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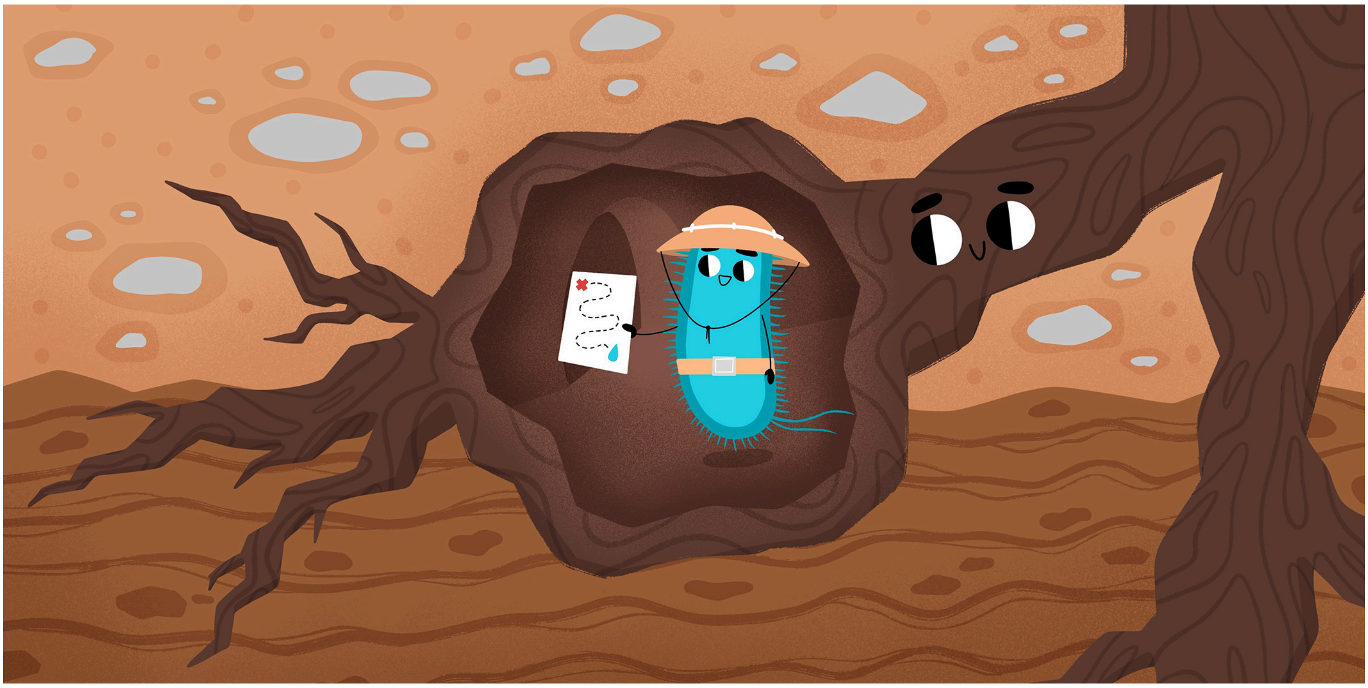

UNDERGROUND HEROES: PLANTS AND MICROBES PARTNER TO SHAPE OUR WORLD

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Did you know that microbes and plants can help each other survive? Microbes—like bacteria and fungi, for example—can help plants find food and water and can even make them healthier during stressful times. In return, plants give microbes food and a place to live. The world as we know it would not exist without plants, microbes, and their partnerships. Unfortunately, changes to climate will also change our environments. Therefore, studying how plants and microbes partner will help us predict environmental changes to our planet and its inhabitants. In this article, we discuss how microbes and plants partner to support life on Earth.

THE PLANT MICROBIOME

Every plant on Earth has trillions of microbes that live closely with it. Together, all these microbes are called the **plant microbiome**

PLANT MICROBIOME

Microbial communities that interact with plants and influence their growth, nutrient uptake, stress tolerance, and resistance to pathogens.

(Figure 1). What are these microbes doing, exactly? Are they helping or hurting plants? Most microbes that we know of help their plant hosts by increasing the amounts of nutrients, like sugars, proteins, and water, that are available to plants. Microbes can also strengthen a plant's ability to fight off infections. Without a microbiome, plant health suffers.

