frontiers | Frontiers for Young Minds

An Alien place on Earth: The Red Sea as a model for Future Oceans

Edited by
Rúben M. Costa and Christian R. Voolstra

ISSN 2296-6846
ISBN 978-2-83251-829-8
DOI 10.3389/978-2-83251-829-8

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

About Frontiers for Young Minds

Frontiers for Young Minds believes that the best way to make cutting-edge science discoveries available to younger audiences is to enable young people and scientists to work together to create articles that are both accurate and exciting. That is why distinguished scientists are invited to write about their cutting-edge discoveries in a language that is accessible for young readers, and it is then up to the kids themselves – with the help of a science mentor – to provide feedback and explain to the authors how to best improve the articles before publication. As a result, Frontiers for Young Minds provides a collection of freely available scientific articles by distinguished scientists that are shaped for younger audiences by the input of their own young peers.

What are Frontiers for Young Minds Collections?

A Collection is a series of articles published on a single theme of research and curated by experts in the field. By offering a more comprehensive coverage of perspectives and results around an important subject of research, we hope to provide materials that lead to a higher level of understanding of fundamental science. Frontiers for Young Minds Collections will offer our international community of Young Minds access to the latest and most fundamental research; and, most importantly, empowering kids to have their say in how it reaches their peers and the wider public. Every article is peer reviewed according to the Frontiers for Young Minds principles. Find out more on how to host your own Frontiers for Young Minds Collection or contribute to one as an author by contacting the Frontiers Editorial Office: kids@frontiersin.org

An Alien place on Earth: The Red Sea as a model for Future Oceans

Collection editors
Rúben M. Costa — King Abdullah University of Science and Technology, Saudi Arabia
Christian R. Voolstra — University of Konstanz, Germany; King Abdullah University of Science and Technology, Saudi Arabia

Citation
Costa, R. M., Voolstra, C. R., eds. (2023). *An Alien place on Earth: The Red Sea as a model for Future Oceans*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-83251-829-8

Cover image
FourPlus Studio

Participating sections

Biodiversity

About this collection

Our oceans are changing. Elevated greenhouse gases caused the increase of Earth's average temperature (or global warming) and contributed to what we now know as climate change. This in turn has a big influence on the oceans and the organisms that live in them. Given that oceans are changing so rapidly, how are marine organisms affected by this? Can they adapt? How can we study those adaptations? Where should we start?

In between Africa and Asia, in the Middle East region, lies a vast mass of seawater connected to the Indian ocean by its southern end. This water body is called the Red Sea, some say because of the presence of a reddish-brown cyanobacteria in its waters, others say because red was the color representing "south" (of the Mediterranean civilization) in ancient times. Its location makes it a unique environment with high temperatures and salinities (the amount of salt dissolved in water), creating a complex environmental gradient from north to south in its more than two thousand kilometers of length. Despite these harsh, almost alien conditions, the Red Sea is home to large green mangroves and seagrass meadows, more than a thousand species of fish (many of them unique to the Red Sea), hundreds of species of corals and countless invertebrates. At the microscopic level, we make new discoveries every day so that our knowledge on the diversity of bacteria, microalgae, and viruses is constantly increasing.

But if it is so difficult to sustain life in the Red Sea, how do all these organisms still prosper in it? This is one of many questions scientists are trying to answer by studying how abiotic factors such as temperature, salinity and nutrients of the Red Sea can affect its organisms (or biota). Moreover, due to its extreme conditions, the Red Sea can also act as a unique laboratory to study and learn about the future impacts of climate change on ecosystems: it represents a time machine that allows us to look into the future of tropical oceans and lets us understand how organisms thrive in environmental extremes.

The aim of this collection is to explore the current knowledge we have on the Red Sea biodiversity and its adaptability to environmental change. From coral reefs and the mutual beneficial relationships (symbiosis) between organisms, to seagrasses and brine pools, we aspire to learn how life can find a way to flourish even when the odds seem to be against it. More importantly, by understanding the present conditions of the Red Sea, we might be able to predict how organisms from other regions will adapt to fast changing climate.

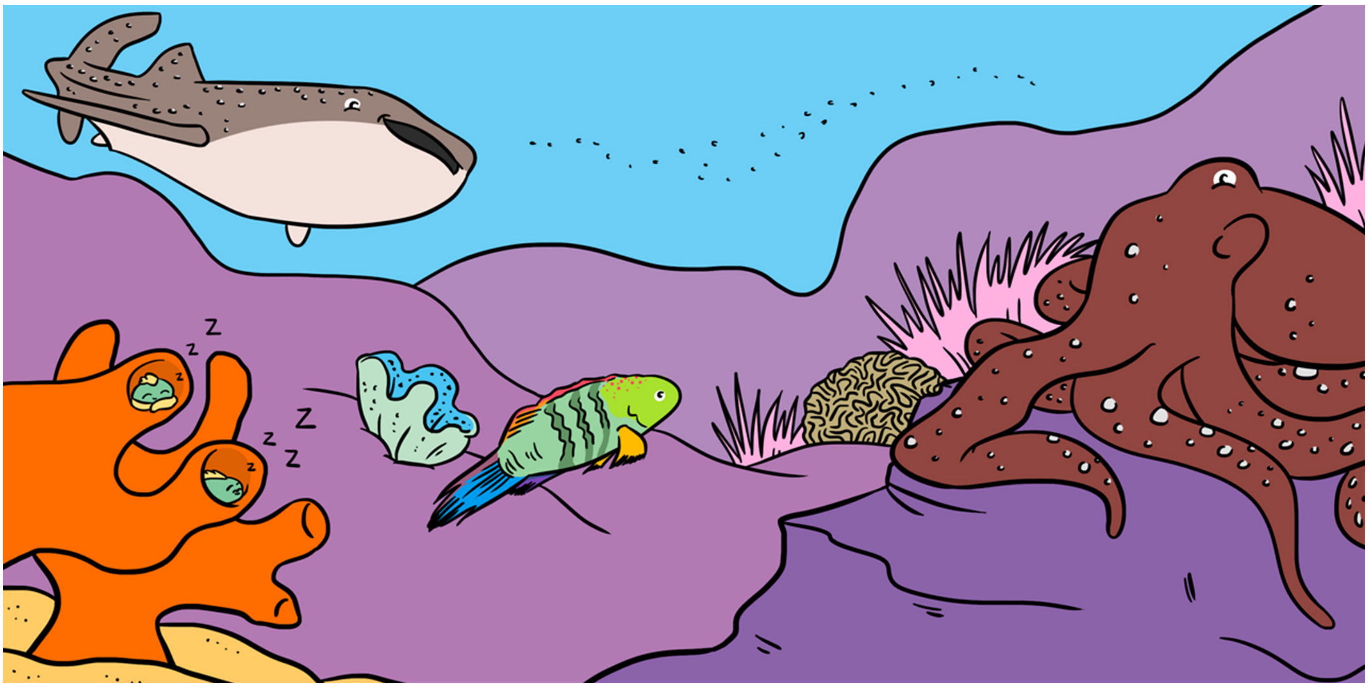
In loving memory of Noura Zahran,
a shining star from the Red Sea.

Table of contents

Chapter 1 - The incredible life within the red sea

Chapter 2 - Lessons from the red sea: From local animals to distant aliens

BIODIVERSITY
Published: 15 October 2021
doi: 10.3389/frym.2021.571379



WHAT LIVES IN THE OCEAN? AN INTRODUCTION TO THE BIODIVERSITY OF THE RED SEA

Marcelle M. Barreto**, Marcela Herrera and Manuel Aranda

Biological and Environmental Science and Engineering Division/Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

YOUNG REVIEWER:

FABIAN
AGE: 14

Have you ever wondered how many species are out there? Biodiversity refers to all the different plants and animals in the world, and it is incredibly important for our well-being. All organisms have a role in the environment, and healthy ecosystems depend on high biodiversity. For example, tiny plant-like organisms living in the ocean are responsible for most of the oxygen we breathe. Mangroves and coral reefs are homes for many wonderful fish, and they protect our coastlines from storms. The Red Sea is one of the world's most biodiverse oceans. It is a unique home to many different species that cannot be found anywhere else in the world. Scientists have estimated that there are around 29 species of sharks, 17 of whales and dolphins, 5 of marine turtles, 1,078 of fish, 359 of hard corals, and many more invertebrates. Imagine all the tiny microorganisms that we cannot see!

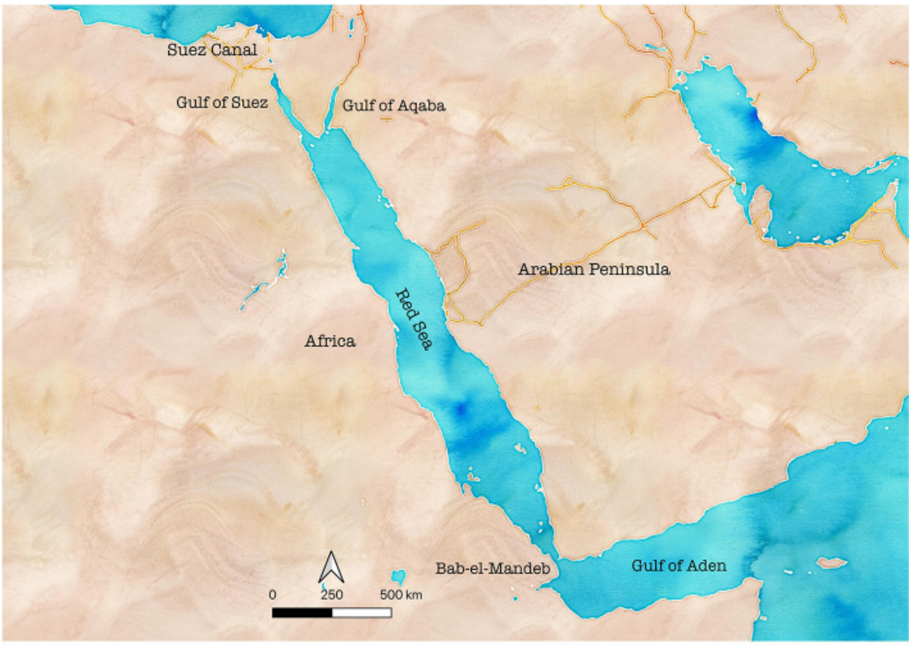


Figure 1

Figure 1

Map of the Red Sea and its most important geographic features. Map tiles by Stemen Design, under CC BY 3.0. Data by OpenStreetMap, under CC BY SA.

THE RED SEA AND ITS UNIQUE BIODIVERSITY

The Red Sea is a large body of water that separates Africa and Asia. It is connected to the Mediterranean Sea via the man-made Suez Canal, and to the Indian Ocean through a very narrow opening in the Gulf of Aden called Bab-el Mandeb (Figure 1). The Red Sea started forming due to a combination of events: the movement of the African and Arabian tectonic plates, and a change in sea level during a major ice age about 30 million years ago. The Red Sea became shallow and isolated and eventually limited the movement of animal and plants to the Indian Ocean. Unlike many seas, the Red Sea does not get water from rivers, so the water is very salty. It is actually one of the saltiest seas on Earth! It is also very warm, as the climate in this region of the world is extremely hot and sunny. Conditions in the nearby Indian Ocean are very different from those in the Red Sea, so species that came to the Red Sea needed specific **adaptations** to allow them to live there [1]. Because of this, the Red Sea has many species that can only be found in the Red Sea and nowhere else in the world!

ADAPTATIONS

Special characteristics of an organism that help the organism survive in its environment.

WHERE THE OCEAN MEETS THE LAND

Just like we have forests on land, we also have trees and shrubs growing in the salty water near shore, in hot places like the Red Sea. These are called mangrove forests and they are very important because they protect the shore from big waves and are also home to many animals. Mangrove trees are different from other types of trees because they have special adaptations that allow them to live in the sea. Their roots have many pores to help them breathe, which is very important in their low-oxygen environment. They also have various ways to remove excess salt (Figure 2A). Some species of mangrove trees can expel more than 90% of the salt absorbed from the seawater! There are also other plants growing in the sea. Sea grasses live under water and provide shelter and food for organisms like turtles and sea cows. Sea grasses also have an important role in protecting the coast from **erosion** because their leaves soften the force of waves and help trap sediments such as sand or mud.

EROSION

The process of removing soil, rock, and sediments by natural forces such as water flow or wind.

ECOSYSTEM

A community of many different organisms living together and interacting with their physical environment.

A CORAL REEF WORLD

Coral reefs (Figure 2B) are very special **ecosystems** that can only be found in certain areas of the world. Less than 1% of all the world's oceans are covered with coral reefs! The Red Sea contains one of the longest coral reef systems in the world, extending almost 2,000 km per side [2]. Coral reefs are primarily made of corals, which are actually colonies of tiny animals called polyps. Together with sea anemones and jellyfish, corals belong to a group of organisms called the Cnidaria. There are many different types of corals, but all can be grouped in one of two types: hard corals or soft corals. Hard corals, as the name suggests, have a hard skeleton, while soft corals do not. Corals can also have many different shapes and colors! Amongst the most abundant hard corals in the Red Sea is the brain coral (Figure 2C). Can you see why it has this name?

INVERTEBRATES

Animals that do not have backbones or internal skeletons.

Coral reefs are home to many other sea creatures that are important for keeping reef communities in balance. Every animal has an important role in the reef ecosystem. Many of these animals are **invertebrates**, which means they do not have backbones or internal skeletons. Echinoderms, for example, live on the sea floor and cannot swim (Figure 2D). You have probably seen them: sea stars, sea urchins, sea cucumbers, feather stars, and brittle stars. All these animals are covered with tiny spines that protect them against predators, but even more fascinating is that they have something called radial symmetry. This means that you can divide their bodies into identical parts, like cutting a pizza into equal slices! Echinoderms protect reefs by eating algae and preventing them from growing over corals, which can harm corals by blocking the sunlight. In addition, some echinoderms live burrowed in the sand, so by moving around they help increase the amount of oxygen in the sediment, allowing other organisms to live there.

EXOSKELETONS

External skeletons that support and protect the bodies of some invertebrate animals.

Well-known crustaceans can also be found in the Red Sea coral reef (Figure 2E). Have you ever seen crabs, shrimp, or lobsters before? These animals have **exoskeletons**, which are external skeletons that support and protect their bodies. One cool example of coral reef crustaceans is the pistol shrimp. These shrimps have large pincers, one larger than the other, with which they can produce a snapping sound.

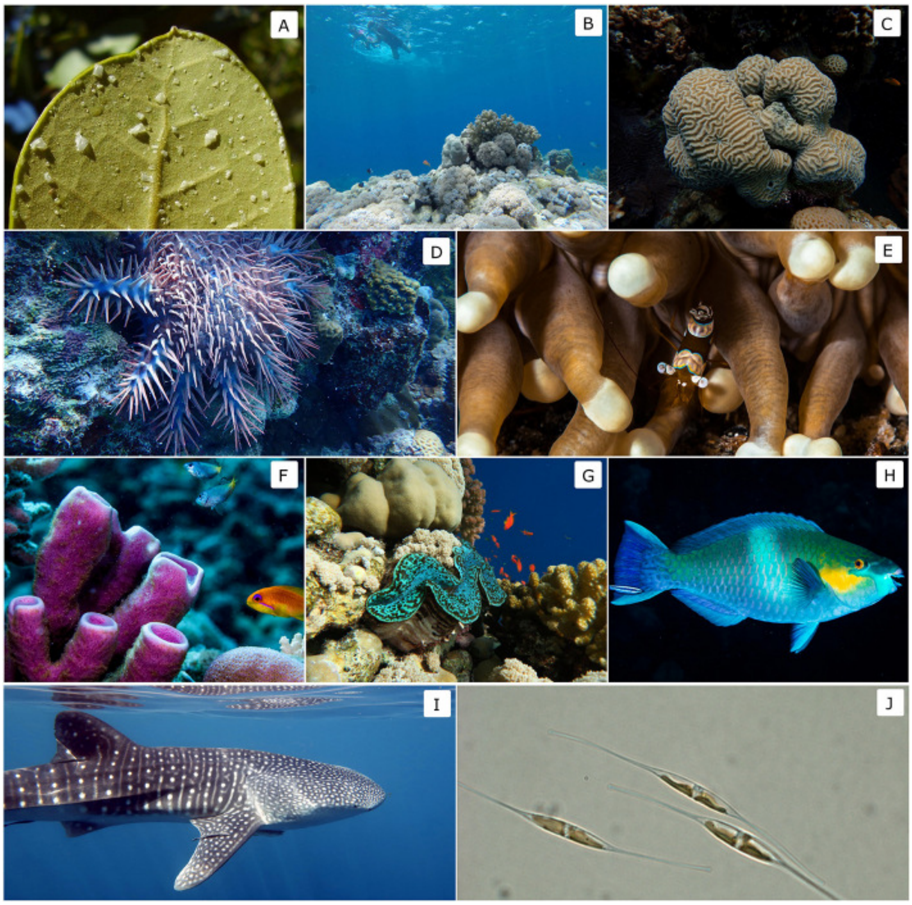


Figure 2

Figure 2

Biodiversity in the Red Sea. **(A)** Salt excretion under mangrove leaf. **(B)** Coral reef ecosystem. **(C)** Brain coral. **(D)** Crown-of-thorns sea star. **(E)** Shrimp. **(F)** Marine sponge. **(G)** Giant clam. **(H)** Rusty parrotfish. **(I)** Whale shark. **(J)** Diatom, a type of plankton (Photo credits: **A**: Peripitus, Wikimedia commons; **B–D**: Marcelle Muniz Barreto; **E,F,H**: Morgan Benett-Smith; **G**: Susann Rossbach; **I**: Royale Hardenstine; **J**: Francisco Aparicio).

In fact, if you go snorkeling in the Red Sea, you will probably hear it! They use this pincer movement to stun their prey.

Some of the most abundant and funky animals in the Red Sea coral reef belong to the group Porifera, the sponges. Sponges are very simple animals that spend their entire lives attached to one place in the reef. Their bodies are full of pores, which are small openings through which they filter particles of food and oxygen from the water. Sponges come in many different shapes and colors. Because many are shaped like hollow tubes, they make good homes for tiny animals such as shrimp, worms, and fish (Figure 2F). You can see many fish sleeping inside sponges at night!

Animals like sea slugs, sea snails, bivalves such as clams and mussels, octopuses, and squids belong to the group Mollusca. They are soft-bodied but, in the case of bivalves, grow a hard shell to protect themselves. In the Red Sea coral reef, you can easily see a famous mollusk: the giant clam (Figure 2G). The bright blue tissue peeking out between the shells makes giant clams very easy to identify. These clams live in a **symbiotic** relationship with tiny algae, which generate energy from photosynthesis and give it to the clam. With this extra

SYMBIOTIC

A close relationship in which both organisms benefit.

energy, giant clams can grow bigger than other clams. Another cool example is the mimic octopus, which can change its color to blend in with the surroundings and squirt out ink to distract predators. These octopuses can even grow back their arms if they lose them!

Unlike the invertebrates, fish have internal skeletons and backbones—they are vertebrates. Fish also have gills that enable them to obtain oxygen from the water. All fish are important for coral reef health, because they have different functions. Red Sea plant eaters, like parrotfish (Figure 2H) and surgeonfish, eat various types of algae and help keep them in check so they do not grow over corals. Meat eaters like groupers and sharks keep populations of smaller fish and other organisms in balance.

FROM BIG TO SMALL

Coral reefs contain only a part of the Red Sea's biodiversity. Many marine organisms live in the open ocean, ranging from microscopic plants to very big animals. Sharks, for example, are one of the oldest vertebrates on Earth. Scientists think the first sharks appeared more than 400 million years ago! In the Red Sea, there are 29 known shark species [3]. One of them is the whale shark (Figure 2I). The whale shark is actually the biggest fish in the world and can measure almost 20 m, which is bigger than a city bus [4]! They have spots all over their bodies in patterns that are specific for each individual.

Marine mammals like whales and dolphins can also be found in the Red Sea. They belong to a group called Cetacea, which can be divided into two groups: baleen whales, which use the bristles in their mouths to filter prey from the water, and toothed whales, which use teeth to catch their prey. There are around 17 species of cetaceans in the Red Sea [5]. These animals can use **echolocation**—they use reflected sound waves to map their surroundings, allowing them to find prey and predators and to move around in the environment. Noise pollution from boat traffic or the oil industry can be dangerous to cetaceans because it can affect their ability to echolocate.

ECHOLOCATION

Technique used by some animals (like dolphins and bats) to navigate their environment. They emit soundwaves and listen to the echoes of those sounds to identify objects near them.

What about the organisms we cannot see? The ocean is full of organisms so tiny that you need a microscope to see them. They are called plankton. They are very diverse and abundant, with a single teaspoon of seawater containing thousands of them! Phytoplankton are a type of plankton that perform photosynthesis. They are essential for all marine life, because they are the basis of the marine **food web**. Phytoplankton are also responsible for much of the oxygen we breathe. Zooplankton are either tiny animals that live their whole lives as plankton (Figure 2J) or larvae, which are the young stages of other, bigger animals such as crustaceans, clams, and fish. Zooplankton perform the largest daily migration on the planet: during the day they are in deeper waters, protected from predators and excessive

FOOD WEB

The energy relationships among organisms, basically who eats whom in an ecosystem.

sunlight, and then they rise to the surface at night, where they can feed on phytoplankton.

As you can see, the Red Sea is full of life. Having many species is a very important quality because it helps an ecosystem to resist disturbances better and recover from them faster. And as you have learned, all the species in the Red Sea have their unique functions, which means we need as many species as we can to keep the Red Sea, and other oceans, healthy! That is why getting to know these species better and protecting them is essential, to guarantee the well-being of both ecosystems and people. There are a few things you can do to help the Red Sea and our oceans in general. Reducing use of single use plastics is one of them. Marine plastic pollution is a big problem for animals in the sea. They can mistake it for food and eat it, or get entangled in it. You can also ask the adults in your life to buy seafood that is sustainably farmed or caught. Just check for eco-labels and certifications! Can we count on you to help?

REFERENCES

1. DiBattista, J. D., Howard Choat, J., Gaither, M. R., Hobbs, J. P. A., Lozano-Cortés, D. F., Myers, R. F., et al. 2016. On the origin of endemic species in the Red Sea. *J. Biogeogr.* 43:13–30. doi: 10.1111/jbi.12631
2. Berumen, M. L., Hoey, A. S., Bass, W. H., Bouwmeester, J., Catania, D., Cochran, J. E. M., et al. 2013. The status of coral reef ecology research in the Red Sea. *Coral Reefs* 32:737–48. doi: 10.1007/s00338-013-1055-8
3. Spaet, J. L. Y. 2019. "Red sea sharks—biology, fisheries and conservation," in *Oceanographic and Biological Aspects of the Red Sea,* eds N. M. A. Rasul and I. C. F. Stewart (Cham: Springer International Publishing). p. 267–80.
4. Borrell, A., Aguilar, A., Gazo, M., Kumarran, R. P., and Cardona, L. 2011. Stable isotope profiles in whale shark (*Rhincodon typus*) suggest segregation and dissimilarities in the diet depending on sex and size. *Environ. Biol. Fishes* 92:559–67. doi: 10.1007/s10641-011-9879-y
5. Costa, M., Fumagalli, M., and Cesario, A. 2019. "Review of Cetaceans in the Red Sea," in *Oceanographic and Biological Aspects of the Red Sea,* eds N. M. A. Rasul and I. C. F. Stewart (Cham: Springer International Publishing). p. 281–303.

SUBMITTED: 10 June 2020; **ACCEPTED:** 14 September 2021;
PUBLISHED ONLINE: 15 October 2021.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Barreto MM, Herrera M and Aranda M (2021) What Lives in the Ocean? An Introduction to the Biodiversity of the Red Sea. Front. Young Minds 9:571379. doi: 10.3389/frym.2021.571379

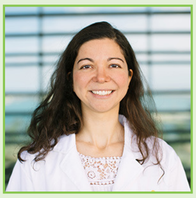
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

FABIAN, AGE: 14

Fabián is a world traveling, 14 year old, ninth grade polyglot who loves the ocean and being creative. His hobbies are: mountain biking, lego, inventing, acting, and reading, but especially reading. He loves being a part of the Frontiers for Young Minds program and looks forward to next year!

AUTHORS



MARCELLE M. BARRETO

I was always interested in nature as a child, so choosing environmental sciences as a career was not a surprise to anyone. Now I am a Ph.D. student, focusing on coral reefs. I am exploring new strategies to try to save coral reefs from current threats, such as climate change. When I am not at work, you can usually find me traveling, dancing, working on handcraft projects and playing my ukulele. *marcelle.munizbarreto@kaust.edu.sa

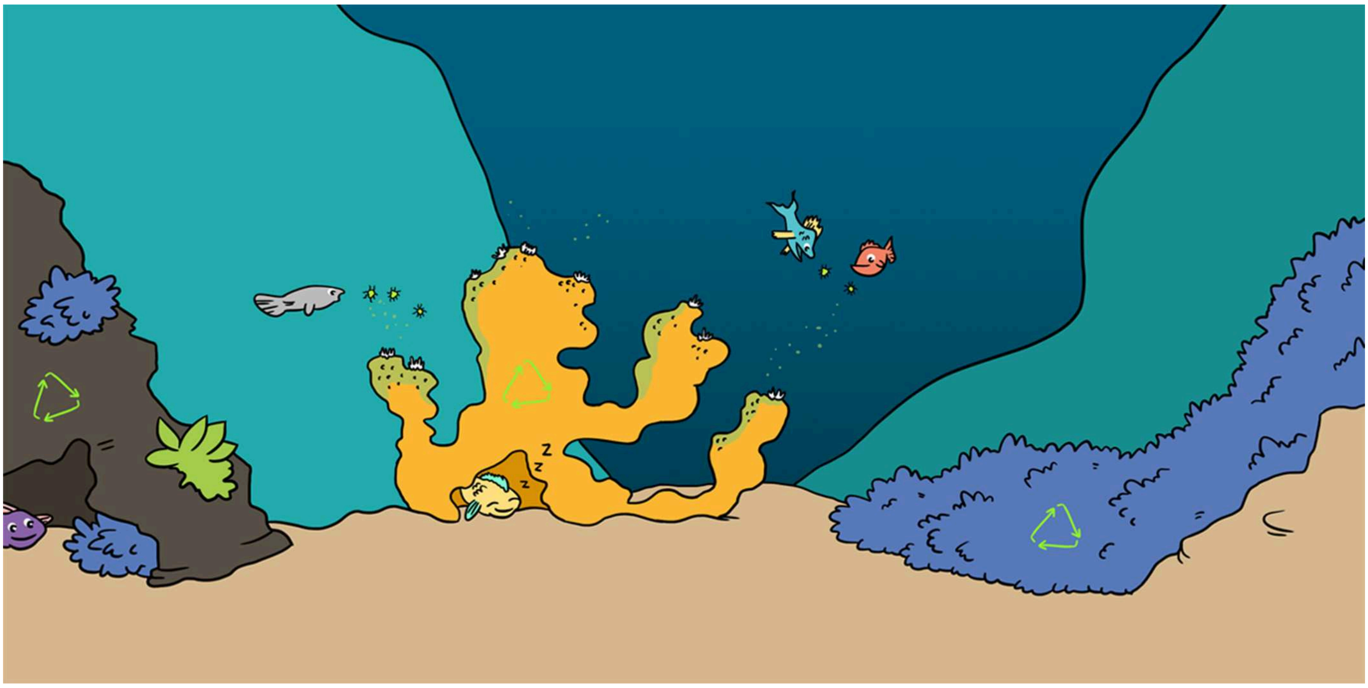
MARCELA HERRERA

I am a marine scientist who wants to understand how different organisms adapt to the changing conditions of our oceans. I love to travel, explore the underwater world, and try new foods.

MANUEL ARANDA

I am a Biology Professor at the King Abdullah University of Science and Technology in Saudi Arabia. I study why corals are so sensitive to climate and how we might be able to help them. In my free time I like to cook and to play Playstation with my son.

BIODIVERSITY
Published: 17 December 2019
doi: 10.3389/frym.2019.00143



WHY ARE CORAL REEFS HOTSPOTS OF LIFE IN THE OCEAN?

Nils Rädecker * ***and Claudia Pogoreutz***

Biological and Environmental Science and Engineering Division, Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

YOUNG REVIEWERS:


ABRAHIM


JIHAD


JOUD


SAMAR


SULTAN

The tropical ocean contains very little food or nutrients. Like life in a desert, life in the tropical ocean is difficult for all organisms. Yet, coral reefs are colorful oases full of life in the middle of this marine desert. How can millions of species call coral reefs their home? All organisms living there play their roles in recycling the small amounts of food and nutrients that are available. Because nothing is ever truly wasted, coral reefs can flourish in a marine desert that has hardly any food. Although coral reefs existed on this planet long before the dinosaurs, they are facing serious problems today. Warming oceans can harm corals, leading to the loss of coral reefs. However, corals in the northern Red Sea are very resistant to warm temperatures. Some scientists believe that these Red Sea reefs may be able to survive even when reefs are disappearing elsewhere around the world.

OASES IN A MARINE DESERT

NUTRIENT

A substance required for the survival and growth of an organism.

Every living creature needs energy and **nutrients** to live and grow. Because of this, organisms living in places where food and nutrients are scarce need to be creative to survive. Similar to deserts on land, the tropical ocean is very low in food and nutrients. This is also the reason why the tropical ocean appears so clear and blue: very few creatures grow there. Yet, coral reefs form vibrant, colorful oases full of life—right in the middle of these ocean deserts. Although coral reefs only cover a very small part of the seafloor in the tropical ocean, they are home to a quarter of all known marine species. Coral reefs are also very important for millions of people, because fishes and other reef animals are important food sources, and the reefs themselves help protect coasts from storms and waves.

The famous scientist and explorer Charles Darwin was one of the first to wonder how so many different animals and plants could live in coral reefs even though the surrounding water contains so little food and nutrients [1]. Now, after more than a century, scientists are finally beginning to understand this so-called "Darwin Paradox." In this article, we look at how millions of species of coral, fishes, invertebrates, algae, and microorganisms each play their role in making coral reefs true oases in the marine desert.

CORALS: ENGINEERS OF THE REEF

SYMBIOSIS

Two different organisms living in a close relationship. In the case of corals, both corals and their algae benefit from the symbiosis. However, not all symbiotic relationships are good for all organisms. Parasitic tapeworms, for example, live in the gut of other organisms and steal food and nutrients from them.

PHOTOSYNTHESIS

A process by which green plants and algae produce their own food. In this process, the energy of the sunlight is used to make sugars from carbon dioxide (CO_2) and water (H_2O).

There would not be coral reefs without stony corals. Corals are very different from most animals, because they grow attached to the seafloor and live in colonies. Each colony is made up of thousands of little animals, called polyps. Every polyp has its own mouth and tentacles to catch food, like the tiny shrimp and worms swimming in the sea. Together, these polyps build a skeleton made of limestone, so that they can grow and be protected from predators. Over hundreds to thousands of years, these skeletons grew into the massive underwater structures that form the coral reefs we see today (Figure 1).

Like all other animals, corals need food and nutrients to grow and also to build reefs. So, how do corals survive and grow in an ocean where there is hardly any food to catch? The answer is as fascinating as it is simple: they can grow their own food! This is because corals live in **symbiosis** with other organisms in and on the coral's body, like bacteria, algae, and fungi. These symbiotic relationships are very important to keep the coral animal fit and healthy. For example, corals form a very special partnership with tiny algae that live within the cells of the coral. These algae can perform **photosynthesis**, a process by which the algae capture light energy from the sun and use that energy to turn carbon dioxide (CO_2) into sugars. The sugars are their source of energy. The algae produce so much sugary food that they can even share a large part of it with the coral. As the corals consume the sugars,

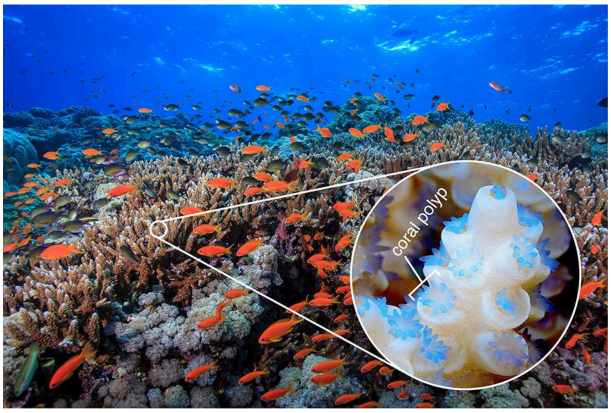


Figure 1

Figure 1

Coral reefs in the Red Sea are colorful and full of life. These reefs are home to millions of species, from tiny bacteria to sharks. Coral reefs are built from the limestone skeletons of corals. Each coral consists of hundreds to thousands of animals. These animals are called polyps. The polyps live together in one colony. Each polyp has a mouth and tentacles to catch food from the ocean. In addition, small algae living inside the corals produce sugars as food for themselves and the coral. Photo credit: Tane Sinclair-Taylor.

they produce more CO_2 for the algae. This exchange of sugars and CO_2 between the coral and their algae allows these symbiotic partners to efficiently recycle energy and nutrients (Figure 2A). Therefore, corals do not need to catch much prey from seawater [2]. This powerful partnership between corals and tiny algae is the reason why coral reefs have survived on this planet for hundreds of millions of years. Over time, the coral reefs continue to grow. Today, some coral reefs are so large they can even be seen from space, like the 2,300 km long Great Barrier Reef in Australia.

WHO EATS WHOM ON THE CORAL REEF?

Corals and algae are not the only organisms living on corals reefs. Millions of other species of animals, plants, and microbes call reefs home, too. Unlike corals, most creatures on a coral reef do not live in a symbiosis with little algae that produce sugar for them. They need to find their own food. So how do all these species survive, if there are so few nutrients in the surrounding water? Similar to the partnership between corals and their algae, food and nutrients are efficiently recycled over and over again on the entire coral reef. The **food web** of coral reefs is so complex that nothing is ever wasted: one creature's leftovers are a feast for another creature (Figure 2B). Corals and their algae are part of the fuel that drives the coral reef food web. The algae produce so much sugar that not even the coral can eat all of it. The left-over sugar that the coral will not eat is used to produce a slimy mucus. Some of the mucus covers the coral and helps protect it from diseases or from drying out during low tide. But a lot of the mucus ends up in the seawater, too. Because the mucus contains a lot of sugar, bacteria and other microbes eat it. The bacteria in turn get eaten by small critters, like crabs, shrimp, snails, and worms living in the water or on the seafloor. Next, reef fishes feed on these small organisms. At night, the fishes rest and sleep, well-hidden in the branches of the coral. As the fish digest the foods they have eaten, they eventually poop. The poop returns nutrients into the seawater

FOOD WEB

The connections between organisms, in terms of how they get their food and nutrients and how they pass food and nutrients on to other organisms.

around the coral. These nutrients are quickly taken up again by algae within the coral, helping them grow and perform photosynthesis. In this way, the feeding and pooping of many animal species on the reef creates an endless loop, in which nutrients are re-used [3]. With so many different species feeding and pooping on a coral reef, there are many endless nutrient loops, recycling food so efficiently that hardly any nutrients are ever lost. This is why millions of species on a coral reef can survive, even though the seawater around them contains so little food.

CORAL REEFS IN DANGER

Coral reefs have lived in the tropical oceans for hundreds of millions of years. Recently, however, increasing numbers of coral reefs around the world have started to die and disappear. The reason behind this ultimately boils down to growing human populations [4]. People use coral reefs as food sources. With more and more people living close to coral reefs, a lot of fish are taken from the reefs. As a consequence, many coral reefs are badly overfished. With fewer and smaller fish on the reefs, the feeding and pooping loops are disturbed, which changes the re-use of food and nutrients. Also, because there are fewer algae-eating fish, these fish cannot keep the algae in check. Some of these algae can then overgrow and harm corals.

However, the greatest problem for coral reefs is climate change [4]. Climate change makes the oceans warmer. While corals like tropical warm waters, they do not like it too warm. When the sea around corals gets too warm, the tiny symbiotic algae inside the coral will provide less or no sugars to the coral. In addition, the algae will also produce substances that may damage the tissues of the coral. Thus, the algae are no longer helpful for the coral when the water gets too warm, so the coral has no other choice but to get rid of these algae by releasing them into the sea. Without the tiny algae inside, the corals lose their colorful appearance and the white skeleton inside corals becomes visible. This is called coral bleaching. Without the algae, the bleached coral is also cut off from its main food supply: the sugars made by the tiny algae. Bleached corals, therefore, become weak very quickly, and will eventually starve and die if the water stays too warm for too long [4].

