SOIL BIODIVERSITY

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SOIL BIODIVERSITY

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This Collection is the work of more than 50 scientists and Young Reviewers from all around the globe. Our role as editors, together with the authors, was to share our love of soil biodiversity with you. In this Collection, you will discover that soils are full of life. We will introduce some of the methods and techniques used by scientists to observe the life below our feet. We will show you that belowground life is essential to have healthy soils and, therefore, for us. However, you will soon realize that belowground life is changing and under multiple threats. The authors will give ideas on how we can protect soil biodiversity and invite you to actively help us in studying and protecting this valuable ecosystem. We have divided this article Collection into four sections, each of which is introduced below. To make our articles accessible to as many of you as possible, we have created a website hosting translations to languages other than English.

Soils are alive
Soils are not just rock and dust but are astonishing living systems that are full of life! In this first section, you will read about little creatures that you might already know, like earthworms. You will also discover many new creatures, like springtails and mites, that live close to you in your garden, in the parks, or in nearby fields. Our authors will even show you an entire world of tiny creatures not visible by the naked eye: tiny bacteria, fungi, and protists. Soil biodiversity is about the diversity of these organisms.

But how many different organisms are there? How different are they from each other? To answer these questions, scientists need tools and methods to observe and understand the biodiversity under our feet.

How can we observe this beautiful world under our feet?
In the articles in this section, the authors describe the tools and methods they use to observe and understand soil biodiversity. It is not easy to see the creatures in the soil and what they are doing under our feet; therefore, soils are often called the "black box". Some scientists are using the body fat of soil creatures to identify them and monitor what they feed on; others use DNA to identify soil organisms, like forensic investigators in the movies. In addition, our authors will explain how soil organisms are "talking" to each other and how we study these interactions.

What are scientists learning from studying these soil creatures? Is soil biodiversity important to us?

Why is soil biodiversity so essential to us?
In this section, the authors illustrate that soil biodiversity maintains processes essential for our well-being. For example, you will learn that soil bacteria can keep your food safe by protecting it from diseases. We will highlight that soil biodiversity is essential

for nature to work. For example, the authors will demonstrate that soil organisms are vital for recycling dead matter and releasing the nutrients in it. In addition, you will see how soil organisms are directly affecting greenhouse gas emissions such as carbon dioxide and methane by controlling soil processes. Controlling these emissions is critical for keeping our climate stable.

Soil organisms are alive, moving, and interacting, but are all these organisms and their important functions changing with time? Are these communities of soil organisms set in stone?

Soil communities are changing

You probably know that a lot of trees, flowers, and animals can change over the year with the seasons; flowers and fruits appear in spring and summer, leaves drop from the trees in fall. Soil animals are also changing with the seasons. And, like us, soil organisms can move to new places or disappear from others, either permanently or temporarily. These changes can be natural but can also be the result of human activities. Our authors will show you that agricultural practices and the effects of climate change (such as reduced rainfall) are affecting soil organisms, their functions, and the services they provide to us.

As we saw previously, soil biodiversity is essential for us, so any changes could be disastrous. So can we protect the organisms in the soil in the same way we protect other organisms such as tigers and pandas?

Protecting soil biodiversity

In the final section of this Collection, our authors will show you how to protect soil biodiversity. We can reduce our impacts and conserve this wonderful belowground life. But we can even go a step further and restore lost soil functions using our knowledge of soil biodiversity; for example by using fungi to restore soils. However, this is only possible if we understand soil biodiversity and its function. This is where you can help, for example by participating in a citizen science project and going outside to help researchers.

Conclusion

This Collection is about illuminating the "black box" of soil and showing you some of the fantastic creatures living under our feet. You will learn how scientists are studying soil biodiversity and how this soil biodiversity is essential for us. However, you will also see that soil biodiversity is under threat and needs to be protected. Many people across the globe will be needed to effectively protect these vital systems below our feet. That's why it is important to spread the word about the beauty and fragility of belowground life. We hope that this Collection will make you a champion of soil biodiversity and that you will pass on this message so that everyone will become more aware of, and be better able to protect soil biodiversity.

Now it is your turn to explore and engage with the content of this Collection. We hope there will be something for all of you!

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EARTHWORMS OF THE WORLD

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YOUNG REVIEWERS:

ANNA-MARIE
AGE: 16

KAYTLIN
AGE: 14

For decades, scientists have known where the highest numbers of species that live aboveground are found. So, they made maps of the world showing these patterns. For most of the aboveground groups, the highest numbers of species occur in the tropics and numbers decrease toward the poles. However, until recently, we did not understand such global patterns for many organisms living in the soil. We decided to create global maps of earthworm species richness. Earthworms provide humans with many useful services, such as moving the soils and improving their quality, which can increase the amount of food that is grown. If we want to protect earthworms and the services they provide, these global maps of earthworms are important because we need to understand where they are and why they live there.

MAPPING THE WORLD'S ANIMALS

There is around 150 million km^2 of land on earth. That is an area so huge that it is hard to imagine. With so much land, how do we know where the animals are, and how many there are? Why would we even want to know about the numbers of animals and their patterns across the world? Well, for example, we may want to know where to create **nature reserves** to protect the most species. Or maybe we are simply interested in knowing what the general pattern of animal and plant populations are, and whether that pattern is consistent across lots of different species. For example, tropical forests are known for having many different species of birds, but is that true for other animals?

NATURE RESERVES

Areas where the animals, plants, and the environment are protected.

To learn about the numbers of animals, people (both scientists and non-scientists) usually do surveys. A **survey** is simply counting the number of species (or number of individuals present) using a suitable technique for that species. For example, if we want to survey butterflies, we use a hand-held net and try to capture as many butterflies as possible using consistent methods, surveying a certain area of land for a given amount of time. However, doing surveys takes time, and it can also cost a lot of money. Additionally, we will never be able to do a survey at every location in the entire world. So, how do we know how many animals there are across the world?

SURVEY

Counting the number of species (or number of individuals present) using a suitable technique for that species.

We can use math! Specifically, we can use something scientists call **statistical models**, or just models for simplicity. For many decades, scientists have been creating models to estimate how many species of birds, plants, and other aboveground species there are across the globe. Unfortunately, this method has never been used for many of the organisms beneath our feet. So, we decided to create a model for earthworms. Earthworms are particularly cool (Figure 1). These soil organisms provide humans with many **ecosystem services** [1]. They help break down the fallen leaves so that the nutrients go back into the soil, they help make our crops grow better, and they help keep our climate the way we need it. Also, for a soil organism, earthworms are quite easy to survey because we can see them! Besides, there is quite a lot of information available about earthworms.

STATISTICAL MODELS

The process of trying to use known factors (such as temperature) to predict a factor that we may not be able to measure (such as the number of earthworm species).

ECOSYSTEM SERVICES

Benefits to humans provided by the natural environment and the organisms in it. Ecosystem services can include increasing food production, breaking down fallen leaves, and helping to keep our climate the way we need it.

WHAT DID WE DO TO UNDERSTAND GLOBAL PATTERNS OF EARTHWORMS?

To create a model to estimate the number of earthworms across the world [2], we needed data specifically about earthworms. Earthworm data consists of the numbers of earthworm species, collected using surveys. One person cannot survey everywhere, but we wanted to get as many surveys from across the globe as possible. So, we asked lots of other scientists to send us data from their surveys. These people were earthworm scientists that we knew, or who had already published the results of their surveys in scientific journals. We were confident that

Figure 1

Figure 1

There are 7,000 described species of earthworms across the globe [1], and they vary considerably in their appearance. **(a)** *Scherotheca gigas* is an earthworm often found in France and Spain (photograph taken by Iñigo Virto). **(b)** *Aporrectodea smaragdina* is found in the Alps and eastern Europe (photograph taken by Michael Steinwandter).

the data were trustworthy, especially the data that had already been analyzed and published. When scientists publish papers, their data are always checked and critiqued by other scientists. The surveys were often done using slightly different methods, but many scientists simply dug a square hole in the ground, searched the soil for earthworms, and counted the numbers of earthworm species they removed. In total, we gathered data from 180 researchers across the globe, containing just over 9,000 surveys of earthworms.

The number of earthworm species scientists counted in their surveys ranged from no species in several surveys to 12 species found in another. We also needed information about the climate (for example, the temperature and rainfall) and the soil (such as the **pH**) at the location of each survey. We got this type of information from freely available databases.

PH

The scale used to specify how acidic (lemon juice is acidic) or how alkali (baking soda is alkali) something is.

Models ultimately use a certain factor (such as climate, soil pH) to estimate the number of earthworm species in an area. To understand how models work, imagine this: we survey lots of beaches and ask ice cream sellers how many ice cream cones they have sold. We then get information on the average temperature at each beach. We could then create a model showing how temperature affects the number of ice cream cones sold at each beach. As you might expect, the hotter the temperature, the more ice cream cones are sold. Using this model, we could then estimate how many ice creams will be sold at any temperature, which gives us an idea about ice cream cone sales on beaches where we cannot survey. We can do something similar for earthworms to see how the numbers of species found in a survey changes with an environmental factor like temperature.

Our earthworm model contains many details about the environment—12 different aspects in total—but the basic principle remains the same. The 12 environmental details included information about the soil, the type of vegetation covering the ground, and the climate. Using our model, we then estimated how many species of earthworms there are for all points in the world, and we made a map of that (Figure 2).

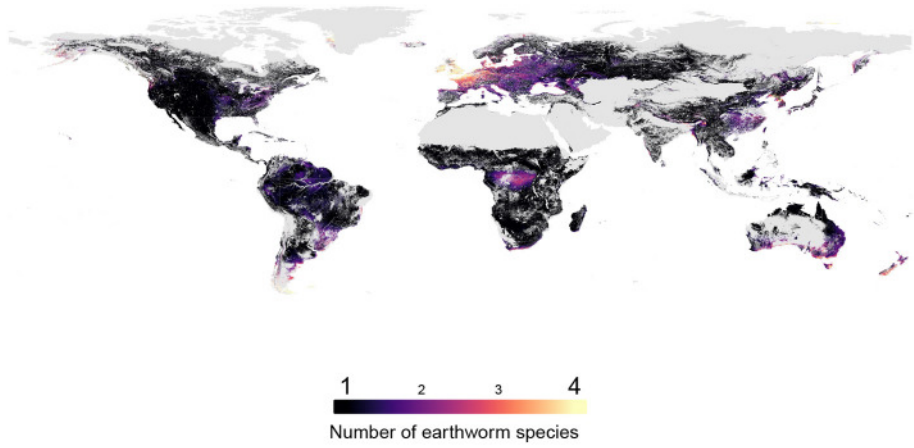

Figure 2

Figure 2

The number of earthworm species across the world, created using our model. In total, 180 researchers provided data from just over 9,000 surveys. This survey data was combined with data about the environment, such as pH, so that we could predict the number of earthworm species across all areas of the world—even where no surveys have been done. Typically, the number of earthworm species in any one place varied between 1 (areas in dark purple) and 4 (areas in bright yellow), but areas in the temperate region, such as Europe, had the highest number of earthworm species (shown in the yellow shades).

TEMPERATE REGION

The earth's middle latitudes, which span between the tropics and the polar regions. The temperate region typically has more distinct seasons (spring, summer, autumn, and winter) compared to tropical climates.

WHAT WE FOUND OUT ABOUT EARTHWORMS

As we mentioned at the beginning of this article, we usually expect the tropics to have the highest numbers of species. This is because, typically, we find more species in places that have higher temperatures. What our maps show is that this is not the case for earthworms. Our model indicates that, if you were to do a survey in a tropical region and one in a **temperate region**, you would find more earthworm species in the temperate region.

Why might this be? There are many aspects of the environment that shape the number of earthworm species found in a survey. And although the soil is important, we found that climate (for example, temperature and amount of rain) was the most important factor determining the number of species. As earthworms prefer to live in moist, warm conditions, the temperate region is much more suitable for them. There are more earthworm species where the environmental conditions are ideal. As long as the environment is not too extreme—too dry, too wet, too hot, too cold—it is very likely that there will be earthworms. Some species of earthworms may like conditions that are slightly different from most other earthworms. Alternatively, some species of earthworms may tolerate living in regions that are less than ideal, because there are fewer species to compete with for food, for instance, but this is an area scientist are still studying.

EARTHWORM MODELS CAN BROADEN CONSERVATION EFFORTS

Earthworms are really important for many ecosystem services that humans need, such as increasing food production. With the new knowledge gained from our model, we hope that earthworms will now be considered when scientists and conservationists think about creating nature reserves. Typically, nature reserves are established based on the number of species of plants or other aboveground organisms. But, since high numbers of earthworm species do not exist in the tropics (unlike many aboveground plants and animals), we need to think about earthworms and other soil organisms separately, and potentially establish nature reserves just for them.

Also, as we found that climate is the main aspect of the environment correlated with the numbers of earthworms, the fact that our climate is changing is concerning. Our future research will establish how the numbers of earthworms change as the climate changes, since some species may respond positively to changes in climate, whereas others may not. We need to understand how climate change will affect earthworms and other soil organisms, so that we can prepare to protect these valuable organisms for the future.

ORIGINAL SOURCE ARTICLE

Phillips, H. R. P., Guerra, C. A., Bartz, M. L. C., Briones, M. J. I., Brown, G., Crowther, T. W., et al. 2019. Global distribution of earthworm diversity. *Science* 366:480–5. doi: 10.1101/587394

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2. Phillips, H. R. P., Guerra, C. A., Bartz, M. L. C., Briones, M. J. I., Brown, G., Crowther, T. W., et al. 2019. Global distribution of earthworm diversity. *Science* 366:480–5. doi: 10.1101/587394

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

YOUNG REVIEWERS

ANNA-MARIE, AGE: 16

My favorite subject is biology, I like bionics. In future I would like to work on new materials, new substances. I am curious about the mysteries of the universe, there is so much to discover.

KAYTLIN, AGE: 14

I am a first-year high school student that likes to travel and explore different cultures and things. In my free time I read, do martial arts, teach myself Japanese or let my creativity run loose by writing stories, drawing, or taking pictures.

AUTHORS

HELEN R. P. PHILLIPS

Helen has always loved animals, but never really enjoyed doing field work. She continued learning about ecology, and eventually realized that using large datasets and doing computer-based work, such as programming, was what she found interesting. Since then, Helen has focused on global datasets of biodiversity, using them to investigate where biodiversity is in the world, and how human activities might be affecting global patterns. Recently, her work has involved earthworms and other soil biodiversity. When not working, Helen likes to play computer and board games, sew, make music, and play with her pet rabbit. *helen.phillips@smu.ca

ERIN K. CAMERON

Erin enjoyed playing outside as a child and loved science but did not consider becoming a biologist. Eventually, she started helping out with research examining how human activities affect songbirds and found it fascinating. Once she started to work on soil organisms and saw how much is still unknown about them, she was convinced that she wanted to study ecology. Now she investigates how human activities affect soil biodiversity and functioning of ecosystems and enjoys cross-country skiing, bicycling, and kayaking in her free time.

NICO EISENHAUER

Nico has been interested in nature since his early childhood. He dug for earthworms, caught frogs and fish, and helped lizards survive the winter months. He has always been fascinated by the beauty of nature and driven by the question of why a specific plant or animal species occurs in one place, but not in another. During his study of biology, he discovered his interest in earthworms and their important activities, which are crucial for the functioning of ecosystems. When not at work, Nico likes playing soccer and badminton, running, and spending time with his family and friends.

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BELOWGROUND MOUNTAINEERS: CRITTERS LIVING IN MOUNTAIN SOILS

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YOUNG REVIEWERS:

MERCY SCHOOL INSTITUTE
AGES: 15

The soil beneath our feet still requires more exploration, although we know that it is home to a vast number of organisms. It is basically a black box we cannot see into to observe its inhabitants and the processes they contribute to. In this article, we will tell you about soils that are even less explored. We are talking about mountain soils at high elevation: they are not easily accessible but harbor many exciting species, some of which are specialized to live only in mountain soils. We are a team of soil ecologists who dedicate our research to revealing the secrets of animals living in mountain soils. We will tell you which and how many soil critters can be found in high-elevation soils of the European Alps, in both natural mountain ecosystems and those used for farming. Further, we explain some clever ways these species have adapted to the harsh alpine environment.