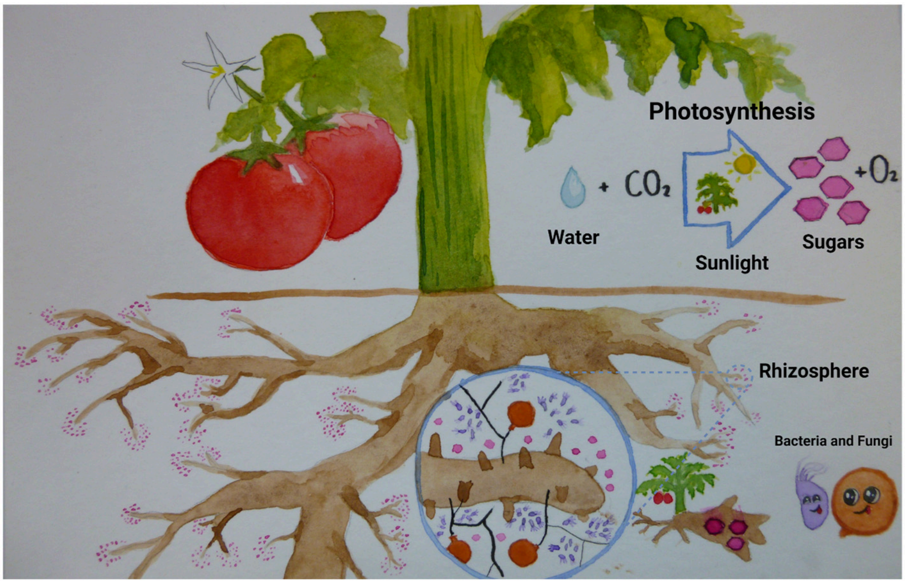

Figure 1

Figure 1

The below-ground compartment around the roots is called the rhizosphere. Research has shown that the rhizosphere facilitates close interactions between and among microbes and mycorrhizal fungi, allowing them to exchange nutrients. Although fungi can often be seen by the human eye, powerful microscopes are needed to see the billions of bacteria and other microbes in the rhizosphere.

Although research on plants and microbes has come a long way since its start in the late 1800s, we still have plenty to learn. Researchers are currently working on ways to use microbes to produce larger crops, more food for our growing population, and healthier forests for future generations [1]. Learning more about how microbes interact with each other and with plants brings us one step closer to accomplishing these goals.

Where exactly do plants and microbes interact? One main area of research focuses on the underground space around the plant root, called the **rhizosphere**. The rhizosphere is home for many types of microbes, and it is a hotspot for plant-microbe interactions. We still do not completely understand how microbes communicate with each other or share food, so these are important questions to answer. If we understand the rules that plant microbiomes play by, then we will be better at predicting the ways that climate change may affect plants and their microbes.

RHIZOSPHERE

The soil within 2 mm of plant roots.

Research has already helped us engineer plants that can withstand drought and increased temperatures, and that can grow larger and faster. But we are still unsure how microbes will interact with plants as Earth's climate changes. Will some microbes lose their ability to help plants grow? Will plants be overtaken by **pathogens**, becoming

PATHOGENS

Any organism that can cause disease.

sick and stunted? Will we be unable to supply food to Earth's growing human population?

BACTERIA AND FUNGI: KEY PLAYERS IN PLANT MICROBIOMES

Bacteria and fungi make up more than 90% of a plant's microbiome. As a result, much research focuses on how these microbes interact with plants.

How can bacteria help plants? Bacteria have been living with plants for hundreds of millions of years, and for centuries bacteria have been known to help plants grow. One of the most well-studied groups of bacteria is rhizobia, which convert nitrogen gas in the atmosphere into ammonia. Plants can use ammonia to make amino acids, the building blocks of proteins (Figure 2A). We call this conversion **nitrogen fixation**. Nitrogen-fixing bacteria help plants receive the resources they need to remain healthy. However, nitrogen fixation is not the only way that bacteria help their plant hosts. Bacteria also balance plant

NITROGEN FIXATION

The conversion of atmospheric nitrogen to ammonia.