However, it is not just the corals that have a problem when the ocean gets too warm. Without corals, all the other species living on coral reefs lose their homes as well. As a result, entire coral reef **ecosystems** are slowly disappearing worldwide. This directly affects the lives of many people who depend on healthy coral reefs: fishermen have fewer fish to catch and fewer tourists come to see the reefs. Without healthy coral reefs, fishermen, hotel managers, diving instructors, and many other people could lose their jobs and income. Thankfully, there are many ways to protect coral reefs. For example, fishing bans can help

ECOSYSTEM

A community of organisms and the environment they live in.

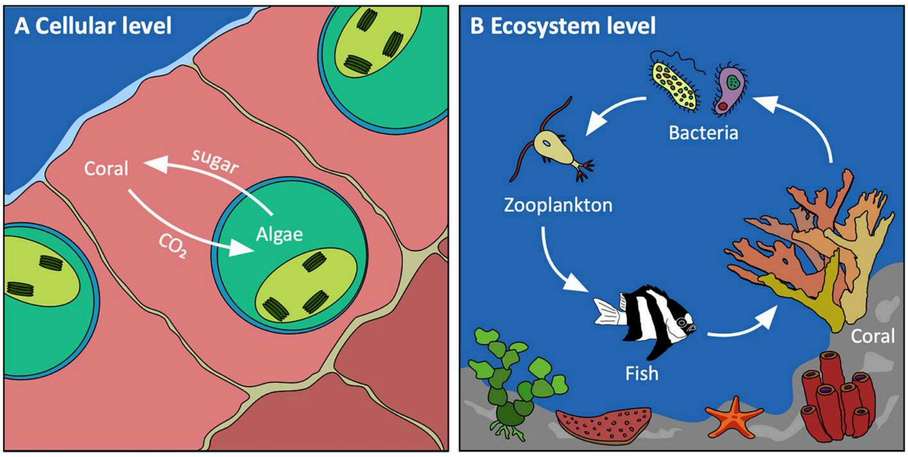


Figure 2

Figure 2

Corals reefs are full of life because they very efficiently recycle the small amount of food and nutrients available in the tropical ocean. **(A)** Corals and the algae living inside the corals help each other. The algae produce sugar, which the corals eat. In digesting the sugar, corals produce CO_2, which can be used by the algae to produce more sugar. **(B)** Corals also support other reef organisms. The nutrients corals release are eaten by bacteria and other small organisms, and these organisms are then eaten by larger organisms. The poop from the larger organisms returns nutrients to the environment. In this way, food and nutrients are recycled in the complex food web of the reef.

create safe areas for fish to grow. This way, future generations will also be able to catch fish on coral reefs.

ARE RED SEA CORAL REEFS TOUGHER THAN OTHER REEFS?

The Red Sea is one of the hottest seas on our planet and is very low in nutrients. Even under these extreme conditions, vibrant coral reefs can be found along nearly the entire Red Sea coast. Red Sea coral reefs are very different from most other reefs around the world. Many of the species found on Red Sea reefs can be found nowhere else on the planet. Further, while most other corals bleach when seawater temperatures go higher than 30°C, corals in the northern Red Sea survive warmer temperatures without bleaching. Scientists from around the world are currently trying to find out why these Red Sea corals are so heat resistant. Maybe it is the environmental conditions of the Red Sea that make the corals that live there tougher? Maybe Red Sea corals could be transplanted to other regions, to replace the reefs that have died from ocean warming? While we are only beginning to answer these questions, Red Sea coral reefs promise to be a refuge for many coral species threatened elsewhere [5].

A FUTURE FOR CORAL REEFS

Coral reefs are fascinating hotspots of life in the ocean. Even after centuries of research, there is still a lot to learn about these reefs. Scientists keep finding new species and even discover coral reefs in places where they never expected them in the first place. However, climate change and overfishing are severe threats to these ecosystems. Therefore, the future of coral reefs will depend on our actions to save them. All of us can help do their part to help protect coral reefs: for example, eating less coral reef fish, recycling plastic waste so it does not end up in the ocean, or reducing energy consumption to slow climate change. This way, coral reefs of the future may remain colorful oases full of life in a marine desert.

ACKNOWLEDGMENTS

First and foremost, we would like to thank the team of young reviewers for their supportive and helpful feedback. We would also like to thank Ruben M. Costa as well as Christian R. Voolstra for initiating and coordinating the Frontiers for Young Minds Red Sea collection. Further, we would like to thank Tane Sinclair-Taylor for providing the stunning photos for this manuscript.

REFERENCES

1. Darwin, C. 1842. *The Structure and Distribution of Coral Reefs*. London: Smith, Elder and Co.
2. Muscatine, L., and Porter, J. W. 1977. Reef corals: mutualistic symbioses adapted to nutrient-poor environments. *Source Biosci.* 27:454–60. doi: 10.2307/1297526
3. Wild, C., Huettel, M., Klueter, A., Kremb, S. G., Rasheed, M. Y. M., and Jørgensen, B. B. 2004. Coral mucus functions as an energy carrier and particle trap in the reef ecosystem. *Nature* 428:66–70. doi: 10.1038/nature02344
4. Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B. C., et al. Coral reefs in the anthropocene. *Nature* 546:82–90. doi: 10.1038/nature22901
5. Osman, E. O., Smith, D. J., Ziegler, M., Kürten, B., Conrad, C., El-Haddad, K. M., et al. 2018. Thermal refugia against coral bleaching throughout the northern Red Sea. *Glob. Chang. Biol.* 24:e474–848. doi: 10.1111/gcb.13895

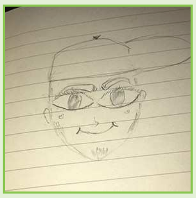
SUBMITTED: 25 June 2019; **ACCEPTED:** 27 November 2019;
PUBLISHED ONLINE: 17 December 2019.

EDITED BY: Christian Robert Voolstra, Universität Konstanz, Germany

CITATION: Rädecker N and Pogoreutz C (2019) Why Are Coral Reefs Hotspots of Life in the Ocean? Front. Young Minds 7:143. doi: 10.3389/frym.2019.00143

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS



ABRAHIM

I am your average teenager. I like sports, music, but science has been a passion of mine since I was a child.

JIHAD

My name is Jihad. I like music and have participated with KAUST since 2015.

JOUD

Art is my life. I am interested in drawing and crafts. I love arranging flowers. Interior design is my passion. I like the view of the sunrise and going to the beach. I love horse riding.

SAMAR

Someone reading and trying #reader.

SULTAN

I love music #love drawing.

AUTHORS

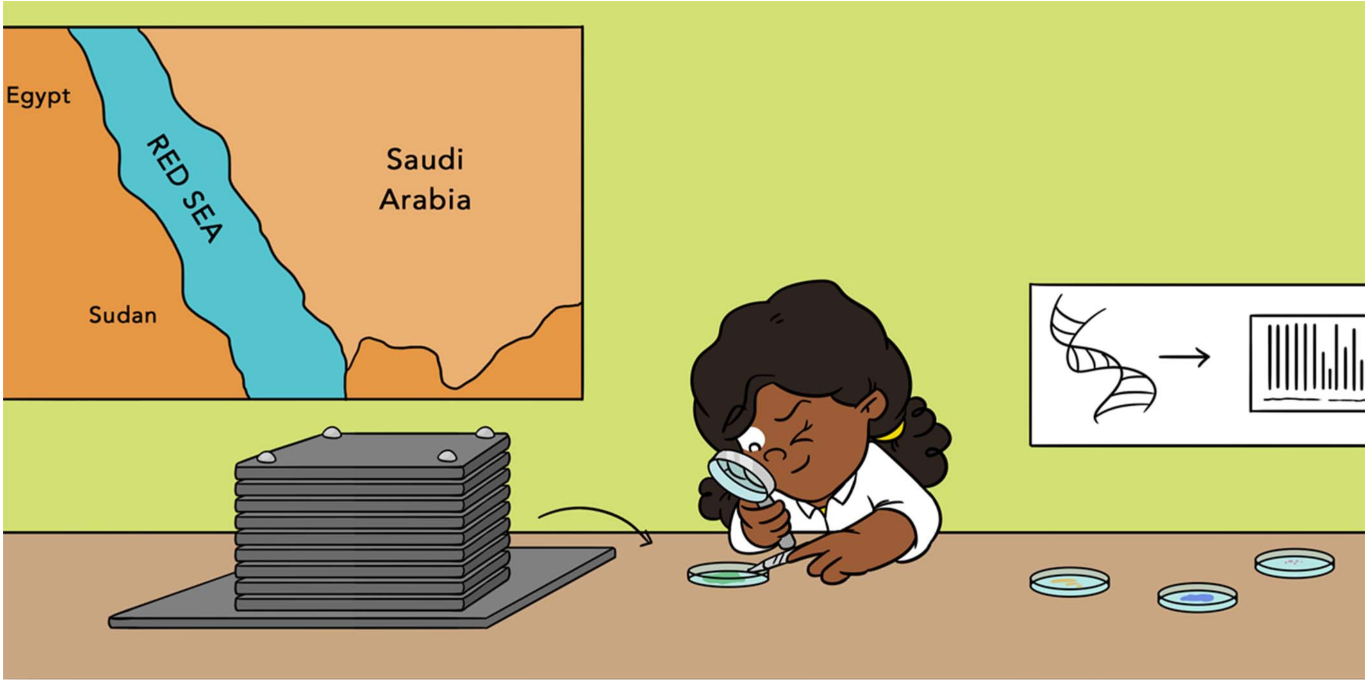
NILS RÄDECKER

Every time you think you understand something about how nature works, nature has this way of laughing at you and doing the opposite of what you expected. This complexity fascinates me and made me study biology in the first place. For my research, I am working with corals, some of the simplest animals on the planet, to understand the basic processes that help organisms to survive in their environments. *nils.radecker@kaust.edu.sa

CLAUDIA POGOREUTZ

Every child has this odd friend who scoops up slugs and worms off a road after a rainfall "to rescue them," or who is intrigued by the strange behavior of a particularly gross critter. I used to be, and still am, this odd friend. Now I am also a post-doctoral researcher working on the diversity and function of microbes in and on marine animals. In particular, I am trying to understand how bacteria help corals in their every-day lives.

BIODIVERSITY
Published: 18 March 2020
doi: 10.3389/frym.2020.00011

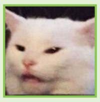


TREASURE REEF: REVEALING THE HIDDEN CREATURES OF CORAL REEFS

Jennifer Otoadese and Susana Carvalho *

Biological and Environmental Sciences and Engineering, Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

YOUNG REVIEWERS:


BJORN
AGE: 15


HAZEM
AGE: 14


REBECCA
AGE: 15


SAMUEL
AGE: 14


XENIA
AGE: 15

Under the oceans, scientists estimate that there are hundreds of thousands of sea creatures yet to be discovered. These hidden animals can be found in the open ocean, in deep trenches at the bottom of the sea, and in coral reefs. In tropical coral reefs, hidden animals include tiny fish, crabs, octopuses, sea snails, starfish, slugs, and other mysterious animals that are hard to see. These mysterious animals can help us better understand how coral reefs function. But how can we study what we cannot find? Scientists working along the east coast of the Red Sea in Saudi Arabia are using two new methods to bring these hidden creatures from the reef to the laboratory. Like detectives, these researchers are finding, describing, and learning about the roles these tiny animals play in keeping coral reefs healthy. We protect what we know, so the race is on to find and preserve the Red Sea's biodiversity.

AN UNDERWATER MYSTERY

What if we could figure out how to protect our oceans so that life underwater thrives? Or, what if we find a marine area that has been damaged, and we could bring back the original fish and the web of life that the fish depend on? Establishing what is called no-take marine protected areas may be just the answer to these questions. No-take marine protected areas prevent any human activity, such as fishing, mining, or oil drilling, from taking place, allowing the marine life to thrive without interference by people. But establishing these protected areas is tricky. To know what to protect, we have to identify all the organisms in that area. We also need to understand the level of **biodiversity** and connection between **ecosystems** that is necessary for the larger marine environment to thrive.

BIODIVERSITY

The variability between the characteristics of different living things. This includes diversity within species (different sizes, colors, genetics, etc.), between species, and diversity of habitats (for example, deserts, forests, lakes, coastal areas, mountains).

ECOSYSTEMS

A dynamic area of plants, animals, microorganisms, and their non-living environment interacting together.

And here lies the mystery: how can we protect what lies beneath the surface of our seas if we barely know what is there? According to scientists, more than 80% of the oceans are unmapped and unexplored [1]. The race is on to find and identify marine species, because knowing about the world's marine species is important for protecting our oceans. Extinctions from habitat loss and climate change are progressing at alarming rates. Around 20% of marine species are at risk of extinction and we urgently need to document what is happening in order to better understand why and to learn how to prevent it.

Scientists at the Red Sea Research Center in Saudi Arabia are using two scientific research tools to study the smaller life in the Red Sea reefs. If we unlock the mysteries of life in coral reefs, we may be better able to design marine protected areas that flourish for you and for future generations to treasure.

WHAT LIES BENEATH?

Underwater, coral reefs can offer spectacular beauty with their colorful corals, fish, sponges, giant clams, and turtles. Coral reefs are like the rainforests of the seas. They provide people with countless goods and services, including food, shoreline protection, sacred spaces, and regulation of processes on earth that make our planet habitable.

For other species, coral reefs are life-giving. In the movie "Finding Nemo," Nemo lived in a sea anemone, in the shelter of a coral reef. Reefs are important nurseries for young fish and help to provide protection from predators and nutrients (food) for growth. But if you look even closer at life in the reef, you can find equally astounding creatures the size of your fingernail and even smaller. Creatures like tiny crabs, octopuses, worms, snails, starfish, and fishes (Figure 1) exist there. Because of their size, these creatures are hard to find using traditional marine surveys, which only capture what the eye can see. These traditional methods include using divers to take photos of easy-to-see organisms and looking at pictures taken from space using

Figure 1

Figure 1

Examples of animals living on coral reefs collected using ARMS in the Red Sea. From left to right, on the upper row: a crab, an octopus and a worm; on the lower row: a sea snail, a starfish and a fish. Photo credits John K. Pearman.

SENTINEL SPECIES

An important species in an ecosystem that can tell scientists about the health of that ecosystem. Loss of a sentinel species can provide advance warning that an ecosystem is in danger.

ARMS

Autonomous reef monitoring structures are made of multiple plates placed on top of each other, mimicking the 3D structure of reefs. ARMS enable the study of hidden organisms that, because of their small size or because they mainly come out at night, are often unseen using visual reef surveys by divers.

DNA

Long strands of chemicals that contain the genes—or blueprints—of an organism. The genes in an organism's DNA contain the information that helps to determine its shape, size, and behavior.

satellites. To get the full picture of biodiversity, we need to go smaller, because these micro-creatures, some of which hide or only come out at night, are estimated to make up 70% of coral reefs.

These hidden creatures represent most of the reef biodiversity, but if we do not look at them, how can we know if we are losing species because of climate change or pollution, or gaining species that were not there before? These changes to coral reefs can threaten the health of the marine environment.

With information about the smallest forms of marine life we can:

1) Find similarities and differences—between reefs, between near-shore and off-shore environments, between seas, and across all the oceans on Earth;
2) Investigate if there are key species, called **sentinel species**, that help scientists to figure out if an ecosystem is healthy or degraded; and
3) Establish early warning systems. If there are sentinel species that we know should be present for a healthy system, and we discover these creatures are missing, we can warn governments and marine managers that they must take action to protect that marine environment. Some of these actions may include controlling discharges of sewage, improving water treatment, or even limiting fishing activities.

Two techniques have recently been combined to find the creatures living out of plain sight. They are called **autonomous reef monitoring structures (ARMS)** and **DNA** barcoding.

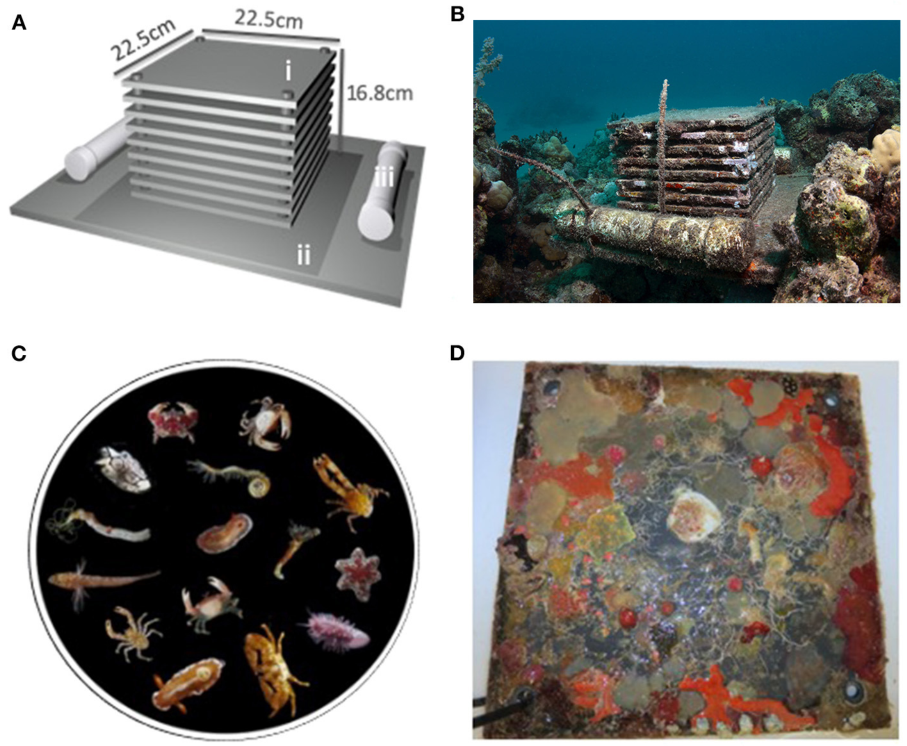


Figure 2

Figure 2

(A) Drawing of an autonomous reef monitoring structure (ARMS), showing the dimensions and the main components: (i) nine strong plastic plates with spaces for animals to settle and hide; (ii) a base; (iii) weights to allow for stability against waves and currents. **(B)** One ARMS unit sitting on a Red Sea coral reef. **(C)** Examples of creatures >2 mm in size that have been collected in the Red Sea using ARMS. **(D)** One ARMS plate after 2 years under water, showing some organisms that settled and grew there. Photo credits Joao Curdia **(A)**, Jessica Bouwmeester **(B)**, and John K. Pearman **(C,D)**.

A TALE OF TWO TECHNIQUES: FROM THE OCEAN TO THE LABORATORY

What Are Autonomous Reef Monitoring Structures (ARMS)?

ARMS are sets of nine plates placed on top of each other, with spaces in between to allow for creatures to crawl inside and water to flow through (Figures 2A,B). The design of these ARMS mimics the 3D nature of a coral reef, with some parts exposed to light, other areas with limited light, and some areas that allow animals to find refuge from predators. ARMS are first made in a workshop before a scientific diver takes them underwater and places them on the bottom of a reef. After 1–3 years, the diver returns to collect the ARMS from the site. The ARMS will then be covered in marine growth, including animals, plants, algae, and bacteria. Marine scientists carefully photograph all the life they find on the ARMS (Figure 2D). Where possible, the largest creatures (>2 mm; Figure 2C) uncovered on each ARMS is identified by scientists called taxonomists, whose job it is to classify animals to a particular family or species (its **taxonomy**). If a taxonomist cannot identify the organism, there is now a new way to identify these creatures through their DNA—a tool called DNA barcoding.

TAXONOMY

The science of classifying living things into groups called, among others, families or species that share common characteristics.

What Is DNA Barcoding and How Can We Use It?

DNA barcoding is an amazing new technique that can help scientists discover and catalog the biodiversity of our oceans. Marine organisms lose cells constantly and these cells are released into the

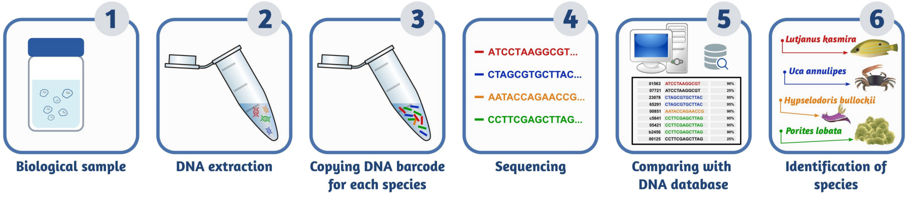


Figure 3

Figure 3

Identification of organisms using eDNA barcoding. (1) An environmental sample containing cells and DNA from organisms (eDNA) is blended with a special detergent to release the DNA that is inside the cells. (2) The DNA is extracted (separated from) from the other cellular components using a series of chemicals. (3, 4) The extracted DNA is analyzed (sequenced) for the "barcode" that identifies the species of the organisms. (5) The sequences are compared with online databases, and (6) the species can then be identified[1] .

[1] Search database icon - Adapted from Search database by Markus, NO. thenounproject.com. Animal drawings - Courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). Animal drawings courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science.

ocean environment. Every individual cell contains the DNA (genetic information) of that species and can be collected from the water, sediment, or ARMS. This genetic information is called **environmental DNA**, or eDNA, because it is collected from the environment, and eDNA can be used to get an inventory of which species are present at a certain place and time. Each organism's DNA functions as a unique "barcode," like the codes you find on products in the supermarket. The closer two species are, the more similar their DNA is. By examining eDNA, we can find out what species or family the organisms in an environment belong to (Figure 3). These unique DNA codes can be compared to an online database that links that unique code with the name of the species. Sometimes, new species are discovered that are not included in the database. It is estimated that only 86% of life on Earth has been discovered and recorded—there is still so much we do not know [2].

In the Red Sea, DNA barcoding of eDNA is helping us find sea creatures that no one in the world has described before. As the collection of eDNA expands, researchers can begin to find patterns telling them where the species live and whether species are appearing or disappearing.

UNVEILING THE MYSTERY CREATURES OF THE RED SEA

Red Sea Research Center scientists have deployed ARMS spanning the Saudi Arabian coast from north to south since 2014. These scientists have found over 10,700 distinct species associated with Red Sea reefs. This is 10 times more than the fish species and 30 times more than the coral species than had previously been identified in the region. Most of the species belong to a group called Arthropoda (such as crabs), followed by fish, mollusks (animals with shells, including snails), and worms (Figure 4). Several species could not be assigned to any known group. Following recovery of the ARMS in the central part of the Red Sea, eDNA barcoding was applied to ARMS deployed at eleven reefs. Scientists found that the groups of organisms identified changed as reefs become more distant from the shoreline toward the center of the Red Sea.

Another thing the scientists learned is that, to conserve and protect species, a marine protected area including a network of protected

ENVIRONMENTAL DNA (EDNA)

Genetic material from cells found in an environmental sample, such as seawater, sediments, reefs, or ARMS—that can be used to identify what species were present at a certain time and location.

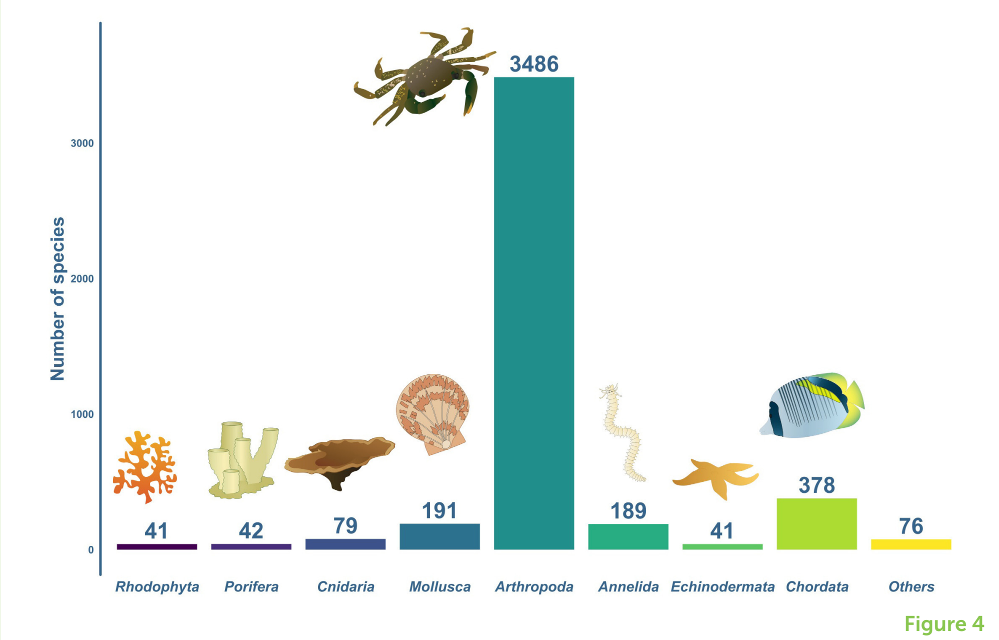


Figure 4

Species found using ARMS in the Red Sea. The XX axis lists the various phyla (groups of related living things that ranks below the kingdom) of the organisms collected, while the YY axis shows the number of species. You can see from the graph that most of the species collected belonged to the phylum Arthropoda, including the crabs.

reefs must be established, instead of just protecting the most species-rich reef. This is because some reefs contain species that are very different from those found in another reef, so protecting only one reef will not safeguard the biodiversity of the region.

CAN THE MYSTERY OF THE SEAS BE SOLVED?

Can we fully know what lies beneath the surface of the seas? Yes and no. Yes, because we now have tools like ARMS and eDNA barcoding that allow for a more rapid and less expensive way of identifying the overwhelming diversity of life in our seas. As these tools evolve and our computer technologies grow, we can expect new and creative methods for identifying marine life. No, because global changes are also causing some of these species to be lost before we can identify them. Also, there are many parts of our seas that are so inaccessible that we cannot use ARMS or collect samples of eDNA in those regions. What we do know is that a biodiverse ecosystem with many different species is more likely to be resilient and to withstand changing conditions. Recording and understanding all marine life inhabiting coral reefs in the Red Sea is one contribution scientists are making to help protect and conserve the planet's marine treasures.

ACKNOWLEDGMENTS

The authors were grateful to João Curdia for adapting Figure 3, and to the co-authors of the original source articles. Special thanks to the editors Rúben Costa and Christian Voolstra, the reviewers, and the Science mentor (Royale S. Hardenstine) for their thoughtful and critical assessment of our article. Their constructive comments and have strengthened this publication. Finally, we would also like to thank Susan Debad for making our article more accessible to a young audience. The research upon which this article is based was supported by the Saudi Aramco-KAUST Center for Marine Environmental Observations.

ORIGINAL SOURCE ARTICLES

Pearman, J. K., Leray, M., Villalobos, R., Machida, R. J., Berumen, M. L., Knowlton, N., et al. 2018. Cross-shelf investigation of coral reef cryptic benthic organisms reveals diversity patterns of the hidden majority. *Sci. Rep.* 8:8090. doi: 10.1038/s41598-018-26332-5

Carvalho, S., Aylagas, E., Villalobos, R., Kattan, Y., Berumen, M., and Pearman, J. K. 2019. Beyond the visual: using metabarcoding to characterize the hidden reef cryptobiome. *Proc. R. Soc. B* 286:20182697. doi: 10.1098/rspb.2018.2697

REFERENCES

1. NOAA. 2019. Available online at: https://oceanservice.noaa.gov/facts/exploration.html (accessed May 30, 2019).
2. Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B., and Worm, B. 2011. How many species are there on earth and in the ocean? *PLoS Biol.* 9:e1001127. doi: 10.1371/journal.pbio.1001127

SUBMITTED: 15 September 2019; **ACCEPTED:** 28 January 2020;
PUBLISHED ONLINE: 18 March 2020.

EDITED BY: Christian Robert Voolstra, Universität Konstanz, Germany

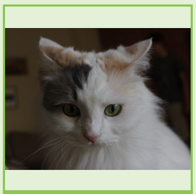
CITATION: Otoadese J and Carvalho S (2020) Treasure Reef: Revealing the Hidden Creatures of Coral Reefs. Front. Young Minds 8:11. doi: 10.3389/frym.2020.00011

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

BJORN, AGE: 15

I enjoy 3D modeling and coding, studying, and sports in my free time. I come from Canada, and I believe that making information accessible for all is fundamentally important in preparing for the future.



HAZEM, AGE: 14

I am Hazem. I am 14. I like to learn things about biology.

REBECCA, AGE: 15

I am a TCK, and I currently live in an international school in Saudi Arabia. I am half-Canadian and half-Kiwi. I play the violin, rugby (along with various other sports), and love art and gastronomy. I love nature, hiking, and forests.

SAMUEL, AGE: 14

My name is Samuel and I am from New Zealand. I absolutely love being able to read and understand scientific articles about the latest scientific discoveries. I have lived in Latvia for 2 years and Qatar for 7 years. Trying new things is great and I feel that I should try all the experiences before I am too old to do them.

XENIA, AGE: 15

My name is Xenia. I like Science and I think it is awesome to be able to read a scientific article and actually understand what it says. In my spare time I like to read, do gymnastics, and take pictures.

AUTHORS

JENNIFER OTOADESE

Having lived near the shores of the Arctic, Pacific, Atlantic, and Indian oceans, I am happiest in, on or beside the water. My first snorkeling expedition was in the Red Sea 17 years ago; the beauty of the Sea's diversity was astonishing. I want my children, you, your children to have the same opportunity to behold the splendor of our Blue planet. This is why my career has and will continue to be supporting transformative scientific research and engagement teams to do their best work. I have had the privilege of coordinating marine research, facilitating high-level, cross-sectoral conversations toward 2050 low carbon scenarios, documenting western and indigenous knowledge of climate change in the Arctic, coordinating youth-driven global environmental assessments, and changing policies to protect forests and livelihoods.

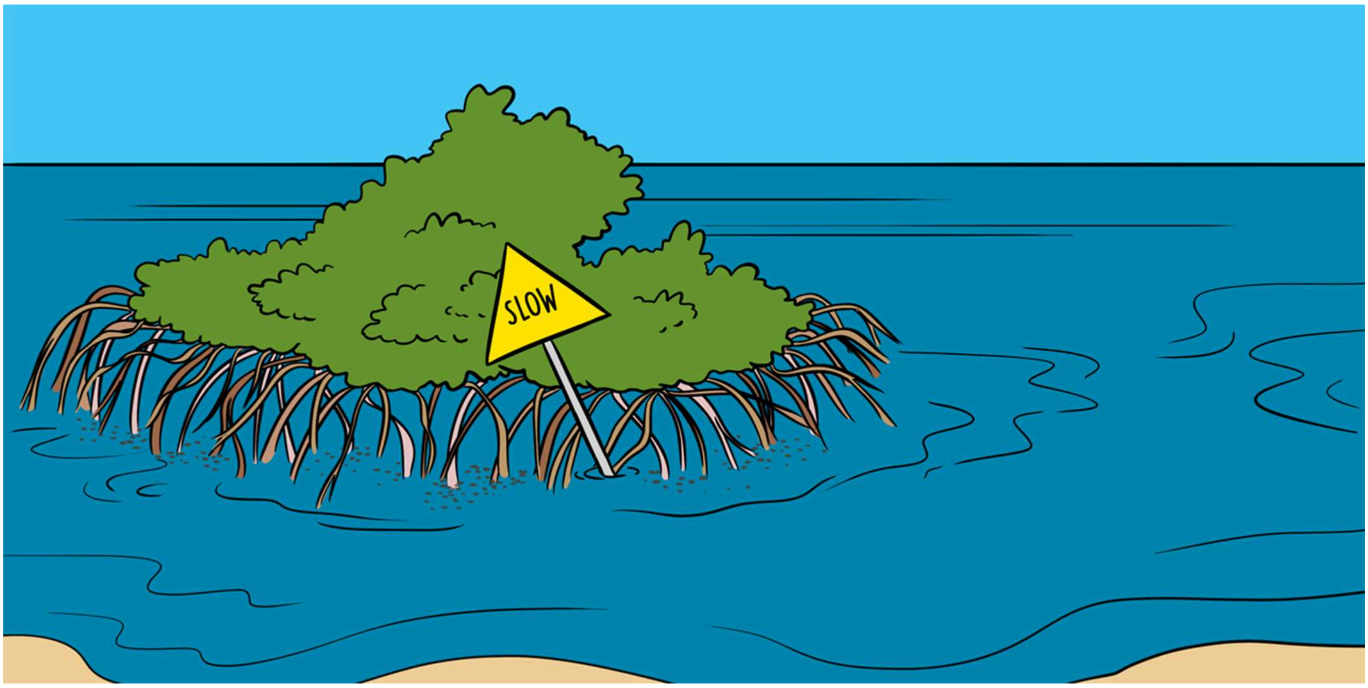
SUSANA CARVALHO

I am a marine ecologist passionate about understanding and protecting marine biodiversity. Living in Saudi Arabia since 2012, I have been working at the King Abdullah University of Science and Technology. I investigate how biodiversity and functioning of the Red Sea ecosystems change as a result of human or

natural disturbances. I have been particularity involved in studies incorporating DNA-based tools in aquatic biomonitoring and biodiversity projects from microbes to fish. I am also very interested on how biological diversity is distributed around the world. *susana.carvalho@kaust.edu.sa

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 16 September 2019
doi: 10.3389/frym.2019.00114



HOW SEAGRASSES SECURE OUR COASTLINES

***Marco Fusi*[1,2*] *and Daniele Daffonchio*[1]**

[1] *Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia*
[2] *School of Applied Sciences, Edinburgh Napier University, Edinburgh, United Kingdom*

YOUNG REVIEWERS:


ARNAB
AGE: 14


FABIAN
AGE: 12


MALSHI
AGE: 12


SAVANA
AGE: 13


SUBHAAN
AGE: 13


ZIA
AGE: 12

Seagrass meadows are hidden underwater grass fields that protect the coast and offer shelter to many sea creatures. Seagrasses are flowering plants that evolved from the land back to the sea, and they now occupy the sea bottom in shallow waters along the coast all over the world. Human activities, such as fishing methods that rely on heavy nets that are dragged across the sea floor, put this important ecosystem at serious risk. In this study, we aimed to measure how seagrasses contribute to coast protection by trapping rock debris transported by the sea. Seagrasses reduce erosion of the coast and protect our houses and cities from both the force of the sea and from sea-level rise caused by global warming. Seagrasses do this by softening the force of the waves with their leaves, and helping sediment transported in the seawater to accumulate on the seafloor.

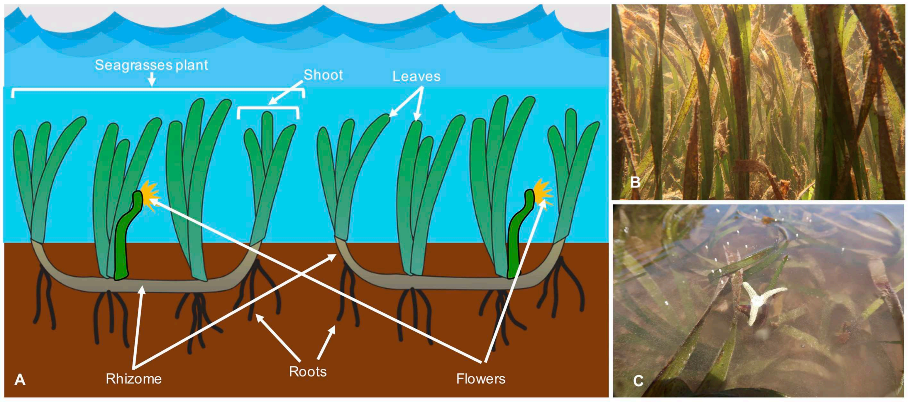


Figure 1

Figure 1

(A) In this drawing of seagrass plants, the major structures of the plants are labeled. **(B)** Seagrasses of the species *Enhalus acoroides*, one of the most abundant species in the Red Sea. **(C)** Female flower of *Enhalus acoroides* that emerged during low tide. Just like other flowering plants, seagrasses generate fruits and seeds.

SEAGRASSES: MARINE PLANTS THAT EVOLVED BACK TO THE SEA

When we speak about ecosystems that thrive on the coast, we often think about beautiful mangrove forests or endless coral reefs. However, we tend to forget that coasts are inhabited by other kinds of species that form an important ecosystem: seagrass meadows.

Seagrasses, like mangrove trees, are flowering plants that evolved from the land back to life in the sea, about 100 million years ago [1]. As with all flowering plants (also known as angiosperms, from the Greek words *angeion*, "case," and *sperma*, "seed"), seagrasses usually flower once per year during their reproductive season, the same way many plants on land do during the spring. Instead of using bees or other insects for pollination, seagrasses use marine creatures—like crabs, sea worms, or shrimp—that live burrowed in the **sediment** amongst seagrass roots [2]. These sea creatures walk and swim among the male flowers of seagrasses and get pollen attached to the spiny and hairy parts of their bodies. When these creatures then walk and swim among the female flowers, the plant is pollinated [2].

