Frontiers for Young Minds

The Ocean, volume 5

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ISSN 2296-6846
ISBN 978-2-8325-6552-0
DOI 10.3389/978-2-8325-6552-0

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The Ocean, volume 5

Collection editors
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Citation
Claustre, H., Scheurle, C., Lorenzoni, L., Chiba, S., King, E., eds. (2025). *The Ocean, volume 5.* Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-6552-0

Cover image
FourPlus Studio

Participating sections

Earth Sciences

Biodiversity

About this collection

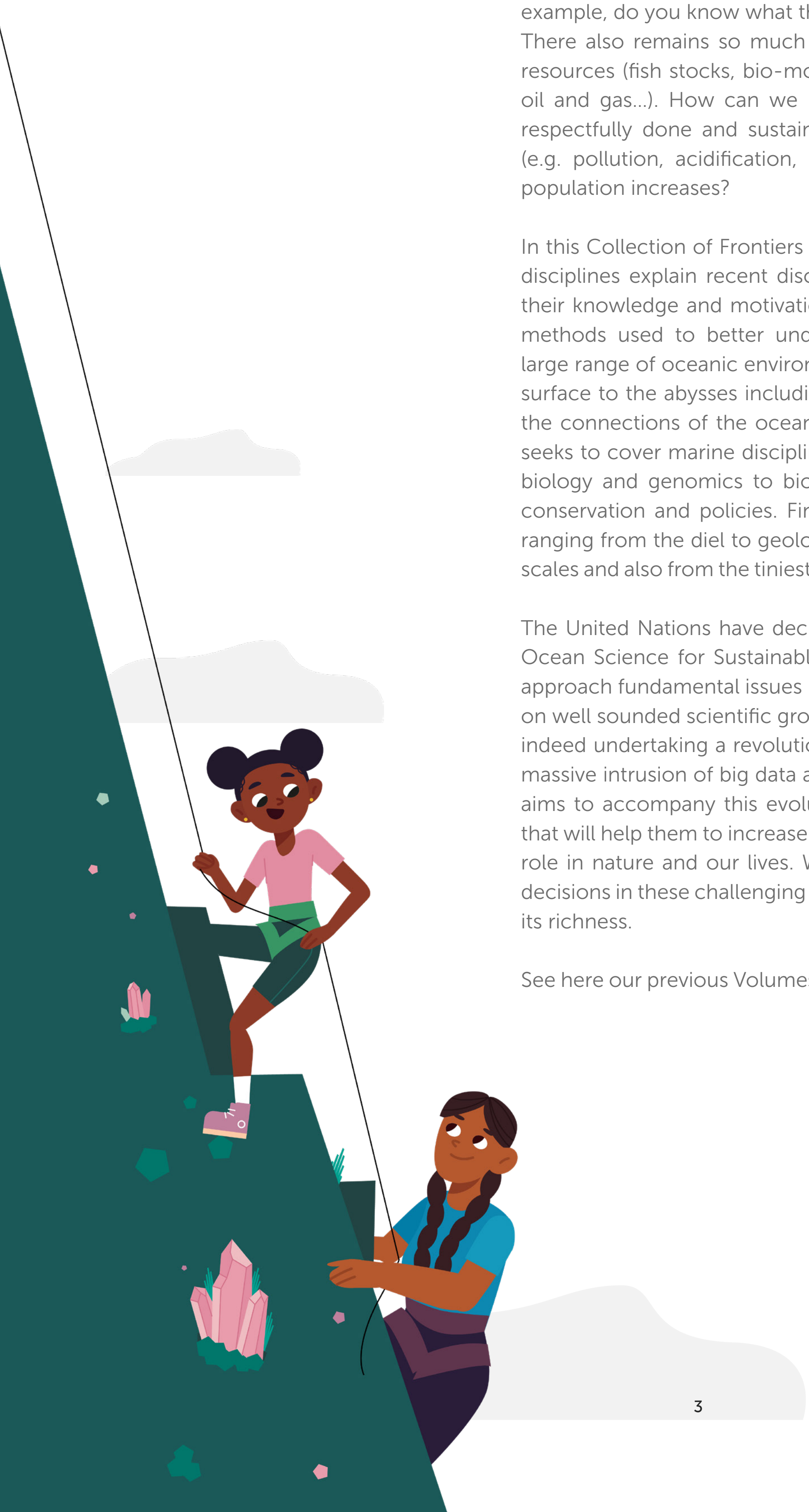
The ocean allowed life to develop on earth billions of years ago, it is vital for all of us and it will guarantee the future of humanity. The ocean is vast, deep, harsh and somehow “rebellious” to reveal its secrets and hence, there is much that is unexplored and not yet understood.

Scientists need to study the ocean to better understand its functioning, its properties, as well as how it shapes our environment and impacts us. For example, do you know what the role of the ocean is on weather and climate? There also remains so much to explore and investigate as diverse oceanic resources (fish stocks, bio-molecules, renewable energies but also minerals, oil and gas...). How can we make sure that our use of these resources is respectfully done and sustainable and how can we minimize our impacts (e.g. pollution, acidification, deoxygenation) on the ocean as our human population increases?

In this Collection of Frontiers for Young Minds, ocean scientists from various disciplines explain recent discoveries or fundamental concepts. They share their knowledge and motivations and give insights into innovative tools and methods used to better understand our ocean. The Collection targets a large range of oceanic environments from the open ocean to the shores, the surface to the abysses including specific areas like coral reefs. It also targets the connections of the ocean with its interfaces (atmosphere, ice, coast). It seeks to cover marine disciplines that range from physics to chemistry, from biology and genomics to biodiversity and ecology, and from economy to conservation and policies. Finally, it encompasses a great variety of scales, ranging from the diel to geological time-scales, 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. The oceanic sciences are indeed undertaking a revolution thanks, in particular, to robotization and the massive intrusion of big data and artificial intelligence. This Ocean Collection aims to accompany this evolution 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, Volume 2, Volume 3 and Volume 4!



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BIODIVERSITY
Published: 10 June 2025
doi: 10.3389/frym.2025.1472709

DO YOU KNOW THAT THERE ARE FUNGI IN THE OCEAN?

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YOUNG REVIEWERS:

ALEX
AGE: 10

Did you know that fungi, like mushrooms and molds, are super important for our planet? Fungi can form critical relationships with other organisms. For example, many plants rely on fungi to help them grow and thrive. However, fungi are not always friendly and sometimes they can hurt plants by causing disease. Did you also know that there are fungi in the ocean? While you might not be able to see these fungi when you go to the beach (because they can only be seen with a microscope), they are found everywhere in the ocean. Marine fungi are pretty cool, but we do not know a lot about them yet or what roles they play in the ocean. Scientists are starting to learn more about how marine fungi help the ocean and

keep our planet healthy. This article will explore the amazing world of marine fungi!

WAIT—THERE ARE FUNGI LIVING IN THE OCEAN?

What kinds of organisms do you think of when you imagine a beach? You probably think of dolphins, starfish, sea anemones, or maybe even sharks... but did fungi make your list? Marine (ocean) fungi are different from the mushrooms you normally see on land. One of the reasons scientists did not know about marine fungi for so long is that no one has ever seen a marine mushroom! Instead, the fungi in the ocean are microscopic and live "secret" lives.

So far, <1% of marine fungi have been identified, although scientists estimate that there are over 10,000 types of marine fungi living in Earth's oceans [1]. Some of these fungi are called **obligate marine fungi**, because they have only been found living in the ocean. Many obligate marine fungi have adapted specifically to life in the ocean and some even form important relationships with other organisms, like seaweeds, sponges, corals, and seagrasses. Marine fungi can be found everywhere, from the waves breaking on the beach, down to the hydrothermal vents of the deep seafloor. However, when examining the ocean, scientists have also found fungi that commonly live on land. Scientists are unsure whether these land-based fungi are playing active roles in the ocean, or whether they are just using the ocean to travel to distant lands. Fungi that can survive both on land and in the ocean are called **facultative marine fungi**.

While most marine fungi are microscopic and no marine mushrooms have been observed to date, there is one place where scientists have found macroscopic marine fungi, which means organisms that *can* be seen with the naked eye [2]. These fungi exist in the form of lichens, which are a **symbiosis** between bacteria and fungi. In their symbiosis, these microscopic organisms work together to form the macroscopic lichen. You can see lichens living on rocks along the coastlines. Next time you go to the beach at low tide, look at the rocks and try to find some marine lichens (Figure 1)!

WHAT DO FUNGI NEED TO SURVIVE IN THE OCEAN?

Living in the ocean is not easy. There are several **adaptations** that marine fungi need to be able to survive in the ocean environment. Adaptations are traits that organisms gain to help them survive better in a certain environment. Adaptations needed by marine fungi include high salt tolerance (the ocean is salty!), protection from the sun's dangerous ultraviolet light, a way to stay alive when food is limited, ways to withstand the high pressure of living in the deep sea, and the ability to spread and reproduce in the ocean ecosystem. The need

OBLIGATE MARINE FUNGI

Fungi that can only live in a marine environment.

FACULTATIVE MARINE FUNGI

Fungi that live in freshwater or on land, but that can also grow and survive in marine environments.

SYMBIOSIS

A close, long-term relationship between two or more organisms.

ADAPTATION

A natural process in which an animal or plant becomes better suited to its environment by gaining new traits that make it more successful.

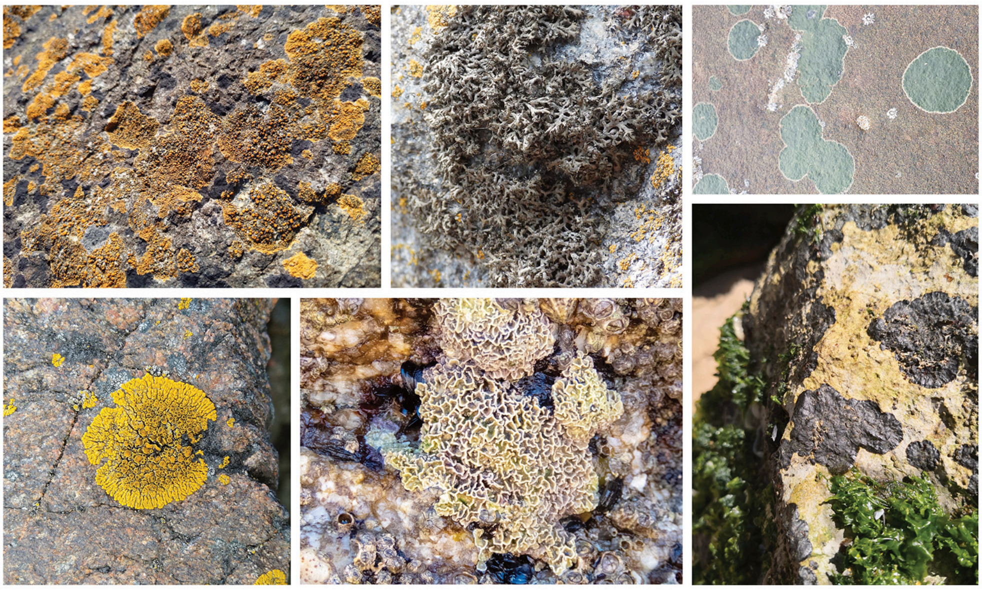

Figure 1

Figure 1

Coastal marine lichens come in many shapes, colors, and sizes. In some places, you can see them on rocks or cliffs along the beach. They can also be found on rocks under the water, but you will need to wait for a low tide to see them or you will get wet [photos from iNaturalist: © Chris McKee (CC-BY 4.0), Vesa Oikonen (CC0 1.0), Paco Bergson (CC-BY 4.0), Mikko Heikkinen (CC0 1.0), Óscar Sampedro (CC-BY 4.0), and Noa Nieto (CC-BY 4.0)]!

for so many adaptations makes facultative marine fungi particularly interesting. To transition from life on land to life in the ocean, these fungi need to be good at a lot of things.

ARE MARINE FUNGI FRIENDS OR FOES?

One way marine fungi survive in the ocean is by associating with other organisms, like the symbiosis that forms marine lichens. However, these relationships are complicated and are not always positive. Some marine fungi are **parasites**, meaning they live inside or on other organisms and, like tiny vampires, take nutrients away from that host organism. Parasitic marine fungi play an important role in the ocean by killing other marine microbes, releasing their nutrients into the seawater as food for other organisms [3].

PARASITE

Any organism that lives inside of or attached to another organism which it uses for food, like a vampire, harming the organism it infects.

PATHOGEN

Any organism that can cause a disease or harm the organism it infects.

In addition to parasitic fungi, other marine fungi can also cause diseases. For example, a marine fungal **pathogen** called *Fusarium* is killing sea turtles and infecting their eggs. These pathogenic fungi grow in sea turtle nests, covering the surface of the eggs and making chemicals that break down the eggshell. The infected eggs become yellowish-blue and die. The eggs generally become infected through contact with contaminated beach sand. However, scientists have recently seen that pathogenic fungi can be transported from land into the ocean by floating particles of plastic and by contaminated plant parts, such as wood and leaves, that are carried to sea turtle nests by the water and wind [4]. These fungal foes are reducing the numbers of marine turtles that hatch. By working to detect *Fusarium* in the environment, scientists are trying to understand how to prevent turtles from getting fungal infections.

However, lichens teach us that not all marine fungi are foes—some are friends! Many fungi that live on land have important relationships with plants, but for a long time scientists did not know if marine plants had any fungal friends. Scientists have recently found that some seagrasses form relationships with marine fungi [5, 6]. While the specifics of these friendships are still being researched, the symbiosis looks similar to that of land plants and their fungi, so scientists believe the relationships are likely to help seagrasses thrive.

WHY HAVE I NEVER HEARD OF MARINE FUNGI?

If marine fungi are new to you, do not worry—many scientists have not heard of marine fungi either! Studying these fungi is difficult. First, many marine fungi are microscopic, making them hard to find and study. While scientists have had some success taking ocean samples to the laboratory to try to grow and study marine fungi (Figure 2), these fungi often need very specific food, which can be tricky to make in the lab. How can scientists study something they cannot see or grow?

Figure 2

Figure 2

Scientists can grow some microscopic marine fungi in the lab, like these from seagrasses, by giving them specific food. The fungi grow so much that they become visible to our eyes. Scientists can then study these fungi to learn more about them. However, this process is very tricky, as not all fungi like the same food (photo © Cassie Ettinger).

To get around this challenge, scientists are now using **DNA sequencing** to look for marine fungi. This technique can be performed on ocean samples without the need to see or grow the fungus. DNA sequencing tells scientists which specific fungi are found in a certain

DNA SEQUENCING

The laboratory process of reading the genetic code in an organism's DNA.

place. Scientists can then compare this information to databases that were made from studying the fungi that live on land. However, this technique is still challenging because many marine fungi are newly discovered and do not match these databases. By collaborating and sharing methods and data, scientists can work together to describe marine fungi and bridge gaps in their knowledge of which marine fungi are present and what they might be doing in the ocean.

Another challenge is answering the question of whether facultative marine fungi should be considered true marine fungi. Scientists often find facultative marine fungi in samples collected far away from land [7]. While DNA sequencing has allowed scientists to survey marine fungal diversity in different locations, it cannot tell them what the fungi are doing in these locations, making it hard to know whether facultative marine fungi are truly living in the ocean. Many obligate marine fungi have recently gained the adaptations that allow them to survive in the ocean and they have close relatives that live on land, making it difficult to identify fungi that are actively growing in the ocean from those that are temporary tourists using the ocean to travel to distant lands.

ARE MARINE FUNGI IMPORTANT FOR OUR PLANET?

Even though scientists are still learning about marine fungi, they already know these organisms have crucial roles in the ocean. Some marine fungi can break down dead plants and animals by feeding on them. This process recycles nutrients, like carbon, back into the ocean, making the nutrients available for other marine life. Some fungi can even break down harmful substances like plastic or oil that find their way into the ocean. For example, ocean sites contaminated by oil spills can be cleared up by marine fungi that are effective at breaking down these complex compounds [3, 7]. Although a marine fungi-based solution to clean up plastic pollution has yet to be tried, plastic-eating fungi already exist in the oceans [3]. These fungi will be a great help in solving environmental pollution. Marine fungi also produce fascinating natural products called **secondary metabolites**, which might help fight human diseases. Scientists are researching whether secondary metabolites might be useful as medicines.

SECONDARY METABOLITES

Special chemicals made by fungi and bacteria to protect themselves, better survive in a new environment, or compete with others.

In summary, although scientists are still figuring out all the roles marine fungi play, we know that these ocean organisms are just as important as the fungi on land, and that studying them may lead to life- and planet-saving solutions. So, the next time you think about fungi, remember they are not just on land—they live in the ocean, too (Figure 3)!

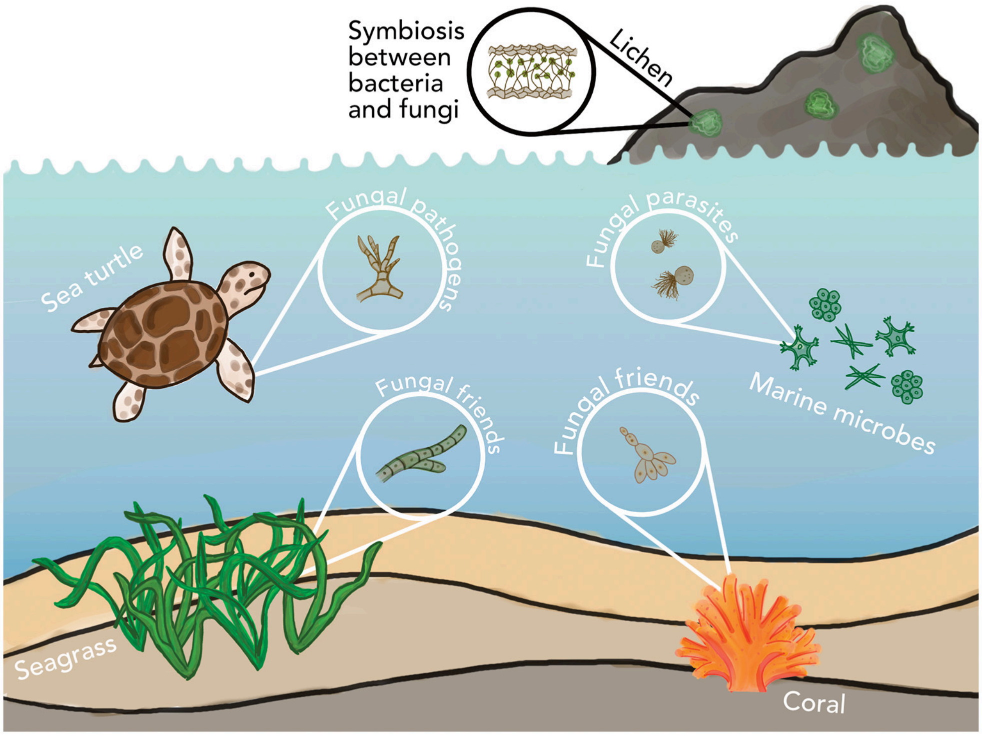

Figure 3

Figure 3

Marine fungi can be found everywhere in the ocean. Lichens are the visible (macroscopic) symbiosis between fungi and bacteria found along the coastlines. Other types of fungi are invisible to us (microscopic) and can form relationships with seagrasses and corals. Other marine fungi are harmful pathogens and parasites that can infect and kill sea turtles and other marine organisms.

ACKNOWLEDGMENTS

JA was supported by the NSF REU the National Summer Undergraduate Research Project, Award No. 2149582. JS is a CIFAR Fellow in the program Fungal Kingdom: Threats and Opportunities and was partially supported by NSF awards EF-2125066 and IOS-2134912. CE was supported by the National Science Foundation (NSF) under a NSF Ocean Sciences Postdoctoral Fellowship (Award No. 2205744).

REFERENCES

1. Gonçalves, M.F. M., Esteves, A. C., and Alves, A. 2022. Marine fungi: opportunities and challenges. *Encyclopedia* 2:559–577. doi: 10.3390/encyclopedia2010037
2. Cunliffe, M., 2023. Who are the marine fungi? *Environ. Microbiol*. 25:131–134. doi: 10.1111/1462-2920.16240
3. Gladfelter, A. S., James, T. Y., and Amend, A. S. 2019. Marine fungi. *Curr. Biol*. 29:R191–R195. doi: 10.1016/j.cub.2019.02.009
4. Gleason, F. H., Allerstorfer, M., and Lilje, O. 2020. Newly emerging diseases of marine turtles, especially sea turtle egg fusariosis (SEFT), caused by species in the *Fusarium solani* complex (FSSC). *Mycology* 11:184–194. doi: 10.1080/21501203.2019.1710303
5. Fraccaro de Marins, J., and Carrenho, R. 2017. Arbuscular mycorrhizal fungi and dark septate fungi in plants associated with aquatic environments. *Acta Botanica Brasilica* 31:295–308. doi: 10.1590/0102-33062016abb0296

6. Vohník, M., Borovec, O., Kolaríková, Z., Sudová, R., and Réblová, M. 2019. Extensive sampling and high-throughput sequencing reveal *Posidoniomyces atricolor* gen. et sp. nov. (Aigialaceae, Pleosporales) as the dominant root mycobiont of the dominant Mediterranean seagrass *Posidonia oceanica*. *MycoKeys* 55: 59–86. doi: 10.3897/mycokeys.55.35682
7. Amend, A., Burgaud, G., Cunliffe, M., Edgcomb, V. P., Ettinger, C. L., Gutiérrez, M. H., et al. 2019. Fungi in the marine environment: open questions and unsolved problems. *mBio* 10:e01189–e01118. doi: 10.1128/mBio.01189-18

SUBMITTED: 29 July 2024; **ACCEPTED:** 07 May 2025;
PUBLISHED ONLINE: 10 June 2025.

EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Fei Peng

CITATION: Arroyo J, Stajich JE and Ettinger CL (2025) Do You Know That There Are Fungi in the Ocean? Front. Young Minds 13:1472709. doi: 10.3389/frym.2025.1472709

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

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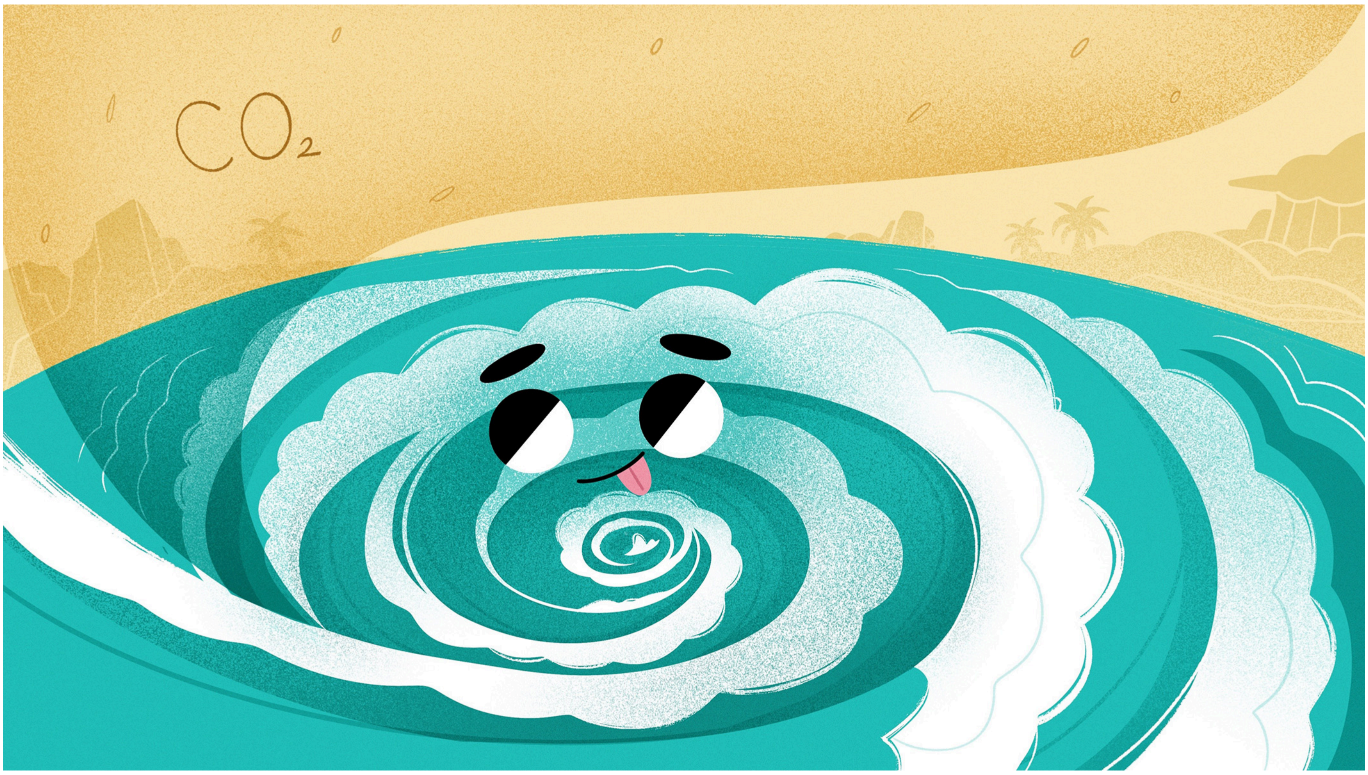
EARTH SCIENCES
Published: 30 May 2025
doi: 10.3389/frym.2025.1471573



CAN OCEAN SWIRLS HELP FIGHT CLIMATE CHANGE?

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AGE: 14

Carbon dioxide (CO_2) is a gas that is important for plants and helps keep our planet warm. Too much CO_2 in the air can cause climate change. Small, spinning currents in the ocean, called eddies, play a huge role in moving CO_2 between the ocean and the air. These ocean eddies can change the amount of CO_2 moving in and out of the ocean by more than 30% in some areas. Depending on how they move through the water, eddies can either help to take carbon dioxide from the air into the ocean or move it out of the ocean into the air. Understanding how ocean eddies work is super important for knowing how the ocean helps manage CO_2 and fights climate change. By studying these swirling currents, scientists can better predict how the ocean will respond to a changing climate and how it will continue to support life on Earth.

THE OCEAN ACTS AS A GIANT SPONGE FOR CARBON DIOXIDE

The ocean acts as a giant sponge for carbon dioxide (CO_2), playing a crucial role in fighting climate change. Every year, the ocean absorbs about 26% of the CO_2 released into the air from activities such as burning fossil fuels to make electricity, cutting down forests, and manufacturing cement. This means that the ocean takes in a massive amount of CO_2, helping to reduce the greenhouse gases in the air that contribute to global warming. By soaking up this extra CO_2, the ocean helps to keep our planet's climate more stable. Without the ocean's ability to absorb CO_2, climate change would be much more severe, making the ocean's role in managing carbon dioxide essential for a healthy Earth.

CARBON SINK

An ocean area that absorbs and stores carbon dioxide from the air.

CARBON SOURCE

An ocean area that releases carbon dioxide (CO_2) into the air.

EDDIES

Small, spinning currents in the ocean, like mini whirlpools, that moves water and nutrients around.

