nutrients through photosynthesis. In turn, corals offer shelter and nutrients to the algae (Hoegh-Guldberg et al., 2007).

The biology of corals presents many shapes and anatomy and involves intricate reproductive strategies, including both asexual and sexual reproduction. Understanding the intricate biology of corals is crucial for their conservation and management, particularly in the face of growing threats such as climate change, ocean acidification, and pollution. (Hughes et al., 2019).

A.Anatomy

Tropical coral diversity encompasses many species, each exhibiting unique adaptations and ecological roles within coral reef ecosystems (Veron, 2000). From reef-building corals to soft corals, the number of species is huge, divided into many families.

They possess identical defining traits, which include a straightforward stomach with a solitary mouth opening enveloped by stinging tentacles. Most coral organisms reside in communities of hundreds to thousands of genetically identical polyps, collectively forming a 'colony.' This colony comes into existence through a mechanism known as budding, wherein the original polyp produces duplicates of itself.

Most shallow water tropical corals have a mutually beneficial relationship with photosynthetic algae known as zooxanthellae. This symbiosis allows corals to thrive in nutrient-poor tropical waters by harnessing the photosynthetic products of zooxanthellae (Muscatine & Porter, 1977). Through photosynthesis, zooxanthellae provide corals with essential nutrients, including glucose, glycerol, and amino acids, while benefiting from the coral host's shelter and nutrients (Muscatine & Porter, 1977; Rowan & Powers, 1992).

This mutualistic partnership is critical for the growth and survival of symbiotic corals, as it enhances their ability to deposit calcium carbonate and build their exoskeletons (Falkowski, 1984). However, environmental stressors, such as elevated sea temperatures, can disrupt the symbiosis, leading to coral bleaching and compromising the health and survival of both the coral host and zooxanthellae (Baker, 2003).

Tropical hard corals, scientifically known as Scleractinia, are characterized by their stony, calcium carbonate exoskeletons.

Corals form colonies of various shapes, including branching, massive, and encrusting structures. They are incredibly diverse in form, even within a single family, which makes authentication complex. These fascinating organisms form the backbone of coral reefs by providing shelter, food, and spawning grounds for an immense variety of marine life.

Corallites and septa are essential components of the skeletal playing a critical role in the growth, protection, and overall biology of hard corals.

Soft corals are a diverse group of marine organisms in the class Octocorallia. Unlike hard corals, which form solid calcium carbonate skeletons, soft corals possess a flexible internal structure with their polyps embedded within a fleshy mass of coenenchymal tissue. (Fabricius & Alderslade, 2001). The designation "soft coral" typically pertains to organisms found within the two taxonomic orders known as Pennatulacea and Alcyonacea. Their polyps embed within a fleshy mass of coenenchymal tissue.

Also known as octocorals, it is a diverse group of marine organisms within the phylum Cnidaria. Unlike hard corals, which form solid calcium carbonate skeletons, soft corals possess a flexible internal structure composed of proteinaceous material called gorgonin, giving them a soft, fleshy appearance. (Fabricius & Alderslade, 2001).

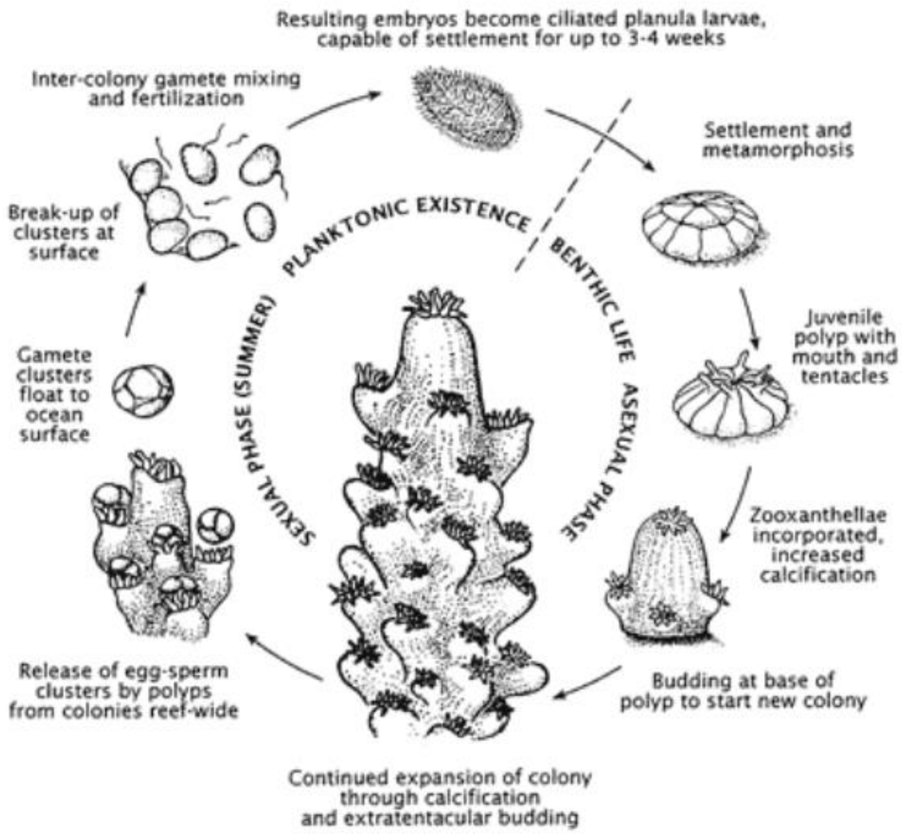
We recognize them by their polyps, which typically have eight feather-like tentacles arranged in a circular pattern around the mouth. These tentacles contain specialized cells called pinnules that aid in capturing plankton and other tiny organisms for feeding (Bayer, 1981).

Soft corals often form colonies, and their vibrant colors and intricate shapes make them a visually stunning component of coral reef ecosystems. They can exhibit a wide range of colors attributed to pigments produced by the coral or by the symbiotic algae residing within their tissues (Benayahu & Loya, 1983). They have evolved various chemical defenses to deter predation and compete for space on the reef. Many soft corals produce toxic compounds, such as terpenoids, diterpenes, and alkaloids, which help protect them from predators and suppress the growth of neighboring organisms (Faulkner, 2000).

B.Reproduction

Coral reproduction involves complex reproductive strategies that ensure the survival and genetic diversity of coral populations. Corals use both sexual and asexual modes of reproduction. These reproductive strategies contribute to the resilience and persistence of coral populations in response to environmental changes (Harrison and Wallace, 1990).

Sexual reproduction in corals occurs through the release of gametes, where sperm and eggs are simultaneously released into the water column during mass spawning events (Harrison and Wallace, 1990; Baird et al., 2015). This synchronized spawning enhances the chances of successful fertilization and genetic exchange among different coral colonies (Babcock et al., 1986). The timing of spawning is often governed by environmental cues, such as temperature, lunar cycles, and sunset/sunrise (Baird et al., 2015). Fertilized eggs develop into free-swimming larvae, known as planulae, which eventually settle on suitable substrates to establish new coral colonies (Heyward & Negri, 1999).



<u>Figure 2.</u> Life cycle of *acropora cervicornis*, a spawning hermaphroditic coral. (Cynthia Shaw-science-art.com)

The intricate process of sexual reproduction ensures genetic diversity, resilience, and adaptation in coral populations, playing a vital role in the persistence and health of coral reef ecosystems.

Asexual reproduction, such as budding and fragmentation, also plays a significant role in coral reproduction, allowing for rapid colony growth and expansion (Babcock et al., 1986).

One common form of asexual reproduction in corals is budding, where new polyps develop as outgrowths from the parent colony, allowing corals to expand their populations rapidly. This process allows for forming clonal colonies, leading to the growth and spread of genetically identical individuals (Baird & Hughes, 2000). Fragmentation is another mode of asexual reproduction, where portions of a coral colony break off and develop into new independent colonies (Loya et al., 2001). Fragmentation can occur naturally due to physical disturbances or can be facilitated by human activities such as anchor damage (Loya et al., 2001). Asexual reproduction enables corals to rapidly occupy available space and recover from disturbances, enhancing their ability to persist in dynamic reef environments (Baird & Hughes, 2000; Loya et al., 2001). The combination of sexual and asexual reproduction strategies contributes to the resilience and adaptability of coral populations, allowing them to withstand environmental challenges.

2.Coral reef ecosystem

Tropical corral reefs are among the richest ecosystems in the world, equivalent to the equatorial forests on earth in terms of biodiversity. These ecosystems support a wealth of biodiversity, with over 25% of marine species relying on coral reefs for habitat and sustenance while it only recovers 0.2% of the sea. The intricate web of life in coral reefs, including fish, invertebrates, and algae, contributes to their ecological resilience.

We can cite the example of the Great Australian Coral Reef, the largest living reef in the world and the most extensive living construction visible from space.

A.Formation and differences

Coral reefs undergo a series of distinct formation steps over long periods. Initially, coral reefs start as fringing reefs, growing near the shoreline. Over time, as calcium carbonate deposits from coral polyps and algae accumulate, they may evolve into barrier reefs separated from the mainland by a lagoon. If these barrier reefs continue to grow and expand, they can develop into atolls, circular reefs surrounding a central lagoon. The formation and evolution of coral reefs depend on complex ecological interactions, geological processes, and sea-level changes over thousands of years (Darwin, 1842).

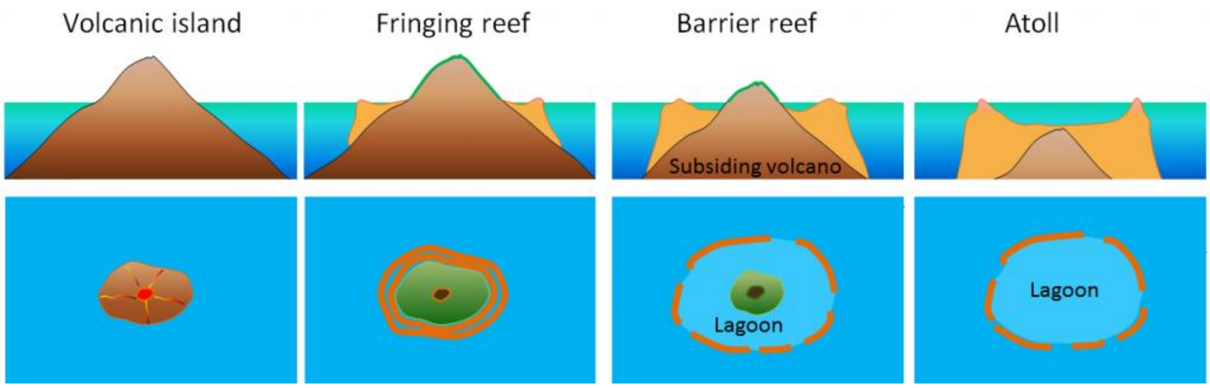


Figure 3. Steps in the formation of coral reefs (Steven Earle, “Physical Geology”).