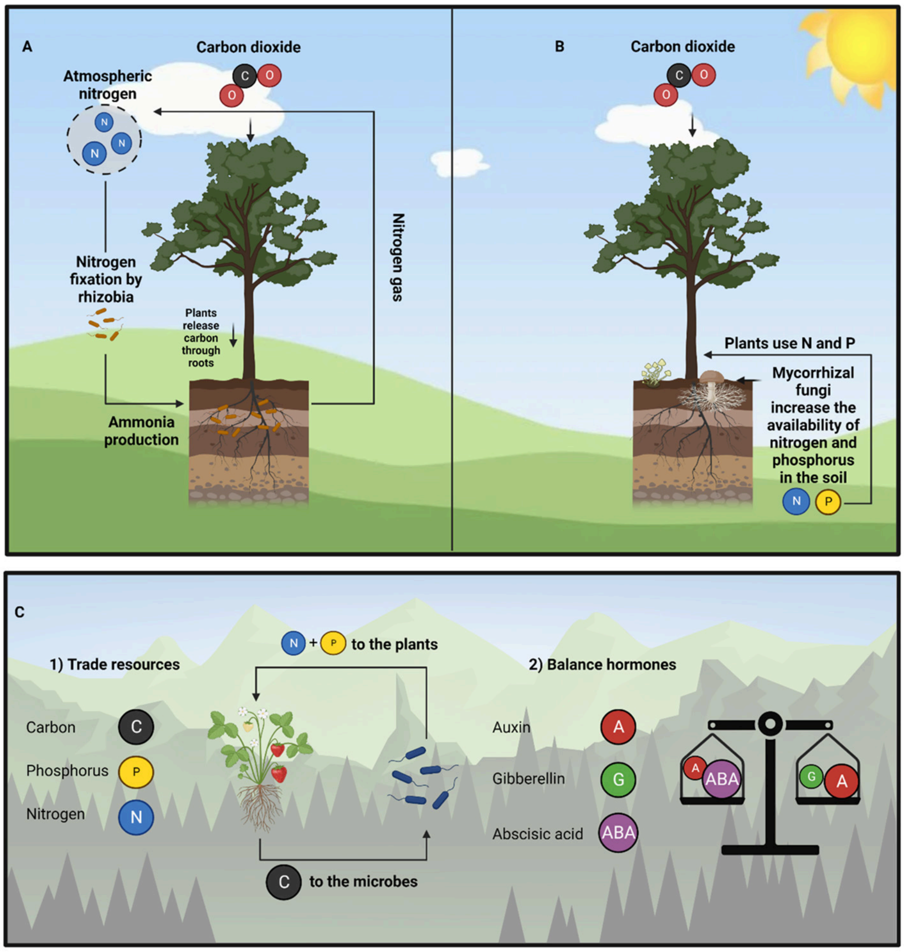

Figure 2

Figure 2

Common ways that bacteria and fungi partner with plants. **(A)** Rhizobia or other nitrogen-fixing bacteria can convert atmospheric nitrogen into nitrogen sources that plants can use, like ammonia. Bacteria can then convert ammonia into other usable forms of nitrogen that help themselves and plants grow. **(B)** Mycorrhizal fungi can trade carbon for nitrogen and phosphorus, which plants need to survive. **(C)** Microbes and plants also partner when bacteria and mycorrhizal fungi trade resources with plants. Microbes also balance plant hormones, which aids plant growth and development.

hormones that are critical for plant growth and development. Many research groups around the world are researching how bacteria and plants help each other.

How can fungi help plants? Like bacteria, fungi have also been living alongside plants for hundreds of millions of years. Evolution has engineered certain types of fungi, known as **mycorrhizal fungi** (myco = fungus and rhiza = root), that partner with more than 90% of all plant species on Earth. When mycorrhizal fungi colonize plant roots, they exchange resources each needs for their growth like carbohydrates, amino acids, and water. Research has shown that mycorrhizal fungi take up **organic matter** from the soil and give plants nutrients like phosphorus, nitrogen, and water (Figure 2B). When and how mycorrhizal fungi identify their plant host are important questions that still need complete answers.

MYCORRHIZAL FUNGI

Fungi that form a symbiotic relationship with plants, in the plant's root tissue.

ORGANIC MATTER

Carbon molecules that are produced from the decomposition of living matter such as leaf litter or fallen tree branches.

MYCORRHIZAL HELPER BACTERIA

Bacteria that increase mycorrhizal colonization, growth, and abundance.

Bacteria and fungi work together to help plants. Bacteria called **mycorrhizal helper bacteria** have been shown to support the relationships between plants and mycorrhizal fungi [2]. The more nutrients mycorrhizal fungi can provide to their plant host, the higher the chances that the plant will survive and reproduce. It is still unclear how bacteria and mycorrhizal fungi interact, but evidence suggests that mycorrhizal fungi provide nutrients and shelter to some bacteria.