The amount of CO_2 that moves back and forth between the air and the ocean changes depending on factors such as changing seawater temperatures. If an ocean region takes in CO_2, it is called a **carbon sink**. If it releases CO_2 into the air, it is called a **carbon source**. Scientists measure this CO_2 exchange with electronic sensors, but these measurements are usually taken in small areas. Studies that cover much larger areas of Earth's oceans often have less detail and can miss out on important processes. This means we might not fully understand how much small changes in the ocean help with CO_2 absorption. By learning more about these small changes, we can better understand how the ocean helps keep our planet healthy. Ocean **eddies** are one cause of these small changes.

WHAT ARE OCEAN EDDIES?

GULF STREAM

A strong, warm ocean current in the Atlantic Ocean that flows from the Gulf of Mexico along the eastern coast of the United States and across the Atlantic to Europe.

Imagine the ocean is like a large bowl of soup. When you blow on the soup, it creates swirling patterns on the surface. Similarly, the wind blows across the ocean, creating small, spinning circles of water called eddies (Figure 1). Eddies in the ocean are often created by the twisting and turning of powerful currents, such as the **Gulf Stream**, which flows along the U.S. East Coast. When these strong currents meander or waver, they can create a sort of swirling disturbance in the water. Over time, this swirling disturbance can become more pronounced and eventually "break off" from the main current, forming a circular eddy. Although they can be 200 km wide, eddies are considered small compared to the vastness of the global oceans—the Pacific Ocean, for example, is about 20,000 km wide! Eddies move warm water to cold places and cold water to warm places, mixing things up in the ocean. This helps tiny sea creatures and nutrients travel around, making the ocean a healthier place for all the fish and animals that live there. It is like the ocean's way of stirring its big soup pot, to keep everything balanced and lively!

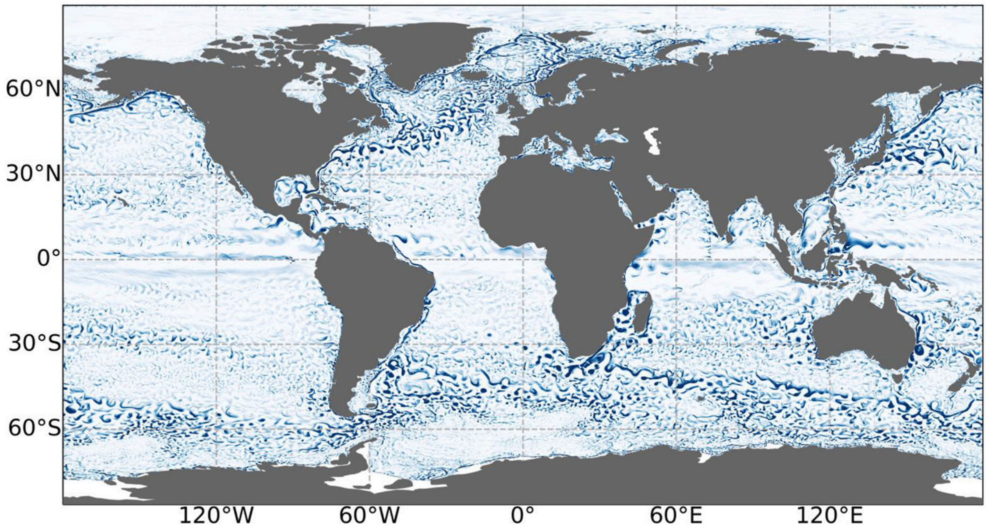

Figure 1

Figure 1

A global map showing swirling currents, called eddies, in the ocean. The blue colors represent how strongly the water is spinning, with the darkest blue showing us where the eddies are located.

EDDIES MOVE CO_2 BETWEEN THE AIR AND OCEAN

Scientists are still learning how ocean eddies affect how much CO_2 moves between the ocean and the air. It is tricky to study these effects because there are not many measurements available, and studying eddies is complex and computer intensive. Recent research has shown that in some parts of the ocean, eddies are good at pulling CO_2 into the ocean [1]. However, scientists are still trying to figure out exactly how eddies influence ocean CO_2 absorption as a whole, across all the world's oceans. There are still lots of questions to answer, like whether eddies make certain areas of the ocean better at capturing CO_2 from the air or whether our current studies might be missing important details.

COARSE-GRAINING

A method to look at the big picture by combining smaller details into larger groups.

AIR-SEA CO_2 EXCHANGE

The process by which CO_2 moves between the ocean and the air, helping to control the amount of CO_2 in the atmosphere, which influences climate change.

To investigate how eddies affect the exchange of CO_2 between the ocean and air, we use a method called **coarse-graining** [2, 3]. This technique helps us separate eddy features smaller than about 200 km across from larger-scale flows in the ocean, using a super-detailed ocean simulated with a powerful computer [4]. Using this simulated ocean, we can estimate how eddies contribute to **air-sea CO_2 exchange**, as shown in Figure 2. We found some interesting results.

Eddies make the biggest changes to CO_2 exchange in specific ocean regions, like areas near the poles and in the middle latitudes (30–45° latitude north and south) of the ocean where powerful currents meet. In these areas with lots of eddies, eddies are responsible for more than 30% of the variations in how much CO_2 is exchanged between the ocean and the atmosphere, influencing whether more CO_2 is absorbed or released. On the other hand, in quiet parts of the ocean, eddies hardly affect CO_2 exchange at all. This shows us

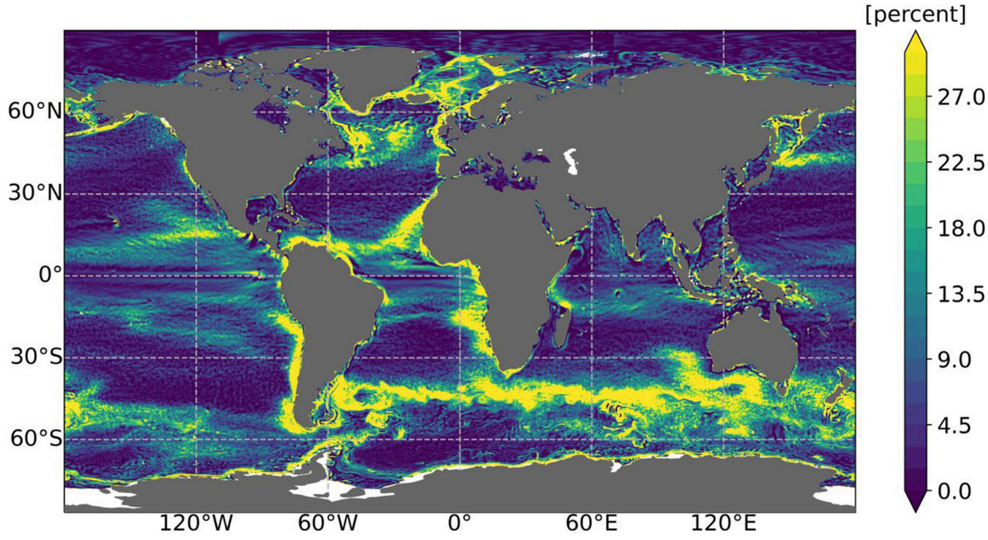

Figure 2

A global map showing how eddies affect how much CO_2 is exchanged between the air and the ocean. The colors tell us what percentage of the differences in air-sea CO_2 exchange is caused by eddies in any part of the world's oceans. For example, you can see that near Japan, in the Southern Ocean near Antarctica, and around the coasts of the United States and Brazil, eddies contribute to more than 25% of CO_2 exchange. In some areas, like near the equator, eddies play a smaller role, contributing around 5%. The yellow areas show where eddies strongly affect CO_2 exchange, while the dark blue areas show where their effect is smaller.

that understanding and studying eddies is really important to better understand how the ocean as a whole absorbs and releases CO_2.

HOW DO EDDIES IMPACT LOCAL CARBON ABSORPTION?

Now we know that ocean eddies cause some of the CO_2 movement between the ocean and the air. But the big question is whether these swirls help the ocean absorb more CO_2 (making the ocean a carbon sink) or release it into the air (making the ocean a carbon source). To figure this out, we analyzed all the oceans and found that, in some places, ocean eddies are helping the ocean absorb CO_2.

While in other places the eddies are causing the ocean to release CO_2 into the air (Figure 3). Taken altogether, eddies can affect the absorption/release of over 300,000 tons of CO_2 every year. That is equivalent to the amount of CO_2 that would be released by 30,000 car trips around the earth! This shows that the influence of these small ocean swirls on air-sea CO_2 exchange is large and can be very different from place to place in the ocean.

The ocean becomes a carbon source or a carbon sink because of how ocean eddies twist and turn in different ways. We found that if an eddy is spinning in a way that brings water with more CO_2 to a part of the ocean with less CO_2, the receiving part will get too much CO_2 and release it into the air. But if the eddy spins the other way, bringing water with less CO_2 to an area that does not have much CO_2, the ocean absorbs more CO_2 from the air. In short, the spinning of ocean eddies sets whether the ocean is a carbon source or sink, and these changes in different parts of the ocean.

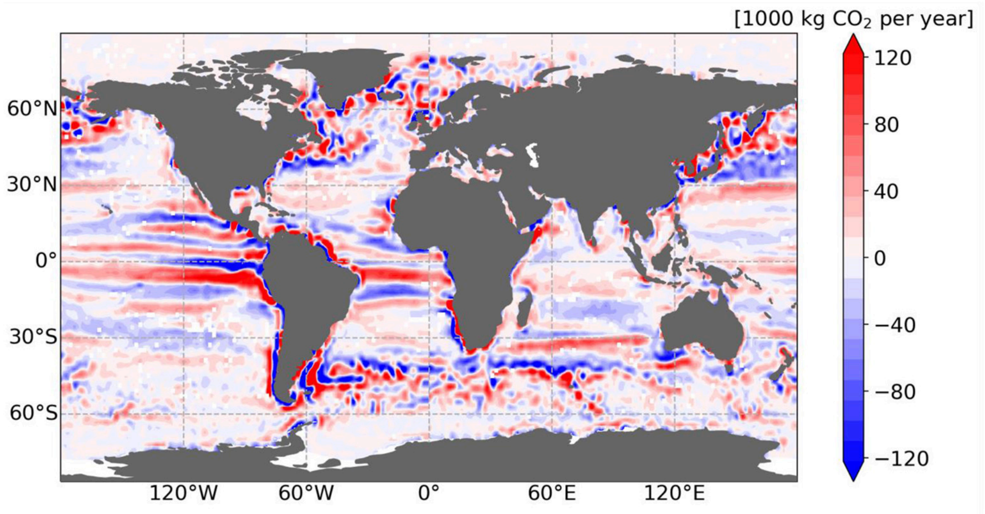

Figure 3

Figure 3

A global map showing how eddies affect the amount of CO_2 that the ocean absorbs or releases. Blue colors indicate where eddies help the ocean absorb CO_2, while red colors show where eddies help to release CO_2 from the ocean into the air. The darker the color, the more CO_2 is absorbed or released.

As the ocean gets warmer due to global warming, scientists think that eddies might become even more active and important in influencing how CO_2 moves between the ocean and the air [5]. For example, with more heatwaves in the ocean, higher ocean temperatures might make the swirling currents work differently, which could affect how much CO_2 gets moved around. To understand this better, scientists need to monitor the ocean more closely and improve their computer models to predict how eddies will influence our climate. Knowing more about ocean eddies will help us plan better ways to protect our planet from climate change.

ACKNOWLEDGMENTS

YG and M-LT were supported by the Yale Center for Natural Carbon Capture. The authors thank Elizabeth Grant for her valuable feedback, which improved this manuscript. Support for this research was provided by the Yale Center for Natural Carbon Capture. We would like to acknowledge high performance computing support from Cheyenne and Casper supercomputers provided by National Center for Atmospheric Research's Computational and Information Systems Laboratory, sponsored by the National Science Foundation.

ORIGINAL SOURCE ARTICLE

Guo, Y., and Timmermans, M.-L. (2024). The role of ocean mesoscale variability in air-sea CO_2 exchange: a global perspective. *Geophys. Res. Lett.* 51:e2024GL108373. doi: 10.1029/2024GL108373

REFERENCES

1. Ford, D. J., Tilstone, G. H., Shutler, J. D., Kitidis, V., Sheen, K. L., Dall'Olmo, G., et al. 2023. Mesoscale eddies enhance the air-sea CO_2 sink in the South Atlantic Ocean. *Geophys. Res. Lett.* 50:e2022GL102137. doi: 10.1029/2022GL102137
2. Guo, Y., and Timmermans, M. L. 2024. The role of ocean mesoscale variability in air-sea CO_2 exchange: a global perspective. *Geophys. Res. Lett.* 51:e2024GL108373. doi: 10.1029/2024GL108373
3. Storer, B. A., and Aluie, H. 2023. FlowSieve: a coarse-graining utility for geophysical flows on the sphere. *J. Open Source Softw.* 8:4277. doi: 10.21105/joss.04277
4. Guo, Y., and Timmermans, M. L. 2024. Global ocean pCO_2 variation regimes: spatial patterns and the emergence of a hybrid regime. *J. Geophys. Res.: Oceans* 129:e2023JC020679. doi: 10.1029/2023JC020679
5. Guo, Y., Bachman, S., Bryan, F., and Bishop, S. Increasing trends in oceanic surface poleward eddy heat flux observed over the past three decades. *Geophys. Res. Lett.* 49:e2022GL099362. doi: 10.1029/2022GL099362

SUBMITTED: 27 July 2024; **ACCEPTED:** 07 May 2025;
PUBLISHED ONLINE: 30 May 2025.

EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Gui Wei

CITATION: Guo Y and Timmermans M (2025) Can Ocean Swirls Help Fight Climate Change? Front. Young Minds 13:1471573. doi: 10.3389/frym.2025.1471573

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

SIYU, AGE: 14

Yu is an enthusiastic 14-year-old boy from Beijing who loves exploring and asking "why" and "how". Excelling in science and math, frequently discussing different problem-solving approaches with others. In his free time, Yu delves into books, documentaries, and online resources to find new topics and eagerly shares insights with friends. His passion for learning extends beyond academics as he visits museums and reads scientific books to enhance critical thinking and discover fresh perspectives on the world.

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BIODIVERSITY
Published: 26 March 2025
doi: 10.3389/frym.2025.1472723

ORGANISMS THAT CREATE HOMES FOR OTHER ORGANISMS ON MARINE SHORES

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YOUNG REVIEWERS:

VICTORIA
AGE: 10

The intertidal zone is a narrow strip along marine shores where the ocean meets land. Tides make this environment different from any other. Every day, low tides expose the intertidal zone to the air, while high tides completely submerge it. Given the daily alternation between dry and wet conditions, one would expect that very few species could live at the intertidal zone. Yet, it is common to find diverse and abundant communities there. How can so many organisms thrive in these stressful environments? The answer is foundation species. Foundation species, such as some bivalves, seaweeds, and seagrasses, often cover large areas of the intertidal substrate, and their body structures create 3-dimensional homes for smaller creatures. Not only do foundation species provide habitats, but they also protect smaller species from environmental stress, making an otherwise dangerous place substantially safer. This makes foundation species the heroes of stressful environments like the intertidal zone.

THE STRESSES OF THE INTERTIDAL ZONE

The ocean covers over 70% of the world's surface and includes many different ecosystems. Perhaps one of the most fascinating is the **intertidal zone**. The intertidal zone is the narrow strip on the shore that is fully covered by seawater at high tide and exposed to the air at low tide. This zone is relatively small compared to other marine environments, but it experiences unique challenges that are not present anywhere else.

Twice a day, every day, the tide changes. Therefore, the organisms living at the intertidal zone are forced every day to switch from being underwater to being exposed to the air and vice versa. During low tides, organisms must deal with environmental stresses resulting from being exposed to the air. For example, while water temperatures are relatively moderate, the air can be really hot in the summer or really cold in the winter. Additionally, intertidal creatures can lose a lot of water when they are in direct contact with the air. On the other hand, during high tides, organisms can be beaten by waves, which might damage or even kill them. Finally, intertidal organisms can be eaten by land-based predators such as birds and mammals when they are out of the water and by ocean-based predators such as fish when they are underwater (Figure 1).

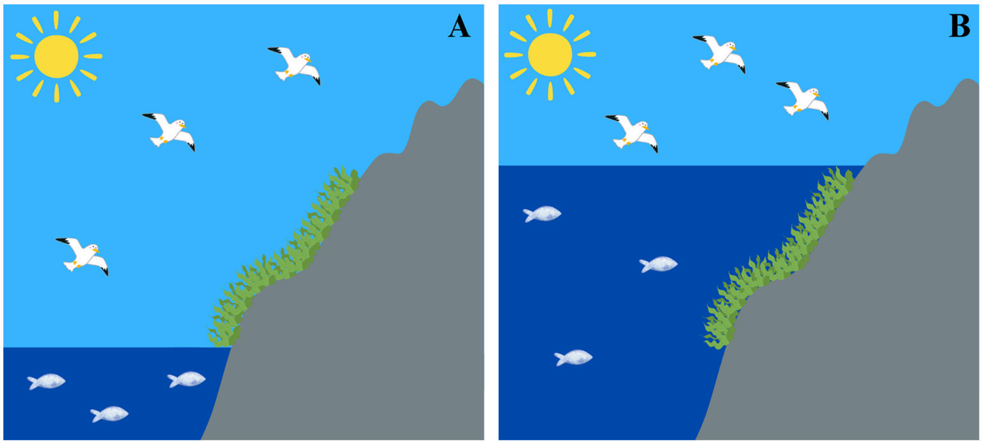

Figure 1

WHAT IS A FOUNDATION SPECIES?

In such a stressful environment, you might expect to find only a few hardy species. However, intertidal zones often have a high **biodiversity**. Why? One explanation is that many small species find refuge in populations of **foundation species**. Foundation species are organisms that typically occupy large areas of the **substrate**, and the 3-dimensional structures of their bodies create homes for many small organisms [1]. Think, for example, of the trees in a forest. Trees

INTERTIDAL ZONE

The narrow strip along a marine shore that is covered by seawater at high tide and exposed to the air at low tide.

Figure 1

The intertidal zone has different challenges depending on whether it is low tide or high tide. **(A)** At low tide, intertidal foundation species (such as the seaweeds shown here) form canopies that help many small organisms to avoid extreme air temperatures and water loss, and that protect them from predators such as birds. **(B)** At high tide, intertidal foundation species are fully under water and their canopies protect many small organisms from waves and predators such as fish.

BIODIVERSITY

Diversity of species and their genetic variants in a biological community.

FOUNDATION SPECIES

Organisms that occupy large areas of an environment and whose body structures create safe habitats for many small species.

SUBSTRATE

The surface that an organism lives and grows on, which typically is rock, sand, or mud on marine shores.

create habitats for many creatures by increasing the 3-dimensional complexity of the habitat and by creating a canopy that protects forest creatures from harsh conditions such as intense sunlight and strong winds. In fact, trees are foundation species. At the intertidal zone, foundation species also create canopies that protect many small organisms from harsh conditions such as extreme air temperatures and water evaporation during low tides and wave action during high tides (Figure 2).

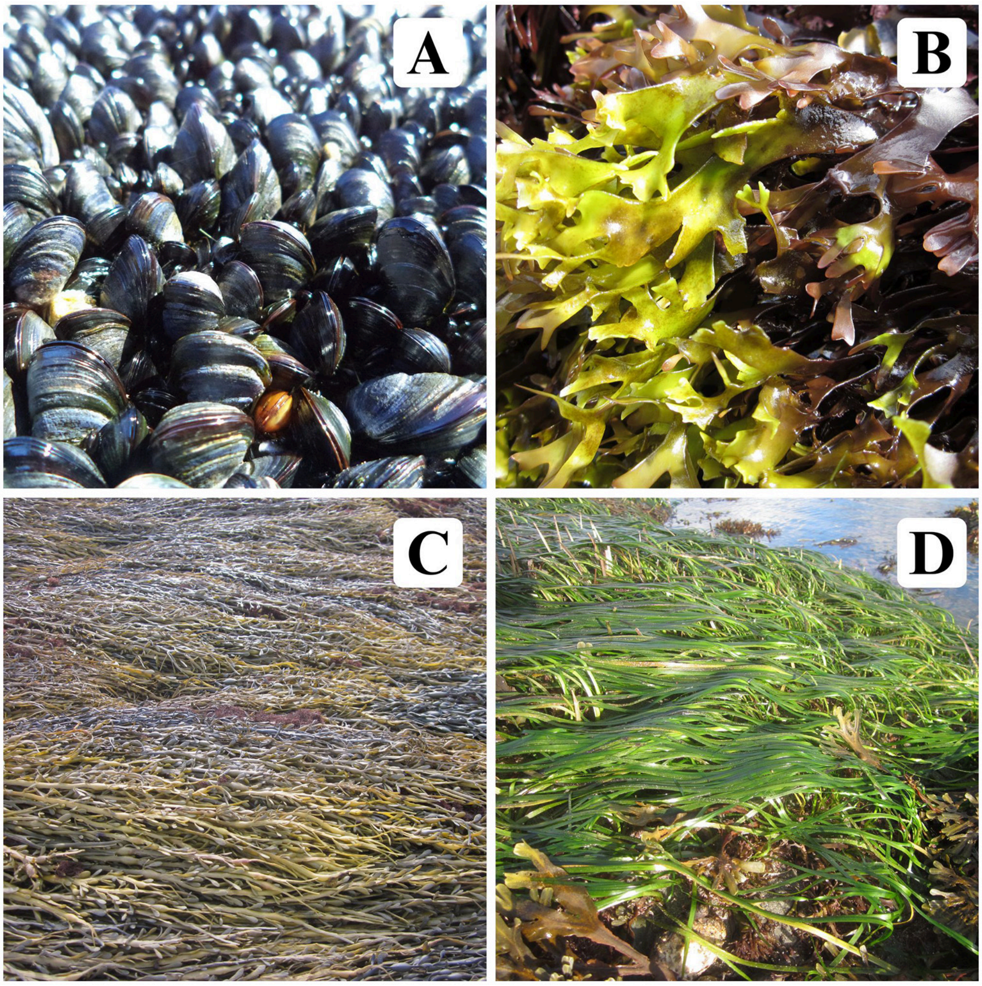

Figure 2

Figure 2

Intertidal foundation species come in many forms: **(A)** bivalves (mussels shown here), **(B)** red turf algae such as Irish moss, **(C)** large brown algae such as knotted wrack, and **(D)** seagrasses. These photographs were all taken at low tide (photo credits: Ricardo A. Scrosati).

Foundation species can also make it easier for small organisms to survive thanks to small gaps in the **understory** where such organisms can hide from large predators. Furthermore, through their complex body structures, foundation species also increase the 3-dimensional structure of the habitat and thus create extra spaces where other organisms can live. Organisms can live both on a foundation species itself and in the gaps that the foundation species creates (Figure 3). A coral reef is a good example. In some areas, if corals were not present, the ocean floor would be almost barren and not very habitable for other creatures. However, with corals, there are more spaces to live in and places for small fish to hide, making coral reefs some of the

UNDERSTORY

Habitat found below a canopy.

most biodiverse areas in the ocean. Many foundation species live in the intertidal zone and have adapted to thrive in the ever-changing conditions, creating habitats for other creatures and increasing the biodiversity of the community.

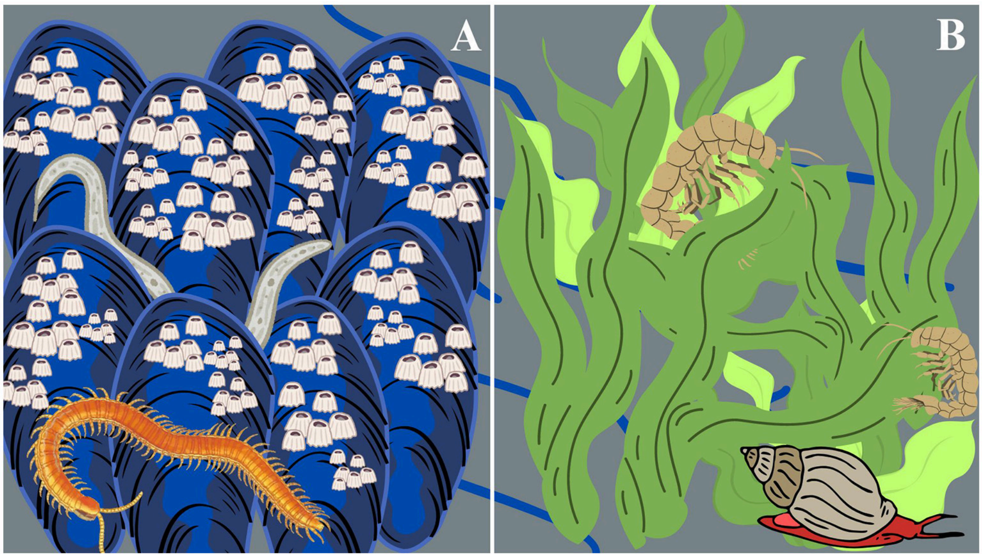

Figure 3

Figure 3

Zooming into foundation species reveals many small organisms living in their protection. **(A)** Barnacles live on the extra substrate provided by mussel shells and worms take shelter among the mussels. **(B)** Snails and crustaceans like amphipods avoid temperature extremes and drying out during low tides under the canopy created by seaweed fronds.

MEET INTERTIDAL FOUNDATION SPECIES: BIVALVES, SEAWEEDS, AND SEAGRASSES

Bivalves are mollusks that have two shells and often act as foundation species at the intertidal zone [2]. Bivalves include mussels, oysters, and clams, all of which can form extensive clumps of densely packed individuals attached to the intertidal substrate. The small spaces between individual bivalves are safe spaces for small animals to live, as the shells of the bivalves protect those animals from waves, predators, extreme temperatures, and drying out. The shells can also be an extra substrate (similar to rocks) that small algae and **invertebrates** can grow on. The close quarters of a dense clump of bivalves also trap **sediments** among the bivalve shells, creating an environment for small burrowing invertebrates.

INVERTEBRATES

Animals that lack a vertebral column.

SEDIMENTS

Particulated solid materials such as sand or mud.

Seaweeds, also known as macroalgae, can also be foundation species in intertidal habitats [3]. Some red seaweeds such as Irish moss are foundation species that live low in the intertidal zone. They live permanently attached to the substrate and produce upright **fronds**, forming dense clumps where many small organisms can live. Similar to bivalves, the canopies created by these fronds limit temperature extremes by providing shade and retain moisture during low tides, making the habitat more favorable for small organisms. Brown seaweeds such as knotted wrack are larger and create a more complex canopy than those red algae. As the fronds of knotted wrack

FRONDS

The leaf-like structures of a seaweed where photosynthesis mostly occurs.

are very flexible, they lay flat on the shore at low tide, providing shade, retaining moisture, and creating more spaces for critters to hide in. These brown seaweeds also act as an anchor for smaller algae and invertebrates to attach to and grow from.

Seagrasses are marine flowering plants that act as foundation species on many sandy, muddy, and rocky shores [4]. Seagrasses such as eelgrass have roots that keep sediments in place and thus create areas for burrowing invertebrates. Seagrasses also form canopies that can keep temperatures relatively stable and prevent water loss during low tides. These canopies also keep large predators from accessing intertidal habitats during high tides, making them important nurseries for young fish, for example.