Hermatypic corals, or reef-building corals, are the primary architects of coral reefs. These corals belong to the family Scleractinia and secrete calcium carbonate to form hard skeletons, which provide the structural framework for coral reefs. Hermatypic corals have a mutualistic relationship with symbiotic algae known as zooxanthellae, which help provide them with energy through photosynthesis. This association allows hermatypic corals to thrive in nutrient-poor tropical waters, contributing to coral reef ecosystems' remarkable biodiversity and ecological significance (Glynn, 1997; Muscatine and Porter, 1977).

B. Tropical coral reef around the world, case study of the Seychelles reefs

Tropical reefs are found in all the world's oceans, on the coasts of almost all continents, except Europe and Antarctica, which has cold water reefs. Their distribution is unequal globally, depending on nutrient intake, temperatures, solar radiation, and coastline shape.

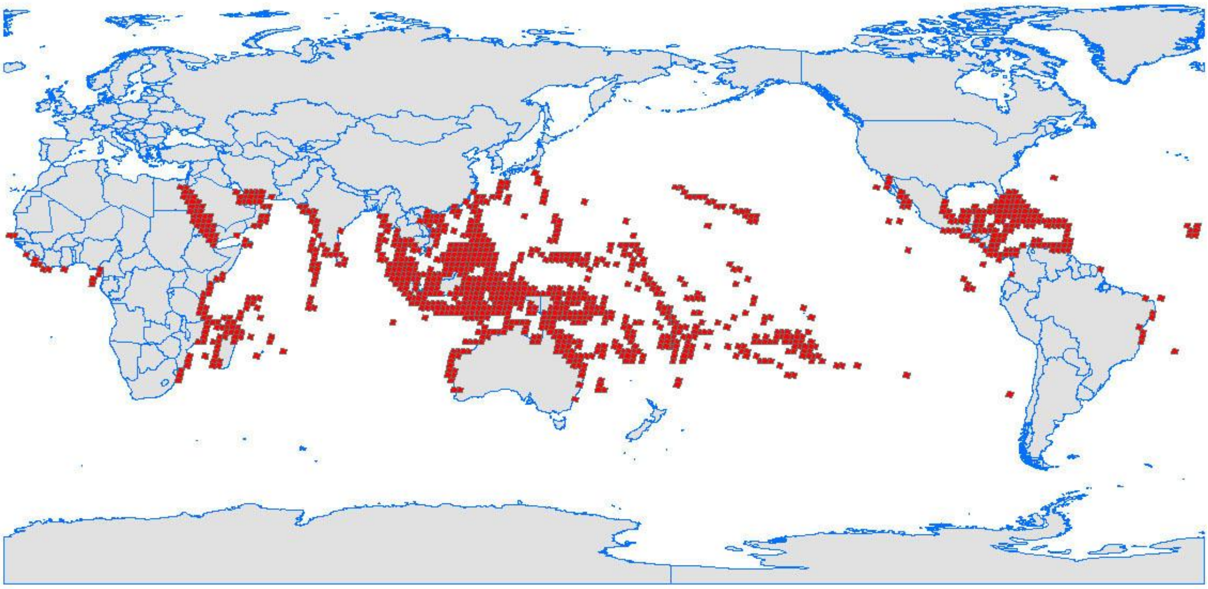


Figure 4. World map of tropical coral reef. (NASA)

The map is centered on the Oceania, which is the region of the world where we find the largest diversity of corals worldwide, especially in the coral triangle. (Veron et al., 2011) There is also a hot spot in the Caribbean but with diversities 10 times less important than in the Indo-Pacific area. Finally, the Red Sea has a very high debt rate. This area has high seawater temperatures; corals have developed adaptive capacities with increased resistance to high temperatures (Bezhad et al., 2016). In the context of climate warming, this area is very interesting for studies on the resistance of corals to extreme temperatures. To a lesser extent, Maldives and Seychelles are also hotspots for coral diversity.

Seychelles is a small country of only 455 km^2 or 200 times smaller than Portugal. However, thanks to its 115 islands, its exclusive economic zone extends to 1.37 million km^2, the 25th largest in the world. This area is home to many coral reefs, including Aldabra, a UNESCO class, which is one of the largest atoll in the world with 155 km^2. The country's economy is directly linked to fishing, contributing to 27% of GDP with small-scale coastal fishing, especially the canned tuna fishing on the capital island of Mahe. Seychelles is a popular tourist destination due to its heavenly beaches and incredible biodiversity. Ecotourism is also developed, with diving, hiking, and wildlife viewing.

The islands experience a tropical climate characterized by the southeast trade winds, which prevail for approximately eight months each year following the monsoon season from November to February, as documented by Hagan et al. in 2008. Additionally, sea surface temperatures in the region typically range from 24°C to 31°C annually, and ocean salinities also exhibit variation, ranging from 34.5 ppt to 35.5 ppt (Novozhilov et al., 1996).

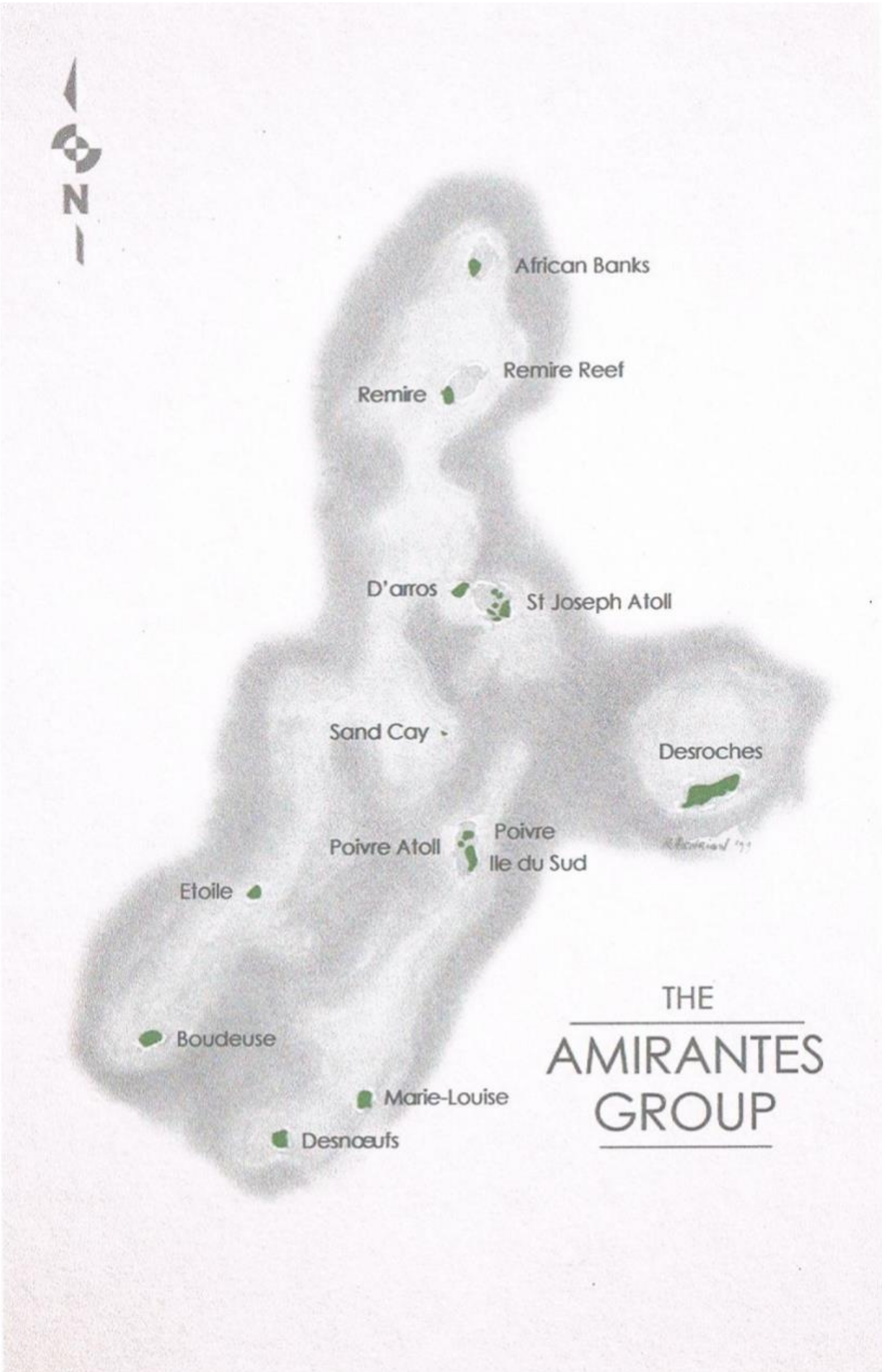


Figure 5. Map of the Amirantes islands in the Seychelles' archipelago. (GlynnBurridge.com)

These islands are granitic with an uneven relief; the Morne Seychellois culminates at 906 meters on the main island of Mahé. They are part of the geological formation called the Seychelles Batholite (De Waele et al., 2001).
These small islands and corral atoll extend over 1000 km to the coast of northern Madagascar.

Figure 6. Satellite image of D’Arros Island and Saint Joseph Atoll. (Google Earth. 2023. D’Arros island and Saint Joseph atoll.)

D'Arros Island and St. Joseph Atoll comprise an expanse of 11.5 square kilometers of low-lying terrain surrounded by extensive reef flats and the corresponding outer reef slopes. These two landmasses, D'Arros and St. Joseph are separated by a channel measuring ¬ ~ 1 km in width and plunging to a depth of 60 meters. They are on the Amirantes Bank, located approximately 255 kilometers southwest of Mahé, the primary island of the Seychelles (Gadoutsis et al., 2019).
The southwestern Indian Ocean is the habitat for a remarkable array of 320 complex coral species, including seven species found exclusively in this region (Ahamada et al., 2004). Many coral species are also present within the Seychelles, establishing the archipelago as a focal point for coral diversity.

3.Importance of coral reef and threats on corals

Coral reefs are crucial ecosystems that provide a wide range of benefits to both marine life and human communities (Baird et al., 2015). They support unparalleled biodiversity, serving as habitats for countless species and acting as nurseries for many commercially valuable fish species. Moreover, coral reefs protect coastlines from erosion, provide a source of livelihood for millions of people through tourism and fisheries, and contribute to global carbon and nitrogen cycling (Reguero, 2018). However, these vital ecosystems are facing severe threats, primarily driven by human activities. Factors such as climate change-induced coral bleaching, ocean acidification, overfishing, pollution, and coastal development are causing widespread coral degradation. According to scientific references, including the Intergovernmental Panel on Climate Change (IPCC) and the National Oceanic and Atmospheric Administration (NOAA), urgent action is needed to mitigate these threats and protect coral reefs to ensure the continued well-being of both marine ecosystems and the communities that depend on them.