MICROBES SUPPORT THE HEALTH OF FORESTS AND FARMLANDS

Earth has roughly three trillion trees and more than 600 million farms. This means that the microscopic interactions between plants, fungi, and bacteria impact the fate of our forests and food. Research has shown that microbes can be sprayed on plant seeds or soils to boost crop yields [1] and to remove toxic compounds from forest soils [3]. We still do not know how much these microbes will help plants during stressful times, like heatwaves and droughts. Therefore, much research focuses on how climate change will impact plants and their microbiome.

What about the microbes that may not help plants, like pathogens? Researchers predict that global warming will increase the number of plant pathogens [4] and decrease the number of mycorrhizal fungi. We know that the climate controls much of how plants and microbes come together [5]. Changes to Earth's climate could cause some trees and crops to become less abundant or even extinct. Manufactured goods such as wood and paper, and foods such as rice and vegetables, would be more difficult to produce. It is possible that changes to food production will prevent us from feeding the Earth's growing population in the next 30 years. Sustainable solutions must be created!

Although these predictions may seem frightening, research continues to focus on ways to preserve our forests and farms by using our knowledge of microbes. How, exactly? Researchers around the world are using DNA sequencing and satellite imaging to find out which microbes pair with which plant types in forests and farmlands (Figure 3). With this information, we can identify the proper microbes and spray them on plant seeds or mix them into the soil, to help plants during heatwaves, droughts, and floods.

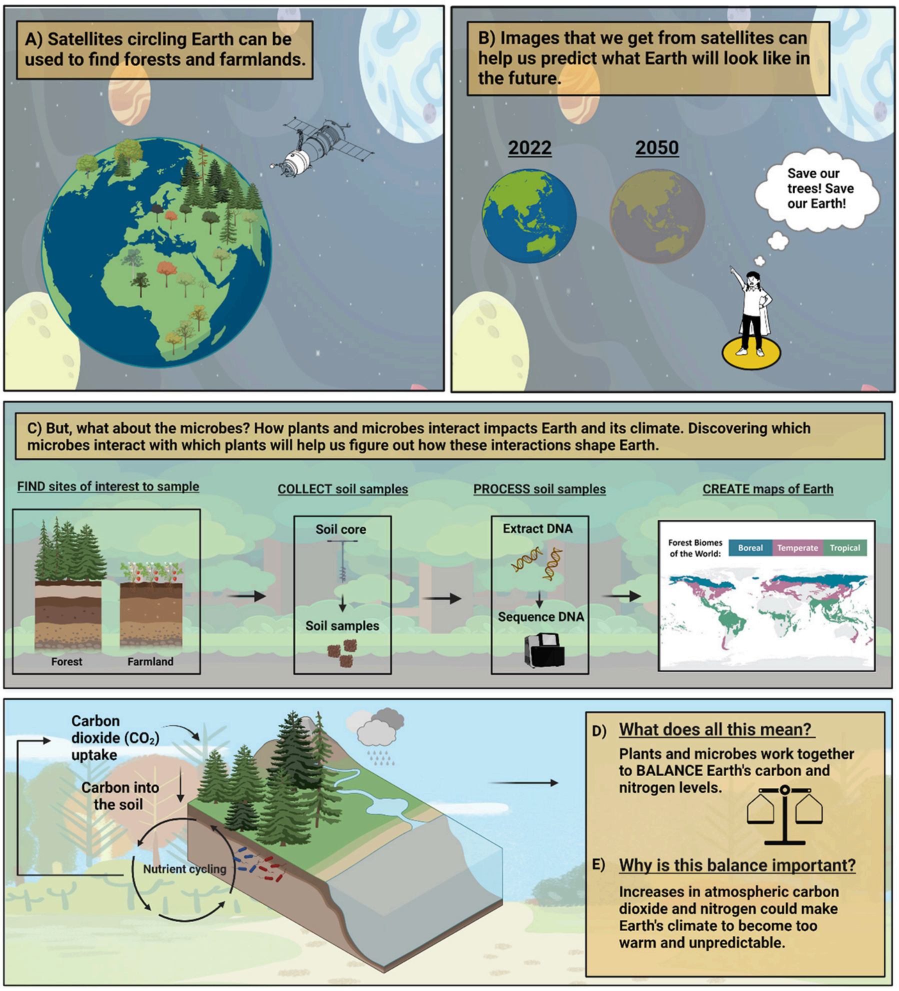

Figure 3

Figure 3

Plants and microbes come together across the globe. **(A)** Satellites can help us see our world from high above the ground. **(B)** Satellite images can show us how patterns change over time. This information can help us estimate the amount of food we will be able to produce and how high carbon dioxide levels will become in the future. **(C)** Researchers are identifying the microbes present in soil samples at various sites all over Earth. **(D,E)** They are using their findings to understand the connections between plants, microbes and the Earth.