TYING IT TOGETHER

Many organisms that live in the stressful intertidal zone rely on one or more foundation species. Bivalves, seaweeds, and seagrasses all live on the shore and provide safe places for other small organisms by creating living space that is protected from environmental extremes and predators. Often, different kinds of foundation species, each creating homes for different organisms, live near each other, resulting in an impressive biodiversity across the whole shore. Unfortunately, foundation species are at risk due to climate change and other human pressures such as pollution, overharvesting, and coastal development. Climate change is bringing bigger storms and more extreme temperatures beyond what foundation species can handle. If intertidal foundation species are lost, the diverse communities that call them home will likely be lost, too. Fortunately, since foundation species do such a good job at creating homes and maintaining biodiversity, restoring biodiversity in damaged intertidal systems can sometimes be relatively simple. Instead of having to recreate a whole community, reintroducing the foundation species is a good strategy that will naturally draw critters looking for homes and can help rebuild a biodiverse community.

REFERENCES

1. Altieri, A. H., and van de Koppel, J. 2014. "Foundation species in marine ecosystems", in *Marine Community Ecology and Conservation*, eds. M. D. Bertness, J. F. Bruno, B. R. Silliman, and J. J. Stachowicz (Sunderland: Sinauer Associates), 37–56.
2. Cameron, N. M., Scrosati, R. A., Valdivia, N., and Meunier, Z. D. 2024. Global taxonomic and functional patterns in invertebrate assemblages from rocky-intertidal mussel beds. *Sci. Rep*. 14:26. doi: 10.1038/s41598-023-50549-8
3. Watt, C. A., and Scrosati, R. A. 2013. Bioengineer effects on understory species richness, diversity, and composition change along an environmental stress

gradient: experimental and mensurative evidence. *Estuar. Coast. Shelf Sci.* 123:10–8. doi: 10.1016/j.ecss.2013.02.006

4. Maxwell, P. S., Eklöf, J. S., van Katwijk, M. M., O'Brien, K. R., de la Torre-Castro, M., Boström, C., et al. 2016. The fundamental role of ecological feedback mechanisms for the adaptive management of seagrass ecosystems – a review. *Biol. Rev.* 92:1521–38. doi: 10.1111/brv.12294

SUBMITTED: 29 July 2024; **ACCEPTED:** 14 February 2025;
PUBLISHED ONLINE: 26 March 2025.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Rong Lu

CITATION: Cameron NM and Scrosati RA (2025) Organisms That Create Homes for Other Organisms on Marine Shores. Front. Young Minds 13:1472723. doi: 10.3389/frym.2025.1472723

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

VICTORIA, AGE: 10

Victoria is a curious and energetic 10-year-old in 5th grade. She loves reading and hanging out with her three adorable cats. On the softball field, she shines as the star pitcher for her team. Victoria is also a talented harpist, playing the harp since she was 4 years old. She enjoys playing Minecraft and Roblox. She dreams of becoming a scientist someday.

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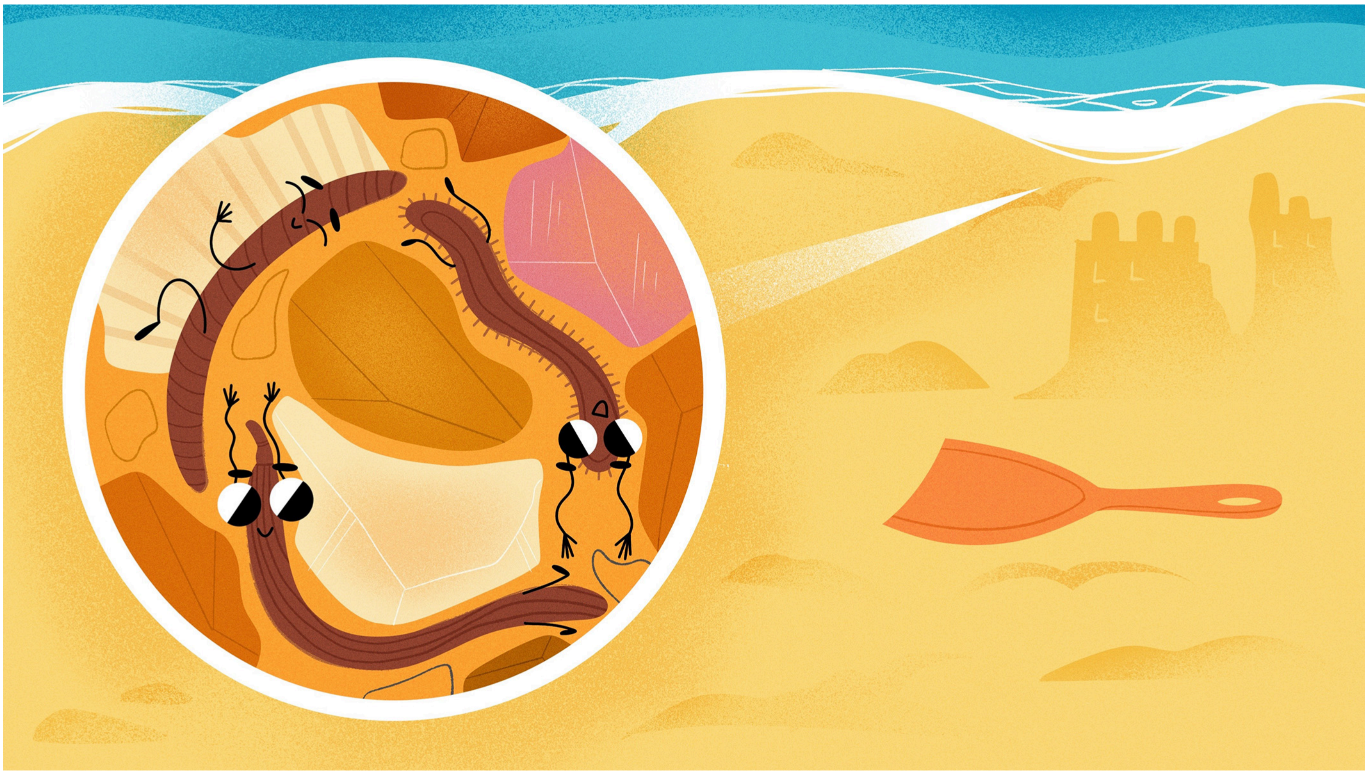
BIODIVERSITY
Published: 26 February 2025
doi: 10.3389/frym.2025.1472123



LIFE AMONG THE SAND GRAINS

Will M. Ballentine [1*]***, Nickellaus G. Roberts*** [2]***, Meghan K. Yap-Chiongco*** [2]***, Kenneth M. Halanych*** [3]***, Kevin M. Kocot*** [2,4] ***and Kelly M. Dorgan*** [5,6]

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YOUNG REVIEWERS:


ANNAMEKA
AGE: 14


GURSHAAN
AGE: 14

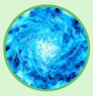

MANHEER
AGE: 13


PRISHA
AGE: 13

Have you ever played with sand at the beach? Did you know you were also playing with thousands of tiny animals? The sand in the ocean is home to many small creatures called meiofauna, but you can only see them under a magnifying glass or microscope. Meiofauna are so tiny that sand grains seem like boulders to them. Meiofauna are too small to move these boulders, so they wriggle through spaces between them. Living in such tight spaces has led them to evolve long, skinny body shapes like worms. They also have special body parts to grip sand grains and avoid being washed away. Meiofauna are small, but they still play a big role in the ocean, feeding larger animals and recycling waste on the ocean floor. There are tens of thousands of species of meiofauna worldwide, and many more are waiting to be discovered.

RAFSAN

AGE: 15



RITVIK

AGE: 13

TANISH

AGE: 14

LIFE IN THE SAND

Life comes in all sizes! There are things we can see, like ladybugs, whale sharks, and strawberries, but there are also microscopic organisms that we cannot see with just our eyes, like bacteria and mold spores. However, there is also a realm between these two worlds. Thousands, if not millions, of different kinds of animals about the size of a pencil tip or smaller, live between the grains of **sediment** found in oceans, lakes, rivers, and caves. These animals are called meiofauna.

SEDIMENT

Tiny pieces of dirt, sand, rocks, and organic matter that settle at the bottom of rivers, lakes, or oceans.

MEIOFAUNA ARE DIVERSE

Meiofauna are extremely diverse, with tens of thousands of different species from branches across the tree of life [1]. Most groups of animals including crabs (crustaceans), snails and clams (mollusks), and worms (annelids) have meiofaunal species too. These species have evolved many times from their larger-bodied relatives. In addition, juvenile (young) stages of some larger animals can be small enough to live among sand grains. These young animals are called temporary meiofauna. Temporary meiofauna have complex life cycles with **adaptations** to survive life as a larva in the water, as a meiofaunal juvenile in the sediment, and then as a larger adult. There are other animals, like mud dragons (kinorhynchs) and hairy bellied worms (gastrotrichs) that only exist as meiofauna. Most permanent meiofauna hatch as a miniature version of their parents and live their entire lives between grains of sand.

ADAPTATION

A change in a plant or animal that makes it better able to live in a particular place or situation.

Although meiofauna can be seen with the naked eye, you need a magnifying glass or microscope to tell them apart. Once you get a closer look, it is remarkable how complex and diverse these tiny animals can be (Figure 1)! Some meiofauna are covered in spines, others have many hairy legs. Some have tails that make sticky glue, and others have mouthparts that extend far out of their bodies and are used like a harpoon to collect food. These are just some of the diverse adaptations that help meiofauna live in a world where sand grains are the size of boulders.

WHAT DO MEIOFAUNA HAVE IN COMMON?

Meiofauna must squeeze through tight spaces, dodge predators, and avoid being washed away in storms or being crushed by moving sand grains. To do all this, meiofauna have become highly adapted to their environment. Many have worm-like bodies that allow them

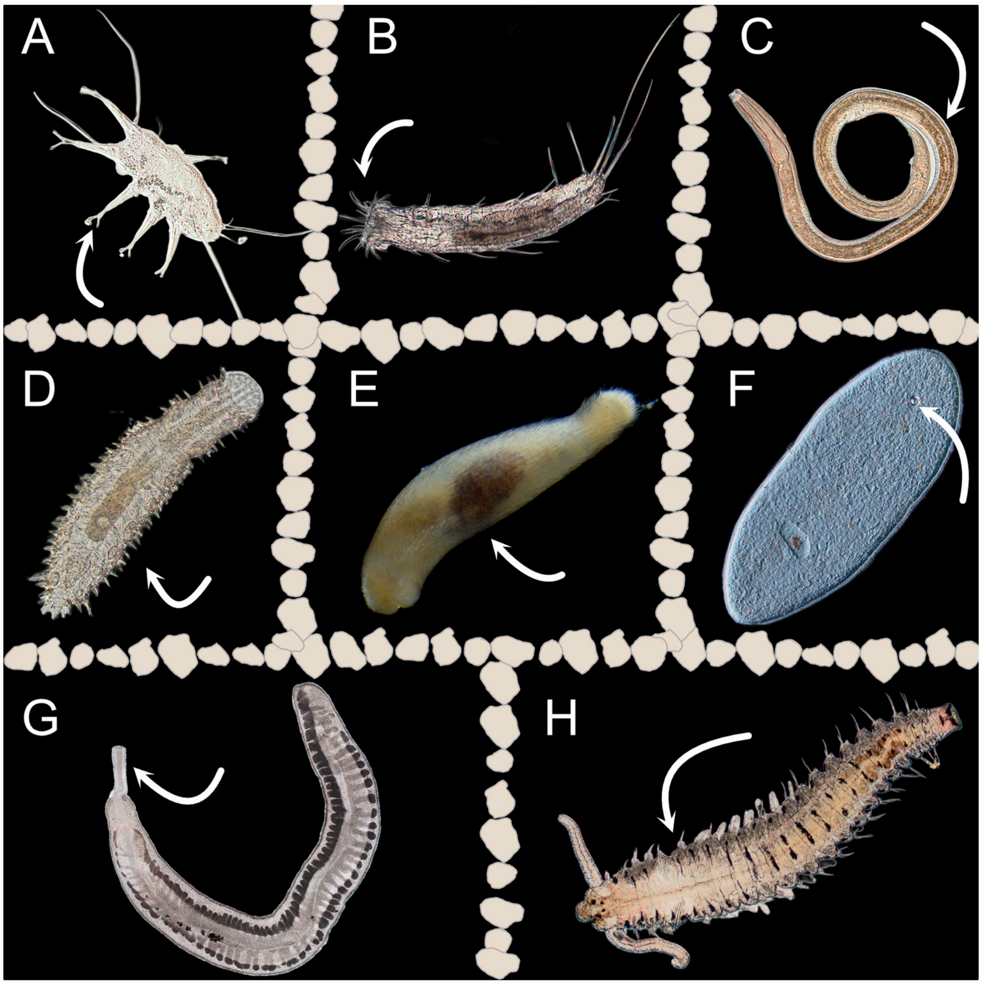


Figure 1

Figure 1

(A) Tardigrades have sticky toes for gripping sand grains. **(B)** Kinorhynchs have spines extending from their mouths, bodies, and tails. **(C)** Nematodes are small, skinny worms that slide between sand grains. **(D)** Gastrotrichs are covered in sticky tubes that help them stick to and move among sand grains. **(E)** Aplacophoran mollusks cover their bodies in armor made of thousands of spines. **(F)** Aceol worms have a statocyst that helps sense which way is up and down. **(G)** Nemerteans have a long tongue-like structure that captures prey. **(H)** Spionid worms are temporary meiofauna and only live between sand grains as juveniles.

to wriggle through tight spaces. To prevent being washed away, they have ways to stick to sediment, like producing mucus or having specialized sticky structures called **adhesive glands**. Because sand is constantly shifting, meiofauna need protection from being crushed by the sand-grain boulders. Many meiofauna have either internal or external protective structures that can act like armor. Some even have spines for defense.

ADHESIVE GLANDS

An adhesive gland is a special structure on the surface of the animal that produces special glue that helps meiofauna stick to sand grains.

Because life in the sand tends to be dark, many meiofauna rely on specialized structures to sense the world around them. Meiofaunal annelid worms, for example, have tentacle-like structures near their heads. They use these tentacles to feel around ahead of themselves. Other meiofauna have a gravity-sensing organ called a **statocyst**—a small, fluid-filled chamber that holds a tiny, rock-like ball called a statolith. When the animal moves, the statolith rolls around and touches sensory cells in the chamber. These cells send signals to the animal, helping it figure out which way is up or down in the darkness.

STATOCYST

A tiny organ in some animals, like jellyfish or crabs, that helps them sense balance and know which way is up or down.

Adaptations like a worm-shaped body, adhesive organs, and statocysts can be found in meiofauna that are not closely related, and distantly related species can look similar. When two species from unrelated groups evolve similar adaptations or features, it is called **convergent evolution**. For example, the reason birds, bats, and butterflies all have wings is because they help the animals do the same thing—fly. Convergent evolution can also occur when animals live in similar habitats. Many meiofauna that might not be closely related look similar because they evolved to live between the grains of sand.

CONVERGENT EVOLUTION

When different animals or plants evolve to look or behave similarly, even though they are not related.

HOW AND WHY DO SCIENTISTS STUDY MEIOFAUNA?

Scientists are still discovering and describing new species of meiofauna, and there are likely tens of thousands of species yet to be described. The scientists who identify and catalog new species of organisms are called **taxonomists**. Taxonomists also study how different species are related, to better understand the diversity of life. They often travel all over the world to find new species.

TAXONOMIST

A scientist who names and classifies living things into groups.

The first challenge taxonomists face when studying meiofauna is separating animals from the sand. Because the animals and sand grains are the same size, meiofauna can't be filtered out with a net or a sieve. Instead, scientists use the difference in density to separate the relatively light animals from the heavier particles of sand. You can try this method too, by following the directions in Figure 2 the next time you are at the beach.

Once the meiofauna have been separated from the sediment, scientists use microscopes to get a closer look (Figure 3). Taxonomists examine their anatomy (what body parts and organs they have) to identify species and describe new ones. Another challenge in studying meiofauna is that distinguishing differences between animals is more difficult when animals are very small. Because meiofauna often have shared characteristics, they can be difficult to tell apart from each other.

Sometimes scientists use **DNA** to tell similar meiofauna apart. DNA is like a blueprint for building an animal, studying DNA can help answer a lot of questions about how and where meiofauna have evolved. Comparing DNA among different animals helps taxonomists determine how closely related they are and identify new species. However, getting enough DNA from small animals like meiofauna is hard. Scientists have been improving methods to extract DNA and determine the information encoded in the DNA. Thanks to advances in technology, scientists today can sequence DNA from a single meiofaunal animal. Sometimes scientists find meiofaunal animals from two or more far-away places that look identical but, when they study their DNA, they find the species are more genetically different

DNA

Deoxyribonucleic acid, is a molecule inside cells that carries the instructions for how living things grow, develop, and function. It acts like a blueprint for building our bodies.

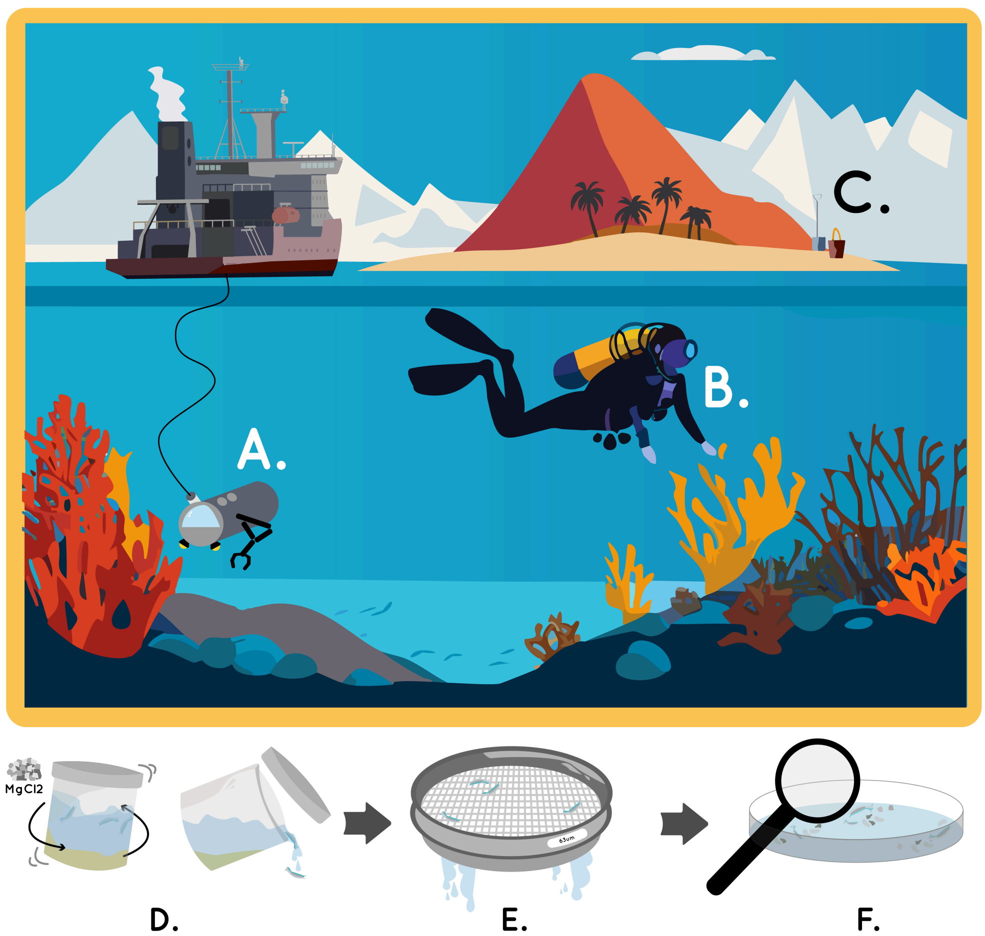


Figure 2

Figure 2

Meiofauna can be found all over the world. **(A)** In the deep sea, scientists use special equipment like advanced nets and manned drones to collect sediment. **(B)** Scientists collect meiofauna from the sand formed from dead coral around coral reefs. **(C)** Most groups of meiofauna can be found just feet from the shore. **(D)** To collect meiofauna, scientists collect sand, swirl it well, and pour the liquid through a sieve or coffee filter. **(E)** Meiofauna are too large to pass through the filter, so they get stuck. **(F)** A magnifying glass or a microscope can be used to look for meiofauna.

than humans and chimpanzees. These similar-looking but genetically different species are called **cryptic species**.

CRYPTIC SPECIES

Different species that look almost identical but are not the same.

Scientists also study meiofaunal behavior, such as how the animals move and eat. These researchers use very small, specialized tools. For example, to catch and move these tiny animals, scientists use small sticks with eyelashes or cat hairs attached. Scientists put meiofauna in clear sand and have even built tiny treadmills to observe how they respond to water flowing through the sand (Figure 3B) [2].

Figuring out how many species of meiofauna there are, how to identify them, how they are related, and how they behave is important for understanding the whole ocean. In some parts of the ocean, you can find thousands of meiofauna in a single teaspoon of sand. These animals grow very quickly, from babies to adults in just a few months. Because they are abundant and grow quickly, meiofauna are important players in moving nutrients through ecosystems. When organisms in the ocean die, they eventually sink to the sea floor. Many meiofauna eat these leftovers, recycling their nutrients back into the food web. After eating this material, meiofauna themselves become important food for young fish and crabs. Meiofauna help keep the seafloor

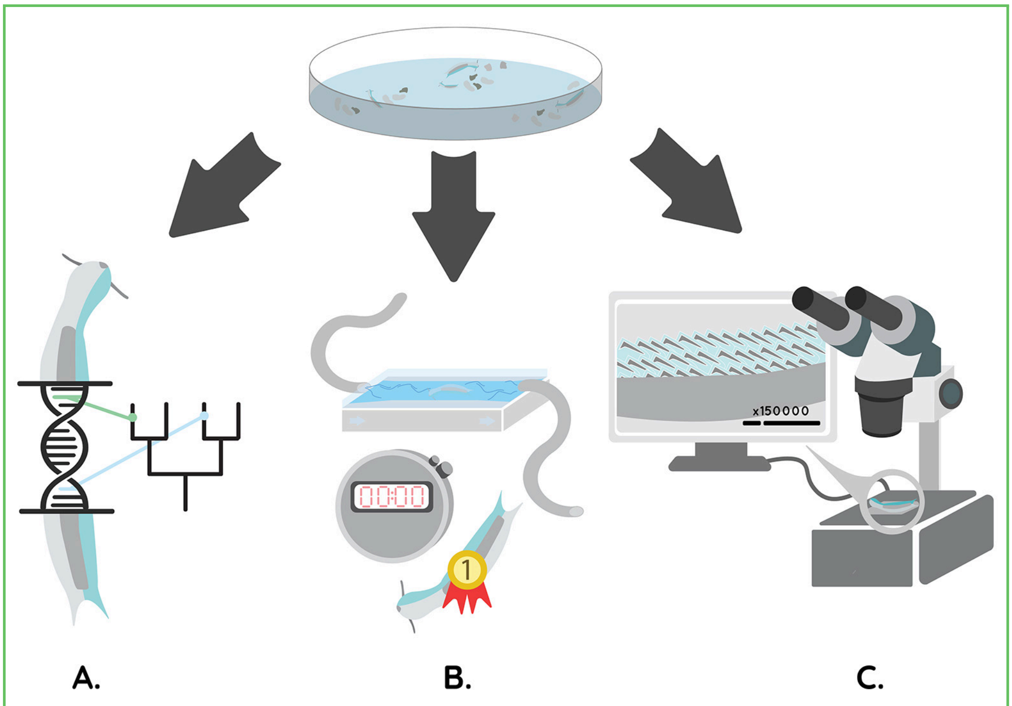


Figure 3

Scientists use a variety of tools to study meiofauna including: **(A)** DNA sequencing, in which organisms are ground up and their genes are analyzed to understand how they live and how they are related to each other. **(B)** Behavioral studies, in which scientists study how meiofauna navigate the complex spaces among sand grains using treadmill flow chambers and clear sand. **(C)** Microscopy, which allows scientists to see and study characteristics that are normally invisible to the naked eye.

healthy by stirring water down into the sediments, bringing oxygen and nutrients to microbes living there, which recycle this material. Without meiofauna, less of this valuable food would be recycled, and the sea floor would be more like a trash can and less like a recycling bin.

BIOINDICATOR

A living thing, like a plant or animal, that shows how healthy the environment is.

Meiofauna can also help scientists understand how healthy an environment is. Because they are small and cannot move very far, meiofauna are used as **bioindicators** for environmental and climate change [3]. Just like a doctor uses a thermometer to help diagnose a sickness, scientists can use meiofauna to diagnose the environment. This can be done by counting the number of each species or by studying DNA and counting the different sequences. The species or sequence counts can be compared to the diversity in samples taken from different places or from the same place at different times. For example, after an oil spill in the Gulf of Mexico, scientists compared the diversity of meiofauna at sites across the region before and after the oil spill, to determine how the oil spill affected the meiofaunal community [4]. They found fewer species of meiofauna after the oil spill, but after a year, the diversity increased again.

MEIOFAUNA MATTER

The seafloor is filled with diverse and interesting meiofauna that live between the grains of sand. Within this secret world of sand, animals of all shapes glide and stick through small spaces, navigating their "meio-scopic" environment. Next time you play in the sand or walk along the beach, remember that you are stepping on thousands of little animals specially adapted to survive in the shifting sands. Figuring out how many species of meiofauna there are, how to identify them, how they are related, and how they behave is important for understanding the whole ocean.

ACKNOWLEDGMENTS

This work was funded in part with federal funding from the Department of the Treasury under the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived economies of the Gulf Coast States Act of 2021 (RESTORE Act) to KD, KH, and KK made available through the Alabama Center of Excellence. Support was also provided by the NSF CAREER grant 1844910 to KD and CAREER grant 1846174 to KK. We thank the participants of the 2022 Smithsonian Marine Station Meiofauna Diversity and Taxonomy Workshop, the participants of the 2022 Biodiversity and Integrative Taxonomy of Invertebrates course at Friday Harbor Labs, and the participants of the 2023 Dauphin Island Sea Lab Meiofauna Diversity and Taxonomy Workshop for permission to use their photos in the figures.

REFERENCES

1. Schmidt-Rhaesa, A. 2020. *Guide to the Identification of Marine Meiofauna*. Munich: Dr. Fredrich Pfeil.
2. Ballentine, W. M., and Dorgan, K. M. 2024. The meioflume: a new system for observing the interstitial behavior of meiofauna. *Integr. Org. Biol.* 6:obae016. doi: 10.1093/iob/obae016
3. Balsamo, M., Semprucci, F., Frontalini, F., and Coccioni, R. 2012. *Meiofauna as a Tool for Marine Ecosystem Biomonitoring*. InTech. doi: 10.5772/34423
4. Brannock, P., Learman, D., Mahon, A., Santos, S., and Halanych, K. 2018. Meiobenthic community composition and biodiversity along a 5500 km transect of Western Antarctica: a metabarcoding analysis. *Mar. Ecol. Prog. Ser.* 603:47–60. doi: 10.3354/MEPS12717

SUBMITTED: 28 July 2024; **ACCEPTED:** 04 February 2025;
PUBLISHED ONLINE: 26 February 2025.

