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The Ocean, Volume 3

Edited by
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Sanae Chiba and Emily King

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The Ocean, Volume 3

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Earth and its Resources

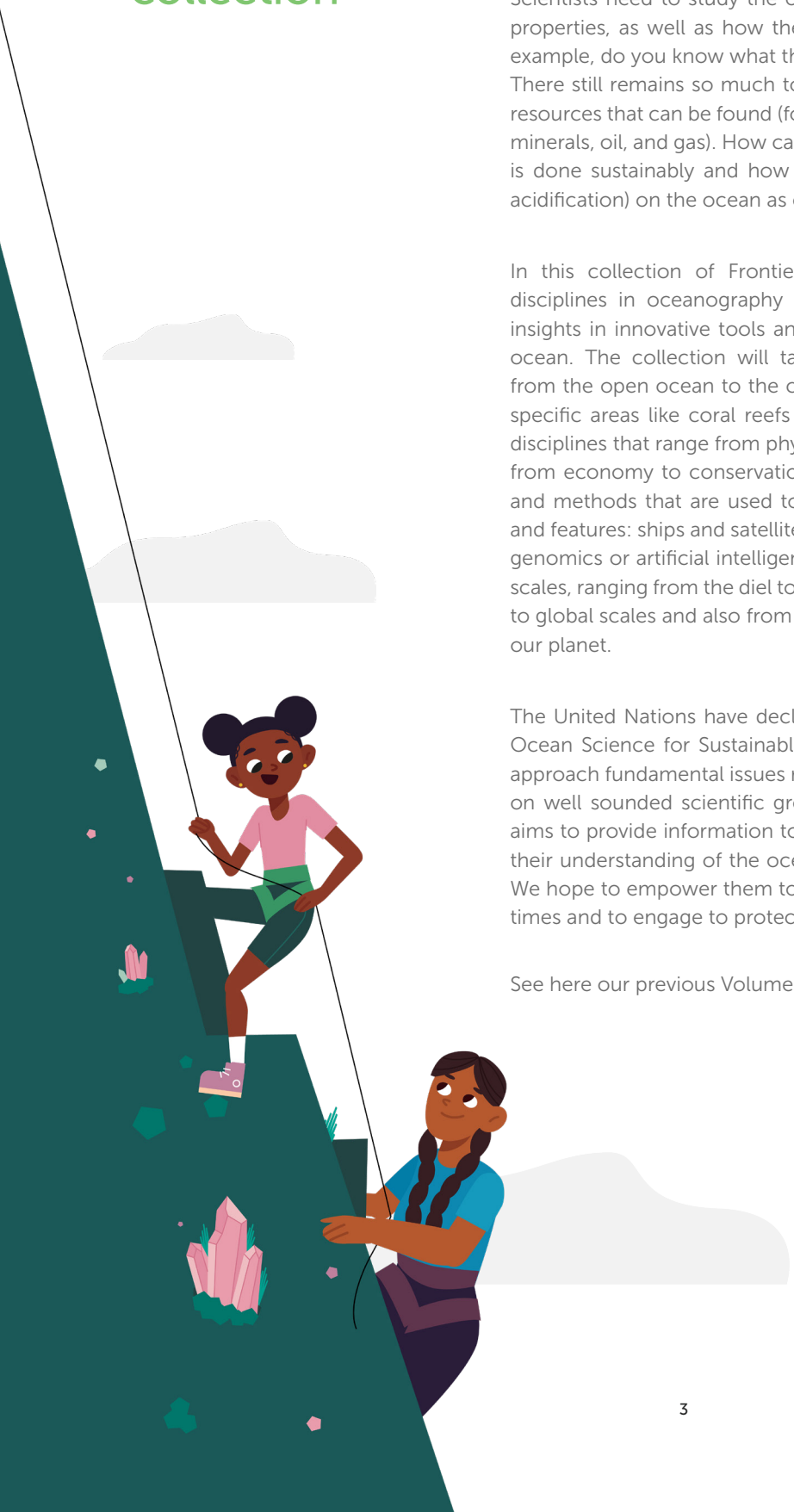
About this collection

The ocean was the origin of life on earth billions of years ago and it is vital for the future of humanity. It is vast, deep, harsh and somehow "rebellious" to uncover its secrets and hence, there is much that is unexplored and misunderstood. Scientists need to study the ocean to better understand its functioning and properties, as well as how they shape our environment and impact us. For example, do you know what the role of the ocean is on weather and climate? There still remains so much to explore in ocean biodiversity and the diverse resources that can be found (for example, fish stocks, bio-molecules, and also minerals, oil, and gas). How can we make sure that our use of these resources is done sustainably and how can we minimize our impacts (e.g. pollution, acidification) on the ocean as our human population increases?

In this collection of Frontiers for Young Minds, scientists from various disciplines in oceanography share their knowledge and motivations, give insights in innovative tools and recent discoveries to better understand this ocean. The collection will target a large range of oceanic environments from the open ocean to the coast, the surface to the abysses also including specific areas like coral reefs or sea-ice environments. It will cover marine disciplines that range from physics to chemistry, from biology to ecology and from economy to conservation and policies. It will address innovative tools and methods that are used to observe and characterize oceanic properties and features: ships and satellites, the highly diverse variety of robots as well as genomics or artificial intelligence. Finally, it will encompass a great variety of scales, ranging from the diel to geological time-scales and from loco-regional to global scales and also from the tiniest cells to the biggest living animals on our planet.

The United Nations have declared the 2021-2030 period as the "Decade of Ocean Science for Sustainable Development", stressing the urgent need to approach fundamental issues related to the ocean and the future of humanity on well sounded scientific grounds and knowledge. This Ocean Collection aims to provide information to young readers that will help them to increase their understanding of the ocean and its central role in nature and our lives. We hope to empower them to make informed decisions in these challenging times and to engage to protect, study and enjoy its richness.

See here our previous Volumes: Volume 1 and Volume 2!



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AN UNDERWATER PANDEMIC IS WIPING OUT CARIBBEAN CORALS

Maya Gomez*, Lily Haines and Valeria Pizarro

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In many parts of the Caribbean, diving underwater will transport you to a colorful world of fish, sponges, mammals, and more. This dazzling undersea rainforest is created by rock-like animals called corals. But just like humans, corals can get sick—and right now a disease is spreading throughout the Caribbean, infecting and killing some of the world's oldest and largest animals at an alarming speed. The deadly disease is called stony coral tissue loss disease (SCTLD). This article explains what we know about SCTLD and how to spot it in the ocean, how far the disease has spread, what kinds of corals are getting sick, and how we can work together to stop it. We need everyone's help to save the corals and in turn save the homes of an incredible amount of sea life.

YOUNG REVIEWERS:

AYA
AGE: 11

TARIQ
AGE: 13

CORALS ARE UNDERWATER ARCHITECTS

At first glance, some corals (called **stony corals**) look a lot like rocks. However, if you look really closely, you may see circles of tentacles, swaying with the water currents. Each circle of tentacles is a tiny animal

STONY CORALS

A marine animal that builds a hard skeleton out of calcium carbonate, leading to the creation of entire coral reefs! Corals are Cnidarians and are closely related to anemones and jellyfish.

called a **polyp**. As stony corals grow, they slowly add one, two, or a few polyps at a time to their community, each one an exact copy of the last. Eventually, hundreds or even thousands of individual animals will live in harmony as a coral colony.

POLYPS

Small animals that can live by themselves or in community with many others. For example, a single coral colony is made of hundreds or thousands of polyps.

As stony corals add to their colony, the corals begin to take unique shapes. Some corals look like the horns of elk or deer, due to their extensive and intricate branches. Other corals create magnificent castles constructed of tall pillars. Some corals look like dinner plates, and others create massive mounds and boulders! Many of these shapes have grooves, ridges, and holes—structures that serve as perfect homes for fish and other sea creatures. As hundreds and thousands of coral colonies grow together, they create one of the most beautiful and diverse ecosystems in the world: coral reefs. Because of the role that stony corals play as architects and creators, they are often called reef builders.

Corals also come in many colors, including green, brown, yellow, red, and even purple! However, corals do not get to pick which color they would like to be. Rather, much of their color comes from the presence of another organism living inside of their tissues: **symbiotic microalgae**. Symbiotic microalgae are teeny-tiny cells that do more than provide corals with their colorful pizzazz. Like plants, these tiny algae perform photosynthesis, allowing them to create and share much of the food that corals need to survive. These tiny cells are grateful for the corals as well, because corals give them both a safe place to live and the nutrients that they need to carry out photosynthesis. This kind of relationship, in which two organisms live in close harmony with one another, is called **symbiosis**. This is why the tiny algal cells are called symbiotic microalgae!

SYMBIOTIC MICROALGAE

Tiny algae that live within the tissues of stony corals, providing the corals with up to 90% of the food that they need to survive.

SYMBIOSIS

A close relationship between two different organisms, which often helps one or both of the organisms involved.

Not only do corals play irreplaceable roles in marine ecosystems, but they are also really important in the lives of humans. Coral reefs provide food for billions of people around the world, protect the coasts from tropical storms, are tourism magnets, produce life-saving medicines, and are a fundamental part of many cultures. Plus, coral colonies can live for a very, very long time. In fact, some coral colonies can continue to grow for up to 5,000 years! This is longer than any other animal on Earth. Corals are amazing!

CORALS ARE IN TROUBLE

Corals are in serious trouble due to climate change and disease, and coral colonies are dying faster than ever before. When corals die, they leave their skeletons behind. Though dead corals can continue to provide homes for reef creatures for a little while, over time these skeletons start to erode due to water currents and wave pressure. As coral skeletons break down, the homes of the many organisms living on the reef disappear.

In the Caribbean, a new disease is relentlessly infecting and killing corals like never before. The disease is known as stony coral tissue loss disease (SCTLD), nicknamed "skittle-D." Of the 45 known species of reef-building corals in the Caribbean, almost half can catch this disease. Once infected, a coral colony that took hundreds of years to grow can die within a couple of weeks or months (Figure 1). However, coral species catch the disease at different rates. Species that catch the disease quickly once it has arrived at a reef are considered highly **susceptible** to SCTLD. Some of the most susceptible stony corals include brain, pillar, star, and starlet corals. SCTLD can exist on a reef for multiple years, and species with lower susceptibility are often infected later on.

SUSCEPTIBLE

Able to be infected with a disease or illness.

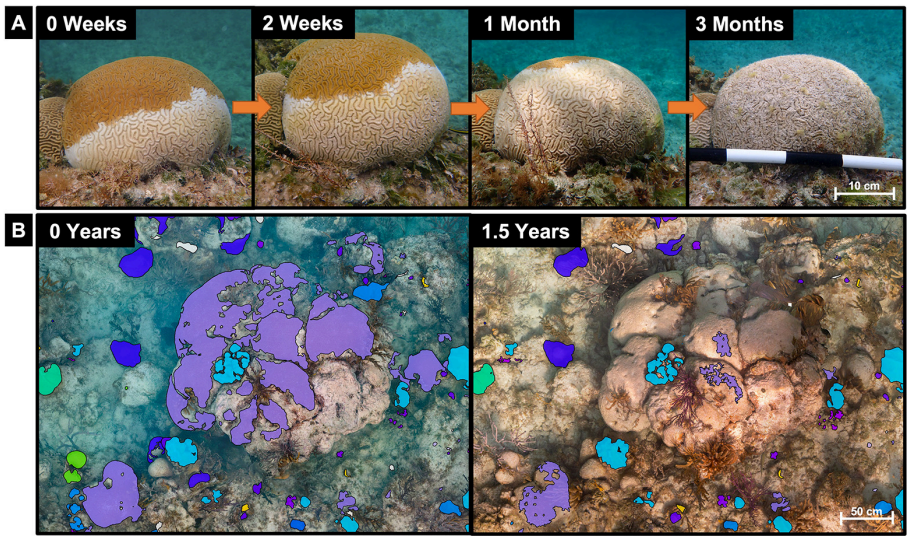

Figure 1

(A) A colony of grooved brain coral (*Diploria labyrinthiformis*) infected with SCTLD. The first signs of the disease are spots of white skeleton that expand over time. Live coral is yellow-brown in color and dead coral is white. Images are labeled with the time that passed since the first photo (Photo credit: Natalia Hurtado). **(B)** A top-down view of a coral reef in the Bahamas where SCTLD is present. All living coral is colored in, and the colors represent different species of coral. Images were taken 1.5 years apart (Photomosaic credit: Will Greene. Coral outlines created using TagLab).

Although the exact cause of SCTLD is still unknown, researchers believe that it is probably caused by either a bacterium, virus, or combination of the two.

THE RAPID SPREAD OF SCTLD THROUGHOUT THE CARIBBEAN SEA

SCTLD was first spotted off the coast of Florida in 2014. Scientists have since discovered the disease off the coasts of 20 more countries in the Caribbean, reaching from Mexico to Honduras to St. Lucia (Figure 2).

SCTLD spreads alarmingly quickly through the water. With the vast majority of new outbreaks occurring within the last few years (between 2019 and 2021), SCTLD seems to be picking up speed. For example, in the Bahamas, SCTLD has been estimated to travel at a rate of up to 50 meters (55 yards) per day [1]. Like COVID-19, SCTLD is now considered

Figure 2

Countries experiencing SCTLD outbreaks as of November 2022. You can see that the disease is common throughout Florida and the Caribbean region. Countries with SCTLD outbreaks are shown in red. [Map is based on available Atlantic and Gulf Rapid Reef Assessment (AGRRA) data].

Figure 2

an underwater **pandemic** because of its quick and shocking spread across the Caribbean region.

PANDEMIC

An outbreak of disease that begins in one place and spreads across other countries and/or continents.

However, SCTLD can be spread in more ways than just by water currents. For example, SCTLD was first spotted in the Bahamas in late 2019, in the area surrounding a major shipping port in Freeport, Grand Bahama. Just a couple of months later, in early 2020, the disease was identified on the reefs near a shipping port in another part of the Bahamas—Nassau, New Providence. The separation of 200 kilometers between these outbreaks—and the lack of disease around the islands between them—led researchers to believe that the disease arrived by way of commercial shipping vessels [1]. When commercial ships travel from one place to another, they take on large amounts of ocean water, known as **ballast water**, to make them more stable while they are moving. When the ships arrive at their destinations, they release their ballast water. While it may seem harmless, the release of ballast water containing diseases like SCTLD can cause outbreaks in new locations.

BALLAST WATER

A large amount of water that is taken up by and stored within ships. The added weight increases stability and maneuverability during travel.

After arriving in the Bahamas, SCTLD has likely spread between islands and reefs *via* local currents and smaller boats. Once present on a reef, SCTLD can spread quickly from coral to coral through the water column, through the movement of sediments across the sea floor, and through physical contact by underwater animals and divers [1].

WHAT DOES SCTLD MEAN FOR THE FUTURE OF CORAL REEFS?

Due to SCTLD, Caribbean corals are dying faster than they have ever before. In a matter of months, reefs are transforming from coral-dominated havens to algae-covered graveyards. This rapid decrease in live coral is creating an imbalance between the rate that the remaining stony corals can build new reef and the rate that ocean currents are eroding the coral skeletons that are left behind. This imbalance will affect the structure of Caribbean coral reefs in the coming years, as water pressure erases cracks, crevices, and other critical habitat—flattening the reef as a whole [2]. Sea creatures are already starting to lose their homes, and before long, humans will begin to notice the effects as well—especially when it comes to reduced fishing, tourism and coastal protection.

WE CAN STOP THE SPREAD, TOGETHER

Despite this bad news, we have not lost hope! By working together, we can stop the spread of SCTLD and reverse the decline of Caribbean coral reefs. One way to slow the spread of SCTLD is through **antibiotic** treatments, similar to medicines the doctor gives you when you are sick! Trained scuba divers will put an antibiotic paste right on the line separating living coral tissue from the newly dead skeleton. For many coral species, this will hopefully stop SCTLD in its tracks, preventing it from spreading to the rest of the coral colony [3]. However, treated corals can get reinfected with SCTLD, so the same corals and reefs must be continually monitored over time, and more antibiotic paste must be applied if necessary.

ANTIBIOTICS

A medicine that fights infections caused by bacteria. They work by either attacking and killing the bacteria or by preventing the bacteria from growing and multiplying further.

Additionally, all boaters, divers, fishermen, and ocean-lovers can help stop the spread of SCTLD. The first way to contribute is by learning how to identify the disease. If you think you see SCTLD while snorkeling, fishing, or diving in the Caribbean, snap a picture, record the location, and report it to a local conservation organization. This helps us monitor the spread between reefs within a country and between countries in the Caribbean.

Next, do your best not to spread SCTLD from infected reefs to healthy reefs. If you are going scuba diving, fishing, or snorkeling in the Caribbean, it is important to disinfect your gear before traveling to a new site (Figure 3). Boat drivers should be careful to not carry any water between reefs—they should make sure to pump out any bilge water at reefs where SCTLD is present, and to disinfect any remaining bilge water before releasing it into open water. Bilge water can be disinfected by adding 1 cup of natural detergent (for example Seventh Generation, Earthbound Elements, Tru Earth, or another natural detergent that contains sodium percarbonate) for every 20 liters (approximately 5 gallons) of water and letting it soak for 10 min. It

is critical that commercial ships also take the proper steps to disinfect their ballast water.

Figure 3

A guide for decontaminating scuba, snorkel, and fishing gear. To disinfect wetsuits and other scubawear, fill a bucket with fresh water and add natural detergent according to the manufacturer's instructions. Soak all wetsuits and scubawear for 5 minutes before rinsing with fresh water and air drying. To disinfect other scuba, snorkel, and fishing gear, add 3–4 caps of bleach for every 1 gallon of water (fresh or salt). Soak the gear for 5 minutes before rinsing with fresh water and air drying. Leave the bleach solution in the sun for a day to break down before disposing of it (Illustration by Freshnsalty.me).

With your help, we can slow the spread of SCTLD and discover its root cause, eventually stopping the spread altogether and saving the world's coral reefs!

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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

AYA, AGE: 11

Aya wants to study marine biology. She wants to specialize in sharks and rays. She does not have a favorite subject in school since she likes all of them. In her free time she likes to read books, speedcube, build in roblox, play violin, and draw mythical creatures.

TARIQ, AGE: 13

Tariq has a passion for Engineering and Geopolitical history. In his spare time, he loves to watch YouTube videos about history and technology, and read about history and politics.

AUTHORS

MAYA GOMEZ

Maya Gomez is a research associate at the Perry Institute for Marine Science (PIMS). As part of the coral team, Maya's work focuses on data collection and analysis to monitor Caribbean coral reefs and inform conservation/restoration efforts. She is also part of a team working to track and treat stony coral tissue loss disease outbreaks in the Bahamas. Maya began her Ph.D at the University of Southern California in the fall of 2022, and currently she studies stony coral growth formations and calcification in the face of climate change and disease, and in collaboration with PIMS. *mgomez@perryinstitute.org

LILY HAINES

An ocean-lover at heart, Lily Jane Haines is a marine biologist, graphic designer, and journalist. A specialist in coral reef restoration, she received her master's degree from Simon Fraser University in 2018 while working as a researcher at the Cape Eleuthera Institute in The Bahamas. As a scuba divemaster, wilderness first responder, and first aid instructor, her technical experience in ocean science paired with her journalism background give her a unique skillset as communications director at the Perry Institute for Marine Science. Above all, she is passionate about saving the world's reefs—one coral at a time.

VALERIA PIZARRO

Valeria Pizarro (Ph.D) has been studying corals and coral reefs for over 20 years. She began her research in her home country, Colombia, while working on her master's degree. Since then, she has led and participated in many projects including research on coral biology and ecology, the design and implementation of marine protected areas, and coral restoration. Currently Valeria manages the coral program at The Perry Institute for Marine Science and, since 2019, one of her main projects is on stony coral tissue loss disease—assessing the spread and treating corals around the Bahamas.

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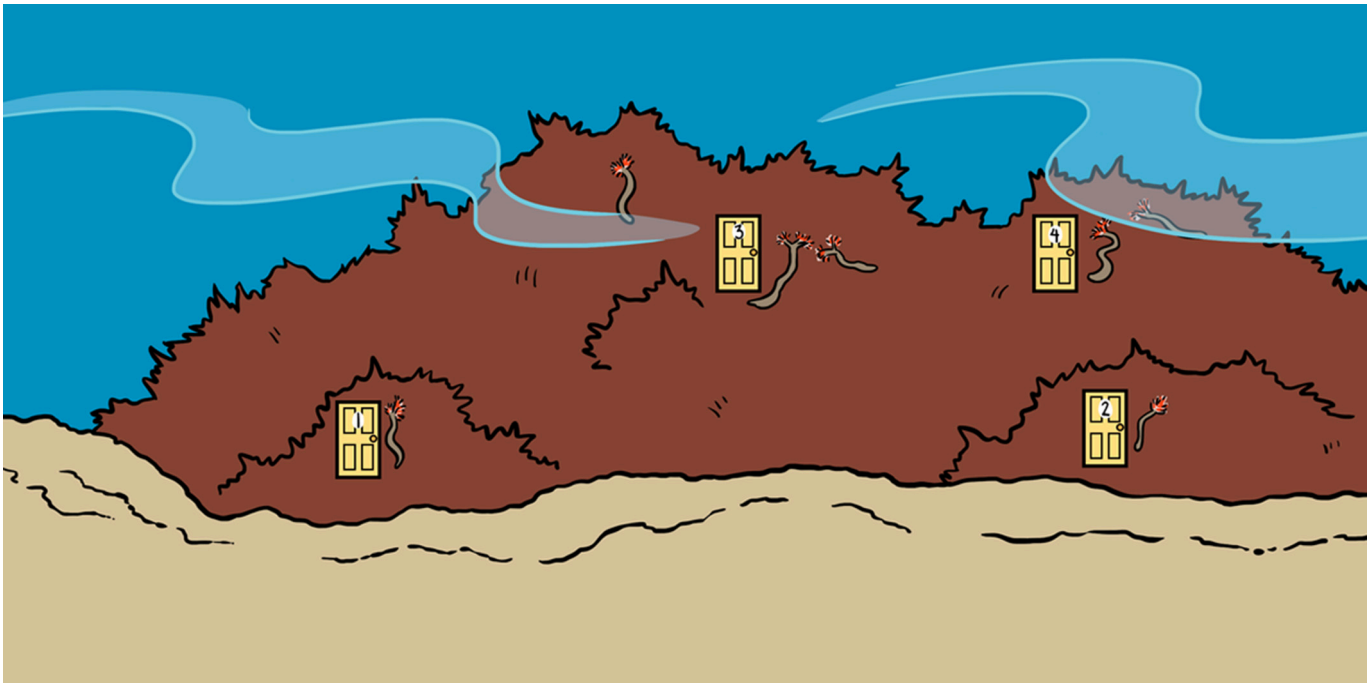

A NEW HOPE? MEDITERRANEAN ALGAE MATS ARE THRIVING WITH LIFE

***Felix I. Rossbach*[1*], *Edoardo Casoli*[2], *Milan Beck*[1] *and Christian Wild*[1]**

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YOUNG REVIEWERS:


I. C. VAL RENDENA
AGE: 14


ISABEL
AGE: 12


MARGARIDA
AGE: 15

Our oceans are full of life and home to many different species. High species diversity often concentrates in specific areas called "biodiversity hotspots" (e.g., coral reefs). These hotspots develop with the help of a few key engineering species (e.g., corals). In the Mediterranean Sea, well-known biodiversity hotspots are seagrass meadows. Macroalgae beds represent another typical habitat but usually do not provide the same diversity as seagrass meadows. High biodiversity is essential for an ecosystem's stability and our lives: healthy coastal ecosystems provide food and shelter for fish species and stabilize the seafloor. We investigated a relatively unknown type of red macroalgae and were surprised to find it thriving with marine organisms such as sea stars, anemones, and tube worms. With the latter being an example of an extraordinary group of marine animals, we would like to take this example and show you what we learned about this new hotspot for diversity.

INTRODUCTION

Earth's oceans are full of life—they are home to many different species. Certain locations in the ocean, such as coral reefs, have a high **diversity** of species, meaning many different types of organisms live there. In the Mediterranean Sea, seagrass meadows are well-known diversity hot spots—but there are others! High diversity is essential for an ecosystem's health and stability. Healthy coastal ecosystems provide food and shelter for fish species, including species that humans eat, so it is important that the diversity of ocean ecosystems be maintained. We investigated a less-studied type of ocean habitat to understand its diversity—beds of red **macroalgae**. We were surprised to find that these habitats are thriving with marine organisms such as sea stars, anemones, and tube worms! In the remainder of this article, we will explain why macroalgae are important habitats, and we will focus on the diversity of one fascinating group of inhabitants—the tube worms.

DIVERSITY

A measure of the variety of species in a habitat. Considering the number of different species and their abundances.

MACROALGAE

Large marine organisms that can perform photosynthesis, like plants do on land.

SESSILE MARINE ANIMALS NEED SPACE!

In the ocean, we can find many animals that have evolved to live attached to the ocean floor or some other surface—they are called **sessile** animals. Unlike animals found on land, sessile animals cannot move around during their adult life. Corals are the most well-known example of sessile marine animals, but other examples are barnacles and sponges. The high number of sessile animals in the ocean requires a lot of free space for them to settle down. This can create a space shortage, and as a result, any free area will quickly be colonized by sessile animals. This free space can be anything, from rocks and man-made structures like jetties or ships to other living organisms like plants and macroalgae.

SESSILE

Attached to a surface and unable to move around. Sessile animals typically have a filtering mechanism to get food, since they cannot graze or hunt for prey.

ANNELIDS

Worms that have a body built by many similar sections, called segments, and therefore look like they have rings around their bodies. The earthworm is a well-known annelid.

A SPECIAL KIND OF MARINE WORM

Worms that live in the ocean, called marine worms, come in all shapes and sizes. One group of worms, called **annelids**, is characterized by their **segmented** bodies. This means that their bodies consist of a long chain of similar parts—like the wagons of a long train. Sessile annelids called tube worms attach themselves to a surface when they are larvae, and they cannot move around once they become adults. These worms build solid tubes around themselves for protection against predators. Since they cannot move around, they filter tiny food particles from the passing currents with delicate, feather-like tentacles called **radioles** (Figure 1). Two things are very important for tube worms: an excellent spot to attach to and access to passing water currents so they can filter out enough food. The perfect home for a tube worm is a water-current-exposed surface, like the leaves of seagrasses or the bodies of marine macroalgae that grow upright in the water [1].

SEGMENTED

In biology, this means a body is divided into a series of similar parts. Like many passenger wagons on a train.

RADIOLES

Feather-like tentacles that help marine worms to catch food and to take up oxygen from the water.

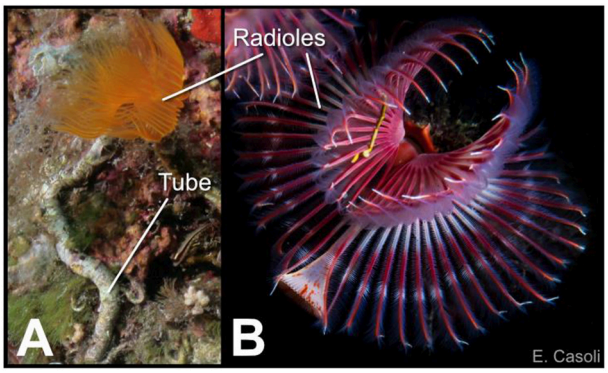

Figure 1

(A) A tube worm attached to a rock. The white tube has a similar texture to a clam shell. The orange radioles catch tiny food particles from the water currents. **(B)** Radioles can be very colorful in some tube worm species. Looking closely, you can see that each radiole has tiny branches that help catch food particles (Photograph credit: E.C.).

THE RED ALGAE APARTMENT COMPLEX

Red algae are photosynthetic organisms that can use sunlight to produce energy to grow—like plants do on land. Macroalgae species, including red algae, form dense mats and provide habitats for many species (Figure 2). Their leaves and bodies provide living space and can also change the environment for their inhabitants. For example, they keep out predators or strong water currents [2], just like a real house! Because of their ability to shape the environment, these species are called **ecosystem engineers** [3]. Well-known examples of ecosystem engineers on land include trees, which create homes for birds, and beavers, which create ponds with their dams.

ECOSYSTEM ENGINEERS

A species that creates or modifies a habitat. These species may have huge impacts on the diversity of an area.

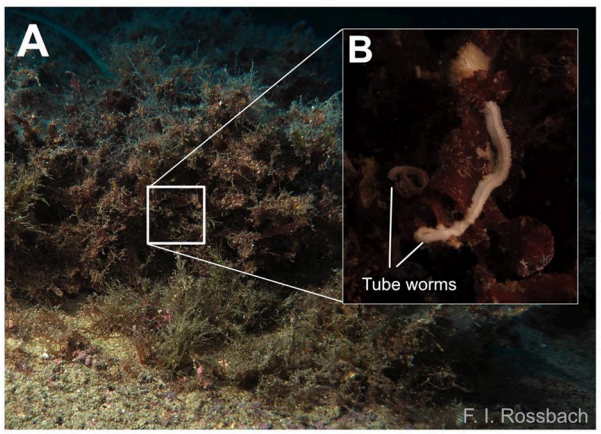

Figure 2

(A) A red algae mat growing on an underwater rock at 30 m water depth. **(B)** Zooming in, you can see that there are various animals growing on the algae. The white stripes in this picture are the tubes of tube worms (Photograph credit: F.R.; modified from the source article).

Red algae mats function like giant apartment buildings with all kinds and sizes of flats. At the bottom of the mats, closer to the ocean floor, water movement is reduced, and it is much darker than it is in the top layers [2]. The leafy areas on top of an algae mat (Figure 3A) provide more prominent places for settlement, and they are exposed to water currents. Red macroalgae grow only a few centimeters per year and can live more than 2 years [4], so they form relatively stable long-term

habitats. As a result, every animal species can find an apartment tailored to its needs, and a diverse community can develop.

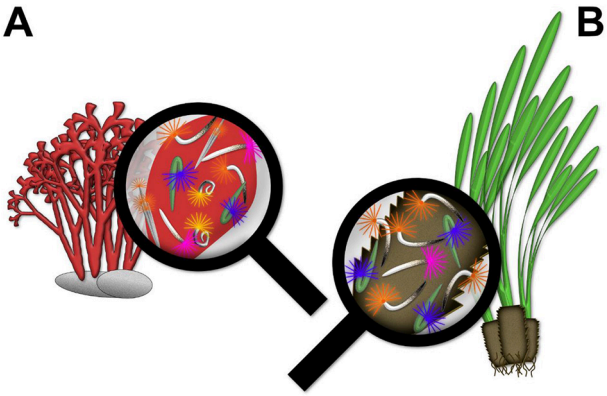

Figure 3

Figure 3

(A) Red macroalgae and **(B)** seagrass habitats for tube worms. Both are home to many individual tubeworms. But the compositions of the communities are different. We found similar numbers of tube worms on the algae and the stems of the seagrass. But the distribution was more balanced on the red algae. Can you spot the differences?

When we began our study, red algae mats had not been studied very much. We were surprised to find many groups of sessile organisms living in red algae mats, each in high **abundance** (numbers) and with high diversity. Since tube worms are such fascinating animals, we wanted to learn more about them and about their relationship with the red algae.

ABUNDANCE

The number of individual organisms per area.

THE INHABITANTS OF THE ALGAE MATS

To look at the importance and health of the habitat formed by red algae, we investigated several factors: the total number of tube worms present, the number of different species of tube worms that lived there (diversity), and how many tube worms of each species were there (abundance).

We found high numbers of tube worms inside the 5 cm thick mats of red macroalgae. The numbers we found were similar to those found in another well-studied tube worm habitat: seagrass mats. However, we found more types of tube worm species on the macroalgae, meaning tube worm diversity was higher in the macroalgae compared to seagrass. We also looked at the abundance of each different species that we found. We observed that only a few tube worm species were very abundant on the seagrass. However, on the macroalgae, many different species of tube worms were present in large numbers (Figure 3). These results show that macroalgae mats are a valuable habitat for tube worms.

In a healthy and stable habitat, the distribution of different species is more balanced than in a damaged habitat [4]. The more even distribution of tube worm diversity on the red macroalgae shows that the community is probably more resilient to any disturbances, like

pollution or climate change. That makes it less likely that a rare group of tube worms will disappear completely.

CONCLUSION

Many species—including tube worms—are losing their homes because of human activity near the coast, and some habitats have already disappeared. For example, the seagrass in the Mediterranean Sea is in danger because of climate change and water pollution [5]. Larger sessile animals, like Mediterranean corals, have died off after warming events in the last few years [6]. Macroalgae have been observed to take over damaged areas in tropical reefs, but this shift is often accompanied by a loss of diversity loss [7], meaning the ecosystem becomes less healthy and resilient. But our studies showed that macroalgae could provide homes for many different species—creating a habitat with similar or even higher diversity than previously known habitats like seagrass. Red algae mats have not been studied very much, and we were surprised to find such large numbers of tube worms and so many other animal species. While environmental changes generally lead to loss of habitat and decreased diversity, macroalgae mats might be a hidden gem of diversity, giving us hope that natural richness can still survive in unexpected locations. There is still a lot to discover!

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ORIGINAL SOURCE ARTICLE

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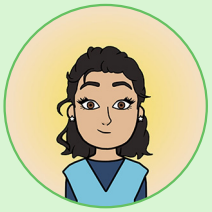
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

I. C. VAL RENDENA, AGE: 14
We are a small class going to a school in the middle of the Dolomites in the northern part of Italy. This is our last year at secondary school, so we are enjoying this last year together. The most of us love skiing and snowboarding in the winter, and hiking and football during summer time. We have a cool science teacher who loves nature and

she teaches us all about biodiversity and climate change so we enjoy our lessons a lot.



ISABEL, AGE: 12

Hello, I am Isabel. I am 12 years old and I really like writing stories. I also like reading and playing drums. I am really interested in diplomacy.

MARGARIDA, AGE: 15

My name is Margarida, I am 15 years old and I like reading, climbing and writing. I love science, especially astrophysics and I have absolutely no idea what I want to do when I grow up. I also really like biology.

AUTHORS

FELIX I. ROSSBACH

Felix is a marine biologist and research diver who wants to understand how marine ecosystems work and how different species interact to build a thriving community. He is specifically interested in learning about the roles of key species that shape the living space for others. He loves photography, diving, and sharing his discoveries with other ocean enthusiasts. *felixivorossbach@gmail.com

EDOARDO CASOLI

Edoardo Casoli is a research fellow at the Sapienza University of Rome, where he teaches "Structure and Functioning of Marine Ecosystems" and "Impact of Climate Change on Marine Biodiversity." He is interested in the ecology of marine communities and focuses on the effects of human activities and climate change on organisms living on the seafloor. He is passionate about underwater photography, a powerful tool to connect people with science and promote marine ecosystems conservation.

MILAN BECK

During his studies in marine biology, Milan traveled all the way to the Mediterranean and the Arctic to understand the impacts of climate change on various marine macroalgal habitats. He is especially interested in working with and developing new technical solutions to research these coastal habitats in a more effective and non-invasive way.

CHRISTIAN WILD

Christian Wild is a professor of marine ecology at the University of Bremen, Germany, and he initiated this project when he realized the exceptional biodiversity associated with red algae mats. Whenever he looked into the mats using a stereo microscope, he saw organisms he had never observed. The number of different species reminded him of coral reefs, the focus ecosystems of his research group.

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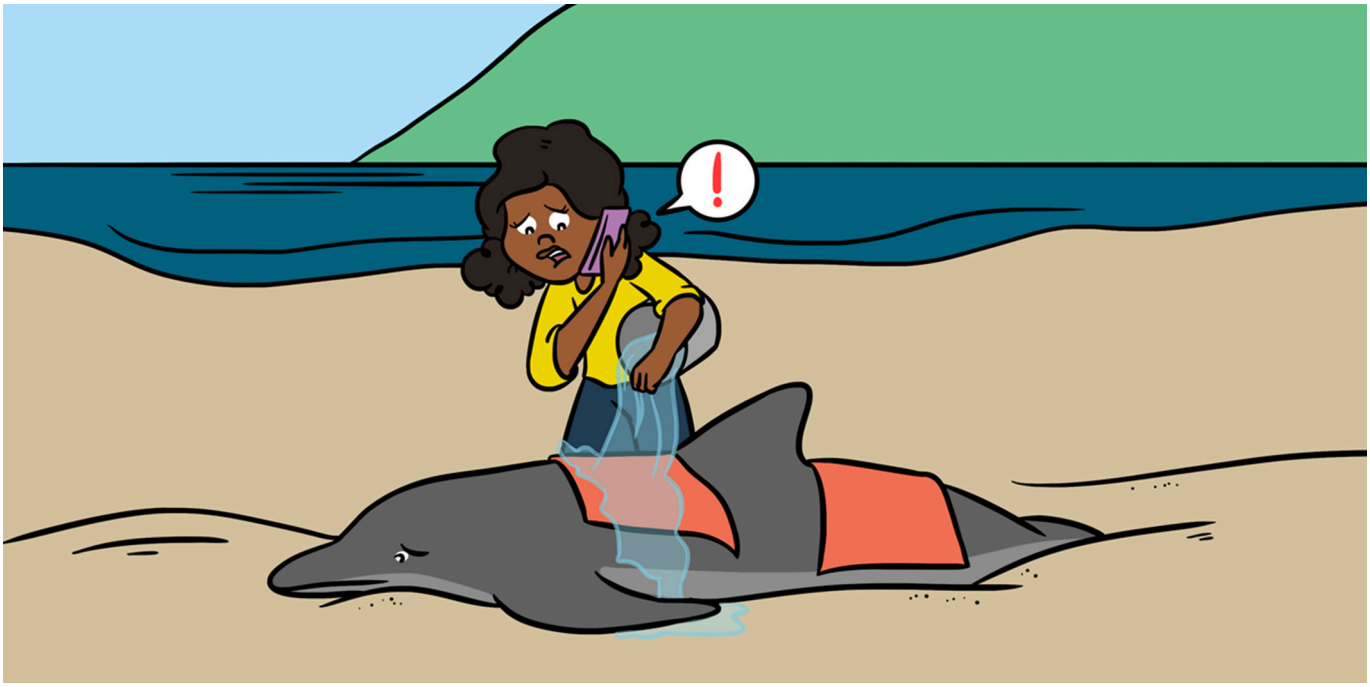

WHY DO MARINE MAMMALS STRAND ON LAND AND HOW CAN HUMANS HELP?

Rebecca M. Boys [1*†], ***Karen A. Stockin*** [1,2] ***and Katharina J. Peters*** [1,3,4*†]

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[2] *Animal Welfare Science and Bioethics Centre, School of Veterinary Science, Massey University, Palmerston North, New Zealand*
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YOUNG REVIEWERS:


ALICE
AGE: 13


SAI
AGE: 14


SARA
AGE: 14

Have you ever heard about, or maybe even seen, a whale or a dolphin that was helplessly lying on the beach or stuck in very shallow water? These are called "stranding events" or "strandings," and have been documented since the fourth century. Back then, strandings involving cetaceans (whales, dolphins, and porpoises) were welcome events because they provided a rich source of food and other resources for the people nearby. But today, we tend to see strandings as events in which animals need human help. There are several types of strandings, each with their own possible causes. In this article, we explain what stranding events are, what might cause them, and how you can help if you ever find a stranded animal.

WHAT ARE STRANDINGS?

CETACEANS

(Pronounced: SE-TAY-SHUNS) A group of aquatic mammals including whales, dolphins, and porpoises.

STRANDING

An event in which a cetacean becomes beached/stuck on land.

Cetaceans are a group of aquatic animals including whales, dolphins, and porpoises. For hundreds of years, humans have witnessed times when these animals have become stuck ashore, which are called **strandings**. Many years ago, strandings were often considered gifts from the gods, as they provided food and other resources such as bones (used for making tools and jewelry) and oil (used for cooking and burning in lamps). Most stranding events involve single animals, but in some places, mass strandings—involving up to hundreds of animals—can happen [1, 2]. Mass stranding events often occur regularly in the same spots (called stranding hotspots), including Cape Cod in the USA, Tasmania in Australia, and Farewell Spit in New Zealand (Figure 1A). It is unknown why strandings occur frequently in some spots; however, it is possible that shallow bays and spits of land in these locations (Figures 1B, C) cause the animals to become disorientated; then, as the tide goes out, they can become stranded [1].