WHAT ARE MOUNTAIN SOILS?

When we talk about mountain soils, we usually refer to soils at high elevation, particularly soils above the treeline where there are only scattered trees, or no trees at all. In the European Alps, this zone can be found above 2,000 m; in the Central European Alps, above 2,300 m. Of course, some mountain soils are found on lower mountains or even hills, but we will focus on the beautiful world of soil animals that live in natural grasslands, grazed pastures, and even bare soils on higher mountains like the European Alps, from 1,500 to 3,000 m.

Some mountain areas above the treeline, in what is called the **alpine zone**, may seem to be untouched by humans. But this is not true—farmers have gently used many such grasslands for centuries and even millennia, as pastures for small stocks of cows, sheep, and goats in the summer months (Figure 1A). Why did farmers of the past (and some even today) hike up so far with cows and sheep? Why not just use the meadows in the valley bottom, which are easily accessible? Well, they *do* use the valley meadows, but the alpine pastures are home to many colorful and nutritious herbs and grasses that cows and sheep love to eat and which are very healthy for them. Also, during hot summers, the temperatures at higher elevations are much more bearable for the animals.

WHICH AND HOW MANY ANIMALS LIVE IN MOUNTAIN SOILS?

The beauty of mountains lies not only aboveground in the colorful flowers and shrubs, but also beneath our feet. To study the soil critters, we remove square soil blocks of 20 × 20 and 15 cm deep (Figure 1C) and extract the **invertebrates** using a **Kempson apparatus**. The Kempson apparatus uses heat and light from lightbulbs to force the animals to escape from the soil as the blocks dry out. The animals are then collected from water-cooled buckets containing a collection fluid. Further, we also install **pitfall traps** in our study locations (Figure 1B). Pitfall traps are open glass jars, dug into the ground so that organisms like spiders and beetles will fall into them and be trapped. This is a very useful method to see what is crawling on the soil surface. Using these techniques, we found a diverse community of earthworms, millipedes, beetles, and insect larvae in mountain soils.

Soil biodiversity is especially high in the **subalpine zone**, from 1,500 to 2,000 m. This border area contains forests and manmade pastures. In this zone, soil animals typically found in mountain forests (such as woodlice and centipedes) co-exist with species from natural grasslands (earthworms and millipedes). In subalpine pastures in the Central European Alps, we found up to 115 earthworms per square metre in the upper 15 cm of the soil layer, as well as 60 millipedes,

ALPINE ZONE

A climatic zone that can be found in higher mountains or arctic areas. It is the zone where tree cannot grow because of the low temperatures.

INVERTEBRATES

A large group of animals that have no vertebrae (backbones). Common soil invertebrates include insects (beetles, fly larvae), earthworms, millipedes, centipedes, woodlice, and spiders.

KEMPSON APPARATUS

A device in soil laboratories for extracting animals from soil blocks. Being heated from above, soil animals seek to escape the dry and hot conditions and fall into a collection bucket.

PITFALL TRAP

A simple method to catch ground-dwelling insects and invertebrates. These are glass jars that are dug into the soil and are left active for one or several days.

SUBALPINE ZONE

A climatic zone that includes the mountain forests up to the natural treeline. It includes also a transition zone between these forests and the alpine grassland where only small shrubs and single trees can grow.

Figure 1

Figure 1

In the European Alps, centuries of traditional farming created species-rich grassland soils. **(A)** The alpine zone above the treeline is often grazed by cows and sheep. Below in the subalpine zone, forests were also cut down to create pastures and hay meadows. Rocky areas increase at higher elevations and are dominant in the high alpine, which is the area above most vegetation (Gsies/Valle di Casies, South Tyrol, Italy). **(B)** We assess soil invertebrates by installing pitfall traps (yellow arrow) (Dolomites, South Tyrol, Italy). **(C)** Soil blocks are removed and taken to the laboratory to be studied (Matsch/Mazia, South Tyrol, Italy) (Photograph credits: Michael Steinwandter).

55 beetles, and 50 larvae of flies and midges [1]. All these soil invertebrates profit from the sporadic presence of animals that roam the fields, including cows, sheep, and wild mammals such as deer, chamois, and Alpine ibex. The grazing animals keep the vegetation short, remove troublesome shrubs, and therefore keep the grasslands open. Additionally, they leave behind lots of dung, which is a welcome food source for many soil animals such as earthworms, millipedes, and dung beetles (Figure 2) [2]. However, if farmers bring too many cows and sheep up to these areas, we can observe negative effects of trampling and too much dung, which results in reduced numbers of some types of soil animals. For example, we found only about 5 specimens of millipedes and 45 beetles per square metre in an area that was overused by farmers.

The higher we go, the fewer individuals and types of soil animals we find (Figure 3). In the alpine zone, from 2,000 to 2,800 m, trees cannot grow because temperatures are too low and the summer growing season is short. In this alpine zone, some types of soil animals reach the upper limit of their comfort zone. Earthworms and millipedes decrease in numbers and can rarely be found at elevations above 2,500 m, even if roaming sheep add extra food in the form of dung. We found only 20 earthworms and 10 millipedes per square metre in the alpine zones we studied. On the other hand, fly and midge larvae increase massively in numbers (more than 750 per square metre) and partly take over the important ecosystem functions of earthworms, such as the breakdown of dead plant material [3].

NIVAL ZONE

A rocky and often snow-covered area of high mountains and arctic regions that follows the alpine zone. Here, almost no plants grow, but mostly lichens and mosses.

In the European Alps, areas above 2,500 m are often covered with snow for much of the time, making life very challenging for soil animals. These zones, called the high alpine zone and the **nival zone** (above 3,000 m), are usually not used by farmers. These areas are inhabited mainly by small soil animals such as springtails and mites. These cold-weather specialists survive beneath the snow cover, which acts like a blanket to keep temperatures slightly above freezing, even when the air temperature falls well-below freezing.

Figure 2

Mountain soil invertebrates from our research sites in the Stubai Alps and Oetztal Alps in Tyrol, Austria. **(A)** A lifted cowpat unveils the feeding burrows of earthworms (*Lumbricus rubellus*), dung beetles, and insect larvae. **(B)** The pill millipede (*Glomeris transalpina*) is commonly found in alpine shrubland in the Central European Alps. **(C)** Larvae of fungus gnats (Mycetophilidae) feed on sheep dung in high alpine pastures (Photograph credits: Michael Steinwandter).

HOW CAN THESE ANIMALS SURVIVE?

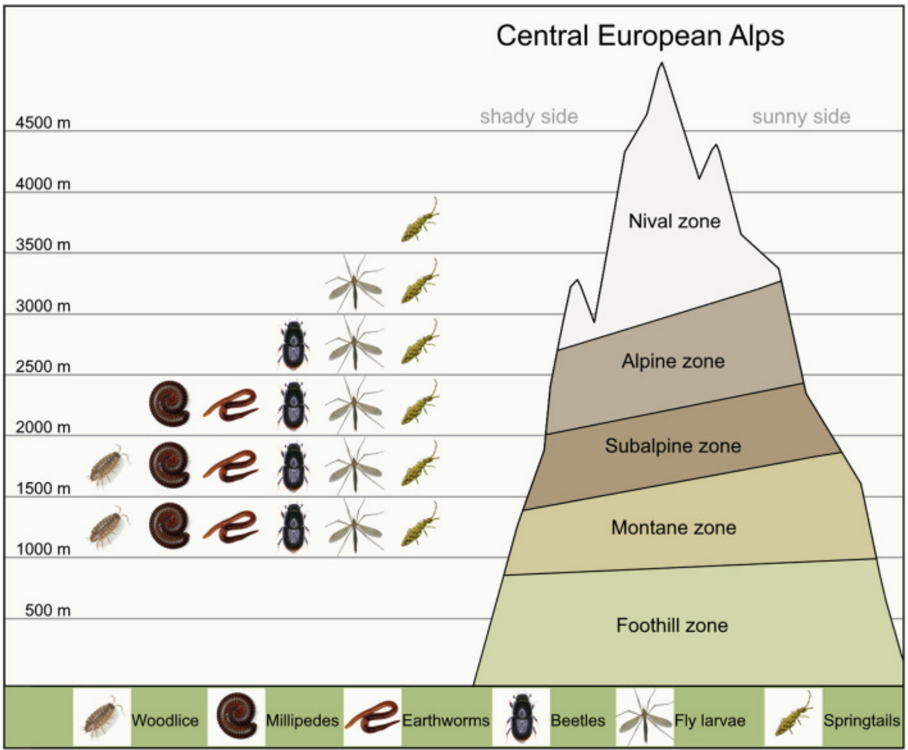
ADAPTATION

The ability to adapt to new environmental conditions by optimising body characteristics and/or behaviour. For example, alpine invertebrates adapted to the harsh mountain environment.

Adaptation is key to survival at high elevations. Adaptation is the ability to adapt to new environmental conditions by optimising body characteristics and/or behaviour. Soil animals in these ecosystems experience low temperatures and often encounter snow even in the summer months. They also face stronger sun rays and less and less living space the higher the elevation. These animals cannot be picky about what they eat—they must feed on any available food sources. For example, while in lowlands some beetles feed on plant-based food only, in alpine pastures they also feed on other animals and their shed-off skins or carcasses, as well as on dung, if it is present [4]. The adaptation to this broader menu increases the chances that these beetles will successfully gather enough energy to survive and thrive.

Another survival strategy of mountain soil animals is that they can prolong their life stages if the summers are too short to allow them to reach the next stage. For example, during a snowy, cold summer when a millipede cannot get enough energy to produce its eggs, it can wait another season and produce eggs the following year when the conditions are more favourable. While this is a useful adaptation, it also means that these millipedes must survive longer in the harsh environment to successfully finish their egg production.

Soil animals at high elevations have also adapted their bodies to the harsh conditions by decreasing their body size (smaller bodies can heat up more easily), by losing their wings (without wings the animals can stay close to the soil surface and avoid strong winds), by changing their body colours (darker bodies can heat up more easily), or/and



	Woodlice	Millipedes	Earthworms	Beetles	Fly larvae	Springtails
3500-4000	–	–	–	–	–	???
3000-3500	–	–	–	–	200*	3000*
2500-3000	1	15	35	55	900	9500
2000-2500	1	55	85	55	750	18000
1500-2000	15	55	110	75	450	30000
1000-1500	30	45	235	115	550	40000

Figure 3

Figure 3

Distribution of typical soil invertebrates at the various elevation zones of the Central European Alps. The zones start and end at different elevations on the sunny side and the shady side. The table shows how many animals per square metre can be expected at each elevation zone, based on currently available data. Generally, the number of soil animals is decreasing with increasing elevation, with different animal groups reaching their limit at different elevations (such as millipedes at 2,500 m, beetles at 3,000 m). Asterisks (*) indicate that very limited, highly variable data are available (Image credits: modified after Wikimedia Commons).

by producing anti-freeze in their bodies, to prevent their bodies from freezing at low temperatures.

DO MOUNTAIN SOILS NEED HELP?

Now you know that mountain soils are interesting places that are home to many soil invertebrates, some of which can only be found in mountain soils. Because these soils and their inhabitants are still understudied, the possibility of finding new species there is quite high. However, like many ecosystems nowadays, mountain soils are threatened and need to be protected. One big problem that species-rich subalpine pastures face is that farmers are abandoning these lands, because these traditional methods of farming do not generate enough money. When cows and sheep are no longer grazing the alpine grasslands at the treeline, these areas will be taken over by persistent shrubs that form dense and unpassable shrubland. Also, the increasing temperatures resulting from climate change will lead to an upwards migration of soil animals, as they try to escape temperatures that are too warm for them. But because there is less and less space as the elevation increases, these animals will have problems finding enough room to live, and they might experience a higher risk of extinction.

But the good news is that we can all help! For instance, by supporting mountain farmers and buying their products (like milk and cheese) we can increase the chances that they can continue to maintain beautiful alpine pastures. Further, we can personally take care of mountain soils by not damaging them when we go hiking, mountaineering, or skiing. We should stay on the trails and take our trash back home instead of leaving it in the mountains. Lastly, we can take political action, by raising our voices against the building of new entertainment facilities such as ski areas, mountain huts, and mountain bike trails, which can harm these natural and sensitive areas.

We all need to be extremely careful with this precious ecosystem called soil. Let us keep in mind that mountain soils needed centuries—and in high mountains, even millennia—to form, but these ecosystems and the fascinating soil organisms that live there can be destroyed in minutes, without our protection!

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as a potential conflict of interest.

YOUNG REVIEWERS

MERCY SCHOOL INSTITUTE, AGE: 15
We are fun and dynamic leaders, and we love to hang out with our friends.

AUTHORS

MICHAEL STEINWANDTER
I am a soil ecologist and soil zoologist in the AlpSoil Lab, mainly working with critters such as earthworms, spiders, and preferably millipedes. I conduct my research in soils at all elevations, including the lowlands, but I really love to discover the soil life in mountain forests and pastures above the treeline. This comes from my passion for hiking and mountaineering, something you are born with when you grow up in the Dolomites (South Tyrol, Northern Italy). Beside doing science, I am fascinated by all of nature. Therefore, I am also a professional hiking guide and environmentalist. *michael.steinwandter@eurac.edu

JULIA SEEBER
I am a soil ecologist in the AlpSoil Lab, interested in understanding the relationships between soil animals and their habitats, and which soil processes the animals contribute to. I like to go on field trips to see and investigate the habitats, but I also like to do experiments with the animals in the laboratory, to watch them do marvellous things such as breaking down dead plant material. My favourite soil animals are earthworms because without them, the soil ecosystem would be much less efficient. My love of mountain sports, such as skiing and hiking, is easy to combine with my love of doing science in mountains.

frontiers FOR YOUNG MINDS

BIODIVERSITY
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SPRINGTAILS—WORLDWIDE JUMPERS

Anton Potapov [1,2*]

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YOUNG REVIEWERS:

ANSHUL
AGE: 9

LUVENA
AGE: 11

MILES
AGE: 8

PRANATEE
AGE: 12

Springtails are tiny, six-legged animals that you meet every day, but hardly notice. They can survive in big cities, on ice in Antarctica, in the deepest caves, and in rainforest canopies. Some scientists call them the earliest known and the most numerous insects on Earth. Springtails are famous jumpers—if they were as large as humans, they would easily be jumping over 10-story buildings. This ability allows them to escape from danger. Every day, springtails are very busy, improving soil health and supporting numerous species of spiders, beetles, ants, and other small predators on our planet. They are a key part of soil biodiversity, but we still need to learn a lot about them and many of these beautiful animals are yet to be discovered.