EDITOR: Emily King, Xiamen University, China

SCIENCE MENTORS: Halima Sultana and Indramohan Singh

CITATION: Ballentine WM, Roberts NG, Yap-Chiongco MK, Halanych KM, Kocot KM and Dorgan KM (2025) Life Among the Sand Grains. Front. Young Minds 13:1472123. doi: 10.3389/frym.2025.1472123

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

ANNAMEKA, AGE: 14

There are so many things in this world that are just waiting to be revealed. I find pleasure in discovering things I never knew existed and concepts I never delved into explained. For me, science is not "studying" if people do not showcase it to be. This page is important as it allows students like me to learn in a fun way and explore different topics we never knew about.

GURSHAAN, AGE: 14

I love learning about science and enjoy asking questions and finding answers. I am committed to deepening my knowledge and aim to make meaningful contributions to the scientific community.

MANHEER, AGE: 13

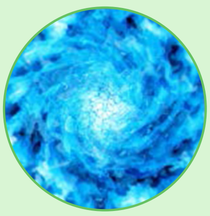
I am a passionate learner with a keen interest in exploring the wonders of science. Fascinated by how the world works, I enjoy diving deep into topics like biology, chemistry, and physics and apply them to real-world challenges.

PRISHA, AGE: 13

I am passionate about maths and science and especially enjoy biology and chemistry. In my free time, I enjoy playing tennis and listening to music. My hobbies also include playing the violin and keyboard, as well as reading a variety of books, especially fantasy and adventure.

RAFSAN, AGE: 15

Hey there! I am Rafsan – a sports enthusiast who loves football, athletics, and chess, with a strong interest in science and a drive to learn and challenge myself.



RITVIK, AGE: 13

I love science and their topics. This mainly fall under astronomy. I am fascinated by astronomy because it is more than just the night sky and stars, it is an expanding area of space. Not only that, but the possible existence of life on other planets. It is so inspiring to see scientists around the world working so hard to discover so valuable information, just so we can learn more about our place in space.

TANISH, AGE: 14

Hi, I am Tanish. I am a curious 14-year-old with a passion for geography, science, and understanding how the world works. Fascinated by maps, I love exploring different countries and cultures, always eager to learn about new places. Science is another big interest, and I enjoy diving into topics like ecosystems, weather patterns, and the natural world. With a big imagination and a knack for asking great questions, I am always on a quest for knowledge, discovering how things fit together to make our planet unique.

AUTHORS

WILL M. BALLENTINE

I am an oceanographer who studies how marine animals interact with their physical environments, and how those interactions affect animal shape and size. I use techniques from fluid dynamics, mechanics, and biology to study how life among sand grains has shaped meiofauna form and function over evolutionary time. I became interested in marine science as an undergraduate when I took a course on marine invertebrate diversity and became fascinated by the hundreds of thousands of species living in our oceans. *willballentine@gmail.com

NICKELLAUS G. ROBERTS

I am a graduate student interested in invertebrate zoology and bioinformatics. I am primarily interested in some of the amazing organisms that inhabit the world's oceans. My primary research involves sequencing the genomes of the world's smallest animals, most <1 mm in size, ranging from microscopic worms at the deepest depths of the ocean to tiny filter-feeding organisms found in tide pools. While I grew up in the desert, I became interested in microscopic invertebrates when I went to college in Santa Barbara, California, and studied the great diversity of organisms off the west coast of the United States. In the future, I hope to continue to study the amazing lives of the world's smallest marine animals.

MEGHAN K. YAP-CHIONGCO

I am an evolutionary biologist interested in how the differences in genomes of marine invertebrates lead to different body shapes and sizes. Growing up in Northern California, my family would often go to the beach, but I was afraid of the ocean until I was in high school. I did not become interested in marine biology until I took a course in college where I fell in love with marine invertebrates. Since then, I have worked toward understanding how organisms can look so different from one another using techniques in genomics, bioinformatics, and morphology.

KENNETH M. HALANYCH

I am a marine evolutionary biologist who has worked on animal diversity in several environments, including extreme environments like Antarctica and hydrothermal vents. My laboratory has used both genetic and morphological tools to study a variety of invertebrates including sponges, sea stars, worms, and clams. My interest in marine biology started when I was in high school and on field trips in the Chesapeake Bay. This led to a career of asking questions about how animals are related and how they have adapted to their environments.

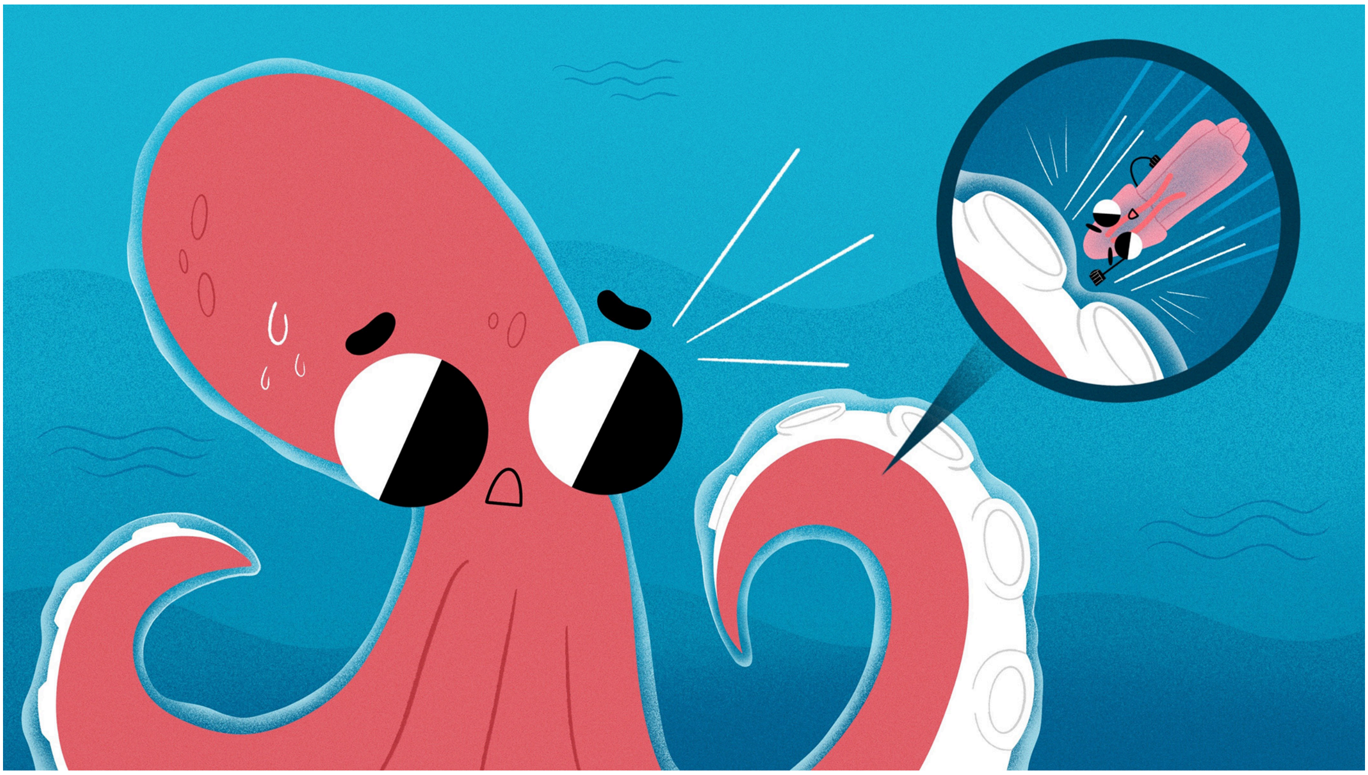
KEVIN M. KOCOT

I am an invertebrate zoologist specializing in the biodiversity and systematics of small-bodied animals that are likely more diverse than currently understood. My research combines traditional and modern approaches to explore the hidden diversity and evolutionary relationships of these fascinating organisms. I am particularly interested in the worm-shaped Aplacophoran molluscs, a group that has many species that have not yet been named. I am passionate about training the next generation of taxonomists in both traditional and modern skills and contributing to our understanding of life's diversity on Earth.

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 work with engineers to learn their tools and techniques and use them to understand what life is like for worms.

BIODIVERSITY
Published: 05 February 2025
doi: 10.3389/frym.2025.1426702



PARASITES: THE HIDDEN HITCHHIKERS OF CEPHALOPODS

***Linda Yacsiri Guadalupe Marmolejo-Guzmán*[1], *Sheila Castellanos-Martínez*[2], *Chelsea O. Bennice*[3], *Warren K. Carlyle IV*[4] *and Ma. Leopoldina Aguirre-Macedo*[1*]**

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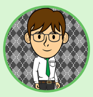
YOUNG REVIEWERS:


ANVITHA
AGE: 10


LORENZO
AGE: 13


RICCARDO
AGE: 12

Cephalopods (cuttlefish, squid, octopus, and nautilus) are remarkable marine creatures with extraordinary features like high intelligence, impressive camouflage abilities, blue blood, and three hearts. Yet, beneath the waves, they face a hidden threat from microscopic parasites. Parasites can wreak havoc on cephalopods, causing wounds that lead to infections, stomach aches that affect their appetite, and changes in their behavior. Luckily, cephalopods have a defense squad in their blood that battles these invaders. It is not all doom and gloom—parasites can help scientists uncover areas of the ocean where cephalopods travel and whether these areas are facing threats such as pollution and climate change. Scientists can examine

the relationship between cephalopods and their parasites, helping cephalopods all over the world stay as healthy as possible. Dive into this thrilling underwater world, as we embark on an adventure to solve the mysteries of cephalopods and their secret hitchhikers.

KNOWING CEPHALOPODS

Currently, there are about 1,000 known species of cephalopods found in oceans all over the world, from the steamy tropics to the freezing waters of the Arctic and the Antarctic to the deep abyss. Cephalopods that exist today include nautiluses, octopuses, cuttlefishes, and squids. In this article, we will focus on coleoid cephalopods, popularly known as octopuses, squids, and cuttlefishes (Figure 1). Cephalopods are not ordinary sea creatures; they are rockstars among all other mollusks, like mussels, clams, and snails! Cephalopods have their head connected to their muscular "foot" (a characteristic of the Mollusca group) that has evolved into appendages known as arms and tentacles. Cephalopods (octopuses, squids, and cuttlefishes) have eight arms lined with suckers to sense their environment. Their arms are involved in many different behaviors. Squids and cuttlefishes have a pair of feeding tentacles that only have suckers at the very end of the appendage. Cephalopods also have "smart" skin that changes color and texture in <1 s. Similar to clams and snails, coleoid cephalopods have copper-based blood, called hemolymph, with a blue color, but their blood circulates in a closed circulatory system oxygenated by two gill hearts and delivered throughout the body by a third main heart!

Even more astonishing, cephalopod intelligence rivals that of vertebrates. They have highly complex nervous systems that process huge amounts of information from their environments, allowing for quick decision making, communication, and problem solving. This is important for a squishy, shell-less animal that is on the menu for many marine predators. They have also been known to recognize individuals. In short, cephalopods' incredible features have fascinated scientists for centuries, inspiring us to learn more about their lifestyles.

CEPHALOPODS AND OCEAN HEALTH

In ocean ecosystems, cephalopods help to maintain nature's balance because they function as both predators and prey. They have a diverse diet including worms, clams, snails, crabs, and fishes [1]. They are also a favorite snack for predators such as sharks, seals, whales, dolphins, seabirds, and eels. Furthermore, cephalopods alert scientists about the ocean's health because they are some of the first species to notice when the oceans are in trouble, such as rising seawater

Figure 1

Examples of the diversity of coleoid cephalopods: **(A)** day octopus, **(B)** blanket octopus, **(C)** southern blue-ringed octopus, **(D)** flamboyant cuttlefish, **(E)** giant Australian cuttlefish, **(F)** common cuttlefish, **(G)** bigfin reef squid, **(H)** bobtail squid, **(I)** stubby squid.

Figure 1

temperatures or increased pollution. As ocean guardians, cephalopods signal potential problems in the underwater world.

Like us, cephalopods can get sick, and **parasites** are a major health threat. Cephalopod parasites can cause skin sores, loss of appetite, and even changes in their behavior [2]. Parasites can disrupt entire populations of cephalopods, which can affect the entire ecosystem. It is critical to keep cephalopods healthy because of their important roles in marine food webs, source of food for humans, relevance for scientific studies and education (in zoos and aquariums), as well as our economy. They are one of the top animals SCUBA divers and ocean goers want to see. Cephalopods even serve as the inspiration for soft robots!

PARASITES

An organism that attaches to a host for transport, food or shelter, often harming the host.

HOW DO PARASITES AFFECT CEPHALOPODS?

Parasites are tiny, sneaky creatures that love to live on or inside another animal, which is called the **host**. The host acts as a house and a source of food. This is a bit like having a houseguest who never leaves! Parasites can cause cephalopods a lot of trouble—they can make them feel tired, swim strangely, lose their appetite, or change their behavior. They might even get hurt, bleed, or have wounds on their skin that can become infected. If the water cephalopods live in is polluted or if the water temperature drastically changes (as can happen

HOST

Organism that provides food, shelter, or a place to live for other organism, sometimes while being harmed in the process.

with climate change), the situation can be even worse. Under these changed conditions, parasites have the upper hand in this underwater battle, making it harder for cephalopods to stay healthy.

HELMINTHS

Parasitic worms, including flat, ribbon-like cestodes (tapeworms) and shorter, broader trematodes (flukes). These worms infect various organs in animal hosts.

COPEPODS

Tiny crustaceans that live in the ocean, which can be either parasitic or free living.

PROTOZOANS

Microscopic organisms of single cell that can live in water, soil, or inside other organisms.

WHO ARE CEPHALOPODS' PARASITE HITCHHIKERS?

Not all cephalopod parasites cause severe diseases—some can live in a cephalopod's body without apparent harm. By 2018, scientists had identified about 230 parasites affecting cephalopods. These parasites, which we will call "cephalopod hitchhikers", can be classified into three main groups: **helminths**, **copepods**, and **protozoans**.

Helminths are worms with peculiar names, such as digeneans, cestodes, and nematodes. They are generally found in the digestive tracts of cephalopods (Figures 2A–F). Helminth infections are usually rare, but some can damage cephalopods' tissues. In a rare case, parasites can live in an octopus's mouth area (Figure 3) [3]. Nematodes, also called roundworms, infect cephalopods' digestive systems and muscles, causing sores and other negative effects. Alarmingly, some nematodes can be transmitted to humans if they eat raw or undercooked cephalopods, leading to painful gastrointestinal issues. It is vital to cook octopus and other seafood properly to prevent potential nematode infections.

Next up are copepods, often called ocean lice. While many copepods play crucial roles in the ocean ecosystem, some species are parasitic and can damage host organisms (Figure 2G) [4]. Parasitic copepods can be found in the gills and mantle damaging gill tissues and causing irritation in the skin, and small scratches that can hurt or get infected by viruses or bacteria. Also, these parasites can cause breathing problems and make it harder for octopuses to breathe properly.

The third group of cephalopod parasites includes protozoans. Protozoans, tiny single-celled organisms, are the most frequent hitchhikers, particularly a type called marosporidians (Figure 2H). Imagine invaders in your kitchen, breaking things, making a mess, and changing the environment so nothing functions properly. That is what marosporidians do in the stomachs of octopuses. They cause stomach issues, block nutrient absorption, and weaken the animal's overall health, affecting its growth and ability to defend against other diseases (Figure 3). Although these protozoans do not kill cephalopods directly, they open the door to more problems, leaving cephalopods vulnerable to bacterial and viral infections [4].

IMMUNE SYSTEM

A complex network of organs, cells, and proteins that work together to protect the body from infections and diseases.

HOW DO CEPHALOPODS DEFEND THEMSELVES AGAINST PARASITES?

An animal's **immune system** is key for protection against infections and diseases. Cephalopods do not have the type of immune system that

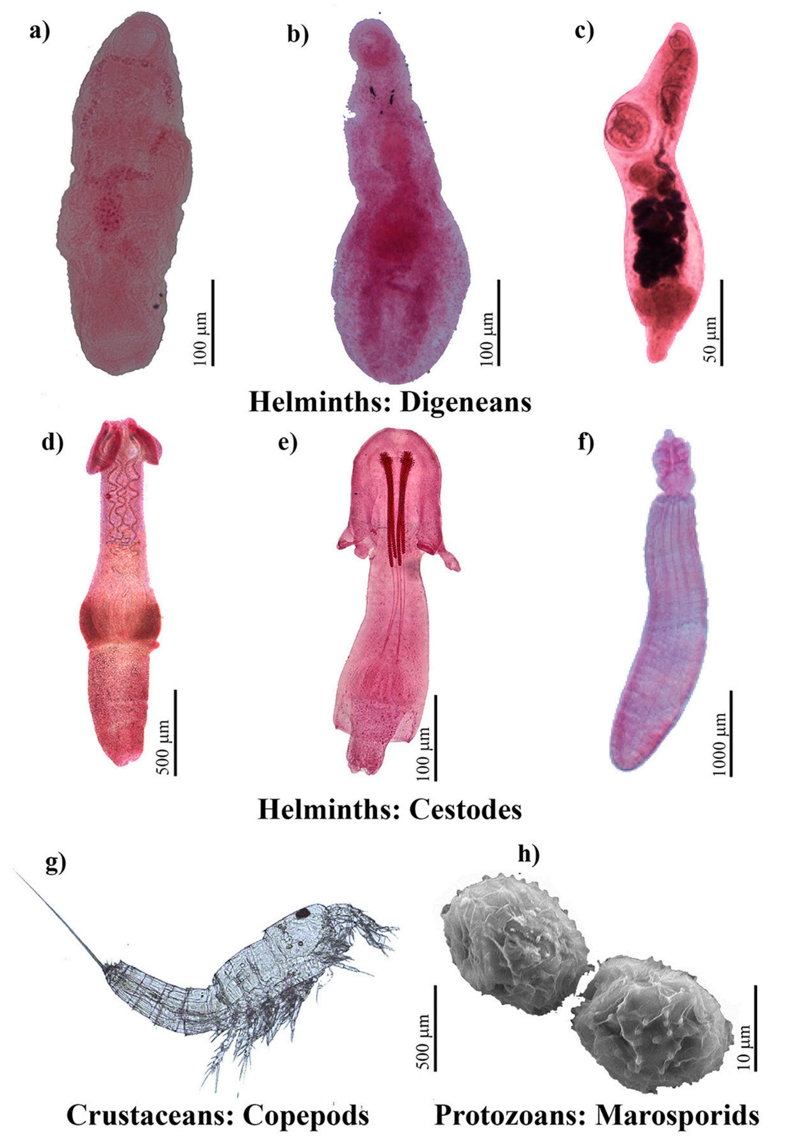


Figure 2

Figure 2

Parasites found in octopuses can make it difficult for the animals to absorb nutrients properly, but these parasites do not harm humans. **(A–F)** Six types of helminths classified into digeneans and cestodes based on their physical appearance. **(G)** Copepods, which are a type of crustacean, also known as ocean lice. **(H)** Marosporidians, which are a type of protozoans. **(A-C, G)** Part of the Collection of Aquatic Parasitology Laboratory at Cinvestav Mérida.

HEMOCYTES

Cells found in the blood of invertebrates that help fight off pathogens, combat infections, and keep the organisms healthy.

remembers germs, like humans do, which means they can get sick from the same disease repeatedly. This also means vaccines would not work on them. However, the immune system of cephalopods has effective external barriers and an internal army. External barriers, such as mucus and skin, help prevent parasites from entering the body [5]. If external barriers are breached, cephalopods have special cells and proteins that join forces to destroy the invader. In terms of protective cells, cephalopod blood contains proteins (like hemocyanin-the respiratory pigment that makes the blood blue!), and cells called **hemocytes**, which are important for wound repair and immune responses. Wounds cause an increase in circulating hemocytes, which are like the soldiers in cellular defense—they charge the "battlefield" and surround the invader. If the invader escapes the hemocytes, other tissues come to the rescue and destroy the invader.

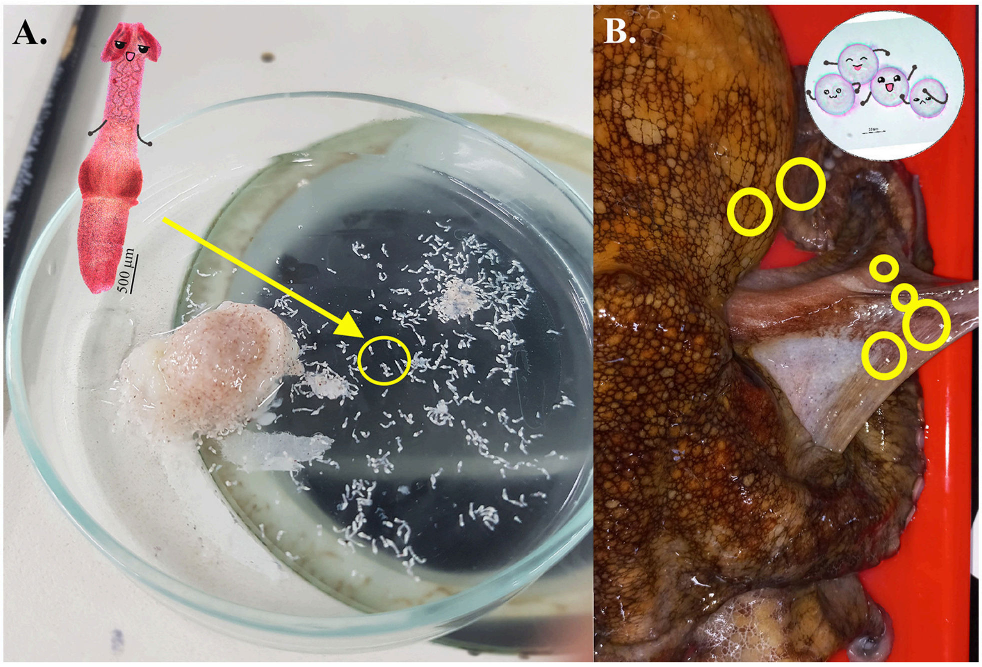


Figure 3

Figure 3

(A) A helminth parasite called *Prochristianella* is a worm that lives in the mouths of certain octopuses. The mouth tissue can have hundreds or even thousands of these parasites, but they do not harm humans that eat octopus. Yellow arrow indicates individual tapeworms and a single tapeworm to the left. **(B)** A helminth called *Aggregata polibraxiona* (small white spheres top left) usually lives in the digestive tract of most octopuses. When there is a heavy infection, it can show up as spots on the octopus's skin (yellow circles).

AGGLUTININS

Proteins found in the blood that help cells or particles stick together as part of the immune response.

Cephalopods also have substances in the fluid hemolymph called **agglutinins**, which are always ready to tackle parasites [5].

PARASITES: HITCHHIKERS OR MARINE DETECTIVES?

Now you know that cephalopods, like many other animals, can be negatively affected by parasites, and this can cause problems for ocean ecosystems. But surprisingly, these parasites can also play an essential role, acting as "detectives" in the sea.

Parasites act like secret tags that help scientists track the movements of cephalopods in the ocean. Imagine each of these parasites as a sticker that cephalopods collect when they explore different places in the sea. These stickers only stick when cephalopods visit areas where these parasites reside. So, if scientists find a squid or octopus with these stickers outside of those areas, they can infer that the cephalopods have previously visited those locations. These parasite stickers also provide scientists with clues about the timing of these visits and the environmental conditions of the habitats where they flourish. Thus, the more types of parasite stickers scientists find, the more details they can learn about the cephalopods' journey and movements.

Finally, even though parasites might seem unpleasant at first glance, they can also play a crucial role helping scientists understand the threats ocean animals face, like climate change and pollution, and how we can help protect the oceans from these threats. Because parasites depend on the food web to complete their life cycles, studying which parasites are present in ocean animals can help reveal information about the animals' diets, movements, and even changes in the environment, like pollution or climate shifts.

In summary, parasites of cephalopods are mysterious underwater creatures that can harm their cephalopod hosts while helping scientists unravel the hidden secrets of the oceans. Scientists are continuing to learn about cephalopods and their tiny tag-along parasites to protect octopuses, squids, and cuttlefishes and keep marine environments healthy.

ACKNOWLEDGMENTS

This work was supported by the National Council of Humanities, Science and Technology [755501, 2019] and the Research Fund of the Cinvestav, Merida Unit, as well as autogenerated external services resources by MLA-M, Cinvestav-Merida. The authors thank the underwater photographers that contributed photos to this manuscript: Lawrence Scheele (giant Australian cuttlefish), Yury Ivanov (bigfin reef squid and bobtail squid), Sam Glenn (blue-ringed octopus), Damsea (common cuttlefish), Oksana Golubeva (flamboyant cuttlefish), Magnus Lundgren (blanket octopus), Brandon Hannan (day octopus), EV Nautilus (stubby squid).

REFERENCES

1. Hanlon, R., Vecchione, M., and Allcock, L. 2018. *Octopus, Squid, and Cuttlefish: A Visual, Scientific Guide to the Oceans' Most Advanced Invertebrates*. Chicago, IL: University of Chicago Press. doi: 10.7208/chicago/9780226459738.001.0001
2. Fiorito, G., Affuso, A., Basil, J., Cole, A., de Girolamo, P., D'Angelo, L., et al. 2015. Guidelines for the care and welfare of cephalopods in research–a consensus based on an initiative by CephRes, FELASA and the Boyd Group. *Lab. Anim.* 49(2 Suppl):1–90. doi: 10.1177/0023677215580006
3. Marmolejo-Guzmán, L. Y. G., Hernández-Mena, D. I. G., Castellanos-Martínez, S., and Aguirre-Macedo, M. L. 2022. Linking phenotypic to genotypic metacestodes from *Octopus maya* of the Yucatan Peninsula. *Int. J. Parasitol. Parasites Wildl.* 19:44–55. doi: 10.1016/j.ijppaw.2022.08.001
4. Hochberg, F. G. 1990. "Diseases of mollusca: cephalopoda. Diseases caused by protistans and metazoans", in *Handbook of Pathogens and Diseases in Cephalopods*, ed. O. Kinne (Helgoland: Biologische Anstalt Helgoland), 47–227.
5. Castellanos-Martínez, S., and Gestal, C. 2013. Pathogens and immune response of cephalopods. *J. Exp. Mar. Biol. Ecol*. 447:14–22. doi: 10.1016/j.jembe.2013.02.007

SUBMITTED: 02 May 2024; **ACCEPTED:** 15 January 2025;
PUBLISHED ONLINE: 05 February 2025.