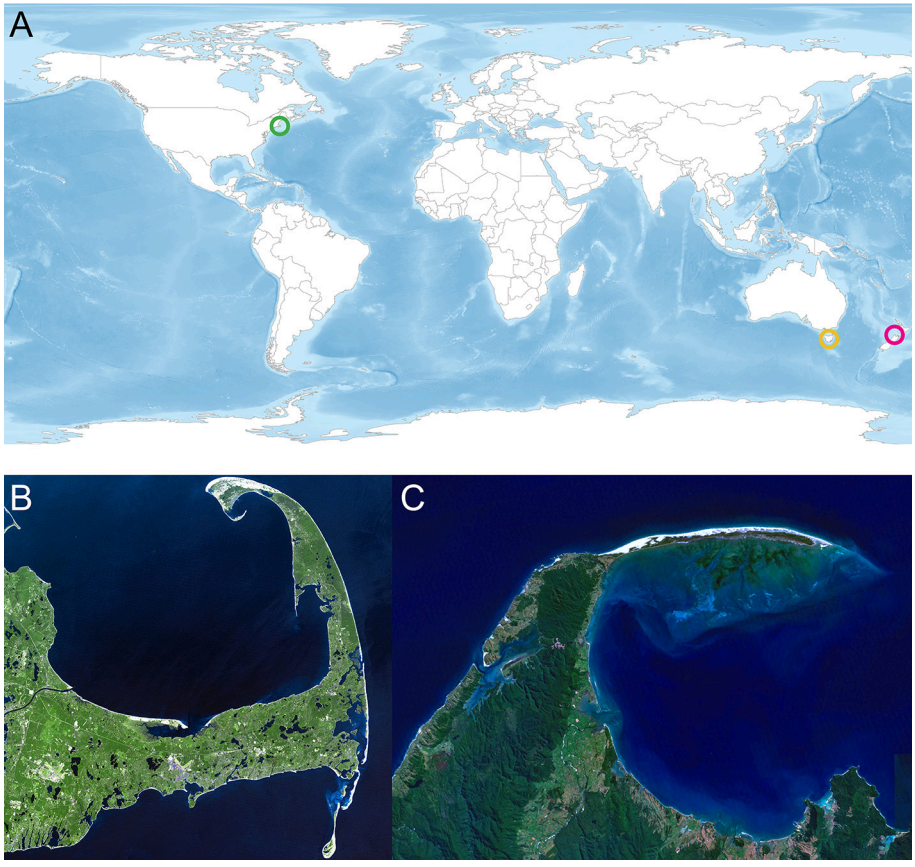

Figure 1

(A) World map with water depth indicated by color: darker blue represents deeper water. Circles show locations with high frequency of mass stranding events: Cape Cod, USA (green), Tasmania, Australia (yellow), and Farewell Spit, New Zealand (pink). **(B)** Cape Cod, USA and **(C)** Farewell Spit, New Zealand are stranding hotspots with shallow bays mudflats and a "spit" of land to the north (Photo credit: NASA).

Strandings can occur for various reasons: as mentioned for stranding hotspots, geographical features may be involved, such as the shape of bays; but extreme tides and extreme or unusual weather might also be involved. Certain biological factors could also play a role in strandings, such as poor animal health or old age. Sadly, human factors can also

cause strandings. Cetaceans may become ill from pollution, and they can also be injured by ships or can become entangled in debris such as ropes and old fishing gear [1–3]. Strandings are generally categorized into four types:

Single Stranding (Figure 2A): In a single stranding, one animal (or a mother-calf pair) is stranded. This is the most common type of stranding. These stranded animals often have underlying health issues, such as illness, complications while giving birth, or they might have poor nutrition or be starving. However, single strandings may also be related to human activities, like harassment by people (such as frequent close contact by humans swimming with and/or following the animals closely on jet skis or boats) or entanglement in fishing gear.

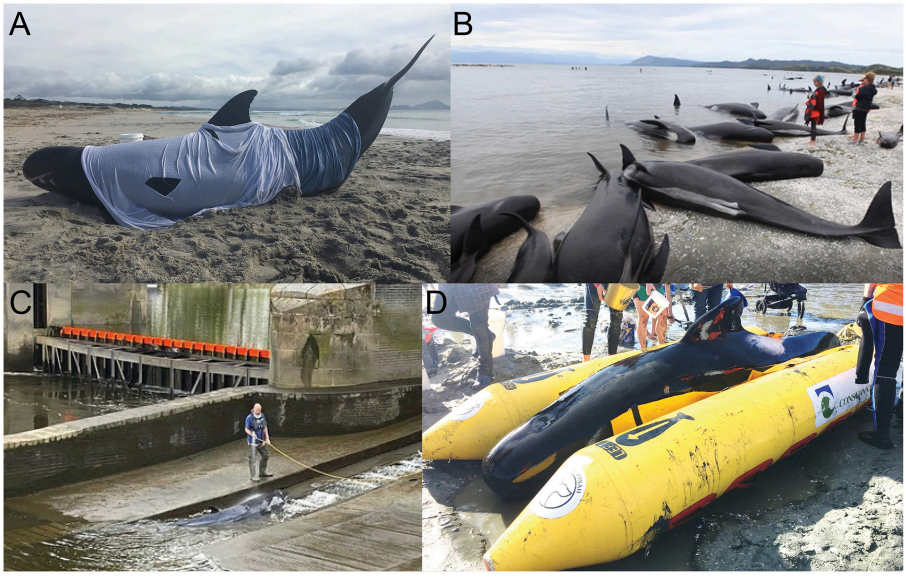

Figure 2

Figure 2

(A) Single stranded cetacean (pygmy killer whale) that died after stranding on a New Zealand beach (Photo credit: Rebecca M. Boys). **(B)** Mass stranding event of long-finned pilot whales in New Zealand. Some individuals were refloated, but many others died (Photo credit: Rebecca M. Boys). **(C)** Minke whale calf that became trapped in a loch when it swam up the Thames River, London, UK. Sadly, the animal was not well and needed to be euthanized to end its suering (Photo credit: The Independent). **(D)** A long-finned pilot whale is prepared for refloating using inflatable pontoons in New Zealand (Photo credit: Rebecca M. Boys).

Mass Stranding (Figure 2B): In a mass stranding, two or more individuals strand in the same area at the same time. Many of the animals in mass strandings appear outwardly healthy. However, animals can be harmed by the stranding event itself or may be injured by scavengers like seabirds. Mass strandings often involve species known to have strong social bonds, such as pilot whales *Globicephala* spp.

Unusual Mortality Event: In unusual mortality events, many animals, often in large numbers, strand over a wide geographic area and long time frame. These animals are often already dead when they are found. Unusual mortality events are generally linked to disease outbreaks, but large-scale catastrophes such as oil spills have also caused them. Other human activities, such as the use of high frequency sonar, have also been linked to unusual mortality stranding events, particularly of beaked whales.

Out-of-Habitat Situation (Figure 2C): Out-of-habitat strandings occur when an animal is found in an area that would be considered unusual for the species, such as the minke whale (*Balaenoptera acutorostrata*) calf reported in the Thames River in London, or the beluga whale (*Delphinapterus leucas*) seen in the Seine River in France. These are considered stranding events even though the animals may not be "stuck" on the shore. In some cases, these animals may be healthy and are just lost, but they may become ill or injured due to the inappropriate habitat.

THE IMPACT OF STRANDING

In some cases, stranded animals may be ill or injured, while in others they may appear healthy. However, the stranding event itself can cause significant damage to an animal because the animal is out of its natural water environment [4]. Cetaceans have evolved to live in water, so they cannot support their own body weight on land. Therefore, when they are stranded, their organs can be crushed. The inner heating/cooling system of their bodies, known as the **thermoregulatory system**, is also adapted to being in water, which means cetaceans can quickly overheat on land. The skin of cetaceans is also designed to be in water, and it becomes dry and easily damaged when not submerged. In sunny conditions, stranded cetaceans can get painful sunburns, with skin blistering.

THERMOREGULATORY SYSTEM

The biological system that regulates the body temperature of a human or an animal.

HOW DO EXPERTS HELP STRANDED ANIMALS?

Today's responses to strandings often focus on trying to save animals by refloating them at sea (Figure 2D). However, depending on the situation, refloating an animal might just be extending its suffering instead of saving its life. In some cases, animals may have significant injuries (both inside and outside the body), illness and/or have become severely weakened due to stranding [2, 4]. These animals are unlikely to survive even if they are refloated. In these cases, experts can use **euthanasia** to end an animal's suffering, or they can keep it comfortable until its natural death occurs [3, 5]. These options can be the best choice from an animal-welfare perspective. Therefore, before an animal can be refloated, it should undergo a thorough medical examination by cetacean stranding experts and/or veterinarians. These professionals should make sure, to the best of their ability, that the animal will not suffer and that it is likely to survive, if refloated [2, 4].

EUTHANASIA

The process of humanely ending an animal's life to stop its suffering.

WHAT IF YOU FIND A STRANDED CETACEAN?

To best protect an animal's welfare and increase its chance of survival, there are several first-aid procedures that should be followed in

stranding response [1, 2, 4] (Figure 3). However, even with good intentions, untrained people can worsen an animal's situation through stress and injury, and may also put themselves and others at risk of injury or disease [1–5]. Here are some simple "do's and do not's" to follow if you find a stranded cetacean.

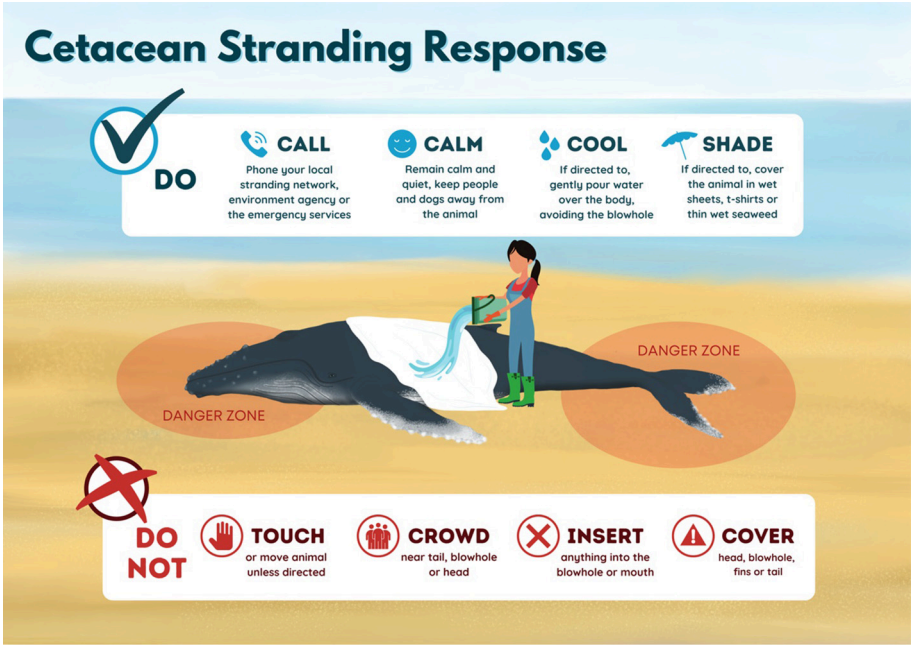

Figure 3

Figure 3

Do's and do not's for cetacean stranding events (Image credit: Katharina J. Peters and Rebecca M. Boys).

DO

- CALL: Phone your local stranding network, environmental agency, or emergency services. Tell them the location and number of animals, and try to give a description of any visible injuries. Take photographs if possible and send these to the experts. Click here to find information on your local stranding network.
- CALM: Remain calm and quiet, keep people and dogs away from the animal(s). Procedures should be done quietly, gently, and slowly, and only at the direction of the stranding experts.
- COOL: While waiting for experts, you can begin to keep a stranded animal cool by gently pouring water over its body. It is very important NOT to pour water into the **blowhole**, as this is how cetaceans breathe.
- SHADE: While waiting for experts, you can cover the animal in wet, thin sheets or something similar. You could also use a thin covering of wet seaweed. NO cover should be placed over the head or blowhole, the **dorsal fin** (on the back), or the tail. Try to avoid covering the **pectoral fins** (on each side of body) if possible.
- COMFORTABLE: If the stranded cetacean is small and lying on its side, and if the stranding experts direct you to do so, you can gently roll the animal onto its belly. In most species, you must

BLOWHOLE

The hole(s) at the top of the head through which cetaceans breathe air.

DORSAL FIN

Fin on the back of cetaceans' bodies.

PECTORAL FINS

Broad, flattened limbs on the side of cetaceans' bodies (their "arms").

ensure the pectoral fins (on each side of body) are tucked close against the body before beginning this rolling. Once the animal is upright, carefully dig shallow trenches/holes in the sand under the pectoral fins, so that the fins can hang in a natural position. Be aware that sand may build up over these holes as you pour water on the animal.

DO NOT

1. TOUCH the animal unless it is necessary. Stranded cetaceans may have diseases, so it is important to keep yourself and others safe by not touching the animal.
2. MOVE, push, pull/drag, or roll an animal to get it back into the sea. It must be assessed by a stranding expert or veterinarian before it can be refloated. Moving an animal incorrectly can cause injury or even death.
3. PULL or push on any fins. Fins are very delicate and moving them inappropriately can cause severe damage.
4. COVER the head, blowhole, fins, or tail.
5. STAND close to the tail. The animal may suddenly thrash and could easily injure you.
6. CROWD close to the blowhole or head. The animal breathes from the blowhole, so if you are close you may inhale air containing any disease-causing organisms the animal may be carrying.
7. INSERT anything into the blowhole or mouth, and do not try to feed the animal or make it drink.

CONCLUSION

Stranding events are a natural occurrence, however, sometimes they can be caused by human activities. Strandings can cause significant damage to an animal, so it is important that stranded cetaceans are thoroughly examined by trained professionals to decide how best to assist them. If they are likely to survive, they can be refloated but sometimes they may need to be euthanized to end their suffering. It is important that any help is undertaken carefully by trained people. So, if you find a stranded cetacean always make sure you call your local stranding network, environment agency or emergency services before trying to help. This is essential to keep both you and the cetacean safe.

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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

ALICE, AGE: 13

I am a 13 year old 8th grader who enjoys Science and Spanish classes at school. I spend a lot of my spare time either taking dance, martial art practice, and many other classes.

SAI, AGE: 14

I have always been interested in Science, have won Olympiad medals in Science and I am still exploring what I wish to be when I grow up. In my free time, I enjoy learning classical dance "Bharatanatyam" as well as listening to music. Some of my favorite books include Wonder, Gallery of Rascals, Island of Adventure, etc. I also enjoyed working in my school environment council and sing for the school choir. I am an avid cinephile.

SARA, AGE: 14

I am a science enthusiast and wish to be a chemist in future. I take pleasure in reading Percy Jackson books and represent my school in inter school Tennis competitions. Learning western music vocals is one of my favorite hobbies. I watch good TV series from around the world and am delighted to spend time with my friends.

AUTHORS

REBECCA M. BOYS

I have recently completed my Ph.D. in Zoology at Massey University, New Zealand. I am interested in understanding how we can assess cetacean welfare at strandings to help make management decisions. Previously, I have worked on projects estimating the number, movements and survival of sperm whales, and bottlenose dolphins. I grew up on a boat and love to spend time around the sea where I surf, freedive, sail, and enjoy seeing marine life. *r.boys@massey.ac.nz

KAREN A. STOCKIN

I lead the Cetacean Ecology Research Group at Massey University, New Zealand. My research interests combine animal welfare science, behavior and veterinary pathology, and are particularly focused on human impacts that affect cetacean populations. Previous research has addressed the impacts of marine mammal tourism and pollution. Currently, my research focuses on both conservation and animal welfare during human-wildlife interactions at strandings.

KATHARINA J. PETERS
I am a German-Australian behavioral ecologist and live in Australia. I have studied many different animals species, but my main focus is marine mammals. My core research interest is to study the effect of humans on marine mammals and use this information to better manage the conservation of wild populations and their environments. My projects focus on Weddell seals in Antarctica, bottlenose dolphins in Shark Bay, Australia, and whales and dolphins in New Zealand waters. *k.peters@massey.ac.nz

†These authors have contributed equally to this work

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BIODIVERSITY
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THE UNSEEN MICROBES IN THE GUT, LIVER AND SKIN OF TUNAS

Elsa Gadoin[1], Christelle Desnues[2], Emmanuelle Roque d'Orbcastel[1], Thierry Bouvier[1], Jean-Christophe Auguet[1], Elyse Boudin[1] and Yvan Bettarel[1]*

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YOUNG REVIEWERS:

MOAB CHARTER SCHOOL

AGES: 9–12

OLIVE

AGE: 12

The microbiome is the name for the collection of microbes that live on or in another organism. The human microbiome has received a lot of attention, but in fact every living thing hosts a community of microbes that can be helpful—even vital—or sometimes harmful. In this study, we investigated the microbiome of tuna to identify the specific bacteria that populate it and whether the microbiome varies depending on the type of tuna, the ocean it lives in, or the organ. We found that the gut microbiome differs according to species due to feeding habits, while the skin microbiome differs according to the environment and is linked to the bacteria in the surrounding seawater. Bacteria that can cause food poisoning in humans were concentrated in the gut and liver of tuna, highlighting the importance of removing the organs before consuming this fish, which is one of the most widely eaten in the world.

THE SECRET WORLD OF THE MICROBIOME

Although **bacteria** have a bad reputation as organisms that make us sick, we now know that bacteria are essential for human health and the health of other animals, both on and in the sea. Invisible to the naked eye, bacteria are found in the gut, mouth, nose, lungs, kidneys, liver, and even on the surface of the skin! While it is true that some bacteria can cause disease, many are extremely useful, if not essential, to the organisms they live in or on—with roles in digestion, the immune system, behavior, and more [1]. All these bacteria, together with other **microbes** such as viruses, **archaea** (primitive single-celled organisms) and fungi, make up what is called the **microbiome**, which means "small living community."

The microbiome has received a lot of attention in recent years. Scientists have begun to understand that an organism is not just an individual, but a complex community of organisms. Studying the microbiome of animals is interesting for several reasons. First, it teaches us about the microbes themselves—they are tiny but infinitely interesting—and about their interactions with other organisms. Second, studying the microbiome allows us to identify microbes that are dangerous to the humans who eat the animals that contain those microbes. This is why researchers track the presence of microbes in the animals—including fish—that end up on our plates.

There are still a lot of mysteries. For example, do all living organisms have their own specific microbiomes? Does an organism have the same bacteria everywhere in its body? Is the microbiome different between males and females? And does the microbiome vary depending on where an animal lives? These are some of the questions we wanted to answer with our research on one of the ocean's top predators—one that humans consume in large quantities: tuna!

In many coastal countries around the world, tuna is a major source of both income and food. Sometimes tuna can give humans food poisoning, caused by the presence of bacteria that produce harmful compounds such as **histamine**, which cause unpleasant reactions in humans [2]. Understanding where these bacteria live inside the tuna and how they cause histamine to build up in the fish's flesh are the first step toward preventing people from getting sick.

To unravel the mysteries of the tuna microbiome, we focused on two species that are among the most widely consumed: yellowfin and skipjack tuna. While an organism's microbiome contains multiple types of microbes, our study focused on just one type: the bacteria.

BACTERIA

Microscopic organisms present nearly everywhere on Earth. Some are dangerous and can cause infection, but others are essential for life—for example, bacteria in the gut help to digest food.

MICROBES

An organism so small that it cannot be seen with the naked eye. Microbes, which include bacteria, viruses, archaea, and fungi, are the most abundant organisms on earth and are found everywhere—in the air, in the water, and associated with all living organisms.

ARCHAEA

Microscopic, single-celled organisms, usually found in extreme environments. Archaea were initially considered to be bacteria, for they share many characteristics, but they are now considered as another domain of life.

MICROBIOME

A community of microbes present in a living organism. Our research focused on bacteria, so we use "microbiome" to refer only to the bacteria in an organ.

HISTAMINE

A chemical produced by certain bacteria in tuna and other fish. Ingestion of histamine can cause an allergic reaction in humans, with symptoms including diarrhea, vomiting, redness, itching, and fever.

TIME TO GO FISHING!

First, we needed fish. So, we went out with local professional fishers and caught 48 skipjack and yellowfin tuna in the waters off the Ivory Coast (Atlantic Ocean) and off Reunion Island (Indian Ocean) (Figure 1). Our aim was to examine the bacteria living on the tunas' skin and in two important organs: the gut and the liver. These organs are both involved in digestion, but the liver also performs other functions such as removing toxins from the blood and producing many chemicals essential for health. Once the fish were caught, stunned (to reduce stress) and killed, we swabbed their skin to collect mucus—fish skin is covered with a layer of slime that protects the fish from the external environment. The fish were then kept on ice until we could get back to the laboratory.

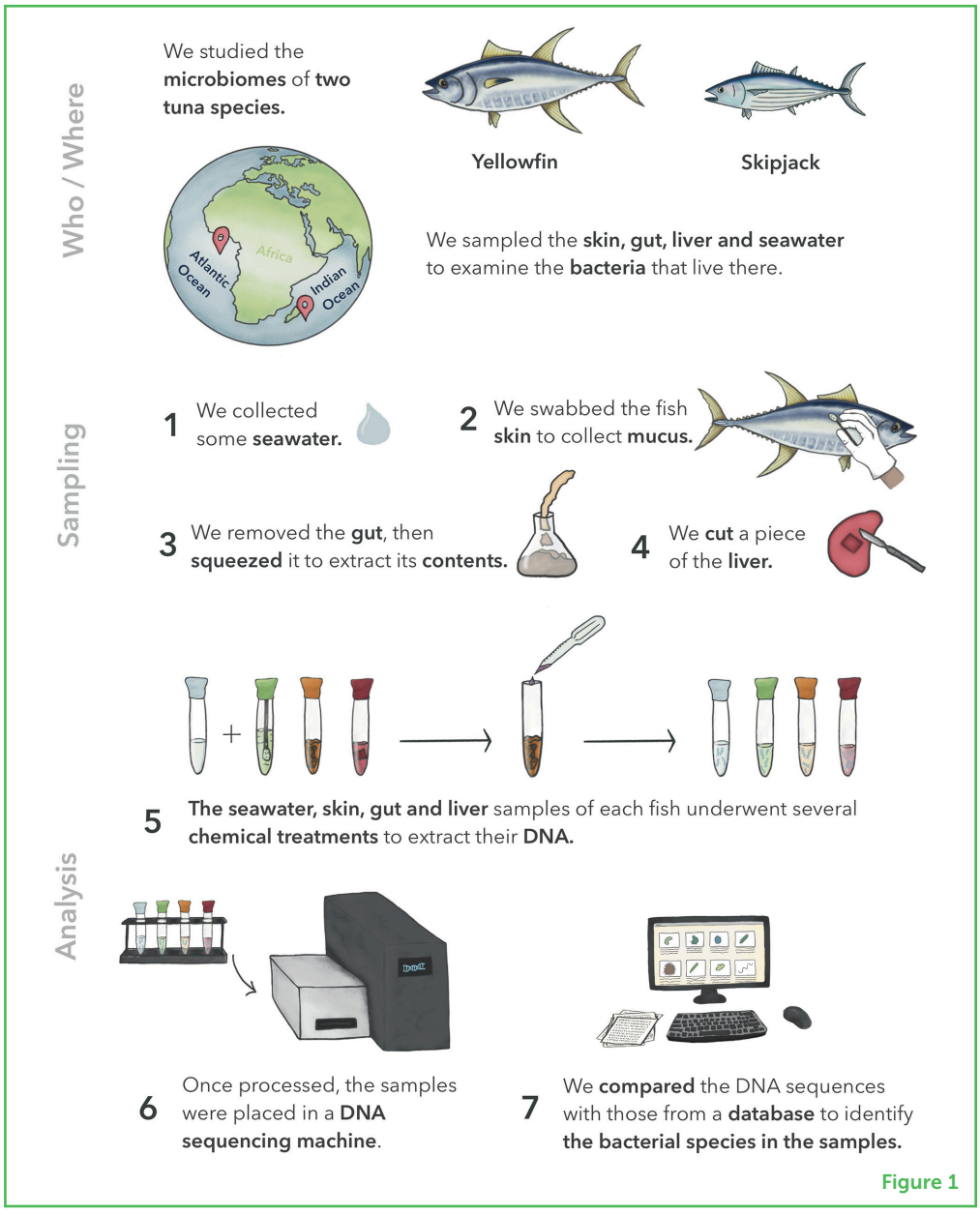


Figure 1

The different methodological steps of our study, from the sampling of tuna in the two oceans, to the identification by DNA sequencing of the bacteria living on their skin, gut, and liver.

In the lab, we dissected the tuna to remove the digestive tract, collect the gut contents, and to slice off a small piece of the liver so we could look for the presence of microbes. The fishers then took the meat, which was either sold to a local market or used to feed their families. Tuna is a precious resource, and it was not wasted! When we were at sea, we also sampled the seawater so we could compare the bacteria in the water to those in our tuna samples, to see if bacteria were transmitted to the fish through the water they lived in.

Since microbes are so small, advanced technologies must be used to identify their presence. To check which types of bacteria were present in the skin, gut, liver, and seawater samples, we looked at bacterial **DNA**, which contains all of the bacterias' genetic information. First, we treated the tissue samples with chemicals to remove the DNA from the bacterial cells. Then we put the DNA in a machine called a sequencer, which can read the genetic information like a barcode. We then compared our DNA samples with a database of bacterial DNA, which allowed us to identify which types of bacteria were present in our samples (Figure 1).

DNA

Found in every living organism on Earth, DNA is a molecule that carries the genetic instructions for that organism. The sequence of molecules in DNA is unique to each species.

A BOATLOAD OF BACTERIA

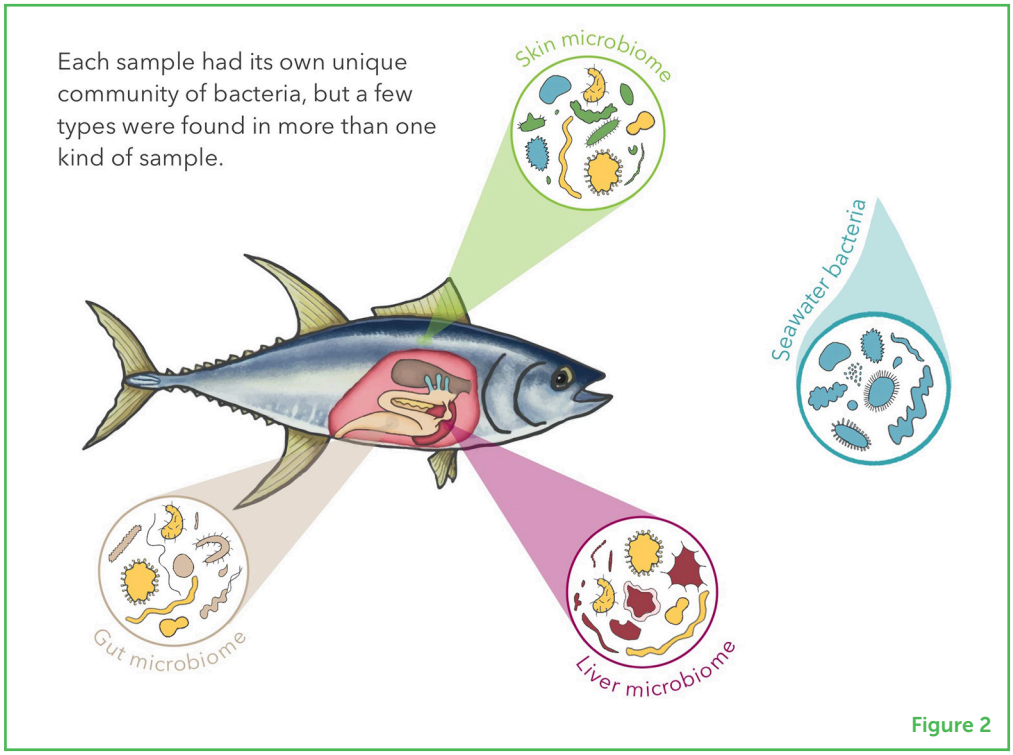
We found that tuna skin contained more than 2,000 different bacterial species—maybe not what you wanted to hear if you love tuna! The tuna gut had about 800 species. We were not surprised by this finding, as this diversity has been previously shown in humans and other animals. Remember, many bacteria are perfectly harmless. However, we did not know what to expect in the liver. We were surprised to find there were about 800 bacterial species in the liver as well! These results are very interesting because they show that, like the skin and the gut, the liver is an important reservoir of bacteria within the body. This had never been observed in tuna.

We also found that each organ hosted bacteria that were not present in the other organs (Figure 2). It seems likely that these different populations of bacteria are involved in the specific functions of each organ—helping the gut to digest food, the liver to eliminate waste products from the body, and the skin to serve as a protective shield.

We also found that a few species of bacteria were present in all three organs, suggesting that certain microbes can move from one organ to another. This is not surprising for the gut and the liver because they are connected by the circulatory system. A few types of bacteria found in the seawater samples were also found on fish skin, telling us that certain bacteria from the water can live on the surfaces of marine animals.

Figure 2

Representation of the diversity of the bacteria living in the gut, liver and skin of tunas, some are common to all three, others are specific to each organ.



Comparison is extremely important in science. This is why we tested two species of tuna (including both males and females), from two oceans, plus seawater samples from both oceans. The data allowed us to see if two tuna species, skipjack and yellowfin tuna, share the same microbiome, if the microbiome changes depending on where the fish live, and whether gender is linked to differences in the microbiome.

WHAT REALLY MATTERS TO MICROBES?

Comparing our data revealed several interesting findings (Figure 3). First, we found that there was no difference between the microbiomes of male and female tuna of either species, in either ocean. In fact, there are only a few differences between female and male tuna: they look the same, eat the same food, live in the same place, and basically have the same way of life. So microbes do not really care about gender!

We did observe differences in the microbiome when we looked closely at each organ: for example, the gut microbiomes of skipjack and yellowfin tuna were very different from each other. This makes sense because these two species have quite different lifestyles. Yellowfin can grow up to 2 meters (6.5 ft) long while skipjack are half that size, so yellowfin can swim deeper in the ocean to find more types of prey. Skipjack tuna stay closer to the ocean surface, where the food options are less diverse. Gut microbiomes did not differ between yellowfin (or skipjack) tuna living in the Atlantic and those living in the Indian Ocean,

Figure 3

Comparison of the bacterial communities in the tuna gut, skin and liver microbiome depending on sex, species and sampling site. A green tick indicates a significant difference, while a red cross indicates no difference.

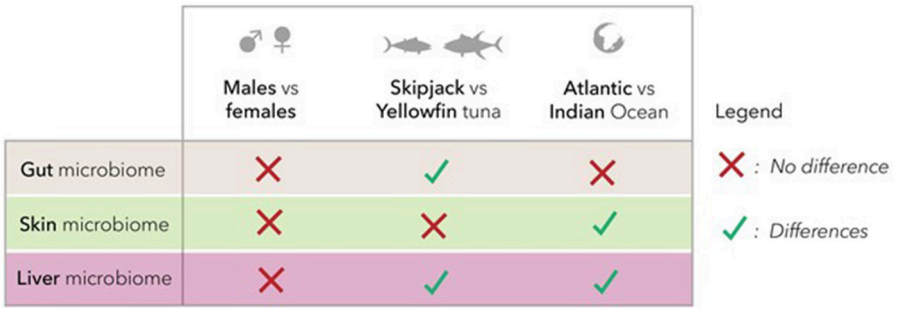


Figure 3

so we can conclude that the gut microbiome depends more on what fish eat than where fish live.

When we looked at the skin, the reverse was true: skipjack and yellowfin had the same skin microbiomes, but there were huge differences between fish caught in the two oceans. The skin of fish is in direct contact with seawater, and it acts as an "exchange zone" between the animal and its environment. This told us that the bacteria living on the skin of tuna are more dependent on the external conditions than they are on the organism that hosts them. This was confirmed by the fact that the skin microbiome samples shared numerous bacteria species with the seawater samples. For the skin microbiome, only location matters!

In the liver, the situation was more complex, as no clear trend was observed. It seems that both the ocean and the species influence the bacteria living in the liver, but more research will be necessary to solve this mystery.

PINPOINTING HARMFUL BACTERIA

So, what did our research tell us about bacteria that can cause food poisoning in humans? As we mentioned, some bacteria can produce a compound called histamine. Histamine production is limited when food is stored at low temperatures, but if fish is not fresh or has not been kept cold enough, eating it can cause histamine poisoning. This can result in rashes, vomiting, and diarrhea, and, in the most extreme cases, it can even require hospitalization. Histamine is not destroyed by cooking—it is almost indestructible. So, did we find harmful, histamine-producing bacteria in the tuna we studied? Indeed, we did, and they were particularly abundant and diverse in the guts and livers of tuna. This is why, apart from keeping fish cold, it is very important to remove the internal organs of fish before cooking and eating their meat!

CONCLUSION

Our study confirmed the results of studies in other animals—that microbes are found in every living thing, including those in the sea, and that microbes can have a big impact—sometimes positive and sometimes negative—on the animals they interact with. New techniques such as DNA sequencing have allowed scientists to identify the microbes present in the microbiome and to better understand their important roles.

Over thousands of years, people have been trying to understand the world by discovering previously unknown environments, species, and phenomena. Just as our ancestors before us analyzed and investigated their worlds, today's researchers have a vast new world of microbiomes to explore—an area of study that has just begun. The microbiome still has many secrets to reveal.

ORIGINAL SOURCE ARTICLE

Gadoin, E., Desnues, C., Roque d'Orbcastel, E., Bouvier, T., Auguet, T., Dagorn, L., et al. 2022. Fishing for the microbiome of tropical tuna. *Microbial Ecol.* doi: 10.1007/s00248-022-02096-4

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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

MOAB CHARTER SCHOOL, AGES: 9–12

We are a 5th and 6th grade class at the Moab Charter School located in...you guessed it...Moab, Utah! We have a wide range of interests: dogs, pickles, grammar, art, ghosts, football, beyblades, video games, hiking and watermelon. We feel lucky to live in such a beautiful place!

OLIVE, AGE: 12

My name is Olive and I am a sixth grader. I love reading, science, biology, medicine, and taking care of animals, and I hope to study veterinary medicine when I get into university. Our family has one dog, one blue tongue skink, and one busy fish tank. I do Aikido and Outschool online classes. My hobbies are: crocheting, reading books, cooking, reading things on the computer, watching cartoons, and walking our dog.

AUTHORS

ELSA GADOIN

Elsa Gadoin has just completed her Ph.D. at the MARBEC lab in Montpellier, France. She is interested in the ecology of marine microbes. She would like to specialize in the study of marine microbiomes to better understand their diversity and functions, as well as the role of the microbial communities living together with marine animals.

CHRISTELLE DESNUES

Christelle Desnues (CNRS Research Director) was passionate about viruses, their ecology, and human health. She studied the diversity, dynamics, and evolution of viruses at human-animal-ecosystem interfaces. With her dual research experience in clinical and environmental sciences, she actively made the bridge between physicians and ecologists, fully in lines with the "One Health, One Medicine" approach, to better understand the interactions between environmental, animal, and human health. We all miss her so much.

EMMANUELLE ROQUE D'ORBCASTEL

Emmanuelle Roque d'Orbcastel is a marine biologist working at the Ifremer Institute, associated with the MARBEC laboratory (Montpellier, France). She works on aquaculture ecosystems, and studies how the environment influences the health of cultivated organisms. She is interested in working with fish farmers, proposing ways to reduce the environmental impact of fish farming.

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Thierry Bouvier is a marine microbial ecologist at the MARBEC lab located in Montpellier, France. He started to study the bacteria and viruses living in the sediment and water column of polar, temperate and tropical oceans.

JEAN-CHRISTOPHE AUGUET

Jean-Christophe Auguet (CNRS Researcher at MARBEC Lab) is an enthusiastic microbial ecologist. His current research focuses on the diversity of microorganisms associated with marine organisms, including pathogenic bacteria, which he studies using molecular tools and next-generation DNA sequencing.

ELYSE BOUDIN

Elyse Boudin graduated with a degree in Ecology Engineering, from the University of Montpellier, in 2019. Now, she is involved in several environmental and educational projects in the South of France. These projects combine research in marine and terrestrial ecology, photography, and the creation of environmental education tools.

YVAN BETTAREL

Yvan Bettarel is a marine microbiologist at the MARBEC Lab, and the principal investigator of this work. He has lived and worked in Vietnam and Senegal to study the role that tropical viruses and bacteria play in ocean health. *yvan.bettarel@ird.fr

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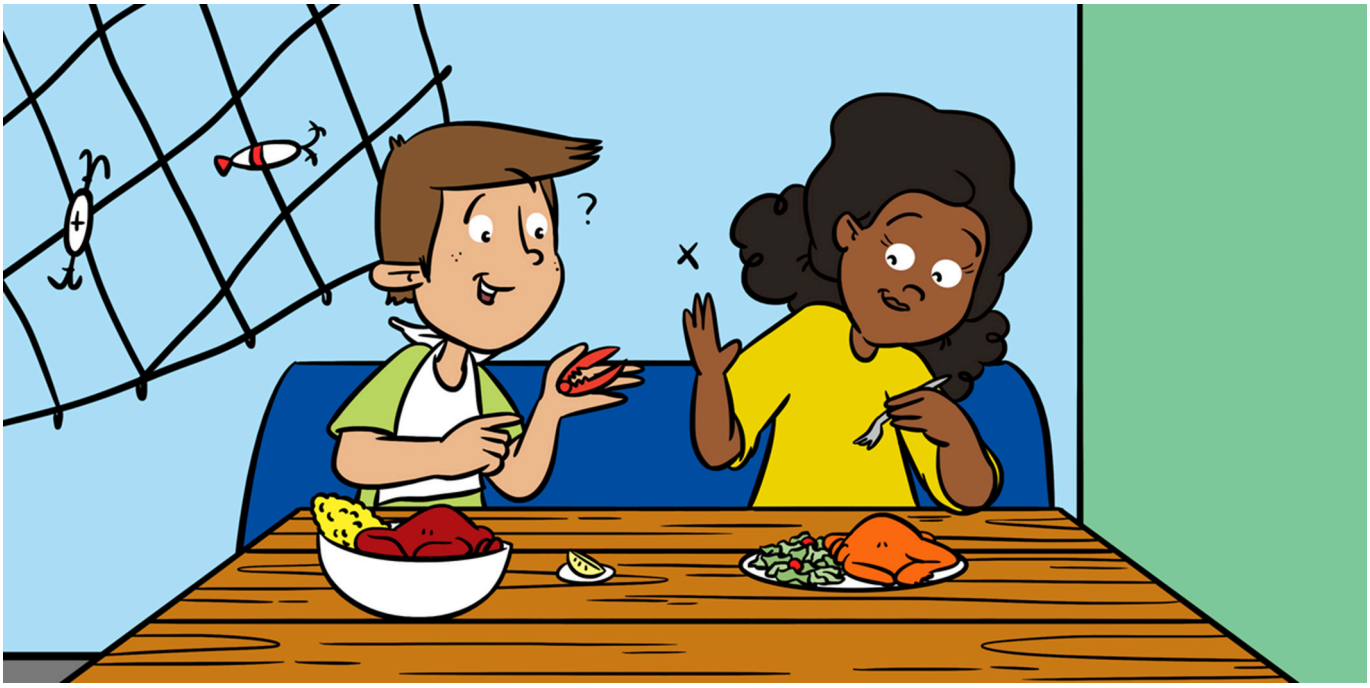

THE ORIGIN OF SOFT-SHELL CRABS

Aorta Xian Lin Ling[1,2], *Hanafiah Fazhan*[1], *Ghazali Azmie*[1], *Yushinta Fujaya*[3] *and Khor Waiho*[1*]

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YOUNG REVIEWERS:

ANA
AGE: 9

BENJAMIN
AGE: 10

VINCENT
AGE: 10

Soft-shell crabs are famous in seafood restaurants because they have a wonderful flavor, are easy to eat, and are highly nutritious! Soft-shell crabs are any regular edible crabs, but in their natural, soft-shell condition—because they have just shed their old shells, in an event called molting. Within a few hours after molting, while they are still in their soft-shell condition, these crabs are harvested and sold as soft-shell crabs. Crabs in the soft-shell condition have higher market value than crabs in the hard-shell condition. By understanding the origin of soft-shell crabs, we can improve the production of these crabs, as well as try to find ethical and sustainable ways to obtain them.

WHAT ARE SOFT-SHELL CRABS?

Images of crabs adorn the signboards and logos of most seafood restaurants, and who does not love to eat crabs? Crabs taste like

other **crustaceans**, such as shrimp and prawns. However, due to their larger body size, crabs contain more meat compared to smaller crustaceans like shrimp and prawns. In most restaurants, crabs are consumed by cracking their hard outer shells to get to the delicious flesh underneath. However, crabs are also served in a soft-shell condition. In general, soft-shell crabs fetch a much higher price compared to hard-shell crabs. This is because soft-shell crabs have a higher nutritional value and, most importantly, they can be eaten whole! This avoids the hassle of prying open the hard outer shell to savor the juicy flesh inside. Therefore, soft-shell crabs are gaining popularity over hard-shell crabs as a healthy and convenient food choice. Are soft-shell crabs a totally different crab species? Where do they come from?

CRUSTACEANS

A large class of aquatic animals with exoskeletons, such as crabs, shrimp, lobsters, and krill.

TO GROW IS TO MOLT

In some ways, crabs are similar to us! As we grow, we become taller and bigger. As a result, our clothes eventually do not fit us anymore and we need to get a larger size. Crabs increase in size as they grow, too! However, unlike us, crabs have hard shells called **exoskeletons** on the outsides of their bodies, which act like protective armor. The exoskeleton cannot expand as a crab grows, so crabs must shed their old shells so they can develop bigger shells, through a process called **molting** (Figure 1). The molting process is complex. Before molting, a new tissue layer forms underneath the crab's old exoskeleton. Molting is controlled by a group of hormones called **ecdysteroids**, which increase to a peak level and then drop drastically in concentration right before molting. This drop signals the crab to take in water so that it expands, cracking open its old exoskeleton so that it can emerge from it (Figures 1A–C). The process of expanding and emerging from the old skeleton typically takes several hours. After emerging, the crab is covered in a new, soft exoskeleton that will harden within a few hours (Figure 1D) [1]. During this short period, the crab expands its soft shell by taking in water like a balloon. This ensures that the new exoskeleton will be much bigger than the old one when it hardens, so the crab will have plenty of room to grow before the next molting. Crabs are exhausted and immobilized when they are in the soft-shell condition. Therefore, molting is extremely dangerous, as the newly molted crab is vulnerable to predators.