Coral reefs are home to many unknown or little-studied species, making them a considerable reservoir of biodiversity, which could have numerous uses in biotechnology, medicine, and agriculture (Faulkner, 2000).

Coral reefs play a significant role in coastal protection acting as a barrier against waves. They are essential for local populations with artisanal fishing, where fish is a large part of the diet and a significant source of protein.

In Seychelles, the coral reef plays a major role in tourism, particularly with the rise of the highly lucrative ecotourism industry. Unfortunately, much tourism has a negative impact, particularly in the Seychelles, with massive CO_2 emissions from air travel that are impossible to offset.

Ecotourism is mainly greenwashing. In the Seychelles, wastes are burnt, energy comes mainly from oil, and air conditioning and swimming pools are standard in hotels. Every tourist, therefore, has an important ecological impact.

Overfishing, which depletes fish stocks and disrupts marine food chains, poses a significant threat to the Seychellois oceans. Moreover, coastal development and pollution, including plastic waste, endanger marine habitats and species (Baker et al., 2023). It is crucial to address these threats promptly and effectively, as highlighted by the Seychelles National Climate

Change Strategy and Action Plan, to preserve the remarkable marine ecosystems of Seychelles for future generations. However, action plans are in place in the Seychelles, with 30% of the marine area protected.

Global warming refers to the increase in the Earth's average temperature due to the accumulation of greenhouse gases released by humans into the atmosphere, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These gases trap the sun's heat and cause gradual global warming. This phenomenon is closely linked to ocean acidification.

Ocean acidification is caused by the absorption of atmospheric CO_2 by seawater, forming carbonic acid. This leads to a drop in the pH of the water, making the oceans more acidic. The acidification harms many marine organisms, particularly species with calcium carbonate shells and skeletons, such as corals, mollusks, and planktonic organisms. It can weaken their structures and reduce their ability to reproduce and develop properly (Doney and Fabry, 2009).

Global warming exacerbates various natural threats to corals. The increased frequency and intensity of extreme meteorological phenomena such as storms (Pielke et al., 2005). The uncontrolled development of certain species, such as the crown of thorns, and the spread of diseases affect more fragile corals due to increased environmental stressors.

4.Coral monitoring

Coral monitoring involves the systematic and continuous assessment of coral reefs to track their health, condition, and changes over time. Monitoring coral reefs is essential for understanding their status and trends, which, in turn, informs conservation and management efforts aimed at protecting these invaluable ecosystems.

A.Importants parameters

Coral monitoring techniques can be used to assess various parameters that are essential for determining the health of the coral reef.

Coral cover provides insights into the abundance and condition of coral populations. It refers to the proportion of the seafloor or substrate covered by live coral colonies. Changes in coral cover can signal the impacts of stressors such as climate change, ocean acidification, pollution, and coral bleaching events. Scientific studies frequently utilize coral cover as a key parameter to evaluate reef health and track trends over time (Hughes et al., 2018).

Coral diversity gives information on the community composition of the reef by measuring the variety of coral families, genus or species present in a reef ecosystem. High coral diversity is indicative of a resilient and ecologically rich reef (Hoegh-Guldberg et al., 2007).

Reef complexity assesses the structural intricacy of a reef, taking into account factors like coral architecture and the presence of crevices and overhangs (Wilson et al., 2007; Graham & Nash, 2013).

Bleaching extent quantifies the severity of coral bleaching events, which occur when corals expel their symbiotic algae due to stress, often caused by elevated sea temperatures.

Fish abundance measures the population density and diversity of fish species within coral reef ecosystems. High fish abundance is indicative of a healthy reef, as fish play vital roles in reef ecology, including herbivory and predation (Graham et al., 2007).

All these parameters are essential indicators of the health and state of coral reefs and are therefore frequently used in coral monitoring programm.

B.Previous techniques

The Line intercept transect (LIT) method is a fundamental technique employed in coral monitoring to assess the composition and condition of coral reefs. In LIT, a predetermined line or transect is laid across the reef substrate, and divers swim along it, documenting different type of parameters intersected by the line at regular intervals. This method provides quantitative data on different reef components, allowing for the evaluation of coral reef health and ecological status. LIT has been extensively used in scientific research to study coral reef dynamics, the effects of environmental stressors, and to support conservation and management efforts (De'ath et al., 2012).

The Photoquadrat method sets up a grid or quadrat on the reef, and photographs are taken at regular intervals within each quadrat. These photographs capture the benthic substrate, including corals, algae, and other organisms. The images are later analyzed to estimate the percentage cover of different components, aiding in the evaluation of coral reef health and changes over time. This method is more precise but does not allow as large an area to be covered as the LIT technique.

C.Photogrammetry

Structure from Motion (SfM) is a photogrammetric technique that reconstructs three-dimensional structures from overlapping 2D images. It is widely employed in geology, archaeology, biology, and other fields.

SfM relies on identifying common features or points in multiple images, tracking them across frames, and computing their 3D positions. This technique allows for the reconstruction of complex scenes and objects. To accurately reconstruct the 3D structure, camera parameters, such as focal length and distortion, must be calibrated (Nocerino et al., 2020). This step ensures precise scaling and orientation of the reconstructed model. SfM initially generates a sparse point cloud of 3D feature positions and then densifies it to create a dense point cloud, capturing finer details of the object or scene. Bundle adjustment is a critical step in SfM that refines camera parameters and feature positions to minimize errors in the reconstructed model. It enhances the overall accuracy of the 3D reconstruction (James & Robson, 2012).

In remote sensing, SfM is utilized to create 3D models of terrain and landscapes from satellite and drone imagery. SfM is also used in ecological research to monitor and measure structures, such as forests and, in our case, coral reefs (Anderson et al., 2018).

SfM plays a role in coral monitoring because the method can be repeated at any given time interval to monitor environmental changes (Nuth and Kääb, 2011).

5. Conclusion

Coral reefs worldwide face a multitude of global threats. The combined impacts of global climate change, alongside localized issues like overfishing and pollution, pose a significant risk to these captivating ecosystems, resulting in a decline in coral cover, biodiversity and, reef complexity. We must take proactive measures to safeguard these ecosystems to prevent potential future economic and social crises. With the ongoing escalation of threats to coral reefs, scientists continually strive to identify effective and innovative tools to enhance the scope, scale, and efficiency of coral reef monitoring. These monitoring techniques furnish invaluable data that enable us to monitor changes in coral reef communities across the globe, providing essential insights for developing efficient preservation and restoration strategies aimed at safeguarding coral reefs on a global scale.

INTRODUCTION

Coral reef monitoring aims to regularly observe and collect data on coral reef ecosystems to assess their health and track changes over time (Hagan et al., 2008; Beyer et al., 2018). The information gathered helps to identify and understand the impacts of human activities, climate change, and natural evolution on coral reefs to implement effective management strategies to protect these valuable ecosystems (Ahamada et al., 2004; Eakin et al., 2022). Monitoring activities may include monitoring water quality, surveying coral and fish populations, mapping reef structure and coverage, and measuring critical environmental variables such as temperature and light levels (Obura et al., 2019). Our study aims to monitor the reef structure, coral cover, and diversity to determine the spatial variation and the factors influencing them.

The techniques of coral reef monitoring are constantly evolving with the application of advanced technology, such as the structure from motion photogrammetry technique. This method allows the creation of 3D maps of coral reefs from 2D overlapping photos. Studies have shown that it could be more relevant than traditional in situ methods to calculate the crucial parameters showing the good health of a coral reef, such as the reef complexity, coral cover, coral diversity, and the bleaching extent (Teague et al., 2022; Nocerino et al., 2020). We are going to focus on the first three parameters in this study. The coral cover represents the percentage of coral covering an area, while coral diversity focuses on the number of species or families in the area. Reef complexity represents the 3D structure of the reef, which means the variation of depth, also named rugosity. These parameters are essential to assess the health of a coral reef; by the coral's role as a keystone, these parameters impact the entire ecosystem. The bleaching extent is the percentage of bleaching in an area, and the recovery rate is calculated by monitoring the same area over time and indicates the differences in coral cover and bleaching extent (Johns et al., 2014).

Bleaching events are critical phenomena that endanger a whole ecosystem by the death of corals, keystone species of tropical reefs (Hagan et al., 2008). Coral reefs are among the most diverse ecosystems in the world, covering less than 0.2% of the sea but hosting more than 25% of the known marine species. Coral species provide shelter, nursery, and food for many marine species (Wall et al., 2015). All over the world, with increasing frequency, coral reefs are threatened by coral bleaching. Bleaching is defined as a stress reaction to an increase in seawater temperature (Glynn, 1984), and the severity of the episode varies according to the duration and intensity of the abnormal environmental conditions.

Moreover, the acidification of the oceans directly linked to the excess of CO_2 released by human activities in the atmosphere accentuated the phenomenon. During a bleaching event, the symbiotic relationship between the zooxanthellae and the coral polyp breaks. It leads to the bleaching of the coral, weakening its structure, and if it lasts too long, the death of the coral (Jones, 1997). These events are occurring with increasing frequency in Seychelles (Zinke et al., 2014) and, more broadly worldwide, directly linked to global warming and the frequency and intensity amplification of El Niño phenomenon (Arif et al., 2022). Due to the importance of coral reefs and the increasing threats they face, coral monitoring is essential to develop our knowledge on the subject and to set up adequate protection strategies. From this perspective, improving coral monitoring techniques is essential, and implementing new technologies could allow us to obtain more accurate data while saving time and resources. In this context, we focus on the SfM photogrammetry technique. This recent technique has shown exciting results in the few scientific studies conducted. Further studies are needed to prove its efficiency and to develop it on a large scale and with different study parameters.

Our work investigates the D'Arros Island and Saint Joseph Atoll coral reefs in Seychelles. The Seychelles is an archipelago of 1,374,000 km^2 in the western Indian Ocean consisting of 116 islands, including 42 granitic and 74 coralline islands (Hagan et al., 2008). D'Arros Island and St Joseph Atoll comprise 11.5 km^2 of low land fringed by large reef flats and associated outer reef slopes. An 1100 m long and 60 m deep channel separates D'Arros and St. Joseph (Stoddart et al., 1979). For the research, we consider the island as a single ecological unit. The islands are on the Amirantes Bank, approximately 255 km southwest of Mahé, the Seychelles' main island (Gadoutsis et al., 2019). The islands have a tropical climate with the presence of the southeast trade winds eight months a year after the monsoon period from November to February (Hagan et al., 2008). The Sea surface temperatures show a typical annual range between 24°C to 31°C, and the ocean salinities vary from 34.5 to 35.5 ppt (Novozhilov et al., 1996). The southwest Indian Ocean is home to 320 species of hard corals, including seven endemic species (Ahamada et al., 2004). Many of these species are found in the Seychelles, making the archipelago a hotspot of coral diversity.