EDITOR: Laura Lorenzoni, National Aeronautics and Space Administration (NASA), United States

SCIENCE MENTORS: Amaresh K. Ranjan and Martina Gaglioti

CITATION: Marmolejo-Guzmán LYG, Castellanos-Martínez S, Bennice CO, Carlyle WK IV and Aguirre-Macedo ML (2025) Parasites: The Hidden Hitchhikers of Cephalopods. Front. Young Minds 13:1426702. doi: 10.3389/frym.2025.1426702

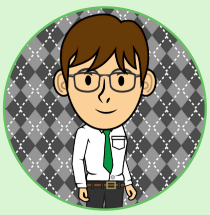
CONFLICT OF INTEREST: WKC was employed by OctoNation® 501(c)(3) Education Nonprofit Organization.

The remaining 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

ANVITHA, AGE: 10

My name is Anvitha Ranjan and I am a 10-year-old 5th grader. I love reading. I can sit with a book for long hours. I love to make my own story presentations in powerpoint too. The other best thing I love to do is ART!! I love painting and drawing, chess and am part of the school music band team. Overall, I am an amiable and kind kid—that is my teachers and my parents say 😊.



LORENZO, AGE: 13

Hey there! I am a curious Italian boy interested in science and politics. I love learning and staying in nature, and I hope to be a good Young Reviewer 😊!

RICCARDO, AGE: 12

Hi! My name is Riccardo and I love art, nature and animals. I am a very cheerful person, who loves playing outdoor with friends. I play volleyball, I go canoeing; and I like playing football with my friends.

AUTHORS

LINDA YACSIRI GUADALUPE MARMOLEJO-GUZMÁN

I am a biotechnologist by profession, but my fascination with water bodies has been with me since childhood. This passion led me to pursue a Ph.D. in marine sciences, with a focus on marine invertebrate diseases, particularly those affecting cephalopods like octopuses. I have dedicated my research to understanding the intricate world of marine life and the diseases that impact it. As a scientist, I find the complexity of cephalopods intriguing, and my work aims to uncover the mysteries of their biology and health.

SHEILA CASTELLANOS-MARTÍNEZ

I am a marine biologist from the Autonomous University of Baja California Sur (UABCS). My academic journey continued with a master's degree in marine resource management at CICIMAR-IPN. I pursued doctoral studies at the University of Vigo, Spain, followed by a postdoctoral fellowship at Cinvestav, Merida. My research has focused on octopus reproduction, tissue study, immune response and parasite classification. Now I am a researcher at IIO-UABC, investigating octopus parasites and bivalve immune response and the damage in their tissues.

CHELSEA O. BENNICE

Dr. Chelsea Bennice is a marine biologist located in south Florida. She enjoys fieldwork and spending time underwater SCUBA diving and observing octopus behavior. Chelsea is currently a research fellow at Florida Atlantic University Marine Science Lab, where she studies multiple octo-topics including behavior, microbiology, and genetics. She is passionate about communicating her science to audiences of all ages and leads a science education and outreach program, Glenn W. and Cornelia T. Bailey Marine SEA Scholars. The community knows Chelsea as Octo-Girl.

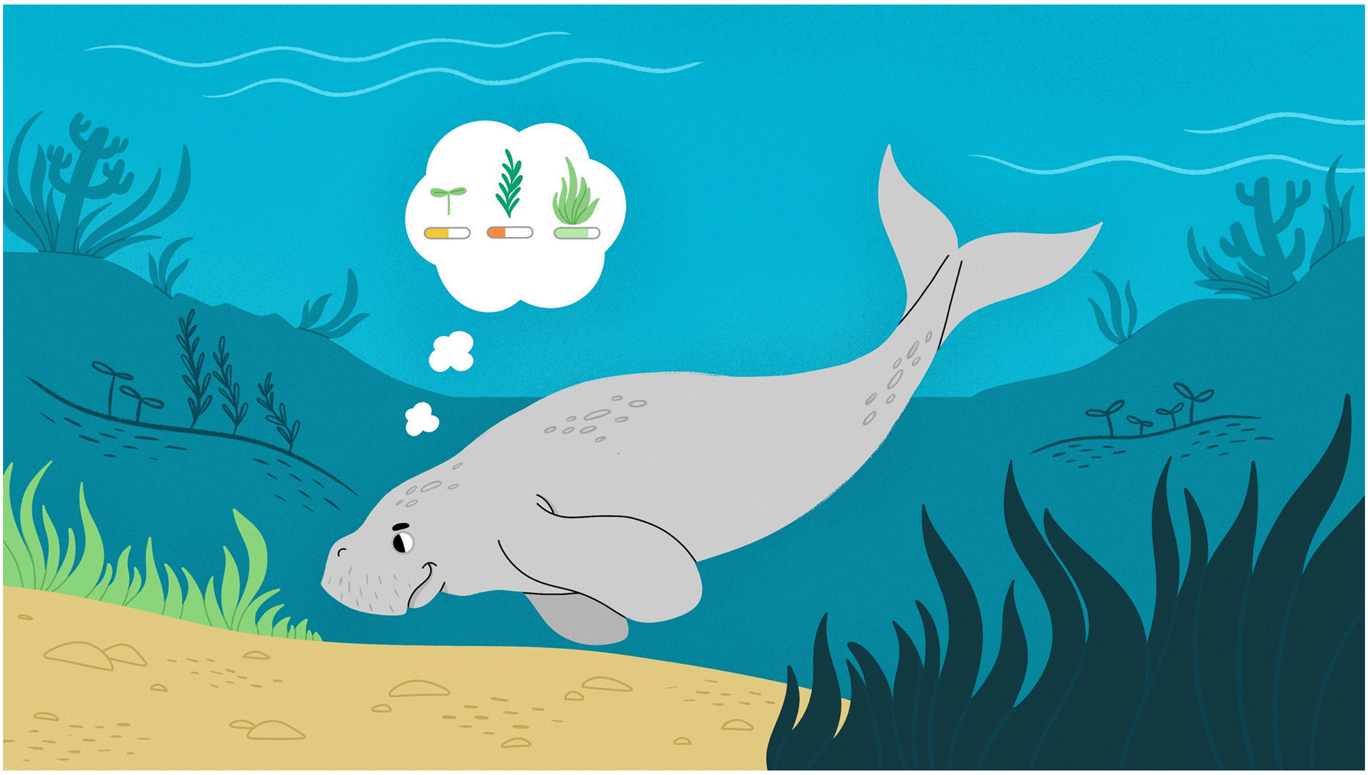
WARREN K. CARLYLE IV

Warren K. Carlyle IV is an author of National Geographic's "Secrets of the Octopus" and the founder of OctoNation, a nonprofit organization that is home to more than a million members working to inspire wonder of the ocean by educating about octopuses. Warren describes himself as the octopus's PR agent—working with journalists, underwater photographers, and researchers to get the word out about these incredible underwater creatures.

MA. LEOPOLDINA AGUIRRE-MACEDO

I am a senior professor at Cinvestav Merida, Mexico. My research centers on the study of the ecosystem of aquatic and marine parasites and the impact in their hosts. I also study bacteria that live in the ocean and how they affect the environment. My work dives into factors influencing parasite transmission and the long-term dynamics of the parasite population. *leopoldina.aguirre@cinvestav.mx

BIODIVERSITY
Published: 29 August 2024
doi: 10.3389/frym.2024.1386359



DUGONGS: UNDERWATER SEAGRASS DETECTORS THAT HELP SCIENTISTS PROTECT IMPORTANT ECOSYSTEMS

Nicole Said**, Anna Lafratta, Alexandra D'Cruz, Ankje Frouws, Caitlyn O'Dea, Kathryn McMahon, Chanelle Webster, Chandra Salgado Kent, Jennah Tucker and Amanda Hodgson

Centre for Marine Ecosystems Research, School of Science, Edith Cowan University, Joondalup, WA, Australia

YOUNG REVIEWERS:


AVINESH
AGE: 13


DAVID
AGE: 9


HARSITH
AGE: 13


MATHI
AGE: 10


THIAGO
AGE: 9

Can you picture cows grazing on a meadow of grass? Did you know that there are also "cows" under the sea that graze on seagrass meadows? Dugongs—a type of sea-cow—are threatened with extinction, mainly as a result of human activities and loss of their main food source, seagrass. Seagrasses are a group of flowering plants that grow in the ocean! Seagrasses are important not only as a food source for dugongs, but they provide a home for many animals, absorb carbon dioxide aiding in climate change mitigation, and so much more! However, seagrasses are declining globally, which is bad news not only for dugongs, but for humans as well. Luckily, dugong presence can aid scientists in understanding the health of seagrasses in an area, as well as help scientists locate and protect our important seagrass ecosystems.

DUGONGS—VEGETARIANS OF THE SEA

Dugongs are mammals that live in the ocean. They have round bodies and smooth skin. You may spot them above the water, as they come to the surface to breathe every 3–12 minutes through their unique snouts, which look like a cross between an elephant's trunk and a dolphin's beak (Figures 1A, B). Dugongs can grow to around 3 meters long, propelling themselves through the water with a wide fluked (dolphin-like) tail. They are found in warm, shallow coastal waters of 46 countries across the Indian and Pacific Oceans (Figure 1C). As migratory animals, they can sometimes travel large distances in search of food. Dugongs are also important to many **Indigenous people** around the world, as part of their culture and a traditional source of food.

INDIGENOUS PEOPLE

Communities consisting of the original inhabitants of a region, with strong cultural ties to the local land and sea and many stories and experiences about changes in the land over time.

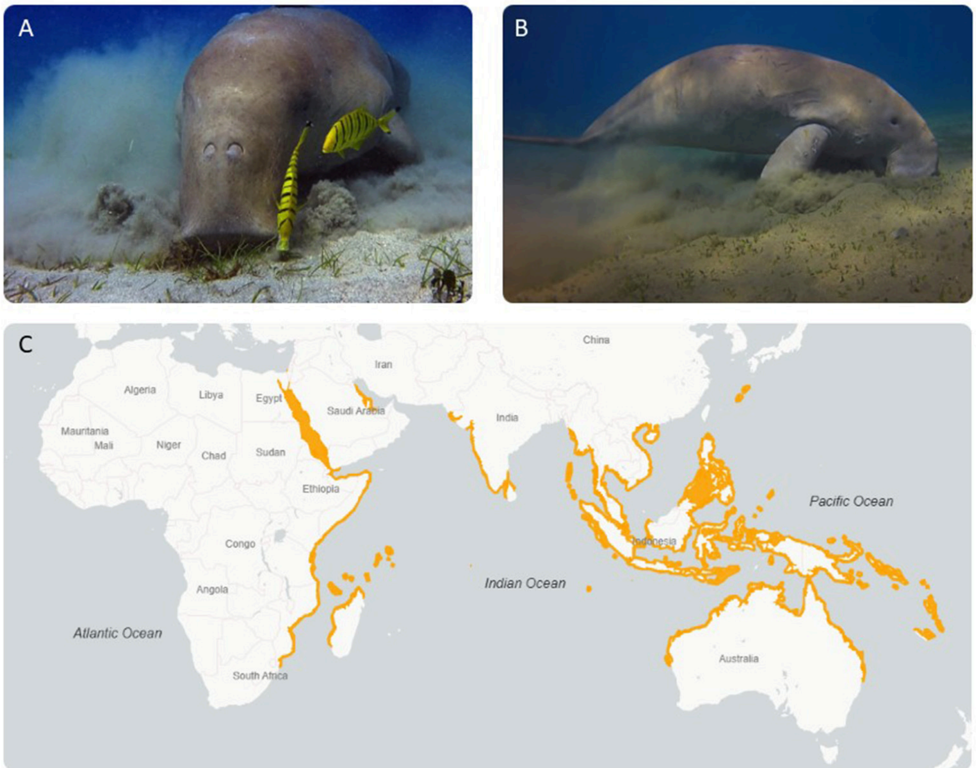


Figure 1

Figure 1

(A, B) Dugongs feeding on seagrass on the ocean substrate. You can see their unique snouts and how these animals use it to munch on their favorite food: seagrass. **(C)** A map showing (in orange) where dugongs can be found [Figure credits: **(A, B)** Ahmed Shawky; **(C)** The International Union for Conservation of Nature (IUCN) 2015. *Dugong dugon. The IUCN Red List of Threatened Species*. https://www.iucnredlist.org.

Dugongs belong to the order (a group of animals which are similar) Sirenia, which contains only four species worldwide [1]. Three of these are different species of manatees (found in North and South America and West Africa), which are somewhat larger and look slightly different to dugongs, with paddle-shaped tails, a different mouth shape, and "nails" on their flippers. The fourth species is dugongs. Dugongs and manatees are both herbivores, which means they are vegetarians that only eat plants. Both dugongs and manatees are known as "sea cows" because their diet consists mainly of seagrass, the only flowering plant found in the sea. Dugongs are only found in marine (saltwater) environments, while manatees rely on both freshwater and saltwater. This makes dugongs the only vegetarian mammals that live in the sea.

Dugongs have a long lifespan—they can live up to 70 years. However, dugongs have a low **birth rate** (one calf every 3–7 years) and take many years to start having calves (babies), which live with their mothers for around 2 years. These characteristics makes dugongs vulnerable to decreases in their numbers. Being large animals, dugongs do not have many natural predators, but dugong calves and sick or injured dugongs are vulnerable to being eaten by large sharks, killer whales, and saltwater crocodiles. However, the main threats to dugongs are caused by humans, including, loss of their seagrass habitats, being hit by boats, and getting tangled in fishing nets. As a result, dugongs are decreasing worldwide and are vulnerable to extinction. Therefore, dugongs and their seagrass habitats need extra attention and protection.

BIRTH RATE

The rate at which a species produces babies. Birth rates can be used to understand how quickly a species can recover, which can help us know if a species needs protecting.

SEAGRASS—CHAMPIONS OF THE OCEAN!

Seagrasses are extremely important for animals that live underwater, and even for humans! They are the main food source not only for dugongs, but also for other marine animals like fish and turtles [2]. Seagrasses are also home to many animals, including fish that humans like to eat. These plants are also champions in our battle against climate change, because they help to lock carbon away into the sediment.

RHIZOME

A section of a plant that runs along the ground or sediment, connecting the roots and leaves together. Rhizomes can store energy made through photosynthesis, which can be used in times of stress.

Seagrasses have leaves, roots, and **rhizomes**, just like many of the plants that grow on land, but they live underwater! Seagrasses reproduce through seeds developed from flowers, creating genetically unique plants, but they can also create exact copies (clones) of themselves (Figure 2B). Because seagrasses are plants, they need light to undertake **photosynthesis**, so are generally found in shallow waters. Seagrasses come in all shapes and sizes. Some seagrasses, like paddle weed, are very small and have paddle shaped leaves the size of your thumb, while others, like ribbon weed, resemble large blades of grass and can grow to the length of your arm, or even taller than you. You can find seagrasses all around the world, off the coasts of all continents except Antarctica, where it is too cold for seagrass to grow. In fact, temperature plays a large part in where seagrasses live, with some species living in warm tropical oceans and others in cool temperate waters.

PHOTOSYNTHESIS

The process plants use to make their own food (sugars) using carbon dioxide, water, and the energy of sunlight.

Over the last 100 years, the world has lost around 19% of its seagrasses, and unfortunately, in some places we are still loosing one to two football fields of seagrass every hour! Seagrass meadows are being damaged by coastal development, like harbors, and more recently, by climate change. When we lose seagrasses, we also lose all the benefits that they provide to the environment and to us, including providing a food source for dugongs.

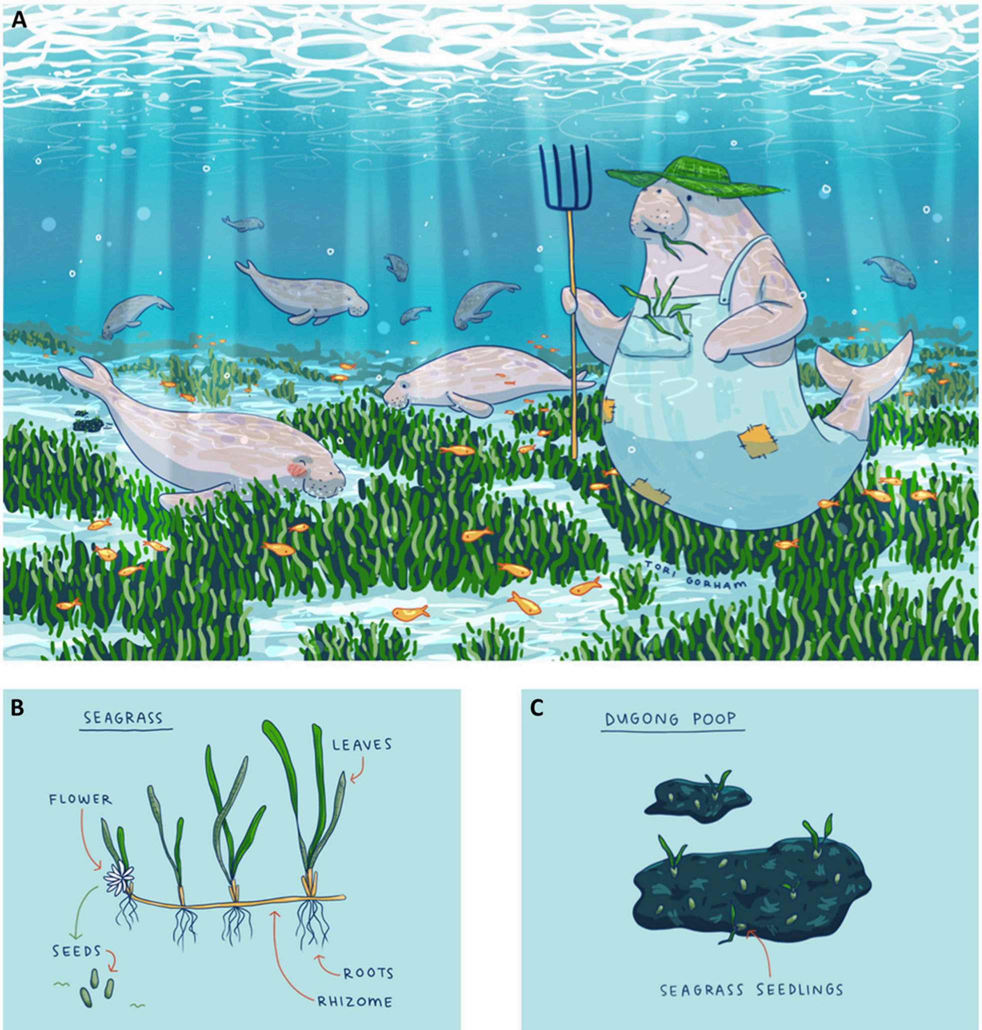


Figure 2

Figure 2

(A) Dugongs eating their favorite food (seagrass!) and creating bare sand patches called "feeding trails". **(B)** Adult seagrass, as well as seagrass seeds that are produced by flowers. Seeds can sprout on the seafloor, turn into seagrass seedlings, and then grow into adult plants to complete their lifecycle. **(C)** Dugong poo can contain seagrass seeds, which can germinate into seagrass seedlings. Therefore, when dugongs move, they can help spread seagrass seeds to new areas (Image credit: Tori Gorham Illustration).

DUGONGS CAN BE GOOD "SEAGRASS FARMERS"

Dugongs spend much of the day feeding on seagrass, farting (eating a vegetarian diet will do that to you), and pooing. They eat a lot: about 40 kilograms of seagrass every day, which is equal to 130 lettuce heads. Dugongs eat both seagrass leaves and rhizomes, leaving bare sand patches through the seagrass meadow as they feed (Figure 2A). In some areas they are considered "seagrass farmers", because over time their feeding behavior changes which seagrass species are most commonly found in a meadow [3]. Small, fast-growing species are generally the first to form a seagrass meadow, which are the species dugongs prefer to eat. Smaller seagrass species have high nutritional value, and by dugongs continually removing small seagrasses as they eat, over time, they stop other slower growing seagrass species, that

POSITIVE FEEDBACK LOOP

A process in which a change causes effects that make the change grow even more, like a snowball rolling down a hill and getting bigger.

GENETIC DIVERSITY

A range of different features that can be passed from parents to offspring. An example is different eye colors in humans.

TROPICAL CYCLONE

Is a circular storm that forms over warm oceans. This can bring strong winds and heavy rain.

are less nutritious, from taking over. This process of dugong grazing influencing which seagrass species are present is known as a **positive feedback loop**, keeping the ecosystem in a state that is favorable for dugongs. Another positive feedback loop occurs when dugongs poo. If the poo contains seagrass seeds, new seagrass plants can also establish and grow from this nutrient-rich fertilizer package (Figure 2C). In fact, seagrass seeds that pass through a dugong are more likely to germinate and grow than seeds that do not. By spreading seeds this way, dugongs also increase the **genetic diversity** of seagrass meadows. You can think about diversity of a species like Superhero characters. For example, when Thor and Black Widow (both human superheros) combine their strengths, they are stronger in the face of enemies. When a single seagrass species (for example paddle weed) has both Thor's and Black Widow's in the meadow, they are stronger in the face of human impacts, including climate change.

WHEN SEAGRASS DISAPPEARS, SO DO DUGONGS

If a seagrass meadow disappears because of an extreme weather event (e.g., cyclone), dugongs will move to find seagrass elsewhere, sometimes, far away. Scientists have tracked some dugongs traveling hundreds of kilometers between patches of seagrass. In fact, the longest distance recorded by one dugong is 1,000 km [4], which is the same as traveling from Paris to Berlin. When there is not enough seagrass to eat, dugongs will delay having calves until seagrass becomes healthier. Over time, this can mean that the number of dugongs in an area will decrease.

Near a small coastal town in Western Australia, there is a beautiful body of water called Exmouth Gulf. It is home to a diversity of marine life, including dugongs and seagrass. Dugongs can be found grazing on seagrass throughout the year, and the Gulf contains critical habitat for dugongs in this part of the world. However, in 1999, something interesting happened. Widespread damage to seagrass in Exmouth Gulf occurred from a **tropical cyclone**. The following year, dugong numbers in the Gulf were unusually low, but 400 km south, in a location called Shark Bay, there was an increase in the number of dugongs. Shark Bay is known for its lush seagrass meadows, and during the cyclone, these meadows did not experience the same damage as the meadows in Exmouth Gulf. Scientists believe that the dugongs in Exmouth Gulf undertook the long journey south to find food [5]. Because it is difficult to identify individual dugongs and there was no tracking data, it is hard to know how long the dugongs may have stayed in Shark Bay. However, several years later, there were larger numbers of dugongs back in Exmouth Gulf, suggesting that the seagrass had returned.

DUGONGS CAN HELP SCIENTISTS FIND SEAGRASS

For the tropical seagrasses that dugongs eat, dugongs are an important **indicator species**, meaning they can aid in telling scientists about of the presence and health of seagrass meadows [6]. Seagrass meadows occur on the seafloor, often in murky water, making it hard to keep track of where the seagrass is and how well it is doing. Dugongs feeding on seagrass come to the surface every few minutes to breathe, so they can be detected from the air across these seagrass habitats. Scientists can fly planes or drones over these large areas and record where the dugongs are, which then tells them where the seagrass may be.

INDICATOR SPECIES

A species that can provide scientists with information on ecological changes simply based on their presence. This can give scientists an indication on the health of an ecosystem.

YOU CAN HELP PROTECT DUGONGS AND THEIR HOMES TOO!

We need to protect and conserve our seagrass meadows to ensure dugongs can thrive in the future. Many people, both scientists and communities, are helping to protect these ecosystems and you can become part of the team. Here are some tips on how you can help!

- First, if you live near the ocean, you can be a "dugong detective" by visiting your local seagrass meadow (Figure 3). There are 72

Figure 3

Figure 3

"Dugong detective" examining different seagrass species to choose its favorite!

seagrass species globally, and you can find them on this website. Pick your favorite seagrass and raise awareness of the importance of seagrass with your friends and family.
- Next, you can help protect seagrass and dugongs by looking after the ocean. An easy way to do this is by recycling, reducing single-use plastics (like water bottles and food containers), and by putting rubbish in the bin.
- You can also celebrate World Seagrass Day on March 1 each year. This day helps to raise awareness of how important seagrasses are and what activities threaten their health and survival.
- Finally, you can find local researchers or protectors and help them save seagrass. The good news is that there are a lot of them, and they may have community projects you can get involved in. Check out Project Seagrass, Seagrass Watch, and the World Seagrass Association as good places to start learning.

ACKNOWLEDGMENTS

Funding for comissioned Figures 2 and 3 was provided by Edith Cowan University.

REFERENCES

1. Marsh, H., J, O'Shea., and T, E. Reynolds III. 2011. *Ecology and Conservation of the Sirenia: Dugongs and Manatees*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9781139013277
2. Orth, R. J., Carruthers, T. J. B., Dennison, W. C, Duarte, C. M., Fourqurean J. W., Heck, K. L., et al. 2006. A global crisis for seagrass ecosystems. *Bioscience* 56:987. doi: 10.1641/0006-3568(2006)56[987:AGCFSE]2.0.CO;2
3. Marsh, H., Grech, A., and McMahon, K. 2018. "Dugongs: seagrass community specialists", in *Seagrasses of Australia*, eds. A. Larkum, G. Kendric,k G., and P. Ralph (Springer International Publishing), 629–661.
4. Hobbs, J-P. A., Frisch, A. J., Hender, J., and Gilligan, J. J. 2007. Long-distance oceanic movement of a solitary dugong (Dugong dugon) to the cocos (Keeling) islands. *Aquat Mamm*. 33:175–178. doi: 10.1578/AM.33.2.2007.175
5. Gales, N., McCauley, R. D., Lanyon, J., and Holley, D. 2004. Change in abundance of dugongs in Shark Bay, Ningaloo and Exmouth Gulf, Western Australia: evidence for large-scale migration. *Wildl Res*. 31:283–290. doi: 10.1071/WR02073
6. Hays, G. C., Alcoverro, T., Christianen, M. J. A., Duarte, C. M., Hamann, M., Macreadie, P., et al. 2018. New tools to identify the location of seagrass meadows: Marine grazers as habitat indicators. *Front Mar Sci*. 4:1–6. doi: 10.3389/fmars.2018.00009

SUBMITTED: 15 February 2024; **ACCEPTED:** 12 August 2024;
PUBLISHED ONLINE: 29 August 2024.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Archana Prabahar and Alfredo Yanez-Montalvo

CITATION: Said N, Lafratta A, D'Cruz A, Frouws A, O'Dea C, McMahon K, Webster C, Salgado Kent C, Tucker J and Hodgson A (2024) Dugongs: Underwater Seagrass Detectors That Help Scientists Protect Important Ecosystems. Front. Young Minds 12:1386359. doi: 10.3389/frym.2024.1386359

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

AVINESH, AGE: 13
My favorite subjects are Science, Math, and History. Some of my favorite things to do in my free time are to watch TV, play chess, and go outside with my friends, especially in the summer. I am part of my school's Science Olympiad team, and I also do Speech and Debate and learn to play the piano. Most important of all, I have a very strong interest in science, and love opportunities to learn about different science topics, just like this article.