SEDIMENT

Sediment is the accumulation of sand, clay, rock debris and dirt that settles in the bottom of lakes, river, and sea.

Like many other kinds of grasses on land, seagrasses are connected by underground structures called **rhizomes**, which are similar to roots that grow underneath the sediment. New shoots of seagrasses can sprout up from rhizomes (Figure 1), and a single plant can sprout many shoots over a long period of time. In the Mediterranean Sea, for example, one plant has been found to be more than 200,000 years old—almost as old as our first *Homo sapiens* ancestor!

RHIZOME

Horizontal underground plant part that can produce the shoot and root systems of a new plant.

All over the world, seagrasses have been estimated to cover between 0.15 and 4.6 million square kilometers [3], an area ten times bigger than the Red Sea. The Red Sea itself hosts 12 of the 60 species of seagrasses present all over the world, and together these seagrasses form an area that extends for more than 100,000 square kilometers, similar the total size of Portugal.

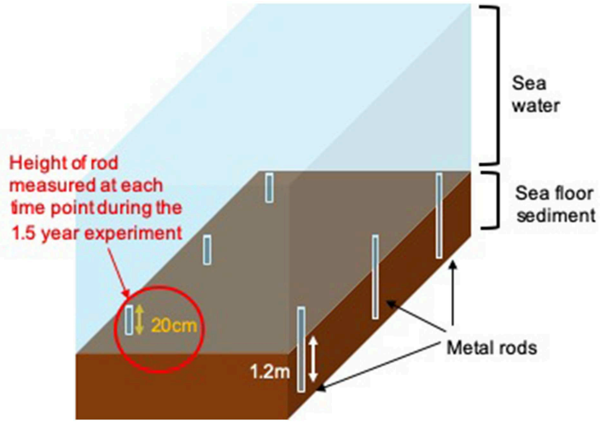


Figure 2

Figure 2

SECP methods for measuring sediment. Six metal rods of 1.4 m in length were inserted into the sediment, leaving 20 cm of the rods uncovered. The distance measured between the sediment and the rods allow us to quickly judge the amount of sediment erosion/accumulation on the plot.

SEAGRASSES PROTECT THE RED SEA COAST

Seagrass meadows, with their leaves extending toward the seawater surface, slow down the marine currents that transport sediment and other particles and allow the settling of this sediment among the roots and leaves of the seagrass. By doing this, seagrasses help to form new layers of sediment on top of the older ones. But how do seagrasses avoid being buried? The trick is in their extraordinary level of adaptation, acquired by living in this constantly changing ecosystem: thanks to rhizomes, each single seagrass plant can adjust its growth and keep pace with **sedimentation**. By helping sediment to accumulate, seagrasses protect the coastline from **erosion** and therefore protect houses, roads, and cities built near the shore.

SEDIMENTATION

The accumulation of sand, clay, rock debris, and dirt that settles on the bottom of lakes, river, and sea.

EROSION

The gradual destruction or reduction of sediment.

SECP

Surface Elevation Change Pins (SECP) is a technique that is used to assess the change in the elevation of the seafloor.

To find out how much sediment seagrasses trap, we set up a measuring system that used six metal rods, following a method called **surface elevation change pin (SECP)**. SECP is used by many scientists to measure the sediment gathered in mangrove forests and saltmarshes (Figure 2).

We established five experimental plots on the sea bottom within seagrass meadows and five in sediment not covered by seagrasses. At the time of the set-up, the rods were firmly secured into the sea floor 1.2 m deep, leaving 20 cm of the rods protruding above the sediment. Over a monitoring period of one and a half years, we checked on the rods three times. For each time point, we measured the height of the metal rods that remained uncovered on the surface of the sediment. If sediment had accumulated between the installation of the rods and our first check, the distance from the tip of the rod to the seafloor would be <20 cm, but, in the case of erosion, the distance would be more than 20 cm. We used the lengths of each of the six rods to calculate the average accumulation/erosion of sediment in each experimental plot. At the end of the monitoring, we were able to conclude that, along the Central Red Sea at the

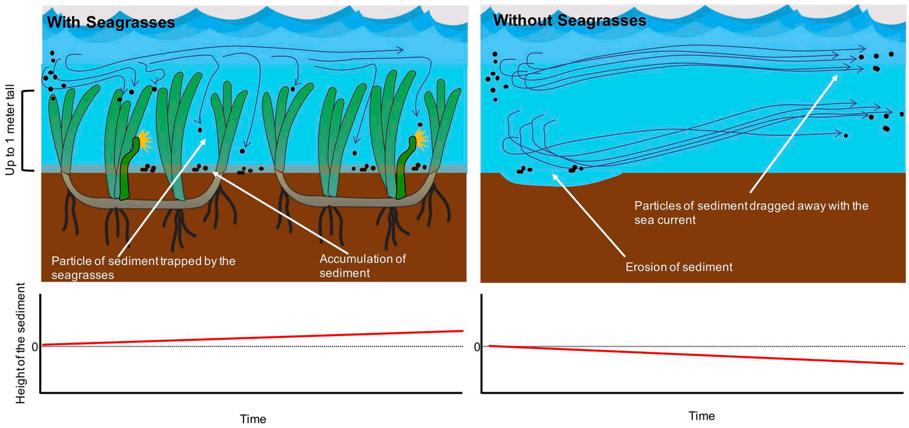


Figure 3

Figure 3

Seagrasses help to trap sediment particles transported by sea currents. The leaves, extending toward the sea surface, slow down the water currents. The slower current is not able to carry the particles of sediment, so the particles drop down and become part of the seafloor, eventually building it up. When seagrasses are not present, the sea current has no obstacles and carries the sediment particles away, lifting them up and eroding the seafloor.

Saudi Arabian coast, seagrasses helped to accumulate sediment, with a sediment accumulation rate of 7.84 mm per year, while in the areas not covered by seagrasses, we saw sediment loss (erosion) of 30.9 mm per year (Figure 3).

This experiment was repeated in several other locations all over the world and similar results were found. In Kenya, for example, we recorded a sediment accumulation of 34 mm per year in seagrass meadows. On the other hand, erosion in areas not covered by seagrasses accounted for a loss of up to 40 mm of sediment per year in Tanzania, and an average loss of 30 mm per year in Kenya. This data clearly shows us how important seagrasses are for holding the sediment in coastal areas, and therefore tells us that we urgently need to establish coastal management laws to protect seagrass meadows.

Coastlines all over the world are full of people. Many cities, resorts, and villages are constructed along the coast and often the risk of coastal erosion caused by this construction is not considered. Also, in the last few decades, human activities, such as the construction of dams along rivers has limited the amount of sediment coming into the sea. The reduced input of sediment has resulted in increased erosion of beaches and rocky shores by the ocean currents. This erosion has resulted in dramatic destruction of buildings. Seagrasses are natural friends that can help to solve this problem.

In summary, seagrass meadows are one of the most effective barriers against erosion, because they trap sediment amongst their leaves. Archaeologists have learned from seagrasses how to protect underwater archaeological sites, like a site in Denmark where dozens of ancient Roman and Viking shipwrecks have been discovered. The archaeologists use seagrass-like covers as sediment traps, to build up sediment so that it buries the ships. Burial creates low-oxygen conditions and keeps the wood from rotting [4].

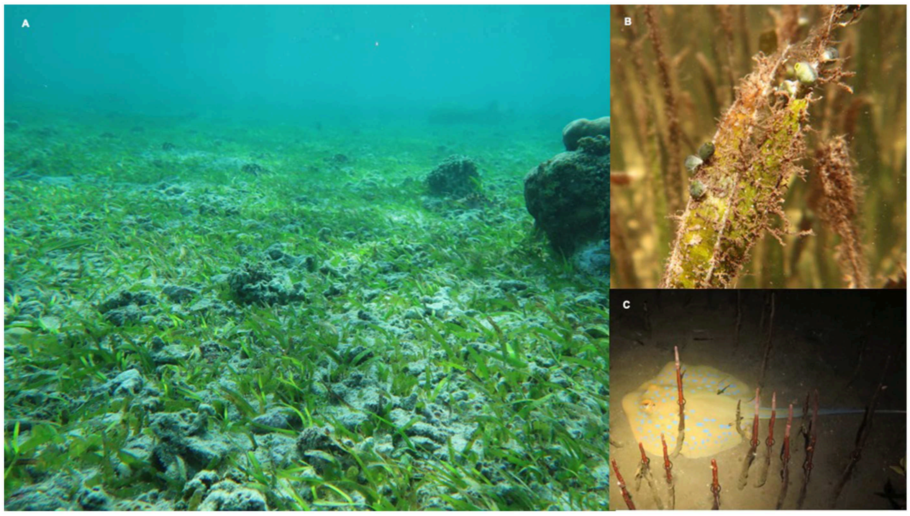


Figure 4

Figure 4

(A) Seagrass meadow. **(B)** Small animals, such as tunicates and bryozoans, can live attached to seagrass leaves. Tunicates are marine animals with hard outer shells and bryozoans are moss-like marine animals. Both animals feed by filtering food from seawater. **(C)** Blue-spotted sting ray, an animal frequently encountered in seagrass meadows.

SEAGRASSES PROTECT BIODIVERSITY AND KEEP THE COAST CLEAN

BIODIVERSITY

All the big and small animals, plants, bacteria, and fungi of the world or of a particular ecosystem like seagrasses, coral reefs, rainforests, mountains, deserts, and many others.

Seagrasses do not resemble the colorful and magnificent coral reefs, but they can have the same high level of marine **biodiversity**. During each dive into seagrass meadows in the Red Sea, we can have amazing encounters. We might bump into a curious blue-spotted ray in search of food, or a very annoyed mantis shrimp that is scared by inquisitive scientists. Octopi, cuttlefishes, and other fishes observe us at a distance. We discovered that Red Sea seagrasses host more than 60 animal burrows per square meter. Crabs, shrimp, bivalves, and fishes find shelter among seagrass rhizomes. Moreover, many little animals, such as bryozoans, tunicates, sponges, and sea worms, anchor themselves to the leaves or the exposed roots of seagrasses (Figure 4). Scientists have recently discovered that the cooperation between seagrasses and animals results in a strong protection of the coast from organisms that cause diseases [5]. Seagrasses have been demonstrated to produce natural compounds that kill the bacteria that bring illnesses to fishes and to us.

Our study highlights the importance of the seagrass ecosystems in the sea. The next question to answer is, "How do we secure the survival of seagrasses in the future of the Red Sea?" Seagrasses are in danger because of the many human activities going on along the coast. Fishing methods that rely on heavy nets that are dragged across the sea floor eradicate and kill these plants as wells as the fast growing city waterfronts pollute the coastal water by uncontrolled wastewater discharge and block the ground freshwater going into the sea, provoking the death of this important ecosystem. Is our duty continue to study the seagrasses ecosystem to seek solutions to make the human being live end thrive together with the seagrasses by changing fishing methods and by designing environmental friendly cities.

ORIGINAL SOURCE ARTICLE

Potouroglou, M., Bull, J. C., Krauss, K. W., Kennedy, H. A., Fusi, M., Daffonchio, D., et al. 2017. Measuring the role of seagrasses in regulating sediment surface elevation. *Sci. Rep.* 7:11917. doi: 10.1038/s41598-017-12354-y

REFERENCES

1. Larkum, A. W. D., Orth, R. J., and Duarte, C. M. 2006. *Seagrasses*. Dordrecht: Springer.
2. Van Tussenbroek, B. I., Villamil, N., Márquez-Guzmán, J., Wong, R., Monroy-Velázquez, L. V., and Solis-Weiss, V. 2016. Experimental evidence of pollination in marine flowers by invertebrate fauna. *Nat. Commun.* 7:12980. doi: 10.1038/ncomms12980
3. Duarte, C. M. 2017. Reviews and syntheses: hidden forests, the role of vegetated coastal habitats in the ocean carbon budget. *Biogeosciences* 14:301. doi: 10.5194/bg-14-301-2017
4. Gregory, D., Jensen, P., and Strætkvern, K. 2012. Conservation and *in situ* preservation of wooden shipwrecks from marine environments. *J. Cult. Herit.* 13:S139–48. doi: 10.1016/j.culher.2012.03.005
5. Lamb, J. B., van de Water, J. A., Bourne, D. G., Altier, C., Hein, M. Y., Fiorenza, E. A., et al. 2017. Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. *Science* 355:731–3. doi: 10.1126/science.aal1956

SUBMITTED: 31 March 2019; **ACCEPTED:** 15 August 2019;
PUBLISHED ONLINE: 16 September 2019.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Fusi M and Daffonchio D (2019) How Seagrasses Secure Our Coastlines. Front. Young Minds 7:114. doi: 10.3389/frym.2019.00114

CONFLICT OF INTEREST STATEMENT: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ARNAB, AGE: 14

I am a 14 years old student who likes computers and other tech related items. I like building stuff with lego as well as doing science. I also like video games, Cities Skylines, and Mario.

FABIAN, AGE: 12

Fabián is a world traveling, 12 years old, seventh grade polyglot who loves the ocean and being creative. His hobbies are: mountain biking, lego, inventing, acting, and reading, but especially reading. He loves being a part of the Frontiers for Young Minds program and looks forward to next year!

MALSHI, AGE: 12

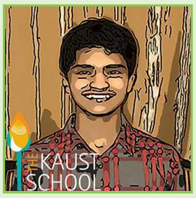
My name is Malshi, and I am 12 years old. I like Science and Math and I am interested in Chemistry. I love reading in my spare time and I love playing the piano. My favorite sport is badminton and in the future, I want to be a scientist.

SAVANA, AGE: 13

I love dogs, my favorite color is red, and I love hanging out with my friends.

SUBHAAN, AGE: 13

I am from Canada and I like memes. I like Marvel and my favorite superhero is Spiderman and my favorite villain is Venom.



ZIA, AGE: 12

One of my favorite subjects in school in school is science. I am very curious about how the daily things we do in our life happen. I especially like biology and cosmology. I watch a lot of documentaries about space and like to research on my interests.

AUTHORS

MARCO FUSI

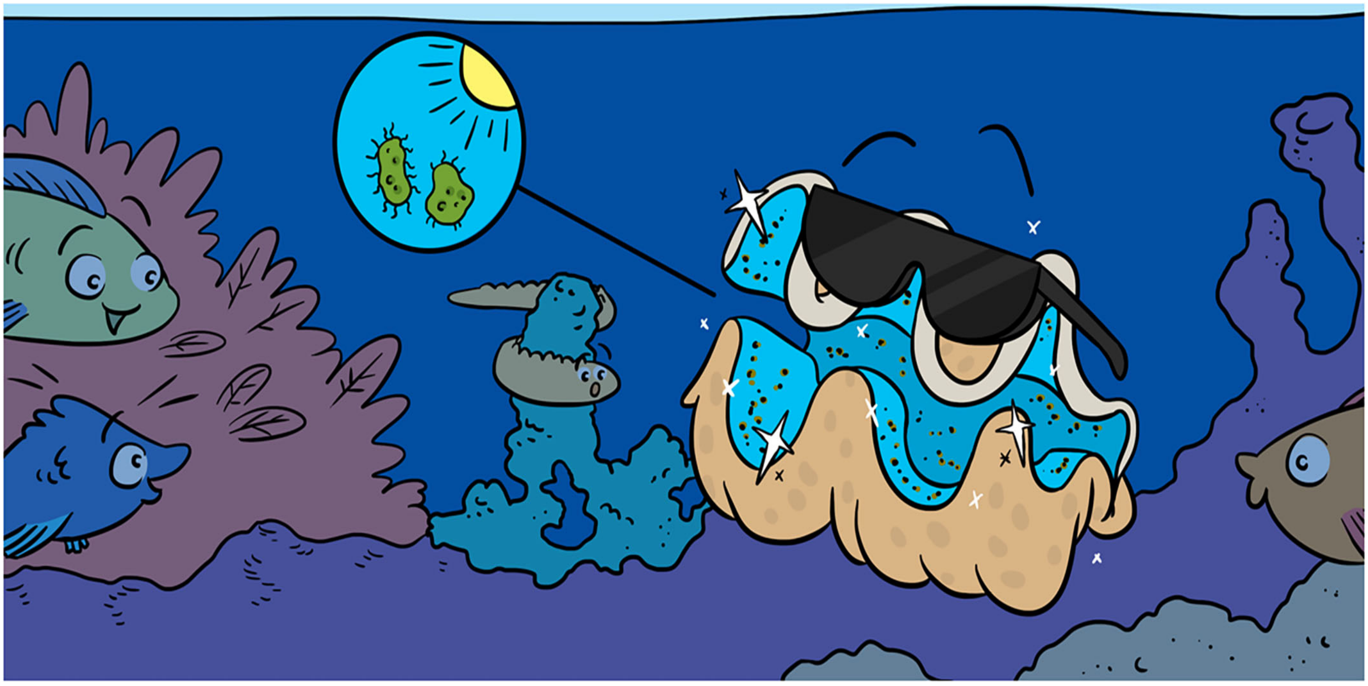
I grew up in Tuscany, a central region of Italy, developing a strong relationship with the Mediterranean Sea. I always seek adventure in it, fascinated by the diversity of its thriving species. I started studying computer science, but I always looked forward to turning my work in something useful for the environment and the sea. So, I started my study in natural sciences at the University of Florence in Italy and I immediately volunteer in many projects involving the sea. This led me to travel across the Indian Ocean, studying mangrove and mangrove crabs with my Master and my Ph.D. and afterward to complete a 5 years of Post-Doctorate

research fellow in Saudi Arabia where I extend my work to seagrasses and coral reef.
*marco.fusi@kaust.edu.sa

DANIELE DAFFONCHIO
Prof. Daffonchio has developed research on the exploration and characterization of bacteria living in and extreme marine and terrestrial environments. He is actually dealing with the study and microorganisms along the water stress continuity from the Arabian Desert to the depth of the brine pools in the Red Sea. A particular focus is on the bacteria-host symbiosis with plants and animals in mangrove, seagrasses, and desert environments.

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 11 August 2021
doi: 10.3389/frym.2021.608617



THE SPARKLING TAN: HOW GIANT CLAMS AVOID SUNBURNS

***Susann Rossbach*[1*]*, Sebastian Overmans*[1]*, Ram C. Subedi*[2] *and Carlos M. Duarte*[1]**

[1] Red Sea Research Centre (RSRC) and Computational Bioscience Research Center (CBRC), Biological and Environmental Science and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

[2] Photonics Laboratory, Computer, Electrical and Mathematical Sciences and Engineering Division (CEMSE), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

YOUNG REVIEWER:

FABIÁN

AGE: 14

As their name suggests, giant clams are among the biggest clams on earth, and they are very colorful animals that live in coral reefs. Giant clams get help from tiny organisms inside their mantles, the colorful part between their shells. These little helpers, tiny microalgae, can use sunlight and carbon dioxide to produce food, which they share with the clams. That is why these clams can grow so big! In return, the clams provide the microalgae with some nutrients. Although sunlight is very important for food production in these organisms, excessive sunlight can lead to a sunburn, like in humans. Therefore, the clams had to evolve their special sparkling tan, a natural sun protection that is a very effective way to protect themselves, and the microalgae inside their mantles, from too much sunlight and from getting a sunburn.

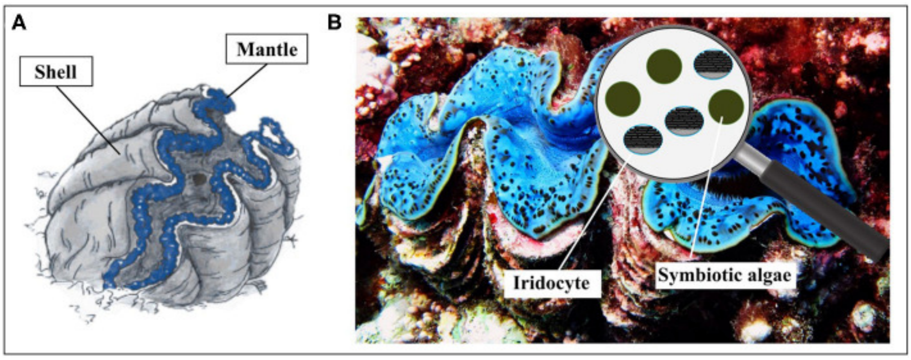


Figure 1

Figure 1

(A) The outer shell of a clam protects the soft, inner parts of its body. **(B)** The colorful mantles of giant clams contain symbiotic microalgae, which perform photosynthesis, and cells called iridocytes, which have mirror-like crystal plates that can reflect UV light from the sun and protect the clams from sun damage.

GIANT CLAMS AND THEIR TINY FRIENDS

When people hear the word "reef," they immediately think of corals. However, there are other big, colorful, and important animals living in these reefs, such as the giant clams, which are common in coral reefs of the tropical Indian and Pacific Oceans. These clams are not only beautiful to look at, but they are also important members of a reef. For example, many fishes eat them, some animals and plants can grow on the outsides of their shells, and there are even animals (like tiny shrimps) that live inside their bodies [1].

As the name indicates, giant clams can become very big. Some of them can even grow over one meter long—probably bigger than the sink in your bathroom at home! Scientists believe that one of the reasons giant clams can become so big is that they get help from other organisms. Those helpers are tiny single-celled **microalgae** that live in the outer, fleshy part of the clam's body, called the **mantle** (Figure 1A). These microalgae, like plants, can carry out photosynthesis, which uses the energy of sunlight and carbon dioxide to produce food. The microalgae that live inside the giant clams produce so much food via photosynthesis that they can feed themselves *and* share some of that food with the giant clam. In return, the clam protects the microalgae against predators while also giving the microalgae some necessary nutrients, such as nitrogen. This relationship is called a **mutualistic symbiosis**, and you might have heard of it before because the same relationship exists between corals and their microalgae. Giant clams rely heavily on the food provided by their symbiotic microalgae. Scientists assume that this symbiosis, and the extra energy that it provides for the clams, is one of the main reasons why giant clams can reach their large sizes [2].

MICROALGAE

Tiny, single-celled organisms that can fix carbon from the atmosphere like plants do on land.

MANTLE

The outer, fleshy part of a clam's body. In giant clams, the mantle is very colorful, with shades of blue, green, and brown.

MUTUALISTIC SYMBIOSIS

A relationship between two or more species, in which both organisms benefit from the interaction in some way.

GIANT CLAMS CAN GET SUNBURNS

Just like plants, the giant clam's symbiotic microalgae need enough light to produce food via photosynthesis. Therefore, giant clams must live in shallow water, where they are close to the surface and thus to the sunlight that enters the ocean. But, as happens to humans, staying in the sun without the protection of shade or sunscreen can become dangerous after a while. That is because sunlight consists of different colors of light. You have probably seen a rainbow with its beautiful colors, ranging from violet to blue and green, to yellow, orange, and red. The color of the light is connected to its energy level, with blue light being more energetic than red light. The light with the highest energy is called **ultraviolet UV light**. UV light is not visible with our eyes and it has more energy than the colors of light you can see in the rainbow. In fact, UV light has so much energy that it can damage or even kill cells of animals and plants [3]. You have probably experienced that yourself! Maybe you spent a day out in the sun but forgot to put on sunscreen. Perhaps your skin got red and itchy, or even started peeling after a few days. The same can happen to all other organisms if they stay in the bright sun for too long without any protection. Because giant clams always sit in the same spot and cannot move to the shade, the same would also happen to them. But, luckily, these animals evolved a very clever way to protect themselves.

ULTRAVIOLET LIGHT

Highly energetic light that cannot be seen by the human eye. UV light from the sun can burn or damage skin tissue.

THE SPARKLING TAN—A SUNSCREEN FOR GIANT CLAMS

Close to the microalgae in their mantles, giant clams have tiny cells called **iridocytes** (Figure 1B). The word "iridocyte" comes from Latin and ancient Greek, where "irido" means "rainbow" and "cyte" means "cell." The name "rainbow cell" makes sense, because researchers think iridocytes are one of the reasons giant clams are so colorful, with mantles in beautiful shades of blue, green, and brown.

IRIDOCYTE

Tiny cells inside the mantle of giant clams, which contain mirror-like plates that can reflect ultraviolet light.

Inside iridocytes, there are small plates stacked on top of each other. These plates are made from a crystal, which makes them look and act like tiny mirrors. When harmful UV light hits these cells, some of it is immediately reflected by the tiny mirror-like plates [4] (Figure 2). Thanks to these tiny mirrors, the reflected UV light cannot reach or damage the cells of the clams or the microalgae, because it bounces away before it can reach them. That is a great natural sunscreen! However, some of the UV light travels into the iridocytes, where it bounces back and forth between the tiny mirror-like plates. By doing so, it loses some of its energy, which makes the light less dangerous to the clams and their microalgae. By the time the light leaves the iridocytes, it has less energy and has changed its color from ultraviolet to blue [5].

The blue light that comes out of the iridocytes is the reason why many giant clams have such a bright blue color, like the clam shown in Figure 1. Other organisms, such as chameleons or copepods (miniscule relatives of crabs and lobsters), also have iridocytes that are responsible for their bright colors. These animals often use their coloration for camouflage or to attract mates. But, as you can imagine, giant clams

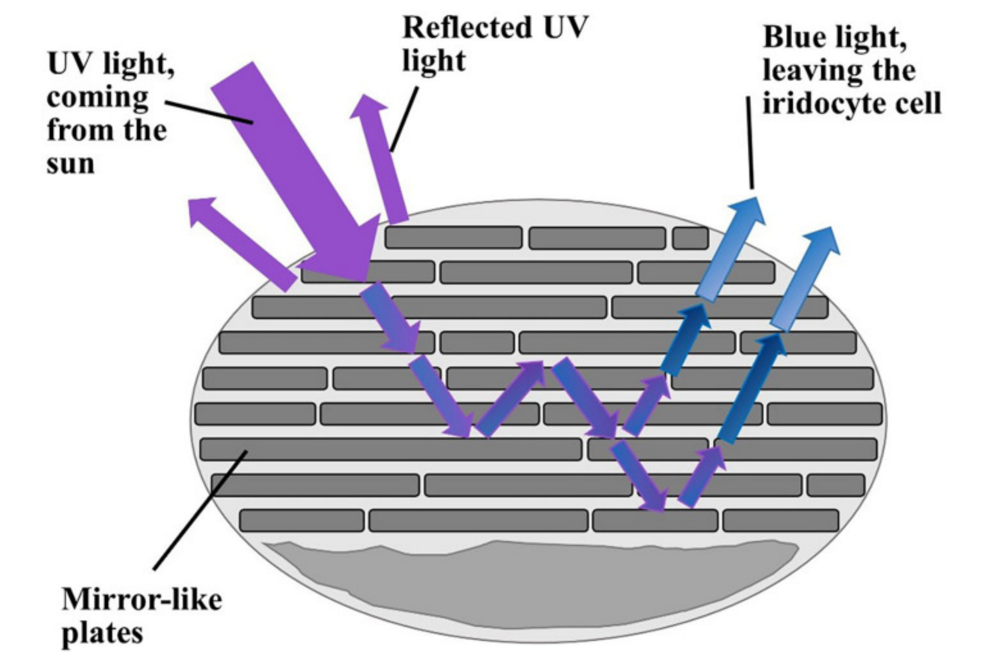


Figure 2

Figure 2

Iridocyte cells have mirror-like plates that either reflect UV light or bounce it back and forth between plates. The bouncing UV light loses energy and eventually leaves the cell as less energetic blue light.

are not very good at hiding. In fact, with their bright colors, they do quite the opposite! Moreover, giant clams do not meet to mate, so they do not use their bright colors to look beautiful to attract potential partners. So, why do giant clams produce blue light? Not only does it help the clams avoid sunburn, it is also the perfect light for the microalgae to use for photosynthesis! This means the iridocytes not only provide a highly effective sunscreen, but they also help the symbiotic microalgae to grow, by giving them their favorite color of light!

IRIDOCYTES AND MICROALGAE MAKE GIANT CLAMS SO #CLAMOROUS

While iridocytes have a blue color due to the blue light they emit, microalgae have a green color. Most organisms that perform photosynthesis use only a little of the green light that comes from the sun, so most of this light gets reflected. That is why plants and many macroalgae appear mostly green. Scientists believe that the beautiful colors found in giant clams result from different mixes of iridocytes (blue/turquoise) and microalgae (green/brownish). If a clam has more microalgae than iridocytes within its mantle, it has a more brownish coloration (Figure 3A), while clams with more iridocytes than microalgae look more blueish or even turquoise (Figure 3B).

This special relationship between giant clams and their microalgae, and the ways they developed to support and protect each other, make giant clams a fascinating animal for scientists to study. While is it

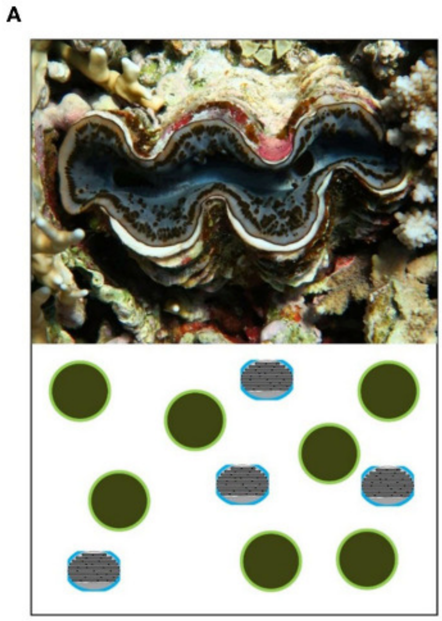


Figure 3

The mix of iridocytes and microalgae determines the color of the giant clam's mantle. **(A)** A brown giant clam has more microalgae than iridocytes. **(B)** A turquoise/blue giant clam has more iridocytes than microalgae.

important to understand the life of these animals and how they survive in the oceans, it is also essential to learn more about their specialized cells, the iridocytes. One day, knowledge of how iridocytes function might inspire technologies that work with light and colors to bring us, for example, better computer or TV screens. Who would have guessed that these ancient clams could be the key to technologies of the future!

ORIGINAL SOURCE ARTICLE

Rossbach, S., Subedi, R. C., Ng, T. K., Ooi, B. S., and Duarte, C. M. 2020. Iridocytes mediate photonic cooperation between giant clams (Tridacninae) and their photosynthetic symbionts. *Front. Mar. Sci*. 7:465. doi: 10.3389/fmars.2020.00465

REFERENCES

1. Neo, M. L., Eckman, W., Vicentuan, K., Teo, S. L. M., and Todd, P. A. 2015. The ecological significance of giant clams in coral reef ecosystems. *Biol. Conserv*. 181:111–23. doi: 10.1016/j.biocon.2014.11.004
2. Rossbach, S., Saderne, V., Anton, A., and Duarte, C. M. 2019. Light-dependent calcification in Red Sea giant clam *Tridacna maxima*. *Biogeosciences* 16:2635–50. doi: 10.5194/bg-16-2635-2019
3. Ravanat, J.-L., Douki, T., and Cadet, J. 2001. Direct and indirect effects of UV radiation on DNA and its components. *J. Photochem. Photobiol. B Biol*. 63:88–102. doi: 10.1016/S1011-1344(01)00206-8

4. Holt, A. L., Vahidinia, S., Gagnon, Y. L., Morse, D. E., and Sweeney, A. M. 2014. Photosymbiotic giant clams are transformers of solar flux. *J. R. Soc. Interface* 11:20140678-20140678. doi: 10.1098/rsif.2014.0678
5. Rossbach, S., Subedi, R. C., Ng, T. K., Ooi, B. S., and Duarte, C. M. 2020. Iridocytes mediate photonic cooperation between giant clams (Tridacninae) and their photosynthetic symbionts. *Front. Mar. Sci*. 7:465. doi: 10.3389/fmars.2020.00465

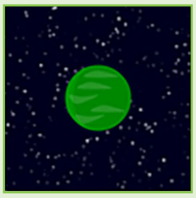
SUBMITTED: 21 September 2020; **ACCEPTED:** 19 July 2021;
PUBLISHED ONLINE: 11 August 2021.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Rossbach S, Overmans S, Subedi RC and Duarte CM (2021) The Sparkling Tan: How Giant Clams Avoid Sunburns. Front. Young Minds 9:608617. doi: 10.3389/frym.2021.608617

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER



FABIÁN, AGE: 14

Fabián is a young scientist interested in space exploration and technologies related to a sustainable future. He enjoys developing technical skills in digital design and fabrication which he hopes to implement in the development of future space exploration technologies. Fabián is an avid reader who enjoys biking, diving, programming, acting and world building.

AUTHORS

SUSANN ROSSBACH

Susann is a marine researcher who wants to understand how marine animals, such as giant clams and corals, build their skeletons. She is especially interested in learning how they can survive in the changing conditions of our oceans. She loves to dive, explore the underwater world, and share the lessons she learns and pictures she takes underwater with others. *susannrossbach@hotmail.com

SEBASTIAN OVERMANS

Sebastian is a biologist who has studied a variety of organisms, ranging from flying bats to sea-dwelling corals. Now he works as a marine scientist in the Red Sea region, where he investigates how UV light interacts with the ocean, and how it affects the health of organisms such as microalgae, corals, and giant clams.

RAM C. SUBEDI

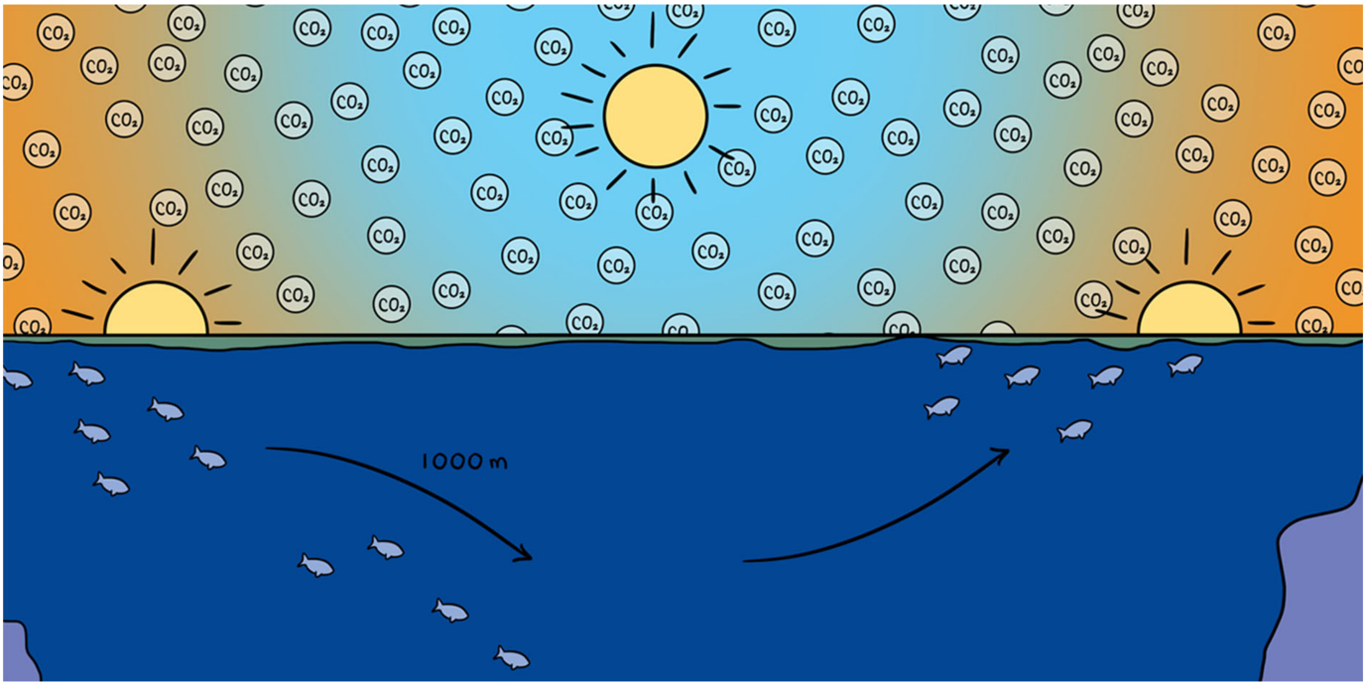
Ram Chandra is a Ph.D. student in the Photonics Laboratory at King Abdullah University of Science and Technology in the Department of Electrical Engineering. He holds a master's degree in physics from the University of Georgia, USA, as well as a M.Sc. (physics) and B.Sc. (physics and statistics) degrees from Tribhuvan University, Nepal, in 2011 and 2007, respectively.

CARLOS M. DUARTE

Carlos is a marine researcher who, after nearly four decades documenting how human pressures impact marine life, wants to establish a global effort to rebuild the abundance of marine life. He loves dogs and enjoys being away in the open sea, reading, swimming, snorkeling, walking, and playing with his grandson Oliver.