The coral bleaching temperature threshold considered 30.5° C in Seychelles (NOAA) has been reached with an increasing frequency in recent decades (Gadoutsis et al., 2019). Two notable bleaching events, in 1998 and 2016, were linked to the El Niño phenomenon (Eakin et al., 2019). The 1998 ocean warming showed a decrease of 90% in hard coral cover on the archipelago's northern islands (Wilkinson, 2000). The islands in the south were less severely affected, with 60% of average mortality (Spencer et al., 2000) due to less impact of the south equatorial current, which provides cooler water. The same happened for the 2016 event; bleaching was much more severe in the inner island, with 90% mortality around Mahe. Studies on D'Arros and Saint Joseph have highlighted a significant decrease in shallow reef coral cover of almost 50% (Gadoutsis et al., 2019). The bleaching events affected the coral genera differently, and some recovered faster than others due to their characteristics, location, and depth. Assessing coral cover and community composition provides essential data on the current condition and recovery of the coral reefs.

Anthropogenic pressures negatively impact reef recovery processes after a bleaching event. Due to their remote location, conservation policies since 1974, and their MPA's statute declared in 2014, thanks to the "Save Our Seas Foundation", D'Arros and Saint Joseph coral reefs are nearly pristine from direct human pressures. Moreover, the islands are home to many coral species, making them a hotspot of biodiversity. For these reasons, D'Arros Island and Saint Joseph atoll are ideal places to separate the global warming impacts from other anthropogenic pressures on many coral families. These islands provide an ideal location to test coral monitoring techniques. Using the 3D modeling, the SfM photogrammetry technique assesses several parameters such as coral cover, diversity, and reef complexity. It provides a high level of accuracy and saves time compared with previous techniques. We aim to evaluate these 3 variables in different areas around D'Arros Island and Saint Joseph Atoll to determine the factors influencing these variables.

As acute warming events become more prolonged and intense, it is increasingly important to better understand the relationships amongst reef complexity, benthic cover and coral diversity in order to better determine their relative importance in structuring reef fish communities and promoting reef resilience, for example.

Aim :

Investigate reef complexity, coral cover, and coral diversity at D'Arros and Saint Joseph atoll in Seychelles.

Investigate variations in the structure and composition of reefs and the driving parameters within a remote marine protected area.

Objectives :

Assess benthic cover, coral diversity and reef complexity of reef zones presenting various environnemental parameters.

Assess the differences and similarities between the 3 variables considering the driving parameters.

Determine if coral cover and diversity correlate with reef complexity.

Assess the applicability of structure-from-motion photogrammetry as a tool to estimate finescale reef structure and composition.

Scientific questions:

Are there spatial differences in coral cover, coral diversity and reef complexity between the different zones of the reef ?

Does coral cover and diversity correlate with reef complexity?

Hypotheses :

There are differences in the benthic cover, coral diversity and structural reef complexity due to the variation of environnemental parameters.

Coral cover and coral diversity correlate with reef complexity.

The SFM photogrammetry technique provides efficient and accurate data.

MATERIAL & METHODS

1. Study Area

We use the SfM photogrammetry technique to map different parts of the coral reef surrounding D'Arros island and Saint Joseph Atoll. Samples are collected randomly at predetermined survey sites, which are selected based on habitat type and geographic orientation. We chose different survey sites to represent best the coral reef environment at D'Arros and St.Joseph. (Figure 8, Table 1)

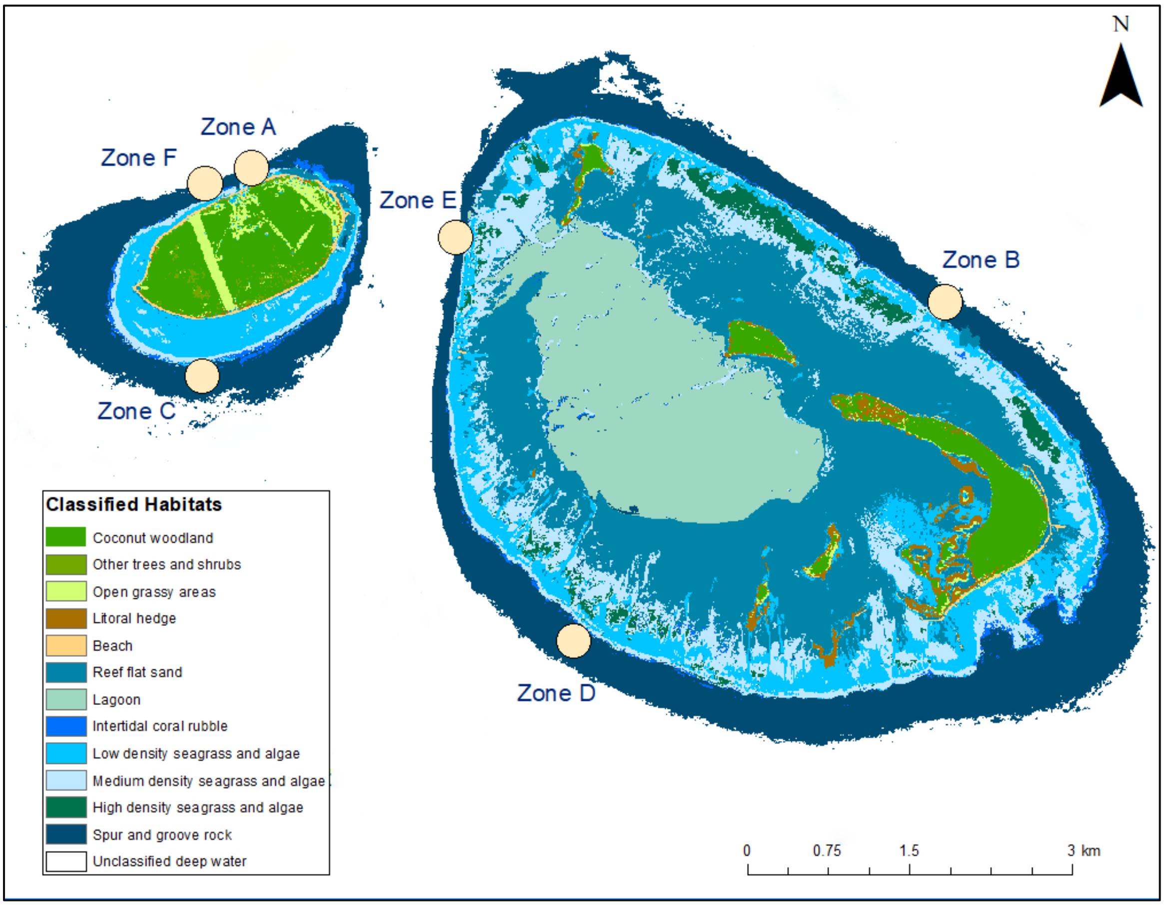


Figure 7. Map of the different sampling areas in D'Arros island and Saint Joseph Atoll. (© Save Our Seas Foundation)

D'Arros Island and Saint Joseph Atoll have five characteristic habitats: Platform reef, Reef slope, Reef crest, Coral plateau, and Lagoon coral patches. (Table 1) These habitats vary in turbidity, nutrient availability, turbulence, wave action, tide exposure, and sea temperature. The study area includes southern coasts and channel sides exposed to higher wave and current action than their northern counterparts.

On the southern coasts, coral-free lines perpendicular to the coast are natural evacuations of the excess water brought by the waves. Sensors measuring the water temperature, though attached to heavy concrete blocks, have already been lost, proving the strength of the currents. The lagoon is subject to a significant tidal action and a warmer water temperature. The reefs around St. Joseph are subjected to warmer, sediment-laden tidal outflows from the lagoon and may experience variations in nutrient availability and turbidity compared to D'Arros. As these environmental factors are known to influence reef ecology, we sample a range of habitat types across our study site.

Table 1. Summary of coral reef habitats and their characteristics (© Save Our Seas Foundation)

	Geographic extent	Benthic cover	Depth range (m)	Monitoring depth (m)	Topography	Substrate
Reef crest	Surrounds D'Arros and St. Joseph	Medium - High	1-6	4-6	Gentle slope with 'spur & groove' formations	Rock or consolidated coral rubble
Steep reef slope	Sections of D'Arros & St. Joseph N-facing and channel sides	Medium - High	6-25	10-15	Steep slope (30-90°)	Consolidated or unconsolidated coral rubble
Coral plateau	D'Arros and St. Joseph S-facing	Low	6-30+	10-15	Gentle slope, low relief 'spur & groove' formation or featureless	Rock or unconsolidated rubble
Platform reef	Insular units; D'Arros N&W-facing	High	10-20	10-20	Undulating, high rugosity	Consolidated coral rubble
Lagoon coral patches	Small patches inside lagoon	High	1-5	1-5	Flat	Rock

2. Structure from motion photogrammetry technique

The protocol is implemented on the six zones, five transects per zone at 5 to 12 m shallow areas. Our protocol is to select survey areas at random sites within the different zones. Two divers carry out the protocol. We select survey areas at random within the different sites. Photos are taken 1.5 meters above the reef by a diver with a stereo assembly of two gopros hero nine separate from 50 cm, mounted on a metal bar to facilitate the maintenance for the diver and the accuracy of the photo. (Teague et al., 2022; Nocerino et al., 2020) We use a slight orientation angle for the gopros to get the best 3D model.

The other diver determines the GPS location and delimites the 10x10m (100 m) studied area square with the tape measure. Three scale bars are placed randomly onto the reef to maximize the scaling quality of the Agisoft model. (Gigli et al., 2023; Bayley and Mogg, 2020) (Figure 9.) The scale bars are two quadrats of half square meters and a 65cm long bar. We use a white marker (tape measure) to calibrate the model.

We need an average of 10 minutes per 100 m^2 transect and five minutes flippering between two transects to get a good map of the zone, allowing an average of 4 transects per dive. We complete the 30 transects of the six zones in eight dives.