WONDERFUL DIVERSITY OF SPRINGTAILS

If you walk out of your house, you will probably meet a springtail, but you might not notice it because most of these animals are only one millimeter long. Springtails, also called Collembola, are insect relatives that can be found in soils all over the world. The best

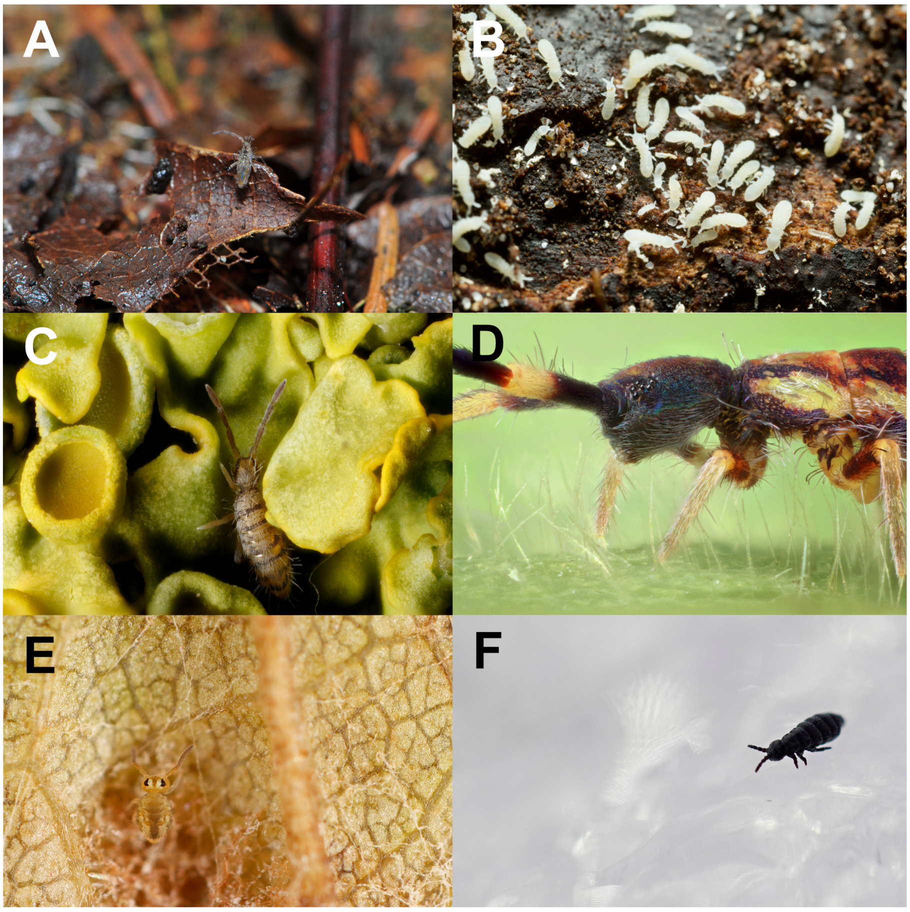

Figure 1

Figure 1

Springtails in their natural environments all over the world. **(A,B)** Most springtails live in dead leaves or wood. **(C–E)** Some springtails are associated with living plants. **(F)** A number of species can be found in extreme environments, like the snow surface shown here (Photo credits: **A**—Dunmei Lin from China; **C–E**—Marie Huskens from Belgium; **F**—Ferenc Erdélyi from Hungary; **B**—Andy Murray from the UK).

place for a springtail to live is the forest floor, where you can find thousands of them in a handful of fallen leaves. But they can also live in other environments, often in moist places where fungi are growing (Figure 1). In fact, springtails live almost everywhere: they are numerous in Antarctica on snow and rocks, they are diverse in tree canopies of tropical forests, they are found on the highest mountains and down in the deepest caves. Several years ago, scientists found the springtail *Plutomurus*, which lives two kilometers below the land surface in a cave in the Caucasus mountains [1]. They lured it out with the help of a smelly cheese. In winter, some springtails jump and wander on the snow surface, which earned them the name "snow fleas." Snow fleas like *Hypogastrura* (Figure 1F) can exist in herds of millions, making the snow gray with their bodies! As masters of survival, springtails also live with us—in gardens, backyards, parks, and sometimes flowerpots.

Springtails were surviving and thriving on the planet long before dinosaurs, and they are among the first animals that walked on land. We know this because scientists found a fossil springtail in prehistoric rocks dated about 410 million years old. This springtail was named *Rhyniella praecursor*, "the earliest known insect." Interestingly, some

Figure 2

Figure 2

Beautiful springtails from Australia, Tasmania, and New Zealand. **(A)** Masterpiece *Katianna*, with spotted coloration. **(B)** Shiny *Lepidocyrtus*, covered with scales. **(C)** Dragon *Womersleymeria,* large and horned. **(D)** Baby *Neelides*, only about half a millimeter in size (Photo credits: **A,B,D**—Andy Murray from the UK https://www.chaosofdelight.org; **C**—Cyrille D'Haese from France).

modern springtails look very similar to *Rhyniella*, which means that springtails survived on Earth through four out of five **mass extinctions** without changing much in appearance. We know of about 9,000 species of springtails living now, which are all listed in a web catalog,[1] but scientists think that there are at least four times as many unknown springtail species on our planet [2]. Some remote areas in Tasmania and New Zealand are inhabited by beautiful and unusual species (Figure 2) and many more are yet to be discovered.

MASS EXTINCTION

Widespread and rapid decrease of biodiversity on Earth during evolutionary history. Five main mass extinctions are recognized.

1 http://www.collembola.org

Springtail species can look quite different from each other. Some species have a round shape, while other species are elongated. Some do not have coloration, others are blue, or black, or have colorful spots and stripes, such as the ball-like *Katianna* (Figure 2A). *Lepidocyrtus* (Figure 2B) has shiny scales, just like fish do. Most springtails are about 1 mm long, but there are tiny and giant species. For example, *Neelides* (Figure 2D) is only about half a millimeter long, while *Womersleymeria* (Figure 2C) can be longer than a centimeter! Most of these giants live on the dead wood of wild tropical forests and are called "dragon springtails."

WHAT DOES A SPRINGTAIL LOOK LIKE?

The name "springtail" comes from the organism's **furca**, which looks like a forked tail and allows many springtails to spring away from danger, just like tiny grasshoppers (Figure 3). The furca can be found under the body, on the abdomen, but not all springtails have one. If a springtail is walking or eating, the furca is attached to the body under high tension, like a compressed spring. As soon as springtail wants to jump, the furca is released and the animal catapults itself

FURCA

A forked tail-like appendage attached to the abdomen of many springtail species.

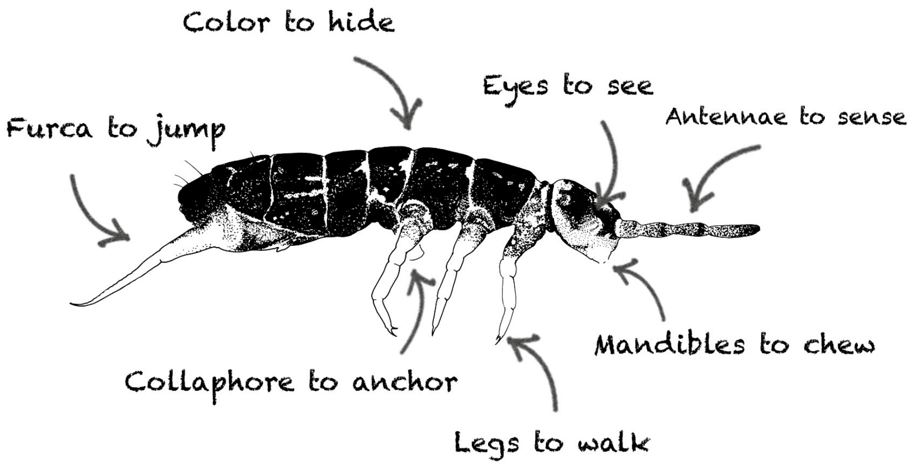

Figure 3

Figure 3

What are the parts of a springtail? This sketch of a springtail was made by taxonomist Mikhail Potapov, who has described more than 200 springtail species new to science.

away from predators, or curious scientists. While jumping, springtails flip over many times, so it looks like they are doing a fantastic acrobatic trick before they crash into something.[2] Springtails are champions at jumping—if they were the size of humans, they could jump over 10-story buildings! As you can imagine, after such a jump it is not easy to land without a parachute. Instead, springtails use a special tube called **collaphore**, which allows them to stick to the surface (for example to a leaf or a stone) when landing.

[2] Check out "trash can springtails" doing 22,440 rotations per minute in slow motion on this video https://www.youtube.com/watch?v=Qu01EUeE5PM.

Like insects, springtails are hexapods, meaning that they have six walking legs. Unlike insects, they never have wings. Springtails can have from two to sixteen eyes (Figure 1D), but species living in soil are often blind. To orient themselves in the environment and communicate with others, many springtails use antennae, which are long organs on their heads. They move the antennae to touch and check the surfaces in front of them. If they find some food, they grasp it and chew it with their **mandibles**.

COLLAPHORE

A tube-like structure that is used by springtails to attach to surfaces.

MANDIBLES

Lower jaws, used to bite and chew the food. Unlike humans, arthropods chew horizontally, not vertically.

HOW DO YOU CATCH A SPRINGTAIL?

If you are interested enough to look for a real springtail, you need to know where to look and how to do it. Springtails like wet places, like moist fallen leaves or mosses. Some large species can be found hiding under the bark of decaying fallen trees. Others are found on stream banks, rocks, mosses, or flowers. If you are lucky, you can also find springtails in flowerpots—if so, chances are it will be the white *Folsomia candida*—one of the most commonly used soil animals in laboratory experiments. While searching for a springtail, be very patient—they are everywhere, but they are masters of hiding and often are colored like things in the environment around them (Figure 1E).

If you find a springtail, you can simply observe it crawling around or jumping, and maybe you can take a photo. Web platforms like iNaturalist[3] or Flickr[4] have thousands of springtail photos from around the world. Such observations can help scientists to understand where species live, and may even help them to discover new species.

[3] https://www.inaturalist.org
[4] https://www.flickr.com

To catch a springtail, you can also use what is called an **entomological aspirator**. But if you want to keep the springtail, remember that springtails do not like dry conditions. After several minutes in an aspirator, some species may die. Many scientists collect springtails from leaf litter, soil, rotten wood, and mosses using a **Tullgren funnel**, which can be built with relatively little effort at home. Springtails can be closely inspected under a microscope. Scientists also keep springtails as laboratory pets—they need a permanently moist surface (for example, a jar with fallen leaves, soil, or clay), some food (baker's yeast would be a good choice), and air (make holes in the lid). Unfortunately, only a few dozen species like to live at home or in the laboratory—and we do really not know why.

ENTOMOLOGICAL ASPIRATOR

Aspirator used to collect small organisms visible to the naked eye [https://en.wikipedia.org/wiki/Aspirator_(entomology)].

TULLGREN FUNNEL

Device used to extract living organisms, particularly arthropods, from soil, detritus, moss, and other substrates (https://en.wikipedia.org/wiki/Tullgren_funnel).

DETRITUS

Dead organic material, for example dead leaves or wood, bodies of dead animals, and excrements. Detritus is inseparable from the microorganisms that decompose it, such as bacteria and fungi.

BUSY SPRINGTAILS RUN THE WORLD

What are all these springtails doing in nature and why should we care about them? Springtails have an important role in ecosystems: as ecosystem "cleaners" they recycle dead material called **detritus**, and they feed on microbes, such as bacteria and fungi [3]. By doing this, they improve soil structure and make nutrients available to plants. Springtails can also pollinate mosses, just like bees pollinate flowers [4]. Being delicious food for many predators is also important—numerous species of spiders, beetles, ants, and other invertebrates survive by hunting springtails. Sometimes springtails are also directly useful to humans. In agricultural fields, they may help plants by feeding on the microbes that cause plant diseases, or they may support other predators that can kill plant pests. However, scientists have only recently started to explore these functions of springtails, and there is a lot to learn yet.

In the modern world many ecosystems are changing. Cities are growing, tropical forests are being cut down to grow food, and increasing temperatures are making frozen places like Antarctica and the northern tundra melt. These changes affect springtails as well as other soil organisms. The most remarkable species are often also the most vulnerable and can become extinct if their natural environments are destroyed. The number of springtails on our planet is likely to decline in the future, since they are numerous in the cold, Polar regions that will be strongly affected by climate change. One hectare of tundra can be inhabited by as many springtails as there are humans on the entire planet. As masters of survival, springtails will adapt to the changing world and live in the new ecosystems. However, many species are likely to become extinct even before being discovered. Studying springtails and sharing the knowledge about them as a hidden but very important part of biodiversity can help us to understand how the nature is organized and how we change it with our actions. Sharing your new knowledge with your friends and family can help with this—the more people who will know about the importance of hidden biodiversity, the better we will be able to understand and protect the nature and our future as a part of it.

AUTHOR CONTRIBUTIONS

AP developed the idea and wrote this manuscript.

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YOUNG REVIEWERS

ANSHUL, AGE: 9

Hello! My name is Anshul and I am a fourth grader in North Wales, Pennsylvania, which is close to Philadelphia. I am very interested in Biology and Entomology. I am an active member of the John Hopkins CTY program, and my favorite hobby is to read.

LUVENA, AGE: 11

Hi, my name is Luvena! I love music, sports, and food. My favorite subjects in school are math and language arts. In my spare time, I enjoy playing piano and reading books with my sister. When I grow up, I would like to be a neurosurgeon.

MILES, AGE: 8

I am a boy who lives in San Francisco. I love sports, games, and playing with my friends. I like eating French fries and chocolate.

PRANATEE, AGE: 12

Hello! I love to bake, especially tarts and pies. In school, my favorite subjects are science, lunch, and recess. I like spending time outdoors and going hiking. I also love going to the beach and have an interest in photography. Watching my favorite TV shows, painting, listening to music, singing, and hanging out with friends are my favorite things to do in my free time. In the future, I would like to either like to be a scientist, or a singer/songwriter and actress.

AUTHOR

ANTON POTAPOV

I am a soil ecologist working at the University of Göttingen, Germany. I particularly enjoy studying springtails, which I am doing in different environments, from Russian taiga to tropical rainforests. I want to understand how springtails and other small animals form complex food webs and drive biodiversity and functioning of ecosystems. *potapov.msu@gmail.com

BIODIVERSITY
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ARMORED MITES, BEETLE MITES, OR MOSS MITES: THE FANTASTIC WORLD OF ORIBATIDA

Carlos Barreto [*†] ***and Zoë Lindo*** [†]

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YOUNG REVIEWERS:

ISABEL
AGE: 10

MARGARIDA
AGE: 12

Oribatid mites are a group of animals related to spiders, scorpions, and ticks. However, they are typically much smaller (most are < 1 mm) and are full of defensive mechanisms to protect them from predators. Generally, oribatid mites live in soils and feed on fungi, bacteria, and soil particles, making them very important for decomposition processes. Oribatid mites also help cycle soil nutrients and contribute to soil formation. Oribatid mites can also be found in aquatic environments and even treetops. They are present all over the world, from forests to deserts, and along the edges of lakes and oceans. They are often the most abundant mesofauna found in soils, reaching impressive populations of up to 500,000 individuals per m^2 in forests. The diversity of oribatid mites varies across vegetation types, climate, and soil properties, such as moisture, pH, nutrient concentrations, and heavy metals.

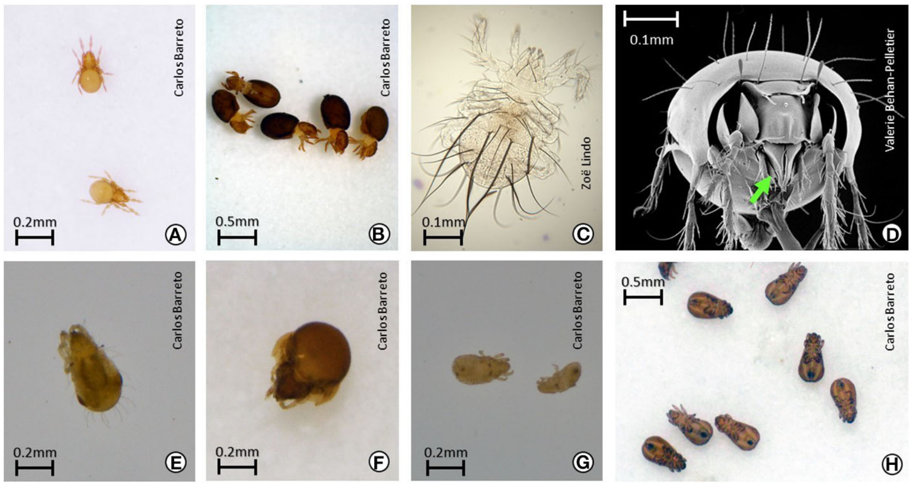


Figure 1

Figure 1

Examples of oribatid mites, with their scientific names. **(A)** *Suctobelbella* sp.; **(B)** *Hoplophorella* sp. (also called box mites); **(C)** defensive hairs on *Palaeacarus* sp.; **(D)** hard body of *Diapterobates notatus* with an arrow pointing to tooth-like structures to help during feeding; **(E)** juvenile *Lepidozetes* sp.; **(F)** adult *Lepidozetes* sp. (notice that young mites and parents are not alike); **(G)** juvenile *Tyrphonothrus* sp.; and **(H)** adult *Tyrphonothrus* sp. (notice that young mites and parents are alike).

WHO ARE THE ORIBATID MITES?