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 09 July 2020
doi: 10.3389/frym.2020.00085



RED SEA FISHES THAT TRAVEL INTO THE DEEP OCEAN DAILY

Maria Ll. Calleja [1,2*] ***and Xosé Anxelu G. Morán*** [1]

[1] *Division of Biological and Environmental Sciences and Engineering, Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia*

[2] *Department of Climate Geochemistry, Max Plank Institute for Chemistry, Mainz, Germany*

YOUNG REVIEWERS:


CHLOE
AGE: 15


HALA
AGE: 15


HUSSAM
AGE: 15


SABREEN
AGE: 10


XENIA
AGE: 15

The oceans of the world are extremely important for life on earth. Every day, they produce a large amount of oxygen needed for breathing and, at the same time, they absorb carbon dioxide produced by humans. If we did not have the oceans, this carbon dioxide would build up in the atmosphere much faster than it is accumulating now, leading to faster warming of the earth. In the ocean's sunlit surface, the carbon dioxide is absorbed by small living cells called phytoplankton. Some phytoplankton are consumed by larger organisms and are transferred to the deep ocean. In this article, we investigate the effects of small, fast-swimming fish that feed at the surface during the night and stay in deep waters during the day. In doing this, these fish move carbon from the surface to feed the bacteria living in deep waters.

WHY ARE THE OCEANS SO IMPORTANT?

The oceans and seas of our planet produce much of the oxygen we and other organisms breathe. This means that when you take a breath, you are inhaling oxygen that is partly coming from the ocean, whether you live close to the sea or in the middle of a continent! Oxygen comes from the ocean because, near the surface, there are billions of very small organisms, called **phytoplankton**, that perform **photosynthesis**, the same way plants do on land. The largest phytoplankton cells are about 1 mm long. They come in lots of different, beautiful shapes that can be seen under a microscope. During photosynthesis, marine phytoplankton release oxygen and absorb carbon dioxide (CO_2), using the energy from the sun. This happens in the upper ocean where there is enough sunlight, and this process helps reduce the amount of CO_2 in the atmosphere. Without marine phytoplankton, the CO_2 that humans produce through the burning of fossil fuels and other industrial activities would build up in the atmosphere even more quickly, and global warming of our planet would speed up. We are very fortunate that 70% of our planet's surface is covered by the oceans, because they help us mitigate climate change.

PHYTOPLANKTON

Photosynthetic organisms that live in the sunlit surface of the ocean. They take up CO_2 from the atmosphere and produce oxygen and organic matter.

PHOTOSYNTHESIS

Process by which green plants and phytoplankton capture sunlight and turn it into energy. It consumes carbon dioxide and generates oxygen as a by-product.

A CARBON CYCLE STORY

What happens to the CO_2 once it is absorbed by the organisms in the ocean's surface? Where does it go? The answer is quite complicated: this little molecule is involved in many biological, chemical, and physical reactions, in what we call the **ocean carbon cycle**. In this article, we will focus on a portion of that cycle connected by animals. During photosynthesis, the phytoplankton transforms CO_2 into **organic** molecules. Organic molecules are substances made of carbon atoms joined together in rings or chains, and other elements, such as hydrogen, oxygen, and nitrogen. For example, amino acids are organic molecules. These molecules are either used by phytoplankton to grow or are eventually released into seawater as waste products. Larger marine organisms eat phytoplankton, and the larger animals are, in turn, eaten by even bigger animals. This way, the organic carbon molecules produced by phytoplankton provide food and energy to all other organisms that make up marine food webs. The waste products of phytoplankton, called **dissolved organic matter (DOM)**, is made of molecules that serve as food for very tiny organisms called bacteria and archaea, which are $<1\,\mu m$ in size (human hair is about $25\,\mu m$ in width!). These tiny organisms live in all depths of the ocean—from the surface to the bottom. Bacteria are the most common organisms on earth and play a very important role in the cycling of carbon in the oceans [1].

OCEAN CARBON CYCLE

Combination of processes that exchange carbon between different reservoirs within the ocean as well as with the atmosphere.

ORGANIC

Part of or derived from an organism or living entity.

DISSOLVED ORGANIC MATTER (DOM)

Organic material freshly produced by phytoplankton in the surface ocean. DOM serves as food for bacteria in the surface and the deep ocean.

BACTERIA IN THE DEEP OCEAN

PROKARYOTES

Single-celled organisms that do not have nuclei. Bacteria are prokaryotes.

Bacteria and archaea are both **prokaryotes**, which means that they are single-celled organisms that do not have nuclei. As bacteria are normally more abundant than archaea, we will use the term bacteria to refer to all prokaryotes. We know that bacteria in the ocean's surface thrive by consuming freshly made DOM from phytoplankton, but what do they consume in the deep ocean? Well, they have to manage with the leftover material from the surface that sinks to the deep waters. The leftovers that make it to the deep ocean are not as delicious as the fresh material from the surface. Because of that, for a long time scientists thought that deep bacteria were much less active than surface bacteria. However, now we know that this is not true! Deep bacteria can be as active as surface bacteria [2] and scientists are still investigating how bacterial life in the dark ocean works. We still know very little about it because, as you can imagine, studying water from the deep sea is not that easy.

FISH THAT SWIM BETWEEN THE SURFACE AND THE DEEP OCEAN HELP FEED DEEP BACTERIA

Modern technologies have provided new information that helps us to better understand the connection between the surface and the deeper layers of the ocean. Scientists have long examined the behavior of schools of small fish that swim up and down between the surface and the deep ocean daily. We call this movement the **diel vertical migration** (DVM) (Figure 2) [5]. These migrating fish connect the surface and deep waters. Some swim as deep as 1,000 m! They move a huge amount of carbon up and down every day. Like other living things, even their own bodies are made from carbon! We know that these tiny fish are only a few cm long and like to stay at the surface during the night, where they eat as much phytoplankton and other prey as they can. Then, when the sun is about to rise, they hurry down to the deep sea. They spend the whole day down there, and when the sun is setting, they hurry up to the surface again. We do not know exactly why these fishes perform DVM, but they may do so to avoid being eaten by bigger fishes. They spend the day safely in the deep, where it is always dark, and go up to the surface to feed during the night, when it is also dark. By spending most of their time in the dark, they avoid being seen by the big fish that want to eat them.

DIEL VERTICAL MIGRATION

Daily synchronized movement of fish and other swimming animals between the surface and the deep layers of the ocean. They spend the day at depth and the night at the surface.

HOW DO FISH AND WATER TEMPERATURE AFFECT THE ACTIVITY OF DEEP-SEA BACTERIA?

We wanted to know whether fish migration might be important for deep sea bacteria. Is there any relationship between the organic carbon that deep sea bacteria consume and the organic carbon that

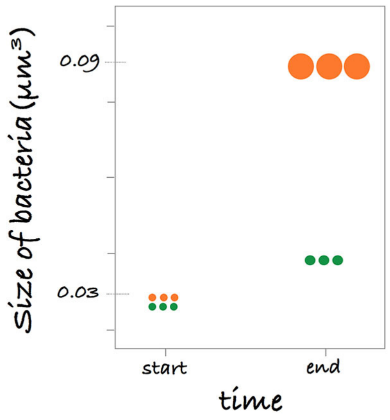


Figure 1

Figure 1

Size of bacterial cells at the start and end of the experiment with water from the surface (in green) and water from the fish layer (in orange). Bacteria from the surface did not grow much, but bacteria from the deep fish layer got very large by the end of the experiment. This tells us that the food available for bacteria in the deep water was very nutritious.

migrating fish provide? To answer this question, we performed an experiment in the Red Sea, one of the warmest seas in the world.

The Red Sea is particularly interesting to us. It can be considered an extreme environment due to its high temperatures, particularly in summer! Deep sea temperatures in other parts of the world are normally between 4 and 8°C. This is the temperature we have in our fridges … quite chilly! However, the deep waters of the Red Sea (from 200 m down to the seafloor) are almost 22°C. At this temperature, we can go out with short sleeves! The higher the temperature, the more active the bacteria are. Thus, the Red Sea, with a large population of migrating fishes and warm, deep waters, was an ideal place for us to test the response of deep bacteria to fish migration.

AN EXPERIMENT IN THE RED SEA

In our experiment, we went out at midday and collected water from the depth at which the fish retreat during the day (which we called the fish layer). We knew, from an instrument similar to radar that can detect the presence of fish, that the fish layer was between 500 and 600 m down. We decided to take water from 550 m and compare it with surface water from 5 m down. First, we filtered seawater through membranes with small pores so that only bacteria and DOM were included in the water, and then we brought this water to the lab for further studies. We placed the water samples in an incubator as close as possible to the conditions on site, so that the bacteria had the same number of light hours, dark hours, and the same temperature that they had in the ocean. Bacteria grow quickly, so we monitored changes in the numbers of bacteria and their size during 8 days, taking daily samples from our experimental bottles to measure how the bacteria were growing and how much DOM they were consuming.

We observed that bacteria from the fish layer grew faster than bacteria from the surface. Not only that, but they also got much fatter (Figure 1)!

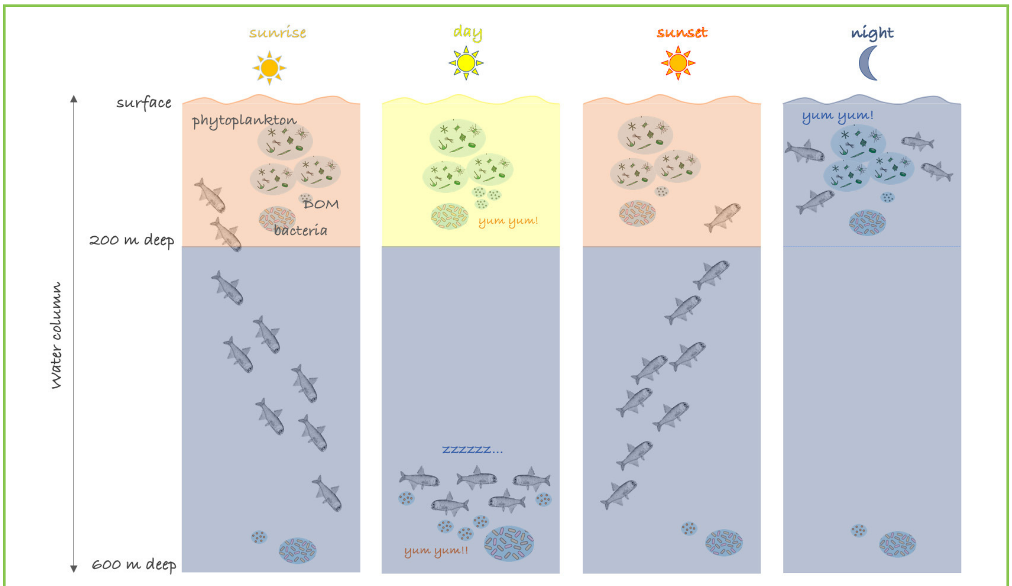


Figure 2

Figure 2

The diel vertical migration of skinnycheek lantern fish in the Red Sea. In the first panel, a school of fish are swimming from the surface to the deep waters around sunrise, and they retreat to even deeper waters during the day (second panel). At sunset, they swim back to the surface (third panel), where they feed on phytoplankton during the night (fourth panel). Phytoplankton always stay at the surface, while bacteria and DOM are present both at the surface and deep waters. During the day, surface bacteria consume DOM produced by phytoplankton, and bacteria in deep waters consume DOM provided by the fish. Representation of phytoplankton, bacteria and DOM are a modification from Buchan et al. [3]. Representation of the skinnycheek lanternfish is a fish illustration from Barton Warren Evermann [4].

That means that the bacteria found the DOM provided by fish more nutritive than that provided by phytoplankton at the surface. We were very surprised by this result. We believe that when fishes are at the fish layer during the day, they are chilling and digesting their night meal. They relax in the deep waters, pee and poo, and part of this pee and poo is DOM that becomes delicious food for the hungry bacteria of the deep sea. With this experiment, we proved that the vertical migration of fish between the surface and deep waters is not only moving carbon up and down, but it is also providing a source of good food for the deep bacteria!

WHAT WE LEARNED

Figure 2 shows what we have learned, represented by the diel vertical migration of the **skinnycheek lantern fish** in the Red Sea. While phytoplankton can only survive in the upper layers where light reaches, bacteria can live everywhere in the ocean. We thought that bacteria in the deep waters were not very active, and that they only consumed the DOM leftovers coming slowly down from the water's surface. However, our experiment suggests that fish migration to deep waters during the day creates a food hotspot for deep bacteria. This had never been seen before.

The next question that comes to our mind is whether this happens in all other oceans. And if so, what are the consequences? Hmm... we still do not know! Every time scientists discover something, new questions arise. There is still so much to learn about the oceans and how carbon is cycled!

SKINNYCHEEK LANTERN FISH

Example of a fish that migrates vertically in the oceans. It stays in deep water during the day and in surface water during the night. It is present in all the oceans.

ACKNOWLEDGMENTS

We would like to thank Nora Gutiérrez Avello (13), Maria de Lluch Calleja Serra (15), as well as the young reviewers and their mentor who read the original draft and provided very helpful feedback to improve it and make it understandable for their age range.

ORIGINAL SOURCE ARTICLE

Calleja, M. L., Ansari, M. I., Røstad, A., Silva, L., Kaartvedt, S., Irigoien, X., et al. 2018. The mesopelagic scattering layer: a hotspot for heterotrophic prokaryotes in the Red Sea twilight zone. *Front. Mar. Sci.* 5:259. doi: 10.3389/fmars.2018.00259

REFERENCES

1. Azam, F., Smith, D. C., Steward, G. F., and Hagström, Å. 1994. Bacteria-organic matter coupling and its significance for oceanica carbon cycling. *Microb. Ecol.* 28:167–79. doi: 10.1007/BF00166806
2. Arístegui, J., Gasol, J. M., Duarte, C. M., and Herndl, G. J. 2009. Microbial oceanography of the dark ocean's pelagic realm. *Limnol. Oceanogr.* 54:1501–29. doi: 10.4319/lo.2009.54.5.1501
3. Buchan, A., LeCleir, G. R., Gulvik, C. A., and González, J. M. 2014. Master recyclers: features and functions of bacteria associated with phytoplankton blooms. *Nat. Rev. Microbiol.* 12:686–98. doi: 10.1038/nrmicro3326
4. Jordan, D. S., and Evermann, B. W. 1902. *American Food and Game Fishes: A Popular Account of All the Species Found in America North of the Equator, With Keys for Ready Identification, Life Histories and Methods of Capture.* London: Hutchinson and Co.
5. Brierley, A. S. 2014. Diel vertical migration. *Curr. Biol.* 24:R1074. doi: 10.1016/j.cub.2014.08.054

SUBMITTED: 31 October 2019; **ACCEPTED:** 29 May 2020;
PUBLISHED ONLINE: 09 July 2020.

EDITED BY: Christian Robert Voolstra, University of Konstanz, Germany

CITATION: Calleja ML and Morán XAG (2020) Red Sea Fishes That Travel Into the Deep Ocean Daily. Front. Young Minds 8:85. doi: 10.3389/frym.2020.00085

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

CHLOE, AGE: 15

Hello! My name is Chloe, I am currently 15 years old. My hobbies include reading, singing, writing and researching. I love to spend hours reading online or with a paperback, depending on my mood, I just love to read. I am currently living with my two Persian cats that love to sing in the night like me and are both lazy like me. In the future, I would like to be a virologist or a genetic scientist, if I do not get to be one of them, I am just gonna be an author …

HALA, AGE: 15

Hey! My name is Hala, I am 15 years old and I spend my free time reading and writing short stories. I have an interest in history, politics, economics, and biology. I hope to study journalism in the future, so that I can write articles like these!

HUSSAM, AGE: 15

My name is Hussam am I am 15 years old. My hobbies include painting, badminton, and photography. My favorite science is biology and I am currently working in a musical production during my after school activities.

SABREEN, AGE: 10

Bonjour (hello), my name is Sabreen I am 10 years old and I have many passions including science and math. I really like reading and one of my favorite book series is Harry Potter. I also enjoy playing sports (netball, tennis, table tennis, swimming …) and baking.

XENIA, AGE: 15

My name is Xenia. I like Science and I think it is awesome to be able to read a scientific article and actually understand what it says. In my spare time I like to read, do gymnastics, and take pictures.

AUTHORS

MARIA LL. CALLEJA

Maria is a marine researcher focused on understanding carbon cycling in the oceans. Her broad interest has brought her to work on systems as different as the tropical and polar ecosystems. Maria's research is focused on the role of microbial organisms in controlling the ocean carbon cycle, and how this is changing in a warming scenario. *maria.calleja@mpic.de

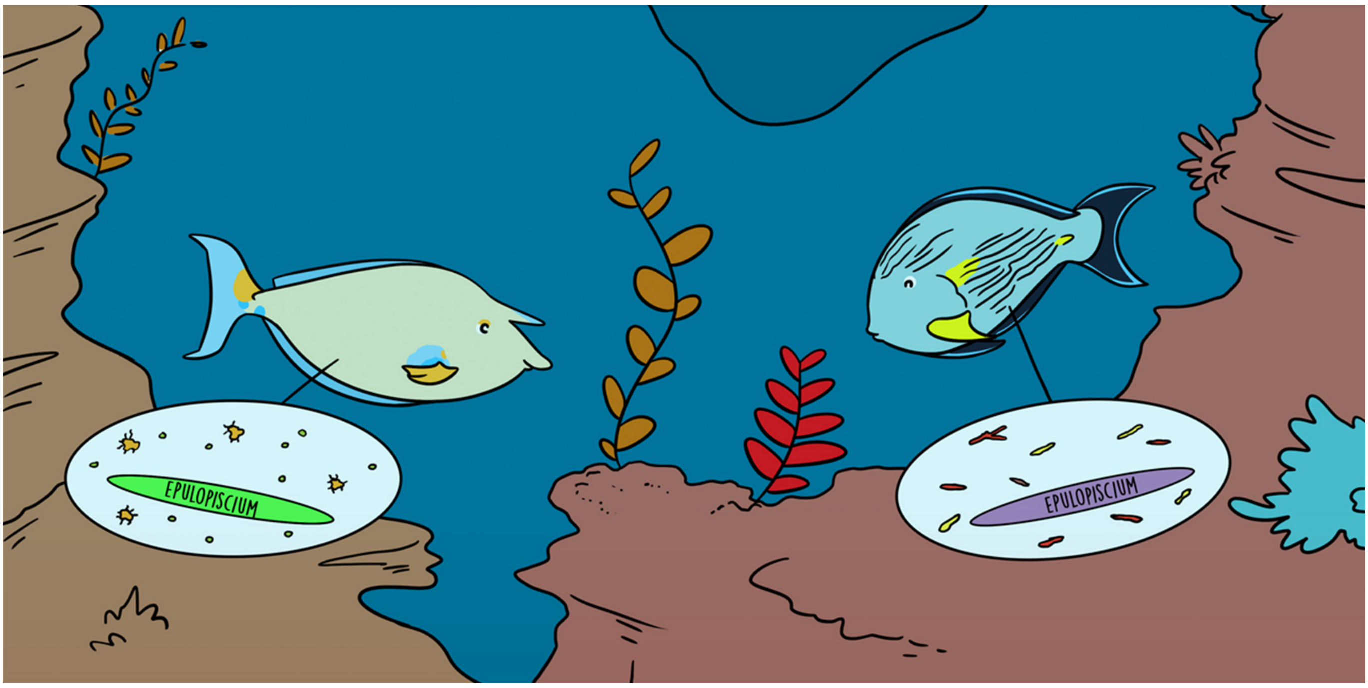
XOSÉ ANXELU G. MORÁN

Xelu is a professor of biological oceanography and microbial ecology focused on small-sized plankton and its role in the ocean carbon cycle. His interests include phytoplankton-bacteria interactions, variability of photosynthesis and primary

production, and long-term changes of marine microbial organisms, aimed at understanding the structure and function of microbial food webs and their response to global change.

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 29 May 2020
doi: 10.3389/frym.2020.00058



A UNIQUE BELLYFUL: EXTRAORDINARY GUT MICROBES HELP HERBIVOROUS FISH EAT SEAWEEDS

Matthew D. Tietbohl[1*], David Kamanda Ngugi[2] and Michael L. Berumen[1]

[1] *Division of Biological and Environmental Science and Engineering, Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia*

[2] *Leibniz Institute DSMZ - German Collection of Microorganisms and Cell Cultures GmbH Department of Microorganisms, Braunschweig, Germany*

YOUNG REVIEWERS:


ALANA
AGE: 12


IDHANT
AGE: 12


KONSTANTIN
AGE: 12


LILIAN
AGE: 11


SHIRHAN
AGE: 12

All animals rely on a unique community of microbes to help digest food. This is especially true for plant-eating animals, which need a complex mix of gut bacteria, also known as microbes, to digest the tough plant material they eat. However, when it comes to herbivorous animals in the sea, like some fish, we know much less about the role microbes play in helping to digest food. Marine algae, better known as seaweeds, are unlike land plants in many ways, so herbivorous fish species likely have unique ways of digesting them. Therefore, we investigated the gut microbes in several herbivorous fishes in the Red Sea to see how they help fish digest algae. Surprisingly, we found that even though these fish had unique gut microbe communities, all were made up by varieties of one type of giant bacteria that appears to have evolved to help them digest their favorite algae!

THE IMPORTANCE OF SLIMY SEAWEED

What do you think about when you hear the word seaweed? Does it sound tasty to you? While many people think of seaweed, known to scientists as marine algae, as a slimy and smelly green mass they get tangled in at the beach or lake, many animals actually think algae is quite delicious! This is especially true of plant eating fishes, also called herbivorous fishes, that are found on coral reefs, which have become specialized in feeding on different types of algae. Algae come in many different shapes and sizes, from algae that form short, grass-like lawns growing on underwater rocks, to large, tough bush-like forms. Algae form important habitats for many animals, but too much algae can kill or overgrow corals. This can lead to coral reefs losing the complex structure that allows them to house thousands of species. Fish that eat algae play an important role, by controlling the amount of algae that grows on coral reefs. When they remove algae, they also create new space where corals or other animals can settle down and grow. By eating algae, they help keep coral reefs healthy and clear of most algae, which allows corals to grow and thrive, creating more habitat for other fish and animals to live!

POLYSACCHARIDE

An energy source that is made up of sugar molecules linked together in a chain, for example, table sugar. Table sugar is a polysaccharide made up by two single sugar molecules—glucose and fructose—linked together.

There is, however, a big problem these herbivorous fishes face when they eat algae. It is not easy to digest! Algae, like all living things, are made up of cells, with each specialized for a certain role. The cells of algae hold complex, large chains of sugars, called **polysaccharides** (pronounced, "pol-ee-sack-ah-ride"). Different algae have their own, unique composition of these large sugar chains within their cells (Figure 1). To get energy from algae, herbivorous fishes need to break down these large chains. Inside the guts of fish are molecules known as **enzymes** (think of them as molecular or chemical scissors) that can break these sugar chains into smaller parts fish can absorb into their bodies. There are many different types of these enzymes, functioning like different workers on a construction team. Each enzyme has a specific job in breaking down different parts of algae. However, not all fish have the right kinds of enzymes to break down algae. So, how are they able to get nutrients from algae that are hard to digest?

ENZYME

A molecule that helps to speed up chemical reactions. In digestion, enzymes are used to break chemical bonds between molecules to produce smaller, easier-to-digest molecules, a bit like scissors.

MICROBES HELP DIGEST FOOD

On land, we know a lot about how herbivores can digest complex polysaccharides in plants, which are structurally similar to algae. Most herbivores rely on tiny **microbes** that live inside their intestine to break down plants. These special gut microbes have evolved the enzymes they need to get energy from food, and herbivores, like cows, rely on their gut microbes to break down the grass and hay they eat into molecules they can absorb [1]. Microbes play a really important role in allowing these animals to get energy from foods they could not eat on their own. While we know a lot about this relationship and how it works with land animals, how it works in sea animals is largely

MICROBE

Tiny living things found in the environment all around us and inside us. They include kinds of bacteria, and related germs. They play a key role in helping animals digest their food.

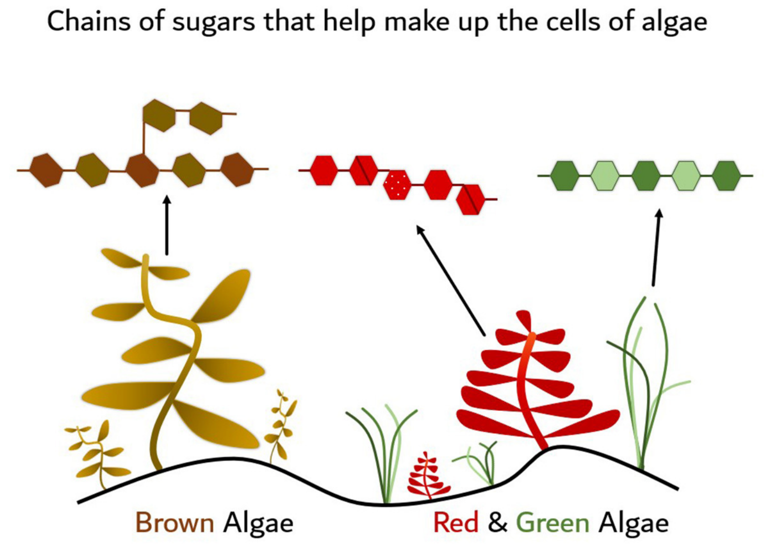


Figure 1

Figure 1

Examples of different types of marine algae, or seaweeds, including brown, red, and green types. Each type of algae has different chains of sugars, known as polysaccharides, which help make up their cells. This means that each fish needs special kinds of enzymes, or molecular scissors, to help break each alga (singular of algae) down into smaller nutrients that are easier to digest. If they do not have the right enzymes, then they will not be able to break down their algae food.

unknown. It is important to learn about how marine animals, like fish, digest their food because it allows us to better understand what they can eat and how they share different species of algae between themselves [2].

Therefore, the goal of this study was to take a first look into the gut microbe community of herbivorous coral reef fish to understand how important the gut microbes are in helping digestion, and to see if different fish have different gut microbe communities or not.

WHAT WE DID

To understand how herbivorous fishes rely on their gut microbes to digest algae, we collected samples from the stomachs of herbivorous surgeonfishes, like Bluespine unicornfish and Sohal surgeonfish, in the Red Sea. We collected fish that we knew ate different kinds of algae to see if differences in diet would change the gut microbes of the fish. Next, we had to see if the microbes had the right tools, or enzymes, that were required to break down the algae that were eaten. To do this, we looked at the **transcripts**, which are like building codes that cells use to make molecules like enzymes, made by the fish's gut microbes!

TRANSCRIPT

Also known as messenger RNA, it is a copy of a piece of the cell's DNA. It is an instruction for the cell to know how to build different types of proteins, such as enzymes.

WHAT WE FOUND

First, we found that of all the microbes in the stomachs of all the fish we sampled, there was one kind of microbe that was most common—**Epulopiscium**. *Epulopiscium* (pronounced "E-pool-oh-piss-ee-um") is a giant microbe, more than 1,000 times larger than other common gut microbes, and as large as the width of a human

EPULOPISCIUM

A large microbe (bigger than a width of a hair and smaller than a frog egg) that has been discovered to live inside the stomachs of certain kinds of tropical surgeonfishes.

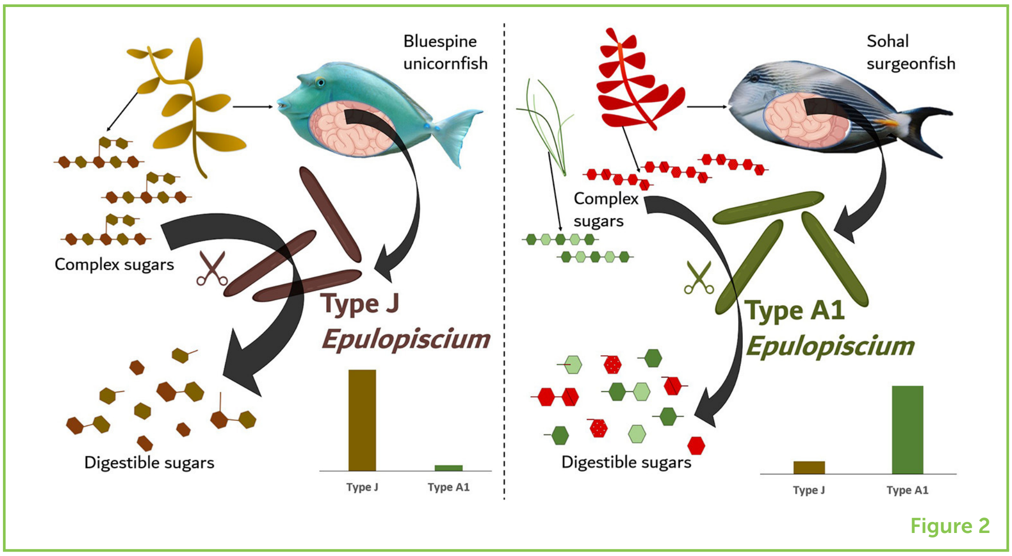


Figure 2

A diagram showing differences in the gut microbes between two kinds of surgeonfishes that eat different types of algae. Bluespine unicornfish eat mostly brown algae and have giant microbes of Type J *Epulopiscium*, while Sohal surgeonfish eat mostly red and green algae and have Type A1 *Epulopiscium*, shown in the small graphs showing the relative amount of each giant microbe type. These giant microbes, about the size of the width of a human hair, are specialized to only be able to break down the kinds of algae their host fish like to eat. They do so by breaking apart complex chains of sugars, called polysaccharides, into smaller, more digestible pieces with enzymes represented by the colored scissors. Stomach and microbe images are from BioRender© and fish images are from FishBase.

hair! Interestingly, not only did this large microbe dominate the gut microbe community, but different fish were found to have different types of *Epulopiscium* living inside them (Figure 2)! The fish that ate mostly brown algae had types of *Epulopiscium* living in their stomachs that were not found in the other fish's stomachs that ate mostly red and green algae. This showed that because these fish ate different algae, they needed a different kind of gut microbe community to digest their food.

Indeed, when we looked at the enzymes made by these giant microbes, we found that they produced certain enzymes that had the ability to break down the different components of the algae that fish fed on. This means herbivorous fishes that eat brown algae have stomach microbes with the enzyme machines needed to break down brown algae. These same brown algae-eating gut microbes would not be as successful at breaking down green or red algae. What we discovered for the first time, is that herbivorous fishes contain special groups of gut microbes with the enzymatic tools needed to break down the specific types of algae they eat! This was really amazing, especially since all this digestion seems to be led by the giant *Epulopiscium*. In other animals, especially land mammals, there is a more diverse community of gut microbes that all help break down plant matter [3]. It turns out that tropical herbivorous fishes have evolved a different, and perhaps unique, way of digesting the complex algae they eat!

We even found that the amount of this giant microbe and its enzymes changes inside the stomach of the fish throughout the day (Figure 3). After herbivorous fishes wake up, they start their day looking for algae to eat, and spend most of their day looking for their favorite algae foods. During the day when they are actively eating, the giant microbe *Epulopiscium* is the most active and produces a lot of enzymes to help break down the algae. But at night when the fish is not eating

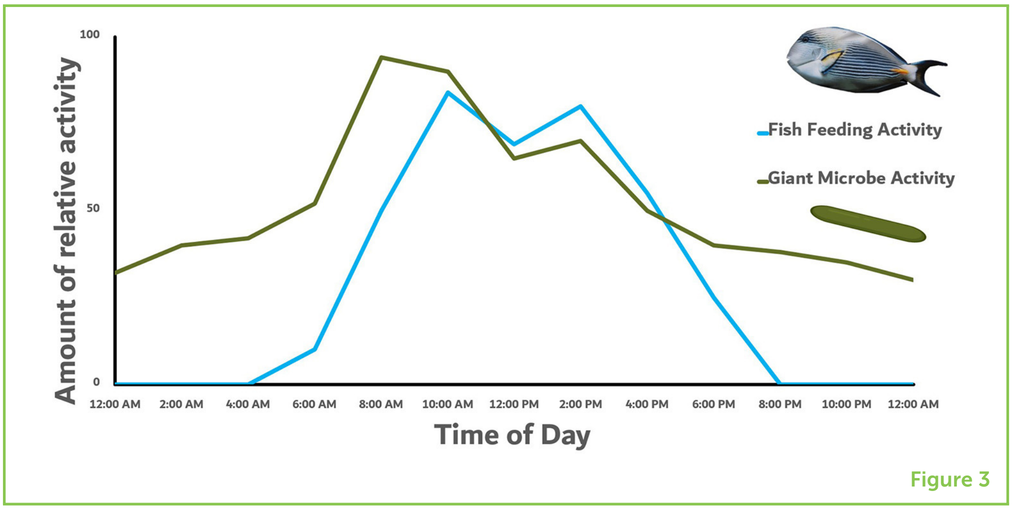


Figure 3

A graph showing the feeding activity of a Sohal surgeonfish over the course of a day. We found that the activity of the giant microbe *Epulopiscium* closely follows the feeding activity of its host fish, providing evidence that they play an important role in helping the fish digest the algae it is eating during the day. The activity of the giant microbe is higher than the feeding activity because it has to digest the algae in the stomach of the fish after it eats the algae. The microbe image is from BioRender© and the fish image is from FishBase.

and rests, *Epulopiscium* slows down and stops producing so many of these enzymes since there is not any new algae in the stomach for it to help digest. Because the activity of *Epulopiscium* fluctuates along with the amount of algae the fish eats over a full day, this provides strong evidence that these fish rely heavily on their *Epulopiscium* gut microbes to help break down the algae they eat!

WHY DOES THIS MATTER?

It may seem obvious that fish gut microbe communities have adapted themselves to the diet of the fish they live inside. However, this is something no one has described in detail before. This discovery of a close relationship between the *Epulopiscium* microbe and the host fish diet has big implications for how we view plant-eating behavior on coral reefs. First, these consistent differences in types of gut microbes may provide a way for herbivorous fishes to occupy the same reef and lower competition for limited food items. If they can only consume and digest certain algae, then they are less likely to eat algae that other species are specialized to digest. Second, this means that these fish may be more limited in what they are able to eat than previously thought. Herbivorous fishes may not be able to get as much energy from different kinds of algae they normally do not eat. Things like pollution or climate change can change the type of algae species found on coral reefs and may change the herbivorous fish community to be made up of only those that can digest the most common algae. But we also know that gut microbe communities may not always be stable and could change over time [4]. With changing algae communities, herbivorous fishes might be able to change their gut microbes for different kinds that are better at digesting algae. However, the flexibility of gut microbe communities is something we still know very little about in marine fish and is an important area for future research!

These Red Sea surgeonfish have taught us a lot about how herbivorous fishes depend on their giant gut microbes to be able to eat algae. However, we have only looked at a few species and there are many different kinds of herbivorous fishes out there. The more we learn about this unique relationship between fish and their gut microbes in the Red Sea, the better we will be able to understand how herbivorous fishes are able to function here, and all over the world!

ORIGINAL SOURCE ARTICLE

Ngugi, D. K., Miyake, S., Cahill, M., Vinu, M., Hackmann, T. J., Blom, J., et al. 2017. Genomic diversification of giant enteric symbionts reflects host dietary lifestyles. *Proc. Natl. Acad. Sci. U.S.A.* 114:E7592–601. doi: 10.1073/pnas.1703070114

REFERENCES

1. White, B. A., Lamed, R., Bayer, E. A., and Flint, H. J. 2014. Biomass utilization by gut microbes. *Ann. Rev. Microbiol.* 68:279–96. doi: 10.1146/annurev-micro-092412-155618
2. Miyake, S., Ngugi, D. K., and Stingl, U. 2015. Diet strongly influences the gut microbiota of surgeonfishes. *Mol. Ecol.* 24:656–72. doi: 10.1111/mec.13050
3. Ley, R. E., Hamady, M., Lozupone, C., Turnbaugh, P. J., Ramey, R. R., and Bircher, J. S., et al. 2008. Evolution of mammals and their gut microbes. *Science* 20:1647–51. doi: 10.1126/science.1155725
4. Jones, J., DiBattista, J. D., Stat, M., Bunce, M., Boyce, M. C., Fairlough, D. V., et al. 2018. The microbiome of the gastrointestinal tract of a range-shifting marine herbivorous fish. *Front. Microbiol.* 9:2000. doi: 10.3389/fmicb.2018.02000

SUBMITTED: 01 July 2019; **ACCEPTED:** 27 March 2020;
PUBLISHED ONLINE: 29 May 2020.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Tietbohl MD, Ngugi DK and Berumen ML (2020) A Unique Bellyful: Extraordinary Gut Microbes Help Herbivorous Fish Eat Seaweeds. Front. Young Minds 8:58. doi: 10.3389/frym.2020.00058

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ALANA, AGE: 12

My name is Alana and I like to read all sorts of books and draw. My favorite color is blue and my favorite animal changes very often. My favorite book character is Percy Jackson.