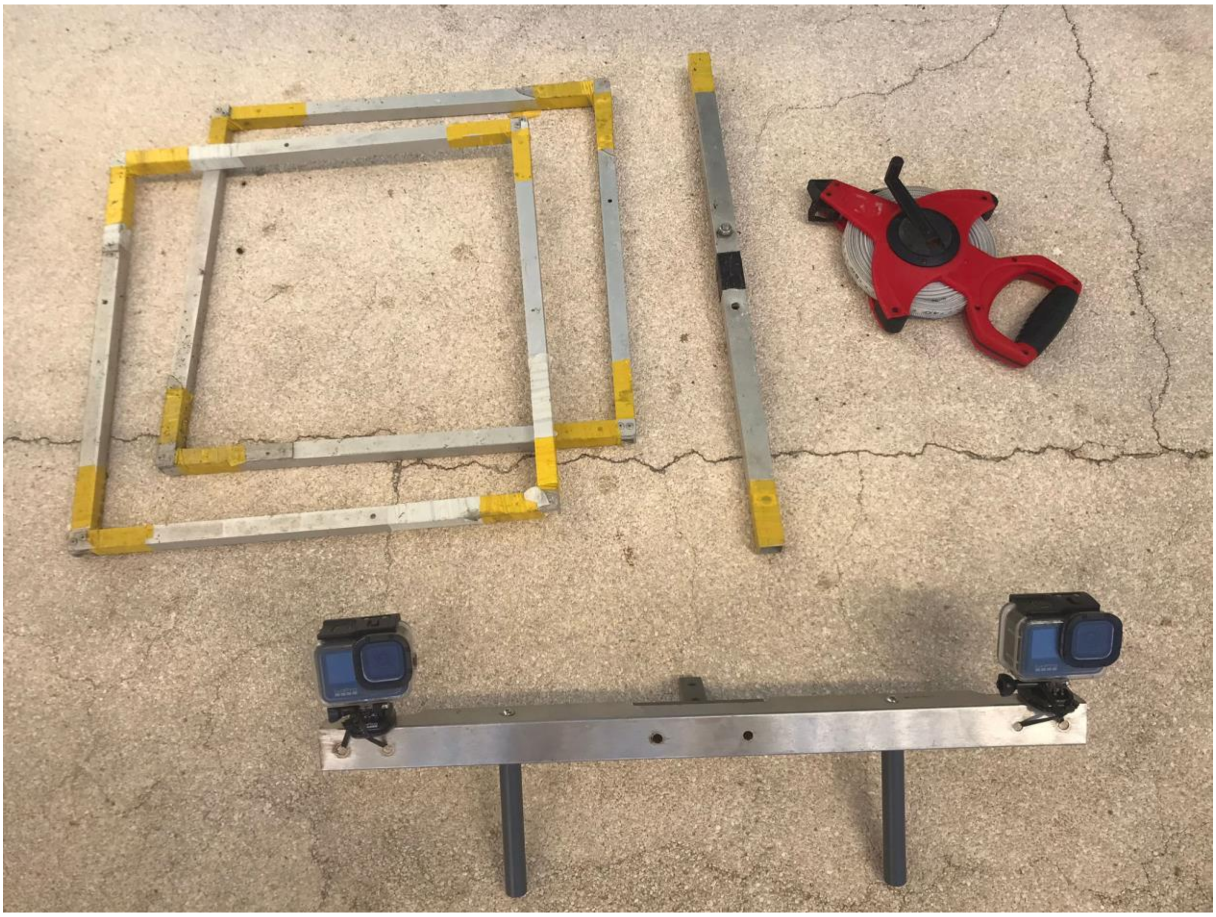
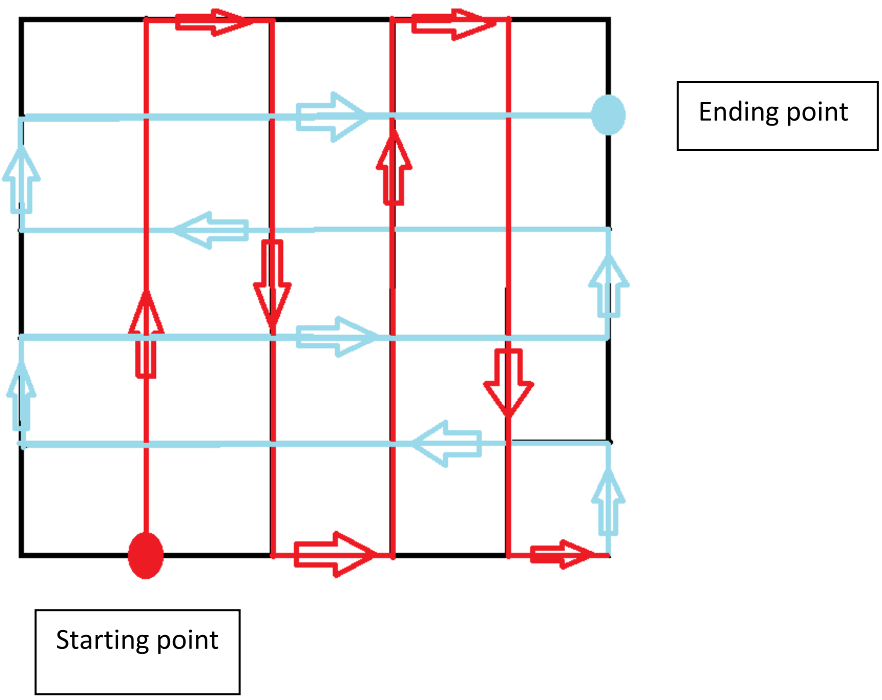


Figure 8. The typical conceptual layout of equipment over the substrate in preparation for a photogrammetric survey. (1) 3 markers. (2) White tape transect of 50m long. (3) Gopro 9 assembly.

The goal is to have the best overlap possible and widen the field of vision with different photos of the same area. We take a picture automatically every second to get a substantial overlap between images both forward (>80%) and sidewise (>60%). (Gigli et al., 2023; Urbina-Barreto et al., 2021) In order to meet these conditions, the diver's speed has to be low to avoid motion blur and to obtain the necessary overlap. The diver must map the area as efficiently as possible and pass twice over the same point at a different angle (Nocerino et al., 2020; Penin et al., 2007). During our protocols, we take between 400 and 800 photos, depending on the transect. We follow the pattern of the Figure 10., drawing four lines two meters apart to map as accurate as possible the 100 m^2 area.



<u>Figure 9.</u> Swimming pattern of the diver to map the reef area using the SFM photogrammetry technique.

3. Data analysis

We use a powerful computer to process the data with different software.
Agisoft needs large amounts of RAM (≥32 GB), a multi-core CPU (Quad-core Intel i7 or higher), and a powerful GPU (Bayley and Mogg, 2020). CPCe, Gwyddion, Excel, and Primer-E do not require much computer power; this software can be used with a standard laptop.

Different steps Agisoft

The professional version of Agisoft Metashape is required. We followed the photogrammetry protocol developed by Bayley and Mogg, 2020 in Table 1. Depending on the transect, it takes approximately two hours of data processing to map each 100 m^2 transect using between 400 and 800 photos. It allows us to create the dense point cloud processing with Gwyddion and the orthomosaics for Coral Point Count.

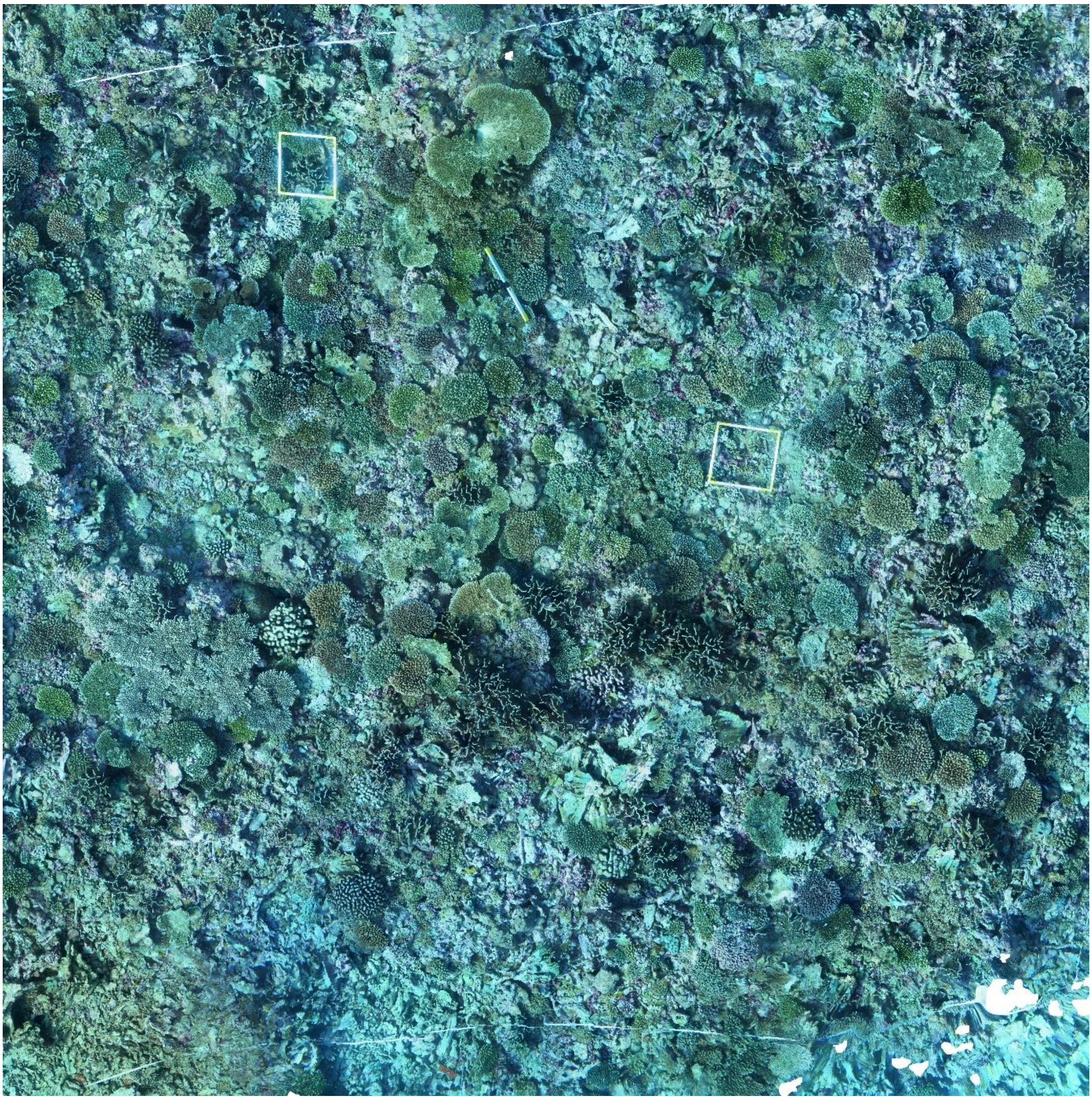


Figure 10. Orthomosaic from zone F2 created with Agisoft Metashape.

Coral coverage and diversity with CPCe

We use orthomosaics supplied by Agisoft Metashape. The orthomosaics' quality must be greatly reduced to be used by CPCe (From 1 to 5GB to 50MB) (Kohler and Gill, 2006). We divide the orthomosaics into five rectangles of equal size. (=replicates from 1 to 5). Coral cover and diversity are evaluated in the same areas as reef complexity, with Gwyddion allowing an adequate comparison. We list corals by family and in separate categories: bleached, diseased, and unidentified corals. (Table 11.) CPCe positions one hundred random points on each 20

km^2 rectangle and compiles the data in a table with the number of occurrences in each replicate. The number of points is statistically determined to have the best time efficiency while keeping a good accuracy of results considering the standard deviation. The table shows a relatively high number of unidentified corals due to the lower image quality induced by CPCe and some blurred areas caused by bugs during the Agisoft Metashape modeling.