Oribatid mites (formal name: Suborder Oribatida) are animals related to spiders, scorpions, and ticks, as they also have eight legs (Figures 1, 2). While many people are fearful of spiders, scorpions, and ticks, oribatid mites are not a concern for the health of humans and are actually beneficial, because they help with soil formation and with returning nutrients to the environment. Oribatid mites are also called beetle mites or armored mites because they typically have hard bodies (like beetles) to protect them from being eaten (Figures 1B,D). They are also sometimes called moss mites because they are abundant within mosses, a type of plant that grows close to the soil surface.

WHAT DO ORIBATID MITES LOOK LIKE?

Most adult oribatid mites are brown, but species range in color from nearly white, to yellow, to reddish-brown (Figures 1A, 2D), to almost black. Males and females look very similar in most species, but the young mites rarely look like the adult mites (Figures 1E–H). The females lay eggs and when the eggs hatch, the young mites (larvae) grow through three more stages before becoming adults. At each stage, they shed their outer body covering, called the **exoskeleton**, as their bodies get bigger. Some oribatid mites carry this old exoskeleton around on their backs as a form of camouflage to protect them from predator mites. Predator mites can eat some oribatid mites. Oribatid mites are mostly oval shaped, but some are very round like a ball when they curl their legs up into their bodies (Figure 1B). All oribatid mites have heads that are attached to the rest of their bodies and eight legs that attach in the middle region of their bodies. Most oribatid mites have tiny holes in their armpits that allow them to breathe; they do not have noses like we do. However, their legs have hairs to help them feel, taste, and even smell (Figures 1C,D, 2C). Their legs also have claws on the tips, similar to human nails (Figure 1D). Most oribatid mites do

EXOSKELETON

The external skeleton that supports and protects an animal's body, in other words, the animals' outer body covering. In can be very hard in oribatid mites.

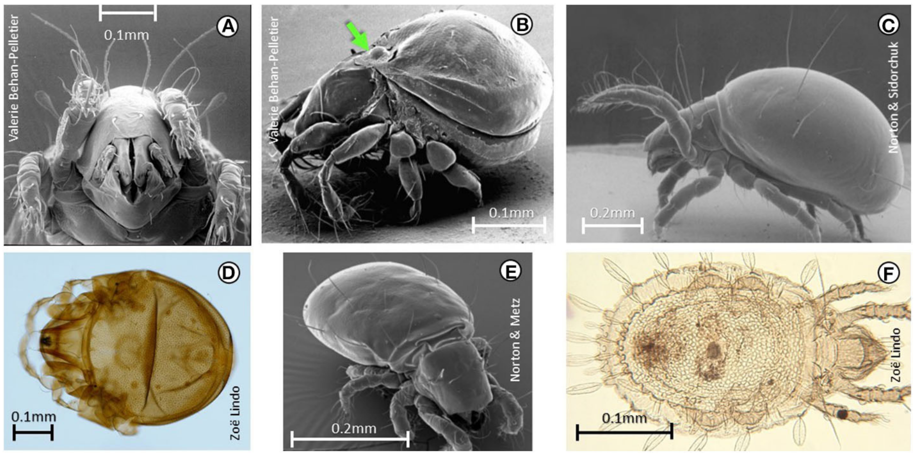


Figure 2

Figure 2

Diversity of oribatid mites, with their scientific names. **(A)** *Melanozetes crossleyi*; **(B)** *Hydrozetes* sp. with an arrow pointing to the lenticulus, the structure that allows this oribatid mite to perceive light; **(C)** *Collohmannia johnstoni*; **(D)** *Cersella* sp.; **(E)** *Nehypochthonius porosus* and **(F)** juvenile *Eupterotegeaus*.

LENTICULUS

The structure that allows oribatid mites to perceive light since they do not have real eyes.

CHELICERAE

Mouthparts present in arachnids like spiders, scorpions, ticks and also oribatid mites.

not have real eyes, but they have structures that can perceive light, for example, a structure called the **lenticulus**, seen in Figure 2B. They also do not have real teeth, but instead have tooth-like structures to help them feed (Figure 1D), called **chelicerae**.

Oribatid mites are very small organisms. The majority are <1 mm long (most 0.3–0.7 mm), which is the diameter of two human hairs side-by-side, but some can be as large as a pencil tip. Because these organisms are so small, we need to use a hand lens or a microscope to observe them. Even though oribatid mites are tiny and might look fragile at first glance, they have existed for many million of years, even before dinosaurs [1]!

Tiny oribatid mites move around in soil on their eight legs, but because they are so small, they usually move only a few meters during their entire lifetime. However, other strategies help oribatid mites to get to distant places, too. Oribatid mites can hitchhike on other animals like birds, frogs, and mammals for example, and then move long distances. Another strategy is, because they are so light, they can be picked up in the wind and travel in the air! How cool!

DEFENSIVE MECHANISMS

Oribatid mites may live for one or more years (some species up to 5 years) in their natural habitats. Because it takes them a long time to become mature adults, they do not have many babies, and they must protect themselves from predators. To protect themselves, oribatid mites have developed many different defensive mechanisms. These protective mechanisms include: hairs that raise (like a frightened cat) (Figure 1C), armored structures that cover their bodies like a tank (Figures 1D, 2A), bodies that roll into a protective ball (Figure 1B), or camouflage obtained by covering themselves in soil, their exoskeletons, or other debris. Many oribatid mites also possess

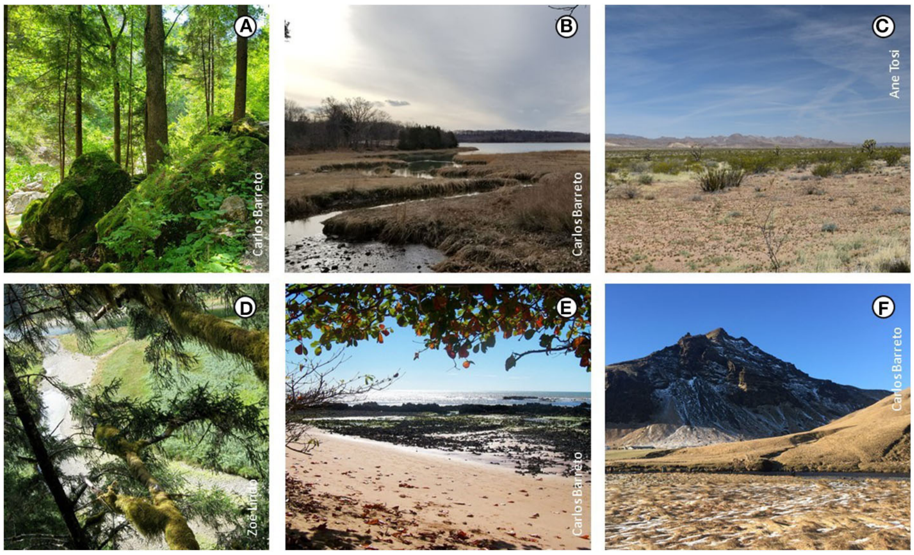


Figure 3

Figure 3

Oribatid mites are found in many different environments. **(A)** Forest (Schwangau, Germany); **(B)** wetland (Massachusetts, U.S.); **(C)** desert (Arizona, U.S.); **(D)** treetop (Vancouver island, Canada); **(E)** edge of the ocean (Espírito Santo, Brazil); and **(F)** edge of a lake (Ásólfsskáli, Iceland).

specialized defensive glands that can release unpleasant chemicals when they are attacked by their predators.

WHY ARE ORIBATID MITES IMPORTANT?

A typical diet for oribatid mites consists of different types of fungi and bacteria. Because of what they eat, oribatid mites are important for ecosystem services like **nutrient cycling**. The mites chew dead leaves, which breaks the leaves down into smaller pieces that fungi and bacteria can further decompose. When the oribatids then eat the fungi and bacteria, the nutrients from the leaves are returned to the soil after they are discharged in oribatid feces. Oribatid mites are considered part of the soil food web, helping with processes like **decomposition** that are necessary for soil formation.

NUTRIENT CYCLING

The movement of nutrients between living things and the earth, including the atmosphere, rivers, and soils. Oribatid mites help recycle nutrients in soils.

DECOMPOSITION

The break-down of dead plants and animals by fungi and bacteria, facilitated by oribatid mites and other soil animals.

WHERE DO ORIBATID MITES LIVE?

Oribatid mites have been found all over the world, from forests to deserts, and along the shores of lakes and oceans in all countries (Figure 3). They live mostly in soils, where they usually are the most abundant and diverse group of small soil animals called **mesofauna** [2]. But they can also live in other habitats, like on the bark and trunks of trees, in mosses, and on other plant leaf surfaces. Oribatid mites are also found at the top of the tallest trees, as well as in some aquatic environments. They are almost everywhere!

MESOFAUNA

This term refers to intermediate-sized animals in soils. Their size ranges from 0.1 to 2 mm.

While there are over 10,000 species of oribatid mites known, we have good reasons to believe that there are many, many more species of oribatids that have not been discovered yet. The number of species of oribatid mites found in any location varies, depending on a number of factors including the type of plants in the location, the climate, the amount of moisture in the soil, the pH of the soil, the concentration of soil nutrients, and the levels of soil pollution. Different species of oribatids prefer different conditions; for example, some prefer soil with lots of nutrients while others prefer low-nutrient soil. Depending on the environment, oribatid mites can reach impressive numbers—up to 500,000 individuals per m^2 in forest soils [3]! This is equivalent to 4000 mites in a handful of soil!

HOW CAN I FIND ORIBATID MITES?

EXTRACTOR

Tool used to help separate oribatid mites and other soil animals from the surrounding soil. The lamp on top of it slightly heats the soil up and have the animals to leave the soil.

If you want to observe oribatid mites and other soil organisms, you will need an **extractor** to help separate the oribatid mites from the surrounding soil, and a microscope or hand lens. In Box 1, we describe the materials you will need to build your own soil oribatid mite extractor. You will need adult supervision for this, but it is easy. Once you have your soil organisms separated from the soil, use a hand lens to see how different they all are. If you have access to a microscope, then even better!

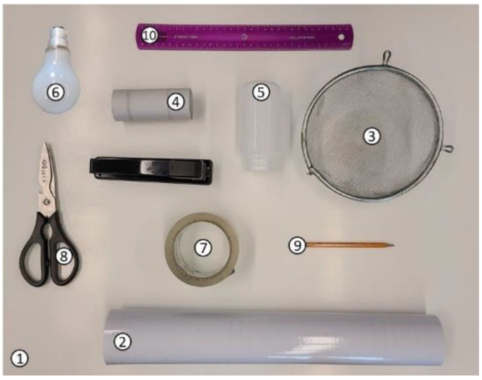
Go to your backyard, or to a public park. Oribatid mites can be found in cities too. You will need to collect two to three handfuls of soil, leaf litter, or mosses (dig up to 10 cm deep) for your extractor. You will also need to be a little patient; it will likely take a minimum of 3 days to extract the oribatids from your soil sample. Okay, time to build the extractor!

Last, if you are interested in soils and who lives in them, there are many other activities that can be found in Chapter VII of the Global Biodiversity Atlas [4]. Links for books, games, videos, and more are all available! Have fun!

Box 1 | Building an oribatid mite extractor

Materials:

- Two sheets of cardboard (about 100 × 60 cm)
- 2 m of adhesive laminate sheet
- Kitchen strainer (about 24 cm diameter)
- Toilet paper roll—10 cm
- Plastic vial
- Table lamp with an incandescent bulb/halogen light bulb (it needs to heat up)
- Sealing/duct tape
- Scissors
- Pencil
- Stapler
- Ruler

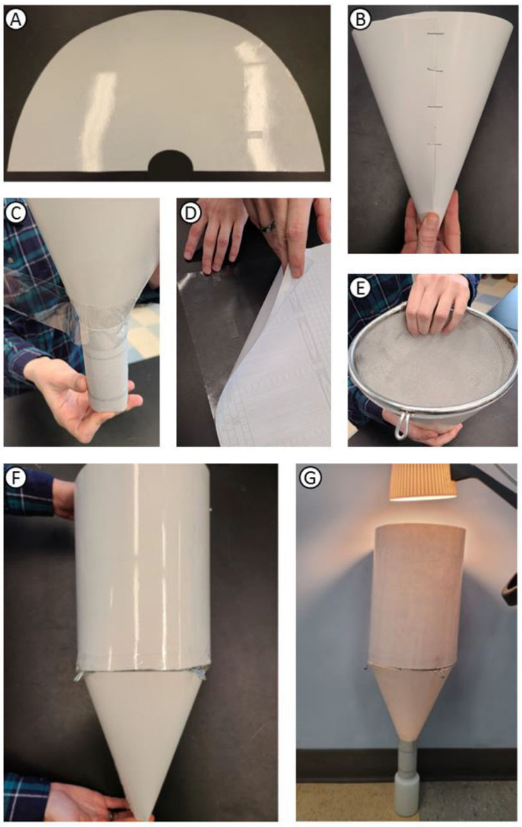


(Continued)

Box 1 | Continued

Methods:

- Draw a semi-circle on one of the cardboard sheets. The semi-circle should have a radius of 25 cm. Cut it out using scissors (A). Cover both sides with the adhesive laminate sheet and cut a semi-circle in the middle.
- Fold it to form a funnel and staple it using the stapler (B). The funnel must have an opening at the bottom—this is where the oribatid mites and other soil animals will pass through.
- Attach the toilet paper roll to the bottom of the funnel using the tape (C).
- Cover the other piece of cardboard with the laminate sheet (D). Use it to create a 25 cm-long cylinder. Close it with staples. This will be attached later onto the big opening (top) of the funnel.
- Place the kitchen strainer on top of the funnel/bottom end of the cylinder (E).
- Use the tape to secure the cylinder to the funnel (with the strainer in between) (F).
- Put the soil sample on the strainer from the top of the cylinder.
- Put the plastic vial at the bottom end of the extractor.
- Put the table lamp near the top opening of the cylinder and turn the light on. This will encourage the oribatids to leave the soil (G).



AUTHORS CONTRIBUTIONS

CB and ZL wrote the manuscript. CB created the figures and made the manual for creating the fauna extractor.

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YOUNG REVIEWERS

ISABEL, AGE: 10

Hi, I am Isabel and I am from Portugal. I am 10 and I like reading, writing, and music. I have three cats and I like to learn about history. I have no idea of what I want to be when I grow up. I really like vegetables (and fruit).

MARGARIDA, AGE: 12

My name is Margarida, I am 12 years old and I like reading, climbing, and writing. I love science, especially anything about black holes and I have absolutely no idea what I want to do when I grow up. I also really like biology.

AUTHORS

CARLOS BARRETO

At a very young age Carlos realized that he liked animals, maybe too much. In school, science was always his favorite discipline, all the way through to high school. That is when he decided that he wanted to do something that involved science and animals. He tried to be a vet; it did not work out. No regrets. So, he became an Ecologist a few years later, and since then, he has been working with little animals (mostly insects and mites) in tropical forests, iron ore and limestone caves, boreal forests, urban fields, and peatlands on three continents: South America, North America, and Europe. *cbarreto@uwo.ca; †orcid.org/0000-0003-2859-021X

ZOË LINDO

Dr. Zoë Lindo is an expert on soil biodiversity and ecosystem function. She has worked extensively in Canadian forests, including the mixed-wood boreal of Alberta, the subarctic taiga of Quebec, the coastal temperate rainforest of British Columbia, and the black spruce/peatlands of Ontario. "The overall focus of my research aims to mitigate biodiversity loss in association with human-induced environmental change and maintain ecosystem functioning in Canadian forest and soil ecosystems. I describe myself as a biodiversity scientist to encompass the breadth of my research in the areas of community ecology, soil ecology, and taxonomy." †orcid.org/0000-0001-9942-7204

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BIODIVERSITY
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SUPER-SMALL PREDATORS IN SOILS: WHO ARE THEY AND WHAT DO THEY DO?

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YOUNG REVIEWER:

AYA

AGE: 10

There are millions of species living in soils. Most of this biodiversity is made up of bacteria and fungi, tiny organisms that make up what is called the soil microbiome. The size and composition of the soil microbiome is mainly controlled by two groups of predators: protists and nematodes. Protists are tiny single-celled organisms, while nematodes are tiny worms and the most numerous animals on Earth. Protists and nematodes together weight more than all the other animals on Earth! Protists and nematodes keep the soil microbiome in balance, which helps plants to grow and keeps soils functioning properly. Without protist and nematode soil predators, the functions and services provided by soils would change so much that it could even affect the Earth's climate. So, let us not forget the importance of these tiny soil organisms!