IDHANT, AGE: 12

Hi. I like traveling. I also like Lego. I have lived in France for around a year. I like photography. I am from India. I like reading, science, and wildlife. Okay. Bye.

KONSTANTIN, AGE: 12

I am from Kalinigrad, Russia. I have one sister who is 1 year old. I like programming and snorkeling. My favorite food is nigiri. I have been in five countries.

LILIAN, AGE: 11

Hi, my name is Lili! I am 11 years old, and I am from Denver, Colorado, in the States. I like to read, especially Percy Jackson. I hope you like our article.

SHIRHAN, AGE: 12

Hi my name is Shirhan and I grew up in Boston. I love to read lots of books mostly Wing of Fire and I hope you like our article!

AUTHORS

MATTHEW D. TIETBOHL

Matt first found his love for the sea lifting up rocks in the intertidal zone of Jamaica, and he has barely looked back since. Matt has always been amazed by the diversity of species and shapes found below the surface of the sea. Combined with his love of spending time outdoors and never-ending curiosity, he found himself pursuing a Master's degree and then a Ph.D. in Saudi Arabia, studying the Red Sea. He is thrilled to be learning more about herbivorous reef fishes and exciting new techniques to better understand how they use and help coral reefs around the world.

*matthew.tietbohl@kaust.edu.sa

DAVID KAMANDA NGUGI

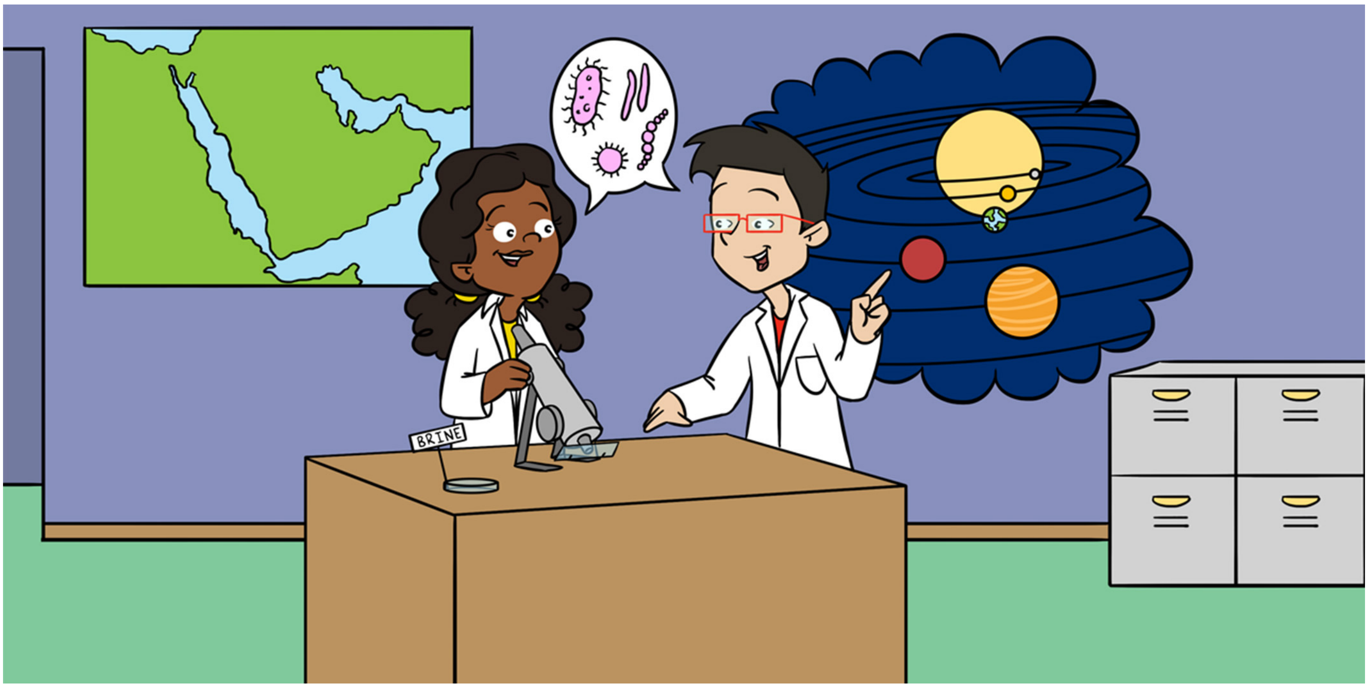
Dr. David Kamanda Ngugi is a microbe ecologist with a special focus on marine ecosystems. He is most interested in using cutting-edge techniques to understand the evolutionary adaptations and roles of "rare" microbes in the ocean. Dr. Ngugi has studied microbes all over the world, from Kenya to Saudi Arabia, Germany and many more places. His work is focused on teaching key information about the roles microbes play in nutrient cycling, extreme environments, and gut systems, like herbivorous fishes!

MICHAEL L. BERUMEN

Dr. Michael Berumen first developed his love for underwater life while mucking around the lakes and rivers of Arkansas, USA. He went on to study butterflyfishes on the Great Barrier Reef in Australia, and later focused his studies on movement and connectivity in coral reef fish. He now works in Saudi Arabia where his lab not only studies fish movement, but many other exciting aspects of ecology and biodiversity. As Mike tells all his students, there is always something exciting to learn on every trip out to sea!

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 27 October 2020
doi: 10.3389/frym.2020.545761



OUT OF THIS WORLD: FROM THE BOTTOM OF THE RED SEA TO THE RED PLANET

André Antunes*

State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau, China

YOUNG REVIEWERS:


CHLOE
AGE: 15


FABIÁN
AGE: 12


NAGA
AGE: 15


SAGE
AGE: 11


XENIA
AGE: 15

The deep-sea brines of the Red Sea are some of the most extreme environments on Earth. They have high salinity, high temperature, high pressure, and no oxygen. Despite such harsh conditions, several organisms still live in these brines. The study of deep-sea brines and their inhabitants has several advantages. In addition to finding several new species, deep-sea brines are a source of useful new molecules produced by these organisms. These new molecules could be used for healing people or even cleaning up our planet. The deep-sea brines could also aid us in looking for extraterrestrial life. These brines are also helpful for planning future space missions due to similarities with conditions on other planets and moons.

WHAT ARE DEEP-SEA BRINES AND HOW ARE THEY FORMED?

The Red Sea is unique! It is growing by a few millimeters every year. In a few million years it will become a full-fledged ocean, like the Atlantic or the Pacific. The Red Sea is growing because of the separation of the

TECTONIC PLATES

Large pieces of the Earth's crust shifting or moving around, sometimes. Bumping into one another or moving away from each other.

Arabian and African **tectonic plates**. The gap left between these plates, which is in the middle of the Red Sea, is filled by patches of new oceanic crust. As oceanic crust is denser than continental crust, these patches create deep spots called deeps (a deeper area or hole in the seafloor) and are scattered across the mid-section of the Red Sea [1].

The movement of the earth's crust happening under the Red Sea exposes massive buried deposits of salt. The deposits were formed from the drying of a prehistoric ocean that existed in this area. The seawater dissolves some of the salt and becomes a brine, which is very salty water. Salinity, which is the word for the measure of saltiness, can increase by up to 7-fold in the brines. These brines are heavy, so they concentrate at the bottom of the sea and accumulate in the deeps formed by the oceanic crust. The high density of the brines and their sheltered location in the deeps prevents them from mixing with seawater. Because of this, deep-sea brines are very stable and look like underwater lakes. They even have waves across their surfaces and beaches at their rims. In addition to higher salinity, brines have other differences from seawater: they have no oxygen and have higher amounts of metals and other elements. Brines also have a lower pH than seawater and a higher temperature.

AN ACCIDENTAL DISCOVERY

Deep-sea brines were accidentally discovered in the 1950s, when researchers collected a deep-sea water sample that was much saltier and warmer than usual. Follow-up surveys discovered at least 25 different deep-sea brines scattered across the center of the Red Sea (Figure 1). Each brine is unique due to differences in local geology, age, and differences in heating from the earth's crust [1]. Atlantis II is the biggest (over 80 km^2), the hottest (68.2°C), and one of the oldest brines. On the other extreme, Kebrit is the smallest (2.5 km^2), the coldest (23.3°C), and one of the youngest brines. Kebrit is also rich in sulfur and is very smelly—"kebrit" is the Arabic word for sulfur, which smells like rotten eggs.

WHAT LIVES IN DEEP-SEA BRINES?

MOLECULAR BIOLOGY

The study of living things based on their molecules (such as DNA or proteins) rather than the whole organism.

For a long time, researchers thought that conditions in the deep-sea brines were too extreme for life. They assumed that no organisms would be able to survive there. However, technical advances, particularly in **molecular biology**, allowed us to explore the brines in more detail and revealed thriving communities. Studies have found microbes, animals, and even viruses in the brines [1]. These studies have discovered many new species, some unlike any other on our planet (Figure 2). These organisms are so unique that some

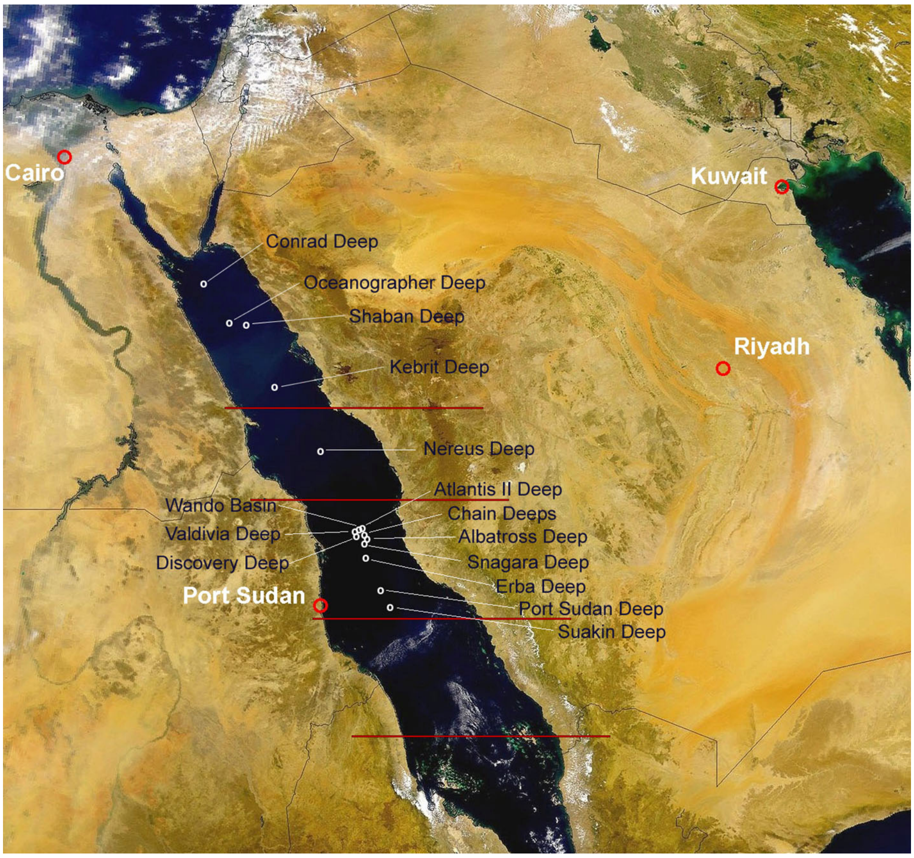


Figure 1

Figure 1

Map of the Red Sea showing the locations of the main deep-sea brines. The red lines on the map show regions with different stages of tectonic activity and development of the brines.

of these findings are equivalent to finding the very first carnivores or vertebrates!

WHY SHOULD WE STUDY BRINE MICROBES?

There are more microbes in our oceans than stars in the universe [4]! Yet, more than 99% of the total microbial diversity remains unexplored. The discovery of new microbes and the study of their abilities are always exciting. We keep uncovering new ways that microbes impact our planet and all life on Earth.

EXTREME ENVIRONMENT

Place with conditions that are very different from the ones that we are able to live in. Some examples include high or low temperatures, acidic or alkaline conditions, high pressure, or high salinity.

Because microbes can grow in such unique conditions, those from **extreme environments** are often a source of valuable new molecules. Their range of applications is so wide that these molecules are seen as the future solutions on how to feed, fuel, and heal the world [5]. Microbes from the brines of the Red Sea also seem to be very useful. Some show anti-cancer activity, while others seem capable of producing bioplastics (biologically-produced plastics that do not rely on the use of oil), cleaning up oil spills, or even capturing carbon dioxide [6]. Scientists think that some of these microbes could be used to restore contaminated sites or even to prevent climate change! Studying extreme environments like the deep-sea brines also helps

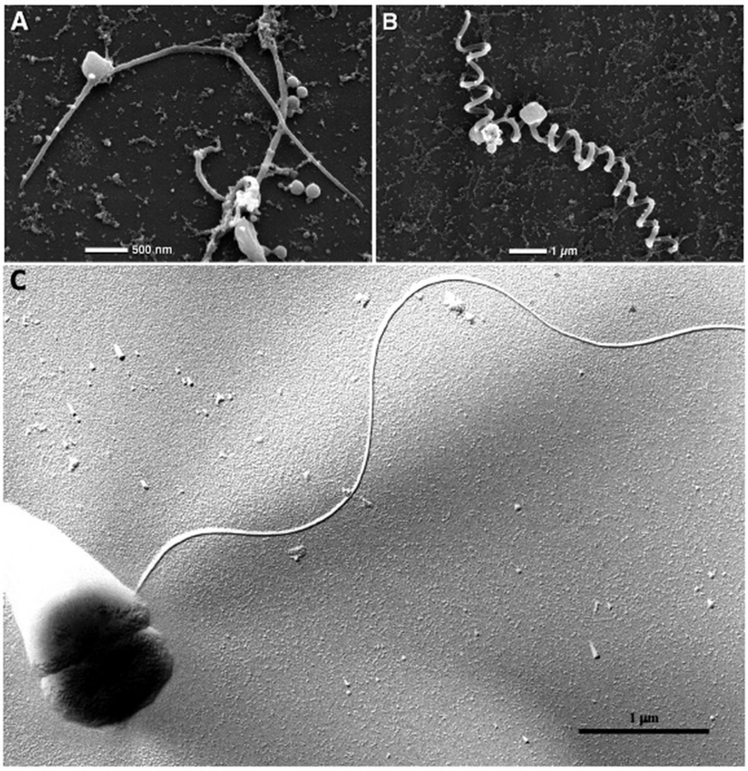


Figure 2

Figure 2

The deep-sea brines contain many exotic new species. *Haloplasma contractile* is a newly discovered bacterium that can **(A)** contract and **(B)** relax its cells. **(C)** *Salinisphaera shabanensis* is another new bacterium found in deep-sea brine that is able to grow well in very different salinities. Both microbes were observed with electron microscopy, a powerful technique in which a microscope uses electron beams instead of light to create an image (Image credits: **A,B**: Copyright © American Society for Microbiology [2]; **C**: Copyright © Springer [3]).

us to test hypotheses about the physical and chemical limits for the existence of life. These findings could aid researchers looking for life elsewhere in the universe.

TO INFINITY AND BEYOND!

Astrobiology is a new science combining many different fields, including biology, geology, chemistry, and planetary sciences. Its main goal is the search for life outside our planet. Currently Mars, Jupiter's moon Europa, and Saturn's moon Enceladus are the top candidates when looking for extraterrestrial life (Figure 3). The extreme conditions that exist in those places are not very different from some extreme places on Earth [7]. The presence of water, which is essential for life, is very likely on Mars, Europa, and Enceladus, and that water probably has high salinity like that found in the brines of the Red Sea. Astrobiology also studies the limits of life—how extreme do conditions have to be before life cannot possibly exist? This goal can be aided by the exploration of extreme environments on Earth. Findings from these extreme terrestrial environments can help us prepare for future space missions looking for life.

The deep-sea brines of the Red Sea are important astrobiological sites [7]. They resemble the predicted conditions at the bottom of the oceans of Europa and Enceladus. They are a source of microbes that

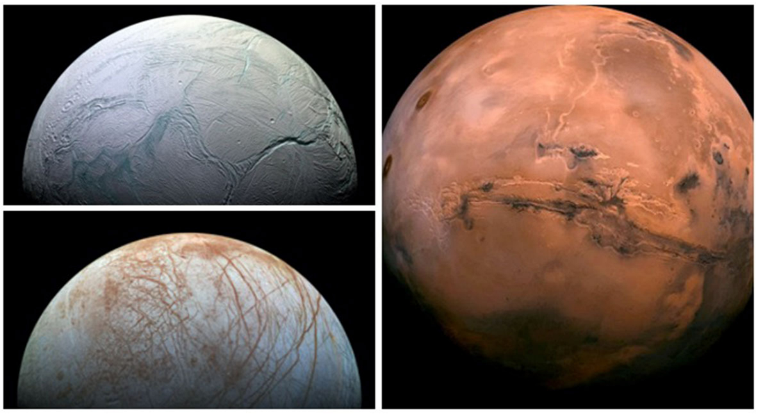


Figure 3

Figure 3

The current main targets for astrobiological research on our solar system are the moons Enceladus (top left) and Europa (bottom left), and the planet Mars (right). Image credits NASA.

have been picked as priority targets for astrobiological studies. Several of these microbes are being tested in simulation chambers and in balloon trips to the upper layers of earth's atmosphere. A selected few will even be sent to the International Space Station for space-exposure experiments. These studies will allow us to see if these microbes can survive and grow when exposed to space or to conditions found on Mars.

CONCLUSION

The deep-sea brines of the Red Sea are amazing, extreme environments unlike any other on our planet. These brines are important for many different fields. They are a source of exotic new microbes, new applications, and are also useful in the search for extraterrestrial life. We have only just started to explore deep-sea brines and their inhabitants and can expect many new findings in the near future.

REFERENCES

1. Antunes, A., Ngugi, D. K., and Stingl, U. 2011. Microbiology of the Red Sea (and other) deep-sea anoxic brine lakes. *Environ. Microbiol. Rep.* 3:416–33. doi: 10.1111/j.1758-2229.2011.00264.x
2. Antunes, A., Rainey, F. A., Wanner, G., Taborda, M., Pätzold, J., Nobre, M. F., et al. 2008. A new lineage of halophilic, wall-less, contractile bacteria from a brine-filled deep of the Red Sea. *J. Bacteriol.* 190:3580–7. doi: 10.1128/jb.0 1860-07
3. Antunes, A., Eder, W., Fareleira, P., Santos, H., and Huber, R. 2003. *Salinisphaera shabanensis* gen. nov., sp. nov., a novel, moderately halophilic bacterium from the brine–seawater interface of the Shaban Deep, Red Sea. *Extremophiles* 7:29–34. doi: 10.1007/s00792-002-0292-5
4. Antunes, A., Stackebrandt, E., and Lima, N. 2016. Fueling the bio-economy: European culture collections and microbiology education and training. *Trends*

Microbiol. 24:77–9. doi: 10.1016/j.tim.2015.11.010
5. Antunes, A., Simões, M. F., Grötzinger, S. W., Eppinger, J., Bragança, J., and Bajic, V. B. 2017. "Bioprospecting archaea: focus on extreme halophiles," in *Bioprospecting. Topics in Biodiversity and Conservation*, Vol. 16, eds R. Paterson and N. Lima (Cham: Springer). p. 81–112. doi: 10.1007/978-3-319-47935-4_5
6. Varrella, S., Tangherlini, M., and Corinaldesi, C. 2020. Deep hypersaline anoxic basins as untapped reservoir of polyextremophilic prokaryotes of biotechnological interest. *Mar. Drugs* 18:91. doi: 10.3390/md18020091
7. Antunes, A., Olsson-Francis, K., and McGenity, T. J. 2020. Exploring deep-sea brines as potential terrestrial analogues of oceans in the icy moons of the outer solar system. *Curr. Issues Mol. Biol.* 38:123. doi: 10.21775/cimb.038.123

SUBMITTED: 26 March 2020; **ACCEPTED:** 16 September 2020; **PUBLISHED ONLINE:** 27 October 2020.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Antunes A (2020) Out of This World: From the Bottom of the Red Sea to the Red Planet. Front. Young Minds 8:545761. doi: 10.3389/frym.2020.545761

CONFLICT OF INTEREST: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

CHLOE, AGE: 15
Hello! My name is Chloe, I am currently 15 years old. My hobbies include reading, singing, writing, and researching. I love to spend hours reading online or with paperback, depending on my mood, I just love to read. I am currently living with my two Persian cats that love to sing in the night like me and are both lazy like me. In the future, I would like to be a virologist or a genetic scientist, if I do not get to be one of them, I am just gonna be an author...

FABIÁN, AGE: 12
Fabián is a world traveling, 12 years old, seventh grade polyglot who loves the ocean and being creative. His hobbies are: mountain biking, lego, inventing, acting, and reading, but especially reading. He loves being a part of the Frontiers for Young Minds program and looks forward to next year!

NAGA, AGE: 15

I am a 15 year old girl, only child, born and raised in India. I have been living in KAUST for 7 years. I love to sing and dance, and perform any kind of sports. I like theater, but not enough to perform live because I always forget my lines

SAGE, AGE: 11

I am Sage, I like drawing, art, and playing my violin. I write stories and read my fave books like Septimus Heap and Harry Potter. I am creative and like adventures, I like customizing clothes and making bracelets and I am a good singer.

XENIA, AGE: 15

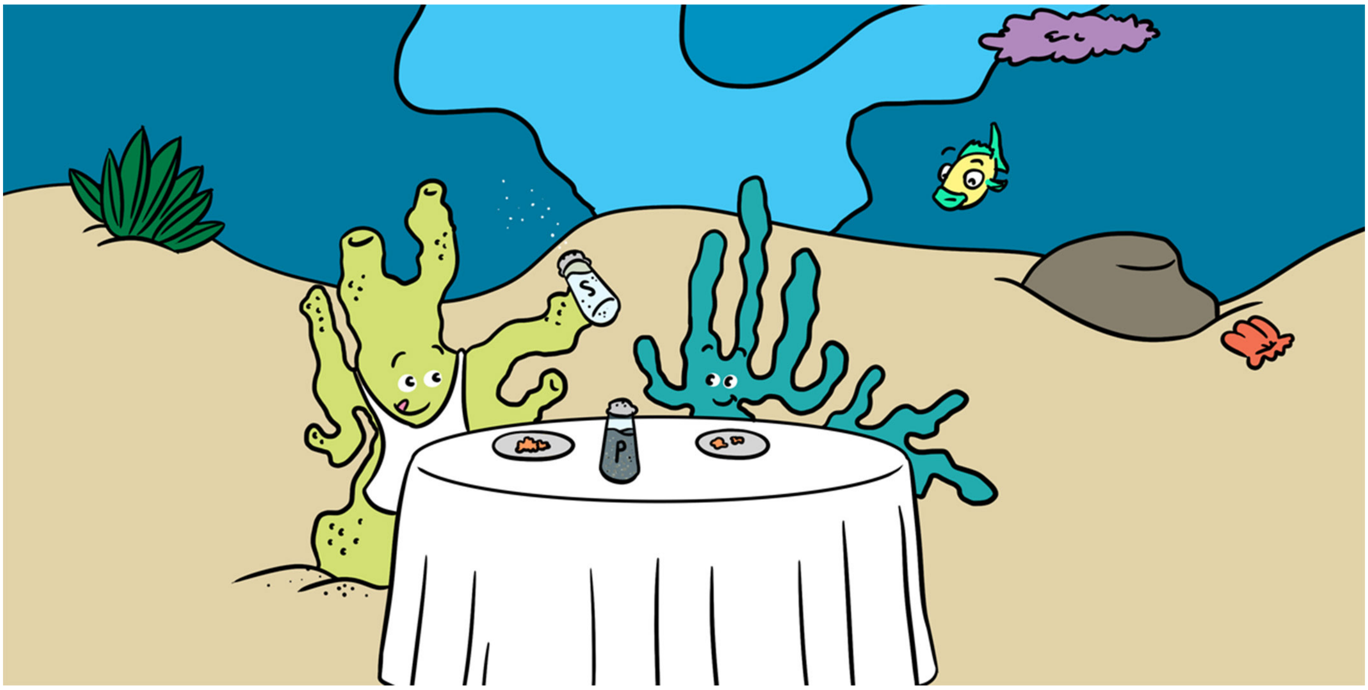
My name is Xenia. I like Science and I think it is awesome to be able to read a scientific article and actually understand what it says. In my spare time I like to read, do gymnastics, and take pictures.

AUTHOR

ANDRÉ ANTUNES

I am an Associate Professor and leader of the Astrobiology Unit of the State Key Laboratory of Lunar and Planetary Science at the Macau University of Science and (Macau, China). I study life on the edge and exotic new microbes living in unexplored extreme environments, from salty lakes, to mines, to deep-sea locations. Many of these environments have conditions similar to those found on Mars and other planets. Studying these environments helps us when looking for life outside our planet and allows us to find the limits of life. Extreme environments are a source of unusual new species and new applications that can help us to feed, fuel, and heal the world. *aglantunes@must.edu.mo

BIODIVERSITY
Published: 07 March 2019
doi: 10.3389/frym.2019.00038



A SALTY CORAL SECRET: HOW HIGH SALINITY HELPS CORALS TO BE STRONGER

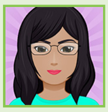
Hagen M. Gegner* and Christian R. Voolstra

Division of Biological and Environmental Science and Engineering, Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

YOUNG REVIEWERS:


SAVANA
AGE: 13


KAREN
AGE: 12


MALSHI
AGE: 12


YOUSSEF
AGE: 12


ZIA
AGE: 12

Corals are mysterious animals that have been around for ages. They are the creators of beautiful reefs. Sadly, the reefs that we love to look at are in danger of overheating and are disappearing from our planet. While this sounds bad, not all corals are affected the same way by warm seawater. Corals from the Red Sea seem to be more resistant to higher temperatures than are corals from other regions. Red Sea reefs are thriving in seawater that is hotter than that in other places. But what is their secret? What makes Red Sea corals stronger and more heat resistant? We know that Red Sea corals not only handle the incredibly high temperatures, but also deal with high salinity (saltiness). This connection between high salinity and high temperature made us wonder: can we find evidence that high salinity makes corals stronger?

ANCIENT CREATURES IN DANGER OF OVERHEATING

Reefs are incredibly colorful, fascinating underwater structures. They are created by some of the world's oldest animals: corals. Corals have been around since the time of the dinosaurs, but unlike those famous creatures, corals did not go extinct. At least not yet.

This impressive survival track record is in danger, due to stressful environmental conditions that make it hard for corals to survive in today's oceans. The biggest problem corals are facing is the quickly rising ocean temperature.

Global Ocean warming leads to the whitening of corals around the world, a phenomenon that is known as coral bleaching [1]. But what is coral bleaching and why is it bad for corals?

When we think of animals, we generally think of them as individuals, like a dog or a lion or a fish. But corals are different. Corals live together

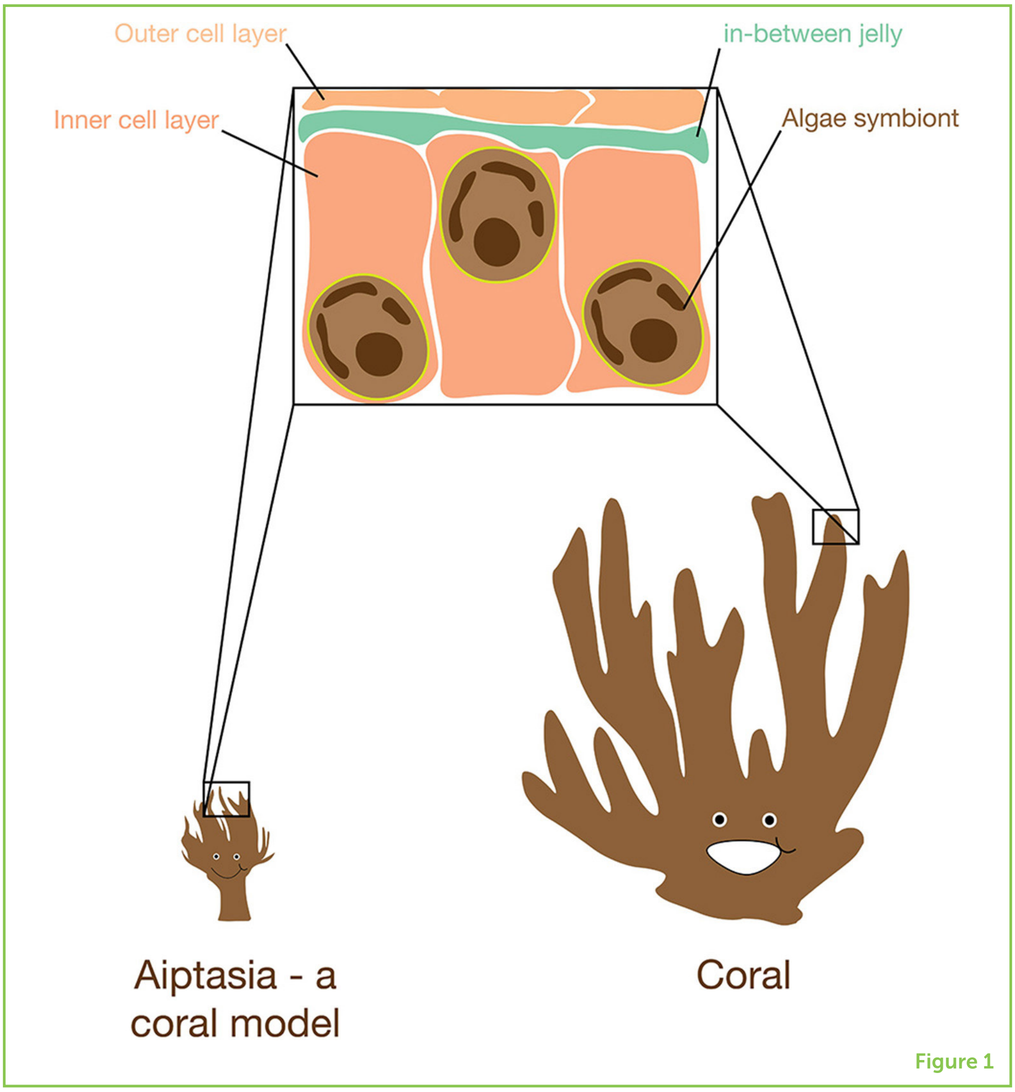


Figure 1

The surprisingly similar tissue of corals and anemones. You can see the very simple cell layering of corals and Aiptasia, the coral model organism, in orange (outer and inner cell layer) and the in-between jelly in green. The algae symbionts are shown in brown and live inside the inner cell layer. They can be found in Aiptasia as well as corals.

with plants, tiny **algae** that provide food and in return are allowed to live inside the tissue, the inner cell layer, of corals or **anemones** (Figure 1) [2]. This type of teamwork and close relationship is called **symbiosis** and the partners involved in it, the coral and the algae in this case, are called symbionts. Algae symbionts can perform photosynthesis, a process you may have heard about that plants use to transform sunlight into energy. In our coral symbiosis, the energy coming from all algae symbionts becomes food for the corals. The algae also provide the beautiful colors we see when we look at coral reefs, because corals themselves are colorless.

ALGAE

Plants that live in the water. They do not flower like land plants and have no roots or stems. You can find them as single cells, for examples, in corals and anemones.

ANEMONE

A close relative of the coral. They have the same structure and live the same way as corals, but are squishier, because they have no skeletons.

SYMBIOSIS

A close relationship in which two living things work together, e.g., algae and the coral or anemone.

Corals faced with difficult environmental conditions, for example, high water temperatures, experience the breakdown of this symbiosis. This results in the loss of their colorful algae friends within them, leaving only the see-through coral tissue on the white coral skeleton—a bleached coral. This bleached coral will no longer have the benefit of the additional food provided by the algae, which makes life hard for them. But not all corals are bleaching at the same level. They bleach at different temperatures, depending on the type of corals or algae, and where they live. To understand how bleaching works, we looked at the strongest corals we could find: Red Sea corals.

THE RED SEA: ONLY FOR THE STRONGEST

When we look at the Red Sea, we can find corals that are more resistant to bleaching than other corals worldwide. But why is that?

Corals in the Red Sea have to handle higher temperatures, yet they seem to grow and do just fine. The Red Sea is a very warm sea compared to other places. There, summer temperatures can reach up to 34°C, while other ocean waters may reach around 29–32°C. Interestingly, corals in the Red Sea are not only living in higher temperatures but also in higher **salinity**. Salinity is a measure of the amount of salt in the water, and the Red Sea has some of the world's highest salt levels. That is why we started wondering whether salinity could be a piece of the puzzle and the ability to live in high salinity one of the secrets of the strong Red Sea corals?

SALINITY

The amount of salt in water, for example, in seawater. You can find a range of different salinities in the ocean, depending on the region. The Red Sea has some of the highest levels of salt.

To answer this and other questions related to coral bleaching, scientists often use a coral model organism, which means an animal that is easier to study than corals but at the same time is very similar to corals. Meet *Aiptasia!* (Figure 1).

Aiptasia is a tiny anemone that shares a similar body structure with corals but lacks the skeleton. Aiptasia also has the same symbiosis with algae that corals have. Aiptasia and corals are closely related and live in similar ways. Besides that, Aiptasia has the advantage that it can be kept in the laboratory and is easy to care for [3]. In contrast, corals need a lot of care. They need big aquarium tanks with lots of technology inside to keep them alive and bringing corals from the reef to the laboratory can be very challenging as well. This makes corals hard to study.

DOES HIGH SALINITY MAKE A DIFFERENCE DURING BLEACHING?

To find out if salinity affects the symbiosis of Aiptasia and its algal symbionts, we thought of an experiment. Aiptasia were kept in three different levels of salinity: low, medium, and high, at a control temperature of 25°C. This temperature is known to be the best for anemones without creating any additional stress. After they got used to their level of salinity, half of the anemones from each salinity level were put under heat stress, by increasing the temperature to 34°C, a temperature that resulted in bleaching. To measure how much the Aiptasia in each group bleached, we counted the algal symbionts living in them. Since bleaching is a visible process (causing see-through vs. brown anemones), we also took pictures to illustrate our results.

After 8 days of heat stress, we looked at our anemones and investigated whether salinity affected how much they bleached. Looking at Figures 2A,B, do you see differences between the anemones in the low, medium, and high salinity after the heat stress?

Indeed, the pictures reveal that anemones that experienced heat stress in the low salinity condition were completely see-through. Compare that with the brownish anemone in the highest salinity level. It seems that there is a difference in the amount of bleaching seen between the different salinities. But wait, pictures can fool us! To measure if our impression was correct, we counted the number of algal cells that were inside the anemones. The bar graph in Figure 2C shows the percentage of algal cells that are still present after heat stress, compared with our control Aiptasia: 100% would mean that the anemone did not bleach, 0% that the anemone bleached completely, and no algae were left. The percentages we calculated from counting the algae confirmed what our eyes told us already. Low salinity anemones bleached more (only 13.6% algae remaining) than higher salinity anemones (30.5 and 37.2% algae remaining).

But what is happening inside the anemones when they are in high salinity to create such an effect?