Reef complexity with Gwyddion

We use the point cloud provided by Agisoft Metashape. Using Gwyddion, we follow the 2D photogrammetry workflow set up by Bayley and Mogg, 2020 in Table 2 (Nečas and Klapetek, 2012). We trace five lines corresponding to the middle of each of the five replicates zone of CPCe. The lines parallel the slope to determine the rugosity, named reef complexity for a coral reef (Sq roughness value). Each line is separated by two meters; the first line aligns on the first meter on the side of the transect, the second at 3 m, the 3rd at 5 m, the 4th at 7 m, and the last at 9 m. Each line extends over 10 m^2 to have the best reef complexity estimation possible of the 100 m transect. We extract five roughness values per transect corresponding to the five lines. We process 19 transects on 30. We are unable to calculate the reef complexity of the 11 remaining transects. We assume that the size of these transects, which were more extensive than the other 19, could not be processed by the software. (+5GB) In addition, we annotate the maximum and minimum depth of each transect.

Table 2. Subcategories used to classify the random point in CPCe.

SUBCATEGORIES (% of transect)
CORAL (C)
Acroporidae (AC)
Agariciidae (AG)
Bleached Coral (BC)
Dendrophyliidae (black) (DEN)
Diseased Coral (DC)
Euphyliidae/Oculinidae (E/O)
Faviidae (F)
Fungidae (FG)
Helioporidae (H)
Mussidae (M)
Other Encrusting corals (OE)
Pocilloporidae (PC)
Poritidae (P)
Unidentified (NA)
SOFT CORAL (SC)
Alcyoniidae (ACY)
Gorgoniidae (GOR)
Nephtheidae (NPH)
SUBSTRAT (S)
Coral Rubble (CR)
Recently Dead Coral (RDC)
Rocks (R)
Sand (SA)
OTHER (O)
Algae (A)
Other Animal (OA)
Other NA (ONA)
Seagrass (SG)
Shadow (SW)
TAPE (T)
Tapes (TA)

Statistics Analysis using Excel and Primer 7

We use the softwares Excel and Primer 7 to process the statistical analysis. We analyze 19 transects from 6 different zones: four transects from zone A, two from zone B, four from C, four from D, two from E, and three transects from zone F.

We extract from CPC and Gwyddion and format the coral cover, diversity, and reef complexity results in Excel. We split Coral diversity into two variables: community composition and the Shannon index. Boxplots are produced for each variable to show our results clearly.

We run PERMANOVAs on Primer 7 for each variable to determine significant differences among zones and transects using a pair-wise test. PERMANOVA stands for "Permutational Multivariate Analysis of Variance." It is a statistical technique used in multivariate analysis to test for differences among the groups' mean of multivariate data.

We combine in a Euclidean matrix the data of coral cover, Shannon index, and reef complexity. Concerning community composition, we transform the data into square roots to reduce the effect of dominance by high numbers. We create A Bray-Curtis dissimilarity matrix to quantify the dissimilarity or similarity between each zone. We plot a CPA for the data visualization. The CAP 1 axis is more important than CAP 2 to quantify the group differences (Anderson and Willis, 2003).

Complementary to the PERMANOVAs, we run PERMDISPs deviation from centroid using pair-wise comparison to test for the zone dispersion differences and a Kruskall Wallis with Mann Whitney pair-wise test for reef complexity.

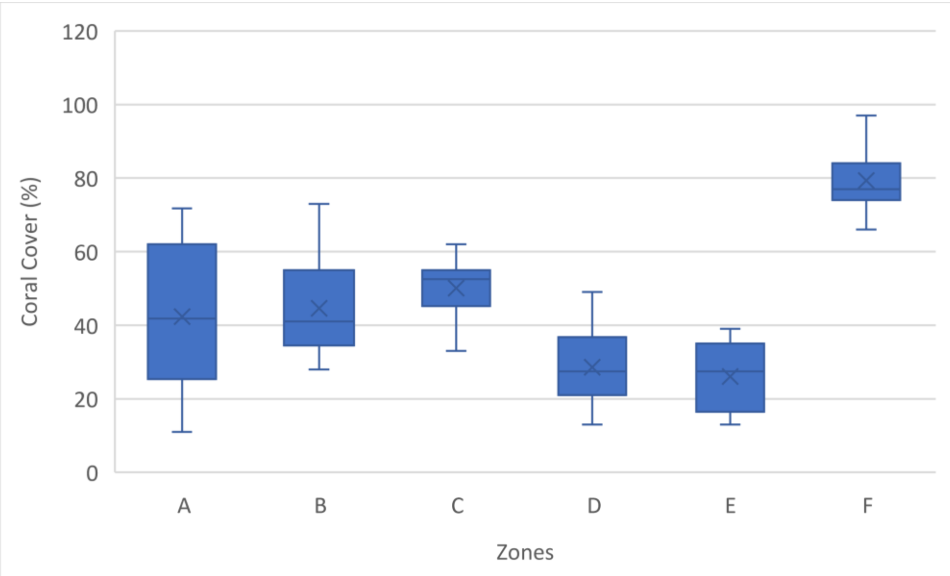
We use the different zones as factors. The alpha value is set at 0.05. In Primer, the values often written as p-value are noted as p-perm during the PERMANOVA and PERMDISP, which means p-permutation and must be less than the alpha value to show significant differences.

RESULTS

Transect E3 presents outliers due to bugs in the modeling by Agisoft Metashape. Therefore, we remove E3 from the dataset. We have 18 transects, divided into 5 replicates noted from R1 to R5, giving 90 replicates.

Coral Cover

PERMANOVA shows significant differences in coral cover among the zones (P-perm = 0.0041 ; Pseudo-F = 6.7248) and among the transects of the zones. (P-perm = 0.0001; Pseudo-F = 12.476)



<u>Figure 11.</u> Boxplots showing the differences of coral cover among the 6 zones. The boxes represent the interquartile range (IQR), the cross is the mean and the median is symbolised by the bar in the middle of the box. The upper and lower whisker lines correspond to the extreme values, not counting the outliers, represented by dots.

We find P-perm less than 0.05 among zones C and D (P-perm = 0.0307, unique perms = 26), C and F (P-perm = 0.0273, unique perms = 35). (Table 2.) We also find significant differences among zones D and F (P-perm = 0.0245, unique perms = 34). Zone F has an average and median (average 79.3, median = 77) well above zone C (average 50.1, median 52.5) and D (average 28.5, median 27.5).

Table 3. Pair wise tests showing significative differences among the zones for coral cover values. (PERMANOVA)

Groups	t	P(perm)	Unique perms	P(MC)
A, B	0.13523	0.8681	15	0.9051
A, C	0.71755	0.4465	35	0.5033
A, D	1.207	0.3028	35	0.274
A, E	0.67614	0.7997	5	0.552
A, F	2.8688	0.0865	35	0.0324
B, C	0.89555	0.4647	15	0.4182
B, D	2.0049	0.2039	15	0.1174
B, E	1.1868	0.6672	3	0.445
B, F	4.5483	0.1043	10	0.0188
C, D	5.045	0.0307	26	0.0013
C, E	5.9415	0.203	5	0.0092
C, F	9.1812	0.0273	35	0.0006
D, E	0.28307	1	5	0.7985
D, F	9.8545	0.0245	34	0.0003
E, F	9.4499	0.2443	4	0.0116

PERMDISP shows significant differences of coral cover among the zones. (P-perm = 0.0001 ; Pseudo-F = 13.695)

Zone A shows significant differences from all the other zones. (Table 4.) Zone A's interquartile range is 36.6175, well above all other zones, notably three times higher than zones F (IQR 10) and C (IQR 9.75) and, to a lesser extent, higher than zone F (IQR 10).

Zone B has an interquartile range of 20.5, twice the IQR of zones C (P-perm = 0.017, t = 2.4425) and F (P-perm = 0.042, t = 2.1767).

Table 4. Pair wise comparisons showing significatives differences among the zones for coral cover. (PERMDISP)

PAIRWISE COMPARISONS

Groups	t	P(perm)
(A,B)	2.77	0.011
(A,C)	7.0282	0.001
(A,D)	5.4234	0.001
(A,E)	3.2644	0.002
(A,F)	6.2259	0.001
(B,C)	2.4425	0.017
(B,D)	1.3081	0.271
(B,E)	0.87495	0.5
(B,F)	2.1767	0.042
(C,D)	1.3132	0.185
(C,E)	0.86532	0.478
(C,F)	0.0386	0.96
(D,E)	0.046084	0.978
(D,F)	1.1492	0.322
(E,F)	0.78742	0.511

Shannon index

PERMANOVA shows significant differences of Shannon index among the zones, (P-perm = 0.0002 ; Pseudo-F = 18.354) and among the transects of the zones (P-perm = 0.0117 ; Pseudo-F = 2.4242)

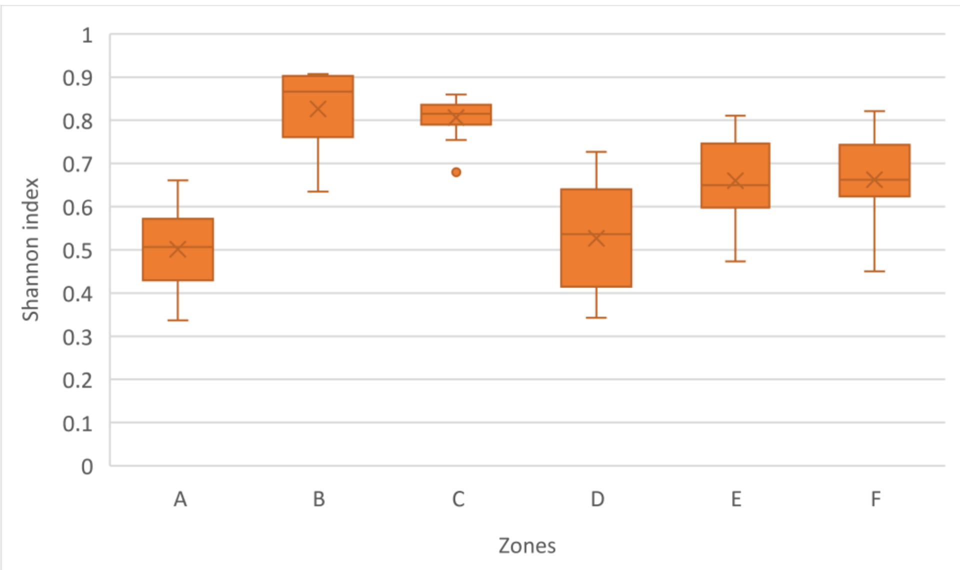


Figure 12. Boxplots showing the differences of coral diversity with the Shannon index between the six zones.