DAVID, AGE: 9
Hi, my name is David and I live in México. I study at home. I like to learn to play the piano and learn English. I have a pet. His name is Tizoc, is a rooster. In my free time, I like to draw shopping centers. I like to know different animals. I love frogs because they come in different sizes and colors. My mom is a biologist and she talks to me about protecting our planet.

HARSITH, AGE: 13
I find sports and computer programming interesting. I like to play cricket, soccer, and badminton. I love to play soccer with my friends and go to try out for soccer teams. I like to spend some time on computer programming like python. I play video games that make me addicted so my interest is to create a video game using the programming method. I also like to explore mind blowing and detailed constructions like castles.

MATHI, AGE: 10
My name is Mathi. My hobby is drawing. I am studying in 5th grade at Orchard Middle School in Solon, Ohio.

THIAGO, AGE: 9
I like the color red, legos, and telling jokes. I have a lot of friends at school and I practice jiu-jitsu every afternoon. I am a big fan of the Ben 10 cartoon.

AUTHORS

NICOLE SAID
Nicole Said is a marine scientist and ocean enthusiast. Her research focuses on human impacts, such as climate change on seagrasses. Seagrasses are one of her favorite things to see underwater whilst snorkeling and diving, along with all of the creatures you can find amongst them. Her favorite seagrass species is *Halophila spinulosa*, a little fern-like plant that grows in tropical waters. *n.said@ecu.edu.au

ANNA LAFRATTA
Anna Lafratta is a lecturer in marine science specializing in coastal vegetated ecosystems, which include seagrass, mangroves, and tidal marshes. She studies the ability of those ecosystems to fight back against climate change. She uses their power to reveal information about the past by looking into their sediments. They are like a big library! Anna loves sharing her knowledge, particularly with communities around the world that rely on coastal ecosystems to survive. She loves diving in the warm waters of the Indo-Pacific region to look for the very small inhabitants of coral reefs, which are difficult to spot but so incredibly beautiful!

ALEXANDRA D'CRUZ
Alexandra D'Cruz is a marine scientist specializing in marine mammals. Alex loves all marine creatures, but her favorites include dolphins, whales, dugongs, and sea lions. She is interested in understanding how human activity impacts marine mammals, and what we can do protect and conserve these charismatic creatures.

ANKJE FROUWS
Ankje Frouws is a marine scientist who loves to be in or around the ocean. She studies the health and genetic diversity of seagrasses and their ability to survive human impacts. Because the ocean is so important for our health and the health of our planet, she thinks we should learn as much as we can about the ocean and improve the way we look after it. Although seagrasses are her absolute favorite, Ankje also loves to visit and work in other coastal ecosystems, like mangroves and coral reefs.

CAITLYN O'DEA
Caitlyn O'Dea thinks seagrass meadows are the coolest thing you will ever see underwater. Whether it is a hungry swan, turtle, or dugong, Caitlyn wants to know how seagrasses are coping with being eaten. Her underwater adventures span from the cold temperate estuaries of southern Australia to tropical paradise on remote islands.

KATHRYN MCMAHON

Kathryn McMahon is a professor in marine ecology who has been lucky to spend many years researching seagrass ecosystems around the world. Her work informs the management and conservation of coastal ecosystems and helps build resilience in these natural systems to human activities and climate change. She loves communicating science to a broad audience and has published seagrass guide-books as well as science publications.

CHANELLE WEBSTER

Chanelle Webster found a passion for the magnificent underwater seagrass meadows back in 2017, snorkeling in Western Australia. That moment began her career in science, running experiments to work out if there are some seagrass populations that can handle climate change better than others, which might be useful for restoration.

CHANDRA SALGADO KENT

Chandra Salgado Kent is an associate professor in marine science specializing in the biology and ecology of marine mammals, which include whales, dolphins, seals, sea lions, and dugongs. She also studies underwater sound in the ocean to learn how these animals navigate through their environment and communicate with each other. Chandra loves being out in the ocean and using mathematics to understand which habitats are critical to the survival of marine mammals and how we can protect them.

JENNAH TUCKER

Jennah Tucker is a marine scientist whose research focuses on the ecology of marine mammals and understanding how these animals interact with humans, each other, and their environment under changing conditions. After growing up wishing she was a fish, she has always had a strong interest in understanding and preserving our ocean-dwelling mammalian counterparts.

AMANDA HODGSON

Amanda Hodgson started researching dugongs back in 2000, when she spied on dugong behavior using a huge helium balloon carrying a video camera. Since then, she has been coming up with different ways to count dugongs and other marine animals like whales, dolphins, and turtles, using new technology like drones and artificial intelligence. Amanda hopes these methods will give us a better understanding of these important animals so we can better protect them.

BIODIVERSITY
Published: 26 June 2024
doi: 10.3389/frym.2024.1331893

THE DIVERSITY OF SCIENCE BEHIND U.S. SEAFOOD

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YOUNG REVIEWERS:

MS. BRINGEWATT'S SCIENCE CLASS
AGES: 13–14

JOY
AGE: 14

Since 2014, people have been eating more and more seafood like fish, shrimp, and plant-based seafood like seaweed. In the United States, seafood even features in some popular television shows such as *Wicked Tuna* and *Deadliest Catch*. But did you know that before you sit down to enjoy a seafood dinner, many types of scientists have been working together to answer questions like: "How many fish can we catch without taking too many?" and "How will catching one species affect other species in the ecosystem?". Scientists even study questions like: "How does catching fish and other types of seafood affect a community?". In this article, we will explore how fish, shrimp, clams, and other seafood resources are managed in the U.S., and why many different types of scientists are needed to make sure that these

resources can sustainably provide food, jobs, recreation, and cultural benefits to people who use them.

WHAT CAN SCIENCE DO FOR SEAFOOD?

Humans eat a lot of seafood. When you think of seafood, you might think of tuna salad, fish sticks, or shrimp, but seafood also includes things like octopus, clams, and even seaweed. In most countries, the amount of seafood eaten has increased during the last 50 years, in part due to expansions in aquaculture (farming fish instead of catching them in the wild) and increased access to seafood products. In the U.S., the average person went from eating 14 kg (31 pounds) of seafood in 1961 to almost 23 kg (50 pounds) in 2021 (Figure 1). That is over 8 million tons of seafood for the whole country in 2021! Seafood is big business, and it even features on popular reality TV shows like *Deadliest Catch* and *Wicked Tuna*. But catching the fish is only one part of the story. Behind the scenes, there are many kinds of scientists working to keep the seafood industry healthy and **sustainable**.

SUSTAINABLE

Describes humans and nature coexisting to support the current and future generations.

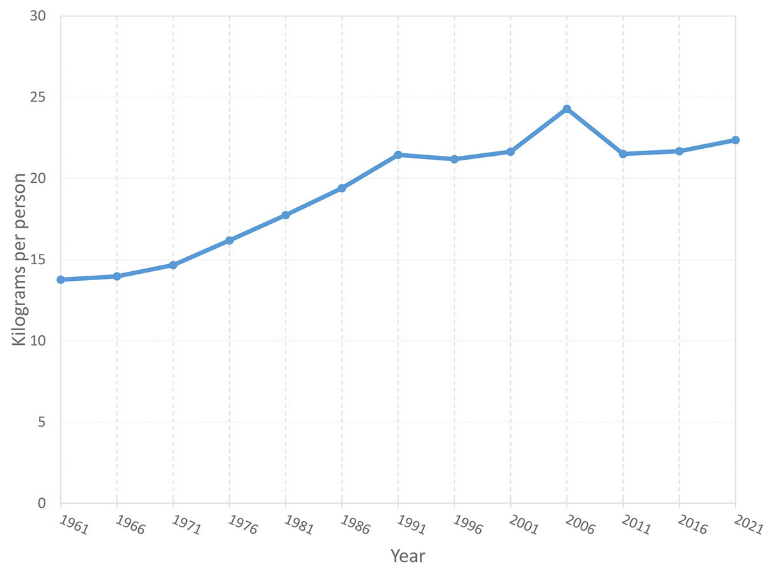

Figure 1

Figure 1

U.S. seafood consumption per person, 1961–2021. Data include all fish species and major seafood commodities, including crustaceans, cephalopods, and other mollusc species. You can see that seafood consumption has risen considerably since the 1960s (reprinted with permission from https://ourworldindata.org).

You might ask yourself why the seafood industry needs science. Well, not only do we need scientists, we need many different types of scientists working together to answer questions like: "How many fish can we catch without taking too many?" and "How will fishing rules impact people and their livelihoods and communities?". Scientists even address questions such as whether the "rules" of fishing are helping or hurting some people more than others. These kinds of questions often have very complex answers that depend on things like the type of fish, types of fishing methods, environmental factors (such as variations in the temperature of the ocean), and human **fishing communities**. In this article, we will explore how scientists from fields

FISHING COMMUNITIES

Places where fishers live, or a community based on a type of fishing gear, species fished for, shared values, or other factors.

like economics, sociology, anthropology, ecology, oceanography, and biology work together to address questions like these, which ultimately help maintain healthy seafood populations that provide food, jobs, recreation, and cultural benefits.

HOW ARE FISHERIES MANAGED IN THE U.S.?

FISHERY

An occupation, an industry, or a season for catching seafood, particularly fish and shellfish. Fishery can also refer to the location where seafood is caught, or the business of catching the species.

The term **fishery** refers to the business of catching seafood—it can refer to an occupation, an industry, or how, where, or when seafood is caught. In the U.S., fisheries that exist within 3 miles of the coastline are managed by the states closest to that fishery. For example, the Atlantic blue crab fishery in the Chesapeake Bay is managed by Virginia and Maryland. These states tell blue crab fishers how many crabs they can take during a certain period of time, or where they can set crab traps during certain seasons, or other rules that keep the fishery healthy. But most U.S. fisheries exist in areas called federal waters. Federal waters cover everything between 3 and 200 miles from the coastline. Fisheries in federal waters are managed by the federal and tribal governments, management councils, and commissions. These groups, along with scientists from other organizations, do research to help make and evaluate the rules for managing and maintaining healthy seafood species—from familiar species like tuna, cod, salmon, scallops, and crab, to some not-so-familiar species like the moonfish and tilefish (Figure 2). In total, the U.S. manages 492 different **fish stocks**, and about 86% of them are considered healthy and not overfished. In addition to keeping seafood populations healthy, fisheries management makes sure that the economic, social, and cultural benefits from fishing are sustainable, meaning that those benefits continue for everyone involved—fishers, fishing communities, and society. And of course, fisheries management works to make sure that other marine (ocean-living) animal populations and **ecosystems** are healthy and sustainable. To do all of these things successfully requires a lot of science from a variety of fields.

FISH STOCK

A group of fish of the same species that live in the same geographic area and mix enough to breed with each other when mature.

ECOSYSTEMS

A group of living organisms that live in and interact with each other in a specific environment.

BIOLOGY AND ECOLOGY

Biology is the study of living organisms, and ecology is a branch of biology that studies the relationships of organisms to each other and their environments. In fisheries management, biology and ecology provide the building blocks for understanding the **life cycle** of a fish stock—how a group of fish of the same species spends their whole life. Biologists and ecologists help us understand how large the fish stock is and how it changes in response to changes in the environment or in response to people catching the fish. Because it would be impossible to count all the fish in a stock one by one, scientists take samples of fish in different areas over time. Information such as age, size, and sex of the fish in the sample is used to predict how many fish there are in a stock and how many can be harvested without causing the population

LIFE CYCLE

The sequence of biological changes that occurs as an organism develops from an egg into an adult, until its death.

Figure 2

A variety of seafood species was harvested in the U.S. in 2021. Did you or your family eat any of these?

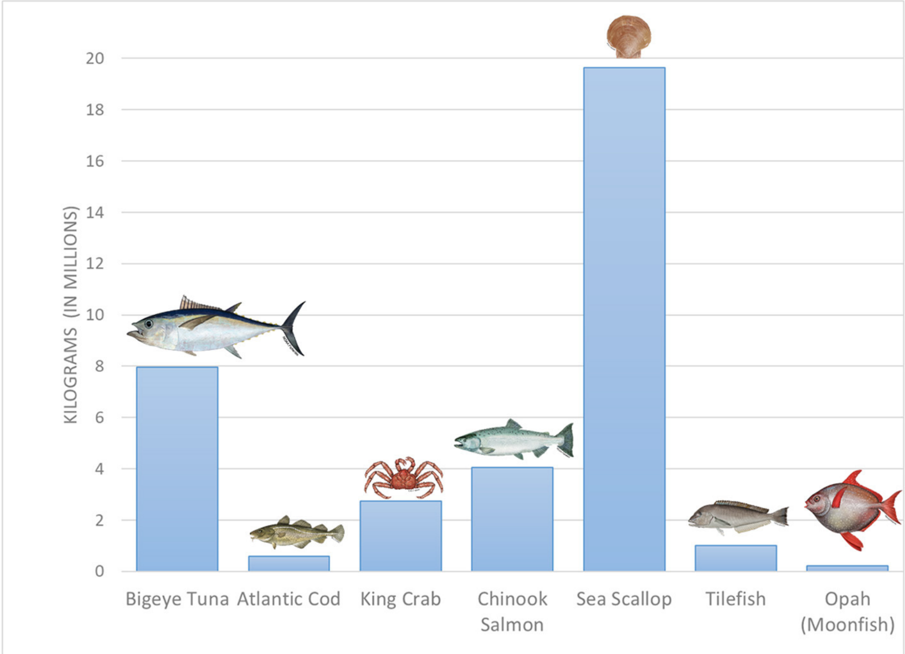

Figure 2

to become too small. In the same way, biology and ecology help scientists understand the life and habits of other marine animals like whales, dolphins, and sea turtles, so that fishers can avoid accidentally harming them. For example, scientists studying loggerhead sea turtles found that when fishers in the North Atlantic swordfish fishery used a certain type of fishing hook and bait (Figure 3), the number of loggerhead sea turtles that were accidentally caught went down [1]. This finding helped both the swordfish fishers, who must stop fishing if they accidentally catch too many turtles, and the population of loggerhead sea turtles.

OCEANOGRAPHY

Oceanography is the study of the ocean, including its temperature, salinity (how salty the water is), pH (a measure of acidity), tides, currents, and other physical, chemical, or biological characteristics. In fisheries management, oceanographers often examine how changes in ocean characteristics affect fish stocks, the ecosystems where fish live, and even patterns of behavior among fishers. Oceanographers might address questions like how climate patterns impact the ocean, and how this in turn may affect fish populations. The information that oceanographers collect can be used to improve stock assessment predictions and to help us better understand processes and relationships within larger ecosystems. For example, scientists studying an ecosystem off the U.S. West Coast found that it is important to include the effects of decreasing pH levels, or **ocean acidification**, in their predictions. They showed that if the ocean

OCEAN ACIDIFICATION

A reduction in the pH of the ocean over an extended period of time, caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere.

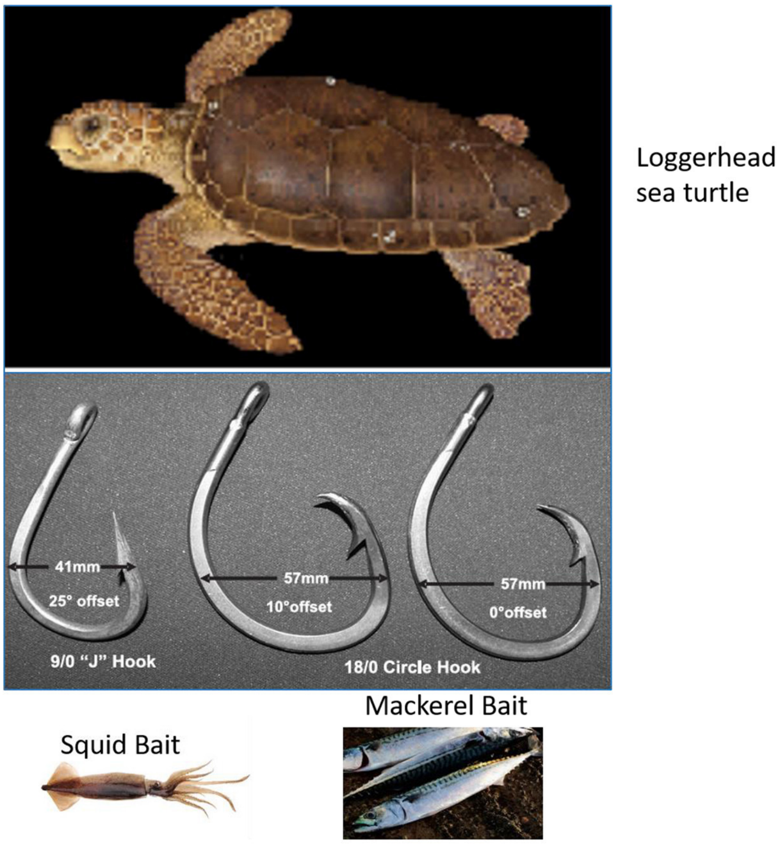

Figure 3

Figure 3

Biology and ecology can help people understand the life and habits of other ocean animals, so that fishers can take precautions to avoid catching or harming them by accident. For example, fewer loggerhead sea turtles were accidentally caught by fishermen fishing with circle hooks and mackerel bait compared to "J" hooks and squid bait.

becomes more acidic, the population size of three different species would decrease and fishers would have to catch fewer of them [2]. This research can help fishery managers set appropriate rules to promote sustainable fishing.

ECONOMICS

Economics is the study of how people and societies use resources for various purposes, or more broadly, the study of decision making. Money is associated with economics because the benefits and costs of decisions are often measured in dollars or other currencies. In fisheries management, economists often look at the costs and benefits of "rules" called management options, so that they can choose the ones that keep enough fish in the water while still supporting fishing communities. Sometimes these options include closing certain areas to fishing so that the number of fish increases or requiring fishers to use certain types of fishing gear that do less damage to marine ecosystems. For example, economists found that fishers in Hawaii would lose less money if fisheries management closed fishing areas in the Eastern Pacific rather than closing fishing areas in the Western and Central Pacific [3]. Understanding the costs and benefits of specific management options can help fisheries managers choose the rule that has the most benefits for fishers, while still making sure that fish stocks and marine ecosystems are healthy.

SOCIOLOGY AND ANTHROPOLOGY

Sociology and anthropology are sciences that study human behavior, human cultures, and other aspects of human societies. In fisheries management, sociologists and anthropologists do research to understand the people and fishing communities who depend on the ocean for food, jobs, or their way of living. These scientists might examine things that are hard to measure, like how the ocean and fish are important to a community's culture, spirituality, or religion. Sociologists and anthropologists might also study things like how many jobs in a fishing community might be affected if a new fishing rule is put in place, or whether the regulation will affect some groups more than others. For example, researchers working in Alaska found that rules designed to increase Native Alaskan participation in fisheries did not work as they were intended to, and were able to suggest different strategies to improve fishing access for Alaska Natives [4]. This research can help fisheries management understand what might and might not help fisheries become more balanced, and ultimately improve the success of fisheries management for everyone. Anthropologists and sociologists have conducted many interviews with fishers and fishing community members, with some interviews dating back to 1895! You can read these interviews and more at Voices from the Fisheries.

This article described just some of the ways that different types of science are used in U.S. fisheries management—there are many more examples and even other types of science, like computer science and genetics, involved in managing fisheries. As fisheries management evolves to meet the changing needs of society and our changing environment, good science from many fields will be needed as well. So if you think you would like a career that helps maintain healthy and sustainable marine environments and all the benefits they provide, you know that there are many relevant fields of science to choose from. And the next time you enjoy a delicious meal of fish or shrimp or any of the other 400+ stocks that are managed in the U.S., remember that a lot of science was involved before that seafood was caught and put on your plate!

ACKNOWLEDGMENTS

The authors would like to thank our young reviewer A. Wesch for their help in preparing this manuscript for submission.

REFERENCES

1. Watson, J. W., Epperly, S. P., Shah, A. K., and Foster, D. G. 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. *Can. J. Fish. Aquat. Sci.* 62:968–81. doi: 10.1139/f05-004
2. Kaplan, I. C., Levin, P. S., Burden, M., and Fulton, E. A. 2010. Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management. *Can. J. Fish. Aquat. Sci.* 67:1968–82. doi: 10.1139/F10-118
3. Chan, H. L., and Pan, M. 2021. Fishing trip cost modeling using generalized linear model and machine learning methods – A case study with longline fisheries in the Pacific and an application in regulatory impact analysis. *PLoS ONE* 16:1–23. doi: 10.1371/journal.pone.0257027
4. Richmond, L. 2013. Incorporating indigenous rights and environmental justice into fishery management: comparing policy challenges and potentials from Alaska and Hawai'i. *Environm. Manage*. 52:1071–84. doi: 10.1007/s00267-013-0021-0

SUBMITTED: 01 November 2023; **ACCEPTED:** 12 June 2024;
PUBLISHED ONLINE: 26 June 2024.

EDITOR: Hervé Claustre, Centre National de la Recherche Scientifique (CNRS), France

SCIENCE MENTORS: Maila Hallare and Emily Chen

CITATION: Wallmo K, Kleiber D, Tomberlin D, Woodworth-Jefcoats P and Oliver T (2024) The Diversity of Science Behind U.S. Seafood. Front. Young Minds 12:1331893. doi: 10.3389/frym.2024.1331893

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

MS. BRINGEWATT'S SCIENCE CLASS , AGES: 13–14

We are a class of 8th grade scientists who have been exploring the theme of water on our planet and the many ways water is connected to various science disciplines and current research efforts.

JOY, AGE: 14
Joy spends her days reading, playing board games, and snuggling with her dog Mabel. She hopes to explore her love of biology when she starts high school next year and has big plans to study veterinary medicine abroad after graduation. In addition to school, Joy loves playing both the viola and piano.

AUTHORS

KRISTY WALLMO
Dr. Kristy Wallmo has worked for NOAA Fisheries for over 20 years, conducting research to help us understand economic values, economic impacts, and trade-offs associated with alternative policies and conditions of marine resources. She is especially interested in exploring avenues for integrating ecosystem service values into fisheries management. One of the many things she enjoys about her job is the opportunity to talk with different people about their attitudes and opinions about the marine environment. *kristy.wallmo@noaa.gov

DANIKA KLEIBER
Dr. Danika Kleiber is a Social Scientist at the National Marine Fisheries Service Pacific Island Fisheries Science Center in Honolulu. Throughout her career she has woven together her background in gender and development and behavioral ecology, which has led to a specialization in applied equity approaches to fisheries research and management.

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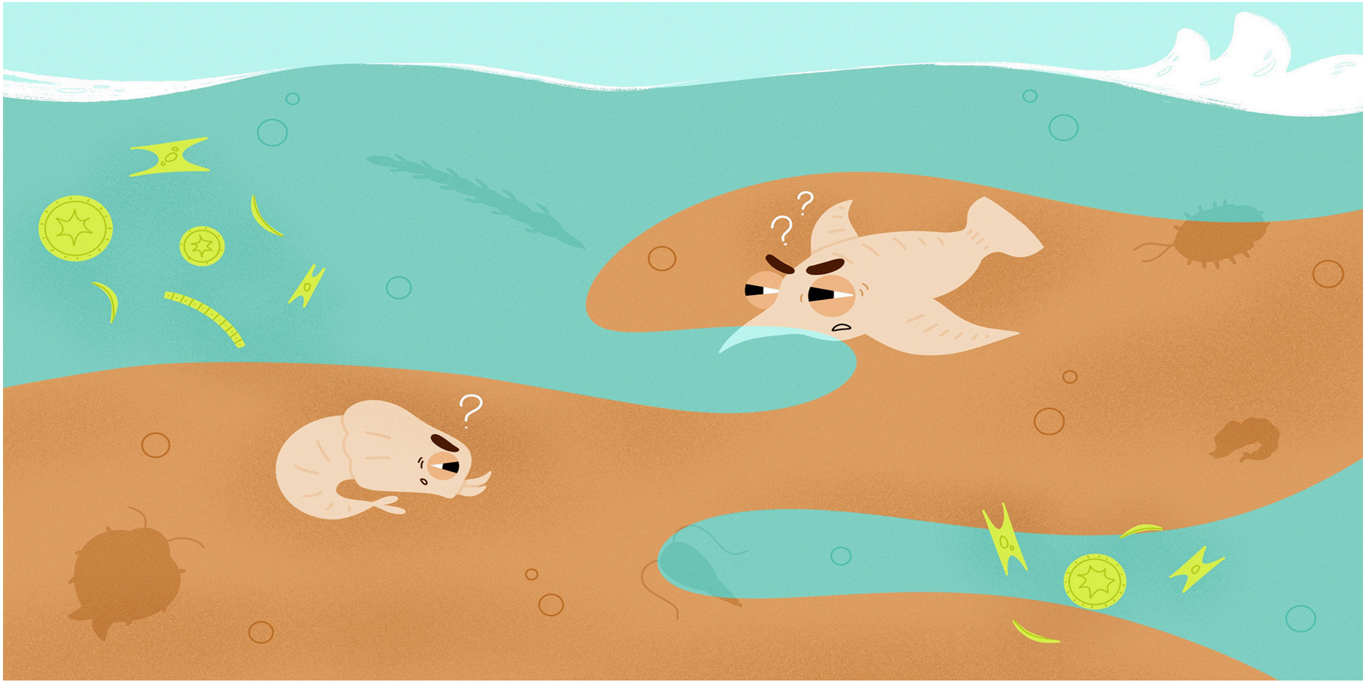
Dr. David Tomberlin is an economist with the National Marine Fisheries Service, the federal government agency that manages the ocean fisheries of the United States. His main professional activities are collecting and analyzing data, writing research papers, and serving as a member of scientific and management groups. David's current interests include coastal habitat management and Southeast Asian fisheries. He has graduate degrees in agricultural and natural resource economics and an undergraduate degree in English literature.

PHOEBE WOODWORTH-JEFCOATS
Dr. Phoebe Woodworth-Jefcoats is a research oceanographer. She studies the North Pacific Ocean, its food webs, and its fisheries. She is especially interested in the effects of climate change. Her favorite part of her job is using data to create images that help her understand what is happening beneath the ocean's surface. Phoebe works at the NOAA Fisheries Pacific Islands Fisheries Science Center. She holds degrees in meteorology, physical oceanography, and marine biology.

THOMAS OLIVER
Dr. Thomas Oliver is a Research Ecologist at the Pacific Island Fisheries Science Center who mostly studies coral reefs and what we can do to make sure that these special ecosystems are managed sustainably. He also advises the Western Pacific Fisheries Management Council on the best ways to keep our fisheries productive and sustainable across the US Pacific.

BIODIVERSITY
Published: 30 May 2024
doi: 10.3389/frym.2024.1310250



HOW MIGHT BROWNER SEAWATER AFFECT MARINE ORGANISMS?