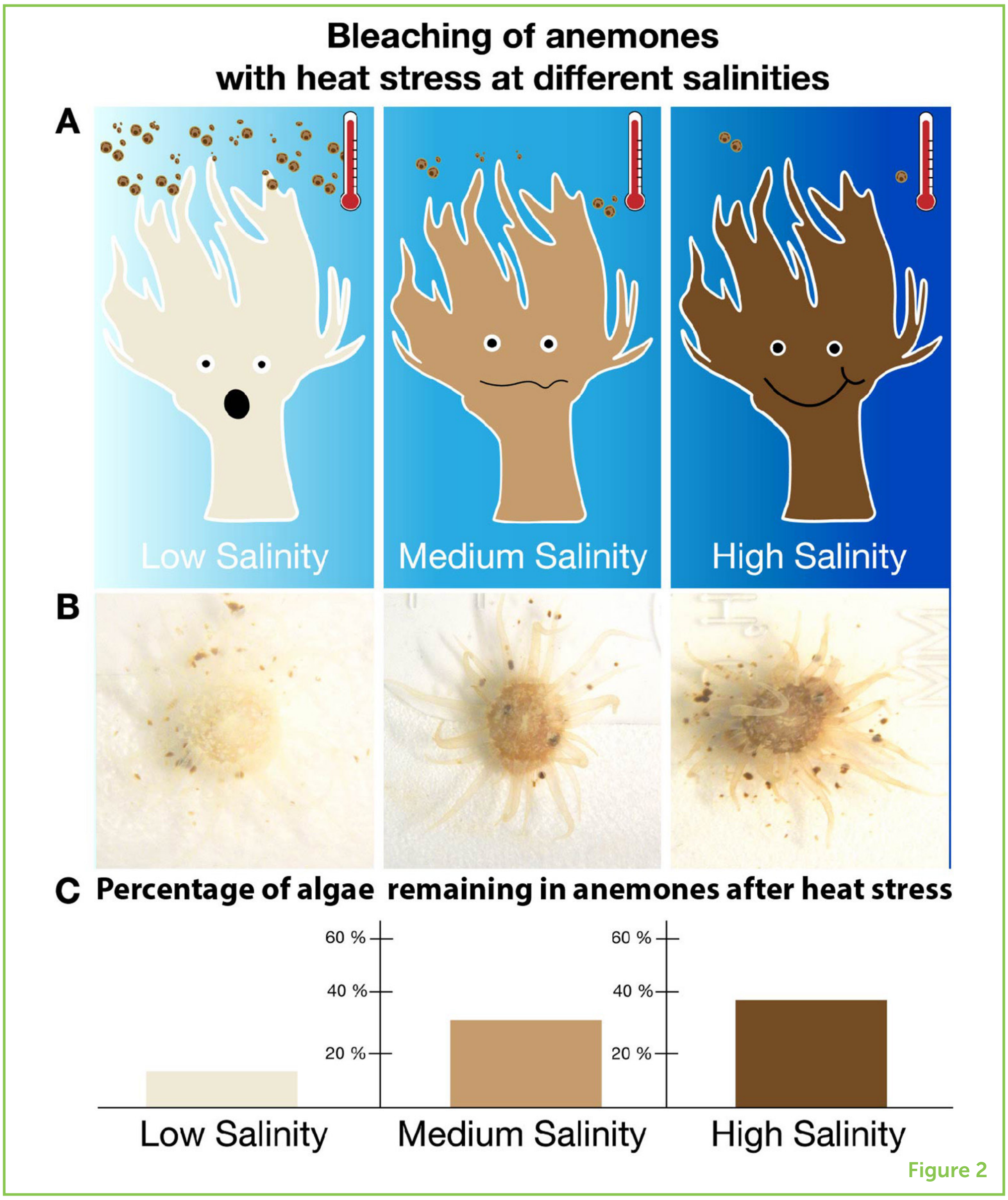


Figure 2

The different effects of salinity during bleaching. Here you see the differences between low, medium, and high salinity on our anemones, after heat stress. **(A)** A cartoon view of the color of Aiptasia. **(B)** Photos of Aiptasia in each condition. The view is from the top. You can see the mouth region and the tentacles. **(C)** A bar graph showing the counted numbers of algae that are still in the anemone after eight days of heat stress. The fact that all the bars are below 100% means that all anemones bleached, but those living in high salinity bleached less.

EXPLODING CHERRIES AND SALTY CORALS

Before we talk about what happens with our tiny anemone in high salinity, let us talk about cherries. Yes, cherries—red, sweet, delicious cherries.

If you are lucky enough to have a cherry tree at home with some cherries on it, you may want to check on them after the next heavy rain. Why? Because you will see that some of the cherries will be cracked open (Figure 3A), even though they were perfectly fine before the rain! You may be wondering how rain can crack open cherries and what this has to do with anemones. The answer has to do with the fact that cherries are sweet and with something called osmosis.

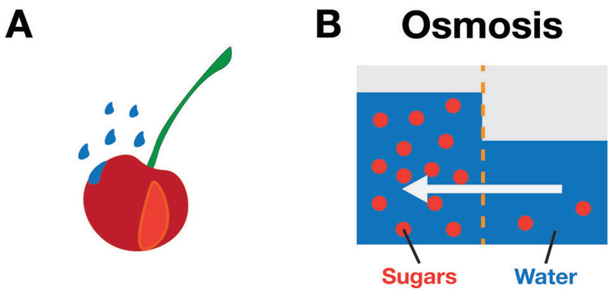


Figure 3

Figure 3

The story of the bursting cherry. **(A)** Cherries crack open after rain due to the difference in the amount of sugar between the inside of the cell and the outside. **(B)** Osmosis is the movement of water from an area with a low concentration of a molecule to an area with a higher concentration. In this case, the water moves from a low amount of sugar outside the cell (right) to a high amount inside the cell (left). The sugar is shown in red, the water in blue, and the white arrow shows the movement of the water.

Osmosis is the movement of water from an area where there is a low amount of a substance, for example sugar, to an area where there is a higher amount (Figure 3B). If you think about the cracked cherry, this means that the water from the rain moved from outside the cherry, where there was no sugar, to the inside of the sugary cells, filling up the cells until they burst. The difference in the amount of sugar between inside and outside of the cherry is what moves the water. Osmosis plays a role in many things, not only the cracking of cherries. Osmosis also plays a role in what happens to our anemones!

Anemones and corals live at different salinities, but they never break open when the salinity changes. Even if you move an anemone from high salinity to low salinity in our experiment, it will not burst like the cherries. Why is that? It is because corals and anemones do not have a difference in the salinity inside their cells compared with the seawater [4]. Corals and anemones produce and break down molecules that are called **osmolytes**, in order to adjust their cells to the seawater environment. That way, they can keep the salinity the same both inside and outside their cells. No difference in salinity means no water movement. That way, these animals do not suffer the same fate as the cherries.

OSMOLYTE

A molecule that is involved in the adjustment to salinity. They are produced or broken down to help reduce the salt difference between the inside of a cell and the outside.

So, this means that the anemones in the high salinity condition in our experiment had to increase the amount of osmolytes in their cells, to adjust to the amount of salt outside the cells. This gave us a hint that the production of osmolytes may be connected to the lesser degree of bleaching that we see in certain corals. What it is exactly about the osmolytes that help the coral survive in warm water we cannot say from the results of our experiment. But we know from other experiments that osmolytes sometimes live a double life in cells. They are not only important for salinity adjustments, but also help reduce the amount of other dangerous molecules that can damage the cells. These dangerous molecules are also linked to coral bleaching [5]. A reduction in these dangerous molecules due to the production of osmolytes may explain why the anemones in high salinity are more resistant to bleaching, compared with the anemones in low salinity.

IN A NUTSHELL

By experimenting with our tiny anemones, we were able to uncover the fact that water salinity somehow affects anemone bleaching. We showed that high salinity reduced bleaching during heat stress. This information is also useful for corals, since Aiptasia and corals are very similar. The exact process that is behind this effect is still mysterious, but we are on the right track to understanding it better. Our next experiments will test this high salinity effect in corals from the Red Sea. Here, corals live in conditions with naturally high salinity and are also known to be resistant to bleaching. What happens when corals from the Red Sea are put into conditions of low salinity? Do you have an idea? We surely will find out—stay tuned!

ORIGINAL SOURCE ARTICLE

Gegner, H. M., Ziegler, M., Rädecker, N., Buitrago-López, C., Aranda, M., and Voolstra, C. R. 2017. High salinity conveys thermotolerance in the coral model Aiptasia. *Biol. Open* 6:1943–8. doi: 10.1242/bio.028878

REFERENCES

1. Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B. C., et al. 2017. Coral reefs in the Anthropocene. *Nature* 546:82–90. doi: 10.1038/nature22901
2. Rohwer, F., Seguritan, V., Azam, F., and Knowlton, N. 2002. Diversity and distribution of coral-associated bacteria. *Mar. Ecol. Prog. Ser.* 243:1–10. doi: 10.3354/meps243001
3. Baumgarten, S., Simakov, O., Esherick, L. Y., Liew, Y. J., Lehnert, E. M., Michell, C. T., et al. 2015. The genome of *Aiptasia*, a sea anemone model for coral symbiosis. *Proc. Natl. Acad. Sci. U.S.A.* 112:11893–8. doi: 10.1073/pnas.1513318112
4. Röthig, T., Ochsenkühn, M. A., Roik, A., Van Der Merwe, R., and Voolstra, C. R. 2016. Long-term salinity tolerance is accompanied by major restructuring of the coral bacterial microbiome. *Mol. Ecol.* 25:1308–23. doi: 10.1111/mec.13567
5. Ochsenkühn, M. A., Röthig, T., D'Angelo, C., Wiedenmann, J., and Voolstra, C. R. 2017. The role of floridoside in osmoadaptation of coral-associated algal endosymbionts to high-salinity conditions. *Sci. Adv.* 3:e1602047. doi: 10.1126/sciadv.1602047

SUBMITTED: 20 November 2018; **ACCEPTED:** 18 February 2019;
PUBLISHED ONLINE: 07 March 2019.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Gegner HM and Voolstra CR (2019) A Salty Coral Secret: How High Salinity Helps Corals to be Stronger. Front. Young Minds 7:38. doi: 10.3389/frym.2019.00038

CONFLICT OF INTEREST STATEMENT: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

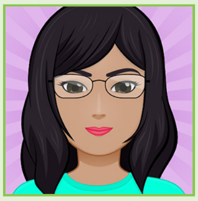
YOUNG REVIEWERS

SAVANA, AGE: 13

I love dogs, my favorite color is red, and I love hanging out with my friends.

KAREN, AGE: 12

I am a very creative girl. My hobbies are sports and studying, and anything to do with art. I really like to try new things and explore things that I find interesting. I say that I am very unique, unlike other people. That is just what makes me, me!

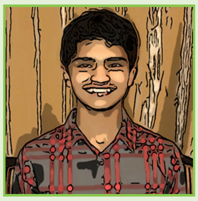


MALSHI, AGE: 12

My name is Malshi, and I am 12 years old. I like Science and Math and I am interested in Chemistry. I love reading in my spare time and I love playing the piano. My favorite sport is badminton and in the future, I want to be a scientist.

YOUSSEF, AGE: 12

I am a runner, swimmer, love to study, and read books. I especially love to read books. I chose Frontiers for Young minds because I wanted two things. My name on an official website! I wanted challenge. As an average seventh grader, I wanted to push myself in knowing new facts regarding science. And now that this is finished, I do not have the same knowledge when I started, than I have now. Thank you Frontiers for Young Minds!! ☺



ZIA, AGE: 12

One of my favorite subjects in school is Science. I am very curious about how the daily things we do in our life happen. I especially like Biology and Cosmology. I watch a lot of documentaries about space and like to research on my interests.

AUTHORS

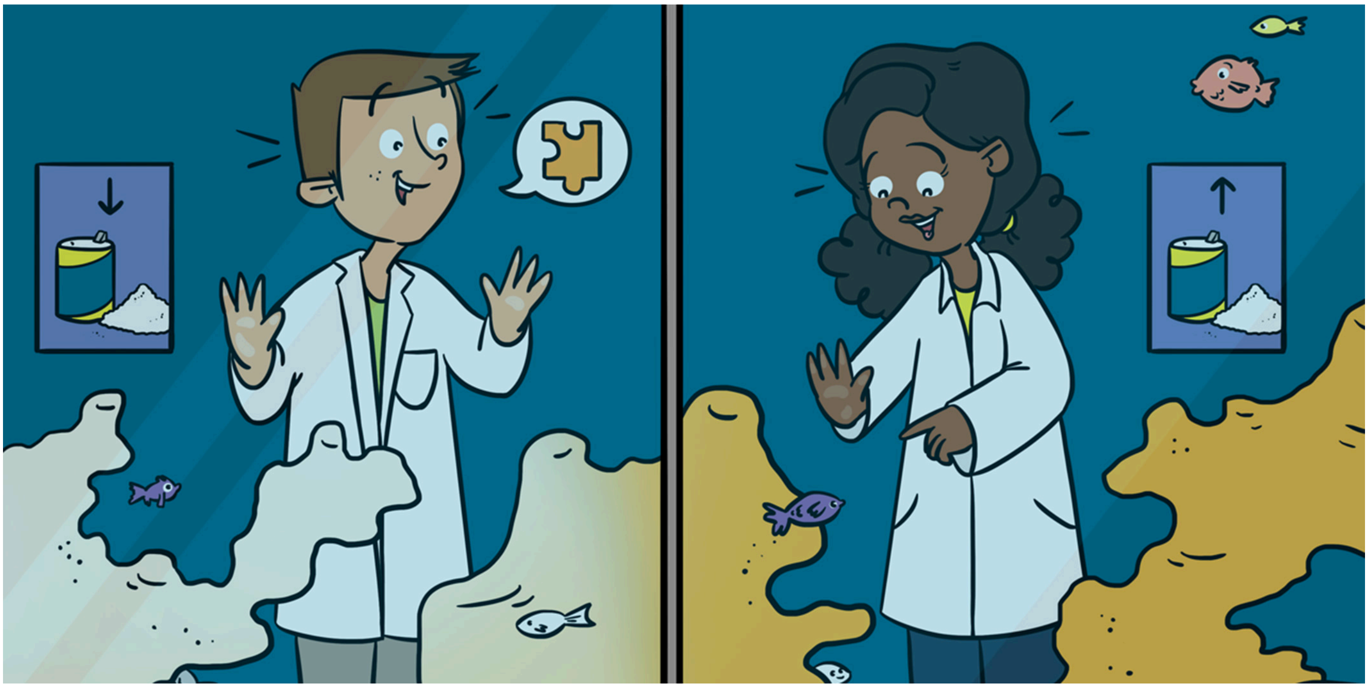
HAGEN M. GEGNER

I was always fascinated by the ocean and loved to explore reefs, but I never thought that I would call myself a Coral Biologist one day. I started out studying General Biology (B.Sc.), after which, I slowly moved closer to Marine Sciences. In the end I was rather curious about the methods used than a single organism in research. So I continued working on fish in Brazil (M.Sc.) and recently, I finished my Ph.D. in Saudi Arabia in which I researched what makes corals stronger during stress. *hagen.gegner@kaust.edu.sa

CHRISTIAN R. VOOLSTRA

I started out studying the development of fruit flies and how the house mouse adjusts to different environments, before diving into coral biology. Nowadays, I, and many other researchers with me, are beginning to understand that all animals and plants team up with tiny living organisms, so-called microbes or bacteria, to digest food, stay healthy, and fight stress. In my lab, we study the different types of bacteria that live with corals and how they help their animal host to survive under stress.

BIODIVERSITY
Published: 03 November 2022
doi: 10.3389/frym.2022.708922



SALT AND SUGARS MAY HELP OVERHEATING CORALS

Hagen M. Gegner [1*] ***and Rúben M. Costa*** [2*]

[1] *Centre for Organismal Studies, Faculty of Biosciences, Heidelberg University, Heidelberg, Germany*
[2] *Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia*

YOUNG REVIEWERS:

ALY
AGE: 13

OWEN
AGE: 9

You may have heard that coral reefs are overheating and are vanishing from our planet. Although this is certainly the case, the news is not all grim and gloomy! Every so often, surprising experiments show us that there is still hope for corals and much more to learn from them. Working along the Red Sea coast, we were surprised to find that corals living in very salty water seemed to be stronger during overheating periods. Moreover, we also found a link between the saltiness of water and the ability of anemones (the close cousins of corals) to deal with heat. In this article, we will explore this relationship by zooming into anemone cells to measure molecules invisible to the naked eye—all with the aim of figuring out how salt can make anemones and corals stronger in the face of increasing temperatures.

HOT REEFS IN A CHANGING CLIMATE

Corals are animals that make beautiful underwater gardens called coral reefs. These reefs are home to millions of other organisms, and some people call them our planet's underwater rainforests. Unfortunately, just like real rainforests, coral reefs are in danger. Ocean warming, a result of climate change, is threatening corals everywhere. In other words, corals are overheating!

When corals start to feel the stress of overheating, which is called heat stress, they lose the vital partners that help them make such lush reefs possible. These partners are tiny plant-like cells called microalgae. Microalgae live inside the coral cells, supplying them with the food needed to grow and stay healthy. This relationship is a type of symbiosis, in which two different organisms live close together and generally benefit from each other. The tiny algae are often referred to as **algal symbionts** (Figure 1). When the algal symbionts are expelled from the coral's tissue due to heat stress, the coral loses its main food supply. This event is called **coral bleaching** because the corals become white due to the loss of their algal symbionts. Without food from the symbionts, corals may eventually starve and die if heat stress continues.

ALGAL SYMBIONT

Microscopic single-celled organisms that live in symbiosis with a coral or anemone cell by producing sugars through photosynthesis, like plants, and sharing them with their host.

CORAL BLEACHING

When organisms such as corals or anemones, that live in symbiosis with algal symbionts, become white due to the loss of their algal symbionts.

SALTIER ANEMONES ARE STRONGER DURING HEAT STRESS

In a previous Frontiers for Young Minds article, we described an experiment in which we used the sea anemone *Aiptasia*—a close relative of corals with the same algal symbionts—to learn more about coral bleaching. We were interested in the effects of **salinity**, the salt content of water, on bleaching. To our surprise, we discovered that anemones in high-salinity seawater are stronger during heat stress. Anemones that lived in saltier seawater bleached less! They kept more of their algal symbionts, which continued to supply the anemone with food. We measured this by counting the algal symbionts inside the anemones [1]. While this was an interesting experiment, we were left wondering why our salty anemones kept their algal symbionts, while anemones growing at a lower salinity did not.

SALINITY

The amount of salt in water. You can find different salinities in oceans or seas depending on their location. The Red Sea is one of the saltiest seas worldwide.

Our main hypothesis was that anemones in high-salinity conditions adjusted their cells to the higher salt content. To do so, the anemones or their algal symbionts must produce something that either helps them handle saltier water or makes them more resistant to heat stress. Moreover, we knew from other experiments that, during heat stress, dangerous molecules called **reactive oxygen species** (ROS), are produced, which contribute to coral bleaching [2, 3]. ROS can damage the cells of anemones/corals and their algal symbionts. Therefore, we thought that, in high-salinity conditions, maybe there are some molecules present that can protect anemones and their

REACTIVE OXYGEN SPECIES (ROS)

Molecules that are generated during the production of energy, a reaction inside every cell that involves oxygen.

Figure 1

A cell within a cell. In addition to all the normal parts of a cell, coral and anemone cells contain an additional cell—an algae cell. Corals and anemones live in symbiosis with their algal symbionts by exchanging nutrients they both need to survive. The symbiont cell can produce a lot of sugars using its chloroplasts. The symbiont gives some of the excess sugars to the coral or anemone cell in exchange for other important nutrients it cannot produce with any of its other cell compartments.

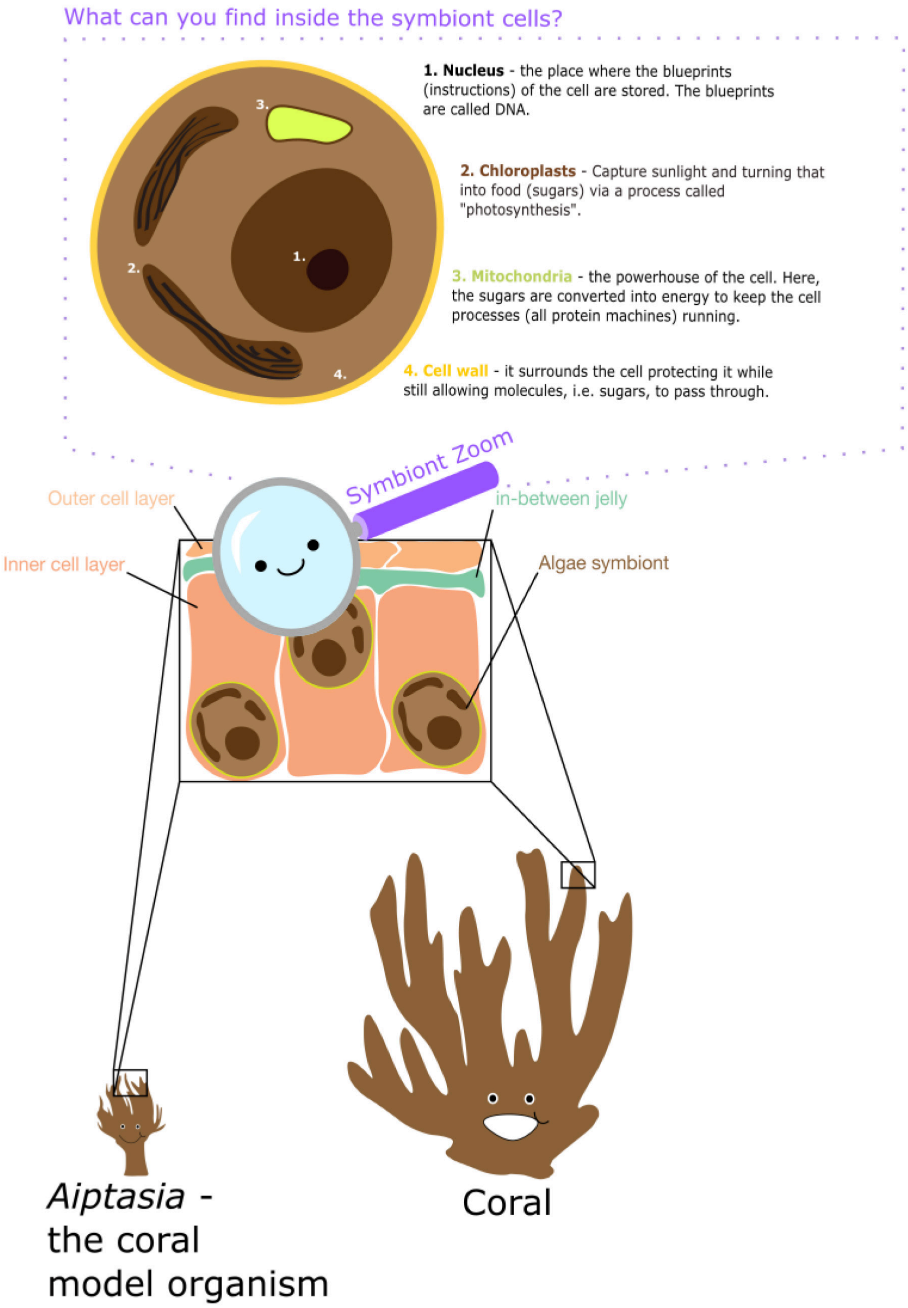


Figure 1

algal symbionts from ROS. To find molecules produced in high-salinity water that could counter the damaging ROS, we repeated our previous experiment—but we analyzed the molecules produced inside the cells of the anemones and their algal symbionts.

SUGAR, THE FUEL OF LIFE

All cells are tiny, closed compartments filled with factories, storage rooms, building blocks, and miniscule molecular "machines." And, just like a machine, the cell needs energy to function properly. Energy is a precious resource for cells. It is created by one of the most important cellular structures, the powerhouses of the cell, called mitochondria. Inside mitochondria, the sugars from the foods we eat are transformed into energy for the cellular machinery. In addition to mitochondria, algal symbionts have special structures, called chloroplasts, that generate food by producing energy-rich sugars from sunlight! This process is known as photosynthesis—the same process your garden plants use to produce their own food!

Since the anemones and corals do not have chloroplasts, they cannot perform photosynthesis to produce sugars from sunlight. However, if they live together with their algal symbionts, they can receive these sugars from those photosynthesizing algal cells. While some of the sugars are used by the algal symbionts to keep their own machinery running, a big portion is shared with the anemone or coral host! What a deal!

HEAT: AN ENEMY OF SUGAR SHARING

Unfortunately, during heat stress, the symbiont's cell machinery gets damaged. This stops photosynthesis and the sugar sharing between algal symbiont and coral. This damage is done by the accumulation of the ROS molecules we mentioned earlier—they can be imagined as tiny "sparks" generated during the energy-production processes. If too many of these sparks are generated, or if they are generated in an uncontrolled way, they can "set fire" to parts of the algal symbionts, destroying them [4]. This may result in bleaching. The details of coral bleaching, the role of ROS, and the ending of photosynthesis by algal symbionts are all complex topics that are still being researched!

MORE SALT LEADS TO MORE SUGARS: AVOIDING OSMOTIC SHOCK

You may be wondering why are we talking about sugars when salt is the factor that protects anemones from bleaching during heat stress, right? The reason is that sugar is not only used for energy! There are many forms of sugars and sugar-containing molecules within cells. Like many other molecules, sugars help cells handle the salinity of the water around them. Sugars influence the natural process of **osmosis** by acting as **osmolytes**. Osmolytes are substances that can either be produced or broken down in the cell to help the cell adjust to the surrounding salinity. If osmolytes are not adjusted rapidly, the cell enters a state called **osmotic shock**, which can damage it. Osmolytes are therefore lifesaving for certain cells.

Anemones use some sugars as an energy resource, but also use sugars as osmolytes to keep up with the high salinity around them. Since the algal symbionts are inside the anemone cells, they too must adjust to

OSMOSIS

Movement of water through membranes. Water always moves toward the side of the membrane that has more dissolved substances, like salt or sugar.

OSMOLYTES

Molecules that are produced, broken down, or transported into the cell to balance the level of dissolved substances, like salt and sugar, between the cell and the surrounding water.

OSMOTIC SHOCK

Sudden change in dissolved substances around a cell, which makes water move in or out rapidly, causing damage to the cell.

the salinity. This salt-sugar link connects the salty environment to the changes inside the anemone cells as well as their algal symbionts.

In our experiment, we put anemones under heat stress at low, medium, and high salinity. Then, we looked to see if any osmolyte sugars were changing, to get an idea of what was going on inside the algae cells. In doing so, we found a sugar-containing molecule that stood out: **floridoside**.

FLORIDOSIDE

A sugar-containing molecule produced inside algal symbionts that can help them adjust to different salinities and to neutralize harmful molecules that arise from energy production.

THE MANY FACES OF FLORIDOSIDE

Floridoside is a sugar-containing molecule and a known osmolyte. We found high amounts of floridoside in the algae cells of anemones that were kept in high-salinity water. By building up more floridoside, the algal symbionts adjusted to the new salinity and did not enter into osmotic shock, avoiding damage!

Interestingly, floridoside lives a double life! It can also act as a ROS neutralizer! In other words, floridoside puts out the "sparks" that are produced during energy production. By preventing ROS from building up in the algal symbionts, floridoside prevents the cell damage that stops photosynthesis and the sharing of sugars between anemone and algal symbiont and that can lead to coral bleaching.

To detect floridoside's ROS neutralizing action, we measured the amount of ROS produced by the algal symbionts during heat stress at different salinities. We observed that the more floridoside that was detected in the algal symbiont, the less ROS were present. This relationship between more floridoside and fewer ROS may explain why anemones bleach less in higher salinity (Figure 2). Floridoside, acting as an osmolyte and ROS neutralizer, may protect the machinery of the algal symbionts and ensure the continued supply of sugars to the anemone. More food for the anemone means more energy, which in turn means more resources to fight against other stressors such as heat stress. This may result in a stronger symbiosis or, in other words, less bleaching!

IN A NUTSHELL

The salinity of water changes the way cells behave and which substances they produce. This means that salinity has a big influence on the entire animal. High salinity causes anemone cells and their algal symbionts to adjust their levels of osmolytes, such as floridoside. They produce more osmolytes the saltier the water gets. Floridoside is a sugar-containing osmolyte that also neutralizes the ROS that can damage algal symbionts. This link between salinity, heat stress, and bleaching can help explain why anemones and some coral species

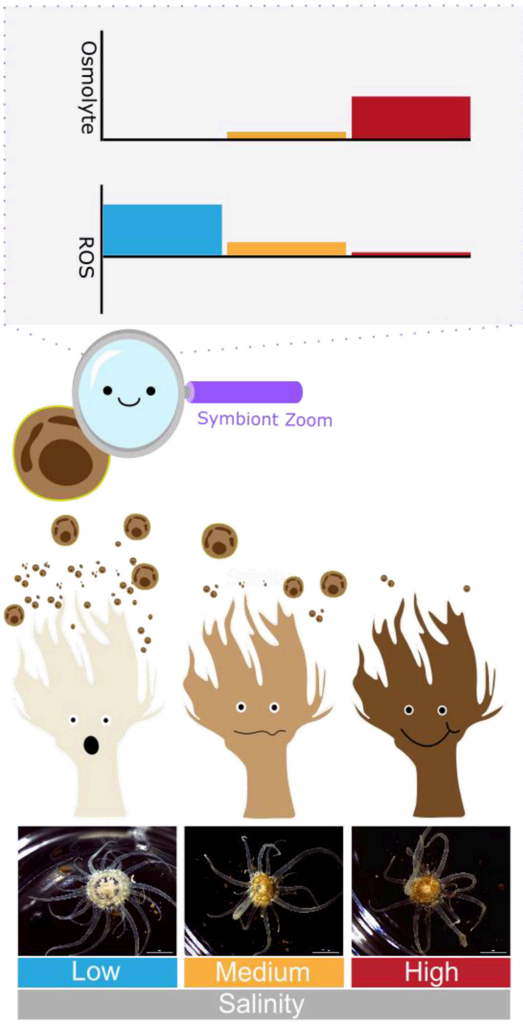


Figure 2

Figure 2

The saltier the better. At the bottom, you can see anemones in low (blue), medium (yellow), and high (red) salinity levels during heat stress. The one with the most algae inside is the darkest—notice this anemone is in the highest salinity, while the anemone in the lowest salinity is completely bleached. The level of the osmolyte floridoside and the levels of ROS were measured in each of these anemones' algal symbionts. In the lowest salinity, we saw low floridoside and high ROS during heat stress. In the highest salinity, we saw high floridoside and low ROS during heat stress. This suggests that a higher salinity is linked to high levels of floridoside. High levels of floridoside seem to protect the algal symbiont from the thermal stress by potentially neutralizing ROS molecules and preventing bleaching.

bleach less during heat stress when living in saltier water, like the ones living in the Red Sea.

As usual in science, this is not the end of the story. There are many molecules that can act as osmolytes, and not all anemones and corals rely on the same ones. They may use different osmolytes to adjust to salinity changes. Also, not all anemones and only a few corals tested show this salinity effect! This opens a lot of new questions for future experiments.

ORIGINAL SOURCE ARTICLE

Gegner, H. M., Rädecker, N., Ochsenkühn, M., Barreto, M. M., Ziegler, M., Reichert, J., et al. 2019. High levels of floridoside at high salinity link osmoadaptation with bleaching susceptibility in the cnidarian-algal endosymbiosis. *Biol. Open* 8:bio045591. doi: 10.1242/bio.045591

REFERENCES

1. Gegner, H. M., Ziegler, M., Rädecker, N., Buitrago-López, C., Aranda, M., and Voolstra, C. R. 2017. High salinity conveys thermotolerance in the coral model Aiptasia. *Biol. Open* 6:1943–8. doi: 10.1242/bio.028878
2. Weis, V. M. 2008. Cellular mechanisms of Cnidarian bleaching: stress causes the collapse of symbiosis. *J. Exp. Biol*. 211:3059–66. doi: 10.1242/jeb.009597
3. Lesser, M. P. 2006. Oxidative stress in marine environments: biochemistry and physiological ecology. *Annu. Rev. Physiol*. 68:253–78. doi: 10.1146/annurev.physiol.68.040104.110001
4. Szabó, M., Larkum, A. W. D., and Vass, I. 2020. "A review: the role of reactive oxygen species in mass coral bleaching," in *Photosynthesis in Algae: Biochemical and Physiological Mechanisms*, eds A. W. D. Larkum, A. R. Grossman, and J. A. Raven (Cham: Springer International Publishing). p. 459–88. doi: 10.1007/978-3-030-33397-3_17

SUBMITTED: 12 May 2021; **ACCEPTED:** 18 October 2022;
PUBLISHED ONLINE: 03 November 2022.

EDITOR: Frederique Carcaillet, Université de Montpellier, France

SCIENCE MENTORS: Dina Mostafa and Kristine Welsh

CITATION: Gegner HM and Costa RM (2022) Salt and Sugars May Help Overheating Corals. Front. Young Minds 10:708922. doi: 10.3389/frym.2022.708922

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ALY, AGE: 13
I am Aly, and I am interested in Biology, Paleontology, and reading about Animals and their behavior. I like Lizards, Sharks, and Bears.

OWEN, AGE: 9
I am 9 years old, and I love bees and chickens. In fact, I keep them as pets! One of my favorite things to do is to read. I also love science and gardening. I am interested in growing carnivorous plants and mushrooms.

AUTHORS

HAGEN M. GEGNER

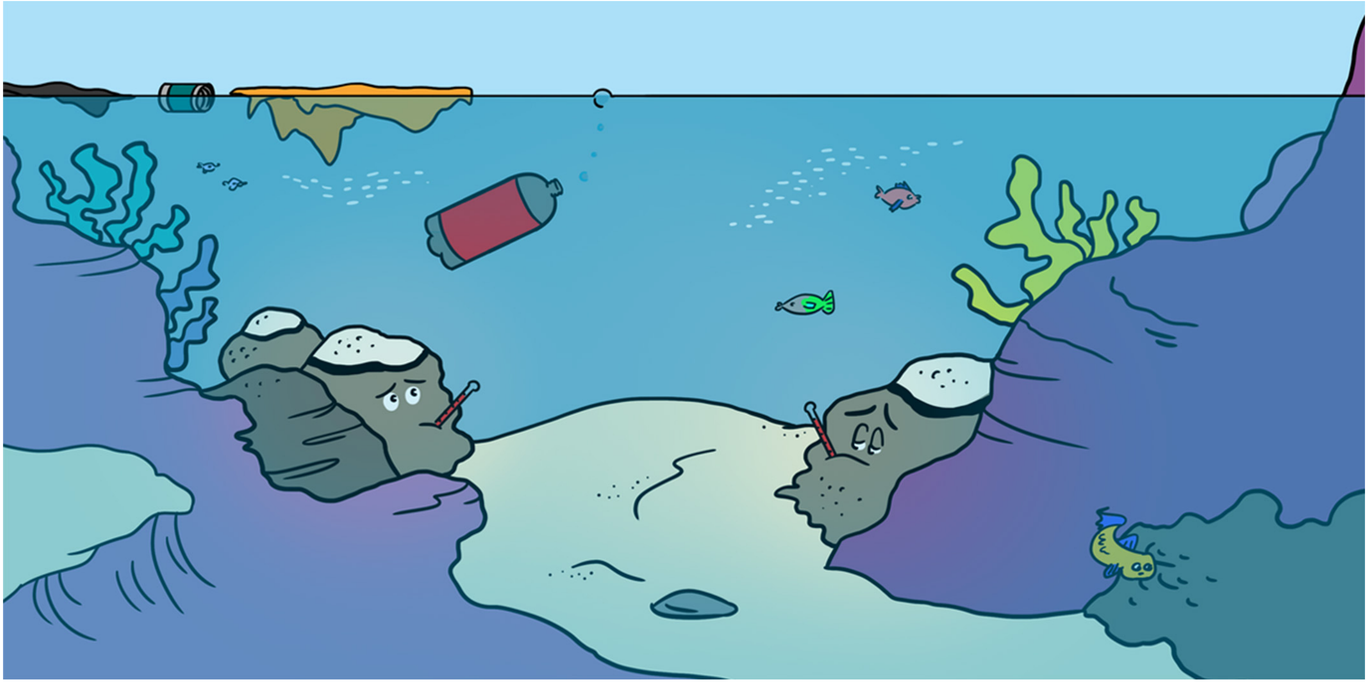
My name is Hagen M. Gegner, I am a scientist. You were reading a study by me as a marine biologist, explaining how corals live with their tiny algal partners. This is something I researched in the Red Sea during my doctoral degree. While I still enjoy marine science, corals, and diving, I started working in landlocked hospitals. Now, I am investigating sick people. Specifically, I am using powerful technologies to find differences in the blood that may explain a disease. Funnily enough, I am using the same technology as I was applying in the Red Sea on corals. *hagen.gegner@kaust.edu.sa

RÚBEN M. COSTA

Hi everyone! My name is Rúben M. Costa and I am a scientist. And I believe that all of us are scientists! Not all scientists wear lab coats, and not all scientists work in labs, but all of us know the importance of asking questions and looking for answers! Throughout my career, I asked a lot of questions, mostly related to health. I started by asking questions about human health, then I pursued questions about coral health, and now I work in Ssustainability, which we can say is the Planet's health. I have been lucky to be a scientist in and out of the lab, and I hope you continue to be a scientist in anything you choose to do in your future! *ruben.martinsdacosta@kaust.edu.sa

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 12 February 2020
doi: 10.3389/frym.2020.00006



CORALS ARE SICK: BLACK BAND DISEASE IS ATTACKING

***Ghaida Hadaidi*[1*] *and Christian R. Voolstra*[1,2]**

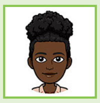
[1] *Division of Biological and Environmental Science and Engineering, Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia*

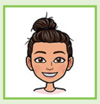
[2] *Department of Biology, University of Konstanz, Konstanz, Germany*

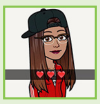
YOUNG REVIEWERS:


NOUF


SAJA


SHOMUKH


SUHA


TAFE

If you snorkel or dive in the Red Sea, you will see large, colorful rocks surrounded by different types of fish. These amazing structures are actually not rocks—they are animals called corals and they build coral reefs. Yes, they are animals! These animals do not live alone, instead they live with tiny plant cells inside them and many other microbes, such as bacteria and viruses. Coral animals and their friends are in danger, because the water temperature is getting higher and because humans throw their trash into the oceans. Did you know that corals can be ill and have diseases, just like human beings? Many coral diseases have been described. One of these coral diseases is called black band disease (BBD). This article will explain what BBD is, what causes it, and how we can help corals to be healthier.