We also run a pair-wise test. We found P-perm less than 0.05 among zones A and C (P-perm = 0.0293, unique perms = 35), C and D (P-perm = 0.0286, unique perms = 32), C and F (P-perm = 0.0268, unique perms = 35). (Table 5.) The significant differences are all with zone C (average: 0.806, median 0.814). Zone C's mean and median values are higher than zone F, with mean and median values around 0.65, and zones A and D, with mean and median close to 0.50.

Table 5. Pair-wise tests showing significative differences between the zones for Shannon index values.

Groups	t	P(perm)	Unique perms	P(MC)
A, B	5.1114	0.0701	15	0.0073
A, C	7.36	0.0293	35	0.0007
A, D	0.54487	0.5745	35	0.6058
A, E	1.4914	0.2003	5	0.242
A, F	2.755	0.0556	34	0.0386
B, C	0.73163	0.4655	15	0.5092
B, D	7.0471	0.0702	15	0.0015
B, E	3.1061	0.3293	3	0.1996
B, F	2.7588	0.1027	10	0.0687
C, D	10.407	0.0286	32	0.0001
C, E	6.7499	0.2067	5	0.0071
C, F	3.8852	0.0268	35	0.0094
D, E	1.9752	0.204	5	0.1475
D, F	3.0156	0.0834	35	0.0325
E, F	0.34065	1	4	0.773

PERMDISP shows significant differences of Shannon index among the zones. (P-perm = 0.006 ; F = 4.2672)

Zone C shows significant differences from all the other zones. (Table 6.) Zone C interquartile range is well below other zones, five times lower than zone D (IQR 0.225) and much lower than zones A and F (IQR 0.143 and 0.119). We also find Significant differences between zones A and D (P-perm = 0.042, t = 2.0588).

Table 6. Pair-wise comparisons showing significatives differences among the zones for Shannon Index. (PERMDISP)

PAIRWISE COMPARISONS

Groups	t	P(perm)
(A,B)	0.35355	0.737
(A,C)	3.4432	0.002
(A,D)	2.0588	0.042
(A,E)	0.10596	0.921
(A,F)	0.139	0.885
(B,C)	3.2553	0.012
(B,D)	1.256	0.233
(B,E)	0.1345	0.889
(B,F)	0.35713	0.751
(C,D)	5.0673	0.001
(C,E)	2.4768	0.035
(C,F)	2.2447	0.034
(D,E)	1.0722	0.307
(D,F)	1.7047	0.086
(E,F)	0.15095	0.899

Community composition

PERMANOVA shows significant community composition differences among the zones (P-perm = 0.0001 ; Pseudo F = 8.1839) and among the transects of each zone. (P-perm = 0.0001 ; Pseudo F = 4.6301)

We run the Pair-wise test. (Table 7.) presents the results. We find Significant differences among zones A and C (P-perm = 0.0297, unique perms = 35), A and D (P-perm = 0.028, unique perms = 35), A and F (P-perm = 0.0256, unique perms = 35). There were also significant differences between zones C and D (P-perm = 0.0284, unique perms = 35), C and F (P-pern = 0.0285, unique perms = 35), D and F (P-perm = 0.0288, unique perms = 35). Zones A, C, D, and F all show significant differences from each other.

Table 7. Pair-wise tests showing significative differences for community composition values. (PERMANOVA)

Groups	t	P(perm)	Unique perms	P(MC)
A, B	2.0446	0.0671	15	0.0282
A, C	2.2692	**0.0297**	35	0.0099
A, D	3.6651	**0.028**	35	0.0004
A, E	1.2479	0.1989	15	0.2436
A, F	2.6695	**0.0256**	35	0.0057
B, C	1.718	0.1365	15	0.0581
B, D	3.4618	0.0661	15	0.0008
B, E	2.0652	0.3387	3	0.0536
B, F	2.7164	0.104	10	0.0064
C, D	3.8487	**0.0284**	35	0.0002
C, E	2.0551	0.0691	15	0.0224
C, F	3.2552	**0.0285**	35	0.0004
D, E	3.0506	0.0665	15	0.0026
D, F	6.5396	**0.0288**	35	0.0001
E, F	4.311	0.0996	10	0.0007

Table 8. Pair-wise comparison showing significative differences for community composition values. (PERMDISP)

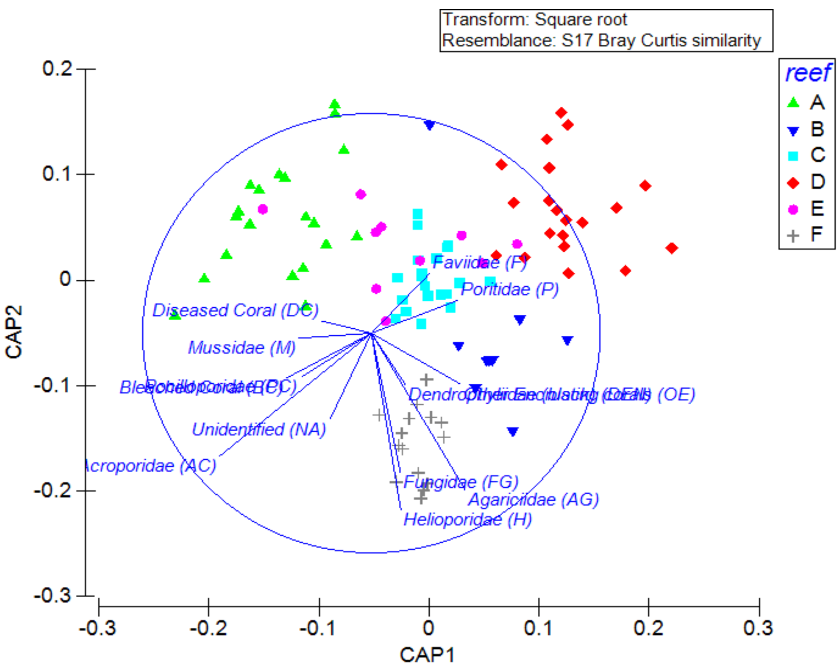
PAIRWISE COMPARISONS

Groups	t	P(perm)
(A,B)	0.45856	0.684
(A,C)	4.3336	0.001
(A,D)	1.9833	0.052
(A,E)	1.2358	0.262
(A,F)	6.7124	0.001
(B,C)	3.5075	0.004
(B,D)	1.8689	0.106
(B,E)	1.2104	0.299
(B,F)	5.2207	0.001
(C,D)	2.482	0.027
(C,E)	2.0738	0.068
(C,F)	1.9927	0.075
(D,E)	0.2444	0.83
(D,F)	4.8267	0.001
(E,F)	3.9667	0.003

The CAP plot shows the differentiation of coral community composition among reefs with different color points, and the vectors show the correlations with each coral family scored. (Figure 13.) The sizes of these first two canonical correlations are reasonably large: $\delta 1 = 0.78$ and $\delta 2 = 0.69$. (Permutation test : $p = 0.0001$ for 9999 permutations) The CAP allows us to visualize better the significant differences among transects A, C, D, and F. The vectors show that some areas are much more representative of certain coral families than others. Zone F has far more Fugidae, Agariciidae, and Helioporidae than any other zone. Faviidae and Poriitidae are most abundant in Zones C and, to a lesser extent, Mussidae and diseased coral in zone A.

We observe differences in dispersion among zones. Zone A has a higher dispersion than C (P-perm = 0.001, t = 4.3336) and F (P-perm = 0.001, t = 6.7124). We observe the same for zone B with zones C and F. (Table 8.)

The vectors show that some areas are much more representative of certain coral families than others. Zone F has far more Fugidae, Agariciidae, and Helioporidae than any other zone. To a lesser extent, Faviidae and Poriitidae are most abundant in Zones C and D. Finally, Acroporidae, Pocilliporidae, and Mussidae are evenly distributed across the zones. To a lesser extent, we observe other unidentified encrusting corals in zone B and diseased coral in zone A.

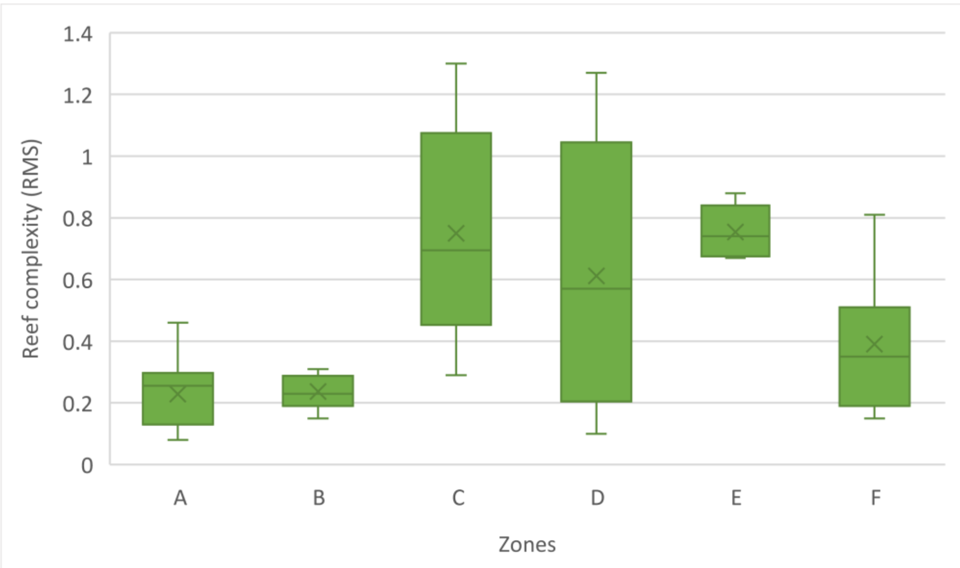


<u>Figure 13.</u> Canonical Analysis of principal coordinates plot showing the community composition dispersion among the different zones.

Reef complexity

PERMANOVA shows significant differences of reef complexity among the transect of each zone (P-perm = 0.0001; Pseudo-F = 89.319) and not among the zones. (P-perm = 0.219 ; Pseudo-F = 1.6419).

The reef complexity data are not normally distributed. We run a Kruskal Wallis with Mann Whitney pairwise test showing significant differences of reef complexity values between the zones. (H = 36.36, p = < 0.001)



<u>Figure 14.</u> Boxplots showing the differences of Reef complexity between the six zones.

Mann Whitney pairwise test shows significant differences among zone A and zones C, D, E, and F also among zone B and zones C, E, and F. Finally, we find differences among E and F. (<u>Table 9.</u>)

<u>Table 9.</u> Mann Whitney pair-wise test showing p-values among the zones, we highlight the p-value lower than 0.05. (alpha value), corresponding to significant differences.