EXOSKELETON

The hard, external covering of the body found in some invertebrates.

MOLTING

The shedding of an old shell by most invertebrates with exoskeletons.

ECDYSTEROIDS

A type of hormone that controls molting and reproduction.

SOFT-SHELL CRAB PRODUCTION

So now you know that soft-shell crabs are crabs harvested right after they molt, while they are still in a soft-shell condition (Figure 2). Producing soft-shell crabs to sell, however, is a long process—it normally takes weeks after crabs are collected. In general, soft-shell crabs can be produced from any edible **portunid** crab species, including Atlantic blue crabs, blue swimming crabs, and mud crabs

PORTUNID

A swimming crab of the *Portunidae* family, characterized by appendages shaped like flattened paddles, for swimming.

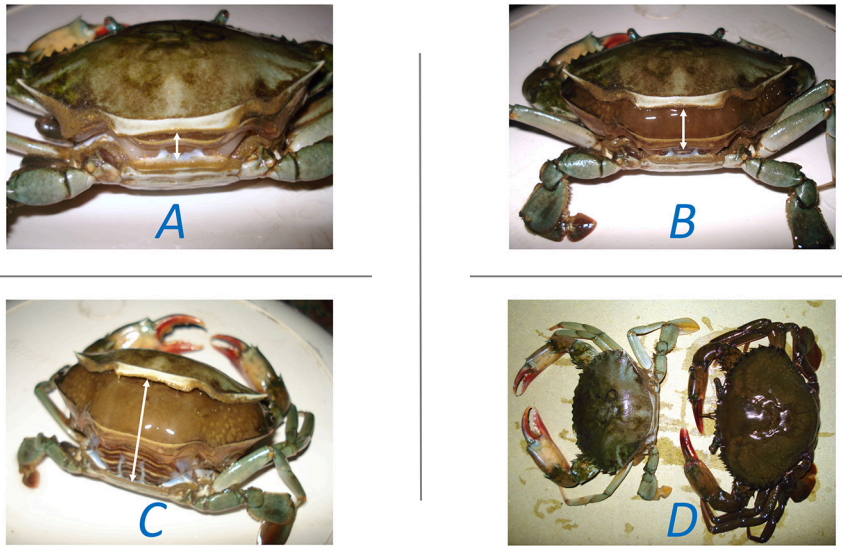

Figure 1

The molting process of a crab. **(A)** The old exoskeleton slowly cracks open from the back of the crab. The white arrow indicates the crack in the old skeleton. **(B)** The crab inhales water to expand itself and increase the size of the crack. **(C)** Once the crack is wide enough, the crab emerges from the old skeleton. **(D)** In the first few hours, the newly emerged crab is in a soft-shell condition and is defenseless. Note the increased body size of the newly emerged crab compared to its old exoskeleton.

[2–4]. Crabs that have not yet matured (called sub-adult crabs) are commonly collected from the wild to generate soft-shell crabs. The size of sub-adult crabs may differ among species. For example, mud crabs with a body size of 5–8 cm, or Atlantic blue crabs of 4–5 cm are commonly captured for soft-shell crab production. Crabs are normally raised in individual cages throughout the production period, so that it is easier to see when they are molting (Figure 2D). They are also raised individually to avoid **cannibalism**, especially in mud crabs, which are prone to fight and feast on their friends when they are hungry or too crowded. Monitoring the crabs every 4–5 h is important so that crabs can be identified and harvested when they have recently molted. After they are harvested, the soft-shell crabs are immediately cleaned using fresh water, individually packed, and frozen at −20°C to ensure their freshness and quality. Frozen soft-shell crabs can then be easily packed and transported [5].

CANNIBALISM

The act of consuming another organism of the same species.

Soft-shell crabs have a higher market value than do hard-shell crabs. The value of soft-shell crabs also depends on the time of harvest after molting—the **calcification** (hardening) process of the new exoskeleton begins immediately. An exoskeleton that has a high water content and low levels of calcification is considered truly soft. This type of soft-shell crab is often pricier and can be turned into mouth-watering dishes for consumers.

CALCIFICATION

The hardening of a tissue due to calcium build-up.

LIMITATIONS OF SOFT-SHELL CRAB PRODUCTION

Soft-shell crab production is becoming a profitable business. Although the process of soft-shell crab production is well-established and can be carried out on a large scale, farmers must still collect a lot of sub-adult crabs from the wild. Crab farmers cannot produce

Figure 2

(A) A worker handling a newly molted crab with soft outer shell. **(B)** Soft-shell crabs are kept frozen to make sure they are fresh when they are shipped to restaurants. **(C)** Close-up of frozen soft-shell crabs. **(D)** A farm worker preparing crab boxes to individually house each sub-adult crab in a culture pond at Barru, South Sulawesi Province, Indonesia. Sub-adult crabs are put into individual cages to prevent cannibalism.

sub-adult crabs because of the low survival during the larval stages. However, wild sub-adult crabs are limited and seasonal. Additionally, collecting sub-adult crabs greatly reduces the overall crab numbers in the wild because those crabs are harvested before they can reproduce and repopulate the wild population (Figure 3). Therefore, uncontrolled crab fishing is not **sustainable**, as it leads to overharvest and threatens the health of the wild crab population. Overcoming the low survival of crabs during the larval stage is now the main priority, and scientists from various countries are working together to solve this mystery.

SUSTAINABLE

Using natural resources in a way that will enable us to use them for a long time.

Another limitation is that crabs tend to molt at their own pace—sometimes it takes more than a month! Therefore, farmers must grow and monitor them for a long period, which increases the production cost. Researchers are currently experimenting with various methods to help sub-adult crabs molt faster and in a more

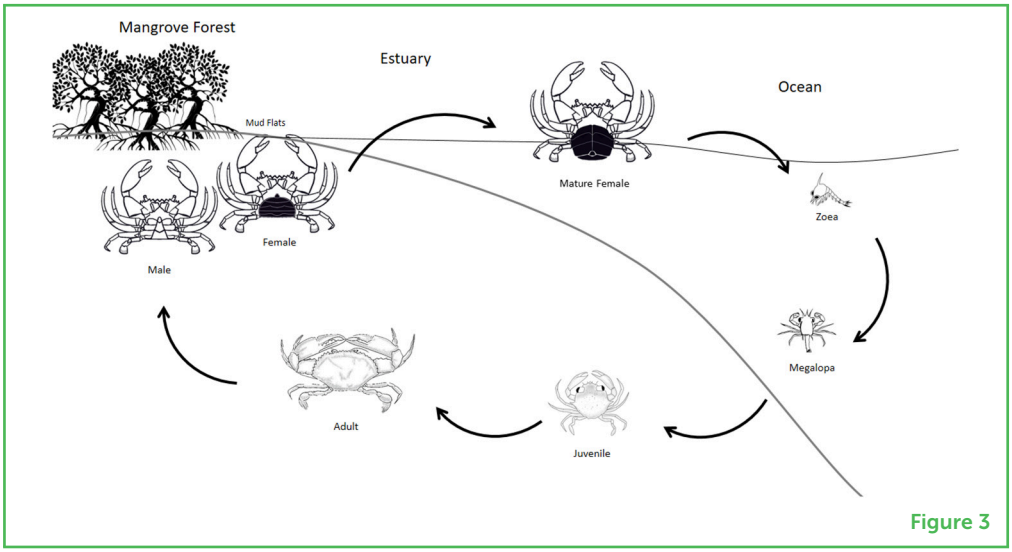

Figure 3

The life cycle of a mud crab begins when larvae (zoeae) hatch from mature females in the ocean. Zoeae grow into megalopae, which slowly migrate back to mangrove mud flats. In mud flats, the crabs continue molting and increase in size as they go through a juvenile (sub-adult) stage and eventually reach the adult stage. Male and female adult mud crabs then mate and the whole cycle repeats itself. Therefore, removing many sub-adults to produce soft-shell crabs for eating is unsustainable, as it results in fewer adults available to repopulate the original crab population.

synchronized way, including the use of ecdysteroid hormones. If this is successful, farmers will be able to produce more soft-shell crabs easily, in a shorter time.

CONCLUSION

Soft-shell crabs are regular edible crabs that have recently completed the molting process. Soft-shell crab production is a promising money-making industry with high market demand due to the excellent taste of the crabs and the unique eating experience. However, the reliance of the soft-shell crab industry on the capture of wild sub-adult crabs is still unsustainable, and it puts tremendous pressure on the currently decreasing wild population. For soft-shell crabs to remain a sustainable food source, it is important to only use farm-produced sub-adult crabs in the soft-shell crab producing process.

ORIGINAL SOURCE ARTICLE

Waiho, K., Ikhwanuddin, M., Baylon, J., Jalilah, M., Rukminasari, N., Fujaya, Y., et al. 2021. Moult induction methods in soft-shell crab production. *Aquacult. Res*. 52, 4026–42. doi: 10.1111/are.15274

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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

ANA, AGE: 9
Hi, I am Ana, I was born in Mexico City in April 2013, I am 9 years old, I live with my mom and my grandparents. We have a dog with whom I play a lot. I am currently studying third grade of primary school, my favorite subject is mathematics. I like to swim, play chess, visit places, and sometimes dance, help cook. I love animals, I would like to be a veterinarian. My favorite food is fried tacos, spaghetti, and chocolate ice cream. I do not like soda, I like nothing with gas. Thanks to Fronties for Young Minds for this review experience.

BENJAMIN, AGE: 10
In school I like science, history, and math. Outside I enjoy playing sports, especially football. I have a pet stick insect called Twiglet, who mostly just does nothing, but sometimes likes to climb on my hands. Oh, and my favorite food is pasta.

VINCENT, AGE: 10

Hello, my name is Vincent and I do not like to study from books. I much rather look at nature and learn from what I see. I like finding insects in the woods and keeping track of my garden's ant nests. Sometimes I leave some sugar at the entrance of the nest and I have noticed that some of them have grown in size. My mum is not very excited about this, because ants are now marching into her kitchen looking for more sugar. I also own a stick insect called Florian and she likes to eat brambles. She has gown quite a lot and is starting to lay many eggs: which means that I have expanded the colony! I also like technology, maybe I will use both my interests together when I grow older.

AUTHORS

AORTA XIAN LIN LING

I am currently an undergraduate student in the Aquatic Resources Science and Management programme at University Malaysia Sarawak (UNIMAS). I am interested in crab aquaculture and hope to learn more about crabs and do research with experienced crab researchers in the future.

HANAFIAH FAZHAN

I am a researcher at the Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu. My passion for crustaceans, especially crabs, started when I was working with them during my Ph.D. studies. To me, crabs are fascinating creatures! They have amazing adaptation abilities and furthermore, edible crabs are delicious! I study the relationships between crab populations based on their structure and their genes. By doing so, I hope to understand how they relate to each other and how adaptation occurs!

GHAZALI AZMIE

I am a senior research officer at the Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu. My main research area is crustacean reproductive biology, with a special focus on the breeding and reproductive functions of mud crabs. I think crabs are very unique and interesting animals, there is a lot more to learn about them—I really enjoy working with crabs!

YUSHINTA FUJAYA

I am a lecturer and researcher at Hasanuddin University, Makassar, Indonesia. I started working in crab cultivation during my university years—from my bachelor's to my Ph.D. After that, I developed a soft-shell crab production technology using herbs. That is why I am often identified with crabs—some friends call me the Queen of Crab. My work is really fun and I love it.

KHOR WAIHO

I am a senior lecturer at the Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu. I obtained my Ph.D. in the field of aquaculture, and I am currently focused on the reproductive processes of aquaculture species, especially crabs! I think that crab culture is an emerging industry with vast possibilities! *waiho@emt.edu.my

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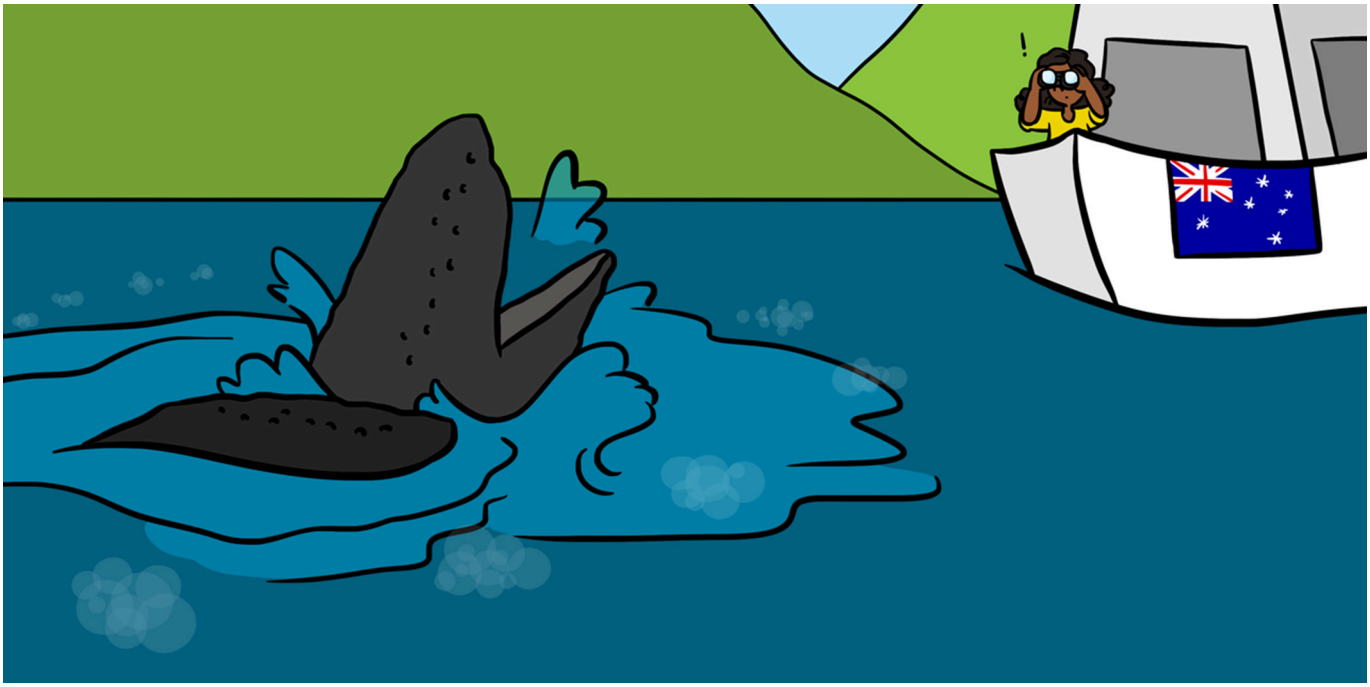

HUMPBACK WHALES HAVE SUPER FEEDING EVENTS IN AUSTRALIAN WATERS

Madeleine J. Brasier [1*] ***and Vanessa Pirotta*** [2]

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YOUNG REVIEWERS:


DEBASISH
AGE: 15


VINCENT
AGE: 10


WILLIAM
AGE: 13

Each year, the east Australian humpback whale population migrates between their Antarctic feeding grounds, where they spend the summer feeding, to their sub-tropical breeding grounds, where they give birth. Historically, this population was once hunted in both Antarctica and off Australia, however, since whaling ended in the early 1960s, this population has continued to recover. As the population continues to grow, we may now be witnessing "new" behaviors. For the first time, scientists have footage of humpback whales bubble-net feeding and feeding in "super-groups" of 20+ whales in Australian waters. This footage was collected by citizen scientists—regular citizens who help scientists monitor this whale population. These feeding observations are important for understanding how this whale population is changing—not just in numbers but also behaviors—and what we can do to protect whale populations into the future.

HUMPBACKS: A HISTORY

Humpback whales are large **baleen whales**, reaching up to 17 m in length and over 30,000 kg in weight. They are called baleen whales because of the hundreds of **baleen plates** that hang from their upper jaw (Figure 1). These plates are made of **keratin**, which is the same substance as our fingernails. Baleen plates are important because they enable humpbacks to filter their food from seawater after they have taken a huge mouthful of fish or krill.

BALEEN WHALES

Large, toothless whales that have baleen plates to filter their prey from seawater. They have streamlined bodies ranging from 6 to 33 m in length.

BALEEN PLATES

Large bristles hanging from the upper jaws of baleen whales, like a large bristly brush. They help to filter their prey (fish or krill) from water.

Figure 1

Humpback whales are large baleen whales with a few characteristics that make them stand out from other whales, such as their humped dorsal fin and their large pectoral fins.

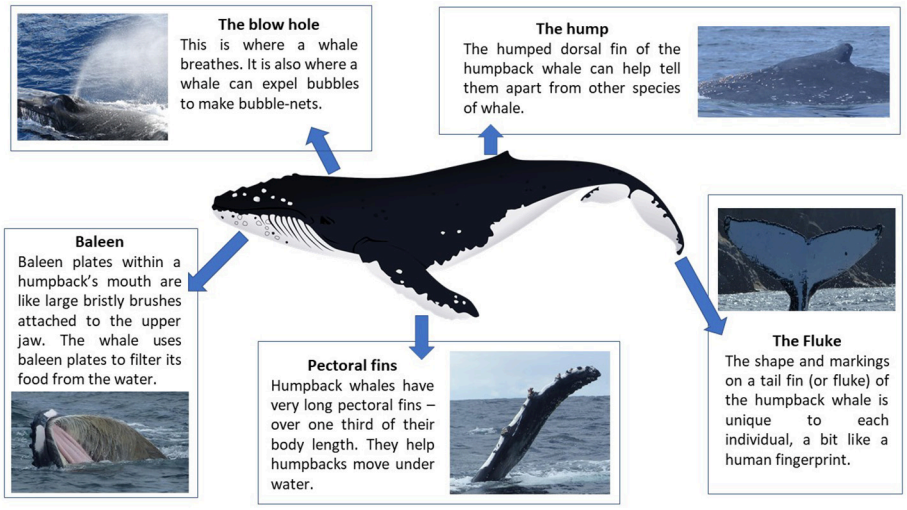

Figure 1

KERATIN

The hard protein that hair, skin, and nails are made of. It also makes the baleen plates of whales.

Compared to other baleen whales, of which there are around 16 species, humpback whales have a few unique physical characteristics. For example, their humped dorsal fin and their large pectoral fins (Figure 1), which can be a third of their body length. Humpback whales use their pectoral fins to perform tight maneuvers, like when feeding.

There are 14 different humpback whale populations around the world, but we focus on the east Australian population in the Southern Hemisphere. Like many whales, east Australian humpback whales were hunted for oil and meat, amongst other things. By 1962, their population was reduced to only a few hundred individuals. Nowadays, the east Australian humpback population appears to be thriving and are considered a conservation success story. Regular monitoring by scientists has recorded an average population increase of 11% per year since the 1960s [1]. The last official survey in 2015 estimated that about 25,000 whales swam past east Australia. Scientists estimate this population could reach over 40,000 whales by 2026, which may well be close to its pre-whaling population size.

As populations increase, it is likely that they will reveal new or re-emerging behaviors. These are behaviors that whales may have done before they were hunted to near extinction. In 2020, scientists in

Australia recorded exciting behaviors never before seen in Australian waters [2]. But first let us understand a bit more about humpback whale migrations and the types of behaviors we might expect to see in different areas of their distribution range.

THE HUMPBACK HIGHWAY

Humpback whales perform some of the longest migrations of any whale species, swimming up to 10,000 km each year. They migrate because they feed and breed in very different places. In the Southern Hemisphere, humpback whales spend the summer in the cold waters of Antarctica, feeding on Antarctic krill, which are small shrimp-like **crustaceans** which live in large groups called swarms. In the wintertime, humpbacks migrate north to mate and give birth in warmer, sub-tropical waters. However, the east Australian population is not the only humpback population migrating to and from Antarctica each year. Figure 2 shows the migration pathways of the nearby Oceania population and the west Australian population. With so many whales swimming up and down Australia's coastlines, these migration routes are often referred to as "humpback highways." These populations may sometimes mix, so it is not always easy to tell the difference between them without collecting skin or tissue samples to identify which population they belong to based on their DNA.

CRUSTACEANS

Animals with a hard outer body made up of different sections e.g., crabs, prawns, barnacles.

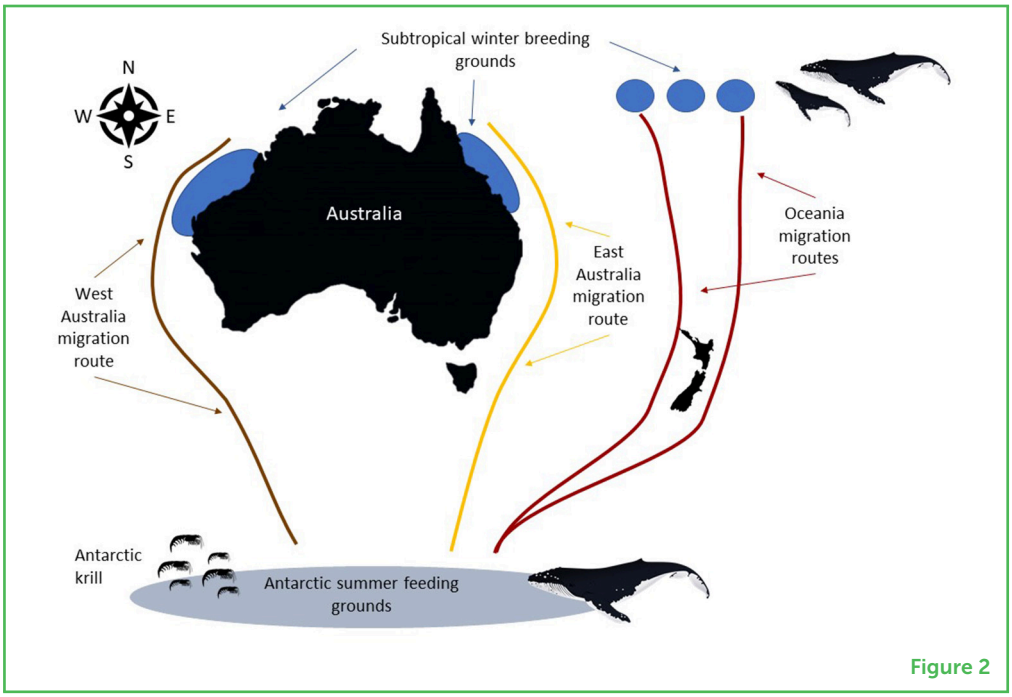

Figure 2

The migration pathways or "humpback highways" of Australian and Oceania humpback whale populations. These whales migrate up to 10,000 km each year, spending the winter in their subtropical breeding grounds off the Australian coast and summer in the cool Antarctic feeding grounds.

Historically, scientists believed that humpback whales followed a "feast or famine" lifestyle. This means they are either in "feast" mode, eating as much as they can on their feeding grounds, or in "famine" mode, not eating at all while they migrate and spend time reproducing/calving on their breeding grounds. However, we now know this is not the case

for east Australia humpback whales. There are now multiple records of humpback whales feeding off the coast of Australia during their migration [3]. In these feeding events, the whales were **lunge feeding**, which is when a whale opens its mouth super wide and lunges at a patch of food to take a mouthful. But, in 2020, humpback whales were also documented **bubble-net feeding** in Australian waters for the first time.

LUNGE FEEDING

Which is when a whale opens its mouth super wide and lunges at a patch of food to take a mouthful.

BUBBLE-NET FEEDING

A specialized way of feeding in which whales deliberately blow bubbles from their blowhole (nose) while swimming in a tight circle, to create a bubble-net around their prey.

SUPER-GROUP

A group of whales containing more than 20 individuals within five body lengths of one another.

CATCHING DINNER IN A NET MADE OF BUBBLES

Bubble-net feeding is when whales deliberately blow bubbles from their nose (the blowhole, Figure 1) while swimming in a tight circle using their pectoral fins. This creates a bubble-net around their food. They then scoop up their tightly packed food by lunging toward it (Figure 3B). This is a more specialized feeding behavior than lunge feeding, and in the Southern Hemisphere, it had previously only been recorded in Antarctica. As scientists, we were very excited to have 10 recorded observations of bubble-net feeding off east Australia in 2020 during the humpback whale southward migration (Figure 3A). To add to this feeding frenzy, we also saw lots of whales feeding together in a big group. This is known as **super-group,** which had also never been documented before in Australian waters (Figure 3C).

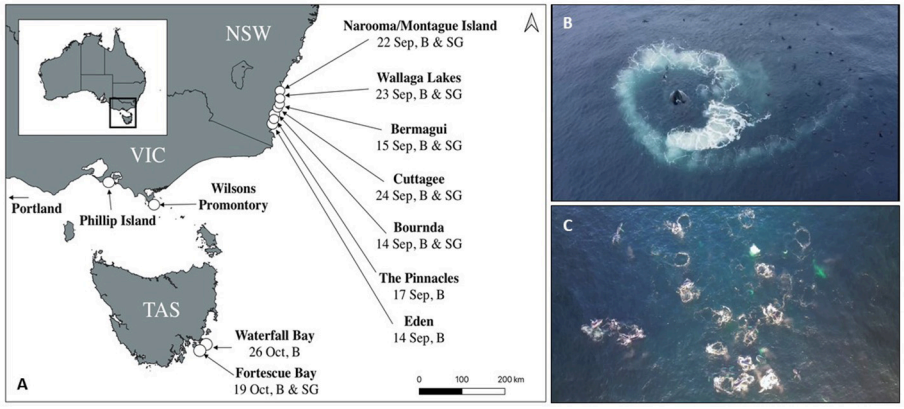

Figure 3

Figure 3

(A) Locations of humpback whale bubble-net feeding **(B)** and super-groups (SG) observations off east Australia in 2020 (Figure credit: Pirotta et al. 2021 [2]). **(B)** Bubble-net feeding, you can see the ring of bubbles created by the whale to trap food and the whale scooping a mouthful of the food in the middle (Image credit: Wild Ocean Tasmania). **(C)** A humpback whale super-group, you can see from the white water lots of whales in the frame close together (Image credit: Brett Dixon).

SUPER-GROUP FEEDING FRENZIES

These super-groups were particularly exciting because we usually only see whales traveling in smaller groups of two to three as they migrate along the east Australian coast [1]. The observed super-groups contained between 20 and 90 whales within five body lengths of one another [2, 4]. This was larger than any group previously recorded off Australia [3]. This may have been observed due to lots of food in one area and favorable sea conditions, which might have been different in previous years.

While we knew some whales fed in Australian waters, we now know it is not just a few individuals within the population. Their ability to grab a snack or meal during their migration may be one of the factors contributing to the recovery of this population. It also highlights how important observations by **citizen scientists** are. In fact, anyone can be a citizen scientist and work together with scientists to interpret their findings [5].

CITIZEN SCIENTIST

A member of the public who is not a scientist but participates in scientific research. In this project, our citizen scientists provided videos and photographs of whales feeding.

CITIZEN SCIENTISTS, CAN I BE ONE?

Citizen scientists can be young people or grandparents, and everyone in between. In whale research, many commercial whale-watching businesses and their visitors collect whale data such as census counts, behavioral observations, and fluke images to identify individual whales. This data can help scientists in a number of ways such as monitoring whale movements and recording interesting behaviors. In this study, commercial whale-watching vessels and recreational drone pilots helped obtain images of bubble-net feeding and super-group feeding events. If you are interested in being a citizen scientist, check out your local nature or conservation groups to see how you might be able to get involved. There are also many online organizations which use citizen scientists to count or identify animals from images. In all cases, be sure to seek parental or guardian approval and abide by all safety procedures or wildlife guidelines.

HUMPBACKS IN THE FUTURE

We are so happy to see the east Australian humpback whale population increasing! However, all whales, including this population, face a number of threats in the ocean. These threats include human impacts, such as increasing amounts of ocean plastics and discarded fishing gear (like nets and lines). Whales may eat plastic or become stuck in fishing gear, both of which can have life-threatening consequences. Other threats include ship strike, sound pollution and human-driven climate change, which leads to increases in sea temperatures and changes in prey distributions [6].

We can all do our bit to help whales. For example, keeping our beaches clean and eating sustainable seafood are great ways to help. Scientists are investigating how whales may be able to adapt to changing ocean conditions, possibly by increased feeding on their migrations or by the emergence of new feeding grounds and behaviors. If we can understand where and when the whales feed, we might be able to help protect them by changing *our* behavior. This might involve reducing vessel and fishing activity in areas where whales are known to feed or rest. If all of us—scientists, citizen scientists, and the public—do everything we can to help humpback whales, populations

of these amazing animals should hopefully continue to thrive long into the future!

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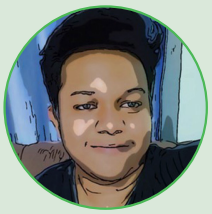
YOUNG REVIEWERS



DEBASISH, AGE: 15
I am a young lad with curiosity to learn and innovate. I am highly interested in reading science fictions. I love to watch sci-fi movies. Cricket is also something I enjoy playing.

VINCENT, AGE: 10
I love animals, sports, video games, and the outdoors! I play baseball daily. I love science and STEM topics. I am in the Science Olympiad Team for my elementary school. I have built water rockets and I also study animals, plants, and birds as a Backyard Biologist for my team. I want to be a vet when I grow up because I like animals. I like reading about science.

WILLIAM, AGE: 13
I love science and everything to do with it. My passion for science helped me land a spot in the Science Olympiad for my middle school and I have been to the National tournaments in the U.S. I am more of a hands-on person, wanting to go to medical school when I grow up, every aspect of science is interesting for me. I also play multiple sports such as soccer, swimming, and baseball.

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VANESSA PIROTTA

I am a wildlife scientist from Australia. My research is focused on using innovative technologies for animal conservation. I have worked around the world studying humpback whales in places such as Tonga, Antarctica, and Madagascar. My most famous research involves using drones to collect whale snot. I enjoy bringing science to life and sharing my research with the world through science communication. I love being around the sea where I free dive, drive boats, and enjoy seeing marine life.

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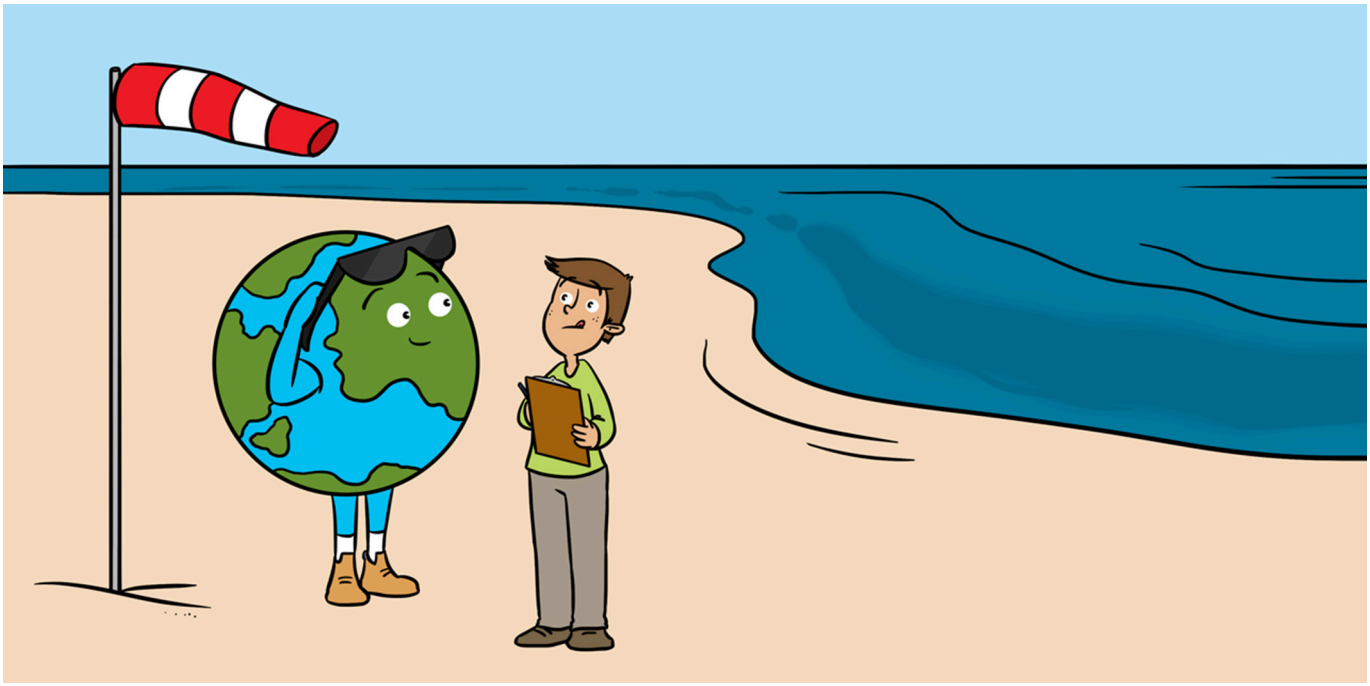

WHY ARE THE EASTERN MARGINS OF OCEAN BASINS FULL OF FISH?

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AGE: 12

At the eastern side of the Atlantic and Pacific Oceans, Earth's rotation combined with winds blowing toward the equator push water away from the coasts. Deep ocean water rises to replace what was pushed away, in a process called upwelling. The colder, deep water that rises to the surface is rich in nutrients and oxygen, and it supports healthy ecosystems. That is, upwelling in coastal oceans equals lots of fish! There are four coastlines where upwelling is crucial, known as eastern boundary upwelling systems (EBUS for short). These regions cover <3% of the world's ocean area, but they are responsible for 20% of the global fish catch. EBUS change constantly along with Earth's changing climate. Given their extraordinary biological productivity, it is very important to understand how global warming may impact EBUS. In this article, we describe what EBUS are and discuss how climate change may affect them and the fish populations in their ecosystems.

INTRODUCTION

"Small, but mighty" is a good way to describe the tiny fish that live in the upper ocean. Sardines and anchovies, for example, may be small, but they play an extremely important role in the ocean food chain and in the marine ecosystem. These small fish are a major food source for bigger fish, which are a major food source for humans all around the world! The largest populations of sardines and anchovies live in regions of the ocean called **eastern boundary upwelling systems (EBUS)**. EBUS are formed by a combination of the Earth's rotation and the surface winds that blow toward the equator along the direction of the coastline. These factors work together to push the water at the surface of the ocean away from the coasts. This horizontal water movement forces deeper water, which is usually colder and richer in oxygen and nutrients like nitrogen and phosphorus, to rise into the upper layer of the ocean where sunlight reaches. When nutrient-rich water reaches the sunlit layer, **phytoplankton blooms** result. **Phytoplankton** are tiny drifting plants. Like plants on land, phytoplankton use **photosynthesis** to transform the sun's energy into complex nutrients and oxygen, and support the whole food chain of the ocean. **Zooplankton**, the tiniest animals in the ocean, eat phytoplankton, while zooplankton themselves are the preferred food of larger fish. The physical process behind this beneficial movement of ocean water is called oceanic **upwelling** (Figure 1).

EASTERN BOUNDARY UPWELLING SYSTEMS (EBUS)

Regions of the ocean where water at the ocean's surface moves away from the coasts and is replaced by colder water, rich in oxygen, and nutrients.

PHYTOPLANKTON BLOOM

Rapid increase of phytoplankton in a particular region, associated with high amounts of nitrogen, phosphorus, and silica—the main nutrients for plants—along with abundant light and oxygen.

PHYTOPLANKTON

Microscopic, drifting plants that live in the sunlit zone of the ocean, and perform photosynthesis.

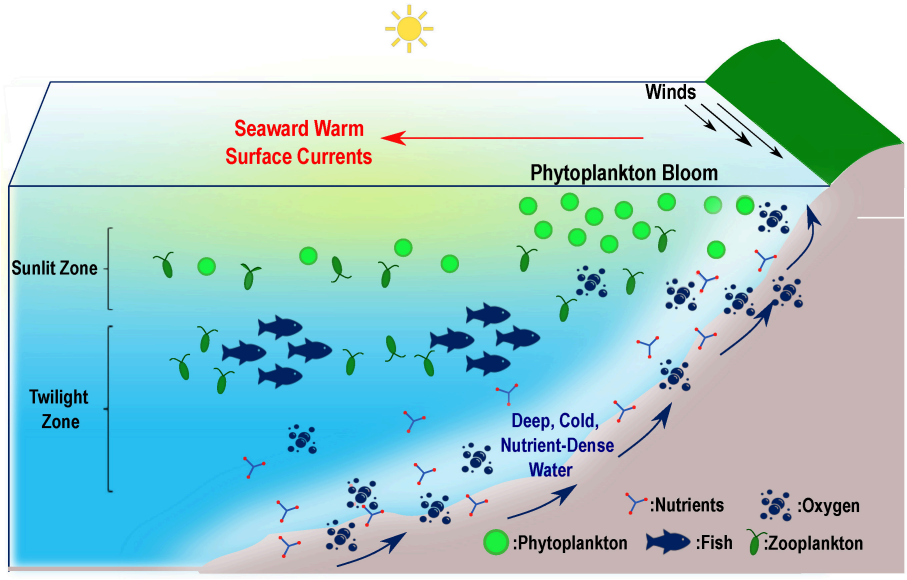

Figure 1

Upwelling is the process by which warm surface water in the upper, sunlit region of the ocean is replaced by deeper, colder, nutrient-rich water from the deeper regions (twilight zone). In EBUS, upwelling is caused by the wind that blows along the coastline and toward the equator, combined with the Earth's rotation. The wind forces the surface water away from the coast.

WHERE ARE THE EBUS AND WHY DO OCEANOGRAPHERS STUDY THEM?

Oceanographers study EBUS because they are one of the ocean's most productive ecosystems, and they are very important for the

PHOTOSYNTHESIS

The process by which plants use sunlight to synthesize food using carbon dioxide and water.

ZOOPLANKTON

Small aquatic organisms including crustaceans and larvae that drift in the ocean. They mostly eat phytoplankton and they are eaten by larger predators like fish.

economies of many countries. There are four main EBUS across the globe: the California and Peru-Chile upwelling systems in the Pacific Ocean, and the Canary and Benguela upwelling systems in the Atlantic Ocean (Figure 2) [1]. Seabirds such as cormorants, pelicans, and gannets, as well as marine mammals, are plentiful and diverse in EBUS because these animals are attracted to the concentrated food source available in these ecosystems. The accumulated excrement (poop) and the remains of dead birds and seals form a very valued soil fertilizer called guano, which is supercharged in nutrients. Not only do EBUS provide up to one fifth of the world's total fish catch [2] despite making up only a very small fraction of Earth's oceans, but, due to guano, they were of crucial importance to the development of modern intensive farming in the nineteenth century!

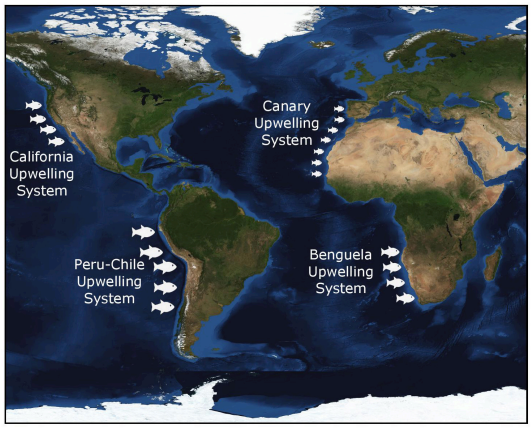

Figure 2

Locations of the four main EBUS. The size of the anchovy and sardine populations in each EBUS is proportional to the size of the fish symbol. The largest population is found in the Peru-Chile Upwelling System, and the smallest in the Canary Upwelling System.

EBUS AND CLIMATE CHANGE

Because fish are an important source of food and income for much of the world, scientists would like to understand how climate change will affect EBUS. Scientists believe that global warming will affect EBUS in two ways: it will change the winds that drive upwelling in EBUS, and it will change the layering of ocean water (Figure 3).

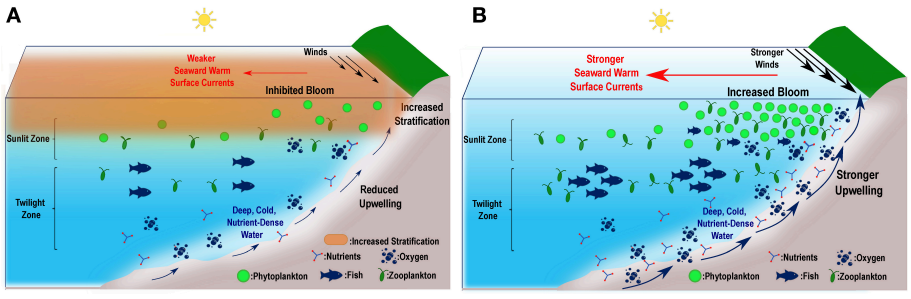

Figure 3

Possible future scenarios for EBUS. **(A)** As a result of climate change, EBUS upwelling may weaken because of increased stratification. Weaker upwelling results in less nutrients in the sunlit zone, which means less phytoplankton, providing less food for zooplankton and fish. **(B)** Alternatively, EBUS upwelling may strengthen because of stronger winds and little changes in stratification. Stronger upwelling results in more nutrients in the sunlit zone, which means more phytoplankton, providing more food for zooplankton and fish.