LIKE OTHER ANIMALS, CORALS CAN GET DISEASES

Corals are animals that build structures called coral reefs. Corals live with other organisms, including microbes, such as tiny plant cells,

Figure 1

A diseased coral. The healthy greenish tissue is separated from the dead white tissue by a black band full of harmful bacteria (green arrow). The black band is a sign of a coral disease called black band disease.

bacteria, and viruses. These partners all depend on each other for food and energy [1]. Unfortunately, this relationship is sensitive and can break down when the coral is stressed. If any partner is stressed, the coral will become more sensitive to diseases. Yes, like all animals, corals can be affected by diseases. Coral diseases are a consequence of changing interactions between the corals, their microbes, and environmental conditions, such as high temperatures or the presence of too many nutrients in seawater. In our study, we investigated one of the most studied coral diseases, one that is caused by a specific group of microbes. This disease is called black band disease (BBD) and it is easy to recognize, because of the visible black bands on the surface of the corals (Figure 1).

BACTERIA

Very small organisms that live everywhere and can be good or bad; some bacteria can cause diseases.

WHAT IS CAUSING BBD IN THE RED SEA?

Because it is common on coral reefs around the world, BBD is the most studied coral disease, and it was also the first to be described [2]. This disease is a serious danger to coral reefs worldwide, because it may lead to the death of corals. Previous studies have shown that the presence of BBD increases during warm summer months [3].

POLYMICROBIAL

The involvement of multiple types of microbes.

SULFATE-REDUCING BACTERIA (SRB)

A group of bacteria that "breathe" sulfur, rather than oxygen.

SULFIDE-OXIDIZING BACTERIA (SOB)

A group of bacteria that uses chemical energy to make sugars.

BBD is known as a **polymicrobial** disease, which means that multiple kinds of bacteria cause this disease. The three types of bacteria that have been found to cause BBD are cyanobacteria (a blue-green type of bacteria), **sulfate-reducing bacteria (SRB)**, and **sulfide-oxidizing bacteria (SOB)**. Like plants, cyanobacteria can use the sunlight to generate sugars and oxygen. Conversely, sulfate-reducing bacteria live in environments that are free of oxygen. Sulfide-oxidizing bacteria by comparison can use chemical energy to make sugars. When they come together, these three types of bacteria create the clear black band on the corals by producing toxic chemicals. When a coral gets sick from BBD, the black band moves across the coral's surface. This

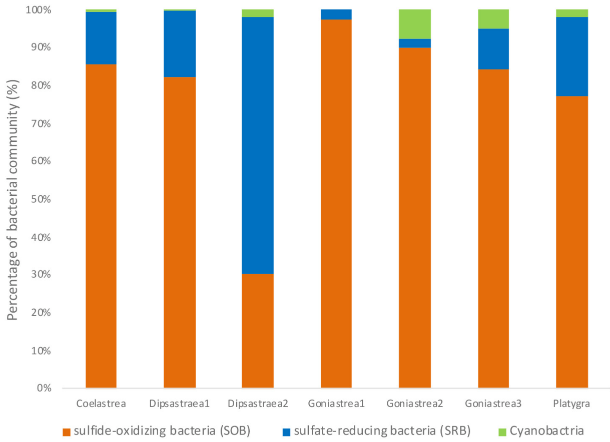


Figure 2

Figure 2

The bacterial composition of black band disease from seven diseased corals. This bar chart shows the percentages of each type of bacteria (cyanobacteria, sulfate-reducing bacteria, and sulfide-oxidizing bacteria) that are present in the black bands of seven coral samples from the Red Sea. The locations from which the samples were taken are listed along the bottom of the chart. The more of a specific color you see in the bars, the more of this type of bacteria was present in the sample.

band contains toxic chemicals (sulfides) and has no oxygen, which eventually causes tissue death.

DO THE SAME THREE TYPES OF BACTERIA CAUSE BBD IN THE RED SEA?

To study BBD in corals from the Red Sea, we collected parts of the black band from the surface of different corals and transferred the samples to small tubes. To figure out which bacteria were present in the samples and to get more information about those bacteria, we analyzed the bacterial **DNA**. Bacterial DNA, like ours, is made from four molecules called nucleotides (A, adenine; G, guanine; C, cytosine; and T, thymine) that are put together in a unique order for each type of bacteria. A specific region of the bacterial DNA can serve as a barcode or fingerprint that allows scientists to distinguish different types of bacteria. Telling the types of bacteria apart is done by a process called DNA **sequencing**, which "reads" the order of the four DNA nucleotides present in the fingerprint region of the bacterial DNA. From there, we can look at the different sequences of the bacteria in our samples and identify which types of bacteria are present.

DNA

The genetic information inside an organism.

SEQUENCING

A method that determines the order of nucleotides in DNA.

We found that the three main BBD-causing types of bacteria, cyanobacteria, SRBs, and SOBs, all exist in the diseased corals from the Red Sea (Figure 2) [4]. We also calculated the percentage of each type of bacteria in our coral samples (Figure 2). Finally, we compared the bacteria from BBD corals in the Red Sea to the bacteria found in BBD corals around the world and found that they were similar.

PRESENCE OF BBD IN THE RED SEA

To understand how many corals in the Red Sea are sick with BBD, we collected samples and information from 22 reefs along the coast of

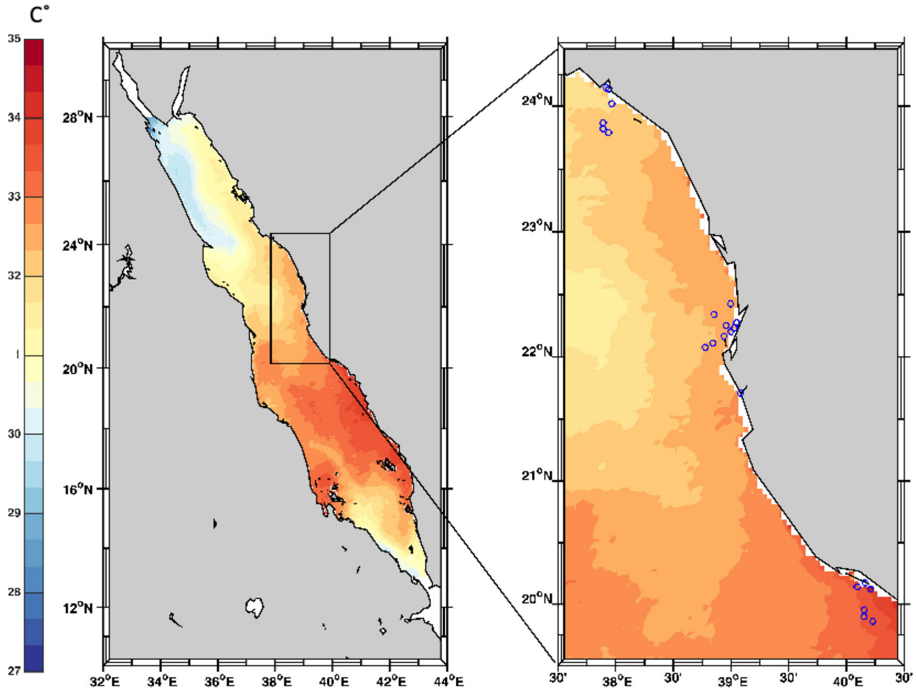


Figure 3

Figure 3

Coral black band disease survey sites in the Red Sea. The panel on the left shows the sea surface temperature of the Red Sea: blue represents lower temperatures from 27 to 30°C and red represents higher temperatures from 32 to 35°C (see temperature bar on the left). As you can see, the temperature is higher in the lower, southern part of the Red Sea. The right box shows blue circles, indicating the 22 surveyed reefs along the central Red Sea coast. The survey was done from 19 October to 3 November 2015 and the temperature data is from the same time.

the central Red Sea (Figure 3). The occurrence of BBD was different between reefs, and only a small percentage of corals were infected. However, toward the southern part of the Red Sea, we found a reef with many diseased corals, and we were interested in why there was so much BBD at this site. After looking into the surrounding environment, the higher incidence of BBD at this site might have been related to the high seawater temperature around this reef and the trash that humans throw into the sea. So, our results and the results of other research groups suggest that keeping the ocean clean helps corals be stronger to fight off diseases.

CONCLUSION

This article describes an investigation into black band disease of different coral reefs in the central Red Sea. Our results suggest that BBD in the Red Sea seems to be caused by interactions of the same three bacterial groups that cause BBD in other reefs across the world. Although the presence of this disease is overall rare, harmful environmental conditions, such as high seawater temperature and water pollution, makes coral more susceptible to disease. In conclusion, clean oceans make for healthier corals.

ORIGINAL SOURCE ARTICLE

Hadaidi, G., Ziegler, M., Shore-Maggio, A., Jensen, T., Aeby, G., and Voolstra, C. R. 2018. Ecological and molecular characterization of a

coral black band disease outbreak in the Red Sea during a bleaching event. *PeerJ* 6:e5169. doi: 10.7717/peerj.5169

REFERENCES

1. Rosenberg, E., Koren, O., Reshef, L., Efrony, R., and Zilber-Rosenberg, I. 2007. The role of microorganisms in coral health, disease and evolution. *Nat. Rev. Micro.* 5:355–62. doi: 10.1038/nrmicro1635
2. Richardson, L. L. 2004. "Black band disease," in *Coral Health and Disease*, eds E. Rosenberg and Y. Loya (Berlin; Heidelberg: Springer Berlin Heidelberg). p. 325–36.
3. Richardson, L. L., and Kuta, K. G. 2003. Ecological physiology of the black band disease cyanobacterium *Phormidium corallyticum. FEMS Microbiol. Ecol.* 43:287–98. doi: 10.1016/S0168-6496(03)00025-4
4. Hadaidi, G., Ziegler, M., Shore-Maggio, A., Jensen, T., Aeby, G., and Voolstra, C. R. 2018. Ecological and molecular characterization of a coral black band disease outbreak in the Red Sea during a bleaching event. *PeerJ* 6:e5169. doi: 10.7717/peerj.5169

SUBMITTED: 13 July 2019; **ACCEPTED:** 20 January 2020;
PUBLISHED ONLINE: 12 February 2020.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Hadaidi G and Voolstra CR (2020) Corals Are Sick: Black Band Disease Is Attacking. Front. Young Minds 8:6. doi: 10.3389/frym.2020.00006

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

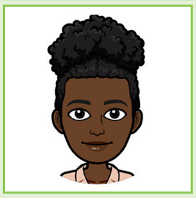
YOUNG REVIEWERS

NOUF

I am someone who is interested in spreading awareness when it comes to our environment, specially our oceans. I find sharks cute.

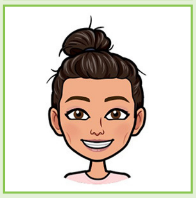
SAJA

I love Biology but specialized in computer sciences. Tupac's verses mean a lot to me. I am not an outgoing person but easy to make friends. The color white always makes me feel comfortable. I am trying to learn how to play guitar.



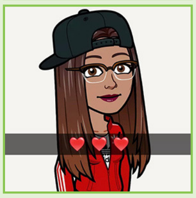
SHOMUKH

I am a person who loves to be at home and who is interested in learning about biology and biochemistry. I also love coloring and drawing.



SUHA

I love life, freedom, my mum, and all things girly!



TAFE

I am a very simple person. I love the sea, my favorite colors are yellow and black, and when I am bored, I like to cook! Love listening to music when I work, love to dance, and do not like waiting... I like experimenting with new things.

AUTHORS

GHAIDA HADAIDI

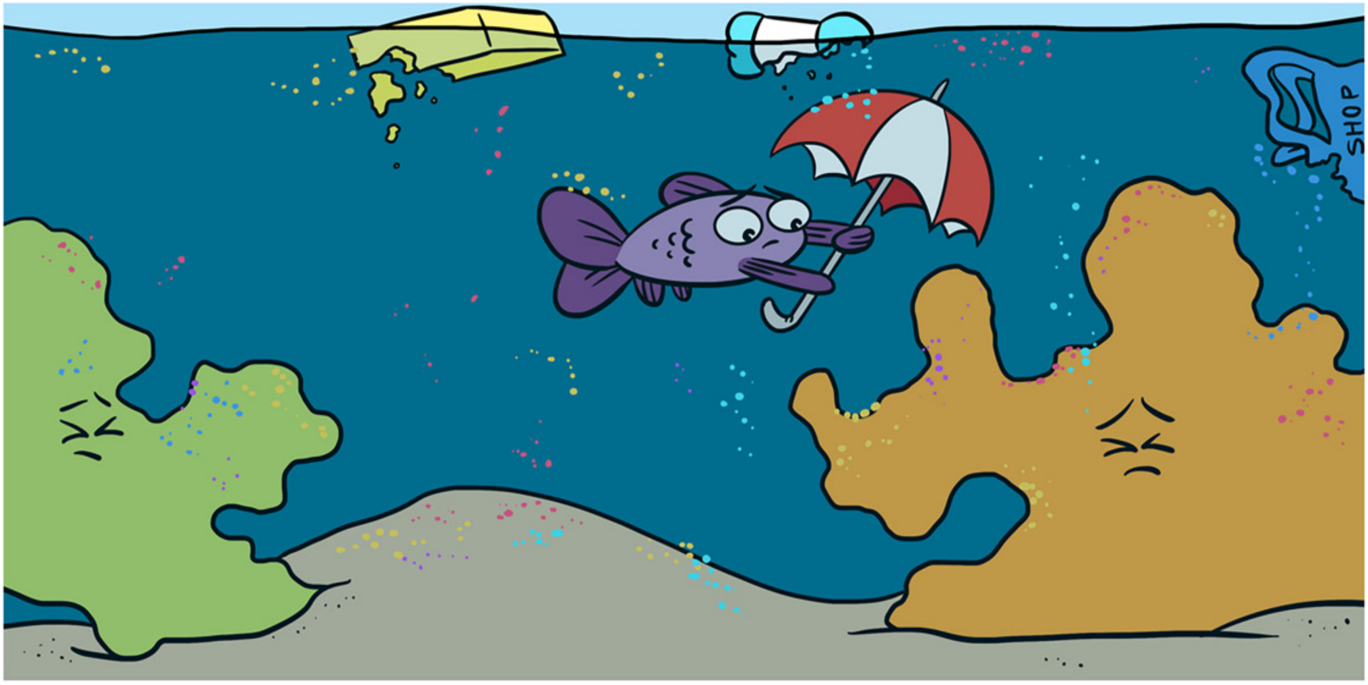
I am a scientist and I used to work in the Reef Genomics lab at King Abdullah University of Science and Technology. I was interested in exploring coral reefs in the Red Sea and how extreme environmental factors affect their life. Seeing these spectacular creatures threatened made me write this article and share it with young kids. This article was part of my Ph.D. project where I aimed to study the role of microbial community under natural environmental stressors in the Red Sea. *ghaida.hadaidi@kaust.edu.sa.

CHRISTIAN R. VOOLSTRA

I started out studying the development of fruit flies and how the house mouse adjusts to different environments, before diving into coral biology. Nowadays, I and many other researchers with me, are beginning to understand that all animals and plants team up with tiny living organisms, so-called microbes or bacteria, to digest food, stay healthy, and fight stress. In my lab, we study the different types of bacteria that live with corals and how they help their animal host to survive under stress. christian.voolstra@uni-konstanz.de

frontiers FOR YOUNG MINDS

BIODIVERSITY
Published: 17 December 2021
doi: 10.3389/frym.2021.608621



MICROPLASTICS: SMALL PARTICLES, BIG THREAT

*Silvia Arossa**, *Cecilia Martin, Susann Rossbach and Carlos M. Duarte*

Biological and Environmental Science and Engineering Division (BESE), Red Sea Research Centre (RSRC) and Computational Bioscience Research Center (CBRC), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

YOUNG REVIEWERS:


ESTELLE
AGE: 10


ISTITUTO COMPREN-SIVO ALTA VAL DI SOLE
AGE: 12


JULIA
AGE: 10


MARCO
AGE: 10

You have probably heard that plastic pollution is becoming a big problem for the environment, and especially for the oceans. When a piece of plastic reaches the sea, the seawater and sunlight make it slowly fall apart into tiny plastic particles. These small particles are called microplastics and are even smaller than a ladybug—and sometimes not even visible. Scientists have found that many marine animals mistake these microplastics for food and eat them! But what about the animals in coral reefs? Many animals in reefs, including corals and giant clams, are fixed to the bottom of the sea and cannot move. So, they cannot escape from the microplastics that are literally "raining down" on them. Recently, we discovered that many of these coral reef animals are not only eating the microplastics, but the plastics can also stick on their bodies like flies on flypaper!

WHAT ARE MICROPLASTICS?

Think about how many plastic objects you use every day in your daily life—at home, at school, and even in your free time. Many plastic objects are used only for a few seconds and then thrown away. This is why more and more new plastic needs to be produced every day.

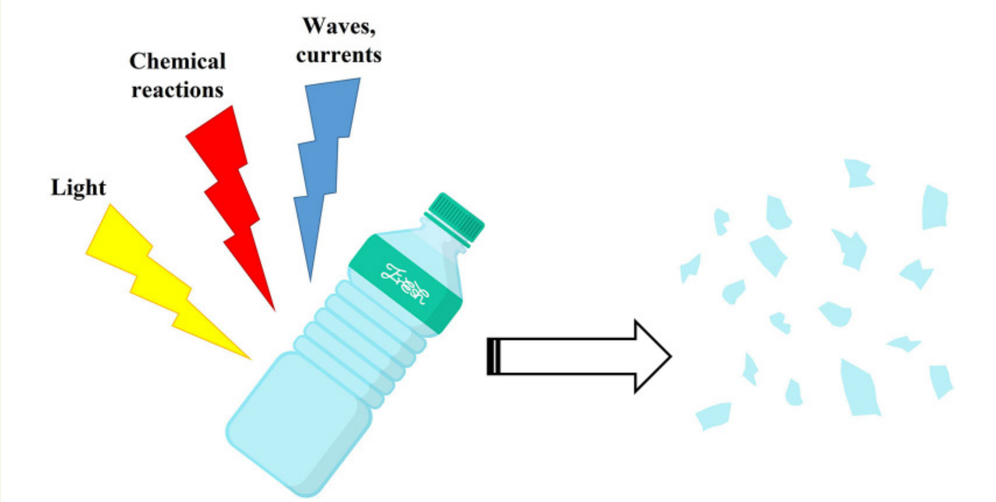


Figure 1

Figure 1

Microplastics are formed in the oceans when sunlight, chemical reactions, waves, and water currents break down large plastic products, called macroplastics. The plastic pieces become smaller and smaller over time and are called microplastics when are smaller than 5 mm in diameter.

Worldwide, about 1,000,000 tons of plastic are produced every day. This equals about 1,000 trucks full of plastic bottles! What happens to a plastic bottle or to a pen after we stop using it? In most cities, recycling is a common practice and plastic is re-used to produce new objects. Unfortunately, recycling does not happen everywhere or to every plastic object. Pens and markers, for example, cannot be recycled because they contain ink. These objects end up in landfills. Sometimes, people do not follow the rules and dispose of plastics in the environment instead of the recycle bin. Consequently, these objects can be washed away by the rain, ending up in rivers and eventually in the ocean.

Did you know that, once it has reached the sea, a plastic bottle takes several 100 years to fully break down [1]? During this time, the plastic bottle can travel around the globe, transported by the water currents. On the way, the waves, currents, sunlight, and chemical reactions break down bottles and other large pieces of plastic trash (called macroplastics) into tiny plastic pieces, which are called **microplastics** (Figure 1) [2]. For some plastic trash, the transformation from macroplastic to microplastic can take up to 1,000 years! Some products that we use daily already contain microplastics, such as toothpastes, scrubs, and skincare products. These microplastics can be washed down the drain while we are showering or brushing our teeth, and eventually they can reach the oceans as well.

MICROPLASTICS

Tiny pieces of plastic smaller than 5 mm in diameter.

WHY ARE MICROPLASTICS DANGEROUS FOR OUR OCEANS?

WATER COLUMN

The space occupied by seawater from the surface of the ocean to its bottom.

Plastic particles are often believed to float on the surface of the ocean. This is true for light plastic pieces like the ones from bags and cups, but heavy microplastics, like those from some broken toys, sink in the **water column** and reach the bottom of the sea. So, plastic can be

Figure 2

Bioaccumulation is the process by which toxic substances accumulate in organisms as they eat other organisms. For example, in the ocean, if one small fish eats one plastic particle and then two of these small fish are eaten by a medium-sized fish, the medium-sized fish has already taken up 2 particles. If two of the medium-sized fish are eaten by a bigger fish, that fish will have 4 particles in its body.

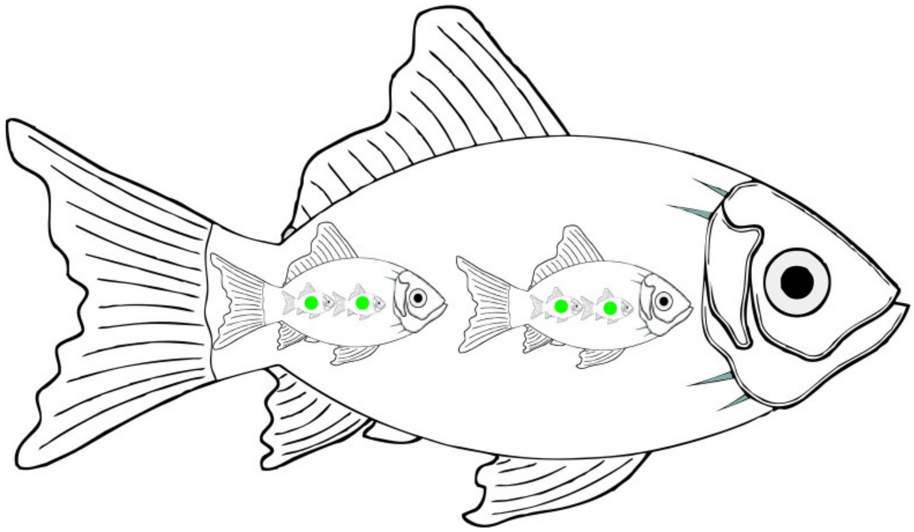


Figure 2

FOOD WEB

The different organisms, from tiny plants to whales and everything in between, that eat each other or that are eaten.

BIOACCUMULATION

Process by which toxic substances accumulate in organisms as they eat other organisms.

everywhere in the ocean! Plastic particles can be mistaken for food by some hungry marine animals, who then fill their stomachs with plastic instead of real food. This is true for both macro- and microplastics, but the smaller the plastic pieces are, the more likely they are to be eaten and enter the **food web**. Just imagine a small fish that eats microplastics by mistake. If a bigger fish now eats a few of these smaller fish, it takes up the microplastics that were inside the smaller fish. The bigger fish has then already multiplied the amount of plastics inside its body. If this eating and being eaten goes on, more and more plastic ends up in some predator animals [3]. This is called **bioaccumulation** (Figure 2).

Scientists have observed that eating microplastics can lead to health problems in many marine animals. For example, sometimes plastic particles are very sharp and can injure the stomach or digestive system. Also, when their stomachs are filled with plastics, animals do not feel hungry and do not eat proper food, so they end up starving! Plastic particles can also act like little sponges that soak up chemicals, especially when the particles travel through the oceans for a long time. When these chemical-soaked plastics are eaten by marine animals, or even by humans, the chemicals can cause a lot of health problems, such as inability to reproduce.

MICROPLASTICS IN CORAL REEFS

Although scientists investigating plastic pollution knew that a lot of plastic waste was ending up in the Red Sea, they were only able to find a little of it floating on the surface or suspended in the water column. They wondered where all the missing plastic went! One possibility is that plastic particles are "raining down" on coral reefs and getting trapped there [4].

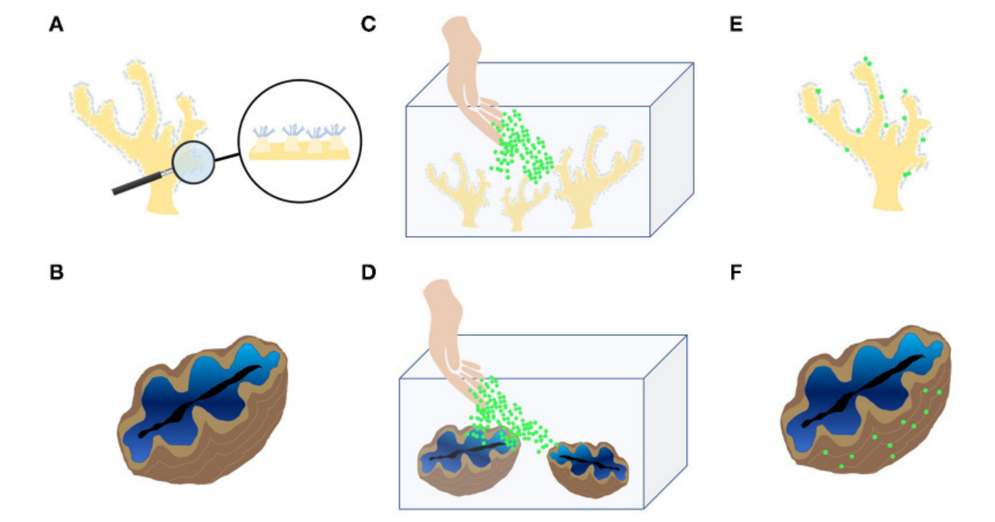


Figure 3

(A) Corals have tiny polyps that live inside the hard skeleton and catch food particles in the water with their tentacles. **(B)** Giant clams also capture food particles from the water, by filtering it. **(C,D)** Scientists added fluorescent green plastic particles into aquaria containing corals or giant clams. **(E,F)** Lots of plastic particles stuck to the skeletons of the corals and the shells of the giant clams.

ECOSYSTEM

All the living and non-living things in an area, including plants, animals, small organisms, water, soil, and rocks.

POLYPS

Tiny organisms that live inside a coral and are responsible of the creation of its skeleton.

Coral reefs are very important **ecosystems**, because they provide protection and food for many other organisms that call the reef their home. What makes coral reefs special is that their structure is built by the hard skeletons of the corals, which are the parts of the corals that we usually see. Besides corals, there are other important animals found in coral reefs, including giant clams. These are very big clams that usually live anchored between the corals (Figure 3B). Giant clams get food by sucking water into their mouths and eating all the tiny particles that are floating in the water. Corals can also catch those tiny particles from the water, using the tentacles on their **polyps**, which are the living part of the coral that sits inside the skeleton (Figure 3A). As both corals and giant clams are permanently attached to the ocean floor, they must wait for food particles to pass by, like the conveyor belt in a sushi restaurant. They also cannot move to escape the plastics that are raining down on them in the water.

EXPERIMENTS ON CORALS AND GIANT CLAMS

Scientists wanted to see how corals and giant clams interact with the plastic particles in the water. Various corals and giant clams were collected from the Red Sea and placed into aquaria. Green fluorescent microplastics, which glow bright green so that they are easy to see, were added into the water (Figures 3C,D). The experiment on corals lasted for 24–28 h and the one on clams lasted for 12 days. At the end of the experiment, using a microscope, scientists counted the microplastic pieces found inside the animals' stomachs and attached to the outsides of their bodies (on the coral skeletons or on the clam shells). They found that each coral piece ate 80 plastic particles every day (1–2 microplastic particles for every 10 polyps), and each giant clam ate 8 plastic particles every day. The real surprise was that *thousands* of microplastic particles were found attached to the

ADHESION

Process of particle attachment onto a surface.

surfaces of corals and giant clams (Figures 3E,F). The amount of microplastics stuck to the skeletons of the corals (a process called **adhesion**) was 40-fold higher than the amount the corals ate. The giant clams had 60 times more plastics stuck to their shells than inside their bodies! This was the first evidence that adhesion of plastic particles to ocean organisms is so strong [5, 6]!

WHY IS THIS STUCK PLASTIC A PROBLEM?

CALCIFIER

Organism that uses calcium carbonate (the same materials of our bones) to create its skeleton.

The finding that the plastic particles can get stuck to the surface of corals or to the shells of giant clams is really important for a number of reasons. First, since corals and clams are **calcifiers** (which means they make their own skeletons and shells out of a substance called calcium carbonate), the trapped microplastics can be built into their skeletons or shells. This could make the structure of the entire reef weaker or lead to health problems for the corals and clams. Second, coral skeletons and clam shells are often homes for other organisms like small fishes, shrimps, worms, or tiny algae. All these organisms could then more easily come into contact with the potentially harmful plastics that are stuck to the surfaces of clams and corals. Last but not least, the large amount of microplastics that the scientists found attached to the reef structures explains why they did not find as much plastic as expected in the waters of the Red Sea—this sea has one of the most extensive coral reef systems in the world.

Scientists hope that this study will help everyone to understand the negative impact that plastic has on all marine organisms and why it is important to reduce the amount of plastic that reaches the oceans. Anyone can help with this! For example, we can choose reusable objects over single-use plastics: think about shopping bags, water bottles and cups. When this is not possible, we should always dispose of plastic trash in the correct bin, for recycling. If we all chip in to reduce the use of plastics and properly dispose of them, we can help to protect our oceans and the animals living there from the big threat posed by these tiny plastic particles.

ORIGINAL SOURCE ARTICLE

Arossa, S., Martin, C., Rossbach, S., and Duarte, C.M., 2019. Microplastic removal by Red Sea giant clam (*Tridacna maxima*). *Environ Pollut.* 252:1257–66. doi: 10.1016/j.envpol.2019.05.149

REFERENCES

1. Ioakeimidis, C., Fotopoulou, K. N., Karapanagioti, H. K., Geraga, M., Zeri, C., Papathanassiou, E., et al. 2016. The degradation potential of PET bottles in the marine environment: an ATR-FTIR based approach. *Sci. Rep.* 6:23501. doi: 10.1038/srep23501

2. Barnes, D. K., Galgani, F., Thompson, R. C., and Barlaz, M. 2009. Accumulation and fragmentation of plastic debris in global environments. *Philos Trans R Soc Lond B Biol Sci.* 364:1985–98. doi: 10.1098/rstb.2008.0205
3. von Moos, N., Burkhardt-Holm, P., and Köhler, A. 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus edulis L. after an experimental exposure. *Environ Sci Technol*. 46:11327–35. doi: 10.1021/es302332w
4. Martí, E., Martin, C., Cózar, A., and Duarte, C. M. 2017. Low abundance of plastic fragments in the surface waters of the red sea. *Front. Mar. Sci.* 4:333. doi: 10.3389/fmars.2017.00333
5. Arossa, S., Martin, C., Rossbach, S., and Duarte, C. M. 2019. Microplastic removal by Red Sea giant clam (*Tridacna maxima*). *Environ Pollut.* 252:1257–66. doi: 10.1016/j.envpol.2019.05.149
6. Martin, C., Corona, E., Mahadik, G. A., and Duarte, C. M. 2019. Adhesion to coral surface as a potential sink for marine microplastics. *Environ. Pollut.* 255:113281. doi: 10.1016/j.envpol.2019.113281

SUBMITTED: 21 September 2020; **ACCEPTED:** 25 November 2021;
PUBLISHED ONLINE: 17 December 2021.

EDITED BY: Christian Robert Voolstra, University of Konstanz, Germany

CITATION: Arossa S, Martin C, Rossbach S and Duarte CM (2021) Microplastics: Small Particles, Big Threat. Front. Young Minds 9:608621. doi: 10.3389/frym.2021.608621

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ESTELLE, AGE: 10

Estelle is an adventurous spirit who has a wide variety of interests from dance and make-up to filthy experiments and baseball. She loves to write and once even had a poem published in an online journal. Estelle loves hanging out with friends just as much as she loves to annoy her little brother and sister. She lives with her family in the Northeast where she gets to swim in the ocean during summer and go skiing and sledding in the winter.

ISTITUTO COMPRENSIVO ALTA VAL DI SOLE, AGE: 12

We are a small class going to a school in the middle of the Alps in Italy and have just entered secondary school and enjoy almost all the subjects! We were honored to have been reviewers of the article that let us understand the big problem that concern plastic in the oceans. We will do our best to keep this planet clean from plastic!

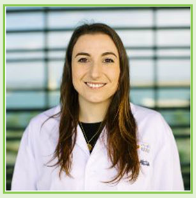
JULIA, AGE: 10

Julia is a 5th grader and enjoyes learning about the environment! She loves animals and is interested in every little fact about them. She loves music and plays the piano, the drums, the viola and helps mom figuring out the bass tab of her favorite songs. Julia also loves drawing and learning about science. She wrote a fiction book and loves her dog.

MARCO, AGE: 10

Marco is a 10 year old boy who loves adventures and nature. He recently developed a passion for soccer and he walks across town to go practice with his friends. Marco has a wonderful voice and he loves singing.

AUTHORS



SILVIA AROSSA

Silvia is a Ph.D., candidate at the King Abdullah University of Science and Technology. She started her journey into the fascinating underwater world by studying sea turtles and sea anemones, then she has gradually become interested in understanding how human activities can influence marine organisms. Nowadays, she is investigating how climate and environmental changes may affect marine vertebrates, invertebrates and even human cells. *silvia.arossa@kaust.edu.sa

CECILIA MARTIN

Cecilia is a marine scientist that started to study the marine world diving through the coral reefs of the Maldives. Now she lives on the coast of the Red Sea, where she is monitoring the plastic pollution that ends up there. She is trying to understand how much plastic is dumped every day in the Red Sea and where this can be found. She is looking for plastic in the coral reefs, but also in the water, on the beaches, on the seafloor, and in the mangroves (plants living between the sea and the shore).

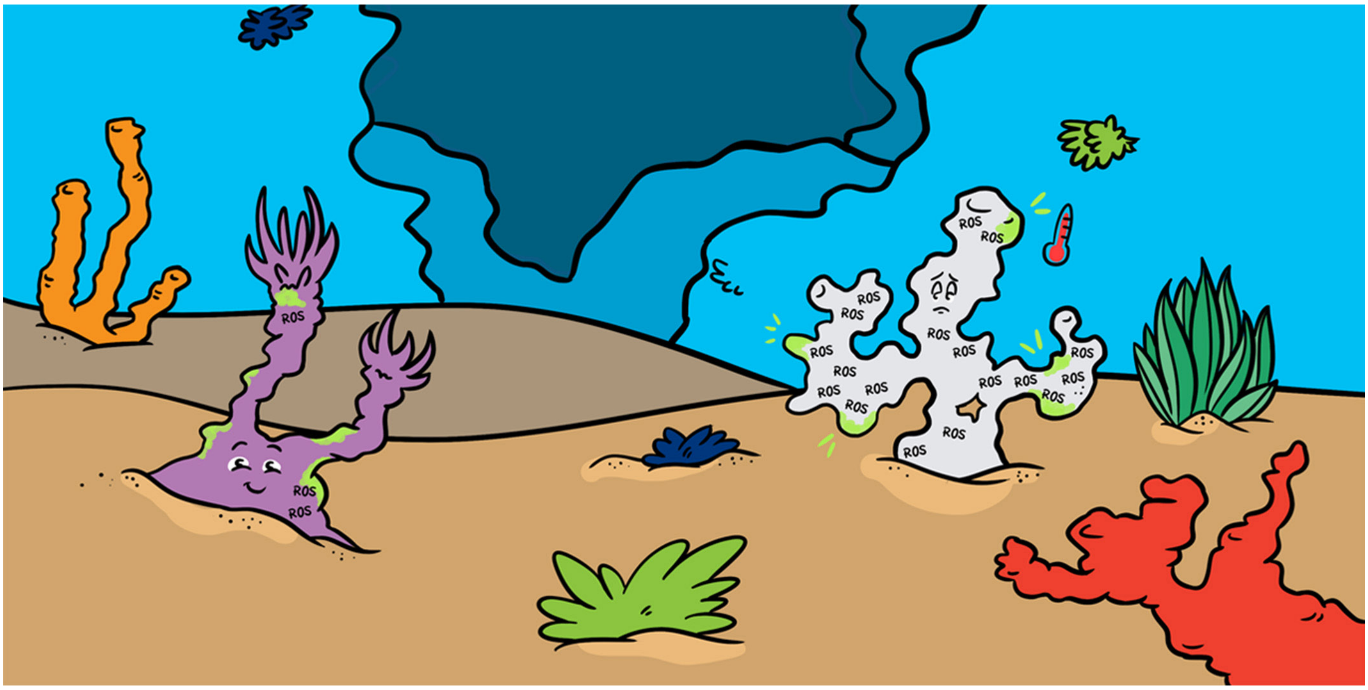
SUSANN ROSSBACH

Susann is a marine researcher that wants to understand how marine animals, such as giant clams and corals, are building their skeletons. She is especially interested in learning how they can survive in the changing conditions of our oceans. She loves to dive, explore the underwater world and share the lessons she learns and pictures she takes underwater with others.