Tharindu Bandara[1,2*], *Sonia Brugel*[1,2], *Agneta Andersson*[1,2] *and Danny Chun Pong Lau*[3]

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[2] *Umeå Marine Sciences Centre, Umeå University, Hörnefors, Sweden*
[3] *Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden*

YOUNG REVIEWERS:


AARON
AGE: 13


ERIC
AGE: 11

Climate change is having many negative impacts worldwide. Increased rainfall caused by climate change has become a serious issue in the northern parts of the world. With more rainfall, a larger amount of brown-colored decaying plant material is transported from the land to oceans, making the seawater browner. The brown color reduces the amount of sunlight that penetrates into the seawater, which can decrease the growth of microscopic plant-like organisms called phytoplankton that rely on sunlight to grow. Phytoplankton are an important food source for ocean animals, such as tiny creatures called zooplankton. This study explored the effects of seawater browning on phytoplankton and zooplankton in the northern Baltic Sea.

RUNOFF

Flow of water over the ground with carrying things like soil and plant leaves.

HUMIC SUBSTANCES

Colored compounds that are found in plant materials. They are released into the surrounding environment when plant material decays.

BROWNING

When the water color turns browner due to the high level of humic substances from decaying plant material.

Figure 1

From left to right, the water gets browner in color due to increasing amounts of humic substances in the water [2] (Photographed by Stefan Löfgren).

PHYTOPLANKTON

Microscopic plant-like organisms that live in water. Like plants, they can produce their food by using carbon dioxide (CO_2), sunlight, nutrients, and water.

ESSENTIAL FATTY ACIDS

Biochemical compounds that are needed for growth and various body functions in human and animals. They are the basic structural components of cell membranes in many organisms.

FOOD WEB

A diagram of how various animals in the environment connect to each other based on who eats whom.

WHAT IS BROWNING?

You have most likely heard about climate change, which is causing changes in the world's weather. Climate change has different effects in different areas of the world (You can read more about climate change in this Frontiers for Young Minds article). For example, due to climate change, some places in the world receive more rainfall, while other places experience severe lack of rain, which is called drought.

In the northern parts of the world, climate change generally results in more rainfall [1]. The increased amount of rainfall causes more water **runoff** from the land to the sea. This runoff usually contains a lot of plant material. When plant material decays, it releases compounds called **humic substances**. The more humic substances that enter the water, the browner the color of the water becomes. We call this effect **browning** (Figure 1). In many places, browning has become a major environmental problem in both freshwater and seawater. This is true in the northern Baltic Sea, for example [3, 4].

Figure 1

WHAT HAPPENS WHEN WATER BECOMES BROWNER?

When water becomes browner, the amount of sunlight that can penetrate into the water is reduced. Lack of sunlight can affect tiny organisms in the water, such as **phytoplankton**, which rely on sunlight, CO_2, nutrients, and water to grow. Browning is expected to reduce the growth of phytoplankton. Phytoplankton are an important source of nutrients, including **essential fatty acids**, which are needed by sea animals to grow and stay healthy. So, reduced growth of phytoplankton means a lower supply of nutrients for ocean **food webs**.

WHAT ARE ESSENTIAL FATTY ACIDS AND HOW DO ANIMALS GET THEM?

Have you ever seen products in supermarkets or pharmacies that are labeled as containing omega-3 fatty acids (Figure 2)? These are also called essential fatty acids, because they are essential (needed) for the health of animals including humans. In humans, essential fatty acids help prevent heart disease and several types of cancer, and they can improve growth and brain development [5–7]. Phytoplankton can produce essential fatty acids, but animals usually cannot. So, how do animals get essential fatty acids? Well, animals receive these important substances through food webs (You can read more about food webs in this Frontiers for Young Minds article). For example, essential fatty acids produced by phytoplankton can be transferred to tiny animals called **zooplankton** when zooplankton feed on phytoplankton. When zooplankton are then eaten by larger animals, such as fish, the essential fatty acids obtained by zooplankton are then transferred to the fish. Therefore, humans can obtain essential fatty acids by eating fish. The omega-3 fatty acids found in many products sold in supermarkets or pharmacies are actually extracted from fish oil.

ZOOPLANKTON

Small animals that live in water. Some of them look like very small crabs and shrimps. Most of them eat phytoplankton.

Figure 2

Figure 2

Capsules of omega-3 fatty acids (also called essential fatty acids), obtained from fish oil, are sold in pharmacies and supermarkets.

HOW DOES BROWNING AFFECT PHYTOPLANKTON AND ZOOPLANKTON?

To find out how browning affects phytoplankton and zooplankton, we conducted a study in the northern Baltic Sea (Figure 3A). We found that northern locations in the Baltic Sea had higher amounts of humic substances in seawater than southern locations did. This shows that browning is more severe in northern locations. We also measured the amounts of phytoplankton in the seawater samples. Interestingly, we found that the northern locations had lower amounts of phytoplankton than the southern locations had. This means there were fewer phytoplankton available to produce essential fatty acids in the northern locations.

We then measured the amount of essential fatty acids in zooplankton. A higher amount of essential fatty acids indicates that the zooplankton are more nutritious for other organisms that eat them. As we expected, the nutritional quality of zooplankton at the northern locations with more browning was much lower than the nutritional quality of zooplankton at the southern locations. The lower nutritional quality of

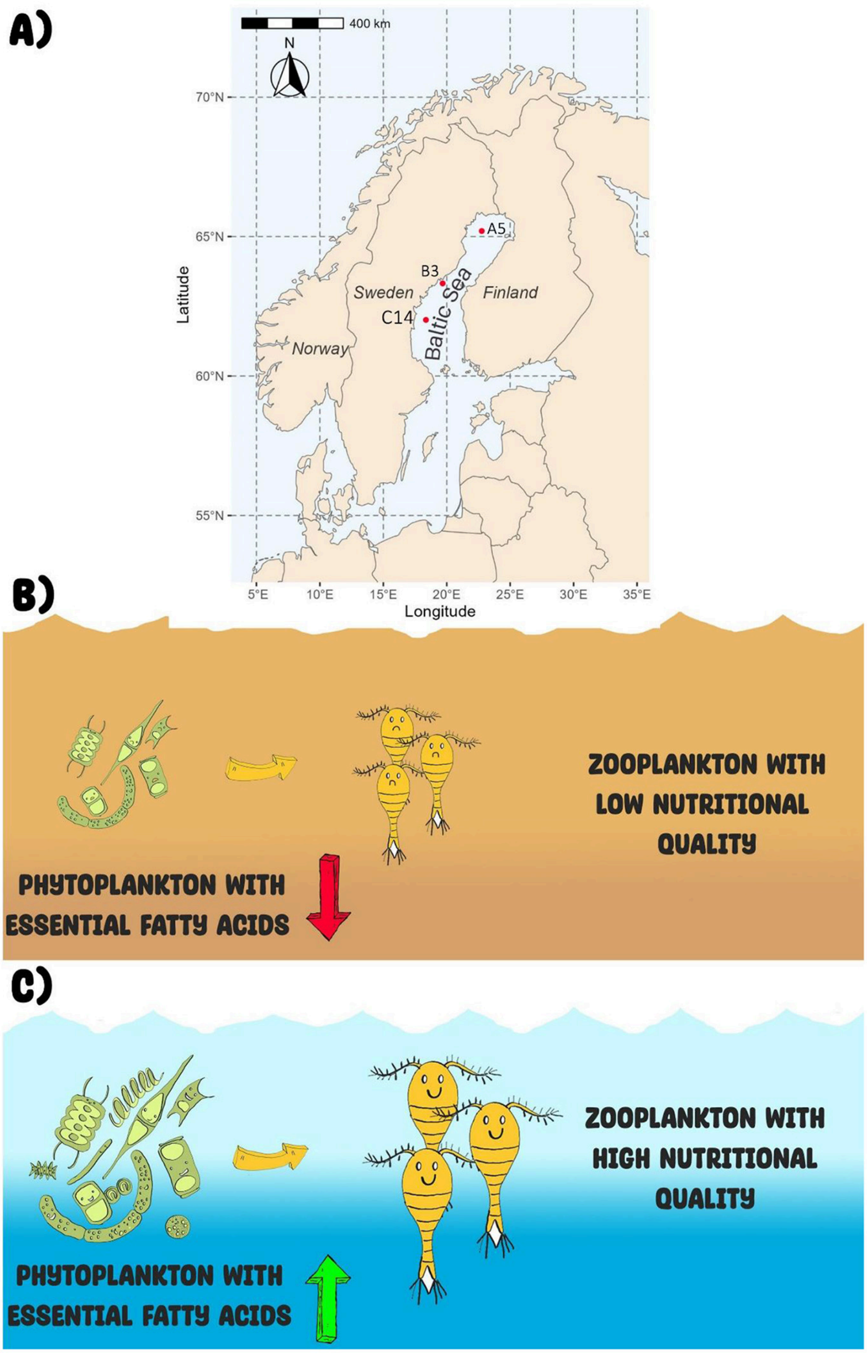


Figure 3

Figure 3

(A) Map of the Baltic Sea. The red dots show the northern (A5 and B3) and the southern (C14) locations of sample collection for the study. **(B)** Northern locations in the northern Baltic Sea had brown water and few phytoplankton producing essential fatty acids. Zooplankton feeding on these phytoplankton had a low amount of essential fatty acids in their bodies, meaning that the zooplankton had low nutritional quality. **(C)** Southern locations in the northern Baltic Sea had clear water and more phytoplankton producing essential fatty acids. Zooplankton feeding on these phytoplankton had a high amount of essential fatty acids in their bodies, so they had a high nutritional quality.

zooplankton was probably due to the lower amounts of essential fatty acids produced by phytoplankton at the northern locations (Figures 3B, C).

WHAT WILL HAPPEN TO MARINE FOOD WEBS?

Zooplankton are a common food for many fish in the Baltic Sea. So, feeding on zooplankton of a lower nutritional quality in browner waters may negatively affect the nutritional quality and health of fish. The negative effects may pass on through the food web when these fish are eaten by other animals such as birds. However, we are not sure exactly what will happen, and we need to carry out more studies to understand how increased browning may affect the nutritional quality and health of other animals in the food web.

WHAT CAN WE DO?

How can we reduce the effect of browning on marine food webs? The first thing we can think of is promoting actions that will help to reduce climate change. Actions such as reducing the use of fossil fuels, educating yourself and others about climate change, and saving as much energy as possible are several ways to slow climate change. In addition, protecting and restoring streams and rivers that have been destroyed by human activities can also help to fight against browning [2]. Restoration of streams by various activities (e.g., addition of large stones and adding wood to streams) can hold decaying plant material for a longer time, which allows humic substances to decompose completely [2, 8]. This may greatly reduce the amount of humic substances entering the sea and reduce seawater browning. Efforts to reduce browning of seawater will help restore healthy marine organisms and food webs.

ACKNOWLEDGMENT

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This project was funded by the Swedish research council FORMAS (FR-2019/0007) grant and by the Swedish research environment EcoChange.

ORIGINAL SOURCE ARTICLE

Bandara, T., Brugel, S., Andersson, A., and Lau, D. C. P. 2022. Seawater browning alters community composition and reduces the nutritional quality of plankton in a sub-Arctic marine ecosystem. *Canadian J. Fisher. Aquat. Sci.* 79:1291–301. doi: 10.1139/cjfas-2021-0118

REFERENCES

1. Andersson, A., Meier, H. E. M., Ripszam, M., Rowe, O., Wikner, J., Haglund, P., et al. 2015. Projected future climate change and Baltic Sea ecosystem management. *AMBIO*. 44:345–56. doi: 10.1007/s13280-015-0654-8
2. Kritzberg, E. S., Hasselquist, E. M., Škerlep, M., Löfgren, S., Olsson, O., Stadmark, J., et al. 2020. Browning of freshwaters: consequences to ecosystem services,

underlying drivers, and potential mitigation measures. *Ambio.* 49:375–90. doi: 10.1007/s13280-019-01227-5

3. Opdal, A. F., Andersen, T., Hessen, D. O., Lindemann, C., Aksnes, D. L. 2023. Tracking freshwater browning and coastal water darkening from boreal forests to the Arctic Ocean. *Limnol. Oceanogr. Lett.* 8:611–9. doi: 10.1002/lol2.10320
4. Paczkowska, J., Brugel, S., Rowe, O., Lefébure, R., Brutemark, A., Andersson, A. 2020. Response of coastal phytoplankton to high inflows of terrestrial matter. *Front. Mar. Sci.* 7:80. doi: 10.3389/fmars.2020.00080
5. von Schacky, C., Harris, W. S. 2007. Cardiovascular benefits of omega-3 fatty acids. *Cardiov. Res*. 73:310–5. doi: 10.1016/j.cardiores.2006.08.019
6. Calviello, G., Serini, S., Piccioni, E. 2007. n-3 polyunsaturated fatty acids and the prevention of colorectal cancer: molecular mechanisms involved. *Curr. Med. Chem*. 14:3059–69. doi: 10.2174/092986707782793934
7. Chang, C. Y., Ke, D. S., Chen, J. Y. 2009. Essential fatty acids and human brain. *Acta Neurol. Taiwan*. 18:231–41.
8. Frainer, A., Polvi, L. E., Jansson, R., McKie, B. G. 2018. Enhanced ecosystem functioning following stream restoration: the roles of habitat heterogeneity and invertebrate species traits. *J. Appl. Ecol.* 55:377–85. doi: 10.1111/1365-2664.12932

SUBMITTED: 09 October 2023; **ACCEPTED:** 14 May 2024;
PUBLISHED ONLINE: 30 May 2024.

EDITOR: Carolyn Scheurle, Institut de la Mer de Villefranche (IMEV), France

SCIENCE MENTORS: Nancy Lo Man Hung and Alfonsina E. Romo-Curiel

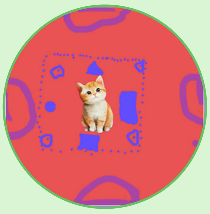
CITATION: Bandara T, Brugel S, Andersson A and Lau DCP (2024) How Might Browner Seawater Affect Marine Organisms? Front. Young Minds 12:1310250. doi: 10.3389/frym.2024.1310250

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

AARON, AGE: 13

I am a 13-year-old with a passion for karate and basketball. When I am not kicking and shooting hoops, you can find me tinkering with robots or wandering through the forest with my dad, soaking in nature's wonders. I have got two adorable rabbits who keep me company, and I love nothing more than goofing around with my sister.



ERIC, AGE: 11

My name is Eric, and I am Brazilian. I am 11 years old and in the sixth grade at school. I like to run and participate in sports such as swimming, capoeira, football, and biking. I also enjoy playing games, playing the violin, going to the beach, and playing with my cat, Crystal. Additionally, I have a keen interest in space and robots.

AUTHORS

THARINDU BANDARA

I am currently a Ph.D. student at the Department of Ecology and Environmental Sciences at Umeå University, Sweden. My main research interest is in studying the effects of climate change on marine food webs, especially in the northern Baltic Sea. Apart from that, I am also interested in studies on fish biology, aquaculture, and fisheries management. *tharindu.bandara@umu.se

SONIA BRUGEL

I am a biological oceanographer at the Department of Ecology and Environmental Sciences at Umeå University, Sweden. I am working with research questions looking at the response of ocean ecosystems to climate change in the Baltic Sea.

AGNETA ANDERSSON

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DANNY CHUNG PONG LAU

I am an aquatic ecologist at the Department of Aquatic Sciences and Environmental Assessment, Swedish University of Agricultural Sciences, Sweden. I am interested in the biodiversity and food webs in both freshwater and marine ecosystems. My research focuses on investigating how these ecosystems are affected by human activities and climate change. I like hiking, exercising, and observing plants and animals in nature.

BIODIVERSITY
Published: 30 May 2024
doi: 10.3389/frym.2024.1320782

PLAYING GENETIC PUZZLES TO DISCOVER UNSEEN MAJORITY OF TINY OCEAN ORGANISMS

Xin Sun *

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YOUNG REVIEWERS:

JOSÉ MARÍA MORELOS Y PAVÓN ELEMENTARY SCHOOL
AGE: 11–12

KARUBAKEE
AGE: 12

The ocean is the home of many amazing living things such as fishes, shrimps, jellyfish, and seagrasses. You might have seen some of these organisms in the ocean or a beautiful aquarium. But did you know that there is another kind of marine life that dramatically outnumbers all other ocean organisms, but they are so small that you cannot even see them? They are microbes! Microbes are important for the ocean because some of them turn waste produced by other organisms back into food, and others can even influence Earth's climate. Scientists want to learn more about ocean microbes. However, it is super hard to grow these microbes in an aquarium or a lab because we need to know exactly what they like to eat and what their favorite conditions are. What can we do? We use a cool technique called metagenomics, which can help us figure out which microbes are found in the ocean by putting together genetic puzzles!

WHY SHOULD WE CARE ABOUT OCEAN MICROBES?

Earth is different from other planets because it has many amazing living things. More than 70% of Earth's surface is covered by seawater, and many organisms live in the ocean. Fishes, shrimps, or seagrasses might quickly come to mind when you think about marine life. However, there is one group of organisms that dramatically outnumbers any of the others, but they are so tiny that we cannot see them with our eyes. These very small life forms called **microbes**. One ml of seawater near the ocean surface has around one million microbes! These microbes include some "bad" ones that make people sick, but most ocean microbes help keep the ocean healthy and are important to sustain life on Earth.

MICROBES

Tiny organisms that are too small to be seen with our eyes. Most microbes are single-cell organisms such as bacteria and archaea.

Here are examples of those environmentally relevant marine microbes. Carbon dioxide is a greenhouse gas, and too much carbon dioxide in the atmosphere warms Earth faster than living things can handle. Cyanobacteria are a group of marine **phytoplankton** (see this Frontiers for Young Minds article), which are tiny ocean organisms similar to plants. With the help of sunlight, phytoplankton take in carbon dioxide to grow, and in the process they release oxygen. Without the actions of phytoplankton, Earth would warm up even faster. Other types of microbes, like ocean bacteria that take in oxygen, are also important. They can break down dead organisms and the wastes organisms produce, and turn these materials back into nutrients that phytoplankton can use to grow [1]. Small shrimps then feed on phytoplankton and the shrimps are part of the diets of certain fishes, forming the food web. Without ocean microbes, the entire ocean food web would collapse.

PHYTOPLANKTON

Tiny organisms live in water and act like plants. They use energy from sunlight to turn carbon dioxide and water into oxygen, and they grow during this process.

SOME MARINE MICROBES LIVE WITHOUT OXYGEN

Some marine microbes live in unique ocean regions where oxygen cannot be detected—areas where living things that *do* depend on oxygen cannot live (Figure 1). These microbes use other chemicals instead of oxygen to "breath", such as different forms of nitrogen (see this Frontiers for Young Minds article) [2], and they can change nitrogen compounds that are essential food for other ocean organisms into gasses, which then escape from the ocean. Thus, microbes in oxygen-free seawater control the rate at which marine life grows and multiplies throughout the ocean. Additionally, one type of released nitrogen gasses, called nitrous oxide, is a greenhouse gas with a warming power around 300 times stronger than carbon dioxide. So, you can see that microbes living in oxygen-free regions of the ocean play several very important roles in keeping our planet healthy and in balance.

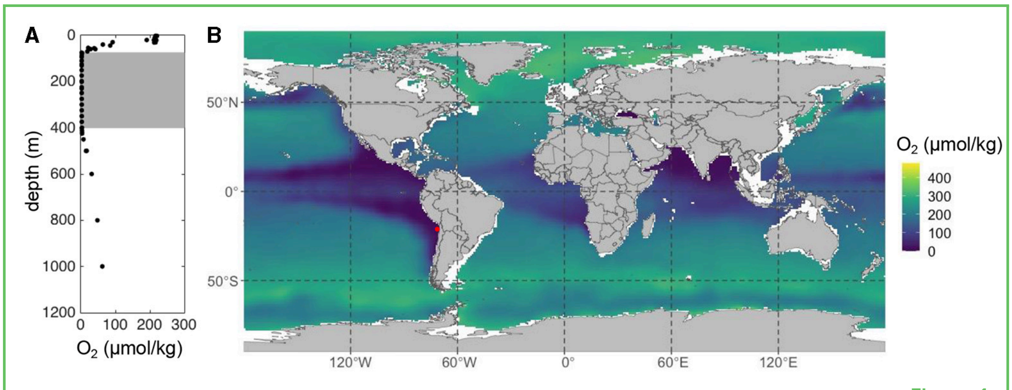

Figure 1

Oxygen concentrations in the ocean. **(A)** In the Eastern Tropical South Pacific [red dot in **(B)**, where we sampled [3]], oxygen concentration changes with depth. Gray area indicates oxygen-free seawater. **(B)** Oxygen concentrations at 200 m depth in the world's oceans (oxygen data from World Ocean Atlas). The dark purple areas are those special oceanic regions with low or no oxygen.

MARINE MICROBES ARE HARD TO GROW IN THE LAB

Most microbes are single cells, so you would think they would be very easy to grow and take care of compared to complex organisms with many cells, such as puppies. In some cases, this is true—some bacteria can double themselves within only a few hours at room temperature, if they are given some simple nutrients. However, growing marine microbes is usually not easy. One reason is that most of the ocean has low concentrations of nutrients. Thus, the most abundant and successful microbes in the ocean are usually those that are good at taking up very tiny amounts of nutrients, but these microbes grow very slowly. Even though ocean nutrient concentrations are low, there are many kinds of nutrients in the ocean. Marine microbes often need a variety of nutrients to grow. Due to the vast diversity but low concentration of ocean nutrients, it is hard to figure out which nutrients ocean microbes need to grow and thrive.

Microbes from seawater without oxygen are exceptionally hard to grow. On top of the difficulties we already mentioned, scientists must ensure that no oxygen is around while they are growing these microbes. That is not easy since nearly 20% of the air is oxygen. Even the systems scientists can purchase to seal bottles to create oxygen-free environments are saturated with oxygen. Consequently, growing microbes in the lab can only help us understand a small proportion of ocean microbes, especially in the oxygen-free parts of the ocean. How can we learn about the diverse microbes that have yet to be successfully grown in the lab?

METAGENOMICS

The exploration of all genetic information from all the organisms collected from a certain environment. Metagenomics does not target just one type of genetic information or one type of organisms; instead, it examines a mix of genetic information from various organisms.

PUTTING TOGETHER GENETIC PUZZLES TO STUDY HARD-TO-GROW MICROBES

Thanks to the development of **metagenomics**, we can now get to know microbes by examining their genetic material, which tells us what kinds of functions they may be performing—without the need to grow them (Figure 2). Metagenomics is the exploration of the genetic information of *all* microbes collected from a certain environment (e.g., ocean, land, rivers, lakes, and inside plants and animals—including humans). To study ocean microbes using metagenomics, scientists collect marine microbes by running liters of seawater through filters with tiny holes, which let seawater run through but trap the microbes (Figure 2). Then, the genetic material of the microbes is separated from other cell parts and is sequenced using laboratory equipment that reveals the genetic code of each microbe (the latter process is called sequencing; Figure 2).

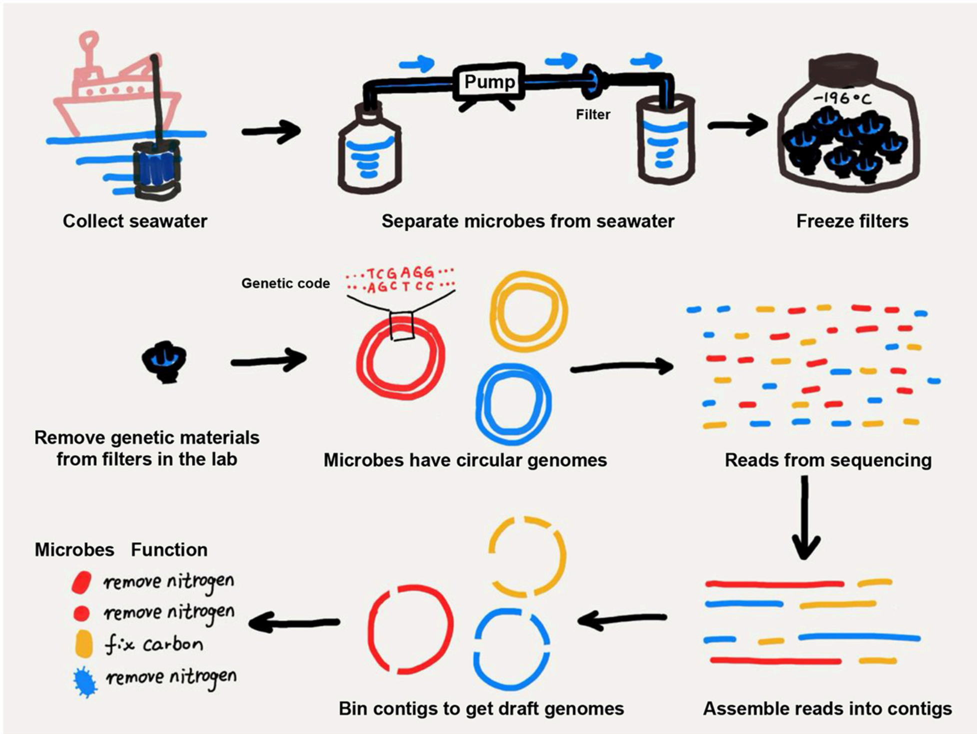

Figure 2

Figure 2

Metagenomics involves sampling microbes from the ocean and putting together genetic puzzles to understand which microbes are present in the ocean and what they can do.

The genetic material of each microbe is mainly stored in a circular genome. However, during sample collection and sequencing, circular genomes break into short pieces (we call them reads). The reads in our samples belonging to different microbes get mixed up together. To understand the genomes of the different kinds of microbes in our samples, we must link these short pieces (i.e., reads) into longer pieces of genetic material (a process known as assembly) and then sort these longer pieces according to which microbes they belong to (a process known as binning). This entire process is like putting together a puzzle with millions of pieces (Figure 2).

PUTTING TOGETHER THE GENETIC PUZZLES

The first step is called assembly. Assembly involves connecting short reads into longer pieces (we call these longer pieces contigs) based on their overlapping parts. For example, if the end of a read is the same as the beginning of another read, we know they were originally linked and belong to the same genome. However, assembly does not give us all the genomes of marine microbes because some parts of each genome are usually lost during sampling and sequencing, meaning there are gaps in the genomes where we have no reads.

The next step is binning, which is putting all the contigs that we cannot link any further into genomes. Like pieces from the same jigsaw puzzle, contigs originally belonging to the same microbial genome share some similarities. The genetic material of living organisms is made up of a combination of four different molecules (called nucleotides), abbreviated A, T, C, and G. Each organism has its own preference for using certain nucleotides more than others, or for putting certain nucleotides next to each other. These preferences can help scientists find contigs from the same genome. Other information can also be used to group contigs into genomes. After binning, we have microbial genomes that still have some gaps compared to the actual genomes of the microbes, and we call them draft genomes or metagenome-assembled genomes (we will use "draft genomes" hereinafter) to differentiate them from the full genomes without gaps.

WHAT DID WE LEARN ABOUT OCEAN MICROBES FROM PLAYING GENETIC PUZZLES?

Draft genomes created by putting together genetic puzzles can provide valuable information about microbes that cannot be grown in the lab. In a recent study, we recovered draft genomes from seawater in the Eastern Tropical South Pacific where there is very little or no oxygen (Figure 1) [3]. By comparing these draft genomes with those from the global ocean [4], we found that there are many microbes living in low- or no-oxygen seawater. More than half of the microbes we found in our samples had never been discovered before (Figure 3). These draft genomes suggest that many of these microbes use nitrogen when oxygen is not available, and some nitrogen might be turned into gases that leave the ocean and enter the atmosphere (Figure 3).