SOIL BIODIVERSITY

Maybe you already know that soils are not just dark-colored dirt consisting of sand, clay, and loam; soils have high **biodiversity**, meaning that millions of organisms of all types and sizes live there. Not only do soils have more biodiversity than any other ecosystem on Earth, but the weight of all soil organisms (including plants whose roots make them about half soil organisms) is far greater than the weight of all other organisms combined [1]. Soil organisms range in size from microscopic viruses to huge fungi that can spread over hundreds of meters—and everything in between! The microscopic life in soils is called the **soil microbiome**, and it is mostly composed of bacteria and fungi. Without its biodiverse microbiome, soils would not be able to recycle nutrients and promote plant growth. This article focuses on two groups of soil organisms that few scientists study: protist and nematodes. By the time you are done reading, I hope you will understand why more research should focus on those tiny organisms!

PROTISTS AND NEMATODES: TINY PREDATORS

Microbiome predators are organisms that feed on **microorganisms**, such as bacteria and fungi [2]. Protists and nematodes are among the most important microbiome predators. **Nematodes** are super small—at least 100 times smaller than the width of a human hair—so they are not visible by the naked eye. The nematode most well-known to scientists is a roundworm that scientist call *Caenorhabditis elegans*, which is frequently used in research. Many scientists, doctors, farmers, and gardeners know nematodes as pests, because some species can infect humans, while others cause plant diseases. In soils, nematodes prey on bacteria, fungi, or other nematodes, and can be parasites of animals and plants. While most nematodes look basically the same, many hundreds of thousands of diverse species exist (Figure 1A)[1]. Eight of 10 animals on Earth are nematodes. In other words, 60 billion nematodes exist for every single human being [3]!

Now try to imagine that there are 1,000 times more **protists** than nematodes in soils! Protists are microorganisms that cannot be classified as animals or plants. Protists are **eukaryotes**, which means they contain a nucleus, just like the cells of animals, fungi, and plants. While the term "protist" might be new to you, you have probably heard of some well-known examples of protists: all eukaryotic algae that perform photosynthesis in lakes and oceans are protists. Some diseases are caused by protists, such as the malaria-causing *Plasmodium falciparum*. Amoebae and *Paramecium* are protists, and there are many more! It is likely that most of the eukaryotic diversity on Earth is composed of protists, with many millions of existing species. But we know fewer than 1 in 100 of the protist species that exist. In soils, protists perform a large range of functions. Most protists feed

BIODIVERSITY

The variety of species in an ecosystem.

SOIL MICROBIOME

All the microorganisms that live in the soil.

MICROBIOME PREDATORS

Organisms that feed on bacteria and fungi.

MICROORGANISMS

Tiny organisms, including bacteria, fungi, and protists.

NEMATODES

Tiny worms that live in all environments and inside hosts. Most abundant animals on Earth.

[1] For an overview of nematode diversity, see https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Laboratory-of-Nematology/Nematode-in-the-picture/Nematode-Pictures.htm.

PROTISTS

All eukaryotes except for fungi, animals and plants, most of which are single celled.

EUKARYOTES

Organisms that have nuclei in their cells, in which DNA is located. Eukaryotes include fungi, protists, plants, and animals.

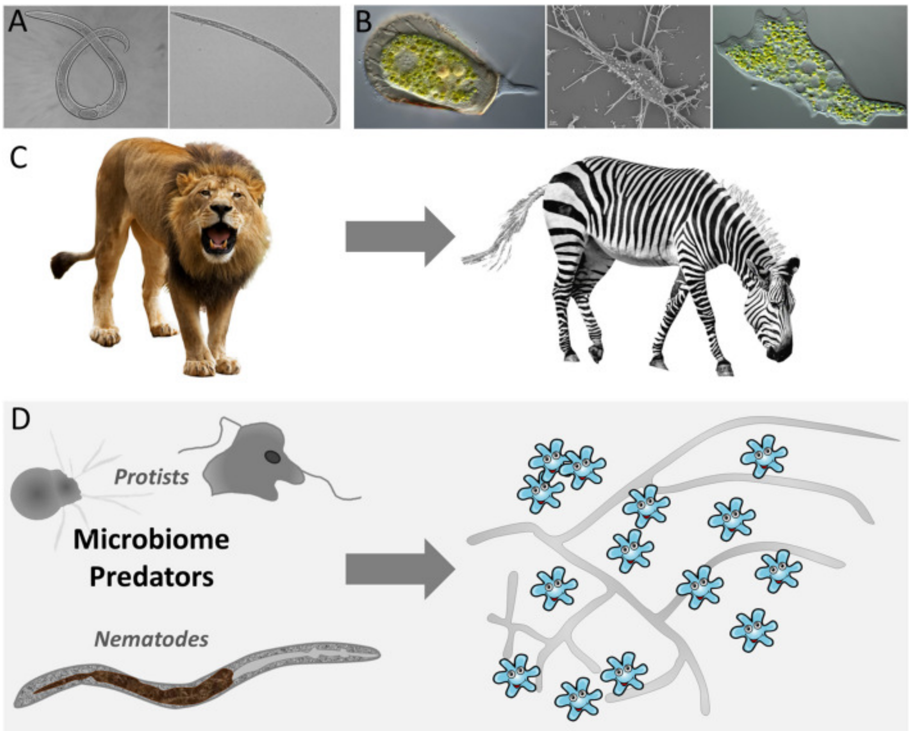

Figure 1

Figure 1

An impression of how nematodes **(A)** and protists **(B)** look like under the microscope. Similar to lions **(C)**, which are well-known predators in savanna ecosystems, microbiome predators **(D)** have essential roles in underground ecosystems. These protists and nematodes feed on bacteria and fungi, changing the composition and activity these soil organisms, which helps to keep the soil healthy [image credits: **A**: nematodes (*Anaplectus porosus* and *Aphelenchoides*) in from Hanny van Megen]; **(B)** protists (*Hyalosphenia papilio*, *Heliamoeba* sp., and *Mayorella viridis*) from www.penard.de with permission from Eckhard Völcker and Steffen Clauß; **(C)** lion and zebra pictures from https://purepng.com/ (under CCO license). **(D)** Bacterial cartoons under the CC0 license from Wikipedia.

on bacteria, but many also feed on fungi or even on bigger animals. Some protists can be parasites of plants and animals, and some live in relationship with fungi, as lichens [4]. Protists have super diverse shapes and can be beautiful (Figure 1B)[2].

Similar to lions or other large predators, microbiome predators prey on many things they can catch (Figures 1C,D). By doing so, these small predators control microbial growth, change the kinds of organisms present in the soil ecosystem, and help the soil to perform its important functions. Microbiome predators commonly feed on the less active microbes, thereby keeping the entire microbiome more active—a feeding strategy again similar to lions that induce prey fitness by feeding on older, slower, and weaker individuals. Microbiome predation also leads to a release of nutrients into soils, which can be taken up by other microbes and plants, helping these organisms to grow.

HOW CAN WE STUDY MICROBIOME PREDATORS?

Since nematodes and protists are tiny and not visible in soils, scientists face the big problem of not being able to directly study them in their natural habitat. One way to study these organisms is to isolate them from the soil. This is a bit easier for nematodes, and you can even try it yourself at home, using coffee filters or tissue paper, water, and a bowl (Figure 2)[3].

[2] For an overview of protist shapes, see http://www.penard.de/.

[3] Here is an online guide: https://www.ars.usda.gov/northeast-area/beltsville-md-barc/beltsville-agricultural-research-center/mycology-and-nematology-genetic-diversity-and-biology-laboratory/people/zafar-handoo/extracting-nematodes-from-soil-samples/!

Figure 2

Figure 2

Nematode extraction at home. Place a handful of soil in two coffee filters on top of each other, close them with clothespins as shown, and place the filters in a bowl filled with water (the water should cover the soil in the filter). The next day, remove the coffee filters, mix the solution and transfer it to a thin glass. Wait and hour, then carefully pour off most of the liquid, leaving only a little in the bottom of the glass. You can now observe nematodes in the remaining solution with a magnifying glass or microscope.

Studying protists is more complicated. Since most soil protists stick strongly to soil particles, the best way to study them in the past was to place tiny amounts of soil together with bacteria, to extract the bacteria-eating protists. However, only few types of protists can be grown this way, and therefore many protist species still are unknown. Today, most researchers use molecular tools to identify soil organisms. Like criminal investigators, we can use DNA extracted from soil to identify these small organisms. Since every organism has a unique DNA sequence, we can use a **DNA sequencing** technology to differentiate individual species based on their unique DNA. This can tell us which soil organisms are present, even though we cannot see them with our eyes or grow them in the lab (Figure 3).

DNA SEQUENCING

A method to determine the DNA sequence of organisms. It can be used to identify organisms.

These extraction, cultivation, and sequencing approaches show us which species are *present* in a soil sample, but not what these species *do*. There are ways to understand the functions of protists and nematodes in soils, including combining predators with various prey microorganisms to observe how they interact. Other scientific approaches can reveal what organisms feed on in soils, by tracing certain soil compounds using special methods as described in [5].

WHY SHOULD WE CARE ABOUT MICROBIOME PREDATORS?

Without microbiome predators, our soils would have a big problem... and a problem with the soil would cause problems for us! Almost all nutrients that enter soils are taken up by bacteria and fungi. If bacteria in soils were not controlled, the most numerous ones would take up all the nutrients and retain them for long periods. Microbes can remain alive in soils for months without predators, and can even enter a long-term survival stage, in which they can survive for decades.

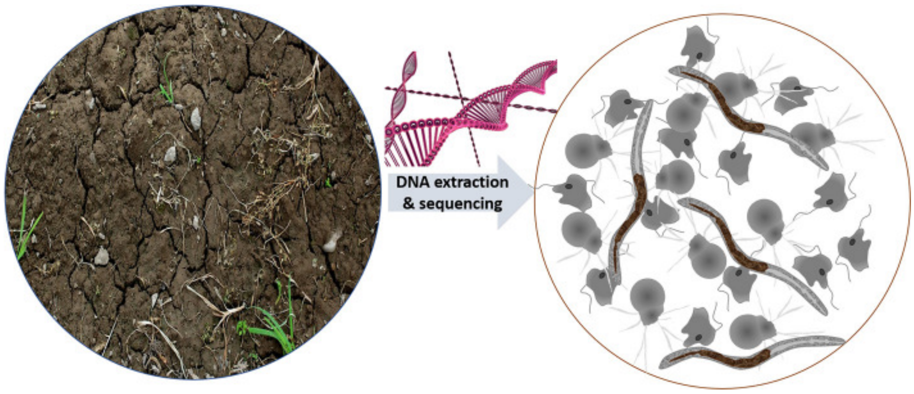

Figure 3

Figure 3

In addition to being well hidden in the soil, microbiome predators are too small to be seen by the naked eye. Scientists often study these organisms by extracting DNA from soils and sequencing that DNA to identify all the species of protists and/or nematodes that are present [image credit: https://www.bioanalysis-zone.com/ and copyright free(CC0)].

As a consequence, the food chain would stop and bigger organisms could not survive. Plants would also take up much less nutrients from soils and would grow slowly, if at all. Microbiome predators make sure that this situation does not happen. By preying on microbes and releasing some of the nutrients that those microbes take up, microbiome predators ensure that plants can access nutrients. The microbiome predators themselves can also serve as prey for larger organisms. So, microbiome predators ultimately save our food supply, by helping the soil to perform its critical functions.

CONCLUSIONS

Protists and nematodes are among the most biodiverse and numerous organisms on Earth. Both protists and nematodes are important microbiome predators and ensure that soils function the way they should. Simply said, without microbiome predators, life in and on soils would not be possible! Indeed, microbiome predators are of key importance for plant growth and they also play critical roles in other microbial processes that occur in healthy soils. By increasing our knowledge about microbiome protists and nematodes, we will also increase our understanding of how soils work. If we can learn how to adjust the types and numbers of microbiome predators in soils, we could help to keep the soil microbiome healthy and protect soil functions. The crucial role of microbiome predators in soils clearly shows that we should not forget *any* group of life on the planet, because even the smallest organisms can have a unique functional importance that helps to keep many other organisms, including humans, alive!

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YOUNG REVIEWER

AYA, AGE: 10
Aya wants to study marine biology. She wants to specialize in sharks and rays. Her favorite subjects in school are reading, writing, math, and music. In her free time she likes to read books, try out challenging puzzles, train for track and cross country, and play the violin.

AUTHOR

STEFAN GEISEN
Stefan is an Assistant Professor at the Laboratory of Nematology at Wageningen University, the Netherlands. He tries to make sense of all the living organisms in soil.

Meaning, he wants to explore what lives in soil and what these organisms do for the ecosystem and for us by steering plant growth. A major focus of his work is on protists and nematodes, small organisms that are the most important predators of microbes in soil. He is father of three boys and in the remaining time he likes to meet friends and do sports. *stefan.geisen@wur.nl

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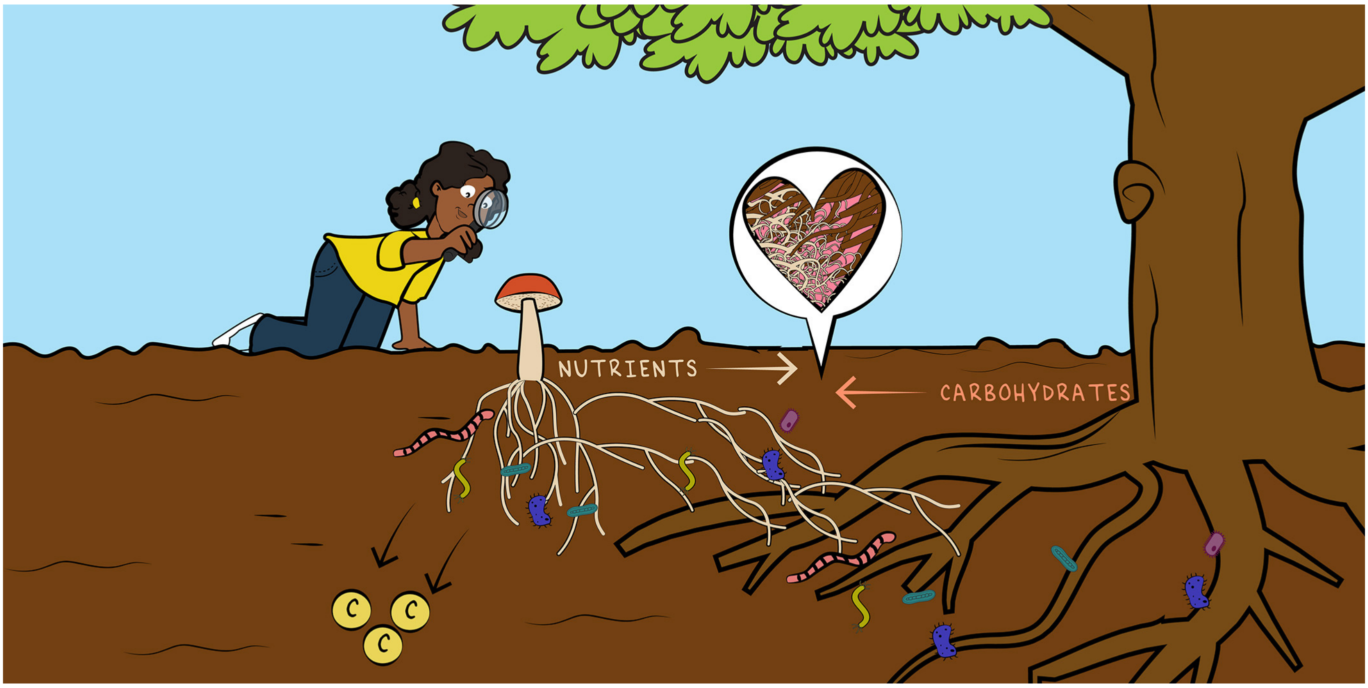

THE SOIL FUNGI: A WEB OF LIFE THAT PROTECTS TREES AND FIGHT CLIMATE CHANGE

Olivia Azevedo [1*] ***and Frank Ashwood*** [2]

[1] *Biological and Environmental Sciences, University of Stirling, Stirling, United Kingdom*

[2] *Forest Research, Northern Research Station, Roslin, United Kingdom*

YOUNG REVIEWERS:

ANNA
AGE: 16

CATHERINE
AGE: 15

Ectomycorrhizal fungi are a type of fungi that develops a mutually beneficial relationship with plant roots. These fungi form ancient and extremely successful partnerships with forest trees worldwide. The trees and their associated fungi have developed a trading partnership: the fungi help the plants reach hard-to-get nutrients, and, in return, the fungi get constant and uninterrupted access to carbohydrates (such as sugars) from the plant. This largely invisible interaction affects the storage and cycling of carbon in soil and benefits plant health and nutrition. Ectomycorrhizal fungi are also important for breaking down dead plants and animals. These fungi contribute to soil biodiversity and can help us to protect our forests in the face of environmental stresses, such as climate change and excessive land use.