UPWELLING

Physical process in which in cold, nutrient-enriched ocean water rises from deep layers toward the ocean surface.

HEAT CAPACITY

The amount of heat required to warm a fix amount of material by 1 degree. The heat capacity of water is higher than that of rock.

STRATIFICATION

The process by which a fluid organizes into layers based on density. In a stratified ocean, warmer, lighter, less salty water rests on top of colder, heavier, saltier water.

Let us start with the winds. If the winds weaken, less water is pushed offshore and upwelling decreases. Likewise, stronger winds would yield greater upwelling because more water at the ocean's surface is pushed away and replaced by larger amounts of deep water. Although scientists are still debating whether it is more likely that winds will strengthen or weaken, most researchers agree that coastal winds will become stronger in the future [3]. This could happen because global warming will cause the land to warm faster than the ocean. If you leave a rock and a glass full of water out in the sun, after an hour the rock will be very hot and the water will only be warm. This is because the land and the ocean have different **heat capacities**. If the land warms up more than the ocean, the land-ocean temperature contrast will increase. Scientists predict that this increased temperature difference will produce stronger winds along the coastlines, and that these winds will increase upwelling. Increased upwelling would bring even more nutrients and oxygen close to the surface, encouraging the growth of beneficial phytoplankton blooms [4].

However, global warming will also cause air temperatures to rise [5]. When warm air heats the upper layer of the ocean, it increases what scientists call ocean **stratification**. Stratification occurs when water with different densities forms layers piled one on top of the other, from the lightest on top to the heaviest at the bottom. Warm water is less dense than cold water, so warm water floats on cold water. The lightest and warmest water is found in the upper ocean and each layer beneath is heavier and colder. Although warmer water in the upper ocean sounds nice for swimming, this warm layer acts as a barrier to upwelling. The more the stratified the ocean water is, the weaker the current that moves the surface water away from the coast. As a result, a more stratified ocean could decrease upwelling, decreasing the amount of nutrients that reach the sunlit zone where photosynthesis happens.

How does this all fit together? Although we know that EBUS' ecosystems may benefit from stronger winds and may be harmed by increased stratification, we do not know if the sum of these changes will be good or bad for the organisms that live there. Scientists are working to predict the future of EBUS with the help of computers. While it is not yet possible for a computer to model all that happens in the atmosphere and ocean, we have made huge progress representing Earth's climate in a realistic way. Results of these computer models show that each of the four main EBUS will likely respond differently to a changing climate. One group of researchers, for example, found that the two EBUS in the Atlantic Ocean may be very sensitive to climate change, whereas the two EBUS in the Pacific Ocean may not be affected by it very much [6]. Nevertheless, computer models agree that global warming will affect EBUS in summer more than in winter. Global warming will change the locations where the strongest upwelling occurs during the summer season, while changes in winter will be smaller [3].

WHAT WILL EBUS LOOK LIKE IN THE FUTURE?

With global warming, scientists predict changes to surface winds, ocean temperatures, and ocean stratification, among others [7]. While each of the four main EBUS is shaped by similar processes in the ocean and in the atmosphere, the combined effect of the expected changes will be unique to each location. As a result, global climate change will impact each EBUS differently. It is still unknown how these climate-ecosystem shifts will affect fish, seabirds, and marine mammals. Through a combination of ocean measurements and computer-based predictions, scientists will continue to study EBUS to understand how we can limit the damaging effects of climate change. While we figure it out, choosing sustainable seafood is an easy way to help sardines and anchovies from all EBUS to stay healthy!

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

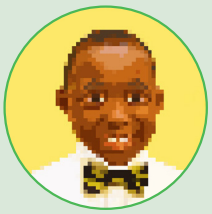
AVENTURA CITY OF EXCELLENCE SCHOOL (ACES), AGES: 11–12
ACES is a Charter School in South Florida that adds depth and breath of real world to its curriculum by engaging our eagles in various community activities and science projects. It has been an honor for the advanced 6th grade Science class to participate in the scientific process by reviewing the manuscript. Students were excited to see how their suggestions were taken into account and made the article more understandable for middle schoolers like them.

AVERY, AGE: 13
Avery is an avid fan of science and engineering. She mixes creativity with logic when problem-solving. Her intrigue and strong work ethic propel her when facing new challenges. She is involved in programs in and out of school supporting the environment and celebrating diversity. Additionally, Avery swims on two teams and plays lacrosse.

ELENA, AGE: 14
I enjoy reading, watching movies and tv, and playing sports.

JAETHANIEL, AGE: 12

Hi my name is Jaethaniel and I love science and Marvel superheroes. I hope 1 day to become a detective. And I would like to go to Yale for school.



LUKE, AGE: 12

Luke is a young published author who is passionate about learning American history. Sharing his expertise with friends and family motivates him. He is a Scholastic Kid Reporter; who has had the privilege of interviewing former President Barack Obama and other leaders. Also, he launched an ongoing charity: water campaign in 2019. Currently, Luke is a member of the debate club, government club, honor roll, track team, Yale Pathways to Science program, and an NYLF Pathways to STEM alumni.

AUTHORS

SARA MILLER

Sara is a Ph.D. student in the Department of Astronomy at Cornell University. Before coming to Cornell, she earned B.S. and M.S. degrees in aerospace engineering at Georgia Tech. Sara grew up in a coastal community in Southern California and developed a love for the ocean at an early age. Her research is focused on ocean worlds of the outer solar system. Specifically, Sara is interested in modeling the fluid dynamics of an ocean that exists under an ice shell on Jupiter's moon, Europa. When she is not doing research, Sara enjoys running, scuba diving, and hiking with her dog.

LUISA LOPERA

Luisa is a Colombian researcher and an ocean lover. She has been interested in earth sciences since she was a kid, and she is now pursuing a career as an oceanographer. Currently, she is a Ph.D. student in the Ocean Sciences and Engineering Program at Georgia Tech. Her research project is to assess the how connected coral ecosystems in the Gulf of Mexico are, to provide information for territory planning.

ANNALISA BRACCO

Annalisa is a professor in the School of Earth and Atmospheric Sciences at Georgia Tech. An avid sailor, she pursued a Ph.D. in geosciences and specialized in physical oceanography after a B.S. in theoretical physics. She is interested in understanding how marine ecosystems interact with ocean currents, and she uses this information to improve ocean sustainability and resilience in the face of climate change. She does so in collaboration with chemical and biological oceanographers and marine ecologists across the globe. When she is not working, she keeps busy with her two kids and three dogs. *abracco@gatech.edu

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THE WEIRD AND WONDERFUL WORLD OF WORMS

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YOUNG REVIEWERS:

ELI
AGE: 12

MIA
AGE: 14

Animals with long, skinny bodies are often called "worms," but there are many kinds of worms—even in the ocean. Annelids (segmented worms) include garden earthworms, but their ocean relatives come in many colors, shapes, and sizes. Some are so small that they live between grains of sand, while others can be longer than a human and eat fish! Marine worms are essential to the ocean food web, as both predators and prey. They help create homes for plants and animals by burrowing and building tubes in ocean sediments. Scientists are still discovering new worm species, and there are still many mysteries about how worms eat, why they live in the places they do, and what roles they play in ocean ecosystems. Worms are a fascinating and important part of ocean communities.

WHAT IS A WORM?

When we think about worms, we usually think about the earthworms we see in the garden or wiggling on the sidewalk after it rains. Or we might think about parasitic worms that live inside other animals, or leeches that feed on blood. While these are the worms we see most often, worms first evolved in the ocean and most species of worms still live there today.

When scientists first began classifying animals by grouping them together according to their physical features, these **taxonomists** created a group called "Vermes," which means "worms" in Latin. "Vermes" included "all animals that are longer than wide," without backbones [1]. This meant that many distantly related animals with a worm-like shape were included in this group. Later, scientists began to recognize and describe many distinct groups of worms. One of these groups, which includes earthworms, is called Annelida, and it is the focus of this article. When we say "worm" from now on, we are talking about **annelid worms**.

TAXONOMIST

A type of scientist who discovers, names, describes, and classifies species.

ANNELID WORMS

A major group of worms with rings of repeating segments along their bodies. One familiar example of an annelid worm is an earthworm.

"Annelida" means "ringed animals." This refers to the repeating segments along their bodies, which distinguish them from other worms. Having many segments means that some can be used for special functions. Imagine if you had 20 sets of arms and legs—you could use some of your arms for juggling, while you flipped pancakes with the other ones, all while riding your bike. Some annelids divide jobs along their bodies—for example, they might use some of their segments for special kinds of feeding, while other segments can build a tube, get rid of waste, or make eggs.

Annelids are an ancient group, with ancestors going back to the time when the very first complex animals began to appear on Earth. Fossils of whole worms are very rare because their bodies are soft and squishy and do not preserve very well. The worm fossils we usually see are from worms that have hard parts, like jaws and teeth, inside their bodies. These parts have been present in the fossil record for over 500 million years.

HOW MANY KINDS OF WORMS ARE IN THE OCEAN?

Scientists do not know exactly how many species of worms live in the ocean, because there are still many to discover. Currently there are about 14,000 known species of annelid worms [2], but many new species are described every year by taxonomists. More than 120 species of Annelida were described in 2021 alone, so we still have a lot to learn about the **diversity** of these worms (Figure 1).

DIVERSITY

The variation in forms of life. Diversity can be the number of kinds of organisms, for example worm species, or the number of different jobs or "functions" in the ecosystem.

Figure 1

Worms come in all shapes and sizes and have special body parts for unique kinds of feeding, defense, and reproduction. Here are a few examples of the diversity of Annelida.

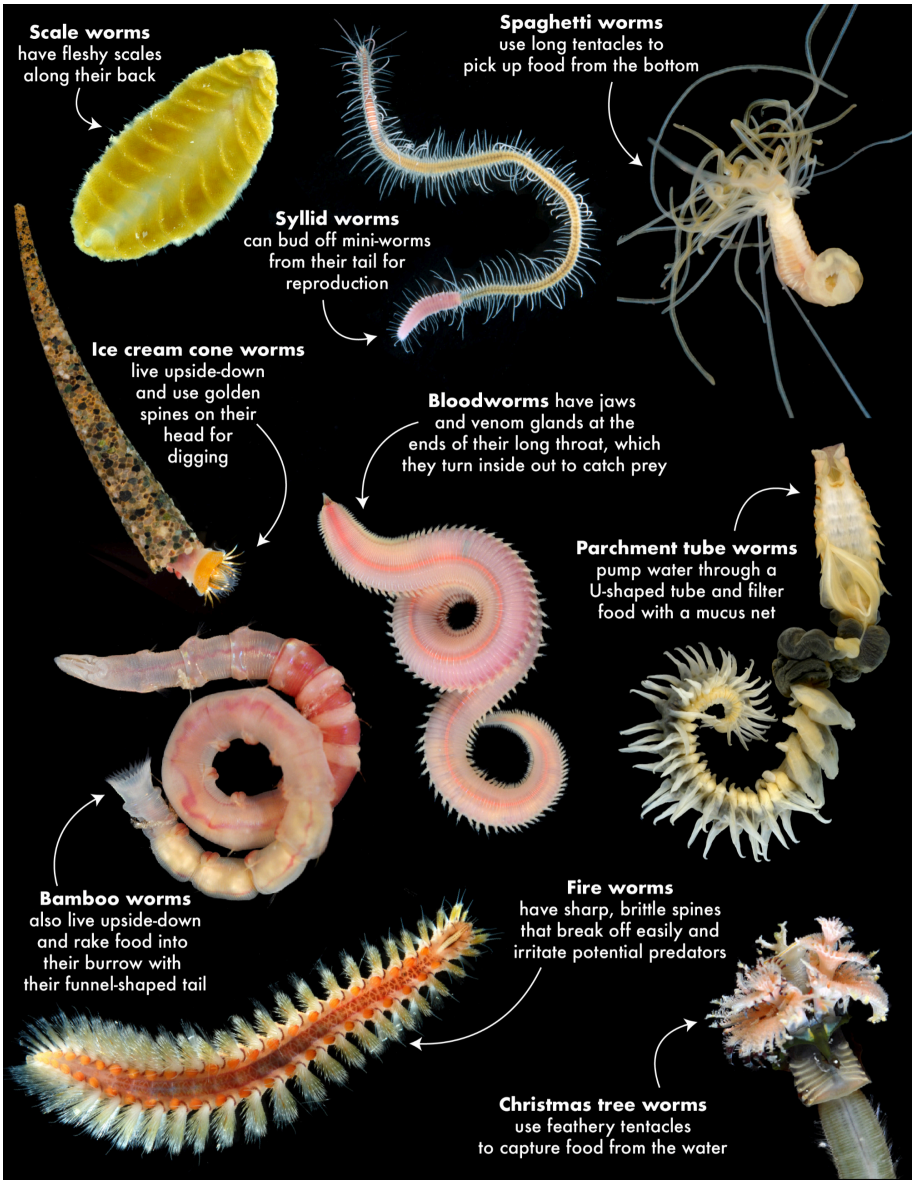

Figure 1

Worms are found in every ocean habitat, from shallow mud to coral reefs, and even in the deepest parts of the ocean. They are common in warm, tropical places, the coldest polar places like Antarctica, and everywhere in between. Worms come in a huge array of shapes and sizes, from microscopic species to the fearsome-jawed "sand-striker" worm that eats fish and can grow longer than a human. Some worms live in very harsh environments, like the super-hot water of hydrothermal vents. Some worms are parasitic and live on or inside other animals, for example, on lobster gills or on feather stars, in sponges or corals, or even inside other worms. Some worms bore holes into solid rock; some are so tiny that they crawl between sand grains as if they were giant boulders; and some swim freely in open water. If you look carefully *anywhere* in the ocean, you will find a worm.

WHAT IS IT LIKE TO BE A WORM?

Although worms live in environments that are very different from those of humans, they need to do the same basic things that people must do to survive: breathe, eat (and poop!), avoid being eaten, and reproduce to make more worms.

SEDIMENT

The mixture of inorganic (particles of rock and shell) and organic (living microbes and dead stuff from the overlying water) materials that accumulates on the seafloor.

Many marine worms live in **sediment**, such as mud or sand. If you have ever gone to a muddy seashore, you might have noticed that the mud is black and smelly just under the surface. This is because the sticky, goopy mud prevents oxygen from getting very far under the surface. So, if you are a worm that lives in mud, getting oxygen to breathe is a big challenge. Some worms stick feathery external gills up into the water where there is more oxygen, and others pump water into their burrows to bring oxygen down to them (Figures 2A, 3A). Some worms have blood just like ours that can store oxygen, which gives them their red color.

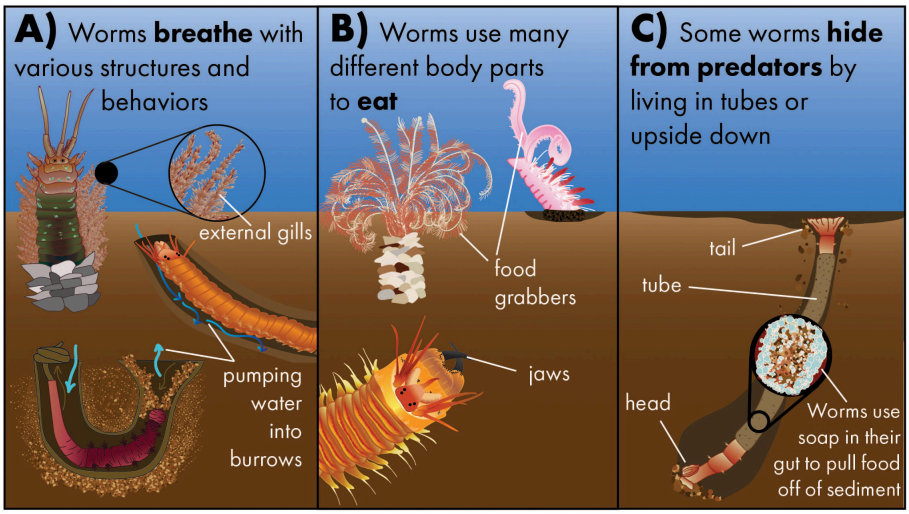

Figure 2

Worms have many special adaptations that help them to **(A)** breathe with various structures and behaviors, **(B)** use many different body parts to eat, and **(C)** hide from predators by living in tubes or upside down.

Just like the earthworms in a garden that eat dirt, many worms on the ocean floor eat sediment. Some of the best worm food on the ocean floor comes from dead plankton, fish poop, and other goo produced by organisms in the water that sinks to the sediment surface. Scientists call this material **detritus**. Worms have special guts with a kind of soap that helps them digest the detritus that coats the sand grains. However, marine worms do not eat just detritus—some of them are carnivores or scavengers, some are herbivores, and some are parasites. Some worms have teeth, jaws, or even venomous fangs for capturing prey or grazing on plants. Some vegetarian worms scrape algae from rocks with special teeth. Compared to the earthworms in a garden, worms in the ocean have evolved a spectacular variety of body parts used to find, grab, and hold onto food (Figure 2B).

DETRITUS

Pieces of organic material such as dead plankton, algae, and fish poop that are an important food source for many organisms.

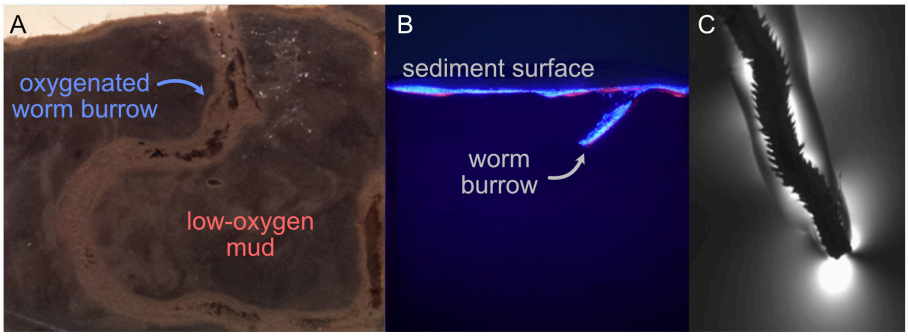

Figure 3

Worms can be challenging to study in their natural habitats because scientists cannot see through the mud to observe them. **(A)** Side-view of a "worm farm"—a worm has burrowed and oxygenated the sediment. **(B)** Side view of "worm farm" in the dark, with colored sediment grains, called luminophores, illuminated by ultraviolet light. Luminophores placed on the sediment surface were mixed down by a burrowing worm. **(C)** A worm burrowing in Jell-O made with seawater, which has similar properties as sediment but is see-through. Scientists shine light through the Jell-O to observe how the worm burrows.

Many animals like to eat worms, so worms have evolved numerous ways to avoid predators. Worms that swim in the water or crawl around on the seafloor surface are more exposed, so they often have venomous or irritating spines or use stinky or poisonous chemicals to be less tasty (Figure 1). Some worms hide from predators by building burrows or tubes in sediment (Figure 2C). To resist getting pulled or sucked out of their homes, worms use stiff hairs on their bodies to hold onto their tubes or burrows. It is common to find worms that are growing back their tails or even their heads after having those parts bitten off by a passing fish!

Breathing, eating, and avoiding predators are all important, but reproduction has kept worms on our planet for millions of years. Some worms just throw their eggs and sperm into the water, but others turn their tails into a zombie mini-worm that carries eggs or sperm, complete with a new head and eyes (see the syllid in Figure 1). Sometimes worms keep their babies inside or on their bodies or inside their burrows until they are almost grown up. Sometimes worms can clone themselves by splitting in half and regrowing a new head and tail.

HOW DO WORMS CHANGE THEIR ENVIRONMENTS?

One of the most important jobs performed by many worms is recycling detritus so that nutrients are available for other organisms. **Microbes** actually do most of the work of breaking down detritus, but they are tiny and can not move much, so it is difficult for them to reach the sediment surface where detritus and oxygen are most plentiful. That is where worms come in. When worms burrow through sediment, they move detritus from the sediment surface to deeper down, where more microbes can find it. This process is called **bioturbation**. Worms also pump oxygenated water into their burrows to breathe, and this brings oxygen to microbes deeper in the sediment [3].

The strategies that worms use to survive also change their habitats. When worms build tubes or burrows, they create homes for other

MICROBES

Single-celled organisms invisible to the naked eye. Sediment microbes are incredibly diverse and do the bulk of the work to break down detritus.

BIOTURBATION

The process of animals mixing sediments by burrowing through them and feeding on them.

animals. This is why we often find larger and more diverse animal communities in areas with tube-building worms. Worms can also serve as an important food source for fish, birds, crabs, and other predators. So, by eating, burrowing, and being eaten, worms transform the detritus that sinks to the ocean floor into nutrients and energy that can be passed up the food web once again.

Though the things worms do are important, these processes can be difficult to study because scientists can not look through the sediment to see worms in action. Scientists must use creative methods to study what worms are doing (Figure 3). For example, scientists use glowing particles to track how much worms mix sediments, put worms in clear Jell-O to observe how they move, and even detect worm activities with sound waves.

Scientists study communities of worms by grouping them based on the different "jobs" they do in the ecosystem [4]. For example, the groups may be based on whether worms find their food below the sediment surface vs. catching particles floating by in the water, or whether worms build a tube as a home vs. making a burrow. Diversity can refer to the number of species, but diversity can also mean the number of unique jobs or functions worms have in the community. Ecosystems with higher functional diversity, meaning more jobs being done, are often healthier and more productive.

CONCLUSION

The ocean contains many habitats to be explored and many thousands of species yet to be discovered. The next time you are looking for shells on a beach, digging by the seashore, or visiting an aquarium, turn over rocks or look inside crevices and keep your eyes open for wiggling and shimmering worms. The puzzle of figuring out which worms are present and what they are doing will keep scientists busy for many years to come.

ACKNOWLEDGMENTS

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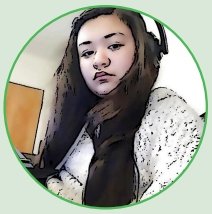
YOUNG REVIEWERS

ELI, AGE: 12
Eli is 12 years old and will be attending the seventh grade. In his spare time, Eli enjoys playing soccer and running. Eli also plays the cello. He has two dogs, a Chocolate lab named, Gunner and a Cavapoo named Oki. Eli wants to be a scientist someday but is still undecided on the field of science.



MIA, AGE: 14
Mia is 14 years old and will be attending the ninth grade. Mia's hobbies include listening to music, playing soccer, baking and performing in a marching band. She plays the flute. Mia wants to get into the arts upon finishing high school.

AUTHORS

KARA J. GADEKEN

I am a marine ecologist and I study how sediment chemistry and ecology interact and affect each other. I am particularly interested in what happens in the sediments when stressful environmental conditions occur, such as low oxygen, and how the sediment's ability to "recycle" changes in response. One of my favorite things to do in my research is design and build new scientific tools to better observe what goes on in the mud. Sediments are cool, weird ecosystems with so many mysteries left to uncover, and I cannot wait to keep digging! *kgadeken@disl.org

ERIN KISKADDON

I am a coastal ecologist specializing in worms and other animals that live in sediments. I am particularly interested in communicating science that can help people manage coastal resources, which is especially important in my home state of Louisiana. Worms are some of my favorite critters because so many other valued natural resources, including the fish and shrimp we put on our plates, depend on them. If we want to sustain our ecosystems and economies, we must consider the worms!

JENNA M. MOORE

I am a museum curator, and I study worm evolution and diversity. Museum curators are a bit like librarians, except instead of collecting books, we create a record of life on earth by preserving specimens for research. In my own research, I use museum collections to study how feeding structures like jaws and mucus nets have evolved in worms. As a taxonomist, I also name and describe species. Worms are my favorite animals because they do so many different and cool things, and they live in secret worlds that humans know very little about.

KELLY M. DORGAN

I am an oceanographer and, for over two decades, I have been studying how worms and other animals that live in sediments interact with their environments. I started working with marine worms in high school and became fascinated by their diversity and curious about what they were doing in the mud. In trying to answer those questions, I have spent many hours watching worms burrow in Jell-O, clear sand, and thin aquariums of mud. I work with engineers to learn their tools and techniques and use them to understand what life is like for worms.

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EARTH AND ITS RESOURCES
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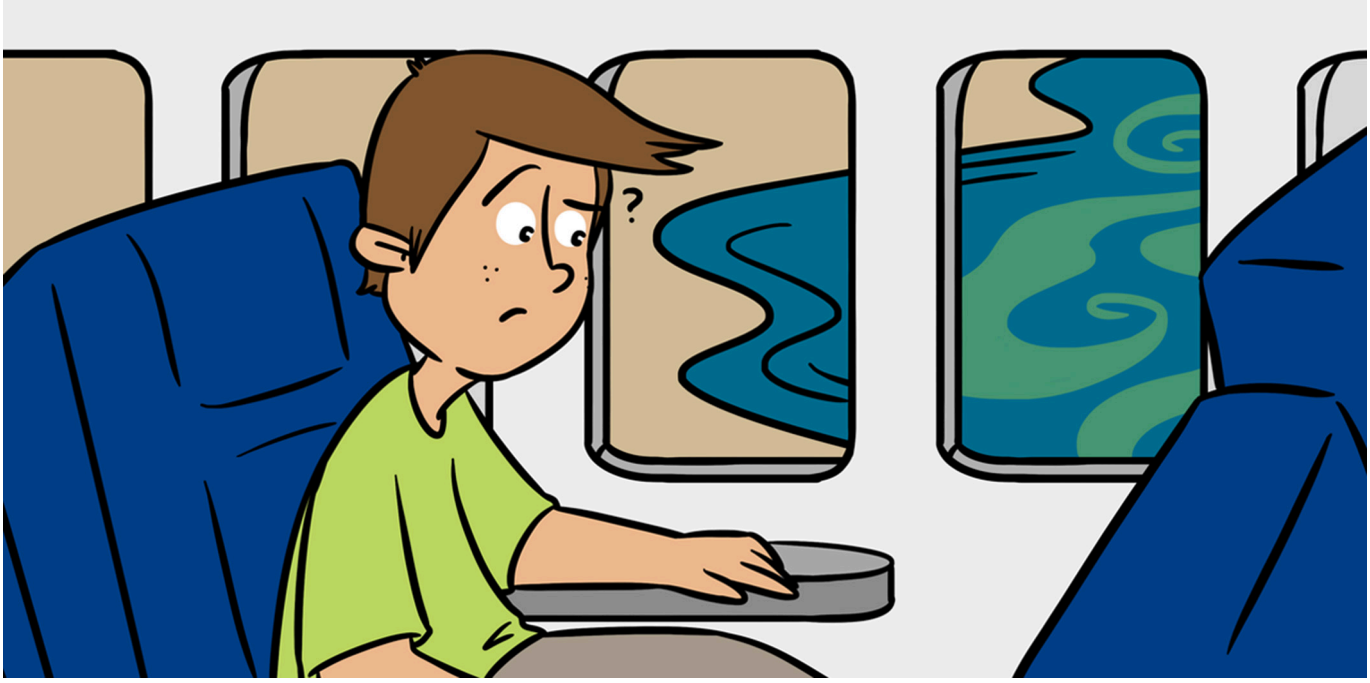

A SEA OF COLORS

Rafael Gonçalves-Araujo [1*], ***Colin A. Stedmon*** [1] ***and Astrid Bracher*** [2,3]

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YOUNG REVIEWERS:

EVA
AGE: 10

IRENE
AGE: 10

KAVIN PORKO
AGE: 12

Although we always associate the oceans to the blue color, other colors such as green, brown, and even yellowish can be observed. The diverse color palette presented in the oceans and other water bodies is due to the presence of colored components that interact with the light in the water. Those components are, for instance, (1) the water itself, which gives a blue color to the oceans; (2) very tiny plants that can give a greenish color to the water; (3) dissolved compounds that turns the water into a brown-yellowish color; and (4) sediments, which gives a milky color to the oceans. In this article, we explain how those components change the color of the water and how marine scientists use satellites to capture those changes from space and convert them into information for their research.

INTRODUCTION

What is the first color that comes to mind when you think of the ocean? Blue, right? Pictures of the planet from space show that what we call Earth is mostly a blue ocean (if we knew this earlier, we may have named it Ocean rather than Earth!). But if we dig a little deeper, we find that the sea can have a range of colors, varying from blue to green or even yellowish-brownish. You can see some of these differences yourself the next time you take a plane trip. Near the coast, the water is often a different color from what it is out at sea. Have you ever wondered what those different colors mean? In this article, we will look at why the color of the sea changes, how this can be captured by satellites in space, and what it can tell scientists about the oceans.

FIRST, WHAT IS COLOR?

Objects that are black absorb (extinguish) all light, so you could say they have no color, because what our eyes actually see as color is the light that is reflected back from an object. White light (like sunlight) consists of a mixture of light of all colors. Milk is white because it contains lots of very small fat particles that reflect all colors equally well. Similarly, a sheet of white paper reflects all colors. Some objects appear a certain color to our eyes because they absorb specific colors, meaning that they actually remove certain colors of light. Light is absorbed by **pigments**, which are chemical compounds that can be found in living organisms (such as green plants) and inanimate objects (such as paints). The colors that are not absorbed by an object are reflected by the object, and that is what we see or measure with scientific instruments. So, what we see is, in fact, the light that is *reflected* by the object we are looking at.

PIGMENTS

Chemicals that add color to a material.

WHAT CONTROLS THE COLOR OF THE SEA?

Some of the sunlight that shines on the sea surface is absorbed by the water and by pigments that can be found in it, and the rest is reflected, creating the blue, green, and yellowish-brownish colors we see when looking at the ocean (Figure 1). Which colors are reflected depends on what is in the water and the properties of water [1]. Water naturally absorbs most red light and reflects a lot of blue light (Figures 1B, 2), which is the one that penetrates deepest into the water and is the most reflected (Figure 2). This can be observed, for instance, in the clearest blue-water tropical oceans (and mountain lakes). Other colors of water result from three things: dissolved compounds, plants, and very fine grains of sand.

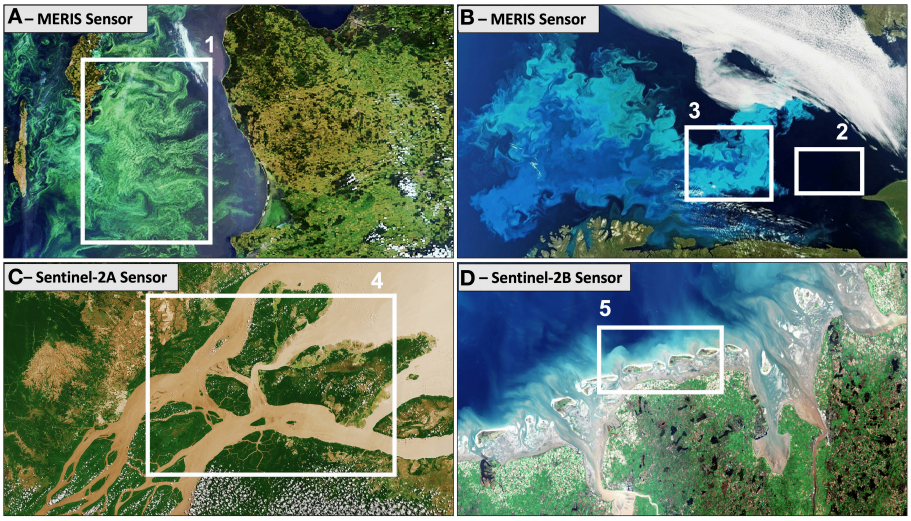

Figure 1

The color of water seen from space, using sensors on board satellites from the European Space Agency. **(A)** The Baltic Sea, showing green waters with lots of phytoplankton (1). **(B)** The Barents Sea, with dark blue open ocean (2) and light blue waters caused by blooms of coccolithophores (3). **(C)** The Amazon, showing the yellowish-brownish coastal waters with river discharge (4). **(D)** The German Bight in the North Sea, highlighting the milky waters full of sediments (5).

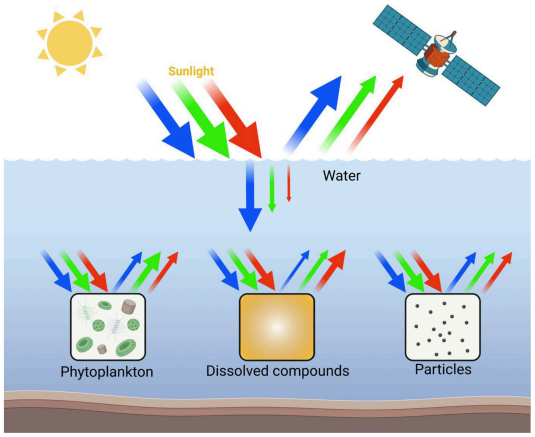

Figure 2

OCRS uses sensors on satellites to monitor the color of the oceans. Sunlight is represented by red, green, and blue arrows that vary in intensity (shown by arrow width). Upward arrows show the light reflected back from the ocean after interacting with water itself (which reflects blue light), phytoplankton (which reflect mostly green light), dissolved compounds (which reflect green and red light), and particles (which mostly scatter light).

DISSOLVED COMPOUNDS: THE OCEAN AS A CUP OF TEA

Make yourself a cup of tea and you will see the water in your cup become yellow or brown, as the pigments in the tea leaves dissolve into the water. The pigments from the dried tea leaves absorb blue light, and the light reflected ends up being yellow or brown. This example helps to explain why seawater can be yellow or brown near places where rivers flow out into the sea. The same way water dissolves compounds in tea leaves, falling rain dissolves soil, which drains into rivers and finally makes its way to the ocean (Figure 1C).

PLANTS: JUST DRIFTING AROUND

Just like plants on land, plants in the ocean have a green color. Plants have pigments that they use to capture sunlight as a source of

energy, through photosynthesis. Most plants in the ocean are part of a group of organisms called **phytoplankton**, which are very tiny—the width of human hair or even smaller (see this Young Minds article for some examples). Because of their size, phytoplankton cells mostly drift around with the ocean currents. When there are lots of phytoplankton cells in the water the ocean (called a **bloom**), the ocean becomes green (Figures 1A, 2), which can often be seen in spring and summer. Some groups of phytoplankton have certain red pigments, making the ocean look red when those phytoplankton bloom. This phenomenon is called a red tide.

PHYTOPLANKTON

Single-celled organisms of water environments that make their own food from sunlight through photosynthesis.

BLOOM

When phytoplankton density increases rapidly due to lots of nutrients and sunlight available in the water. It generally happens during Spring season.

SEDIMENTS: THE OCEANS' "MILKY WAY"

As rocks and soils experience the effects of wind, rain, and erosion over the years, they are broken into smaller pieces, ranging from coarse sand grains to very fine silt that forms clay. These products from eroded rocks and soils are called **sediments**. The very fine grains sink so slowly that they remain suspended in the water for a long time. Near the coasts, these grains are either supplied by rivers or whirled up from the seafloor by storms. Although sediments can be pigmented (colored), they mainly change the color of the water by reflecting (scattering) light in all directions (Figure 2). This is similar to what the fat particles in milk do—making the water become what we often call "milky" (Figure 1D). Some phytoplankton called coccolithophores have white plates made of chalk, which also scatter the light. When these phytoplankton bloom, the ocean water can become light blue or even white (Figure 1B).

SEDIMENTS

Fragments of material that have been broken down. Those materials can be organic (for example, soil) and inorganic (for example, rocks).

MEASURING THE COLOR OF WATER

We can see a lot using only our eyes: the blue of the open ocean, the brown and milky river waters flowing to the sea, and the green phytoplankton blooms at the beach in summer. But with instruments called sensors, we can turn the colors we see into precise numbers. We can use those numbers to follow very small changes in water color, which are invisible to the naked eye. These sensors are called **radiometers**. Some radiometers only measure a specific color, whereas others can measure lots of colors at the same time—either individually or by combining the total signal across several colors (see this Young Minds article for some examples).

RADIOMETER

Instrument to detect and measure the intensity of light.

SATELLITES: SENTINELS FROM SPACE

A satellite is any man-made or natural object that orbits another, larger object. Often, satellites with a range of sensors are intentionally placed into orbit around the Earth. These sensors can include radiometers used to monitor water color, among other things. This technique

OCEAN COLOR REMOTE SENSING (OCRS)

A method to collect information on the color of the ocean's surface and further transform it into information (data) which can be used by scientists to study the oceans.

is called **ocean color remote sensing** (OCRS) and, although it has "ocean" in its name, it can be used to monitor the color of water in lakes, rivers, and other aquatic environments, too. The OCRS technique has been running since the 1970s, when the first ocean color sensor, the Coastal Zone Color Scanner, was integrated into the satellite Nimbus 7. A sensor on board a satellite acts like a camera that takes several pictures of the Earth's surface during its orbit around the planet. That means these sensors capture the sunlight reflected by ocean water after that light is absorbed and/or scattered by dissolved compounds, phytoplankton, and sediments (Figure 2). The individual pictures are then combined into a mosaic, which represents a global map of how and why ocean color changes. This mosaic can be produced once a day, every day! The daily mosaics can be combined over several years to form a time series. Scientists use time series images to study how the color of the oceans varies regionally (for example, across different seas or in coastal vs. open sea areas) and over time (year to year, month to month), and to evaluate if ocean conditions are changing [2].

WHY IS IT IMPORTANT TO STUDY THE COLOR OF THE OCEANS?

The color of the oceans can provide scientists with lots of information. For instance, ocean color can tell us about the quantities and locations of phytoplankton, dissolved compounds, and sediments in different regions. What do those three components have in common? They all include the element carbon. That means the oceans are involved in the global **carbon cycle**. Carbon dioxide (CO_2) is a very important gas in the carbon cycle. CO_2 can influence global temperature and climate. Like other plants, phytoplankton use CO_2 during photosynthesis and therefore help to control the amount of CO_2 in the atmosphere (see more in this Young Minds article). Phytoplankton also represent the basis of the marine food chain, and changes in phytoplankton quantity and distribution may affect the overall life cycle in the oceans and can even impact humans, in terms of the availability of fish for us to eat (see more in this Young Minds article) [3]. Thus, the color of the oceans represents more than beautiful hues, it gives us information about fundamental elements that control life in the oceans and the climate of the entire Earth.

CARBON CYCLE

Process of how the element carbon travels from living to non-living objects.

DO YOU WANT TO HELP OCEAN SCIENTISTS COLLECT DATA?

CITIZEN SCIENCE

Science projects in which the public participates by collecting data. Some projects eventually also train the public to analyze data.

Due to some impressive technological developments in the last decades, citizens (including you!) can help to advance this science through what are called **citizen science** projects. Using your smartphone, you can download applications that collect information about the color of waterbodies near you. This info is sent to scientists

so they can, for instance, correct the data collected from the satellites. One example is called Project Citclops (Citizen's Observatory for Coast and Ocean Optical Monitoring), which has developed a smartphone app called Eye on Water. This app is fun and quite easy to use, and a great way for you to contribute to research and help the scientific community. So, get your hands dirty (or should we say wet) and help ocean-color science!

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YOUNG REVIEWERS

EVA, AGE: 10

My name is Eva and I am 10 years old. I like dancing. I like to dance the styles Jazz, Tap, and Ballet. I also like reading. I normally read Harry Potter, The Keeper of the Lost Cities, and any mythology series by Rick Riordan. I also like writing. I write fiction books. My favorite school subject is math.

IRENE, AGE: 10

My name is Irene. I am in fourth grade at elementary school. I love sweets and the book series Keeper Of The Lost Cities. I play piano and I am currently learning the cello. I love playing with my friends outside and swimming in the summer. I am also in the Student Council at my school. My favorite special is gym and writing. I joined this program because I am interested in science and our environment. I am worried about climate change and the glaciers that are melting.

KAVIN PORKO, AGE: 12

We as a team are excited and delighted in contributing to science by reaching young minds. Reviewing articles written by experts for young children is a wonderful opportunity to seek and learn various aspects of earth and its resources.

AUTHORS

RAFAEL GONÇALVES-ARAUJO

Dr. Rafael Gonçalves-Araujo is a Brazilian oceanographer with a Ph.D. in natural sciences from the University of Bremen in Germany in 2016. Rafa has been fascinated by the ocean since the first time he saw it in his childhood. He studies the carbon cycle, with a focus on the Arctic Ocean. In his research, he combines information from samples collected directly from the oceans with data from satellite remote sensing. Apart from enjoying expeditions to collect water samples, his work also involves lab work, scientific instrumentation, and a lot of time in front of the computer. *rafgo@aqua.dtu.dk

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Prof. Colin A. Stedmon is a chemical oceanographer at the Technical University of Denmark. He obtained his Ph.D. from the University of Copenhagen in 2004. His current research focuses on Arctic marine biogeochemistry. This essentially involves studying the chemical composition of seawater and collaborating with experts in marine physics and biology to understand how the oceans function and, in particular, how the Arctic is changing. He most enjoys the detective work: looking for patterns in data, finding explanations for those patterns, and contributing to an understanding of how the oceans function.