WHAT HAVE YOU LEARNED AND HOW CAN YOU APPLY IT?

In summary, researchers are focused on understanding the ways microbes can be used to enhance plant growth and development. Mycorrhizal fungi and bacteria can help plants obtain adequate nutrients, which can result in larger, stronger plants. However, global warming may change plant–microbe interactions across the planet. It is important to understand how climate change will impact farmlands and forests.

How can you help? Read, explore, question, and repeat. From articles to stories, pictures, and videos, there are many resources related to plant–microbe interactions online and at local libraries. You will quickly find that there is a ton of free information available (for example, the soil biodiversity atlas). The more you learn about your topic of interest, the better you will be at asking interesting questions and developing interesting experiments to answer those questions.

If you liked this article and want to learn more about plants and microbes, you could also contact a researcher who could teach you more about plant–microbe interactions. You could start by writing an email with your science teacher, parent, guardian, and/or friends to the authors of this article or to other researchers who study plant–microbe interactions. Researchers are often excited to share their findings and to help young people who are interested in science—so do not hesitate to ask questions!

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

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SRIJA, AGE: 13
Hi! My name is Srija and I am fun loving girl and I loves painting and paying chess!

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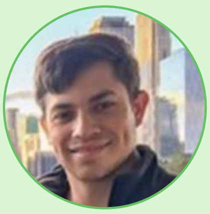

LOUIS BERRIOS
I joined the Peay lab at Stanford University in 2021 after completing my Ph.D. at the University of South Carolina. My research is focused on how bacteria and mycorrhizal fungi interact. In my free time, I enjoy reading and writing about science. I also enjoy playing music and disc golf. *Berriosl@stanford.edu

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I am an ecologist and evolutionary biologist interested in plant-microbiome relationships. My work combines large-scale observations, mechanistic experiments, and molecular approaches to explore the ways plants interact with their associated microbes, how these interactions vary under different conditions, and what impact these interactions have on the ecology and evolution of populations, communities, and ecosystems. I am currently a postdoc in the Peay Lab at Stanford University, working to understand how fungal symbioses influence plant host distributions,

species coexistence, and ecosystem functioning. I completed my Ph.D. in the Schweitzer Lab at the University of Tennessee where I focused on the links between plants, microbes, and their response to global change.

JULIETA ALVAREZ MANJARREZ
I am a biologist with a primary interest in fungi. I have studied various fungal groups in tropical forests, leaving my heart in mycorrhizal fungi. I am currently having my second postdoctoral experience at Stanford University, trying to disentangle the relationships between plant chemical compounds and fungi. I consider hunting mushrooms to be one of my favorite hobbies, as is painting with watercolors.

JAY YEAM
I graduated from Claremont Mckenna College in 2020 with a B.A. in organismal biology and have since been working with the Peay Lab at Stanford University. I love learning about fungi and am particularly interested in mycorrhizal fungi and how they adapt to changing environments. In my free time, you can catch me climbing rocks, skiing slopes, or hanging out with my cat.

GEETHA SAARUNYA CLARKE
I am a genomicist with over 7 years of research experience. I have a bachelor's degree in engineering with a biotechnology major, and a master's degree in biological sciences. I recently completed my Ph.D. in biological sciences at the University of South Carolina. During my doctoral research, I characterized genome rearrangements in the bacterium *Caulobacter crescentus*. My objective during my post-doctoral training is to build algorithms that improve the health care outcomes for people suffering from infectious diseases. If I am not working, reading, or hanging out with my daughter, I enjoy exploring the area in and around Santa Cruz with my family.

AARON CLARKE
I am a doctoral candidate of microbiology at the University of California Santa Cruz. I study how microbes survive in the mammalian stomach. My topics of interest include how bacteria tolerate antibiotics, how bacteria navigate and colonize the gastrointestinal tract, and how non-antibiotic medications influence the growth and distribution of bacteria in the stomach. I have researched many topics related to bacteriology, ovarian cancer, and physiology.

KABIR G. PEAY
I am an associate professor in the Department of Biology at Stanford University. I have an extreme fondness for fungi and mushroom hunting. Research in my lab is focused on understanding how plants and fungi come together to form mycorrhizal symbiosis. By studying these interactions in roots and across biomes, I am hoping to understand how this symbiosis has shaped our planet and how it might be used to create practices that sustain a healthy planet.