FUNGI AND THEIR ROLE IN FOREST ECOSYSTEMS

We often hear that variety is the spice of life. This statement can easily be applied to the many interactions in nature, such as those taking place in forest ecosystems. To lead long and healthy lives, nearly all plants in the wild rely on a complex and varied network of soil organisms feeding on one another. This mostly invisible underground network is made up of tiny bacteria, archaea, fungi, and many other microscopic organisms.

In forest soils, the role of fungi is one crucial piece of the wider ecological network. Fungi have many ecological roles, but two of these are especially important. First, fungi play an important role as **decomposers**. Fungi excel at decomposing dead plant material (called **organic matter**) because they are better than other organisms at completely breaking down the particularly tough materials found in the cells of woody plants [1]. Equipped with a wide range of enzymes, which are special proteins that help produce and speed up chemical reactions, fungi can degrade organic matter and release hard-to-get nutrients, making the nutrients available to plants and other soil dwellers. However, during decomposition, fungi release CO_2 gas as a waste product, which results in movement of carbon from the soil into the atmosphere. Fungi are such excellent decomposers that fungal decomposition is one of the largest global sources of carbon emissions, releasing 85 gigatonnes (one gigatonne equals 1 billion tons) of carbon into the atmosphere every year. For comparison, in 2018, the combustion of fossil fuels produced around 10 gigatonnes [2].

In this article, we will focus on a different important role also played by fungi: their **symbiotic** relationship with trees and other plants. A symbiotic relationship in which both species benefit is known as **mutualism**. Fungi that form mutualistic relationships with plants are known as **mycorrhizal fungi**, from "myco," which means "relating to fungi" and "rhizal," which means "roots." Mycorrhizal fungi form ancient, mutualistic relationships with the roots of around 80% of all terrestrial plant species [1]. Even seemingly barren Antarctica has a fossil record of mycorrhizal communities. Studies show that this teamwork has been ongoing for 400 million years, from the time that plants started to colonize land [3]. Like all fungi, mycorrhizae cannot make their own food, so they receive sugars from their plant hosts, and in exchange provide the plants with water and nutrients, such as nitrogen and phosphorus, from the soil.

Unlike the decomposing fungi that tend to predominantly inhabit the upper portion of the soil and release lots of carbon from their activities, symbiotic mycorrhizal fungi delve deeper into the soil. By doing this, the fungal network becomes a significant carbon sink in the soil, meaning that these fungi keep the carbon locked away from the atmosphere, stored as hard-to-decompose organic matter in the

DECOMPOSER

They are bacteria, fungi or invertebrates that break down dead plants and animals, releasing nutrients back into the soil. Without them, dead organisms and waste would just pile up and plants would not be able to get essential nutrients.

ORGANIC MATTER

Any material produced originally by living organism such as plants, animals and microorganisms that is returned to the soil and can be further broken down (decomposed). Organic matter is carbon rich.

SYMBIOSIS

Any type of close, long-term biological interaction between two different organisms.

MUTUALISM

A relationship between two or more species, in which each species benefits.

MYCORRHIZAL FUNGI

Fungi that form a mutualistic relationship with the roots of plants. The plants receive nutrients and protection from the fungi and the fungi receive sugars from the plants.

Figure 1

Figure 1

The ectomycorrhizal fungus *Lactarius camphoratus*, forming a white sheath around the roots of an oak tree (Photograph credit: Laura Martinez-Suz).

soil. It has been estimated that plants with mycorrhizal association can transfer up to 35% more carbon to soil than non-mycorrhizal plants, and a considerable amount of the carbon in mycorrhizal tissues may stay in the soil for many years [4]. This is important because we need to keep carbon stored in the soil for long periods of time so that there is less in the atmosphere causing rising global temperatures.

Despite the critical roles that fungi play in forest ecosystems, fungal diversity is often overlooked during forest management decisions. Human interference, such as logging or indiscriminate use of fertilizers, can alter the underground network and upset the balance of the entire ecosystem. Like any other web, if just one of the connecting segments is missing or weakened, the whole structure may suffer.

THE FUNGAL SPHERE

There are two main types of mycorrhizal fungi. One type, called endomycorrhiza, live inside plant cells. While we will not focus on these in this article, they are interesting because they are incredible experts in adaptation to many different environments. Endomycorrhizal fungi include arbuscular, ericoid and orchid mycorrhizas. However, the main focus of our article is **ectomycorrhiza** (pl. ectomycorrhizae), which live on the outside of plant cell walls. While multiple mycorrhizal types can coexist in an ecosystem, ectomycorrhiza are dominant in temperate and boreal forests, with ~6,000 fungal species establishing symbiotic associations with many trees and woody plants.

Ectomycorrhizae consist of two types of important structures: **fruiting bodies** and **hyphae**. Fruiting bodies are structures containing spores used by ectomycorrhizae in order to reproduce. Around 4,500 species of ectomycorrhizae have above-ground fruiting bodies (mushrooms),

ECTOMYCORRHIZA

The relationship between a fungus and the roots of certain plants (plural, ectomycorrhizas, or ectomycorrhizae).

FRUITING BODY

Structures made by fungi so they can reproduce. A mushroom is a common type of fruiting body.

HYPHAE

Long, branching structures of a fungus that spread through soil to absorb and transport nutrients (singular, hypha).

Figure 2

Figure 2

The well-known poisonous fungus called fly agaric (*Amanita muscaria*) can form a mycorrhizal association with several types of trees, including pine trees, as shown here (Image credit: Angela Mele).

while up to a quarter have underground fruiting bodies (for example, truffles). Ectomycorrhizae also have hyphae (from Greek meaning "web"), which are long filaments or tube-like structures used by the fungi to absorb and transport nutrients. Hyphae form a mat of fungal tissue around plant roots, creating a casing that envelops the roots like a cast on a broken bone (Figure 1). Fungal hyphae also grow outwards like veins, pushing their way between soil particles, roots, and rocks to capture nutrients that are beyond the normal reach of plant roots. The ectomycorrhizal association also produces antibiotics, hormones, and vitamins useful to the plant, and protects plant roots from harmful conditions in the soil such as low nutrients, disease-causing organisms, and toxic substances. In return, the fungi gain constant and direct access to carbohydrates (such as sugars) produced by their plant hosts during photosynthesis.

ECTOMYCORRHIZAE AND FORESTS: TEAMWORK AT ITS BEST

Ectomycorrhizae prefer woody plant species such as trees and shrubs as their partners. Occasionally they can form exclusive relationships, in which only one fungal species pairs up with a specific tree species. However, ectomycorrhizae typically associate with a wide range of tree species. It is common to find several different mycorrhizal fungi on the root system of a single tree, or one fungal species that is associated with several different tree species. For instance, the Norway spruce can form symbiotic associations with over 100 different fungal species. The well-known poisonous fungus called the fly agaric can colonize the roots of several types of trees, including pine, birch, spruce, and eucalyptus (Figure 2).

The range of plant species colonized by ectomycorrhizae is relatively small—only around 2% of the world's plants. However, the plants that ectomycorrhizae partner with cover large land areas and have a high economic value, for example as a source of timber. In northern temperate regions, pine, poplar, spruce, fir, willow, beech, birch, and oak trees all show ectomycorrhizal associations, while eucalyptus and southern beeches are more commonly associated with ectomycorrhizae in the southern hemisphere.

Ectomycorrhizae give trees and forests the ability to adapt to seasonal and landscape changes, for example by providing adequate levels of water throughout the year and helping the plants to establish themselves in new soils. The fungi also protect the plants from soil degradation, pollution, and shifting climatic conditions. Scientists have observed a direct relationship between the decline of ectomycorrhizal fungi and declining tree health. Because each type of ectomycorrhizal fungus has its own unique set of characteristics, every species is necessary and irreplaceable. For example, certain species prefer cool or moist conditions; others operate better during warm or dry seasons; some are experts at obtaining phosphorus and nitrogen from the soil; and still others are more effective at getting these nutrients from decaying organic matter [5].

Ectomycorrhizal fungi are also an extremely important link between plants and the soil food web, which is the complex community of organisms found in soil. These fungi provide important nutrients to organisms living in the soil around plant roots, such as other tiny fungi, bacteria, protozoa, and invertebrates. The fungi also produce fruiting bodies, which are essential food for wildlife in forest ecosystems. For example, many rodents, such as the northern flying squirrel and western red-backed vole, depend on truffles as their primary food source. Many other mammals eat fungi, including bears, deer, and mice. Humans marvel at the complex and often pretty structures of mushrooms, taking great joy from learning to identify them and studying their ecology, as well as enjoying them as culinary delicacies. Wild fungi are also used for medicines, and the pharmaceutical industry commonly studies the antibacterial properties of ectomycorrhizal fungi.

PROTECTING OUR FORESTS AND FUNGI

Despite the importance of mycorrhizal symbiosis in forests worldwide, conservation of ectomycorrhizal fungi and monitoring them to assess forest health are rarely considered in forest-management decisions. The functions and services that forests provide are dependent on soil biodiversity. Fungi are a major component of this biodiversity, which makes them an important partner for overcoming the global challenges that we currently face. Fungi could contribute to the long-term removal of carbon from the atmosphere, which could help us to combat the effects of climate change. By cycling essential nutrients, fungi could also help to prevent the degradation of soils, so that the land can continue to produce food and sustain life. Scientists and land managers must continue to study and protect ectomycorrhizal fungi, so that these important organisms can maintain their critical role in the web of life on our planet.

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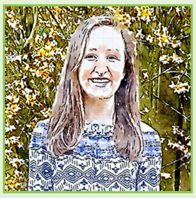
YOUNG REVIEWERS

ANNA, AGE: 16

I wanted to do Frontiers for Young Minds because I thought it would be a great opportunity to learn more about the world around me! I love the sciences, particularly biology and physics. After school I would love to do something with those subjects.



CATHERINE, AGE: 15

I love music and singing, I play the violin and guitar and I also enjoy writing! I am part of a highland dance troup and volunteer with children at local kids clubs and guides. I enjoy attending youth events at my church and doing fitness. I hoped that by reviewing these articles I could learn about new and interesting stuff!

AUTHORS

OLIVIA AZEVEDO

I am a former journalist who decided to become a soil scientist. I moved from Portugal to Scotland where I am currently a Ph.D., student at the University of Stirling. My research involves a lot of digging in forest soils in the hope of finding answers to one important question: what happens to soils and the things living in soils when you plant trees. My research interests include, but are not limited to, the following areas: Soil biodiversity; nutrient cycling; mutualistic relationships linking the above and belowground components of terrestrial ecosystems; soil degradation and management; historical soil landscapes. *olivia.azevedo@stir.ac.uk

FRANK ASHWOOD

A passion for nature encouraged me to study Biology at university, where I volunteered for research projects on invertebrate ecology in Scotland and Mexico. After working as an environmental consultant for a few years, I went back to Uni and did a Ph.D., studying earthworms on reclaimed landfill sites. I now have a great job as a soil ecologist for Forest Research, where I study soil biodiversity in UK woodlands. In my spare time I am a soil biology tutor and do macrophotography (taking photos of the tiny animals living in soil).

BIODIVERSITY
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FROM THE SOIL TO THE CLUB IN THE ROOTS: CLUBROOT

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YOUNG REVIEWER:

JUNIPER
AGE: 11

Among the millions of microorganisms inhabiting the soils, some can be plant pathogens, meaning they can become a disease to plants. Some diseases are more well-known than others. This is the case of clubroot, a very atypical microorganism that infects cruciferous plants, such as cabbage, kale, canola, and the common research plant thale cress. In this article, I will tell you more about clubroot and clubroot disease because there is still a lot to discover about the pathogen and the disease. Maybe you will be part of our lab in the future and investigate a fascinating soil-borne pathogen.

A TALE OF PROTISTS AND PLANTS

Soils are alive. Insects, worms, and microorganisms live in the soil and many of them live in close interaction with plants. Those interactions are not always beneficial for the plants. The soil also harbors creatures that represent a risk for ecologically and economically important plants. Some fungi and worms are

Figure 1

Figure 1

Two important plant hosts susceptible to clubroot: thale cress and rapeseed. Figure created with BioRender.

SOIL-BORNE PATHOGEN

Microorganisms that survive and move about in the soil and can make plants ill.

PROTISTS

Tiny, one-celled organisms that are not animals, plants, or fungi.

CRUCIFEROUS VEGETABLES

Vegetables of the family Brassicaceae, including many green leafy vegetables like cauliflower, cabbage, kale, garden cress, bok choy, broccoli, and Brussels sprouts.

well-known **soil-borne pathogens** for plants, but they are not the only ones. Some **protists** are also devastating soil-borne plant pathogens, although they are less studied and known. Protists are one-celled organisms that are not animals, plants, or fungi.

The clubroot pathogen, or *Plasmodiophora brassicae* like scientist call it, is a protist that affects the roots of **cruciferous vegetables**, such as broccoli, cabbage, cauliflower, the oilseed plant known as canola, and thale cress that is commonly used in plant research [1]. Thale cress and canola are one important host for clubroot, but for different reasons (Figure 1). Thale cress is a very useful plant for scientists that study various aspects of plants, such as their genomes, ecology, and relationships with beneficial microorganisms or pathogens [2]. Thale cress plants infected by clubroot are the perfect model to study how the pathogen affects the plant. Another plant that is extremely important from an economic point of view is canola (Figure 1). Canola is the source of canola oil, a product used in many kitchens around the world. In Canada alone, canola represents around $26 billion dollars (CAD) for the Canadian economy, so a pathogen that puts canola production at risk could be devastating for the economy [1].

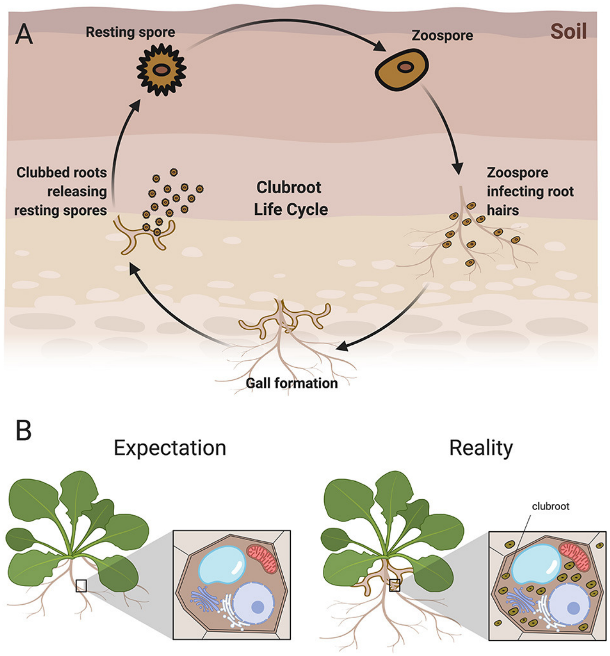

Figure 2

Figure 2

Lifecycle of clubroot and establishment of clubroot disease. **(A)** Clubroot can exist for years as a resting spore in the soil. When the spore contacts a susceptible plant, turns into zoospore and, infects the roots and forms galls. The infected roots eventually release more spores into the soil, which can go on to infect new plants. **(B)** Healthy plant vs. a clubroot infected plant. **(A)** Based on Auer and Ludwig-Müller [3] and created with BioRender.