ASTRID BRACHER

Prof. Astrid Bracher is a biologist by training who, after her Ph.D. in ocean optics in the Southern Ocean and her postdoc in atmospheric physics using satellite remote sensing, is now a professor in environmental physics focusing on ocean color, both from space and field measurements. She works on developing

methods to obtain the concentrations and composition of phytoplankton and other optically active substances, from ocean-color measurements. Apart from that, she appreciates working occasionally in the field, sampling optical data. Overall, she enjoys the interdisciplinarity of her work and the interactions with many different scientists.

frontiers FOR YOUNG MINDS

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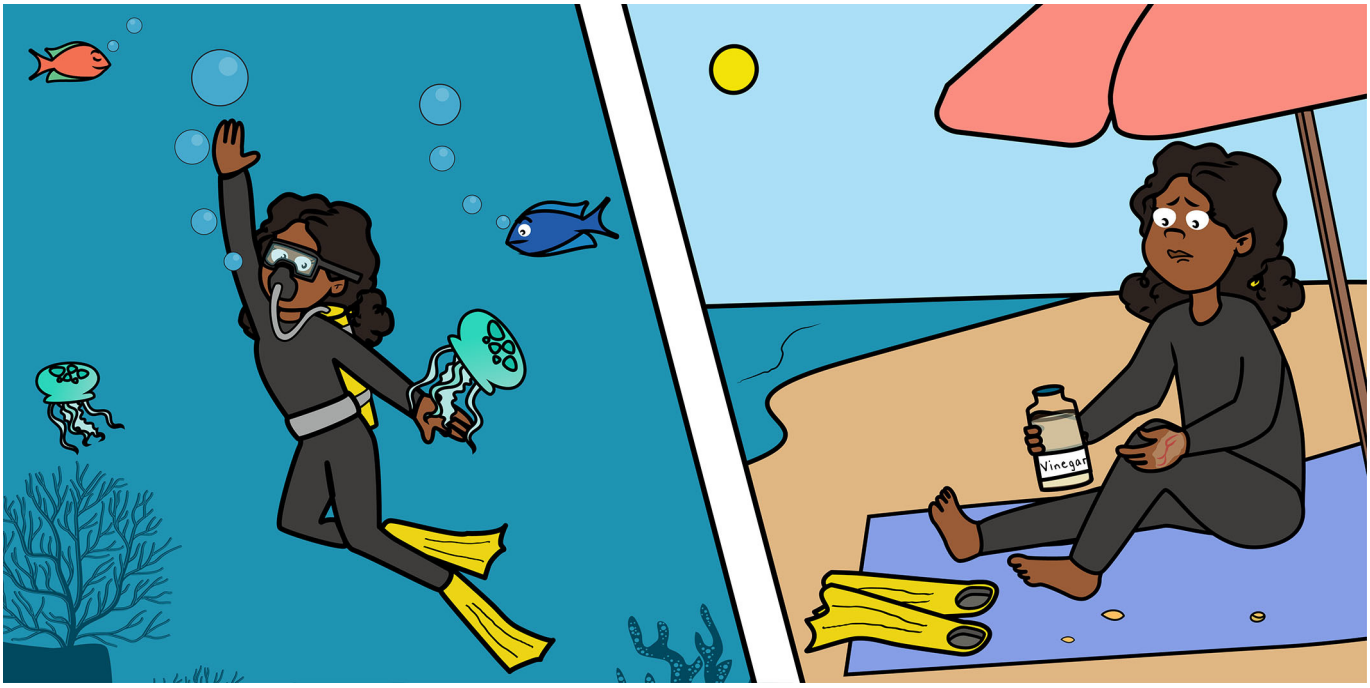

WHAT ARE MEDUSOZOANS, AND WHY DO THEY STING?

José Agüero [1]***, Mariae C. Estrada-González*** [2]***, Leonela Rosales-Catalán*** [3]***, Ariadne Molina-Alonso*** [3] ***and María A. Mendoza-Becerril*** [4*]

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YOUNG REVIEWER:

MEHA

AGE: 15

Medusozoans are marine animals without backbones that live near the coasts, or in the depths of the oceans. Some of them are large, but others are even tinier than a seed. Medusozoans have been living on Earth for more than 600 million years. Their bodies are 95% water. Some medusozoans live attached to a surface, but others can swim freely. All medusozoans have tentacles, armed with stinging cells called nematocysts. When the nematocysts are triggered, the tiny stingers inside them can travel at speeds up to 67 km per hour. Around 3% of medusozoans are harmful to humans. Therefore, when visiting beaches where these harmful medusozoans live, it is necessary to take some precautions. Wearing protective clothing and not touching a medusozoan stranded on the beach will help you stay safe and healthy, so you can enjoy your beach day!

MEDUSOZOANS AT FIRST GLANCE

INVERTEBRATES

Animals that do not have backbones.

Medusozoans are **invertebrate** animals (those without backbones) that live in the sea. Jellyfish and the Portuguese man-of-war may be the medusozoans you are most familiar with, but we will tell you about other kinds, too! Some medusozoans live near the coasts and others live in the depths of the oceans. They are close relatives of corals, sea anemones, and sea pens. Medusozoans do not have heads, brains, hearts, or bones. They often feel soft and gooey. Some medusozoans are quite large, up to 47 m, while others are as small as a tiny seed: <0.5 mm [1]! All medusozoans have tentacles, which may be long or short. The name "medusozoan" comes from one of the most famous characters in Greek mythology: Medusa. This mythical being is known to have snakes instead of hair. The image of snakes waving from her head reminds people of the tentacles of medusozoans.

Here are ten interesting facts about medusozoans:

- They have been living on Earth for more than 600 million years; they were here long before dinosaurs or humans.
- About 95% of their bodies are made out of water.
- Medusozoans do not have heads, but some jellyfish have eyes.
- Of the almost 4,156 known species of medusozoans, only around 3% cause injury to humans [2].
- The stingers released by their stinging cells travel at a speed of 67 km per hour.
- On June 5, 1991, NASA delivered twenty thousand baby medusozoans to space, for 9 days [3].
- The sea wasp, an Australian box jellyfish, is one of the world's most venomous animals.
- Medusozoan' stings do not electrocute people, as you may have seen on TV or in movies.
- There is a tiny medusozoan called a hydra, named after the mythical multi-headed snake that Heracles defeated.
- In China, people have fished for jellyfish for more than 1,700 years, for food and medicine.

TYPES OF MEDUSOZOANS

POLYP

Tubelike animal with tentacles armed with nematocysts that surround its mouth opening.

EXOSKELETON

External protective structure used by some medusozoans.

There are three different types of medusozoans: polyps, medusae, and siphonophores (Figure 1). Let us explore each one!

Polyps are stuck to a surface. You can find them living on rocks, algae, piers, and boats. Typically, they live together and depend on one another to survive. Some polyps can create a structure like a knight's armor on the outsides of their bodies. This is called an **exoskeleton** and it helps protect them from predators. For example, fire corals, a type

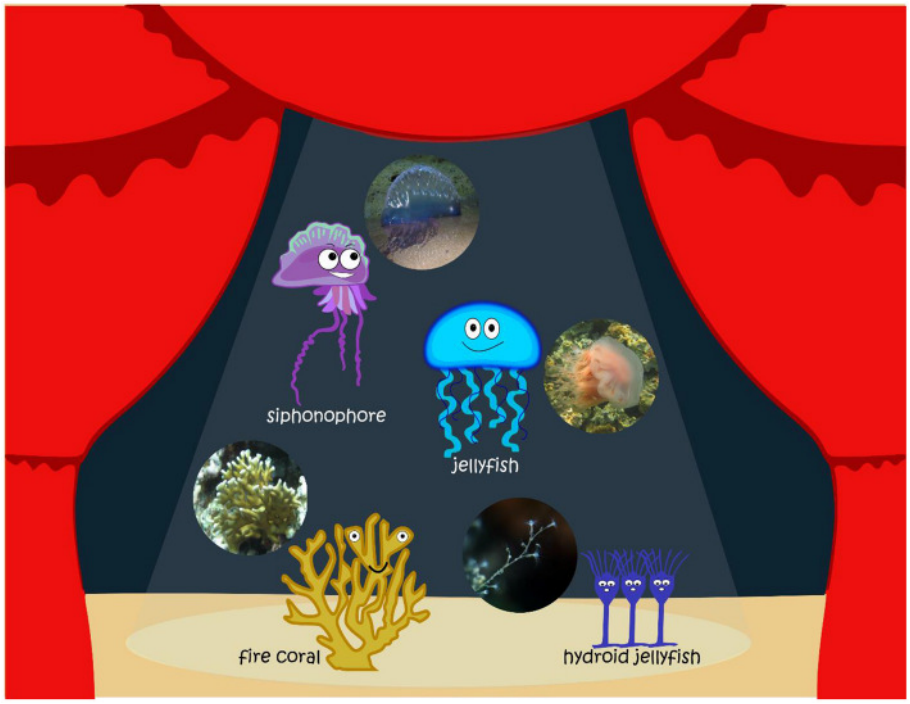

Figure 1

Types of medusozoans. Hydroid jellyfish and fire coral are polyps and live attached to a surface. Generally, siphonophores and jellyfish (medusae) float below the surface of the ocean water at different depths. Despite being a siphonophore, the Portuguese man-of-war floats on the surface of the ocean water propelled by winds and ocean currents only! (Artwork: María A. Mendoza-Becerril. Photograph credits: siphonophore and jellyfish, Vicencio de la Cruz Francisco; hydroid jellyfish, Isaí Domínguez Guerrero; fire coral, Axel Guillermo Castañon Gheno/CC BY-NC 4.0[1]).

[1] See https://www.inaturalist.org/photos/2529156

of polyp, build enormous, beautiful, branching exoskeletons. Many people are tempted to break off pieces for souvenirs when diving or snorkeling, but this is a bad idea. Some people are sensitive to the fire coral's sting, which gives them pain similar to getting burned. Another type of polyp, called a hydroid jellyfish, is small and resembles a fork. Its head and body resemble a fork's handle, while its tentacles resemble the prongs.

Medusae are known as jellyfish, and they look like umbrellas—that is what scientists call their bodies. Their bodies are made of a gelatinous substance called **mesoglea**. Jellyfish swim either just using the movement of the ocean water or by flexing their umbrellas and squeezing water out behind them.

Siphonophores are some of the most fascinating living things in the entire animal kingdom. They are a complex mix of polyps and jellyfish, and they come in a wide variety of shapes and sizes. Each siphonophore is actually a colony containing many polyps and jellyfish. Due to this physical feature, siphonophores are called string jellyfish, or chain jellyfish. The best-known siphonophore is the Portuguese man-of-war. Its body has a purple-blue balloon-like appearance with many tentacles. Sometimes one or more of a Portuguese man-of-war's tentacles break off from the colony. Be careful—the broken-off tentacles can still sting as they drift around.

MEDUSA

The name used by scientists when referring to jellyfish.

MESOGLEA

Clear gelatinous substance found in jellyfish and siphonophores.

SIPHONOPHORE

The name used by scientits when referring to string jellyfish.

NEMATOCYST

Stinging cell of the tentacles of medusozoans.

HOW AND WHY DO MEDUSOZOANS STING?

Regardless of their shape and size, all medusozoans sting. To do so, they use stinging cells called **nematocysts**. These stinging cells are tiny, hard, and balloon- or egg-shaped. Inside each nematocyst is a long, coiled, barbed harpoon. This harpoon sits in a mixture of toxic substances. The amount of toxins that each stinging cell has is small, but there are large numbers of stinging cells in medusozoans' tentacles.

Medusozoans use their stinging cells when they feel threatened, or to capture their food. But how does a medusozoan sting happen? Simple contact explodes their stinging cells. It is important to remember that medusozoans do not attack humans intentionally. Most stings occur when people touch them by accident, in or out of the water.

When you encounter a medusozoan while swimming or walking on the beach, you might accidentally touch its tentacles (Figure 2). At that moment, your skin contacts thousands of nematocysts, so thousands of tiny stings occur. These stings can cause a toxic effect that can even cause death on rare occasions. When a medusozoan stings you, your skin may turn red, and you may feel pain, itching, and intense burning. Sometimes symptoms include nausea, red welts on the skin, fever, vomiting, and a sensation of weakness. In the worst cases, the stings can cause shock, interfere with breathing, and result in drowning. Generally, the symptoms caused by stings disappear within hours or days, but they can leave scars. Stings are most often reported on the legs and chest [4].

WHAT SHOULD I DO IN CASE OF A STING?

If you or someone close to you suffers a medusozoan sting, follow these simple tips [5]. First, keep calm. Second, remove any visible tentacle remnants using an object, to avoid further direct contact with your skin. Third, rinse the affected area with lots of seawater. Never use freshwater (or pee!) to rinse the sting! Last, apply household vinegar to jellyfish stings or baking soda mixed with seawater to siphonophore stings [6].

In the past (and sometimes even today), people have commonly used pee to treat medusozoan stings. Thanks to movies and TV, pee is a famous treatment and is often said to be effective. In the last century, bathers carried a bottle of their own pee when they went to the beach! However, using pee to treat medusozoan stings is not a good treatment. First, pee can cause more nematocysts to explode. Second, pee can generate skin infections, particularly in more severe stings. Third, using pee is unpleasant, especially when stings occur on the face, neck, armpits, and groin.

Figure 2

Here you can see how a medusozoan stings and what you should do if you encounter medusozoans or get stung by one (Artwork: Ariadne Molina-Alonso).

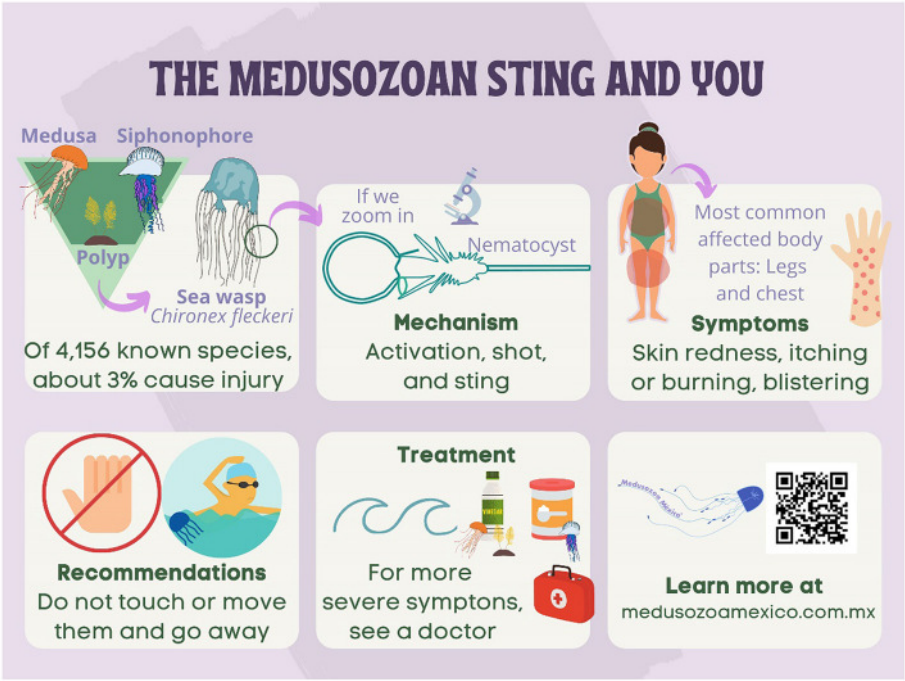

Figure 2

One way to avoid medusozoan stings is to wear protective clothing made of neoprene or nylon. If you see a medusozoan stranded on the beach, do not touch it! Even if it is dead, its stinging cells remain active and can still sting. Additionally, do not go to the beach on days after storms or strong winds, because this weather may carry medusozoans close to shore or onto the beach.

PAY ATTENTION TO THE SIGNS!

At least six countries are in the practice of warning bathers about the presence of medusozoans on beaches. This probably started in Australia, where warning signs that resemble yellow traffic signals are used. On some beaches these signs are up all the time, because those beaches are home to dangerous medusozoans, such as the sea wasp or the Portuguese man-of-war.

Flags are commonly used as signs on beaches. Flag use is common in Argentina, Israel, Mexico, Spain, and the United States. These flags come in various shapes and colors. For example, they may be rectangular, white, or purple and may have the name or drawing of the medusozoan to look out for (Figure 3).

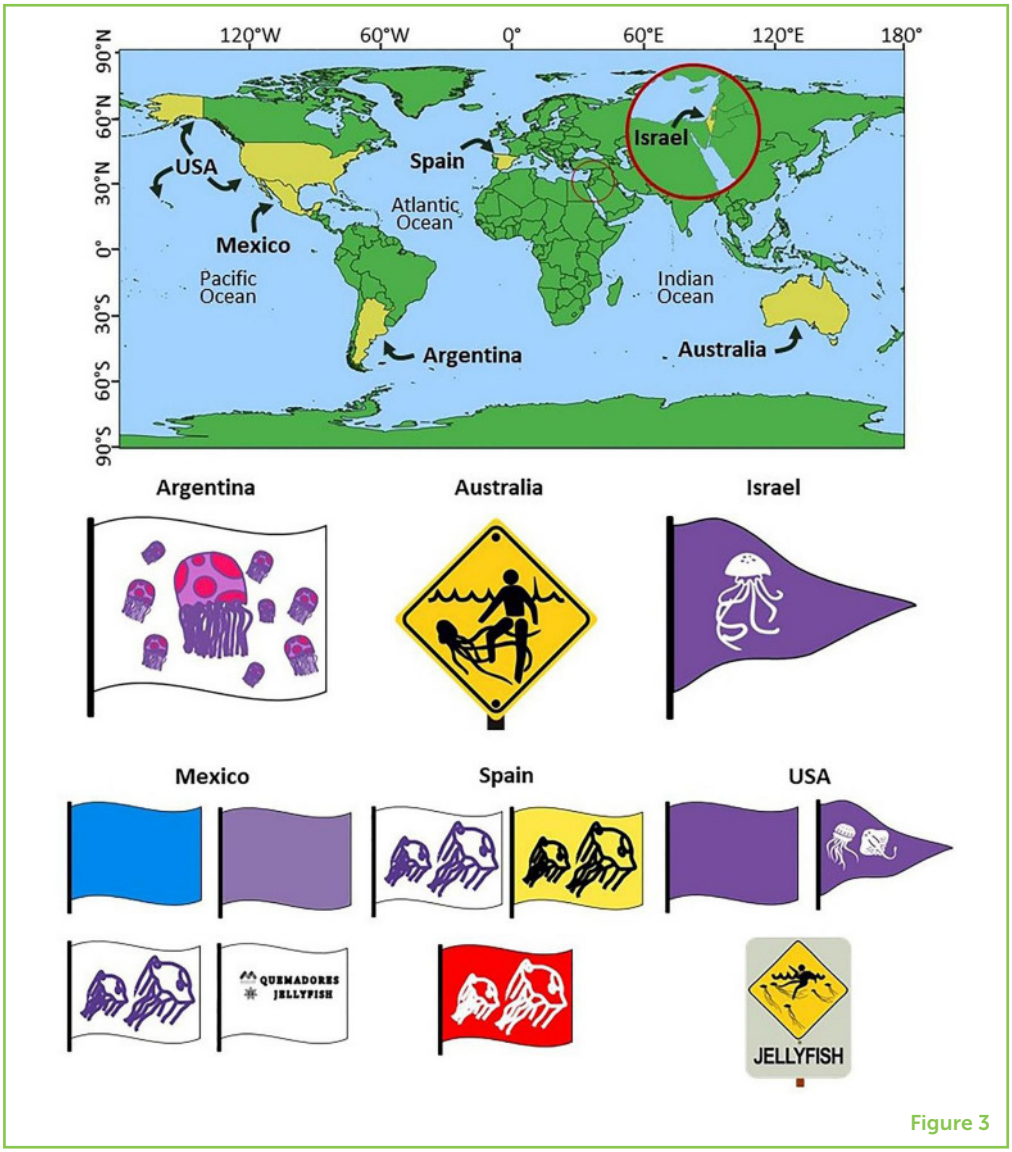

Figure 3

Warning signs to indicate the presence of dangerous medusozoans on beaches in Argentina, Australia, Israel, Mexico, Spain, and the United States (Artwork: Mariae C. Estrada-González).

To summarize, in this article you have learned what medusozoans are and why they sting. You also learned what to do to avoid or treat medusozoan stings. So now that you know more about medusozoans, you, your family, and your friends can enjoy a beach day and stay safe from medusozoan stings!

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YOUNG REVIEWER

MEHA, AGE: 15
Hey, I am a sophomore in high school, and looking forward to a career in medicine. My hobbies include drawing, tennis, and just hanging out with friends! I also love to volunteer and give back to my community. I am excited to be a part of Frontiers for Young Minds, as I want my peers and other students to be able to access these great scientific accomplishments made every day.

AUTHORS

JOSÉ AGÜERO

José Agüero, an independent science writer and communicator, has a bachelor of science from Zamorano University (Honduras) and did his graduate studies at the National Autonomous University of Mexico. His research and interest areas include how living beings function under stress conditions, and how to improve thermal comfort and energy use in buildings. He is also an active member of Medusozoa México and serves as the webmaster of the site.

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Mariae C. Estrada-González is a marine biologist from the Autonomous University of Baja California Sur. She is currently a graduate student at the Northwest Biological Research Center. Her research and interest areas involve the taxonomy, diversity, and ecology of medusozoans distributed in Mexican waters. She is an active member of Medusozoa México.

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Leonela Rosales-Catalán studied marine biology at the Autonomous University of Baja California Sur. Currently, she is an active member of Medusozoa México. Her area of interest is helping the public learn about science, particularly with regard to invasive species found within the Medusozoa group.

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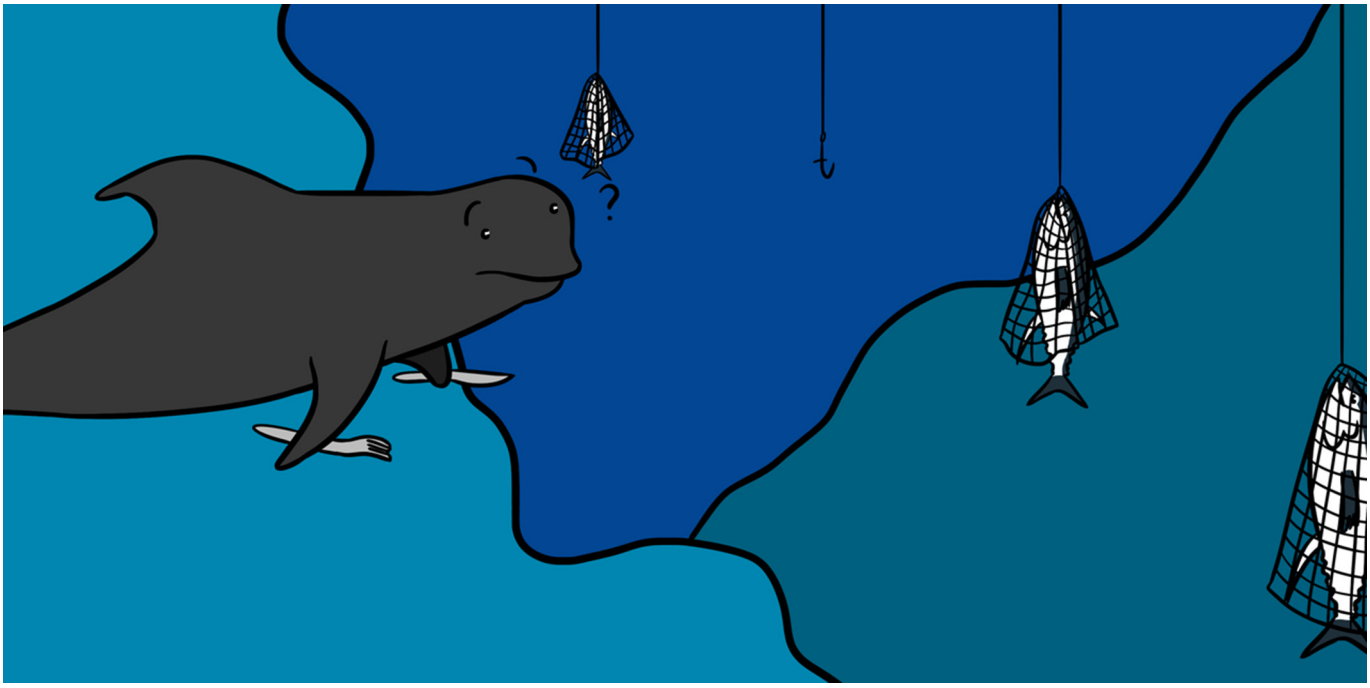

SHIELDING FISH TO PROTECT WHALES AND FISHERS INCOME

Njaratiana Rabearisoa[1,2*], *Alice Arnau*[3], *Manon Bodin*[3], *Constance Hanse*[3], *Marin Portalez*[3] and *Pascal Bach*[1,2]

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YOUNG REVIEWERS:

INTER-NATIONAL SCHOOL OF BERGEN
AGE: 8

MATÍAS
AGE: 16

SEBASTIAN
AGE: 12

Some toothed whale species have gotten used to stealing or damaging fish that have been captured by the fishing equipment of fishers. This stealing is called depredation, and it is a problem for both fishers and toothed whales in all the oceans of the world. Fishers lose their catch and must work harder, and the whales can get injured and forget how to hunt. It is important to develop a solution to prevent toothed whales from stealing fish captured by fishers. Our group of scientists is developing a system that can protect captured fish from being stolen. Basically, our innovation is like Spider-man© throwing a spiderweb over the fish, to hide them from toothed whales! In the near future, we are hopeful that this system will both help the fishers by protecting their catch and help to protect toothed whales.

WHAT IS DEPREDATION AND WHY IS IT A PROBLEM?

You probably already know that fish are an important part of the human food supply. But did you know that **toothed whales** have learned to steal fish from fishers in all the oceans of the world? When fish are captured in fishing gear, some species of toothed whales have gotten used to eating them before the fish are hauled onto the fishing boat. This is called **depredation**. Depredation by toothed whales happens frequently, and it is bad for both the toothed whales and the fishers [1, 2].

Why is depredation bad for toothed whales? Well, instead of hunting wild fish as they should naturally do, these whales would rather eat fish that have already been caught. By doing so, they save energy and easily get a large amount of nutritious food. Depredation can lead whales to forget their own natural hunting strategies, and they might lose the ability to obtain food by themselves. Toothed whales can also be injured by fishing gear—they can get entangled or hooked as they try to remove the fish. All marine mammal species are classified as endangered, and several laws exist to protect these species from human threats, including threats posed by the fishing industry. This is one reason depredation should be prevented.

In terms of the fishers, they cannot sell damaged fish, so to replace the fish lost to depredation, they must do more fishing! This is a waste of time and money because the fishers must use more fuel, deploy more hooks, invest more hours, and fix the equipment damaged by toothed whales. Depredation also has consequences for the total number of fish available to be harvested as human food. Fish are a limited resource. Depredated fish are not counted by the fishers and therefore are not reported in fishery statistics. Consequently, fishery scientists might incorrectly calculate how many fish are left to catch in the ocean (Figure 1).

TOOTHED WHALES

A group of marine mammals, including killer whales or dolphins, that have pointy teeth and feed on fish or squids.

DEPREDATION

The act of damaging or stealing plants or animals grown or bred by humans. For instance, coyotes or foxes sneaking into a farm to eat chickens is depredation.

Figure 1

Depredation affects toothed whales, fishers, and captured fish. Depredation changes the hunting strategies of toothed whales and these animals can also get injured when they try to steal the hooked fish. Fishers lose money and have to work harder to compensate for their damaged catch. Finally, depredation impacts fish species because, since depredated fish are not counted in fisheries statistics, the number of fish left to catch in the ocean is calculated incorrectly.

DRIFTING LONGLINE FISHING

A technique involving a floating mainline set in the ocean, with hundreds of vertical baited branchlines attached to it. This longline drifts for hours to catch fish.

MAINLINE

A horizontal fishing line set in the water and suspended at the surface thanks to large buoys attached at regular intervals. It can be as long as 150 km.

Figure 2

(A) A longliner sets a drifting longline to catch large fish. The mainline is suspended by buoys and the branchlines hang off of it, each one ending in a hook. A short-finned pilot whale is depredating a captured fish and leaves its head on the hook. **(B)** Drifting longlines target large fish, such as tuna and swordfish, which are mainly depredated by two toothed whale species: the false killer whale and the short-finned pilot whale.

BRANCHLINE

A vertical secondary line attached at regular intervals to the mainline, with a baited hook at its end. Fishers can set up to 3,000 branchlines on the same mainline to capture fish.

ECHOLOCATION

A hunting technique used by bats or marine mammals. They emit calls and they listen to their echoes. They use this technique to locate, identify, and hunt their prey.

WHAT KIND OF FISHING DO WE STUDY?

For our work, we focus on a fishing technique called **drifting longline fishing**. Fishers use this method to catch large fish such as tuna or swordfish in the ocean. They sail a type of boat called longliner and set a fishing line called a **mainline** in the water. This mainline is suspended at the surface thanks to large buoys attached at regular intervals. The mainline, which can be as long as 150 km, is attached to vertical secondary lines called **branchlines**, each one with a hook at its end. Each hook is baited with a squid or a mackerel. The branchlines are left to hang down in the water to attract and catch fish (Figure 2A). This entire fishing apparatus is called a longline. Fishers can set up to 3,000 hooks on the same longline. The longline is left to drift for about 6–7 h before being hauled onboard to harvest the captured fish.

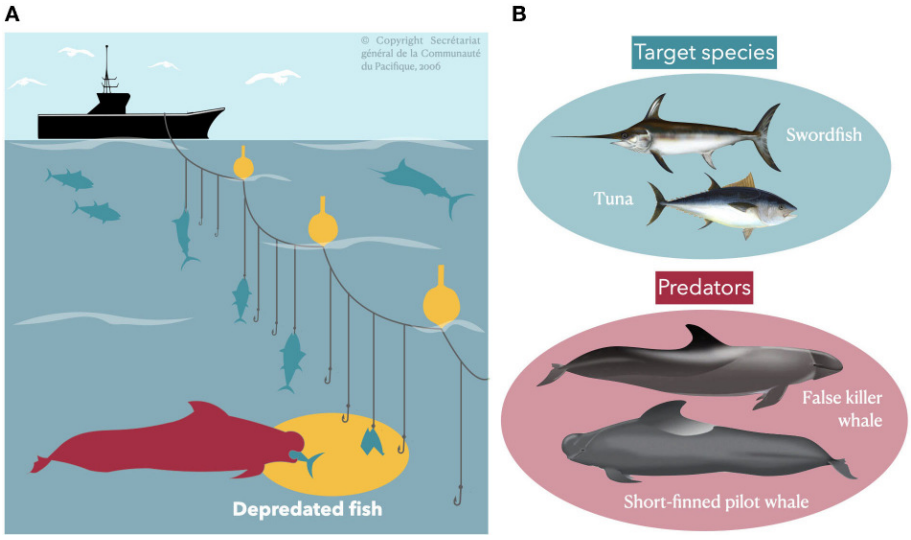

Figure 2

WHICH TOOTHED WHALES ENGAGE IN DEPREDATION?

In tropical waters, two species of toothed whales—the false killer whale and the short-finned pilot whale—are commonly involved in depredation of fish caught on longlines (Figure 2B). Can you guess how big tuna and swordfish captured by longliners are? Tuna can exceed one meter in length, and swordfish can measure 2–3 m in length. However, false killer whales and short-finned pilot whales can be up to 6 m long. When depredating a fish, they tear the flesh off, leaving only the fish's head on the hook (Figure 2A).

To locate and hunt their prey, toothed whales emit calls. Then, they listen to the echoes of those calls that bounce off the objects surrounding them. This technique is called **echolocation**. Toothed whales and other animals, like bats, use this hunting technique to locate and identify their prey, based on the specific echoes that return to them. Toothed whales use echolocation to spot the hooked fish,

and the noises of the boat in the distance also attract the whales. Since hooked fish cannot swim away, it is very easy for the whales to feed on them: it is like a ready-to-eat meal in an all-you-can-eat restaurant! It is *so* easy that toothed whales sometimes swim along the mainline and steal every single captured fish, making the fishers to feel desperate.

PARADEP: A POTENTIAL SOLUTION

So far, several techniques have been tested worldwide to decrease depredation, but none of them work very well [3–5]. We run a project called PARADEP[1], to find an innovative way to reduce depredation by toothed whales. The aim of the project is to design a shield that can hide and protect the captured fish. How does it work? First, picture Spider-man©: his super power allows him to shoot an adhesive spiderweb through a small barrel located on his wrist, right? Our device is similar to this barrel. Two protection nets (which look like Superman's© cape) are stored inside a small case. These cases are attached to the tops of every branchline. When the fish bites the bait and pulls on the hook, the case opens. Then, the protection nets are ejected, slide down the branchline, and wrap the fish up. Then the fish is protected by a shield, as if it were wearing an invisibility cloak. The net shield makes it harder for toothed whales to see and eat the fish, so the net avoids whales from depredating the fish until the line is hauled back onboard. This way, the fisher can harvest undamaged fish, even if toothed whales are swimming near the boat (Figure 3).

[1] https://paradep.com/en

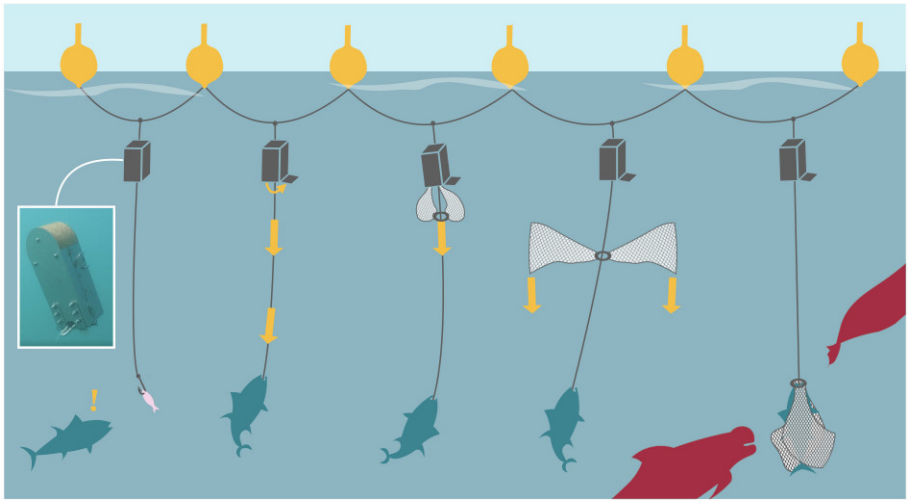

Figure 3

Figure 3

Our PARADEP system could decrease depredation. **(A)** The case (containing the nets) is set on top of the baited branchlines. **(B)** The case opens when the fish bites the bait and pulls on the branchline. **(C)** The nets exit the case, **(D)** slide down the branchline, and **(E)** wrap up the fish to protect it. Toothed whales are unable to depredate the protected fish and will swim away.

Our device will keep fishers from both losing income and working overtime to compensate for the loss of fish. The device is reusable, so it is environmentally friendly and economically attractive for fishers. It will also help protect the toothed whales, because it will reduce their risk of injury and they will have to use their natural hunting skills again.

TAKE-HOME MESSAGE

Depredation of fish caught by drifting longliners causes conflicts between fishers and toothed whales. This interaction needs to change, so that fishers and toothed whales can share the same feeding/fishing grounds without harming each other. By creating a shield around a hooked fish until it is hauled onboard, the PARADEP device may be the solution we are looking for, both for protecting toothed whales and preventing fish from being stolen. We are working with fishers because they want something to help them decrease depredation. They are playing an important role in testing the PARADEP device. After several months of PARADEP testing and collection of feedback from the fishers who are using it, we will know whether PARADEP works well-enough to help reduce depredation by toothed whales throughout the world's oceans.

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We thank the European Maritime and Fisheries Fund for funding the PARADEP project. The project was made possible due to the involvement of Auriane Serval, Chloé Yven, Marc Soria, Nicolas Guillon, Evgeny Romanov, and all those who took part in the fieldwork: thanks to all of them. Additionally, the authors would like to thank Yona Bodin for her feedback and her constructive comments. Our appreciation also goes to Pr Frédérique Carcaillet for her helpful comments to improve the manuscript. Finally, we are very grateful to the young reviewers, their mentors and the journal Editors for all their useful feedbacks.

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YOUNG REVIEWERS

INTERNATIONAL SCHOOL OF BERGEN, AGE: 8
The 8 graders at the International School of Bergen form a dynamic group with highly diverse international backgrounds. They are interested in learning the scientific method and sustainability, but also have a great artistic talent.

MATÍAS, AGE: 16
I love playing music and doing magic tricks, I like science and my favorite subject is physics.

SEBASTIAN, AGE: 12
I like sports, reading, math, animals, and the great outdoors!

AUTHORS

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Njaratiana Rabearisoa is a research engineer at the French Institute of Research for Sustainable Development. She has a Ph.D., in marine ecology. Her main research theme is the negative interactions between protected marine mammal

species and fisheries. She tries to understand when, where, and why negative interactions occur and how to prevent them. She likes traveling, photography, and diving. Since she was a kid, her favorite movies have been The Big Blue and Free Willy. She also grew up reading The Old Man and the Sea, by Ernest Hemingway. *njaratiana.rabearisoa@ird.fr

ALICE ARNAU

Alice Arnau is a master's student at the science faculty of the University of Montpellier. After graduation, she will work in the complex field of environmental management. She will especially dedicate herself to answering questions related to human coexistence with other living organisms (depredation being one of many examples).

MANON BODIN

Manon Bodin is a master's student at the science faculty of the University of Montpellier. She is willing to work in a field that allows her to link science and video games, so that everyone, including children, can learn to like biology.

CONSTANCE HANSE

Constance Hanse is a master's student at the science faculty of the University of Montpellier. She likes to share her knowledge and teach ecology and biology concepts in a way that makes them easy to understand.

MARIN PORTALEZ

Marin Portalez is a master's student at the science faculty of the University of Montpellier. He is majoring in scientific mediation and communication for school-aged audiences. He is passionate about science, especially about the biology and ecology of Mediterranean ecosystems. He is also interested in arts. He uses his skills in both science and arts to run several scientific projects.

PASCAL BACH

Pascal Bach is currently a researcher at the French Institute of Research for Sustainable Development. He has been working for 30 years as a fishery ecologist involved in research projects with scientific partners mainly based in the south west Indian Ocean. The theme of his research is ecosystem-based fishery management, and he is developing ways to decrease the negative impacts of fisheries on non-targeted species. He enjoys meeting the other people involved in fisheries management over a glass of wine, to make the discussions more pleasant.

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BIODIVERSITY
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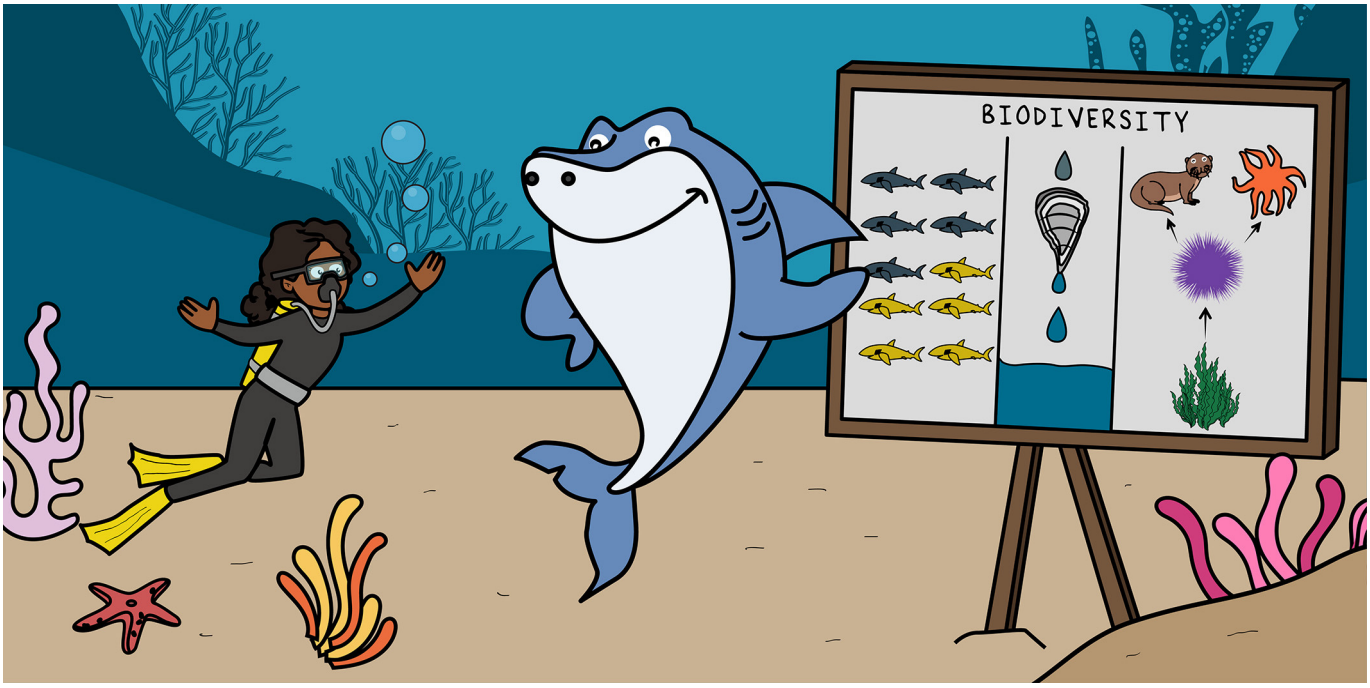

PROTECTING OUR OCEANS: WHY THE DEFINITION OF BIODIVERSITY MATTERS

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YOUNG REVIEWERS

SOMERSET ACADEMY PREP SUNSET

AGES: 10–11

Biodiversity is one of the most-used terms in biology, but there are many ways of measuring and interpreting it. Understanding the meaning of the different measures of biodiversity is vitally important for managing and conserving endangered ecosystems. Marine ecosystems are degrading quickly due to human impacts like overfishing, habitat destruction, or climate change. In this article, we introduce and explain three aspects of biodiversity: taxonomic, functional, and food web biodiversity. All three focus on individual species and their roles in ecosystems and food chains. Each aspect of biodiversity is useful in measuring or achieving conservation goals, depending on the type of habitat or environment that is considered. The examples we provide show that finding the best way to protect an ecosystem requires careful consideration of biodiversity from different perspectives, which will remain a challenge for current and future conservationists.