	A	B	C	D	E	F
A		0.7414	**2.96E-07**	**0.01436**	**0.000771**	**0.006594**
B	0.7414		**1.79E-05**	0.08225	**0.002694**	**0.04893**
C	**2.96E-07**	**1.79E-05**		0.1556	0.9729	**0.003178**
D	**0.01436**	0.08225	0.1556		0.8121	0.3771
E	**0.000771**	**0.002694**	0.9729	0.8121		**0.005219**
F	**0.006594**	**0.04893**	**0.003178**	0.3771	**0.005219**	

<u>Table 10.</u> Pair wise comparison showing significative differences for reef complexity values. (PERMDISP)

PAIRWISE COMPARISONS

Groups	t	P(perm)
(A,B)	2.7422	0.007
(A,C)	8.6366	0.001
(A,D)	9.6642	0.001
(A,E)	0.92519	0.456
(A,F)	2.3937	0.016
(B,C)	8.0491	0.001
(B,D)	8.2099	0.001
(B,E)	1.3528	0.209
(B,F)	3.1571	0.002
(C,D)	2.4987	0.01
(C,E)	5.1295	0.002
(C,F)	4.2309	0.001
(D,E)	5.3736	0.001
(D,F)	5.7498	0.001
(E,F)	1.7345	0.092

Out of 15 comparisons, only 3 show no significant differences: A and E (P-PERM = 0.456; t = 0.92519); B and E (P-PERM = 0.209; t = 1.3528) and E and F (P-PERM = 0.092; t = 1.7345). The interquartile range is very large for zones D and C (D: IQR 0.840; C: IQR 0.623), while zones A, B, and E have an interquartile range of less than 0.20. (<u>Table 10.</u>)

Correlation test among reef complexity, coral cover and Shannon index

The correlation value between the three variables is very low. 0.07 between coral cover and diversity, -0.03 between coral cover and reef complexity, and 0.05 between reef complexity and coral diversity. We find no correlation between the three variables. Therefore, there is no direct link between reef complexity, coral cover, and the Shannon index.

DISCUSSION

Many different coral monitoring techniques have been developed and are available in the scientific literature. SfM photogrammetry technique is one of the most recent and allows 3D modeling of the coral reef to study it precisely. Our study aims to determine the spatial differences in coral cover, diversity, and complexity in the selected zones. Then, determine if coral cover and diversity influence reef complexity. Overall, we found significant differences among the zones for the 3 variables, with more robust differences for some zones. It matches our hypotheses, considering the important differences in environmental parameters between these areas. We do not find a correlation between coral cover, diversity, and reef complexity, which is more surprising and refutes our hypothesis.

Coral cover

The pair-wise test (PERMANOVA) give significant differences only among the zone C and D, C and F, and D and F out of 15 comparisons. We expected to observe more significant differences between zones due to the wide variations in environmental parameters. (Table 1) Zone F has the highest coral cover values and medium to high coral diversity values. The reef's favorable conditions can explain this: low exposure to swell due to its northerly position and its depth of around 12m, which is greater than zones C and D. Therefore, zone F is less exposed to storms and high temperatures, making F less exposed to bleaching events (Gadoutsis et al., 2019).

We observe lower coral cover values for zones C and D due to their constant exposure to southern swell and zip currents visible by the presence of trenches parallel to the reef. We only observe the trenches formed by the zip current in these two zones (Madin & Connolly, 2006). Zone D presents coral cover far inferior to zone C despite similar environmental conditions. Zone E seems to have ideal conditions: low swell impact and nutrient supply but it has low values (Hallock, 2001). This could be due to important daily temperature variations due to warmer water passing by the zone when the tide decreases. However, seasonal temperature variation has a more significant influence than daily variation, which does not lead to bleaching events (Scheufen et al., 2017). However, Teleki and Spencer, 2000 showed that corals subjected to frequent high temperatures, such as in channel lagoons corals, are more resistant. In addition, the strong currents of zone E could significantly increase turbidity, which harms corals (Zweifler et al., 2021).

The pair-wise test (PERMDISP) give significant differences for zone A among all the other zones. The test shows the wide dispersion of data from Zone A compared with other zones. Transect replicates in this zone show highly variable values, from 11% to 71% coral cover at the extremes. We hypothesize that this reef has been differently affected by bleaching events notably in 2015, and subsequent cyclonic episodes.

Agisoft Metashape and CPC software presented some limitations during the protocol. The SFM protocol requires a high degree of precision, particularly in swimming speed and meticulous area coverage. This requires ideal sea conditions, which happened rarely, especially in areas C and D exposed to swell. If the protocol is not carry out perfectly, it leads to blurred areas on the orthomosaic, which complicates coral identification (Gigli et al., 2023). In addition, CPC cannot support the enormous size of orthomosaics (+5GB) and requires a drastic reduction in quality. The drop in quality makes coral identification more complicated and sometimes impossible. Our study led to a high percentage of "unidentified" and "other encrusting corals" where we could not identify the family. It would be interesting to test other promising softwares using artificial intelligence, such as Taglab (Pavoni et al., 2022).

Shannon index

The pair-wise test (PERMANOVA) finds only significant differences among three zones.

Differences among zones A and C, C and F were expected, but not between zones C and D, for the same reasons as coral cover. In addition, for both variables, we expect significant differences between northern zones A, B, and F and southern zones C and D, as well as, to a lesser extent zone E, which has different environmental conditions to any other zone.
Pair-wise comparison (PERMDISP) gives significant differences for zone C among all the other zones. These low variations of the Shannon index in high values for zone C, together with the high values of coral cover presented in the previous paragraph, show a good state of health of the reefs in the zone despite the challenging environmental conditions due to waves and current. We hypothesize that the zone varies little from environmental conditions, notably temperature providing stable and favorable conditions to the coral reef.

Community composition

We chose only the 10 most common coral families to assess community composition. PERNANOVA shows significant differences in coral diversity between the different zones. (P-perm = 0.0001; Pseudo F = 8.1839) Zones A, C, D, and F all show significant differences from one another. (Table 6.) Significant differences in coral diversity were observed between zones A and F with northern exposure and zones C and D with southern exposure, validating our initial hypothesis. However, zones A and F significantly differ, and the same appears for zones C and D, raising questions about the drivers' pattern. For the three variables, coral cover diversity and reef complexity, pseudo-F is higher among the zones than among the transects, which shows more significant differences in mean and median inter-zone rather than intra-zone, supporting our hypothesis.

A critical factor in the coral composition of an area is the vulnerability to bleaching events (Gadoutsis et al., 2019). Indeed, the different families of coral are unequally affected by bleaching. The 1998 bleaching event in Seychelles showed high mortality levels in branching coral species (Acroporidae, Pocilloporidae, Helioporidae) and lower mortality in encrusting corals (Faviidae, Poritidae) (Spencer et al., 2000; Bridge et al., 2014). These 2 families of encrusting corals generally have a slow growth rate, and the larger colonies are more resistant to bleaching events (Harris et al., 2014; Koester et al., 2021). The 1998 bleaching event resulted in 95% mortality of branching corals and strongly impacted reefs less than 10 meters deep (Teleki & Spencer, 2000). These episodes had long-term impacts, with differences in recovery speed between different families. In 2005, seven years after the 1998 bleaching episode, the proportion of coral Acropora was only 1%. Other families dominated the first recovery phase, increasing coral cover by 12% after the bleaching event. By 2015, the proportion of Acroporidae had reached 22%, surpassing all the other families combined. (Obura et al., 2015) Bleaching events have probably affected differently the areas studied, which may have influenced the variations in community composition we observe. In addition to bleaching events, a key factor is vulnerability to cyclonic episodes, some areas are more protected than others by their orientation or depth, such as zone F. Cyclones in the western Indian Ocean tend to move in a generally westward direction due to the easterly trade winds zone B would appear to be more frequently affected by cyclones. However, Cyclones have different trajectories and vary highly from year to year (Thorncroft & Hodges, 2001).

Reef complexity

The pair-wise test comparison (PERMDISP) shows that out of 15 comparisons, only three did not show significant differences. The test shows a wide dispersion of reef complexity values within transects, not just between zones. In addition, dispersion is higher than for coral cover and diversity.

Reef complexity values were calculated with the Gwyddion software using the 2D photogrammetry workflow set up by Bayley and Mogg, 2020 in Table 2. (Nečas and Klapetek, 2012) We could not assess 11 of the 30 transects due to their large size (+5GB), which Gwyddion could not support. Of these 11 transects, one is from zone A, three from B, one from C, one from D, three from E and three from zone F. This lack of data affects the statistical power of our results.

In addition, the variations between max and min depths seem to influence the reef complexity values. As explained previously, reef complexity encompasses the three-dimensional structure of the reef, including variations in depth, commonly referred to as rugosity (Alvarez-Filip et al., 2009). Rugosity calculates variations in depth on a smaller scale, meaning all the infractuosites in the reef. This is our interest and not the overall slope of the coral reef. However, we observe the highest reef complexity values on the transects with the greatest slopes (C1, C3, D3, D5).

Correlation between variables

The initial hypothesis is to observe a link between coral cover, cover diversity, and reef complexity. However, the statistics showed no correlation between these variables (-0.03 between coral cover and reef complexity and 0.05 between reef complexity and coral diversity). Although few studies have been carried out on the subject, similar results have already been observed in the scientific literature. Over the last 30 years, most of the world's coral reefs have seen significant declines in coral cover and reef complexity without establishing links between the two variables (Alvarez-filip et al., 2011). While coral cover remains consistent, the degree of reef rugosity can exhibit significant fluctuations (Komyakova et al., 2013). These fluctuations in reef rugosity may be influenced by variations in other reef organisms, such as sponges and soft corals, within the local ecosystem (Diaz and Rutzler, 2001; Halford et al., 2004). However, we find contradictory results in the literature : Graham & Nash, 2013 have shown a positive correlation between coral cover and structural complexity, particularly in branching corals such as Acropora.
The observed differences in reef complexity are complex and seem to result from a large range of abiotic and biological parameters (Alvarez-Filip, 2011).

CONCLUSION

Our study shows significant differences in inter and intra zones with greater differences among the zones. Significant differences among zones differ for the three variables and some zones show no significant differences.

However, we did not establish any link between coral cover, diversity, and complexity. It may be linked to the limitations encountered in the study, as the limited number of transects processed, varying from one area to another. It would be interesting for future studies to use different software to assess reef complexity, such as the AI-powered Taglab.

Structure from motion photogrammetry saves much time in fieldwork and enables much greater distances to be covered than with more traditional techniques (Line intercept transect/quadrat). Although this technique requires more time to process the data, the time savings are significant.

SfM requires precision during the protocol and ideal environmental conditions, which are only sometimes the case. Lack of precision directly impacts the 3D model, creating blurred areas that affect accuracy. Although SFM has been used in coral monitoring for 10 years, this technique is constantly improving, and coupled with AI software such as Taglab or drone photogrammetry; it might cover precisely extensive areas.

Repeating this coral monitoring at least every year is essential to observe variations in coral cover, diversity, and complexity and to see the impact of bleaching events on these variables. Further studies can be made, notably between reef complexity values and fish richness and abundance.

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