THE LIFE CYCLE OF CLUBROOT

The clubroot pathogen can live in the soil for up to 20 years as an inactive **spore**. Spores are structures created by some plant pathogens that are released to the environment and have a thick cell wall to help it survive for many years in the soil when are not able to infect a plant. If a susceptible plant grows in soil containing clubroot spores, then the resting spores "wake up" turning now in zoospores and attach to the roots of the plant and start an infection. The infection process is divided into two phases: primary infection and secondary infection (Figure 2A). During primary infection, the clubroot pathogen encounter the roots and penetrate, starting the infection. Although primary infection is important, it is during secondary infection that clubroot induces **galls**, also called clubs, in the roots of susceptible plants. Galls are abnormal swelling of plant tissue induced by plant pathogens or insects. The galls prevent the plant from absorbing water and nutrients from the soil and eventually cause the plants to die. The clubroot life cycle concludes with the production of new resting spores, which are released back to the soil, ready to infect a new plant.

SPORE

Structure created by clubroot that has a thick cell wall to help it survive for many years in the soil when it is not able to infect a plant.

GALLS

Abnormal swelling or outgrowth of plant tissues caused by microbial plant pathogens or insects.

CLUBROOT OR A CLUB IN THE ROOTS?

The clubs are the reason why this disease is known as clubroot. When I heard of clubroot for the first time, I thought it meant "a club in the roots." However, as fun as it sounds, that expectation is quite different from reality (Figure 2B). If anyone is having fun in the infected root, it is definitely not the plant! The reality is that the clubs induced by

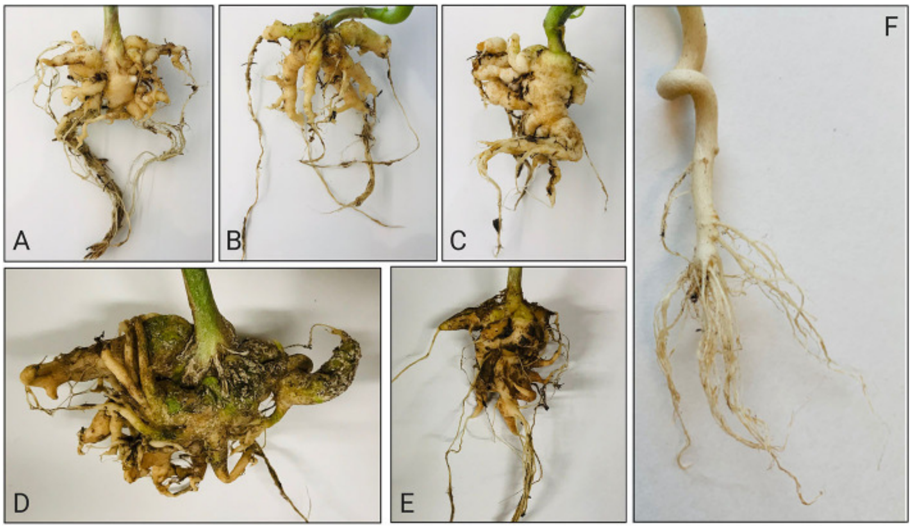

Figure 3

Canola **(A)**, broccoli **(B)**, arugula **(C)**, and kale **(D,E)** roots affected by clubroot, and healthy canola roots **(F)**.

clubroot are devastating. In the laboratory, we found that 21 days after adding clubroot to the soil, susceptible plants start to die. The xylem and phloem, which are the channels used by plants to transport water and nutrients, are totally blocked. It is also interesting to note that the galls caused by clubroot are quite similar in different plant hosts (Figure 3).

HOW CAN WE MANAGE CLUBROOT AND FIGHT CLUBROOT DISEASE?

Although clubroot and the disease it causes were discovered back in the 1600s, there are a lot of things that scientists do not know [1]. To manage clubroot, farmers have been using chemicals, such as fungicides, with little success. Growing plants that are resistant to clubroot disease is the best strategy. However, after only a few years, clubroot develops new strategies to infect those resistant plants, making them susceptible to clubroot disease.

We are trying to fight an enemy that we do not understand very well, so the first step in the war against clubroot disease is to uncover all the tricks that this pathogen is hiding up its sleeves. In the University Laval (Quebec City, Canada), scientists are taking important steps toward understanding clubroot and the disease it causes. They want to know how clubroot escapes the plant immune system and how it can make the cells grow to form the galls. Their ultimate goal is to develop plants that are resistant to clubroot disease that can survive in a field with or without clubroot spores in it. Maybe in a few years you, the young curious mind reading this, will be part of the team tackling this intriguing pathogen.

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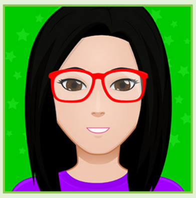
YOUNG REVIEWER



JUNIPER, AGE: 11
I like reading and coding. I also like animals. My favorite subjects in school are mathematics and art.

AUTHOR

EDEL PÉREZ-LÓPEZ
I am an Assistant Professor at the department of Plant Sciences at the University Laval, Quebec City, Canada. I am from a small agricultural town in Cuba and agriculture was always part of my life. That is why I decided to study biochemistry and to investigate the pathogens affecting plants and agriculture. In 2018, when I first learned about clubroot and clubroot disease, I felt in love with that intriguing pathogen, and it is now a central part of my research. I hope that someday one of you, a curious mind reading this, can be part of Edelab (`https://edelabcriv.com/`) to discover the mysteries behind pathogen-plant interactions. *edel.perez-lopez.1@ulaval.ca

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HAVING BABIES IN SOIL: IS SEX REALLY NECESSARY?

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YOUNG REVIEWERS:


DARIO
AGE: 14


LUVENA
AGE: 11


PRANATEE
AGE: 12


VALERIE
AGE: 13

Finding a partner and having sex to produce babies is a common way to reproduce. Yet, upon closer look, we see that nature provides many ways for reproduction. What about a world without males? What first sounds impossible is the reality for many organisms that reproduce asexually, meaning without having sex. Females produce daughters that are clones of themselves, so no partner is required and males are dispensable. An Example of such all-female societies are several species of oribatid mites, which live in soils. These mites were already on earth long before the dinosaurs. Have oribatid mites always been asexual? Why do they reproduce without males? Does asexual reproduction have any advantages? Keep reading to learn about asexual reproduction and why oribatid mites are a key organism to investigate the question, "Why sex?".

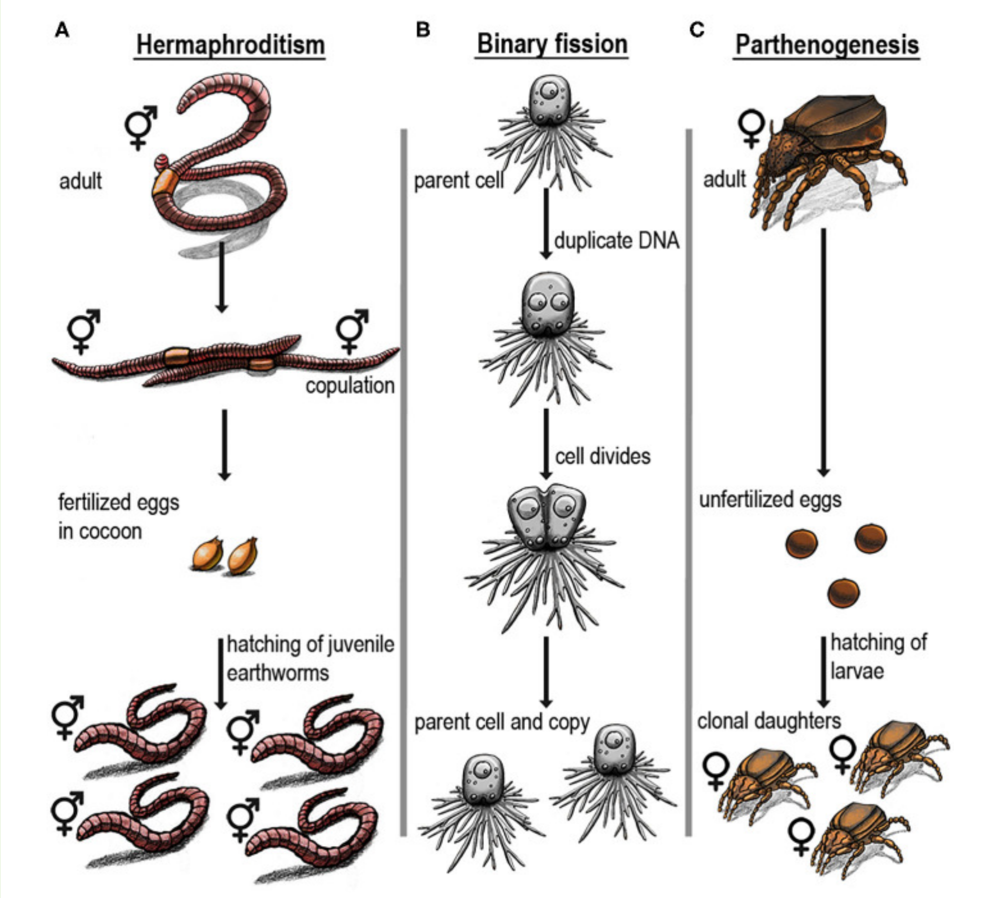

Figure 1

Overview of different reproductive modes described in the text. **(A)** In hermaphroditism, each individual possesses both male and female reproductive organs; earthworms fertilize each other and each individual lays eggs. **(B)** In binary fission, a cell divides into two cells of equal size after duplicating its genetic material. Two individuals are produced from a single parent cell. This method is used by many Protists, for example amoebae. **(C)** Parthenogenesis is a form of asexual reproduction in which an offspring develops from an unfertilized egg cell. Some oribatid mites reproduce via parthenogenesis.

SEXUAL REPRODUCTION

Reproductive mode that requires an egg cell of a female and sperm cell of a male individual. The offspring is a unique individual that carries half of each parent's DNA.

ZYGOTE

A cell resulting from the fusion of a male's sperm cell with a female's egg cell i.e., a zygote is a fertilized egg.

HERMAPHRODITE

A single individual that can produce both egg cells and sperm cells. It is basically both a female and a male.

REPRODUCTION IN SOIL ORGANISMS

All living organisms reproduce to generate new offspring. Almost all organisms, including humans, use some form of sex to reproduce. In **sexual reproduction**, an egg cell produced by a female and a sperm cell produced by a male fuse. The result is a **zygote** that develops into a unique offspring. Each offspring is a mixture of its parents, since it inherits half of its DNA from its mother and half from its father. The new offspring grows, becomes an adult, finds a partner, and finally produces offspring itself. This is the circle of life.

Many kinds of organisms live in soil, and they have a variety of different ways to reproduce. For example, earthworms are **hermaphrodites**, which means that one worm has both male and female reproductive organs. Earthworms reproduce sexually—if two earthworms meet, they exchange sperm cells that fuse with the egg cells of the other earthworm (Figure 1A). Since they have both male and female sex organs, earthworms do not have to worry about finding a partner of the opposite sex because there is always a match. Earthworms belong to a group of soil organisms called the macrofauna, which includes all animals larger than 2 mm. Macrofauna are soil giants compared to most soil organisms.

The greatest number of soil organisms belongs to the microfauna, which consists of organisms smaller than 0.1 mm. Most are single-celled organisms called **protists**. They are so small that one handful of soil contains more protists than there are humans in the entire world. For reproduction, protists do not need a partner at all. Some protists reproduce via a type of **asexual reproduction**, by making exact copies of themselves through a process called **binary fission**. First, they duplicate all their genetic material, and then one cell divides in two (Figure 1B). If repeated several times, many identical copies of one individual independently populate the soil.

PROTIST

Single celled organism that are eukaryotes. Many feed on bacteria and release excess nitrogen, providing essential nutrients for plants and other organisms.

ASEXUAL REPRODUCTION

Any type of reproductive mode that produces offspring without the fusion of egg and sperm cells, also called gametes. The offspring are identical to the parent and/or to each other.

BINARY FISSION

A cell divides into two cells of equal size after duplicating its genetic material. Two individuals are produced from a single parent cell i.e., one daughter and one parent cell.

Another essential group of soil organisms is known as the mesofauna, which includes all soil animals between 0.1 and 2 millimeters in size. The soil mesofauna includes springtails and oribatid mites. These organisms are very common and play a key role in the soil food web. They shred dead organic matter from plants, making the nutrients available to other organisms, including bacteria and fungi, which are then eaten by other belowground organisms. Many oribatid mites live in all-female populations and have done so for millions of years. They do not need sex for reproduction, because they can lay eggs that develop without being fertilized by a male, in a process called **parthenogenesis** (Figure 1C). Each egg contains the DNA only of the mother, which means that the offspring are clones of the mother.

PARTHENOGENESIS

A form of asexual reproduction in which an offspring develops from an unfertilized egg cell.

ADVANTAGES OF ASEXUAL REPRODUCTION

Copying or cloning oneself seems to be much easier than finding a partner, but there are even more advantages of asexual reproduction. If you follow a sexual and an asexual population over time, two major differences appear. An asexual female only produces daughters, and these daughters produce only daughters again when *they* reproduce. The sexual females, however, must produce sons to fertilize the eggs—but only daughters can produce offspring. So, even if sexual and asexual females produce the same number of offspring, the asexual female has more daughters, which means more offspring that can reproduce.

Over time, the asexual population grows much faster and may outcompete the sexual population just by numbers (Figure 2). Scientists call this the "cost of males." In addition to providing greater population growth, asexual reproduction seems to have other advantages: no sexually transmitted diseases, no energy loss, and no chance of being eaten by predators while trying to find a mate.

WHAT IS THE USE OF SEX IF REPRODUCTION CAN HAPPEN WITHOUT IT?

If there are successful ways of asexual reproduction, why do **eukaryotes** bother with complex, risky, and costly sexual reproduction?

EUKARYOTES

Can be animals, plants, single-celled organisms like protists and fungi. These are complex cells, where the genetic information is organized in a nucleus.

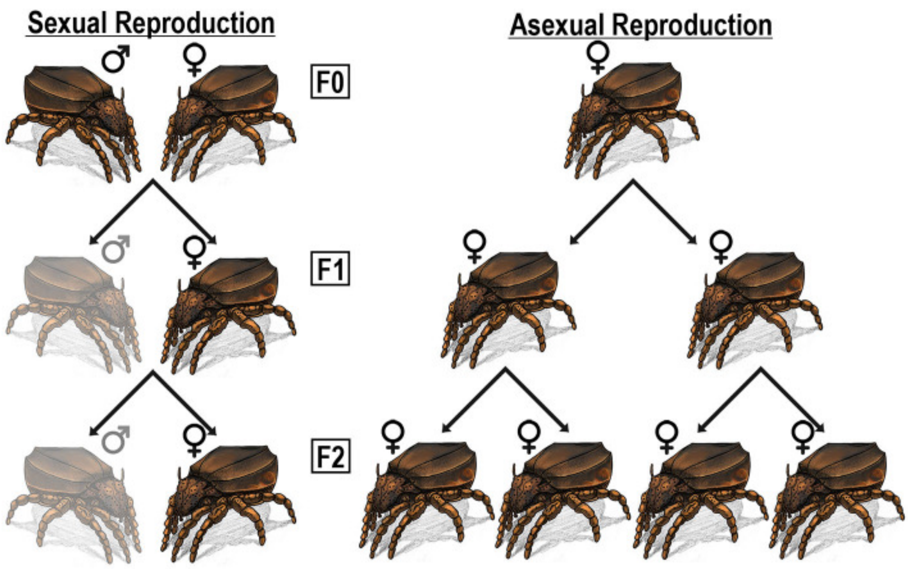

Figure 2

Figure 2

Predicted population growth for sexual and asexual populations. In this example, each female produces two offspring. The size of the sexually reproducing population remains constant over time, because males are needed to fertilize the eggs of the females, but they cannot have offspring themselves. In asexual reproduction, the female produces twice as many childbearing offspring (females), leading to exponential population growth. (F0: parental generation, F1: first set of offspring from parents, F2: next generation of offspring from F1).