As mentioned earlier, nitrogen is an essential nutrient for all living things. So, understanding how much nitrogen is turned into gases and lost from the ocean is important for scientists to estimate the amount of living things that the ocean can support. One main nitrogen-loss process has multiple steps. Previous knowledge of this process was largely based on microbes that can grow in the lab, and most of those lab microbes can perform *all* the steps. If most microbes associated with this process in low-oxygen seawater can also perform the entire process, they could cause loss of nitrogen from the ocean. By examining draft genomes from low-oxygen seawater, however, we found that most microbes associated with the nitrogen-loss process

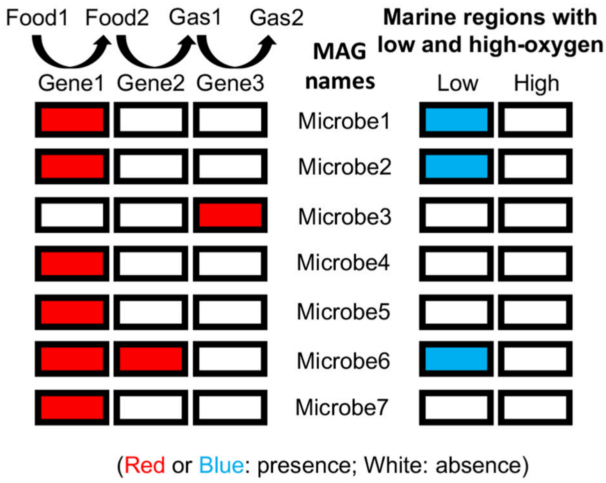

Figure 3

Figure 3

Nitrogen-breathing genes and representation of MAGs in the global ocean. In the ocean, nitrogen is present in forms that serve as food for living things. The process of converting "food" nitrogen to gas forms has several steps. Our research showed that specific microbes can perform specific steps in the process, controlled by different genes. Presence (red) and absence (white) of genes involved in this process are shown for each draft genome. On the right, you can see whether these draft genomes were found in other ocean regions with low or high oxygen where other scientists collected metagenomic data [modified from Figure 2 in Sun and Ward [3]].

could only perform *some* of the steps. This means that many of these microbes *do not* cause nitrogen loss from the ocean. The new microbes that we discovered using metagenomics tell us that we must revisit the way we estimate nitrogen loss from the ocean.

ACKNOWLEDGMENTS

XS was supported by the Simons Foundation postdoctoral fellowship in Marine Microbial Ecology.

ORIGINAL SOURCE ARTICLE

Sun, X., and Ward, B. B. 2021. Novel metagenome-assembled genomes involved in the nitrogen cycle from a Pacific oxygen minimum zone. *ISME Commun*. 1:26.
doi: 10.1038/s43705-021-00030-2

REFERENCES

1. Pomeroy, L. R., leB. Williams, P. J., Azam, F., and Hobbie, J. E. 2007. The microbial loop. *Oceanography* 20:28–33. doi: 10.5670/oceanog.2007.45
2. Ward, B. B. 2013. Oceans. How nitrogen is lost. *Science* 341:352–3. doi: 10.1126/science.1240314
3. Sun, X., and Ward, B. B. 2021. Novel metagenome-assembled genomes involved in the nitrogen cycle from a Pacific oxygen minimum zone. *ISME Commun.* 1:26. doi: 10.1038/s43705-021-00030-2
4. Tully, B. J., Graham, E. D., and Heidelberg, J. F. 2018. The reconstruction of 2,631 draft metagenome-assembled genomes from the global oceans. *Sci. Data* 5:170203. doi: 10.1038/sdata.2017.203

SUBMITTED: 12 October 2023; **ACCEPTED:** 21 May 2024;
PUBLISHED ONLINE: 30 May 2024.

EDITOR: Sanae Chiba, North Pacific Marine Science Organization, Canada

SCIENCE MENTORS: Biswajit Panda and Luisa I. Falcon

CITATION: Sun X (2024) Playing Genetic Puzzles To Discover Unseen Majority Of Tiny Ocean Organisms. Front. Young Minds 12:1320782. doi: 10.3389/frym.2024.1320782

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

YOUNG REVIEWERS

JOSÉ MARÍA MORELOS Y PAVÓN ELEMENTARY SCHOOL, AGE: 11–12
We are the 6th grade class of the public elementary school José María Morelos y Pavón.

KARUBAKEE, AGE: 12
I like to read about space related facts and am highly interested in knowing about world history. I also like to read fantasy books and listen to music.

AUTHORS

XIN SUN
I am Xin Sun, a Simons postdoctoral fellow at Carnegie Science located at Stanford University. I am fascinated by how tiny but diverse microbes drive global nutrient cycles in a changing environment. I am trained as an oceanographer. I have been to the Pacific Ocean and the Chesapeake Bay several times on research cruises. Now, I am combining what I learned through experiments and metagenomics with theories and models. I want to improve our understanding of the diverse ocean microbes and ocean nutrient cycles. *xinsun12@gmail.com

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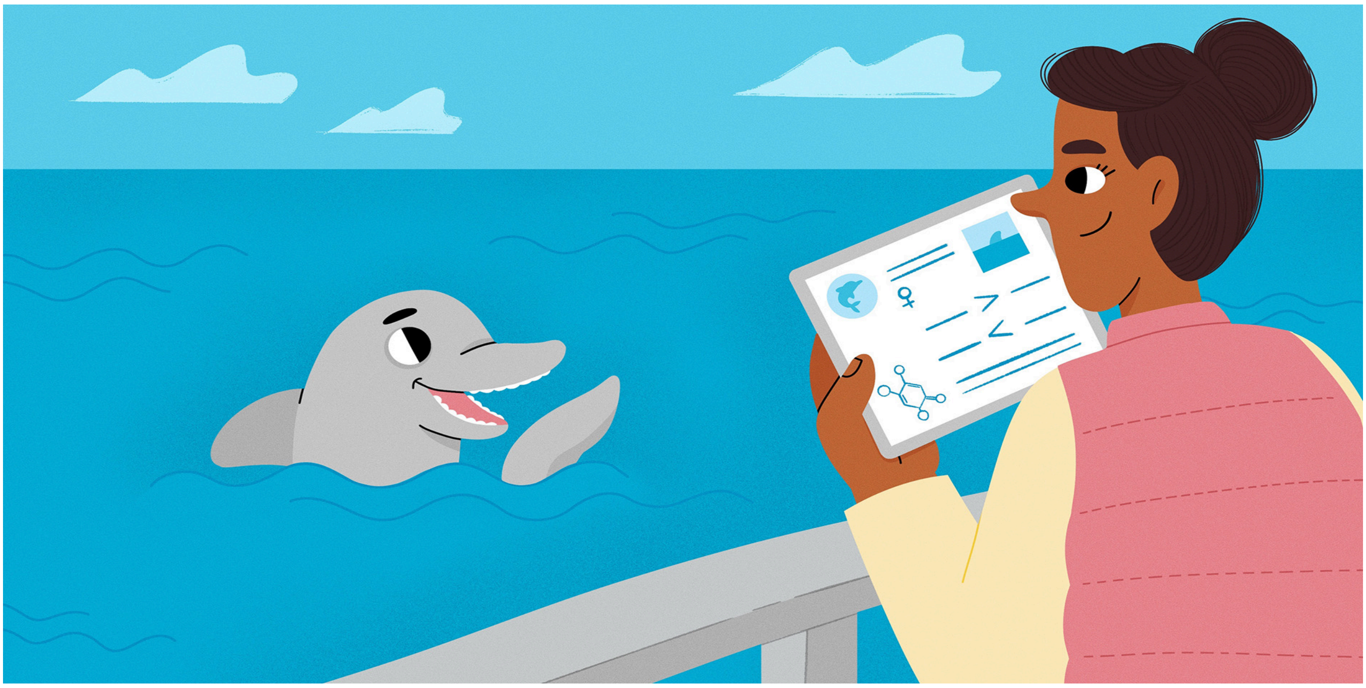
BIODIVERSITY
Published: 30 May 2024
doi: 10.3389/frym.2024.1342551



EPIGENETIC CLOCKS: USING DNA TO ESTIMATE THE AGE OF DOLPHINS

***Katharina J. Peters*[1*] *and Livia Gerber*[2*]**

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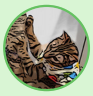
[2] *Australian National Wildlife Collection, National Research Collections Australia, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, ACT, Australia*

YOUNG REVIEWERS:


BENJAMIN
AGE: 11


GEMMA
AGE: 8


JACE
AGE: 10


KINABALU INTER-NATIONAL SCHOOL
AGES: 9–11


VERALYN
AGE: 12

You probably know your age and you might be good at estimating the ages of other people. However, have you ever tried to guess the age of an animal, for example a dolphin? Estimating the age of dolphins is really difficult, because their appearance does not change once they are fully grown. Fortunately, the shape of their DNA changes over time. This allowed us to develop a tool, called an epigenetic clock, to determine the age of dolphins based on their DNA. Using this clock, we can estimate the age of a dolphin with an accuracy of 2 years. Although it is not exact, this still helps us answer questions about the lives of dolphins, such as when they start their own families. Knowing dolphin ages can also tell us if a group of dolphins contains a healthy mix of older and younger individuals. Epigenetic clocks are now being developed for many other species, offering exciting new research opportunities.

HOW TO ESTIMATE THE AGE OF DOLPHINS

When studying animals, one of the most important pieces of information to know about individual animals is their age. Scientists must know how old an animal is to understand many parts of its life history and, for example, to estimate if a population of animals can survive. But estimating an animal's age is not easy when its date of birth is unknown. Across all animal species, there are no general signs for the aging process, such as the wrinkles or gray hair seen in humans. Because there are no visible signs, it is difficult to know the age of fully grown animals, especially if they live for a very long time. For example, how would you be able to tell if a dolphin is 20 or 30 years old?

Whales and dolphins are a particular challenge because they move around a lot and are difficult or forbidden to capture [1]. A good way to estimate a dolphin's age is to pull out a tooth and look at the growth layers of its **dentine**, like you would count the rings in the trunk of a tree. This way, teeth can help scientists find a dolphin's age quite accurately. However, this method is not pleasant for the dolphins and therefore difficult to do with live animals. For some species, such as Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), a pattern of spots on their skin can tell us about their age, because they gain more spots as they grow older (Figure 1). However, individuals tend to have different amounts of spots in general, and it is often quite difficult to see enough of a dolphin's body to clearly see and count the spots. So, trying to age an animal based on its spotting pattern will only give us a rough estimate.

DENTINE

Hard, dense, bony tissue forming most of a tooth, beneath the outer coating of protective enamel.

Because of these difficulties, most studies rely on data collected over a long time, in studies where animals have been regularly observed for many years since their birth, and thus their ages are known. For species that can live for many years, it can be difficult to gather enough data in a human's lifetime.

Figure 1

Figure 1

Indo-pacific bottlenose dolphin with speckling pattern. Photo by Simon Allen.

SHARK BAY DOLPHINS

One of the places where dolphins have been studied for many years is Shark Bay, Western Australia. There, scientists have observed a population of Indo-Pacific bottlenose dolphins for more than 30 years [2], using techniques called **photo-identification** and **biopsy sampling**. For photo-identification, researchers take photos of the dolphins' **dorsal fins**. The shape of the fin is like a human fingerprint, and by comparing the fins of different animals, researchers can recognize individuals. Biopsy sampling means collecting a small piece of dolphin skin that can be analyzed in the lab to get the animals' DNA. Because we have been studying this dolphin population for a long time and we recognize the individual dolphins, we also know when one is born and, therefore, can calculate its age. Thanks to biopsy sampling we have small skin samples from all the dolphins we study.

PHOTO-IDENTIFICATION

A method of identifying individual dolphins using photos of their dorsal fins. The scars and marks on their fins make them unique, like a fingerprint in humans.

BIOPSY SAMPLING

A data collection technique where we take a small skin sample from a live dolphin using a little dart with a sharp hollow end.

DORSAL FIN

The fin on the back of a whale or dolphin.

WHAT IS EPIGENETICS?

Our dolphin DNA samples have opened doors to new methods of age estimation for our dolphin species, using **epigenetics**. Epigenetics is the study of how the environment and an individual's behaviors can affect the way their genes work. Epigenetic changes modify the shape of the DNA, which alters which genes are switched on or turned off. This shape change can happen by adding or removing small molecules to the DNA—a process called **DNA methylation**. As animals age, different sets of genes are switched on or "expressed", meaning that the DNA takes on different shapes throughout an animal's life (Figure 2).

EPIGENETICS

The study of how our genes are affected by our behaviors and the environment we are exposed to.

DNA METHYLATION

Small molecules are added to the DNA to help tell the cells in our body which parts of the DNA to read and use, like how bookmarks help us find the right page in a book. These tags can turn genes on or off, which helps control how our bodies grow and work.

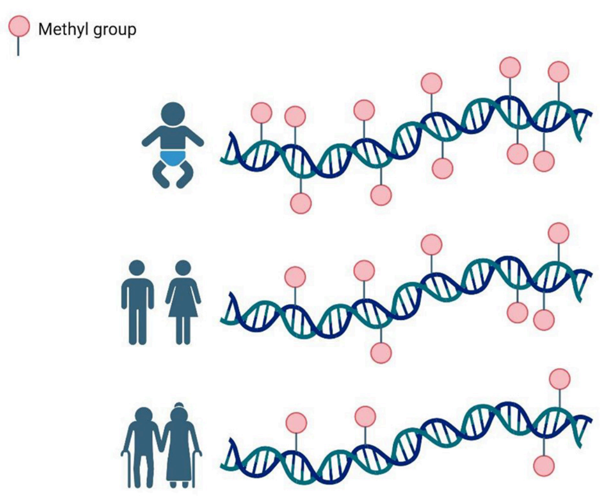


Figure 2

Figure 2

DNA (blue spiral) loses methylation as individuals age. A baby has the most methyl groups attached to its DNA, while adults have less than babies. Older people have the lowest number of methyl groups attached to their DNA. The same can be seen in dolphins and many other animals. These age-related differences in DNA methylation led us to develop our epigenetic clock to determine the ages of dolphins from the DNA found in tiny skin samples.

EPIGENETIC CLOCK

A test that looks at small chemical markers on our DNA to figure out our age. It is based on changes of these markers, called methyl groups, with age.

MACHINE LEARNING

A type of artificial intelligence that learns from data.

Figure 3

There are 4 basic steps in building/using an epigenetic clock. **(A)** Take genetic samples (for example skin) of animals for which you know the age (Age = !). **(B)** Analyze the DNA methylation of these samples. **(C)** Build the clock by connecting the age of the dolphins to the amount of DNA methylation in each sample. **(D)** Using the clock: now you can analyze a sample from a dolphin for which you do not know the age (Age = ?). Based on the amount of DNA methylation, the clock will estimate how old the dolphin is (Age = !).

HOW DOES THE EPIGENETIC CLOCK WORK?

Aging changes the levels of DNA methylation. Newborn dolphin calves have the highest levels of DNA methylation, while old individuals have the lowest. This change in methylation is also referred to as the **epigenetic clock**. Using DNA from skin samples, we measured the levels of DNA methylation in dolphins of a known age, using a new tool called the HorvathMammalMethylChip40 [3], which can measure DNA methylation on up to 37,492 sites on the DNA at once. We then built an epigenetic clock using **machine learning**, which we used to estimate the age of other dolphins of the same species based on their methylation levels (Figure 3). Our clock had an average accuracy of 2.1 years, meaning if we estimated an animal to be 25 years old, it might actually be anywhere between 23–27 years old [4]. This is quite close and therefore a really good result!

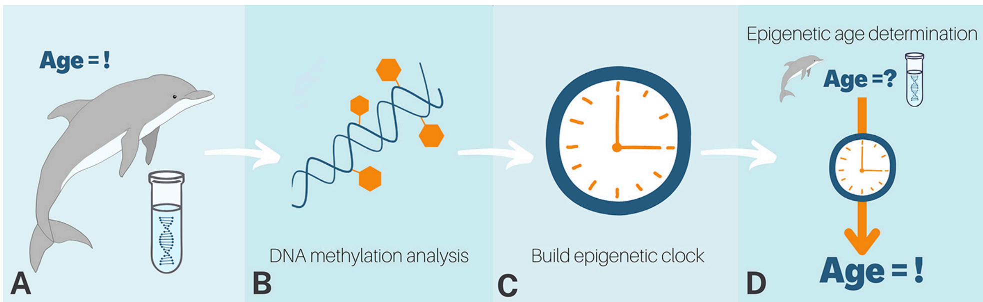


Figure 3

We also tested how well a different clock, developed using skin samples from a related species (common bottlenose dolphins [5]), worked for our samples. Common bottlenose dolphins look almost the same as Indo-Pacific dolphins but are often a bit bigger. We found that the common bottlenose dolphin clock worked almost as well for our Indo-pacific bottlenose dolphins as for the species it was made for.

WHY IS THE EPIGENETIC CLOCK USEFUL?

Dolphins can live for more than 30 years, and in the past it has been very difficult to gather information from many animals with known ages. By using the epigenetic clock, we can now estimate the age of individual dolphins just based on their DNA, which means we only need a small skin sample from each dolphin, and we are good to go! This makes our clock extremely useful for scientists that study Indo-Pacific bottlenose dolphins but who do not have access to long-term data. The fact that the common bottlenose dolphin clock also worked really well for our species means that even researchers studying other closely related species can use our clock. Because it is expensive to build an epigenetic clock, sharing a clock can save researchers thousands of dollars, which they can then use for other interesting research.

WHAT ARE THE NEXT STEPS?

We now know the age for many dolphins in the Shark Bay population. With this knowledge, we can ask further questions, such as at what time in their lives they produce the most calves or what influences their aging. We can also study whether males and females age differently. As so often in science, an answer leads to many more questions! This is an exciting time for us, and we cannot wait to get deeper into this work!

ACKNOWLEDGMENTS

KP was supported by a Postdoc Grant from the University of Zurich. LG was supported by an Early Postdoc Mobility Grant from the Swiss National Science Foundation (P2ZHP3_200011). The A.H. Schultz Foundation and the Claraz Foundation contributed to the sequencing costs.

ORIGINAL SOURCE ARTICLE

Peters, K. J., Gerber, L., Scheu, L., Cicciarella, R., Zoller, J. A., Fei, Z., et al. 2023. An epigenetic DNA methylation clock for age estimates in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*). *Evolut. Applic.* 16:126–33. doi: 10.1111/eva.13516

REFERENCES

1. Read, F. L., Hohn, A. A., and Lockyer, C. H. 2018. A review of age estimation methods in marine mammals with special reference to monodontids. *NAMMCO Sci. Publ.* 10:1–67. doi: 10.7557/3.4474
2. Connor, R. C., and Krützen, M. 2015. Male dolphin alliances in Shark Bay: changing perspectives in a 30-year study. *Anim. Behav.* 103:223–235. doi: 10.1016/j.anbehav.2015.02.019
3. Arneson, A., Haghani, A., Thompson, M. J., Pellegrini, M., Kwon, S. B., Vu, H., et al. 2022. A mammalian methylation array for profiling methylation levels at conserved sequences. *Nat. Commun.* 13:1–13. doi: 10.1038/s41467-022-28355-z
4. Peters, K. J., Gerber, L., Scheu, L., Cicciarella, R., Zoller, J. A., Fei, Z., et al. 2023. An epigenetic DNA methylation clock for age estimates in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*). *Evolut. Applic.* 16:126–33. doi: 10.1111/eva.13516
5. Robeck, T. R., Fei, Z., Haghani, A., Zoller, J. A., Li, C. Z., Steinman, K. J., et al. 2021. Multi-tissue methylation clocks for age and sex estimation in the common bottlenose dolphin. *Front. Mar. Sci.* 8:713373. doi: 10.3389/fmars.2021.713373

SUBMITTED: 22 November 2023; **ACCEPTED:** 14 May 2024;
PUBLISHED ONLINE: 30 May 2024.

EDITOR: Emily King, Xiamen University, China

SCIENCE MENTORS: Milena Salgado-Lynn and Shu Qin Sam

CITATION: Peters KJ and Gerber L (2024) Epigenetic Clocks: Using DNA to Estimate the Age of Dolphins. Front. Young Minds 12:1342551. doi: 10.3389/frym.2024.1342551

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.

The author of original paper Steve Horvath is a founder of the non-profit Epigenetic Clock Development Foundation, which plans to license several of his patents from his employer UC Regents.

YOUNG REVIEWERS

BENJAMIN, AGE: 11

My name is Benjamin. I love cooking for my family and playing video games during my free time. For sports, I do archery and I have a junior black belt in taekwondo. I am very inquisitive and will ask questions to find out more about things that I do not understand. I also enjoy playing with my cats. I have 3 at home and they are a handful.

GEMMA, AGE: 8

My favorite subject is science and I love almost everything related to the ocean. I am an avid reader of science, mystery, and fantasy books. I read National Geographic Kids and enjoy playing around with their app. I am also interested in Thea and Geronimo Stilton books. I have a special liking for those with jokes and games at the end or the ones that you can help them solve the mystery with the given clues.

JACE, AGE: 10

Hi, Jace here. I am 10 years old. During my free time, I am interested in reading and I love to play soccer. I love science books the most (the cool kind, not boring!). I am currently working on my new microscope which makes tiny things HUGE and my telescope which shows things far away! Numbers are awesome, that's why I maze-ter minds. My jokes are legendary because laughing is nice. Lastly I love funny doodles, mazes, maybe some monster sketches.

KINABALU INTERNATIONAL SCHOOL, AGES: 9–11

We are a bunch of regular students who aspire to be very unique scientists one day. We are in Borneo and go to Kinabalu International School. Our aim is to try to make this world a better place through educating children like ourselves while exploring science and making new discoveries, trying to see what is possible., We want people in the world to know and love science and bring everybody's knowledge to new heights.

VERALYN, AGE: 12

I enjoy listening to music especially KPOP and Taylor Swift. I enjoy diving and singing. I love the ocean and love going to the beach. Dolphins and whales have always been a firm favorite favourite of mine.

AUTHORS

KATHARINA J. PETERS

I am a German-Australian marine ecologist and live in Australia. I have studied many animal species, but my main focus is marine mammals. My core research interest is to study the effects of humans on marine mammals and to use this information to better manage the conservation of wild populations and their environments. My projects focus on Weddell seals in Antarctica, and various species of whales and dolphins in Australia and New Zealand. *katharina_peters@uow.edu.au

LIVIA GERBER

I am a wildlife geneticist at the Australian National Wildlife Collection at CSIRO—Australia's National Science Agency. My job is to apply and develop genetic methods to learn more about animals. Using genetics, I am answering questions of why animals behave and look the way they do, live where they live, and how old they are. Over the last years, I have studied male friendships in dolphins, developed a method to age dolphins, and I am now developing epigenetic age estimators for reptiles. *livia.gerber@csiro.au

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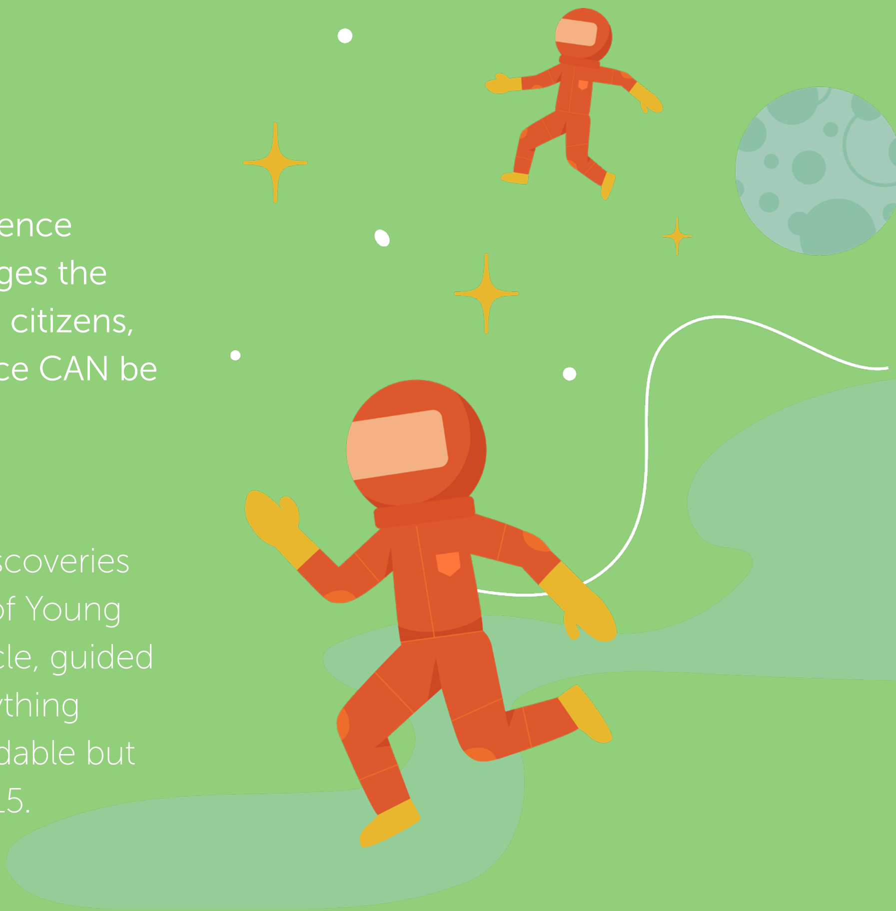

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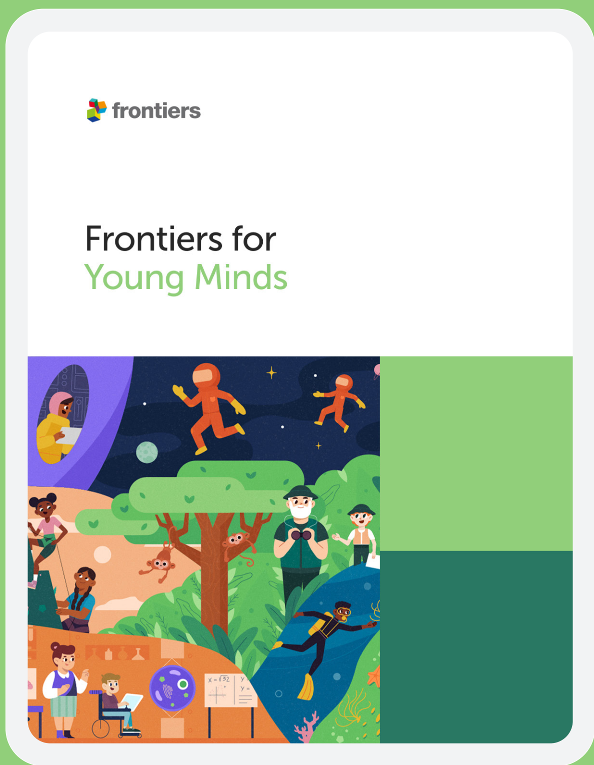

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