DEFINITIONS ARE IMPORTANT

Biodiversity is one of biology's most used keywords, but its definition can be challenging because it can mean different things in different contexts and to different scientists. There are many ways to think about biodiversity, but traditionally it describes the rich variety of life, including plants and animals. Defining the term biodiversity becomes important when **marine managers** consider how human impacts, such as climate change, pollution, or even deforestation, change ocean species and **ecosystems**, or how to conserve species and ecosystems in the face of human-made challenges. If marine managers want to set achievable conservation targets—for example protecting a coral reef—they need to consider *all* definitions of biodiversity [1]. In this article, we will explain several definitions of biodiversity and discuss how they influence conservation efforts.

BIODIVERSITY

The rich variety of life on earth, including animals, plants, fungi, and bacteria.

MARINE MANAGERS

People who are responsible for governing ocean or coastal areas for conservation.

ECOSYSTEM

All the various organisms, such as animals and plants, and the environment they live in.

PROTECTING MARINE ECOSYSTEMS

Marine ecosystems face serious impacts including overfishing, habitat destruction, pollution, and climate change. These impacts have resulted in the declines or extinctions of many marine species, as well as serious changes to the environments they inhabit. Of the 30,000 marine species the International Union for Conservation of Nature has assessed, one quarter (22%) are listed as critically endangered, endangered, or vulnerable. In marine ecosystems, species interact with each other in many ways, forming complex relationships that are dependent on one another. Changes in biodiversity can affect marine food chains, nutrient cycles, climate regulation, and even storm protection [2].

To deal with these challenges, marine managers have been creating and monitoring marine protected areas. These Marine Protected Areas (MPAs) can help to reverse biodiversity declines and help to boost ecosystem health. Properly managing a protected area depends on finding the most useful definition of biodiversity, given the conservation or monitoring goals. There are three broad ways of thinking about biodiversity: a species-focussed approach, which looks at the number of animals, a functional approach, which accounts for the roles species play in ecosystems, and a food-web approach, which considers predator-prey relationships. Each way of thinking about biodiversity has strengths and weaknesses.

TAXONOMIC BIODIVERSITY

Focusses on individual species of animals or plants, or the total number of species in an ecosystem. This is a classic way of considering biodiversity.

A SPECIES APPROACH: TAXONOMIC BIODIVERSITY

Defining biodiversity by the individual species present in an ecosystem—all life forms, from the smallest viruses to the largest mammals—is called **taxonomic biodiversity**. If we measure taxonomic biodiversity, we describe individual species of animals or plants,

the total number of species present in an environment, or how a single species changes between areas or over time. For example, a desert has low taxonomic biodiversity, because it contains very few species. In contrast, a coral reef can contain thousands of different animal and plant species, and thus has high taxonomic biodiversity. Taxonomic biodiversity is the most traditional way of thinking about biodiversity.

For example, marine managers have recently created areas in the open ocean that are closed to fishing. Some of these protected areas are larger than France! However, there are still questions about how species living in these areas benefit, especially the species that migrate large distances, such as turtles, marine mammals, or sharks. Gray reef sharks are a small species of shark that has been declining in numbers. Scientists can study these sharks by tagging them and then following their movements over time. This allows researchers to figure out whether the sharks stay within a protected area or if they must redraw the protected area's boundaries to better protect the species [3]. The shark example is a biodiversity approach that considers just a single species. Alternatively, scientists can consider whether protecting an area has results in changes to a wide variety of species. Increases in the numbers or abundance of species can provide researchers with evidence that a marine protected area is successful at protecting the biodiversity that it harbors.

ROLES IN AN ECOSYSTEM: FUNCTIONAL BIODIVERSITY

FUNCTIONAL BIODIVERSITY

Investigates the various roles or functions species can have in an ecosystem.

Functional biodiversity focuses on the roles or functions organisms have in an ecosystem and how these roles affect the way the ecosystem works. For example, imagine two rocky shore communities. In the first one, you might find three different species of barnacles. In the second community, you find one species of barnacle, a starfish, and an anemone. While both communities have the same number of species, the second community has species that are functionally quite different. The second community has higher functional biodiversity.

In general, a greater number of species allows an ecosystem to recover from disturbances, like coral bleaching or pollution, faster. This is often because of the roles or functions species have within the ecosystem. Functional diversity helps marine managers understand how the species in an ecosystem affect that ecosystem's ability to resist and recover from disturbances.

FUNCTIONAL TRAIT

A specific characteristic of an animal or plant, like its size or its shape. A functional trait impacts the role the animal or plant plays in its ecosystem.

We can measure functional diversity by looking at the characteristics, or **functional traits**, of a species. These might be differences in body shape, body size, diet, or behavior. Studying functional biodiversity helps scientists understand the role a species plays in the environment and helps them to measure whether multiple species do the same

thing in a community or whether a species is unique in its function. From a conservation perspective, marine managers want to ensure that an ecosystem has many species with different functions, as well as species that are performing similar functions. This way, if one species is lost, another will still perform the function, and this helps to ensure that the ecosystem can continue to function properly.

For example, the functionally important species in the Baltic Sea are algae, blue mussels, and seagrass (Figure 1). These species carry out a range of roles and are found on shallow, rocky, underwater islands or near sandy shores (Figure 1). These functionally important species provide important habitats for other species, form the basis of the food chain, and are often nursery grounds for fish. Conservation planning should therefore focus on these three critical species, since they support other species. Depending on where those species occur, marine managers can expand or redraw conservation maps to protect them. Therefore, functional diversity links species within ecosystems and helps us understand their roles and how we can best protect them [4].

Figure 1

Figure 1

Seagrasses are functionally important species because they provide habitats, food, and nursery grounds for many marine species. Because of its important function within the ecosystem, seagrass considered a key species that needs to be included when protected areas are planned. This figure shows a fan mussel found in a Mediterranean seagrass meadow. Fan mussels filter seawater to feed on small particles in the water [image credit: Arnaud Abadie (CC BY 2.0)].

FOOD WEB BIODIVERSITY

Focusses on how animals and plants interact through predator-prey relationships. Food web diversity considers food chains and food webs.

WHO EATS WHOM: FOOD WEB BIODIVERSITY

Food web biodiversity focuses on how animals and plants interact with each other through feeding relationships. For example, if food web biodiversity is high, then a predator, such as a gray seal, can feed on many different species of fish (its prey). If one fish species decreases in number, gray seals can feed on a range of other fish species and continue to thrive. To understand food web biodiversity, we need to understand how many species exist in each part of a food chain, and who eats whom. This information can help us understand how extinctions of one species might affect the whole ecosystem.

In marine kelp forests, for example, large kelp needs nutrients and light to grow. Kelp are the main food source for purple sea urchins, which

in turn are important in the diets of larger predators, such as sunflower starfish or sea otters. Sea otters were hunted in the nineteenth century, which caused purple sea urchin numbers to explode, as predators did not feed on them. In turn, the urchins decimated kelp forests and transformed the ecosystem to bare rock (Figure 2). More recently, researchers found that when numbers of sunflower starfish, another urchin predator, decreased, sea urchin numbers increased and decimated kelp forests again. When protected areas allow predators such as sea otters or starfish to become more numerous, these predators suppress the number of urchins, preventing the destruction of kelp forests [5].

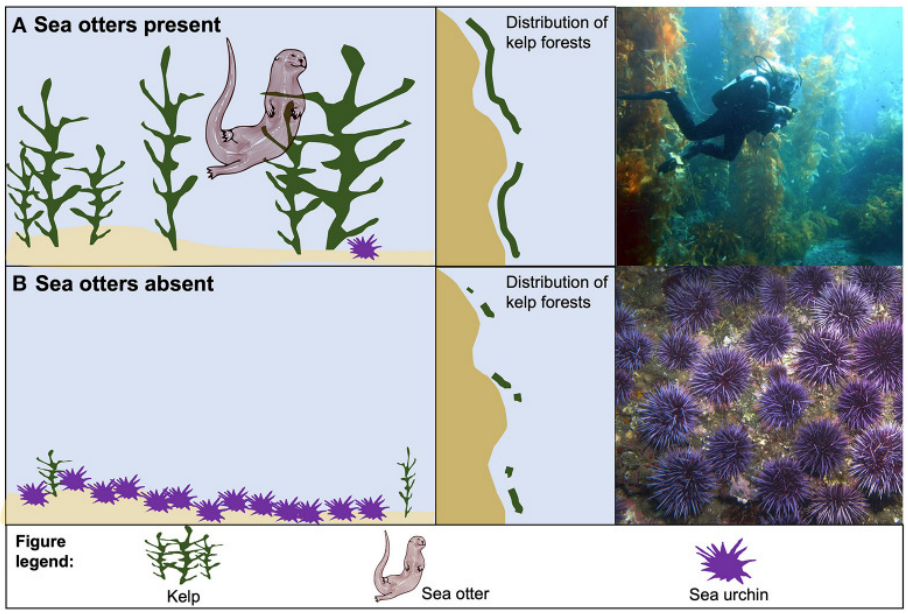

Figure 2

Figure 2

(A) When top predators (such as sea otters or starfish) are present, they keep purple urchin numbers under control by eating them, allowing kelp forests to grow. The picture of the diver shows how large these kelp forests can grow. Kelp forests provide many other animals with shelter and food. **(B)** If sea urchins are not eaten, they can increase in numbers and destroy kelp forests by grazing. This makes kelp forests much smaller or even completely destroys them, impacting the whole ecosystem [figure credits: Eric T. Gunther (CC BY-SA 3.0) and Ed Bierman (CC BY 2.0)].

This is just one example highlighting why food web biodiversity can help scientists better understand how species change over time. Conserving or restoring food web structure and food web biodiversity can have very large and positive management impacts.

CONCLUSION

There is no one right way to measure biodiversity in the marine environment. Instead, the definition of biodiversity depends on the specific area or the conservation target. Are managers looking to conserve a specific species, or to increase the total number of species? If so, then perhaps the taxonomic concept of biodiversity is best. Alternatively, researchers might choose to conserve an area based on the functional traits of species that are found there. If there are species that provide food and shelter for many other species, the functional approach might be the best. Finally, if we understand how species interact, and which species are the most important

in an area's food chains, managers might consider the food web approach to conserving biodiversity to be most useful. Finding the best management approach is not easy—it means scientists need to consider the best definition for biodiversity in any specific scenario. Such choices will continue challenging marine managers now and in the future, as they seek to protect ocean environments and the species that depend on them.

POSITION IN CURRENT LITERATURE

There is no one definition for the term biodiversity. However, if we want to achieve conservation goals or make sure we use the best possible species survey, we need to be clear how to define and interpret it. This paper introduces the classical definition of biodiversity as well as the advantage of considering other concepts. By focusing on marine conservation, we are giving examples of studies in which the different concepts have been applied recently. In the past, the success of a marine conservation project was measured by investigating changes in the number of species or the abundance of a specific species (the taxonomic approach). More recently, scientists and marine managers have considered a more comprehensive measurement of biodiversity: according to a communities' functional and food web biodiversity. Recent examples of these measures of biodiversity are given. In viewing biodiversity as more than just species, these ideas relating to the function and food chains serve as a starting point for understanding how ecosystems work, and how changes in them affect the services humans benefit from. This allows us to implement more successful conservation strategies that are designed for a specific habitat or ecosystem.

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YOUNG REVIEWERS

SOMERSET ACADEMY PREP SUNSET, AGES: 10–11

As the inaugural sixth grade class of Somerset Academy Prep we are excited to learn about all things science. Living in South Florida has really influenced our love for marine biology and the biodiversity in our ecosystems. Participating in different STEM activities is our JAM! We love to work as a team and inquire about the world around us. We feel lucky to collaborate together to review this article and hope to participate in more in the future.

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Lydia is an ecologist trying to understand the rules that make ecosystems work. In her work, she investigates how human disturbances, such as climate change, invasive species, or pollution, affect ecosystems and the species in them. To answer these questions, Lydia analyses observations and conducts experiments in different habitats, including coral reefs, mudflats, saltmarshes, and, more recently, microbial communities. *lydia.bach@gla.ac.uk

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Mark is an ecologist working on the drivers of biodiversity change. He uses food webs to consider how biodiversity changes affect the way that ecosystems work and function. Whilst he works in marine systems, he looks to see whether the rules that underpin these systems also apply to terrestrial and freshwater ecosystems. He uses a mixture of experiments and mathematical models to help understand how ecosystems work.

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EARTH AND ITS RESOURCES
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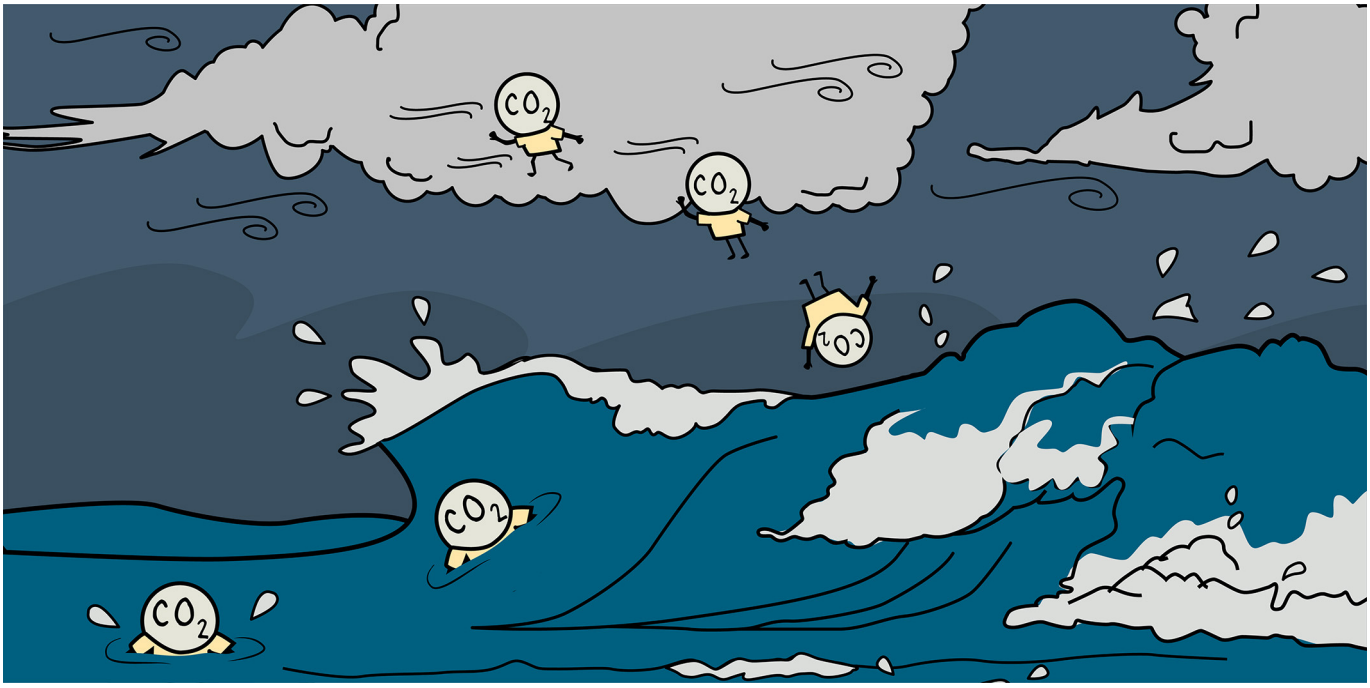

HOW MUCH CARBON DIOXIDE GOES FROM THE AIR INTO THE OCEANS?

Leonie Esters[1*] *and Brian Ward*[2]

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YOUNG REVIEWERS:

FDR-HB_ PERU IGEM TEAM
AGES: 14–17

JADE
AGE: 8

Climate change is occurring today because of a buildup of carbon dioxide (CO_2) in the atmosphere. This buildup of CO_2 is mostly from burning fossil fuels for our energy needs. The oceans take up and store a lot of CO_2 from the atmosphere. To know how much CO_2 the oceans take up, we must understand the processes involved. These processes include the mixing of ocean water. Turbulent mixing is a fast and effective way to mix up ocean water, and it happens when for example wind blows over the ocean and creates waves. However, it is difficult to measure turbulent mixing close to the ocean surface. In this article, we describe how we overcame this problem and how we used our measurements to learn about the exchange of carbon dioxide between the atmosphere and the oceans.

THE ROLE OF THE OCEANS IN A CHANGING CLIMATE

CLIMATE CHANGE

A change in the patterns of the weather conditions over a long time, for example an increase in the global temperature over a long time period.

GREENHOUSE GASES

Gases in the atmosphere that absorb and emit heat energy, increasing the temperature at the Earth's surface.

CARBON DIOXIDE (CO_2)

A gas that occurs naturally in Earth's atmosphere. It is also emitted by burning of fossil fuels. It is the most significant greenhouse gas in Earth's atmosphere.

DIFFUSION

The movement of particles from an area of higher concentration to an area of lower concentration, continuing until a balance is reached.

Rapid **climate change** is a major environmental problem of our times. This climate change is human-made: release of **greenhouse gases** from cars, power plants, and other man-made sources increases the concentration of **carbon dioxide (CO_2)**—one of the main greenhouse gases—in the atmosphere. The CO_2 concentration in the atmosphere has currently reached its highest level in more than 600,000 years. Greenhouse gases in the atmosphere trap some of the energy that would otherwise escape into space, and they reflect that energy back to the Earth. This process increases the overall temperature at the Earth's surface. The greenhouse effect is actually a good thing because it keeps the Earth's average temperature at +15 °C instead of −18°C. The problem is that, currently, the concentration of greenhouse gases in the atmosphere is too high, and this has an enormous impact on our climate.

The oceans also play a role in climate change. An increase in CO_2 has also been observed in the oceans. This is a direct effect of the rising atmospheric concentrations of CO_2. The oceans absorb CO_2 from the atmosphere in an attempt to balance out CO_2 concentrations (nature loves balance). Think of a teabag in a bowl of hot water (Figure 1). The tea spreads from the high concentration in the bag to a lower concentration in the bowl. This process is called **diffusion**. In our real-world example, the atmosphere contains more CO_2 than the oceans do. Thus, the CO_2 diffuses into the oceans. The oceans absorb CO_2 as long as the concentration of CO_2 in the atmosphere is higher than in it is in the oceans. When we burn more fossil fuels, more CO_2 is released into the atmosphere, and thus the oceans absorb more CO_2. The oceans cover two-thirds of the Earth's surface, so they can accumulate and store a large amount of atmospheric CO_2. We are very interested in understanding how the oceans absorb CO_2. This knowledge can help scientists to predict Earth's future climate.

Figure 1

When a teabag is placed into a bowl of hot water, the tea diffuses from an area of high concentration (the bag) into an area of lower concentration (the water).

OCEAN TURBULENCE AND HOW TO MEASURE IT

TURBULENCE

An irregular motion of air or water that is characterized by up-and-down currents.

The diffusion of gases between the atmosphere and the oceans is very slow. The tea from the teabag needs some time to spread through our bowl of water. However, you might have experienced that you can speed up the process by stirring the water with a spoon. Stirring creates **turbulence** in the water. Turbulence is an irregular motion of the water, and it causes faster and more efficient in spreading of the tea than does diffusion alone. The same happens at the interface between the atmosphere and the oceans. The CO_2 uptake through diffusion is very slow, but when the ocean water is turbulent, this process is much faster. This means that the amount of turbulence determines the speed at which gases are exchanged between the atmosphere and the oceans. When there are many breaking waves and whitecaps, the gases exchange faster than when the oceans are calm (Figure 2).

How do we know how much CO_2 goes into the oceans? Through careful analysis! We need to understand the processes involved in gas exchange between the oceans and the atmosphere so that we can help to solve our planet's climate crisis. Measuring ocean turbulence is difficult, especially close to the ocean surface. There are several instruments used to measure turbulence. Typically, scientists go out on ships and set the instruments into the ocean water. The scientists do not want to lose their instruments or the data that the instruments collect, so they tie the instruments to the ship with ropes and cables. However, this causes a major problem: when the instruments measure turbulence close to the ocean's surface, they are actually measuring the turbulence created by the ship's propeller. This is not the natural turbulence that we are interested in! Due to this problem, existing theories about how ocean turbulence drives gas exchange cannot be proven. Such theories were previously tested only in laboratories, lakes, and coastal regions. In these water bodies, it is easier to perform turbulence measurements than it is in the open oceans.

HOW CAN WE SOLVE THE PROBLEM OF MEASURING TURBULENCE?

To overcome the problem caused by a ship's propeller, there are several approaches for measuring turbulence close to the ocean

Figure 2

Turbulent and calm sea conditions create different rates of gas exchange between the atmosphere and the oceans.

Figure 2

surface. These approaches include buoys that drift freely on the ocean surface [1] or methods that involve a special type of images of the ocean surface [2]. Another way to measure turbulence close to the surface is called the **air-sea interaction profiler (ASIP)** [3]. ASIP was developed by Brian Ward (an author of this article) to focus on what is happening at the air-sea interface. ASIP can be set into the ocean without being connected to the ship—we just put it into the ocean and then move the ship out of the area (Figure 3). Once it is in the water, ASIP is pulled from the surface down to a pre-defined depth (a maximum of 100 meters) by a set of thrusters on its lower end (Figure 3A). The thrusters turn off once the intended depth is reached. ASIP will then rise right back to the ocean surface under its own lifting force, like when you press a floating object under water and then it rises again. As it rises, ASIP measures the **water shear**, which is created when the water particles move with different speed. We can use water shear to estimate the level of turbulence. ASIP is designed to measure as it rises, so that the turbulence created by the thrusters does not disturb the measurement. The thrusters and sensors on ASIP are powered by an internal battery. Since the thrusters use the most energy, the number of dives and their depths determine how long ASIP can conduct measurements. The battery lifetime allows for roughly 6,000 meters of total measuring, for example, ~60 measurements from 100 meters deep. Of course, we do not want to lose the profiler in the ocean, so it is equipped with a **global positioning system (GPS)** that sends its exact position to a satellite (like the navigation apps on mobile phones) each time ASIP reaches the ocean's surface. We receive the position from the satellite, so we can pick up ASIP whenever we want. All the data are stored inside ASIP, and we can download that data when ASIP is recovered.

AIR-SEA INTERACTION PROFILER (ASIP)

Instrument to measure among others turbulence close in the uppermost 100 meters of the ocean.

WATER SHEAR

Shear is created when water particles that touch each other move with different speed.

GLOBAL POSITIONING SYSTEM (GPS)

A system that uses signals from satellites to determine a location on the Earth's surface.

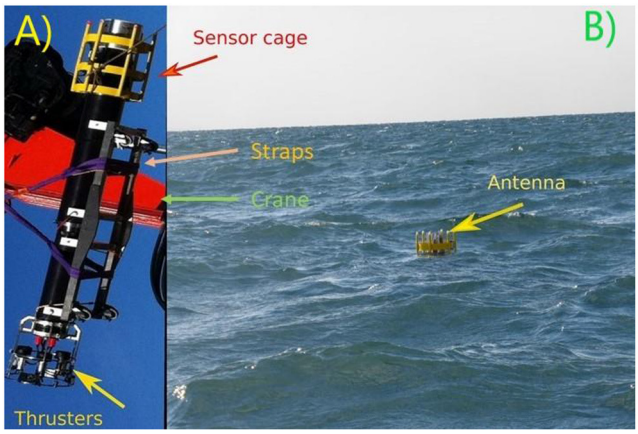

Figure 3

The air-sea interaction profiler (ASIP). **(A)** ASIP hanging on a crane, with its thrusters visible. **(B)** ASIP in the ocean, with only the sensor cage above the water.

OUR FINDINGS IN THE OPEN OCEAN

For our study, we used ASIP in the Atlantic Ocean, from a research vessel called Knorr. We started in Woods Hole (USA) in late June of 2012 and returned in the middle of July. During the cruise we measured ocean turbulence with ASIP. We also measured the levels of atmospheric and oceanic CO_2 using instruments installed on the ship. From our measurements we showed, for the first time in the open ocean, that ocean turbulence speeds up air-sea gas exchange.

Using ASIP's measurements, we showed that the turbulence near the ocean surface could explain CO_2 exchange well. The data also allowed us to improve existing theories. For example, we could use the data to improve the description of surface roughness, which tells us how flat or wavy the ocean surface is. Scientists used to believe that the ocean surface was always completely wavy, but sometimes it is rather flat, like when there is no wind or when there is an oily film on the surface.

Our results are important because they provide an accurate description of the CO_2 exchange between the atmosphere and the oceans. These data can help scientists to predict Earth's future climate as accurately as possible, which could help people to prepare for the effects that for example warmer temperatures cause. Such effects can be droughts or extreme heats in summer. Also, the predictions can help to convince people to consume less CO_2 and avoid an even further increase of the global temperature.

ORIGINAL SOURCE ARTICLE

Esters, L., Landwehr, S., Sutherland, G., Bell, T. G., Christensen, K. H., Saltzman, E. S., et al. 2017. Parameterizing air-sea gas transfer velocity with dissipation. *J. Geophys. Res. Oceans* 122:3041–56. doi: 10.1002/2016JC012088

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3. ten Doeschate, A., Sutherland, G., Esters, L., Wain, D., Walesby, K., and Ward, B. 2017. ASIP: profiling the upper ocean. *Oceanography* 30:33–5. doi: 10.5670/oceanog.2017.216

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YOUNG REVIEWERS

FDR-HB_PERU IGEM TEAM, AGES: 14–17
We are a synthetic biology team with the international Genetically Engineered Machine (iGEM) in Lima, Peru. We are the only high school team in Latin America and are proud of our work with creating a detector for cadmium using bacteria. Most of us are second language learners and the age range of our group is 14–17 years old. We love GMOs!

JADE, AGE: 8
My favorite subject at school is reading and I think I want to be an editor when I grow up. I love following rules. My favorite books are the Cam Jansen mysteries and "My Weird School". I like to ride my bike on sunny days and play games with my mom on cold days. I like cooking, playing with my sister, playing musical instruments, gymnastics, and swimming in heated pools.

AUTHORS

LEONIE ESTERS
Dr. Leonie Esters is a physical oceanographer who is particularly interested in small-scale ocean turbulence and air-sea gas exchange. Currently, Leonie works at in the Meteorological Group at Uppsala University in Sweden. Here, she investigates the influence of turbulence in lakes and the Baltic Sea on the air-water exchange of carbon dioxide and methane, based on direct observations. *leonie.esters@geo.uu.se

BRIAN WARD

Dr. Brian Ward is director of the research group called the Air-Sea Laboratory, within the School of Physics at NUI, Galway in Ireland. He received a Marie Curie Postdoctoral Fellowship to pursue research in Norway immediately upon completion of a PhD in oceanography. Subsequently he moved to the USA, where he spent 15 months in a federal laboratory, 4 years at the Woods Hole Oceanographic Institution, and 2 years as assistant professor at Old Dominion University in Norfolk, Virginia. He has been a lecturer at NUIG for the past 12 years and pursues research into small-scale processes controlling air-sea exchange. He designed and built the ASIP profiling instrument, which is the primary tool described in this article.

frontiers FOR YOUNG MINDS

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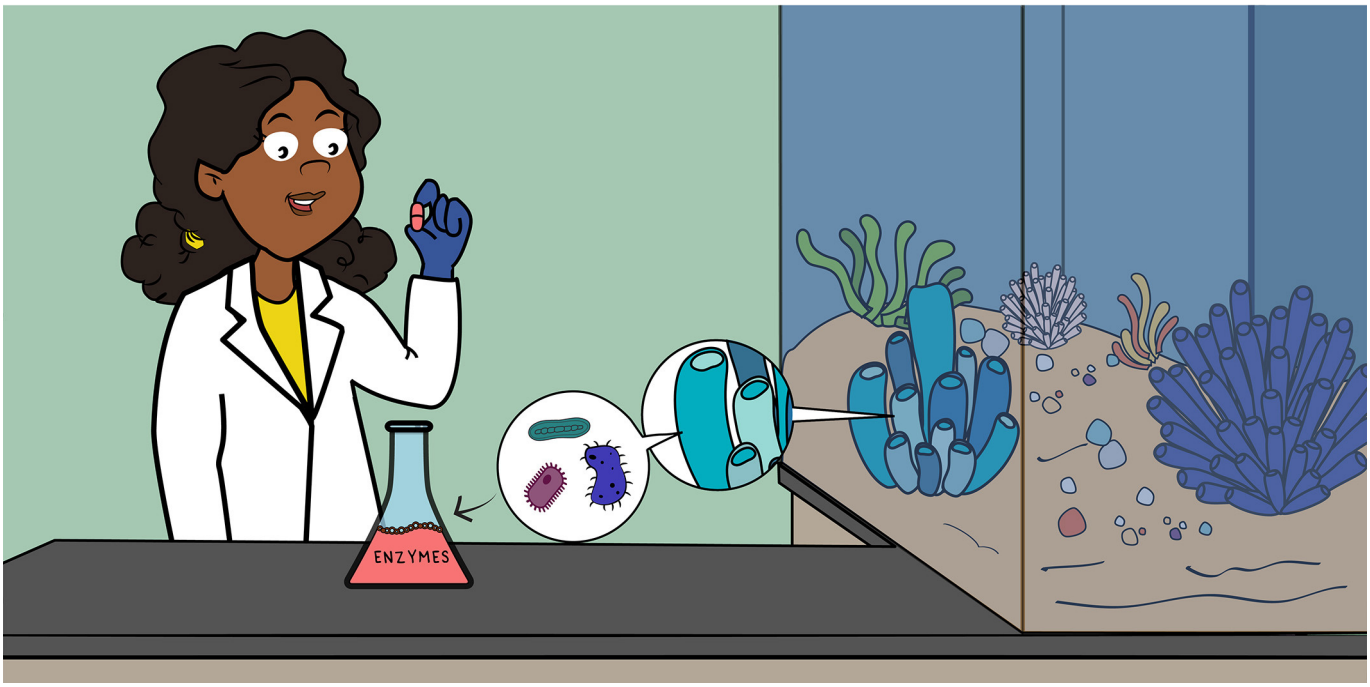

HOW CAN THE MICROORGANISMS LIVING IN MARINE SPONGES HELP US?

Beatriz de Carvalho Ribeiro [1], ***Isabelle Rodrigues Lopes*** [1], ***Bruno Francesco Rodrigues de Oliveira*** [1,2*] ***and Marinella Silva Laport*** [1]

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YOUNG REVIEWER:

TOTORO

AGE: 12

Enzymes are important molecules that help chemical reactions in living beings happen faster and easier. Did you know that enzymes are present in many products used in our daily lives? Enzymes are present in detergents, in our pets' food and in our own food. Sponges that live in the oceans need help from enzymes, too. Microscopic organisms make their homes on marine sponges, and these microbial partners produce enzymes that help the sponges with nutrient digestion! These useful enzymes can also be used by humans in the food industry, such as in the production of bread and cheese, as well as in detergents and cleaning pollutants. In this article, we will explore the enzymes produced by microorganisms living within marine sponges and describe some ways that these enzymes can be used in industry.

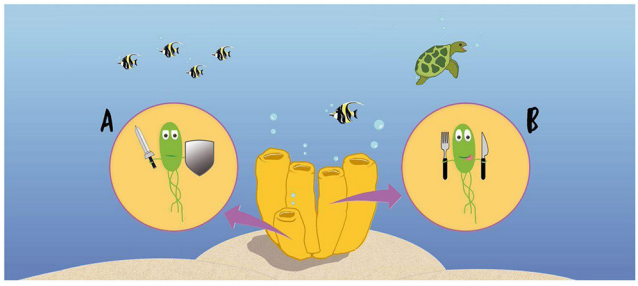

Figure 1

Figure 1

Sponge-microorganism friendship. **(A)** Bacterial partners can help the sponge defend itself against competitor animals, such as fishes and turtles. **(B)** As a "thank-you," the sponge provides a nutritional "banquet" for its microscopic partners.

A FEW FACTS ABOUT SPONGES

When you hear the word "sponge," what comes to your mind? Probably the sponge you use for dishwashing or the one you use while bathing, right? These are artificial sponges, made of synthetic materials. In the past, we used sponges from the ocean, called marine sponges, for these common tasks.

Marine sponges are **invertebrate** animals, meaning that they do not have a spine or skull. Some sponges live fixed to the ocean sediment or to the surfaces of rocks and never move during their lifetimes. Sponges can be of different shapes, sizes, and colors [1]. These animals can inhabit the deep sea, where there is little to no light, or they can live in shallower regions that are more exposed to sunlight.

INVERTEBRATE

Animals that are characterized by the absence of a spine and skull. Marine sponges and octopuses are examples of invertebrate animals.

Did you know that sponges feed by **filtration**? Instead of mouths, they have small holes called pores spread over their bodies. These holes allow water to enter, move to the inside of the sponge, and then exit through an opening in the top of the sponge. As the water travels through their bodies, the sponges absorb oxygen and other nutrients dissolved in the water.

FILTRATION

Process of obtaining oxygen and nutrients through the entry of seawater that circulates through the sponge body and exits through the upper opening.

DO SPONGES LIVE ALONE?

While a sponge may appear to be living alone attached to its rock or the ocean bottom, it is not alone! Invisible to the naked eye, microscopic organisms live inside sponges. These microorganisms include bacteria, archaea, fungi, and viruses, and they perform important jobs for the sponges, including helping them with nutrient digestion and producing vitamins that are crucial for the sponges' diets. The microorganisms also release defensive substances that protect sponges against natural predators, competitors, and harmful microorganisms (Figure 1A) [1].

What do the sponges' microscopic buddies receive in exchange for this help? It has been estimated that a 1 kg sponge can filter up to 24,000 liters of water per day! Because of this large volume of water, sponges accumulate more nutrients in their bodies than they need.

This plentiful food helps the microorganisms within the sponges to produce their helpful substances (Figure 1B).

WHAT ARE ENZYMES?

ENZYMES

Special proteins that make chemical reactions happen faster.

Did you know that microorganisms, plants, and people all have something in common? They all produce substances called **enzymes**. Enzymes are special molecules that make chemical reactions happen faster. The job of some enzymes is to break down large molecules into smaller pieces. The enzymes produced by the microorganisms living inside sponges are what allow these microorganisms to perform their helpful activities, like breaking down large nutrients into vitamins and other substances that the sponges can easily absorb!

Scientists have discovered that the enzymes produced by sponge microorganisms not only benefit the sponges—they can be extremely helpful to humans, too! Humans have found many uses for these microbial enzymes. Microbial enzymes have some advantages over plant and animal enzymes. First, microorganisms produce enzymes in large quantities, and it does not take much time or space to grow microorganisms in the lab. Also, enzymes from microorganisms can be active and stable under harsh conditions. Finally, microbial enzymes are not toxic to humans [2].

HOW ARE ENZYMES USED?

The use of microbial enzymes in industrial processes has received increasing attention over the past few years. This is because using these enzymes can reduce waste and cause less damage to the environment.

AMYLASE

Amylase is an enzyme that is capable of breaking starch into smaller bits. This enzyme is also present in the saliva of humans, where it starts the process of digestion.

Did you know that enzymes are used to create many of the products we encounter in our daily lives? For example, they are used in the production of animal food, medicines, detergents, and paper [3]. **Amylase** is one type of enzyme that is frequently used in industry, because it can break down starch, which is a large, complex sugar, into smaller, more useable bits. In bread baking, amylase helps the dough to rise, which creates bread that is easier to chew and that lasts longer on our kitchen shelves [2].

LIPASE

Lipase is an enzyme which function is to turn the fat in smaller molecules. This enzyme plays essential roles in digestion of lipids in living organisms.

Lipase is another interesting enzyme. It works by breaking down fat molecules called lipids. Some factories just throw away lipids, which are hard to break down or wash off. Lipase can help to clean up these oily pollutants [2]. In the food industry, lipase digests the fat in cheese, which can make some cheeses more delicious and help them to keep their nice aromas and tasty flavors longer.

Figure 2

Scientists find promising enzymes produced by the microorganisms living in marine sponges. They must decide what the enzymes would be best used for, as microbial enzymes can help with manufacturing detergents, production of cheeses, and much more!

There has only been a small amount of research done on enzymes that come from the microorganisms living in marine sponges. The microbial enzymes that have been studied so far are potentially very useful. They have been isolated from sponges living in some of the most extreme marine environments (Figure 2) [3].

In 2017, a new enzyme called **esterase** was discovered, which is produced by a bacterium living in a sponge 760 m deep [4]! This enzyme is active in the presence of high amounts of salt, relatively high pH (8–10) and at low temperatures (4–20°C). How could we use this enzyme? Esterase could be used to make detergents that are good for washing things in cold water. These "cold detergents" are ideal for removing stains like blood and sweat.

ESTERASE

Esterase is an enzyme that helps break down smaller and simpler fat molecules.

In 2018, a new enzyme called a **protease** was identified in the **archaea** *Halococcus* [5]. Isolated from an Indian sponge, *Halococcus* is known to love salt. The protease breaks down proteins into smaller pieces, and it was found to have its greatest activity when it was in a solution three times saltier than seawater! Surprisingly, the protease was most active at 70–80°C, so this incredible enzyme could be ideal for processes that depend on high temperatures [5]. In the leather industry, this protease could remove the hair from animal hides, decreasing the use of toxic chemicals that are normally released into the environment. In the baking industry, this protease also could help to make low-gluten flour for people who need to eat a gluten-free diet [5].

PROTEASE

Protease is an enzyme that speeds up the reaction of breaking proteins in smaller pieces and it is present in plants, human beings and microorganisms.

ARCHAEA

Microorganisms that live in extreme habitats, including thermal cracks at 100°C and the digestive tracts of cows.

CONCLUSION

So now you know that marine sponges are invertebrate animals and do not live alone. Microscopic partners live inside sponges, with mutual collaboration between them. Furthermore, these microorganisms have adapted to the marine environment, developing unique molecule-breaking capabilities. Therefore, marine microbial enzymes are adapted to extreme conditions such as high or low temperatures, high pressures, high salinity, and a wide pH range. These characteristics mean that enzymes can be used to make certain industrial processes greener and cheaper. Despite these great qualities, there is still not

much research being done on these enzymes [2]. Enzymes produced by microorganisms that live in sponges must be studied in more detail, so that the most important uses can be identified for the benefit of man and the planet!

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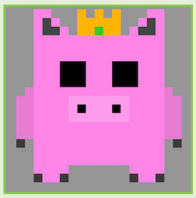
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER



TOTORO, AGE: 12

Hi! I like to get creative and work on cool projects. Sometimes, I do a bit of experimentation or some DIY. When I do science, it makes me feel more creative, and I hope you do too. So, you could also get your brain working, enjoy and be creative!

AUTHORS

BEATRIZ DE CARVALHO RIBEIRO

I have been a bachelor's degree student in biological sciences (microbiology and immunology) at the Universidade Federal do Rio de Janeiro (UFRJ) since 2019. I have always admired the microscopic world and the marine environment. I found a laboratory that brought all these fascinations together, and today I am part of the Molecular and Marine Bacteriology Laboratory at UFRJ. My current line of research is on enzymes produced by bacteria associated with marine sponges and how these enzymes can be used in industries.

ISABELLE RODRIGUES LOPES

Since I was a child, I have always liked nature and science. In 2017, I started studying microbiology and immunology at the Universidade Federal do Rio de Janeiro (UFRJ), and I am part of the Molecular and Marine Bacteriology Laboratory. I research the incredible world of marine sponges and their associated bacteria, more specifically the enzymes they produce and their industrial and biotechnological applications. I intend to discover new enzymes that help the world in some way!