CARLOS M. DUARTE

Carlos is a marine researcher that, after nearly four decades documenting how human pressures impacts on marine life, wants to drive, from science, a global effort to rebuild the abundance of marine life. He loves dogs and enjoys being away in the open sea, reading, swimming, snorkeling, walking, and playing with his grandson Oliver.

BIODIVERSITY
Published: 27 February 2019
doi: 10.3389/frym.2019.00028



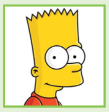
WITH A LITTLE HELP FROM FRIENDS—HOW ALGAE HELP CORALS SURVIVE TEMPERATURE STRESS

Maha Joana Cziesielski and Manuel Aranda*

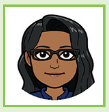
Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

YOUNG REVIEWERS:


ARNAB
AGE: 14


EVAN
AGE: 12


SUBHAAN
AGE: 13


VARSHINI
AGE: 14

Have you ever been in the ocean and admired the many fish living on the reef? Did you notice the colorful rock-like structures? Those colorful rocks are actually animals called corals. Corals are the building blocks of reefs and provide homes for many marine species. However, corals are very sensitive to changes in the environment. Human impact has caused our oceans to become warmer. Corals are struggling to survive. But there is hope: some corals have learned to live in warm waters, such as the Red Sea, and in places with hot summers. This shows us that there is a chance for corals to survive. We studied Red Sea corals and found that they have adapted to warmer waters using specific mechanisms, and some help from their algae friends. By learning what makes some corals stronger, we can hopefully figure out a way to help the weaker corals.

THE SENSITIVE LIFE OF CORALS

Corals are **invertebrate** animals that belong to the same group as jellyfish and **anemones**. Corals have a bone-like skeleton that sets them

INVERTEBRATES

Animals that lack a backbone, or spine, like snails or jellyfish.

apart from their other family members. Corals live together with small **algae**, called **Symbiodiniaceae**. The coral and algae help each other survive. This is known as living in **symbiosis**. The coral gives the algae protection and the algae gives the coral the energy to build a large skeleton [1].

When there are too many changes in the environment, the coral and algae get stress and cannot communicate well. They then stop helping each other and the algae will leave the coral. Because the beautiful colors of coral come from algae, when the algae leave, the coral turns white. This is what we know as coral bleaching. One of the main reasons for coral and algae breaking up is warmer temperatures. Warmer water temperatures stress out the coral and the algae and lead to bleaching. Climate change and other human impacts have increased ocean temperatures worldwide. Every year, coral reefs are experiencing hotter summers. How much heat can our coral reefs survive?

ANEMONE

Is a close relative of corals. Anemones have a similar structures and lifestyle as corals but are squishier. *Aiptasia* is an anemone.

ALGAE

A very simple, water-based plant, like seaweed.

SYMBIODINIACEAE

Is a type of algae.

SYMBIOSIS

The interaction or relationship between two different organisms living closely together, typically providing an advantage to both.

LOOKING INSIDE CELLS TO FIND CORAL'S SECRETS

Before corals bleach, they do not show many other signs of feeling stressed. So, if we want to understand a coral's health, we have to study its cells. Inside cells we have a lot of information, including DNA, RNA, and proteins. These molecules can help us find clues about the communication between the coral and the algae. But also, these molecules can teach us how to know when corals are stressed.

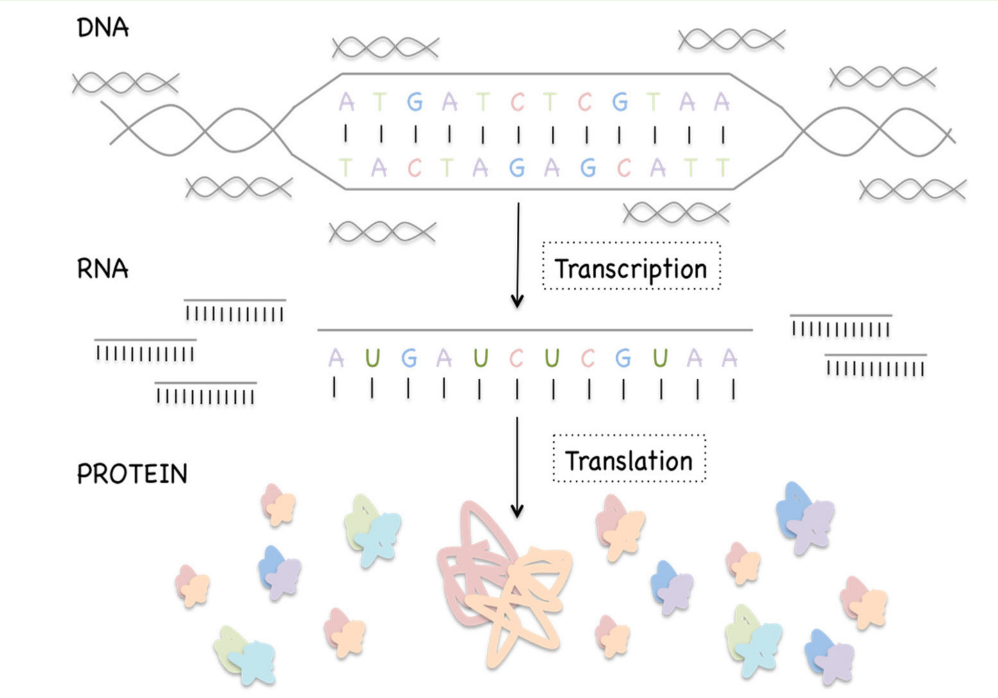


Figure 1

Figure 1

The relationship between DNA, RNA, and protein. DNA contains all the information required for the production of proteins, which perform many important functions in each cell. To make a protein, the cell can access the information it needs by first turning DNA into RNA, through a process called transcription. Then the RNA will be turned into the proper protein through a process called translation.

When an organism is stressed, every cell in its body will react. Everything will do its best to survive! In response to stress, the cell will use its DNA to make RNA, so that it can then make proteins that will fight off the stress (Figure 1). If an organism has been stressed before, it can respond to the stress faster and better. Think of it like visiting a city: the first time you visit, you will need a map to find your hotel. The more often you visit the city, the less you will need the map because you will remember, and you will get back to the hotel faster. Corals that have been in hot water before remember how to best survive. We can see this memory in the cells. The cells that have been stressed in the past will begin making different proteins and make the right proteins faster. So, they respond in a way that is different from corals that have never been in hot water before. Studying these difference lets us see what makes certain corals able to survive heat while others cannot.

STUDYING CORALS THAT ARE GOOD AT COPING WITH HIGHER TEMPERATURES

Corals can have different resistance to warm temperatures. The environment the corals grow up in can influence their behavior. Many species of coral have learned to live in the world's warmest waters, such as the Red Sea or the Arabian Gulf. This shows that corals are able to **adapt** to more stressful environments. To learn what makes some corals tougher than others, we used a model organism: the small sea anemone *Aiptasia*. Anemones are related to coral, but *Aiptasia* is easier to study than coral, because it grows fast and has no skeleton. We wanted to understand what allows some animals to deal better than others with warm temperatures. What do those animals do differently to survive

ADAPTATION

Is to adapt, meaning to make yourself more fit to survive.

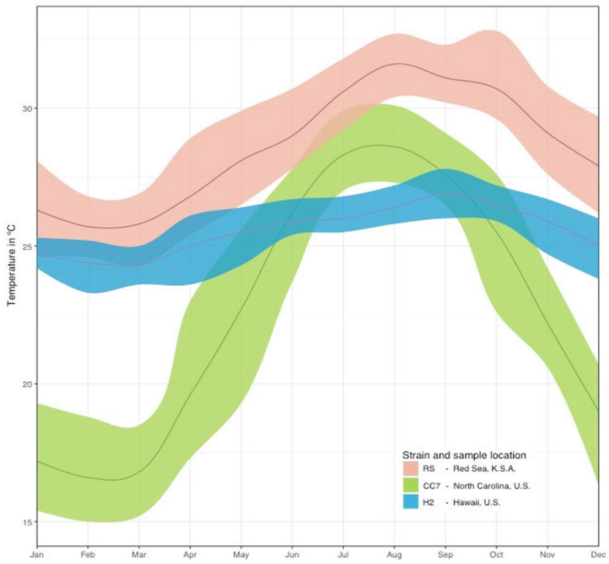


Figure 2

Figure 2

Annual average temperatures of the three locations from which the anemone *Aiptasia* was studied. These anemones were taken from North Carolina (green), Hawaii (blue), and the Red Sea (red). The average monthly temperature is shown by a solid line. Shading around the line shows the maximum and minimum temperatures. This data shows that the Red Sea has the warmest waters [2] (temperature data obtained from www.seatemperature.org).

the heat? For this we studied *Aiptasia* from different places around the world: North Carolina, Hawaii, and the Red Sea (Figure 2).

We took anemones from each location and kept them at the same temperature of 25°C for more than 1 year. Then, for some anemones, we slowly heated the water to 32°C. Anemones were heat stressed for 24 h. After that, we took cells from all anemones to compare their stress levels and responses. Studying the RNA and proteins in the anemones' cells allowed us to compare how different anemones cope with temperature.

REMOVING TOXIC CHEMICALS TO SURVIVE HEAT STRESS

When organisms become stressed, they produce a number of toxic chemicals. Most of the time, each cell in the body can remove the chemicals before they become dangerous. Sometimes, especially when there is too much stress, cells will fail to remove the stress chemicals. Then, those chemicals will build up until they become toxic and cause serious damage to the cells. One common chemical that increases in response to stress is called **reactive oxygen species (ROS)**.

REACTIVE OXYGEN SPECIES (ROS)

A chemical compound that is released during cellular respiration, which can be toxic if not removed by the cell.

ROS is a normal side product of cellular respiration, which is scientific term for the way cells generate the energy they need to live. Stress increases the amount of energy generated by cells, which also increases the levels of ROS. Because too much ROS is so toxic, ROS has been linked to bleaching of the anemones, just like in corals. An even bigger problem is that the anemone not only has to deal with its own ROS, but also ROS from the algae that live with it. The algae can pass their ROS on to anemones [3]. This increases the overall toxic level of ROS in the anemones. An anemone that can properly remove ROS even when it is stressed can cope better with high temperatures than anemones that have trouble removing ROS. We compared the ROS levels between our three anemones before and after heat stress. The Red Sea anemone had the lowest ROS levels. This result told us that Red Sea anemones can survive in the warm waters because they can remove toxic chemicals, like ROS, faster than other anemones can. Since anemones are related to corals, it is very likely that this process of removing toxic chemicals can keep corals healthy in warmer waters, too.

ALGAE HELP ANEMONES ADAPT TO TEMPERATURE

We know that the algae can pass ROS to anemones. So, the more stressed the algae are, the more stressed the anemone will be. In complex system like the coral reef, we cannot study one partner without the other.

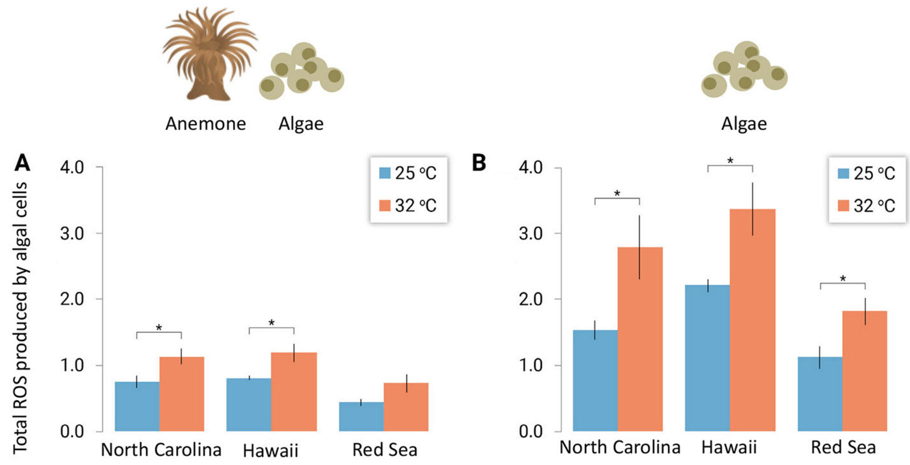


Figure 3

Figure 3

ROS produced by Symbiodiniaceae, the algae that live together with coral and anemones. **(A)** Symbiodiniaceae that lives inside anemones was tested for levels of ROS at both the normal temperature of 25°C and the heat stress temperature of 32°C. **(B)** Symbiodiniaceae that lives outside anemones was tested the same way. The stars between the temperatures of an anemone show where the change in ROS levels was strong. The data show that the algae that live in the Red Sea anemones had the least amount of ROS production in all conditions [2]. This means that the Red Sea anemone and algae were the least stressed when temperatures increased.

We saw that the Red Sea anemones survived in warmer water because they were able to quickly remove toxic chemicals. Next, we needed to understand if the algae were helping the anemones or harming them. We measured the concentration of ROS produced by the algae when it was living inside the anemone vs. when it was living outside the anemone (Figure 3).

In the Red Sea anemones, we saw less ROS in the algae living both inside and outside of the anemones. This meant that the algae from the Red Sea were less stressed by the warm temperatures than were algae that lived with the anemones from North Carolina or Hawaii. By dealing with the stress better, the algae produced less ROS. That meant that less ROS was sent to the anemone, and so both organisms had fewer toxic chemicals to deal with, overall. The Red Sea anemone therefore experienced less stress than the anemones from the other regions. The levels of ROS from the algae in other anemones showed us that other algae are more sensitive to heat (Figure 3). We can see that algae can help the anemones, and therefore also corals, cope better with high temperatures.

ANEMONES AND ALGAE ARE IN THIS TOGETHER

Studying the response of both partners that are under stress, both anemones and algae, showed us how important each of them is to the other. If the algae do not cope well with the heat stress, the anemones will also suffer. Our results show us that the Red Sea anemones are not that different from the other anemones from cold water. Instead, they just get a little more help from their algae friends. We believe, since anemones and coral are related, that this result will hold true for corals, too. This shows how specific coral-algae partnerships can lead to a higher survival success for corals in warm water environments.

By understanding the coral-algae relationship better, we can hopefully find ways to help coral reefs survive in the future.

ORIGINAL SOURCE ARTICLE

Cziesielski, M. J., Liew, Y. J., Cui, G., Schmidt-Roach, S., Campana, S., Marondedze, C., et al. 2018. Multi-omics analysis of thermal stress response in a zooxanthellate cnidarian reveals the importance of associating with thermotolerant symbionts. *Proc. Biol. Sci.* 285:20172654. doi: 10.1098/rspb.2017.2654

REFERENCES

1. Matthews, J. L., Crowder, C. M., Oakley, C. A., Lutz, A., Roessner, U., Meyer, E., et al. 2017. Optimal nutrient exchange and immune responses operate in partner specificity in the cnidarian-dinoflagellate symbiosis. *Proc. Natl. Acad. Sci. U.S.A.* 114:13194–9. doi: 10.1073/pnas.1710733114
2. Cziesielski, M. J., Liew, Y. J., Cui, G., Schmidt-Roach, S., Campana, S., Marondedze, C., et al. 2018. Multi-omics analysis of thermal stress response in a zooxanthellate cnidarian reveals the importance of associating with thermotolerant symbionts. *Proc. Biol. Sci.* 285:20172654. doi: 10.1098/rspb.2017.2654
3. Downs, C. A., Fauth, J. E., Halas, J. C., Dustan, P., Bemiss, J., and Woodley, C. M. 2002. Oxidative stress and seasonal coral bleaching. *Free Radic. Biol. Med.* 33:533–43. doi: 10.1016/S0891-5849(02)00907-3

SUBMITTED: 18 November 2018; **ACCEPTED:** 06 February 2019;
PUBLISHED ONLINE: 27 February 2019.

EDITED BY: Christian Robert Voolstra, King Abdullah University of Science and Technology, Saudi Arabia

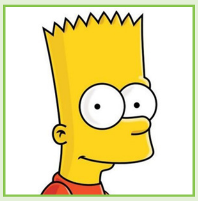
CITATION: Cziesielski MJ and Aranda M (2019) With a Little Help From Friends—How Algae Help Corals Survive Temperature Stress. Front. Young Minds 7:28. doi: 10.3389/frym.2019.00028

CONFLICT OF INTEREST STATEMENT: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ARNAB, AGE: 14

I am 14 years old student who likes computers and other tech related items. I like building stuff with Lego as well as doing Science. I also like video games, like Cities Skylines and Mario.

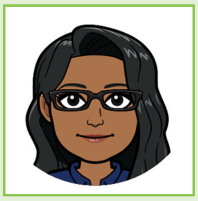


EVAN, AGE: 12

I am born in Greece. I always have bed hair.

SUBHAAN, AGE: 13

I am from Canada and I like memes. I like Marvel and my favorite superhero is Spiderman and my favorite villain is Venom.



VARSHINI, AGE: 14

I enjoy Science since I want to learn about the world, reading, and art.

AUTHORS

MAHA JOANA CZIESIELSKI

I am a final year Ph.D. student at the King Abdullah University of Science and Technology. I have been working what climate change does to coral's and the small algae that live in their cells. When I am not doing Science, I enjoy being physically active either at the gym, dancing, or outdoor activities. *maha.olschowsky@kaust.edu.sa

MANUEL ARANDA

I am a Biology Professor at the King Abdullah University of Science and Technology in Saudi Arabia. I study why corals are so sensitive to climate and how we might be able to help them. In my free time I like to cook and to play Playstation with my son.

BIODIVERSITY
Published: 22 May 2020
doi: 10.3389/frym.2020.00065

AN INCREDIBLE INVISIBLE WORLD: HOW MICROORGANISMS COULD TAKE CARE OF CORALS IN DIFFICULT TIMES

***Phillipe Rosado*[1]*, Natascha Varona*[2]*, Jonathan A. Eisen*[2] *and Raquel S. Peixoto*[1,2,3*]**

[1] *Molecular Microbial Ecology Laboratory, Paulo de Góes Institute of Microbiology, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil*

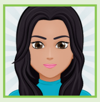
[2] *Genome Center, University of California, Davis, Davis, CA, United States*

[3] *IMAM-AquaRio–Rio de Janeiro Aquarium Research Center, Rio de Janeiro, Brazil*

YOUNG REVIEWERS:

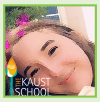

BRAYDEN
AGE: 11


CECILIA
AGE: 11


NAGA
AGE: 15


SAGE
AGE: 10

Have you ever dived into the ocean and seen several colored "rocks" in the water? Those "rocks" might actually be animals called corals! Corals form coral reefs and they are very important, because thousands of marine animals depend on them for survival. Did you know that corals and humans have something in common? Both have what are called mutualistic microorganisms (or as we like to call them, M&Ms) living within them! Mutualistic microorganisms are tiny organisms that strengthen and help both humans and corals when they start to get sick. One of the main causes of coral disease and death is rising seawater temperature. The curious thing is that in some places, such as the Red Sea, the temperature of the oceans is higher than it is in other places, yet there are several corals living happily there. How is this possible? Are M&Ms one of the factors helping corals survive in these high-temperature environments?



SAVANA
AGE: 13

UMAIRAH
AGE: 15

AN ANCIENT ANIMAL NEEDS HELP

Corals have been around for a long time, living in the oceans for millions of years, probably even before the dinosaurs existed. Currently, coral reefs cover only 1% of the ocean area, but one out of four marine animals rely on coral reefs to survive. It is in coral reefs that these sea animals find food, make their homes, protect themselves from predators, and breed their young [1]. What if corals vanished forever? Where would all other coral-dependent animals live? It would surely be a great disaster (Figure 1).

One of the big threats to coral is the rising temperature of the oceans. Although corals have been around for millions of years, they are fragile animals in some ways, particularly when it comes to changes in temperature. Here is what happens: there are organisms called zooxanthellae (pronounced zoo-uh-zan-thel-ee), which are very small and live inside most of the shallow-water corals. These zooxanthellae can carry out **photosynthesis**; in other words, they can turn sunlight into food. They are so efficient at producing food from sunlight that they can feed themselves and feed the coral as well. Therefore, the main source of food and energy for these corals to grow comes from the zooxanthellae that live inside them. In return, corals protect the zooxanthellae and provide some nutrients to help them grow. This very friendly relationship between coral and zooxanthellae is known as **mutualism**.

PHOTOSYNTHESIS

A chemical process used by many organisms (e.g., plants, many microbes) to use the energy of light to make sugars from carbon dioxide.

MUTUALISM

The interaction between two or more species, in which each organism benefits from the interaction in some way.

As ocean temperatures rise, largely due to global warming and the greenhouse effect, the friendly relationship between corals and zooxanthellae becomes less friendly. Zooxanthellae start to produce less food, as well as some toxic compounds, and corals start to kick them out of their homes. In this way, corals lose their main source of energy, and also lose the beautiful brownish/greenish colors they once had, turning white. This phenomenon is called coral bleaching [2]. Because zooxanthellae help to protect corals from the sun, when corals are bleached, they are unprotected from the harmful effects of direct sunlight. In extreme cases, some corals will try to protect themselves by increasing their own bluish, yellowish, or purple colors [3]. These bright colors act as a sunscreen and are the last resort some corals have to protect themselves from the sun.

If corals lose zooxanthellae for a long period of time, they will not have the necessary energy to survive and will eventually die. This is the main negative impact of rising ocean temperatures, and it is at this point that M&Ms may be able to help corals, through their role as **probiotics**.

PROBIOTICS

Living microorganisms that provide health benefits when in traduced to a host.

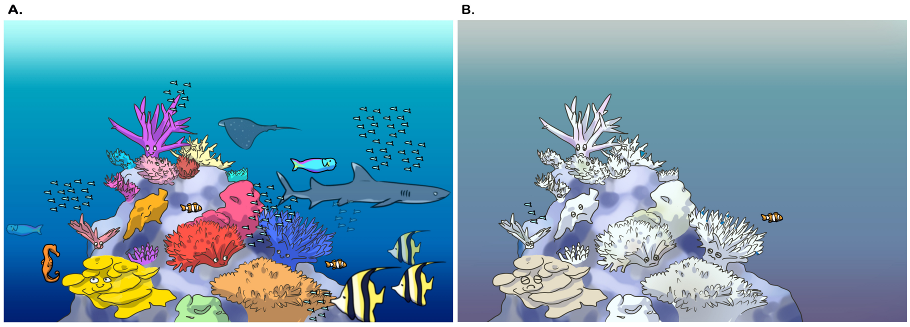


Figure 1

Figure 1

(A) A healthy coral reef, with other living marine beings living in harmony. **(B)** An unhealthy, bleached coral reef, without other living marine beings.

THE GREAT SAVIOR: PROBIOTICS

HOST

An organism that houses another organism as a guest, with the guest typically receiving nourishment and shelter from the host.

Probiotics are microorganisms that can be used to bring health benefits to the organism they live in or on, which is called the **host**. In humans, for example, probiotics have been used to help with the digestion of food and to protect people from invasion by illness-causing microorganisms known as pathogens. M&Ms are good candidates for use as probiotics, because these organisms are already known to provide benefits for their hosts. Positive interactions between M&Ms and their hosts do not occur only in humans and corals. Many plants also use a mutualistic relationship with microorganisms to grow. Legumes, which include important grain-producing plants like beans, peas, and peanuts, are a good example. Legumes have microorganisms living inside their roots, and some of them are called plant growth-promoting rhizobacteria. These beneficial microorganisms provide the legumes with nitrogen, which is an essential element for strong plant growth.

Could it be that providing more mutualistic microorganisms to struggling corals might help them to survive in higher water temperatures? Although corals do not have digestive tracts like humans, or roots like plants, they still have several microorganisms associated with them that can be beneficial. These microorganisms protect corals against pathogens, act as food for the corals, or provide some micronutrients that corals need to grow [4]. So maybe we can also use the good microorganisms that live with corals as probiotics. Researchers around the world have been studying whether probiotics can help corals when corals are endangered by rising ocean temperatures.

A recent study showed that, yes, probiotics may help corals survive during heat stress. In this study, the researchers isolated several microorganisms that live on corals and grew them in the lab. All these microorganisms were tested, using various laboratory techniques, to find out which microorganisms could potentially help weakened corals to survive. The researchers found seven such "potential super microorganisms" and did an experiment to see if

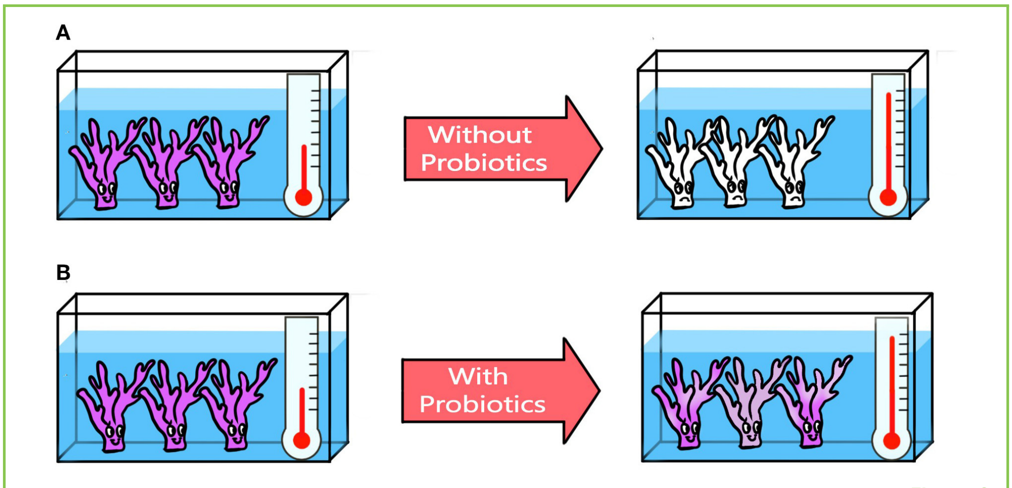


Figure 2

Coral probiotics help corals to survive high water temperatures. **(A)** Corals that are not protected by probiotics lose their zooxanthellae and become bleached when the temperature goes up 4°C above the ideal temperature. **(B)** Corals that are protected by probiotics do not lose their zooxanthellae and maintain their color, even when the temperature goes up 4°C above the ideal temperature. This tells us that certain probiotic microorganisms can help to protect corals against increases in water temperature.

these microorganisms could actually act as probiotics and protect corals in rising water temperatures (Figures 2A,B). To visualize this experiment, imagine two aquariums the size of shoeboxes, each with water and three small corals (the size of ping pong balls) inside. The researchers then raised the water temperature of the two aquariums to a temperature at which the corals begin to weaken. In one aquarium, they added the potential probiotic microorganisms to the corals and in the other aquarium they just left the corals alone, without adding any probiotics. At the end of these experiments, the researchers saw that the corals that received the probiotics were much stronger, happier, and more colorful than the corals that did not receive probiotics. This was the first evidence that probiotics may help corals survive when they are sick or stressed by temperature increases. The "potential super microorganisms" tested could therefore be renamed "actual super microorganisms." An animation showing coral probiotics working is available at (https://youtu.be/toYkTciZyuQ). Remember that, so far, these probiotics have only been tested in the laboratory with a few coral species, so we do not yet know for sure if they would work on all corals in the actual ocean environment.

HOW DO PROBIOTICS REALLY HELP CORALS?

Researchers still do not understand exactly how probiotics help corals. It is possible that these probiotic microorganisms help to keep the mutualistic relationship between zooxanthellae and corals stable, reducing bleaching. Maybe microorganisms somehow manage to soothe this troubled relationship at higher temperatures, preventing corals from expelling the zooxanthellae, so the corals do not lose their main source of energy for growth.

A second possibility is that the probiotic microorganisms themselves could be supplying energy to corals, by releasing large amounts of nutrients or even being eaten directly by corals. If the probiotic microorganisms are somehow feeding the corals, the corals might feel less stress from losing some of the food that comes from the zooxanthellae. There are many possibilities as to how probiotic organisms help corals, and more studies are being done to discover and understand what really happens in this interaction among microorganisms, zooxanthellae, and corals.

THE RED SEA: A POSSIBLE SOURCE OF PROBIOTICS

Try to imagine a place where the average ocean temperature is naturally high. A place that has water temperatures warm enough that no coral from anywhere else in the world could survive. This place is the Red Sea, a region located between Africa and Asia. There, water temperatures can reach up to 33°C [5], while ocean temperatures elsewhere in the world where corals live are ∼25°C.

This temperature difference between the Red Sea and other parts of the world may seem small, but for corals, which are so sensitive to temperature changes, this difference is very large and dangerous. Then how have corals lived happily for thousands of years in the Red Sea? Scientists think this could be because of the helpful microorganisms that these corals have. It is possible that these microorganisms have evolved with corals and have adapted to the high temperatures of the Red Sea, so they can give their corals enough strength to withstand these high temperatures. This makes the Red Sea a possible source of new probiotics to study.

Some studies are being conducted in the Red Sea to find new helpful microorganisms that can turn corals into super corals that are able to survive at high temperatures. If we find such microorganisms, we could use the microorganism to protect corals living in other regions of the world that suffer from high ocean temperatures. This may give these stressed corals a better chance to stay alive, and may also save the lives of all other sea creatures that make coral reefs their homes.

ORIGINAL SOURCE ARTICLE

Rosado, P. M., Leite, D. C. A., Duarte, G. A. S., Chaloub, R. M., Jospin, G., Nunes da Rocha, U., et al. 2018. Marine probiotics: increasing coral resistance to bleaching through microbiome manipulation. *ISME J.* 13:921–36. doi: 10.1038/s41396-018-0323-6

REFERENCES

1. Sheppard, C., Davy, S., Pilling, G., and Graham, N. 2018. *The Biology of Coral Reefs. 2nd Edn.* Oxford: Oxford University Press. doi: 10.1093/oso/9780198787341.001.0001

2. Hughes, T. P., Kerry, J. T., Alvarez-Noriega, M., Alvarez-Romero, J. G., Anderson, K. D., Baird, A. H., et al. 2017. Global warming and recurrent mass bleaching of corals. *Nature* 543:373–7. doi: 10.1038/nature21707
3. Gittins, J. R., D'Angelo, C., Oswald, F., Edwards, R. J., and Wiedenmann, J. 2015. Fluorescent protein-mediated colour polymorphism in reef corals: multicopy genes extend the adaptation/acclimatization potential to variable light environments. *Mol. Ecol.* 24:453–65. doi: 10.1111/mec.13041
4. Peixoto, R. S., Rosado, P. M., Leite, D. C. A., Rosado, A. S., and Bourne, D. G. 2017. Beneficial microorganisms for corals (BMC): proposed mechanisms for coral health and resilience. *Front. Microbiol*. 8:341. doi: 10.3389/fmicb.2017.00341
5. Sawall, Y., Al-Sofyani, A., Banguera-Hinestroza, E., and Voolstra, C. R. 2014. Spatio-temporal analyses of *symbiodinium* physiology of the coral *Pocillopora verrucosa* along large-scale nutrient and temperature gradients in the Red Sea. *PLoS ONE* 9:e103179. doi: 10.1371/journal.pone.0103179

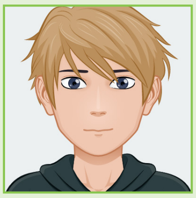
SUBMITTED: 01 October 2019; **ACCEPTED:** 16 April 2020;
PUBLISHED ONLINE: 22 May 2020.

EDITED BY: Rúben Martins Costa, King Abdullah University of Science and Technology, Saudi Arabia

CITATION: Rosado P, Varona N, Eisen JA and Peixoto RS (2020) An Incredible Invisible World: How Microorganisms Could Take Care of Corals in Difficult Times. Front. Young Minds 8:65. doi: 10.3389/frym.2020.00065

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

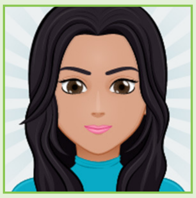


BRAYDEN, AGE: 11

I am from Montana in the USA and I like backpacking, snorkeling, floor hockey, science, learning about missions to Mars, and music. I have a dog named Geba and I like watching the Mandalorian.

CECILIA, AGE: 11

Hi, my name is Cecilia and I am 11 years old. I like reading and hiking. I also play the piano.

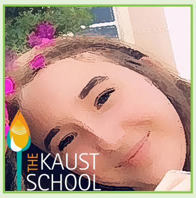


NAGA, AGE: 15

I am a 15 years old girl, only child, born and raised in India. I have been living in KAUST for 7 years. I love to sing and dance, and perform any kind of sports. I like theater, but not enough to perform live because I always forget my lines.

SAGE, AGE: 10

I am Sage, I like drawing, art, and playing my violin. I write stories and read my favorite books like Septimus Heap and Harry Potter. I am creative and like adventures, I like customizing clothes and making bracelets, and I am a good singer.



SAVANA, AGE: 13

I love dogs, my favorite color is red, and I love hanging out with my friends.

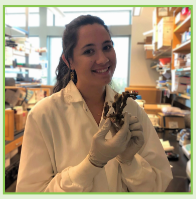
UMAIRAH, AGE: 15

My name is Umairah and I am 15 years old. I am from Malaysia but I have been living in Saudi Arabia for 7 years. I play volleyball and I enjoy Biology in school.

AUTHORS

PHILLIPE ROSADO

I graduated in Biology from the State University of Rio de Janeiro (UERJ) (2015), completed a Master's degree at Federal University of Rio de Janeiro (UFRJ) (2017) on microbial ecology of marine environments and coral microbial manipulation. I am currently doing my Ph.D. at UFRJ, on manipulation of chemicals extracted from coral microbiota to increase coral resilience to thermal and oxidative stress. I have always been fascinated by aquariums and corals and how the invisible world of microbiota works in these environments. That is why I study corals, trying to protect this wonderful ecosystem from global warming.



NATASCHA VARONA

I was first exposed to coral research through an internship at the University of California Santa Cruz (UCSC) and immediately became hooked on these fascinating animals. After transferring from my community college to the University of California Davis (UCD) I wanted to do more to protect them, so I joined a lab at UCD that was doing research on probiotics for corals. I recently graduated with a degree in Biochemistry and Molecular Biology and I hope to get my Ph.D. related to coral research in the future. I also love art, like painting and drawing, and I decided to use that skill to communicate the importance of coral reefs and the threat they are facing.

JONATHAN A. EISEN

I am a Professor at the University of California, Davis, a bit obsessed with all things microbial (and also with birds but that is for another time). I worked on microorganisms as an undergraduate at Harvard College (on beneficial symbionts of clams), as a Ph.D. student at Stanford University (on evolution and mutation in diverse microbes), and in my current and past faculty appointments (on communities of microorganisms, how they interact with each other and hosts, and methods for studying such communities). I am also an active and occasionally award-winning blogger and science communicator.

RAQUEL S. PEIXOTO

I am an Associate Professor at the Federal University of Rio de Janeiro (UFRJ) and currently Visiting Professor at the University of California, Davis. I have been working with beneficial microorganisms since my Master's studies (tracking bioindicators of pollution) and Ph.D. (at UFRJ, studying beneficial bacteria able to protect plants against disease). I merged my two passions (beneficial microorganisms and the ocean) by using the experience and inspiration obtained during my Ph.D. on the development and application of such concepts and ideas for marine organisms. I am very concerned about how global change and pollution are affecting marine ecosystems and so is Felipe, my 7 year old son. He says he wants to be a biologist to help saving corals, although he loves insects and says he wants to save bees, too.

*raquelpeixoto@micro.ufrj.br

Frontiers for Young Minds

Our Mission

To publish high-quality, clear science which inspires and directly engages the next generation of scientists and citizens, sharing the revelation that science CAN be accessible for all.

How we do this?

Top researchers write up their discoveries for kids and our global network of Young Reviewers peer review every article, guided by their mentors, to ensure everything we publish is not only understandable but engaging for their peers aged 8-15.

Discover our latest Collections

See more →

Social Media

@FrontYoungMinds
@FrontiersForYoungMinds
@frontiersyoungminds
#frontiersforyoungminds

Contact us

+41 21 510 1788
kids@frontiersin.org