BRUNO FRANCESCO RODRIGUES DE OLIVEIRA

I just completed my Ph.D. in microbiology at the Universidade Federal do Rio de Janeiro (UFRJ), with a part-time stay at the University College Cork (2020). My fascination with marine microbiology started while I was finishing my master's degree. I was astonished by the infinity of biologically active substances to be discovered in the microbial life of oceanic ecosystems. From then on, I have dedicated myself to understanding the tiny fellows thriving in incredible marine sponges, and how we can harness their genomes to find new, useful industrial enzymes. *bfroliveira@id.uff.br

MARINELLA SILVA LAPORT

I obtained a bachelor's degree in biomedicine (1996) at the Universidade Federal do Estado do Rio de Janeiro, and a Ph.D. degree (2003) at the Universidade Federal do Rio de Janeiro (UFRJ). I did postdoctoral studies at the FioCruz (2004) and at the Université Libre de Bruxelles (2012–2014). I have been an associate professor at the UFRJ since 2004. Currently, I develop and coordinate research activities in the Molecular and Marine Bacteriology Laboratory at the UFRJ. My research focuses on symbioses of microorganisms with sponges and the exploration of microbial metabolic diversity for biotechnological purposes.

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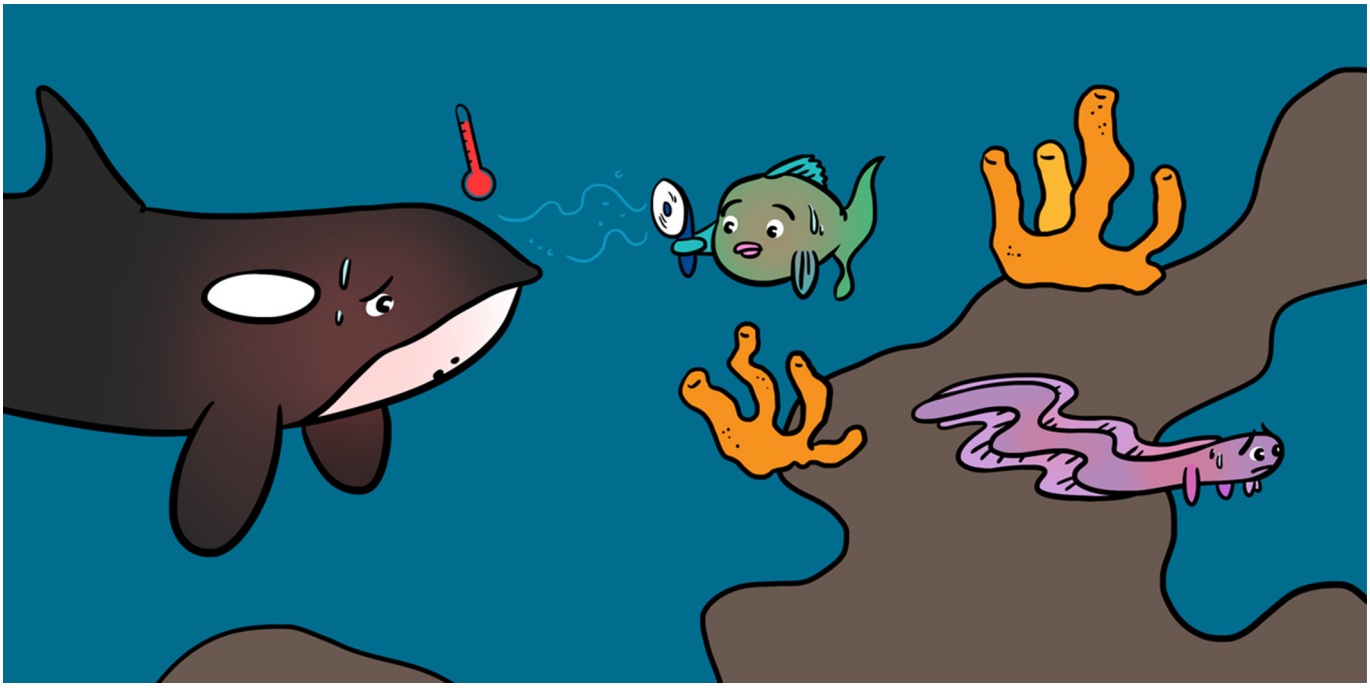

HOW MARINE HEATWAVES IMPACT LIFE IN THE OCEAN

Élise Beaudin * ***and Annalisa Bracco***

Program in Ocean Science and Engineering, Georgia Institute of Technology, Atlanta, GA, United States

YOUNG REVIEWERS:


ALREEM
AGE: 15


NOURA
AGE: 14


SAIF
AGE: 14


YOUNIS
AGE: 15

Heatwaves are long periods of hotter-than-usual weather. They happen both on land and in the ocean. In the ocean, these hot periods are called marine heatwaves. Marine heatwaves can be deadly for marine life such as fish, seabirds, and corals. In the past decade, marine heatwaves have become more frequent, and more intense. Every marine heatwave is harmful to marine ecosystems. Marine heatwaves happen all around the world, from the Pacific Ocean to the Atlantic Ocean to the Mediterranean Sea. Climate scientists predict that, in the future, marine heatwaves will last longer and be more frequent, which will inevitably create more problems for marine life and humans. Therefore, we need to better understand why marine heatwaves occur and how they impact life in the ocean.

INTRODUCTION

HEATWAVES

Long periods of abnormally hot weather that can last days, weeks, or even months.

GLOBAL WARMING

Gradual increase of the Earth's air temperature caused by excess carbon dioxide in the atmosphere from human activities, such as burning fossil fuels and deforestation.

Heatwaves, which are long periods of hot weather, are becoming more common and intense due to **global warming**. When the air gets too hot, water evaporates and causes very dry weather conditions, which can trigger bushfires, droughts, and damage to crops. Heatwaves are responsible for thousands of deaths around the world each year [1], and they threaten many animals that cannot survive long periods of heat. Heatwaves can occur in the ocean as well, and we call these events marine heatwaves.

Marine heatwaves are long periods of warmer-than-usual temperatures, measured at the surface of the ocean [2, 3]. They can persist for days, weeks, or even months, and they can occur at any time of year. Marine heatwaves have disastrous consequences for marine animals and plants, such as the destruction of coral reefs and kelp forests. Many species of fish, marine mammals, and seabirds do not survive major marine heatwaves. Death of marine species is also a major problem for humans, as many people living along the coast rely on fish and other ocean organisms for food.

Marine heatwaves happen all around the world and are becoming more frequent (Figure 1). Notable marine heatwaves occurred along the western Australian coast in 2011, in the Tasman Sea in 2015–2016, in the Pacific Ocean in 2013–2015 (called "The Blob"), and in 2019 [4]. In 2015–2016, an important marine heatwave happened over the northwest Pacific Ocean. The water temperature was over 6°C warmer than usual. This event forced entire fish communities such as Chinook salmon, cod, and sockeye salmon to move far away where the water temperature was more bearable [5]. Many sea lions, whales and seabirds were found beached because of the lack of food caused by the migration of fish [4].

Figure 1

Marine heatwaves happen all around the world. Those shown here have happened since 2000.

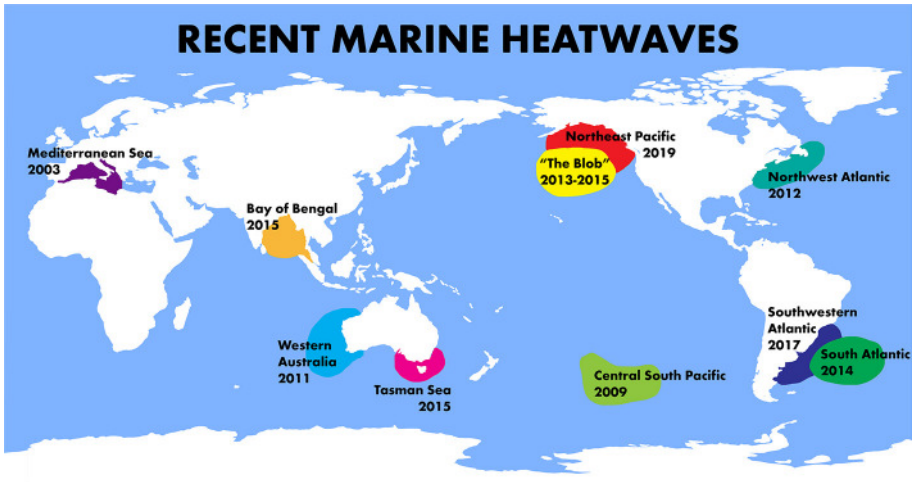

Figure 1

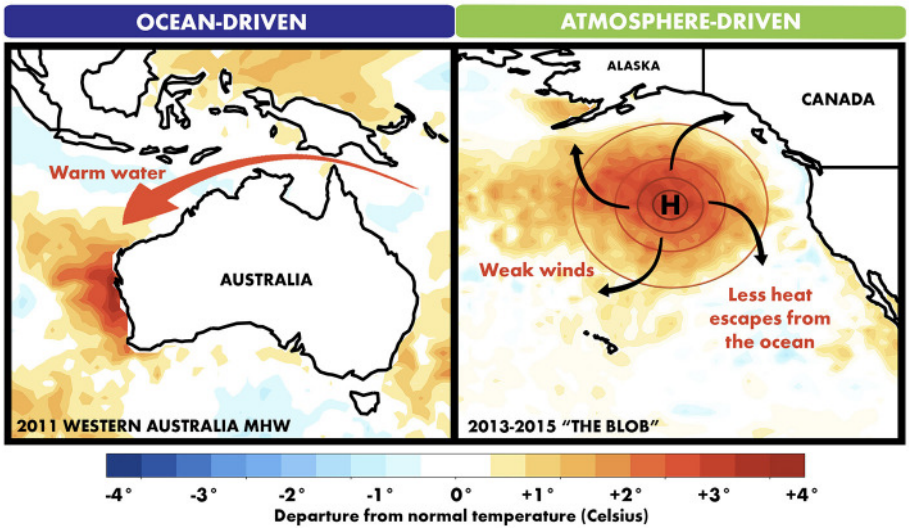

Figure 2

Marine heatwaves are ocean-driven or atmosphere-driven. Ocean-driven marine heatwaves are caused by ocean currents bringing warm waters. Atmosphere-driven marine heatwaves are caused by weak winds preventing heat to escape from the ocean. In both cases, the heat accumulates at the surface of the ocean and creates a marine heat wave.

Climate scientists predict that, due to global warming, future marine heatwaves will become more frequent and last longer. Why do marine heatwaves happen? Understanding what causes these dangerous heatwaves is important if we want to protect life in the ocean.

WHAT CAUSES MARINE HEATWAVES?

Temperatures at the surface of the ocean vary all year long. The surface water gets colder in winter and warmer in summer, due to the energy of the sun. This natural cycle benefits marine life, which migrates according to the water temperature. Certain weather conditions can increase the surface water temperature significantly. If these conditions last for a long time, we call it a marine heatwave. Marine heatwaves are often unbearable for marine life.

The main factors that influence the ocean surface temperature are **ocean currents** and the exchange of heat between the ocean surface and the atmosphere [2] as shown in Figure 2. Ocean currents can bring warm waters to a colder area. Additionally, the atmosphere controls heat transfer into and from the ocean, via the winds. When winds are strong, heat can escape easily from the ocean, just like wind blowing on your skin draws heat away from your body. The opposite is also true: if the winds are weak, the heat remains trapped at the ocean surface for longer. We can broadly classify marine heatwaves into two categories: those driven by the ocean, and those driven by the atmosphere.

An ocean-driven marine heatwave occurred in 2011 offshore of western Australia. During that time, a climate phenomenon called **La Niña** modified the ocean currents and brought warm water to the western Australian coast. The ocean temperatures were more than 3°C

OCEAN CURRENTS

Continuous movement of large quantity of water in the ocean, driven by winds and temperature differences.

LA NIÑA

A weather pattern in the equatorial Pacific Ocean, causing water to become much colder than usual off the coast of Peru, and much warmer off the coast of Australia.

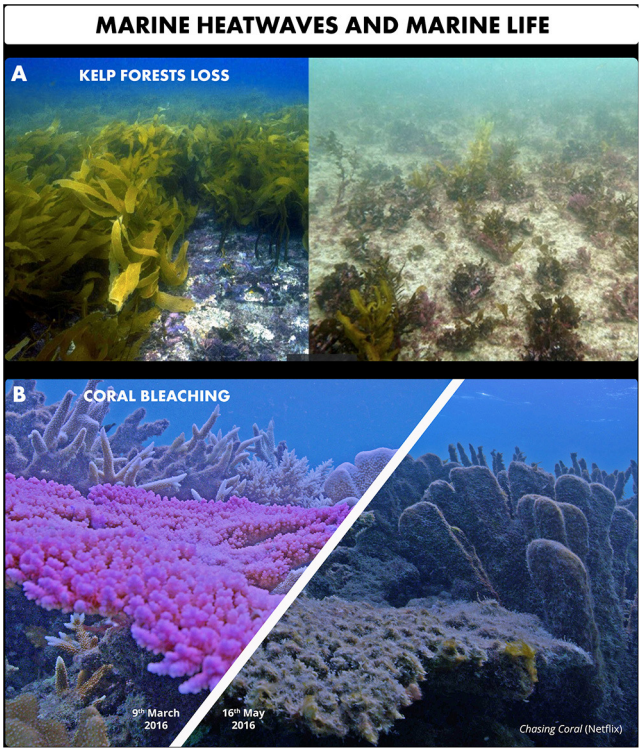

Figure 3

Marine heatwaves have disastrous impacts on marine life. **(A)** A recent marine heatwave caused kelp forest loss in Australia (Photograph credit: Thomas Wernberg). **(B)** Marine heatwaves can cause coral bleaching, which happens when the algae that live on corals and give them their color leave to escape the heat, leaving the corals white (Photograph credit: Chasing Corals, Netflix).

above normal. Weak winds allowed this heatwave to persist for several months [6].

"The Blob" in the northwest Pacific, on the other hand, was caused by the atmosphere. The **atmospheric pressure** (the weight of air) over the region was higher than usual, which led to very weak winds. Those weak winds prevented the heat from escaping to the atmosphere, resulting in the strongest marine heatwave ever recorded at that time [7].

ATMOSPHERIC PRESSURE

Force exerted by the weight of the air above the Earth's surface.

Now that we know why marine heatwaves happen, we can make projections for the future. Marine heatwaves have already become 34% more frequent and 17% longer between 1925 and 2016 [8]. At current rates of global warming, climate scientists predict that global ocean and atmospheric temperatures will keep increasing. As the ocean surface warms up, marine heatwaves will probably become more frequent, more intense, and last longer [3, 8].

MARINE HEATWAVES ARE DISASTROUS FOR MARINE LIFE

Heatwaves have disastrous impacts on marine life. Just like heatwaves on land worsen human health issues and can kill people (for example, through heat stress or bushfires), marine heatwaves affect the health of marine species [1]. In some cases, heat stress destroys marine habitats

(Figure 3). Fish, whales, and sea turtles are forced to migrate to cooler areas of the ocean. Although these animals naturally migrate to hunt for food and reproduce, marine heatwaves force them to change their migration behavior more drastically.

For example, during "The Blob," fishermen unexpectedly saw blue sharks and thresher sharks in the Gulf of Alaska in summer, when these animals are usually found around the coast of California [9]. Many other species of fish, such as coho salmon and Alaskan pollock, experienced impacts on their migration patterns as well. This shift in where fish are found can have an important effect on the food chain [9].

Other marine species, like corals, cannot change location. The 2011 western Australia marine heatwave caused extreme damage to immovable plants and animals. It wiped out kelp forests and caused **coral bleaching**, which happens when the algae living on corals, which give them their color, escape from the heat, leaving the corals white [8].

CORAL BLEACHING

Whitening of corals caused when the algae normally living on them, which give corals their color, leave or die. This happens when the ocean gets too warm.

WHAT DOES THE FUTURE HOLD FOR MARINE LIFE?

Each time marine heatwaves occur, they alter and often destroy marine ecosystems [4]. Some species can adapt to the extreme temperatures, such as fish that can swim away to cooler areas. Many species, like corals or kelp forests, cannot escape the heat—although some are better at resisting it. In general, marine heatwaves are destructive and their impacts on the marine ecosystem could be greater than we currently know. For example, coral reefs provide a habitat for fish, sea stars, crabs, sponges, and clams. Thus, coral bleaching due to marine heatwaves could lead to disastrous consequences for a lot of marine life.

The ocean is valuable; it provides vast economic benefits, from food (such as fish and shellfish) to tourism to all the jobs related to those industries, along with energy for our homes, and even medicines. We need to protect ocean inhabitants and resources. Actions to halt global warming can prevent marine life from dying, including reducing our emissions of carbon dioxide. Marine heatwaves are becoming increasingly more common, so we need to find ways to protect and maintain marine ecosystem systems and all the animals that live there. One solution is to create **marine protected areas**, which are regions of the ocean where human activities, from fishing to mining, are limited or completely banned. These areas do not prevent damage caused by marine heatwaves, but they serve as sanctuaries where marine life can develop peacefully, away from human pressure, and they allow marine life to recover from periods of intense stress such as those caused by marine heatwaves [10]. Understanding the impacts of marine heatwaves on life in the ocean, and developing strategies to

MARINE PROTECTED AREAS (MPAS)

Protected areas of the ocean providing marine ecosystems with an environment with limited to no stress caused by human activities such as fishing, boating and leisure activities.

counteract their impacts, is important as healthy marine ecosystems are necessary to our livelihood and wellbeing.

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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

ALREEM, AGE: 15
Alreem is an animal lover who loves science and adventures, a night owl, I am not a good cook however when it comes to instructions, I can follow and make a decent dish. I have two love birds one is named hades the other is daisy, love them and treat them like my own kids.

NOURA, AGE: 14
I am Noura, I have many interests such as building robots and playing the piano, but science has a special place in my heart and I have always been looking for the latest scientific researchs and projects.

SAIF, AGE: 14
Hi! My name is Saif. I am 14 years old from the United Arab Emirates. I have always been passionate about science, particularly biology and chemistry. I love to read science books and biographies about fascinating people such as Steve Jobs. I also participate in programs and competitions that enhance and improve my passion for science, such as wining the best group project at the National Science Fair in 2020. I also enjoy doing experiments with my science teacher.

YOUNIS, AGE: 15
Hi! My name is younis, and I am 15 years old, I have always felt attracted to science subjects as they are very fascinating, especially environmental management geography geology and space. And through frontiers for young minds I hope to learn more about the world we live in.

AUTHORS

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frontiers FOR YOUNG MINDS

BIODIVERSITY
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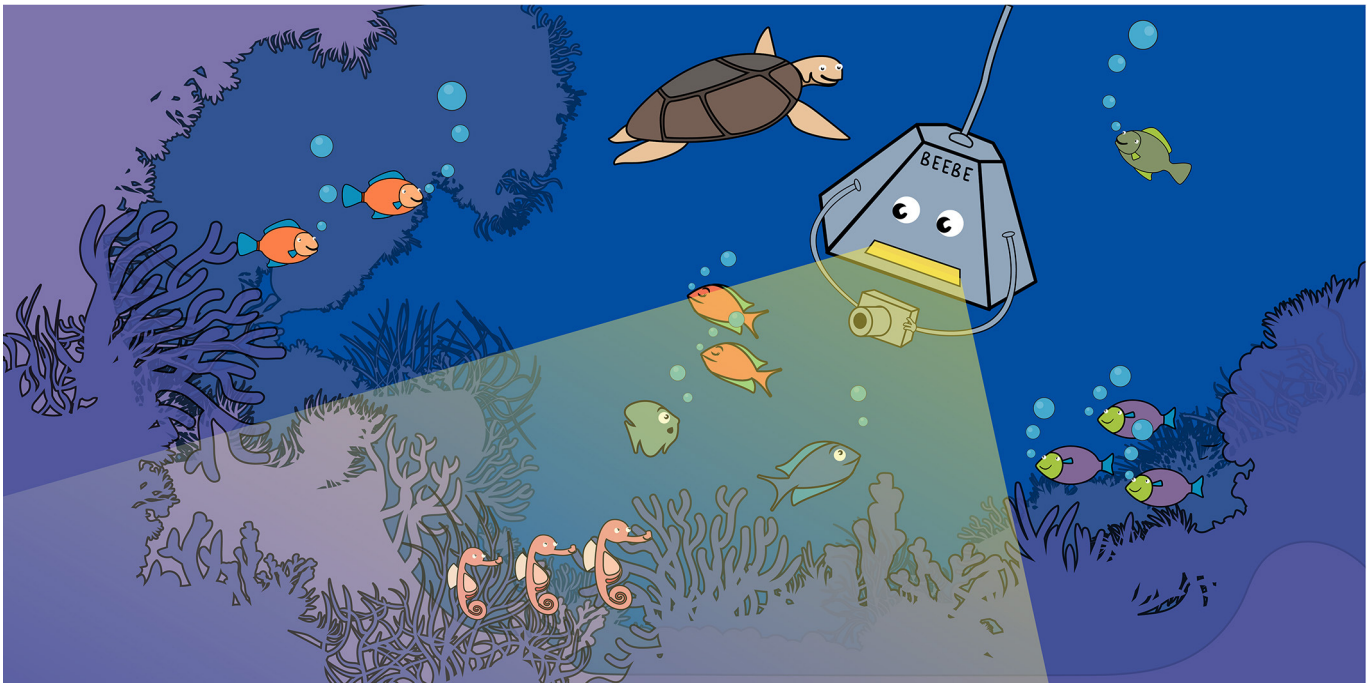

SPIES IN THE DEEP: OCEAN LANDERS EXPLORE THE DEEP SEA

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YOUNG REVIEWERS:

NAVID
AGE: 15

NORA
AGE: 14

Below the surface layers of the ocean, there are ecosystems full of undiscovered life. Scientists love to ask questions like, "Who is there?" and "What are they doing?" An important question scientists are beginning to ask is, "How will these living things react to warmer waters, loss of oxygen, or pollution?" To answer these questions, scientists build equipment to observe life in the deep sea. We built an ocean lander named BEEBE, with a camera, sensors, and waterproof casing. BEEBE helped us study deep-sea ecosystems near the coast of California and learn about the animals that live there. We can use what we learned to recognize vulnerable communities and the

threats some ocean animals face. An ocean lander like BEEBE can be a great tool to learn more about coastal, deep-sea ecosystems around the world!

WHY DO SCIENTISTS CARE ABOUT THE DEEP SEA?

When scientists study tide pools at the ocean's edge, they gather their equipment, drive down to the rocky shoreline, and put on their "science boots." Using only their eyes, they can observe squishy anemones, colorful starfish, and thousands of barnacles clinging to the rocks. To study what's *in* the sea, however, scientists need different tools and techniques. The invention of SCUBA diving was important because it allowed scientists to study deeper underwater ecosystems like coral reefs for the first time.[1] Beyond the coral reefs, the deep sea is as full of life as a tropical rainforest, but it is too deep for humans to visit. To uncover the mysteries of the deep sea, scientists first must build specialized equipment to go deep!

[1] https://www.nationalgeographic.com/news/2010/6/100611-jacques-cousteau-100th-anniversary-birthday-legacy-google/

The deep sea includes everything in the ocean below 200 m. In some places, like California, deep-sea ecosystems can be found close to shore (less than 2 km from the beach). The deep waters are dark, cold, and mysterious. Since there is a limit to how deep the human body can go without special equipment, scientists build technologies to take people deeper [1]. Some scientists have used a one-person submarine to explore places like the Mariana Trench, which is almost 7 miles (11,265 m) below sea level [2]. Others build robots to regularly scan, collect, and record information about the seawater.

Accessing the deep sea is the key to learning about the animals living there. On the land, we have learned how worms need moist, airy soil, and tortoises prefer the dry desert heat. Ocean environments and their animals are just as unique and selective. Certain ocean animals prefer warmer, Caribbean waters, while others like colder, Arctic waters. Like us, marine animals need oxygen to breathe. Rather than coming up to the surface to breathe, most marine animals use oxygen dissolved in the seawater. We have learned that there is generally more oxygen at the surface of the ocean than in the deeper waters. Some animals can tolerate areas with less oxygen, while others need more oxygen to breathe comfortably.

ENVIRONMENTAL VARIABILITY

The changes and fluctuations that occur in an environment over a short period of time.

CLIMATE CHANGE

Climate change is the process of the Earth heating up due to human activity.

Within the surface layers of the ocean, oxygen varies a lot. The constantly moving water is one reason for this: the oxygen levels change a little bit as the water moves up, down, and side-to-side. This is called **environmental variability** because these changes in oxygen happen naturally. Oxygen availability can also change with the seasons, or because of storm systems. In addition, oxygen in the ocean's surface layers is decreasing due to **climate change** caused by humans. As humans continue to burn fossil fuels and pollute the

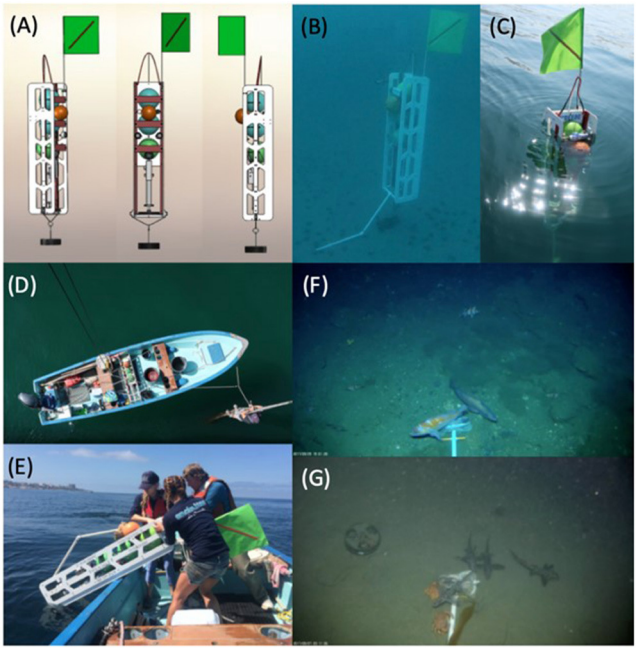

Figure 1

Here are the many stages of DOV *BEEBE*, our deep-sea spy: **(A)** computerized design; **(B)** underwater and in position to collect data; **(C)** floating on the ocean surface, waiting to be retrieved; **(D)** being transported in the back of a small boat; and **(E)** ready for deployment. **(F)** View from BEEBE's camera system showing the rockfish community in a shallower, high-oxygen area. **(G)** View from BEEBE's camera system showing the presence of crabs and chimaeras in a deeper, lower-oxygen area.

environment, they release chemicals into the air that lead to warmer oceans with less oxygen. This change happens slowly but can cause permanent damage.

Animals that live in constantly changing environments may have a better chance of adapting to oxygen decreases caused by climate change. However, if oxygen becomes too low, many animals, like fish, will need to find new homes with more oxygen. Our goal was to figure out how vulnerable the animals along California's coast are to changes in ocean oxygen, by watching their reactions to varying conditions. We hoped that our deep-sea observations would tell us which deep-sea animals and environments will be threatened by future decreases in oxygen, so that we can better protect them.

BUILDING A DEEP-SEA SPY TO EXPLORE

To study animals in the deep sea, we built a deep-water lander, called Deep Ocean Vehicle (DOV) BEEBE, which we call our "deep-sea spy" (Figure 1). A lander is a technology that "lands" in new environments that humans cannot easily get to, like the Mars Lander that studied Mars. Landers can be customized based on the goal of the mission. BEEBE landed on the seafloor and its mission was to observe different deep seafloor communities for up to 3 weeks. We focused on the nearshore deep-sea ecosystems off San Diego, California. This is an **upwelling** area, where cold, deep water, low in oxygen, is brought up to shallower depths in the spring and summer.

UPWELLING

The process of deep, cold, nutrient-rich water rising to the surface.

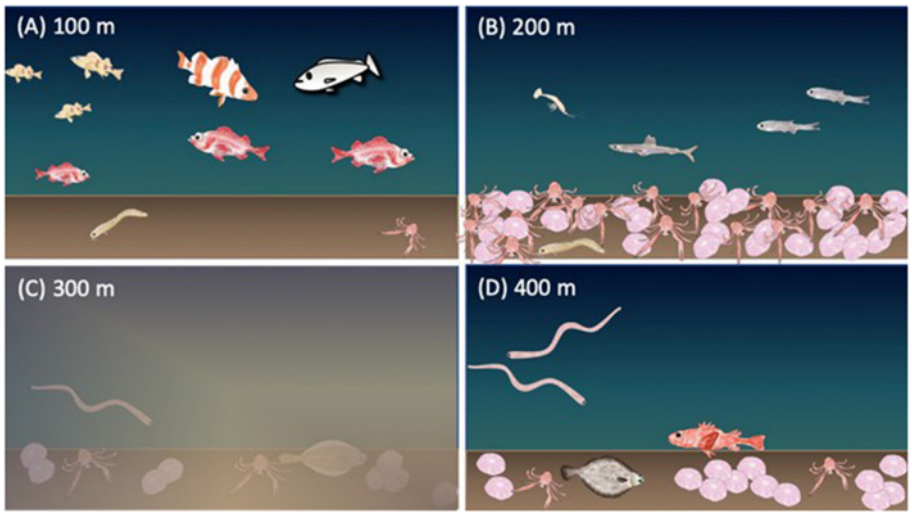

Figure 2

(A) The 100-m community was fish-dominant and included rockfish, pink seaperch, and spotted cusk-eel. **(B)** The 200-m community had many invertebrates like tuna crabs, pink urchins, and spot prawns, with appearances by spotted cusk-eels, lizardfish, and other small fish. **(C)** The 300-m community was invertebrate-dominant with high amounts of sediment in the water, so it was difficult to see. We occasionally saw pink urchins, tuna crabs, Pacific hagfish, and slender soles. **(D)** The 400-m community was invertebrate-dominant, including mostly tuna crabs and pink urchins, with occasional Pacific hagfish, dogface witch eels, shortspine thornyheads, and Dover soles.

Landers like BEEBE are extremely helpful when studying the deep sea because they are small enough for one person to deploy from a small boat! BEEBE stands five feet tall, about the height of an average 12-year old. At the start of each mission, BEEBE traveled to the seafloor with weights and began attracting animals with attached bait (Figures 1B, F, G). With a special camera and lights to brighten the seafloor, BEEBE recorded short videos every 20 min, to capture who was there and what they were doing. With special sensors, BEEBE also collected information on the temperature, saltiness, pressure, and oxygen in the water. After a few weeks of sampling, a signal was sent through the water to tell BEEBE to release the weights, so it could float back up (Figure 1C).

WHAT DID WE SEE THROUGH BEEBE'S CAMERAS?

BEEBE conducted seven spy missions for us, visiting seafloor communities from 100 to 400 m deep. From each spy mission, BEEBE brought back fascinating video footage and information about the ocean waters that we could upload to our computer and learn from![2]

[2] *Check out footage from BEEBE's deployments here*

During each mission, BEEBE observed seafloor communities at different depths. The videos BEEBE recorded revealed that, closer to the surface of the ocean at 100 m, there are mostly fish! We called this environment *fish-dominant* (Figure 2A). Rockfish loved this environment, and many other fish gathered when oxygen levels increased. At deeper depths, like 200, 300, and 400 m, there were fewer fish and more crustaceans and sea urchins. We called this a transition to an *invertebrate-dominant* seafloor (Figures 2B–D). **Invertebrates** are animals without backbones, like crabs or urchins. Pink urchins and tuna crabs covered the seafloor. They seemed to like the

INVERTEBRATES

An animal without a backbone. More than 90% of all living animal species are invertebrates.

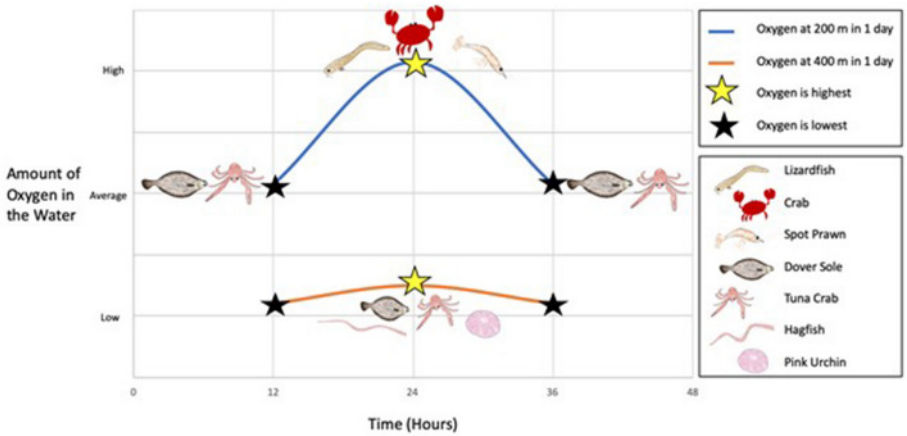

Figure 3

Oxygen variability and animals present at 200 and 400 m. At 200 m (blue line) the water experienced large daily changes in oxygen. The animals observed during oxygen highs were lizardfish, crabs, and spot prawns. During oxygen lows, we saw Dover soles and tuna crabs. Water at 400 m (orange line) experienced smaller daily changes in oxygen. Animals at 400 m, like hagfish, Dover soles, tuna crabs, and pink urchins, like their stable, low-oxygen environment. This shows that certain animals prefer water with high oxygen, while others prefer low oxygen.

colder, lower-oxygen environments. The few fish we observed in the invertebrate-dominant area were much less active, sitting still along the seafloor, compared to those seen at 100 m, which swam around frequently. Being less active could be a behavioral adaptation to preserve energy while living in a cold, low-oxygen environment.

WHAT DID BEEBE'S SENSORS TEACH US?

Our sampling equipment measured the temperature and oxygen level of the seawater every 5 min! This helped us compare ocean environments at various depths. It also helped us see how one environment changes from day to day. The 100 m environment had the most oxygen and highest variability of temperature, meaning the temperature at 100 m changed the most from day to day. At 200 m, the oxygen and temperature were lower than at 100 m. We were surprised to find high oxygen variability here, meaning the oxygen levels changed the most from day to day at 200 m (Figure 3). Conditions at 300 and 400 m had extremely low oxygen levels that did not change much throughout the entire mission. We called these regions **hypoxic** because they are extremely low in oxygen and can be stressful for fish and other organisms.

HYPOXIC

Having an extremely low oxygen concentration, making it difficult for many animals to survive.

HOW DO CHANGES IN OXYGEN AFFECT OCEAN ANIMALS?

Our sensors taught us that water at 200 m experiences the most oxygen variability. By comparing which animals were present in the video footage to the oxygen conditions at the time, we noticed a pattern! We found that some animals prefer high-oxygen waters, while others like low-oxygen waters. For example, during high-oxygen periods, spot prawns, crabs, and lizardfish were more common. During low-oxygen periods, tuna crabs and Dover soles were more common

(Figure 3). This shows that certain animals living at 200 m are sensitive to changes in oxygen. Overall, most animals did not seem bothered by these natural and temporary oxygen changes. However, as oxygen loss worsens due to climate change, we still do not know how each animal will respond to permanent decreases in available oxygen.

SPIES LIKE BEEBE CAN HELP SCIENTISTS UNDERSTAND CLIMATE CHANGE IMPACTS

OCEAN DEOXYGENATION

The loss of oxygen in the ocean due to human-caused climate change.

As climate change causes the ocean to warm, the water loses oxygen. This is a crisis called **ocean deoxygenation**. Exploring with our seafloor lander BEEBE gave us day-to-day insight into which animals and depths may be more sensitive to permanent climate change impacts [3]. What will happen to the animals that prefer high-oxygen conditions, like rockfish, spot prawns, crabs, and lizardfish? These animals may be forced to find new homes in shallower, better oxygenated waters. When animals shift habitats, they may experience more stress or become more vulnerable to predators. It is also possible that, as some animals move away from low-oxygen areas, other animals that are not stressed by low oxygen conditions, such as tuna crabs and Dover soles, may expand into these areas.

Maintaining biodiverse ecosystems with many types of animals is key to supporting a healthy ocean. Oceans around the world are facing similar concerns stemming from warming and oxygen loss. Ocean landers can capture unique footage of seafloor communities in deep-sea ecosystems that are close to shore and could help scientists in other parts of the world explore their understudied seafloor habitats, too. Someday this type of information may help marine managers or young scientists like you to understand which deep-sea ecosystems and species are most vulnerable to warming and oxygen loss. This knowledge will help us to make better decisions about how to manage deep-sea ecosystems and preserve biodiversity in a changing world.

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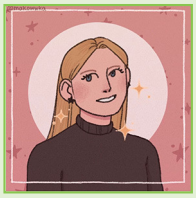
YOUNG REVIEWERS

NAVID, AGE: 15

Navid likes to ask questions or learn new things–especially about science. He is interested in a lot of things and tries to understand them as well as he can. Many of his classmates ask him for help as he is a good teacher as well. In his freetime, Navid likes to do sports like CrossFit or play online with his friends.



NORA, AGE: 14

Hi! My name is Nora and I am 14 years old. I love playing volleyball as well as surfing in the ocean. My favorite subjects are design and science, and I am currently a freshman in High School. In the future I would like to be an architect.

AUTHORS

HALEIGH T. YANG

Haleigh T. Yang completed her undergraduate degree at University of California, San Diego. Spending time in the outdoors helped spark Haleigh's interest in the natural world. Through research, she learned how diverse the ocean is and how important it is for people's livelihoods. She is currently working as a marine naturalist teaching people about the Salish Sea and the animals that call it home–killer whales, humpback whales, salmon and more! She hopes to continue learning about the world in order to teach more people about marine life. *htyang@ucsd.edu

KEVIN HARDY

Kevin Hardy founded Global Ocean Design to design and build unmanned deep ocean landers for oceanographers. He participated in James Cameron's DEEPSEA CHALLENGE Expedition to the Challenger Deep of the Mariana Trench (2012), and the University of Concepcion's ATACAMEX dive to the deepest place in the Peru-Chile Trench (2018). He previously was an ocean engineer at the Scripps Institution of Oceanography for 40 years. He is currently on multiple academic advisory boards. He received a Doctor of Science (honoris causa) from Shanghai Ocean University in 2018.

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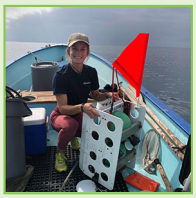
Dr. Nicholas C. Wegner is a Research Fisheries Biologist for the National Marine Fisheries Service in La Jolla, CA. His research focuses on the physiology and behavior of marine fishes and invertebrates. He is particularly interested in the way animals adapt to their surroundings and how environmental factors such as temperature and dissolved oxygen affect their physiology and behavior. Dr. Wegner's claim to fame is

his discovery that a strange-looking fish known as the Opah is able to keep its body warmer than its cold and deep ocean habitat.



ASHLEY NICOLL

Ashley Nicoll received her master's degree from Scripps Institution of Oceanography. She used ocean landers to see the animal communities that live on the seafloor in the submarine canyons and study how they may change between day and night as well as when the water gets deeper. Now, Ashley is pursuing a Ph.D. at Stony Brook University studying changes in how fish move over time.

LISA A. LEVIN

Dr. Lisa A. Levin is a Biological Oceanographer who researches benthic communities in deep-sea and shallow-water environments. She is a Professor at Scripps Institution of Oceanography at the University of California. Together with her students Dr. Levin has participated in over 45 oceanographic expeditions around the world and served as Chief Scientist on about half of these. She has perceived over the years a growing threat to deep margin settings and has turned her attention to conservation issues. She has helped establish scientific networks that bring deep-sea science to policy makers.

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Dr. Natalya D. Gallo is a scientist at the University of Bergen studying marine fjord ecology. Her curiosity about the ocean and its animals began at a young age and has taken her on scientific adventures to study deep sea ecosystems around the world. She is interested in what environmental factors determine where animals live and how they interact, how climate change affects marine ecosystems, and how we can use science to inform ocean management and protection. Before moving to Norway, she worked at the Scripps Institution of Oceanography.

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BIODIVERSITY
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RHODOLITHS: OUR "ROCK-AND-ROLLING" UNDERWATER FRIENDS

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ALYSA
AGE: 11

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If you walk on the beach, you may observe many kinds of stones of diverse colors. Surprisingly, some of these "stones" may be algae! A certain type of red algae creates structures called redstones, also known as rhodoliths. Rhodoliths are important builders and can create extensive banks at the bottom of the oceans. These bioengineers create an oasis for marine life. Marine worms, crabs, and sea stars, for example, can live in and on rhodoliths. However, human activities, including pollution and removal of rhodoliths for aquarium decoration, may harm rhodolith banks. Rhodoliths are sensitive to disturbances and should be protected. In this article, we explain the main attributes of rhodoliths, including their formation, distribution, and importance, as well as conservation measures, we can take. We

hope that what you learn about rhodoliths will inspire you to defend these fascinating "rock-and-rolling" ocean creatures.

MYSTERIOUS REDSTONES: "LIVING ROCKS"

Perhaps, while walking on the beach, snorkeling, or diving, you have seen stones of various colors. You may have even seen a redstone, but you probably did not recognize its importance at the time, because redstones look just like any other stone in the sea—but they are not! While redstones may look like stones, gravel, or rocks, they are in fact made of living and dead **algae** [1]. The algae that makeup redstones belong to the group Rhodophyta (red algae). Redstones have a scientific name: **rhodoliths**! This means stones with a reddish color that roll on the ocean bottom. Rhodolith "stones" are composed of at least 50% red algae.

Rhodoliths live in all oceans: the Pacific Ocean (Southern Japan), near Southern Australia, in the Gulf of California, the Mediterranean Sea, the North Atlantic Ocean (from Norway to Portugal), and the Caribbean Sea. There are many rhodoliths in the South Atlantic Ocean, particularly in the Abrolhos Archipelago in Northeast Brazil [2]. They can be present from the intertidal beach, where we walk, to the open sea, up to 270 meters in depth [1]. Rhodoliths have lived in the seas since the Cretaceous period, 145–66 million years ago [1]. This is the same time that dinosaurs lived on our planet!

Although our "rock-and-rolling" friends are not as famous as dinosaurs, rhodoliths play essential roles in marine ecosystems! Algae produce oxygen, making it available for other marine life. Rhodoliths are also **bioengineers**, meaning that they build structures that serve as habitats and food sources for many sea creatures.

Hopefully, after reading this article, you will understand the importance of these amazing marine "houses" and be motivated to help us preserve them!

HOW ARE RHODOLITHS FORMED?

The algae that form rhodoliths are called **calcareous** algae because they use a substance called **calcium carbonate** ($CaCO_3$) to grow and form banks on the ocean bottom [3]. How do they do this? Well, calcium carbonate is composed of two substances: calcium and carbonate. Calcium (Ca^{2+}) is naturally present in seawater. Carbonate (CO_3^{2-}) is created when carbon dioxide (CO_2) gas from the atmosphere contacts seawater and undergoes some chemical reactions to create calcium carbonate. Then, corals, molluscs, calcareous algae, and other ocean organisms can take up calcium carbonate to build their

ALGAE

Also known as seaweed, representing marine creatures that produce their own food through a process of light capture (photosynthesis), similar to terrestrial plants. Examples: kelps, rhodoliths, rockweed, sea lettuce.

RHODOLITHS

Unattached calcareous reddish stones, composed of at least 50% of a red alga type, that roll on the ocean bottom, establishing extensive banks, as a set of marine houses.

BIOENGINEERS

These are the creatures that are able to carry out constructions or modifications in the environment where they live, for example by building their own houses or making small paths.

CALCAREOUS

Anything that is formed by calcium carbonate, for example, shells, pearl, coastal cliffs, corals, limestones, and some algae (such as rhodoliths).

CALCIUM CARBONATE

It corresponds to a substance formed by calcium (Ca^{2+}) and carbonate (constituted by carbon and oxygen: CO_3^{2-}), constructing the chemical formula $CaCO_3$, which forms the calcareous materials.

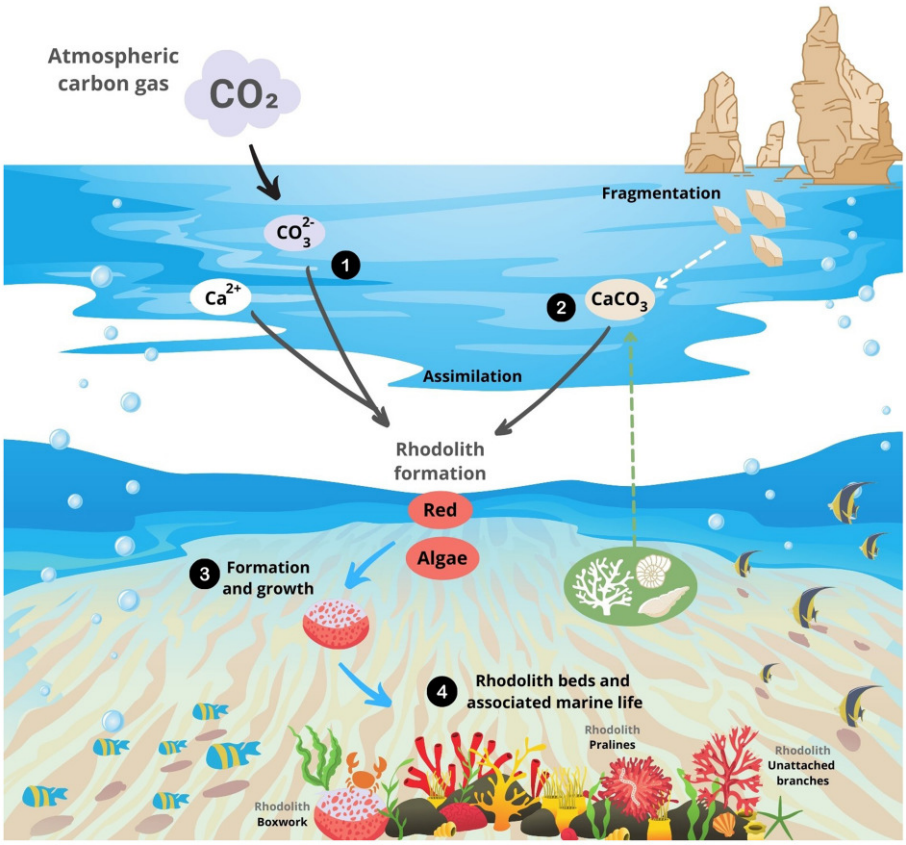

Figure 1

Figure 1

(1) Calcium (Ca^{2+}), found in ocean water, and carbonate (CO_3^{2-}), created when CO_2 from the atmosphere undergoes chemical reactions, combine to form calcium carbonate ($CaCO_3$). (2) Other sources of $CaCO_3$ include dead shells, corals, other algae, and fragments of broken-down rocks. (3) Rhodoliths form and grow by assimilating ($CaCO_3$) into their skeletons. (4) Rhodolith banks on the ocean bottom consist of three rhodolith types: boxwork, pralines, and unattached branches. These banks serve as habitat for other ocean creatures.

skeletons, in a process called calcium carbonate **assimilation**. The breakdown of rock formations in the ocean may also add calcium carbonate to the seawater. When organisms that have skeletons built of calcium carbonate die, the calcium carbonate returns to the water to be used again. By this process, dying rhodoliths are one of the main sources of calcium carbonate in the oceans (Figure 1).

ASSIMILATION

In nature, involves the acquisition of a certain substances by living beings with the aim of using it for their own benefit, for example for food or protection.

RHODOLITHS HAVE A VARIETY OF FORMS

Rhodoliths may grow into different forms [1]. In contrast to coral reefs, they are not attached to the seabed and may "rock and roll" underwater with the ocean currents. When they get too heavy, rhodoliths settle to the bottom and establish extensive banks, which provide important habitats for other sea creatures.

There are three types of rhodoliths: boxwork, unattached branches, and pralines (Figures 1, 2A) [4]. The boxwork type has an internal structure called a nucleus, which can be a small pebble or the remnants of another living creature, such as a piece of coral skeleton or shell. From this nucleus, the rhodolith grows into a compact shape. Unattached branches do not have a nucleus and have several tree branch-like structures. Finally, pralines also have a nucleus, upon

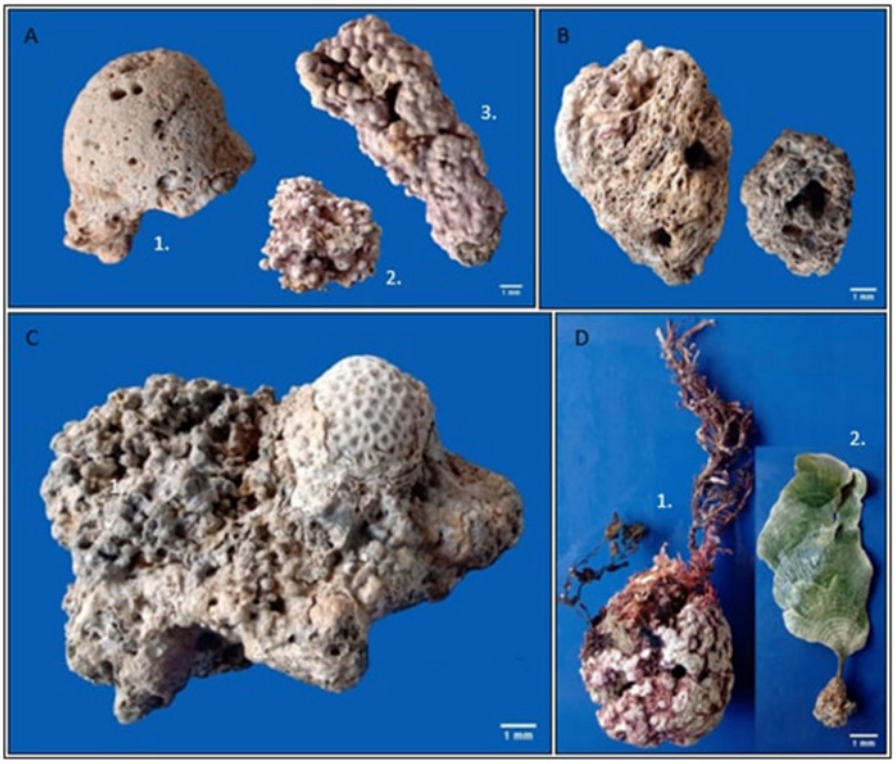

Figure 2

Examples of rhodoliths. **(A)** Rhodolith types: 1. Boxwork; 2. Unattached branches; 3. Praline. **(B)** Internal part of rhodoliths, with the overlapping layering (remarkably on the right photo). **(C)** Rhodolith associated with the starlet coral *Siderastrea stellata*, seen on the top right. **(D)** Algae growing on the rhodolith surface: 1. red algae; 2. calcareous green algae (Photographs' credit: K. Massei).

which multiple bumps develop. All three types of rhodoliths grow by adding overlapping layers of calcium carbonate (Figure 2B).

Many factors may influence rhodolith formation and growth, including the movement of ocean water, the amount of light present, and calcium carbonate availability. Ocean water movement influences their shape: rhodoliths get "rounder" as they roll with the water. The less water movement, the more branches the rhodoliths will have [5]. Light is essential for rhodolith growth because algae need light for photosynthesis [6]. Calcium carbonate in seawater is essential because calcareous algae need this substance for their growth.

As rhodoliths develop, other organisms may stick to their surfaces. The tropical starlet corals are an example because they take advantage of the shelter and attachment surface provided by the rhodolith, making the rhodolith its home (Figure 2C). Other kinds of algae may also attach and grow on rhodoliths (Figure 2D).

IMPORTANCE OF RHODOLITH BANKS

A tropical rhodolith bank can reach a diameter similar to that of a soccer ball, but these banks grow slowly: only 1 to 1.5 mm per year [2]. They also have a long life span (>100 years). These "elders of the sea"

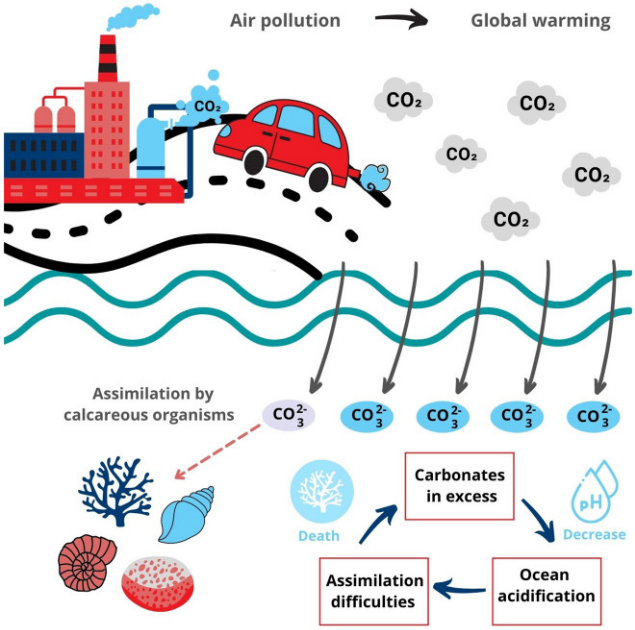

Figure 3

Figure 3

When there is too much carbon dioxide (CO_2) in the air from air pollution, then too much carbon dioxide will be dissolved in the ocean which increases the acidity of the ocean. Ocean acidification makes it difficult for calcareous creatures—like rhodoliths, corals, snails, or clams—to absorb carbonate as they grow and can even result in their death in extreme cases.

are potential indicators of environmental changes that have happened over time.

Rhodolith banks provide several essential benefits. In addition to providing habitats for other creatures and promoting local biodiversity, rhodolith banks can also protect the coasts against the erosive action of waves. They also have important benefits for the local climate. Too many free carbonates (CO_3^{2-}) in the oceans can be harmful. The chemical reactions that generate carbonates also produce hydrogen ions (H^+), which increases the seawater acidity. This is the cause of **ocean acidification**, which is dangerous because it can cause the death of ocean life, including our rock-and-rolling friends. Calcareous organisms like rhodoliths are essential for "storing" carbonates in their skeletons. This process turns carbonates into non-harmful forms and helps to prevent ocean acidification (Figure 3). However, this equilibrium is fragile, and human activities disrupt it [7].

OCEAN ACIDIFICATION

Phenomenon characterized by increased acidity (pH decrease) in seawater due to the carbonates spread, caused essentially by human action, with the burning of petroleum products, such as coal and oil.

Another climate-related benefit of rhodoliths is that the algae "trap" carbon dioxide (CO_2) from the atmosphere during photosynthesis. Carbon dioxide is naturally present in the atmosphere and living organisms release it when they breathe. However, over the last two centuries, the carbon dioxide concentration has increased considerably due to the burning of fossil fuels. When there is too much carbon dioxide in the atmosphere, it can contribute to global warming and climate changes. So, when rhodolith beds capture and trap carbon, they help to lower atmospheric carbon dioxide levels (Figure 3). The carbon stored in marine ecosystems is known as **blue carbon** [8].

BLUE CARBON

Carbon is a component widely found in nature, constituting from graphite and diamond to petroleum. When this substance is stably stored in the ocean it is called blue carbon.

HUMANS AND RHODOLITHS

For humans, rhodoliths are important sources of marine limestone, which has several uses. It can be used in agriculture, to lower the soil's acidity; in the cosmetic industry, to produce toothpaste and bath salts; and in the food industry, as a food supplement. Rhodoliths can also be used to create bone implants that are compatible with human tissues. Finally, rhodoliths can be used in aquariums, as decoration and as living water filters.

While direct harvesting of rhodoliths can obviously damage them, other human actions may also affect rhodoliths and the life forms linked to them. One example is inappropriate waste disposal at sea, causing for example contamination of seawater (organic pollution), increased amount of plastics (plastic pollution), and other materials that are harmful to the ocean balance. Uncontrolled tourism can result in the trampling of rhodoliths that live on coastlines. Among the most damaging human actions are dredging and bottom trawling, directly removing the bottom-dwelling creatures, such as rhodoliths. Drilling for oil and gas are also damaging, and the disposal of waste material produced by drilling can bury entire communities of rhodoliths.

HELP US PRESERVE RHODOLITHS!

We hope you now better understand the importance of our "rock-and-rolling" friends, the rhodoliths! There are still many things we do not know about them, so more research on rhodoliths is needed to better understand their role in regulating Earth's climate and how we can continue to harvest them for important purposes while also conserving their populations. We must be especially careful because they recover so slowly: thousands of years are required to form an extensive rhodolith bank! Protecting rhodoliths is urgent because the destruction of their banks would be catastrophic. Imagine everything else that might be negatively affected: marine species that use rhodoliths as habitat, coastal lands that they protect from erosion, and even our climate, which rhodoliths help to keep in balance the best they can.

So, what can you do to help preserve rhodoliths? Knowing about them—what they are, where they are found, their importance, and the negative impacts of their destruction—is the best way to start protecting them. Now that you know these things about rhodoliths and their benefits for the environment, you can raise other people's awareness of them [9]. If more people understand these organisms, we will be in a better position to create the needed strategies and policies for their conservation. The more people who understand these fascinating, mysterious, "living rocks," the greater our power to preserve them!

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YOUNG REVIEWERS

ALYSA, AGE: 11
As a Year Six student in Adelaide, I have developed a constantly growing interest in science, particularly in the fields chemistry and biology. Throughout my life, also a love of music and mathematics has strongly developed, much to the contrary of the much-hated Physical Education. This Frontiers for Young Minds organization provides an excellent opportunity to learn a significant amount regarding science papers and journals, and general subjects that are currently being investigated.

CLEO, AGE: 11

My name is Cleo, I am interested in science and technology, I like to study wildlife and have rescued some native creatures before. Science about living things is very interesting to me.

SHWETHAKIE, AGE: 11

My name is Shwethakie and I am 11 years old. I love reviewing papers with others and seeing what their perspective is and how it is different to mine. I will enjoy learning about new topics with others as well!

AUTHORS

DIMÍTRI DE ARAÚJO COSTA

Dimítri has had an affinity for marine life since his childhood, having awakened to research during his adventures on the beach. He was impressed by the diversity found in these red rocks, during his undergraduate course in Biological Science, and thus began researching the animals that inhabit the rhodoliths in Brazil. He is interested in taxonomy, ecology, and seeks to raise awareness for the protection of these marine creatures. He did his Ph.D. in Brazil, in partnership with Portugal, and currently works in CIIMAR (University of Porto) to continue his activities in research and education. *dimitri.costa@ciimar.up.pt

KARINA MASSEI

Recognizing the greatness of the ocean, Karina grew up connected to the blue immensity through surfing, doing biathlons, and diving. She graduated in marine biology, environmental education, and is a yoga teacher. With her extensive knowledge on the sea, she founded InPact in the northeast of Brazil with colleagues from the environmental area. They focus on the rehabilitation of marine species, eco-pedagogical nautical tourism activities and launch coral reef monitoring programs.

ANA MOURA

Ana loves the ocean ever since she was a little child: its dimension and mysteriousness intrigued her. She became a marine biologist to be able to learn more about the ocean. Ana has been studying how fish population dynamics reflect the changes that are happening in the planet and the sea, and in what way fisheries can adapt to ensure sustainability. Currently, she is a Ph.D. student at CCMAR in the University of Algarve, working closely with the Portuguese Institute for the Sea and Atmosphere (IPMA).

MARTIN LINDSEY CHRISTOFFERSEN

Martin has always been fascinated by animals. Even though he did a undergraduate degree in biomedical sciences, he became truly happy when enrolling in the Biological Science curriculum. After specializing in earthworms, he moved on to investigating marine crustaceans. After an International Training Program in the Marine Science, USA, he settled in a smaller coastal city, and became a professor. His research interests center around invertebrate taxonomy, metazoan phylogeny,

macroevolutionary theory, and interdisciplinary applications of evolutionary theory in the social sciences and humanities.

MARINA DOLBETH

Marina grew up near the sea and soon fell in love with the little creatures hidden in the rocks. She became a marine ecologist, studying how the biodiversity of coastal ecosystems helps them to be resistant to damage caused by human activities or climate change. Currently, she is a Ph.D. assistant researcher at CIIMAR at the University of Porto.

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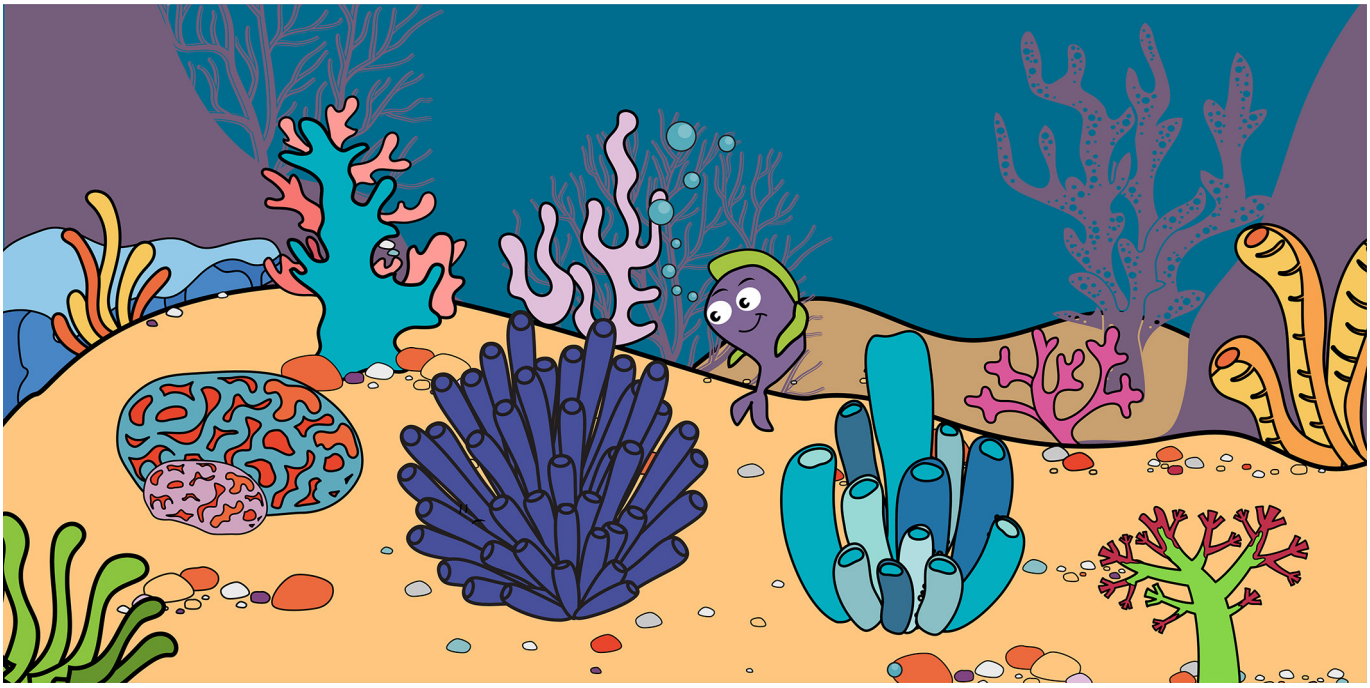

ARE ALL SPONGES SPONGY?

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YOUNG REVIEWER:

JUNIPER
AGE: 9

Sponges are animals that live in oceans, lakes, and rivers. There are close to 10,000 sponge species described by scientists, but far more species await discovery! However, not all sponges look and feel like their kitchen-sink cousins. Over time, sponges have evolved into many sizes and shapes, giving us the huge diversity of sponge species on Earth today. For example, many sponges are rock-hard! These rock sponges use minerals like silica (glass) to build their skeletons—instead of bone like ours. Other sponges have evolved unique ways to eat. Most sponges filter water to get their food, but certain sponges are carnivorous, meaning that they eat meat, including tiny shrimp-like creatures. Sponge species with different body and skeleton shapes and sizes can thrive in very different and unique environments.

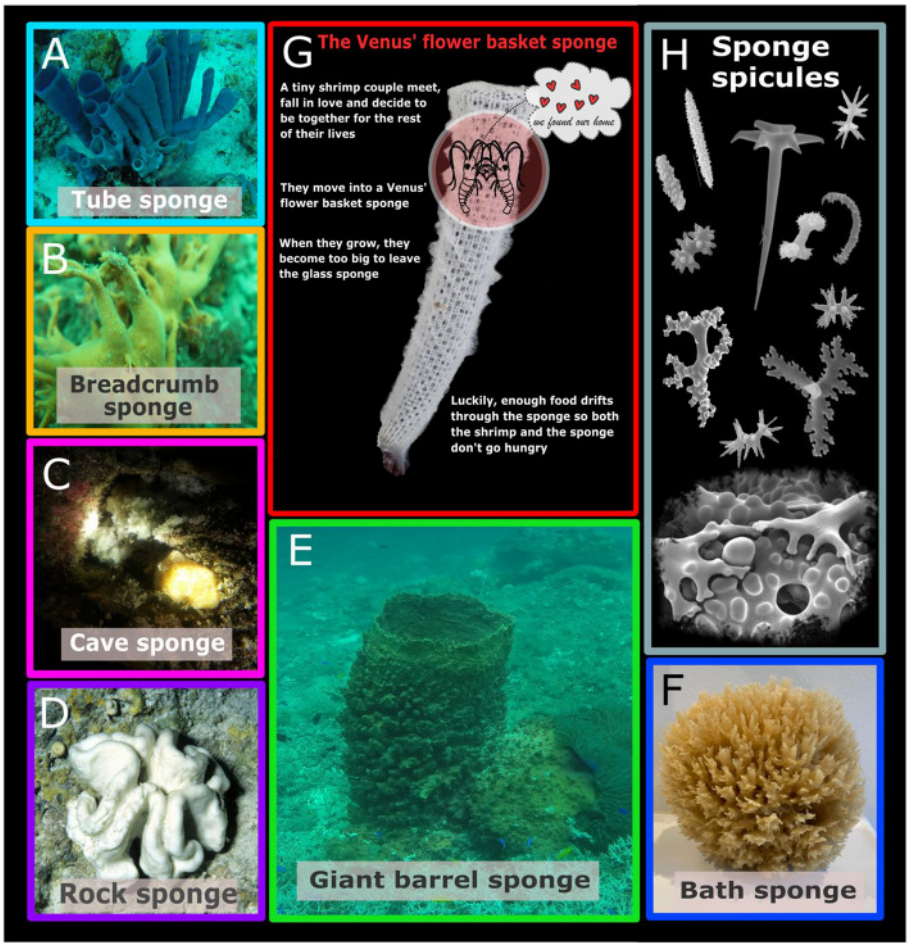

Figure 1

(A–F) Examples of various-shaped sponges and their common names. **(G)** The Venus' flower basket sponge provides a home for tiny shrimps. **(H)** Spicules are microscopic structures, made of silica (glass) or calcium carbonate (similar to limestone), that make up a sponge's body. Notice the many unique shapes of the spicules.

WHAT IS A SPONGE?

Have you ever looked closely at a living sponge? Although they may look more like plants or fungi, sponges are actually animals. Sponges live in waters all around the world, from the deep seas of the Arctic and Antarctic to the shallow and warm tropical seas, as well as in rivers, streams, ponds, and lakes [1]. Adult sponges do not move around—they are fixed to the bottom of the seafloor, on rocks, or on other sandy or hard underwater surfaces (Figure 1).

Unlike humans, sponges do not have stomachs, organs, backbones, or blood. Still, they are multicellular animals, which means that they are made up of many cells that work together, like in the human body. If you put a sponge in a blender, the cells can recognize each other afterwards and reform into tiny sponges! Sponges are the only animals that can rebuild themselves if they are torn apart!

Sponges have many different sizes and shapes. They can be huge and round, or make thin crusts on rocks, or even look like vases or cups (Figures 1A–F). Larger sponges can also serve as homes for other animals like fishes, turtles, and shrimps (Figure 1G).

The sponge body is made of holes and channels through which water is pumped and filtered to obtain particles of food. Because they filter the water, sponges are called **filter feeders** [2]. Some sponges can filter up to 50,000 times their own volume in a day. This would be like an average-sized person drinking 3,500 l (or 925 gallons) of water in a day! Due to this water flow through their bodies, sponges are very important in marine ecosystems.

FILTER FEEDERS

Are animals that feet on food particles from the water. Examples are sponges, baleen whales and sharks.

How do sponges filter so much water? Within their tissue, they have chambers that are lined with special cells that have tail-like appendages called **flagella**. These tails all wiggle around together to create a water current through the sponge body. This current makes the water flow through the sponge and provides the sponge with food and oxygen. This explains why most sponges are full of tubes and holes: they allow the water to flow around inside the sponge [2].

FLAGELLA

Wildly whipping tail structures keeping the water moving inside the sponge body.

WHAT MAKES A SPONGE SPONGY OR ROCK-LIKE?

Some sponge species have lots of tiny, hard parts called **spicules** that assemble into a skeleton and make their bodies stiff. Spicules are made of either calcium carbonate (similar to limestone) or silicon dioxide (quartz/glass), and they come in a dizzying variety of shapes and sizes (Figure 1H). A single sponge can contain several different types of spicules [2]. Spicules are what make some species "spongy" and others "rock-like." Sponges without spicules are generally the most squishy and spongy, like our bath sponge (Figure 1F). Although most modern kitchen and bath sponges are made of plastic, sponges without spicules, like the Mediterranean bath sponge *Spongia officinalis*, have been used by humans for thousands of years as cleaning tools, among other uses. These are the species that kitchen sponges try to mimic. Other sponges have evolved dense skeletons packed with hard spicules. Some of these spicules can form an interlocked network that makes the sponge hard as a rock, and they are unsurprisingly known as rock sponges (Figure 1D) [3]. These spicules are very strong, but they can still be bent, and light can pass through them. This combination of properties makes spicules very interesting to both materials scientists and biologists.

SPICULES

A tiny structure made up of minerals that serves as a piece of the skeleton of sponges and other marine or freshwater animals.

Sponges can look very similar when we hold them in our hands, so scientists called **taxonomists** need to look closely for unique characteristics to tell species apart from one another. Spicules play a very important role in this process because they are unique and can be used to identify different species. Spicules can even be used to identify totally new species of sponges. There are over 9,350 known sponge species in the world. Each of these species has either a distinctive set of spicules or, if the sponge is soft, no spicules at all [3].

TAXONOMISTS

A scientist who groups organisms into categories and studies the relationships between various types of organisms.

Figure 2

A series of images taken over time, showing a small carnivorous sponge (1–3 cm in length) in an aquarium. The sponge catches two tiny shrimps with its hook-like spicules. Although the "arms" are large enough to be seen with the naked eye, the spicules that line the arms are so small that they can only be seen under a microscope (Image credit: J. Vacelet).

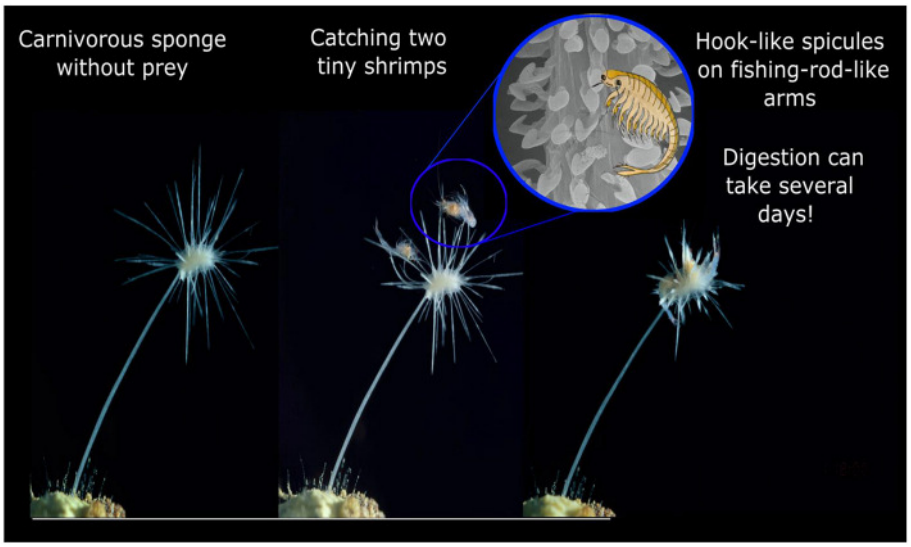

Figure 2

THE CURIOUS CASE OF CARNIVOROUS SPONGES

In addition to making some sponge species rock-like, evolution has also driven other changes in sponges over many millions of years. Although most sponges are filter feeders, certain species have developed techniques to eat larger prey, such as larvae and crabs (Figure 2). These are called **carnivorous** sponges, meaning that they eat meat. Carnivorous sponges have lost the ability to filter food from the water.

CARNIVOROUS

If an animal feeds on other animals tissues, meaning eating its meat, it is called a carnivorous animal.

Most carnivorous sponges live in the deep-sea at depths of more than 4,000 m (13,123 feet). In some regions, these sponges are the most common animals, surviving the cold, dark, crushing pressures of the deep ocean. Scientists think that eating meat is a tactic certain sponges use to survive when other ways of finding food do not work. A similar strategy is used by some plants, like the Venus fly trap, which evolved carnivory to live in food-poor habitats.

Carnivorous sponges generally have long fishing-rod-like "arms" lined with hook-like spicules that are used to capture prey. The spicules work like hook-and-loop fasteners, like Velcro or the seeds that get stuck to you when you walk outside. Prey animals caught in these hooks are slowly digested by the sponge. Sponges catch their food slowly, and it can take them several days to digest their catch.

It is not clear when this unique feeding mechanism evolved, but scientists think that carnivorous sponges have been on Earth for at least 60 million years, meaning that they appeared just after the dinosaur age ended. Since then, at least 150 sponge species have evolved to be carnivorous to survive in extreme, food-poor environments such as the deep sea [4].

Figure 3

(A) Example of a fossil exploration site near Albufeira in the South of Portugal, where loose rock sponge spicules were found within white rocks. **(B)** Bodies of preserved fossil sponges of various shapes and ages. **(C)** A nearly whole fossil rock sponge skeleton, after treatment with acid to remove the stony part around the skeleton.

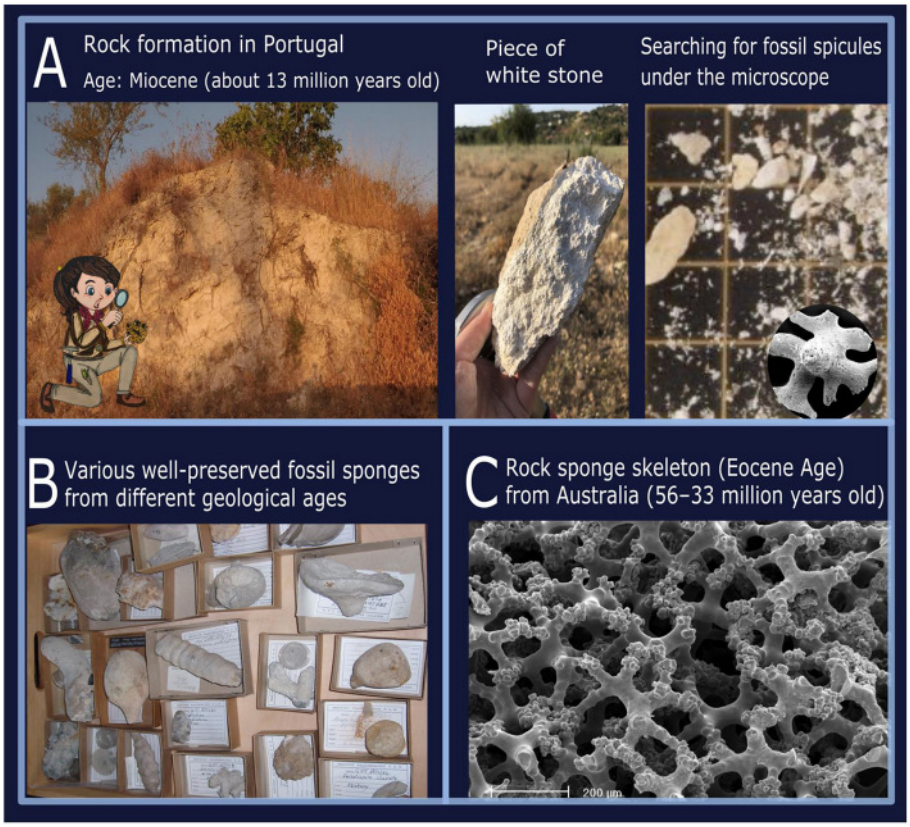

Figure 3

SPONGES HAVE BEEN ON EARTH FOR MORE THAN 550 MILLION YEARS!

It is likely that sponges were the first animals that evolved on Earth. However, not all sponge groups have survived since then. Some species went extinct, while others adapted (like the carnivorous sponges) to survive harsh climatic conditions such as decreased oxygen in the water and increased temperatures caused by global warming. To date, Earth has experienced five big extinction events, and one of the biggest occurred 250 million years ago, before the dinosaurs even existed. This extinction is known as The Great Dying. During The Great Dying, 90% of all ocean life went extinct. It was a harsh time for sponges, and only a handful of species survived. One of the surviving groups was the rock sponges.

PALEONTOLOGISTS

A scientist who studies fossils and the history of life on Earth.

Paleontologists that work with fossils know that rock sponges made it through The Great Dying because scientists have found the skeletal remains of these sponges from the Cambrian Period (about 550 million years ago) onwards throughout the Earth's history. In the fossil record, the skeletons of rock sponges remain largely whole and can be used to identify rock sponges even after millions of years (Figure 3). This is very unique among sponges. Most other "spongier" sponges that have only a few loose spicules or no spicules at all are less preserved in

FOSSIL RECORD

Remains of animals and plants that lived in the past (fossils) and their placement in the rock formation (record).

the **fossil record** because they do not have a formed skeleton. This means that even if paleontologists do find the spicules of these softer sponges, it is much more difficult to identify the species—a bit like finding just a little finger bone instead of a whole skeleton [5].

CONCLUSIONS

The species of sponges that we humans use and are most familiar with are just a few examples of the numerous diverse groups of sponges that exist in nature. Sponges have adapted to lots of different habitats and environmental changes over hundreds of millions of years. These adaptations helped them outlive not only the dinosaurs, but also many other plant and animal species.

Although sponges have various body shapes, colors, and spicule shapes, they still are some of the simplest animals that exist. Nevertheless, from the fossil record, we know that sponges were quite abundant in the past and they are still plentiful today. Like many other animals, sponges are affected by human activities. This means that sponges can be harmed by climate change, pollution, and over-fishing. As we take steps to protect our oceans from these man-made threats, we should be sure to remember the sponges and include these ancient and fascinating animals in our conservation plans.

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JUNIPER, AGE: 9
Juniper is a horse lover, avid reader, and an amazing skier. She also loves mountain biking and camping, and her favorite subject is science.

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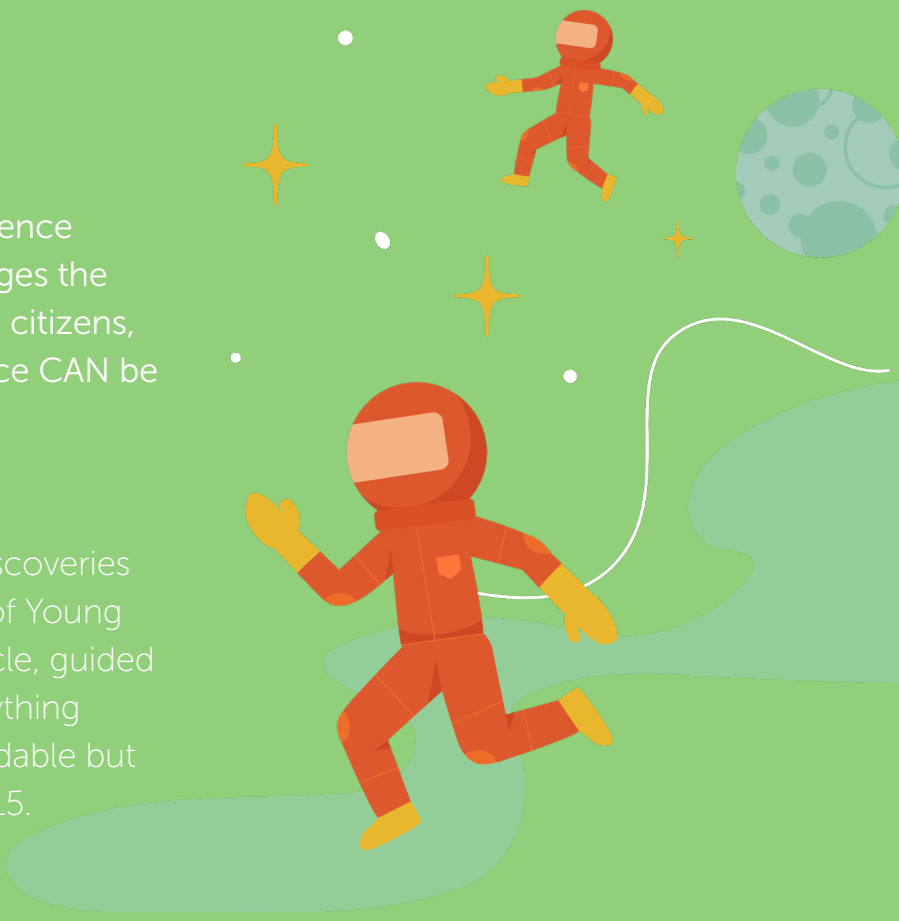

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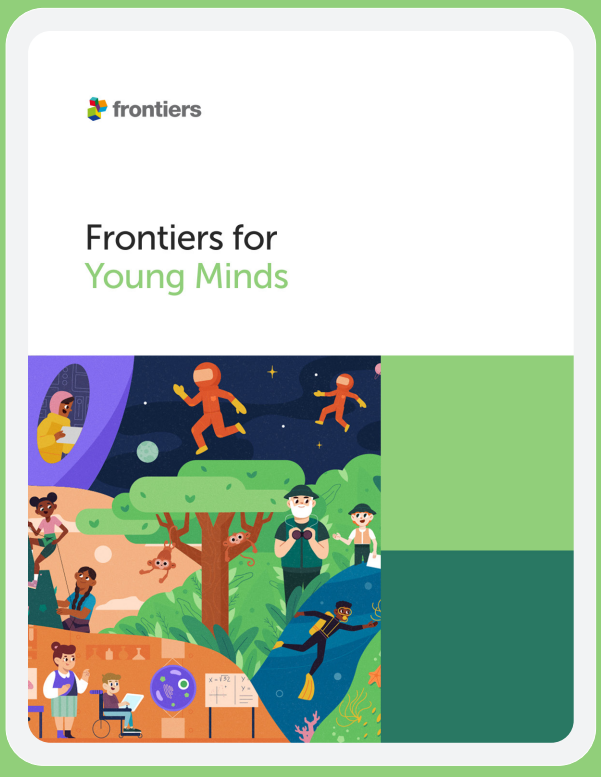

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