More than 98% of all animals use sex to reproduce. This means that sexual reproduction must have clear advantages over asexual reproduction. Therefore, scientists try to explain the benefits of sex mainly by looking for potential problems if sex is not used. One disadvantage that scientists proposed for asexual reproduction has to do with mutations. Mutations are changes in the DNA that are an important cause of diversity among organisms. Occasionally, mutations are beneficial—sometimes they are very harmful—and most of the time they are slightly harmful. When an organism copies itself all the time, slightly harmful mutations keep adding up over generations, causing more and more harm. Once they build up enough, these mutations could lead to the extinction of the species. This does not happen in sexual organisms, because the harmful mutations of one parent can be compensated for by the unmutated DNA from the other parent. Think of two bikes, one with a flat tire and one with a broken pedal. By combining parts from the two, you could still have a functional bike. It would be preferable to have one fully functional instead of two semi-functional ones. Some scientists suggest that this repair mechanism is an essential advantage of sexual over asexual reproduction.

Furthermore, just making copies or clones means that an organism will stay the same for many generations. This leads to problems when the environment changes. For example, the availability of resources such as food could change over time, e.g., due to climate change or the presence of other organisms competing for food. Food may develop a defense strategy, like running faster or becoming poisonous. Parasites can also be a problem. Since all individuals in an asexual population are very similar, they will not have the tiny differences that could help them adapt quickly enough to the ever-changing environment, so they would eventually die out. This means that offspring produced through sexual reproduction have higher chances of survival simply because they are different from those that came before them. This seems to tell us that all asexual organisms should go extinct in the long term. But, knowing that so many asexual organisms thrive in soil, we asked whether asexual organisms truly are doomed to die.

GENES CAN TELL US ABOUT ASEXUAL REPRODUCTION

Our research groups work with soil-living oribatid mites because many asexual species have survived without males for millions of years. We analyze the genes of sexual and asexual oribatid mite species because genes can tell us what happened to organisms in the past. Imagine genes as a captain's logbook, in which important things that happened to an organism in the past were recorded and passed on to future generations. We are still able to see the disadvantages of asexual reproduction in these logbooks. If we compare logbooks of oribatid mites that reproduce sexually to those that reproduce asexually, we can figure out which of the above-mentioned problems occurred and how they were solved. Since we are comparing two very similar species of mites, most of the genes are very similar. However, for some genes we can identify certain differences that must be caused by the consequences of the different reproductive modes.

In contrast to what scientists theorized, we found that asexual species do *not* accumulate more harmful mutations than sexual species (Figure 3) [1]. They do not need to combine two broken bikes to get a functional bike, because they keep the bikes functional. We also found that the asexual mites *do* maintain variability in their large populations [2]. The genes in separate mother-daughter lines are as different from each other as are individuals that mix genes by reproducing sexually. Last, we found that the genes of two (or more) populations of asexual oribatid mites can be as varied as the genes of sexual species. This means that asexual oribatid mites *do not* stay the same for many generations, so they *can* adapt to new environments and are even able to diverge into new species [3].

From our research, it appears that asexual oribatid mites have no disadvantages compared with the ones that reproduce sexually. They keep mutations in check, maintain genetic variability, and adapt over time, all without sex!

WHY IS THIS IMPORTANT?

There are many ways to produce offspring, and they do not always include sex. In theory, asexual species are expected to go extinct. In nature, however, there are various asexual organisms that have persisted over time. There must be ways to overcome the disadvantages of asexuality, as we saw in the asexual oribatid mites.

Figure 3

Asexual oribatid mites get rid of slightly harmful mutations even more effectively than sexual oribatid mites [1]. Asexuals are even better at maintaining healthy genes (indicated by the fancy blue bike) than the sexual species (which still have decent red bikes). A boxplot shows the middle 50% of the data, each with a line in the middle representing the median (center of data). The two lines outside the box indicate the highest (maximum) and lowest (minimum) observations. The three stars on top indicate that this result is statistically significant, meaning it is very unlikely to observe this just by chance.

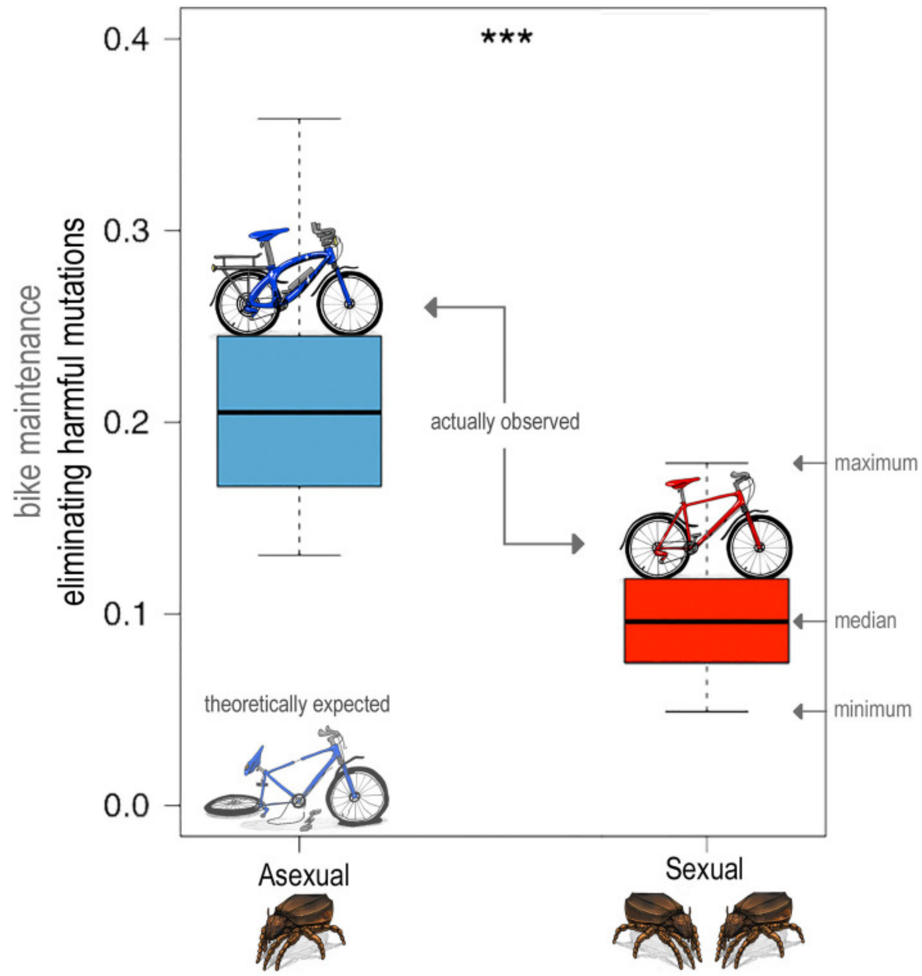

Figure 3

But how do they do it? Do they have special mechanisms that fix mutations? Do they have to maintain a large population size to keep genetic variability? Is it easier to be asexual if you feed on a dead food source, which cannot develop defense strategies that you must adapt to? One future challenge will be to find the mechanisms that most asexual organisms have in common. Scientists continue to work on pairs of related sexual and asexual organisms to shed light on the variety of reproduction modes and to attempt to answer the question, "Why is sex so common?"

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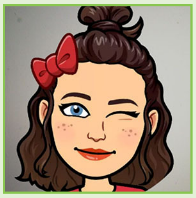
YOUNG REVIEWERS

DARIO, AGE: 14
My name is Dario. I live in a small village in Austria. It is full of nature so in my freetime I like to go out with my dogs or climb trees. My parents are both biologist so I got into biology pretty early.

LUVENA, AGE: 11
Hi, my name is Luvena! I love music, sports, and food. My favorite subjects in school are math and language arts. In my spare time, I enjoy playing piano and reading books with my sister. When I grow up, I would like to be a neurosurgeon.

PRANATEE, AGE: 12
Hello! I love to bake, especially tarts and pies. In school, my favorite subjects are science, lunch, and recess. I like spending time outdoors and going hiking. I also love going to the beach and have an interest in photography. Watching my favorite TV shows, painting, listening to music, singing, and hanging out with friends are my

favorite things to do in my free time. In the future, I would like to either like to be a scientist, or a singer/songwriter and actress.



VALERIE, AGE: 13

I am in 8th grade of a middle school in Austria. My hobbies are horsebackriding, skating, and dancing. I have got a very old cat and we are getting a dog soon. I also like meeting my friends and listening to some music.

AUTHORS

HÜSNA ÖZTOPRAK

At first, I studied biology to become a scientific journalist. During my studies I quickly realized I want to find answers to my own question, so I became a researcher. During my master's research I found and described new species of testate amoebae. I became interested in how asexual organisms diverge into new species. So, I started my Ph.D. at the University of Cologne, Germany. I like to travel and try new foods. At the moment, staying at home is the responsible thing to do. So, when I am not in the lab, I stay in and binge-watch anime. *h.oeztoprak@uni-koeln.de

ALEXANDER BRANDT

I am an evolutionary biologist at the University of Lausanne in Switzerland. In my research I mostly analyze genes using the computer. However, I always enjoy watching (soil) animals (under the microscope) when I have some free time in the lab. I spent a lot of time comparing how many harmful mutations have accumulated in asexual and sexual oribatid mites during their evolution. For this work, I just recently obtained my Ph.D. from the University of Göttingen (about which I am really proud)! In my free time I like watching documentaries about dinosaurs, meeting friends, and I play drums in a rock band.

MARCEL D. SOLBACH

I am a biology Ph.D. student from Cologne. I conducted work on various microorganisms including microalgae, intracellular bacteria in amoebae, and currently on protists as potential plant pathogens. When I am not sitting in the laboratory, I try to build a side-career as a fantasy artist and illustrator—hence I painted the pictures in this article! In my remaining time, I like to play basketball and go swimming, to prevent my aging and aching body from falling apart.

JENS BAST

As a kid (and still as an adult), I was fascinated by animals, mostly cats. And genes. I genetically manipulated my first bacteria at 17. This is how I got into biology and when I started thinking about why the things in nature are the way they are. I use my passion for genes and animals to try to understand what happens in evolution when sex is lost. I enjoy working with other scientists so that we can solve scientific questions together. In my free time I like to cook and eat, to travel, to make music, and to play games.

INA SCHAEFER

The diversity and distinctness of the natural world made me think about what we think is normal and what is unusual. This is why I became a scientist, because science is supposed to be objective. I am fascinated by the soil environment because life in soil is so different from our everyday above-ground experience in many ways. However, because I am a large and clumsy human that cannot see nor move in soil, I need to investigate the DNA of soil organisms to understand what they do and who they are.

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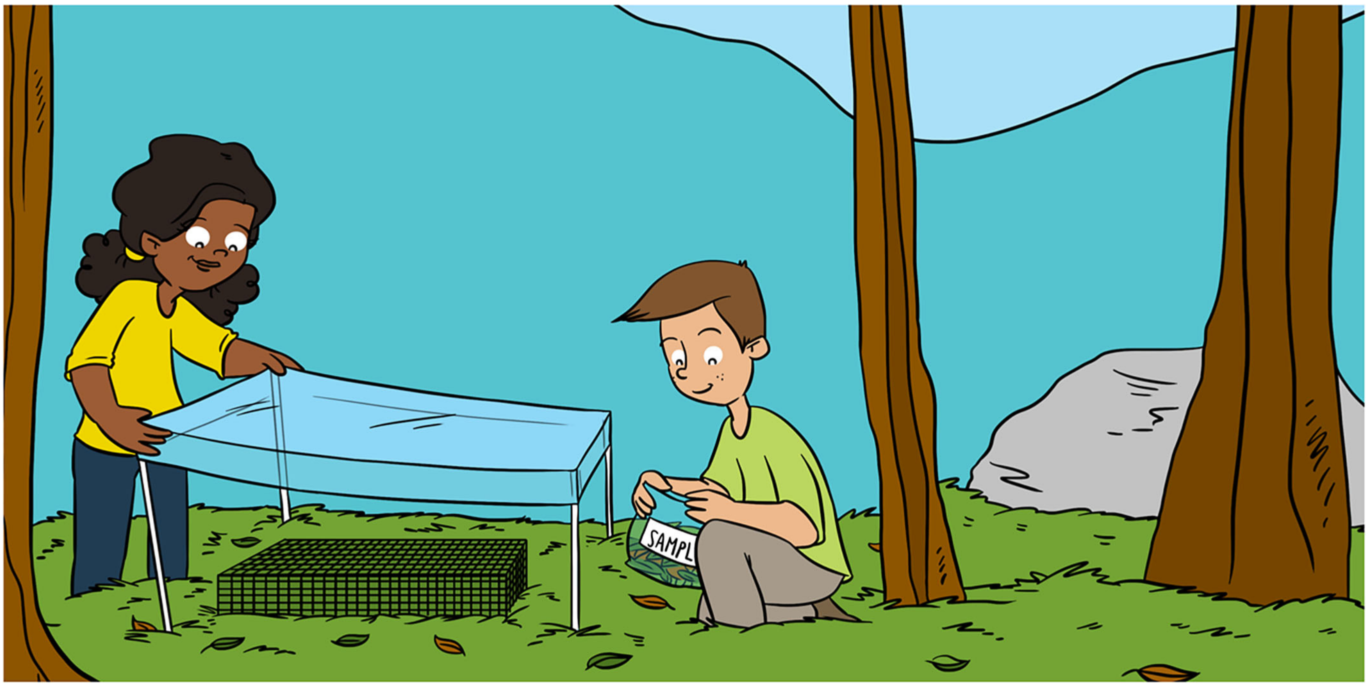

STUDYING THE ACTIVITY OF LEAF-LITTER FAUNA: A SMALL WORLD TO DISCOVER

Dolores Ruiz-Lupión*†, María Pilar Gavín-Centol and Jordi Moya-Laraño

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YOUNG REVIEWER:

SASYAK

AGE: 12

Hundreds of thousands of little creatures live in soils. Some eat live plants, live animals, or both. Others, called decomposers, consume dead plants, and the waste of other living beings (their feces and their dead bodies), and transform them into food for plants. The health of soils depends largely on the presence of decomposers, and thus it is necessary to study how these creatures may be affected by climate change. To this end, we built a new type of traps to catch live soil animals, which we called cul-de-sac and basket traps. Here, we show how these traps are better for studying animal activity (how much they move in the soil) compared to the most used devices to date, pitfall traps. Comparatively, our traps capture more active animals and prevent predators from killing prey inside, which will improve the accuracy of future studies all over the world.

WHY ARE LIVING BEINGS SO IMPORTANT FOR SOILS?

Soils are largely unknown universes, complex systems formed by a mixture of air, minerals, organic compounds, and living organisms that are related to each other and with the environment. These relationships between living beings are called interactions, which take place when organisms communicate, feed on each other or pollinate flowers, among others. Currently, we do not know how many species of animals, fungi, and bacteria live in the first four meters of soil (Figure 1, soil profile); but we do know that soils contain the greatest biodiversity on Earth, with about 1.5 million described species out of a total of an estimated 2 billion. Among this overwhelming biodiversity, **soil fauna** perform many important functions necessary for both soil health and human well-being [1]. For example, one of these functions is the decomposition of dead animals and plants, a process in which dead matter is transformed into food from which plants feed on (Figure 1, orange arrows). Without decomposer animals healthy soils would disappear, and both wildlife and humanity would be affected. Moreover, some of these animals act as ecosystem engineers, creating, modifying, and maintaining the soil structure (as ants or earthworms when digging holes). Other soil-living animals are natural enemies of pests, helping farmers to protect their crops. Therefore, a soil with greater abundance and diversity of fauna will provide more benefits and this is why these organisms are good indicators of soil health [2]. Hence, sampling and analyzing these creatures is essential if we are to understand and preserve the soils and the functions they supply.

SOIL FAUNA

The set of animals that live within or on top of the soil (springtails, mites, spiders, centipedes, earthworms, etc.). This contrasts to soil microbiota (bacteria and fungi) also important for soil functioning.

THE IMPORTANCE OF LEAF-LITTER FOOD WEBS

About 97% of the species of soil fauna are invertebrates, animals without an internal skeleton such as nematodes, potworms, earthworms, slugs, or snails. We mostly like to study a type of invertebrates that often live in the **leaf-litter** layer and that have external skeletons, segmented bodies, and pairs of appendages with joints: the arthropods. These animals can vary widely in size from very tiny to larger than a hand. Soil arthropods are grouped into two size categories: mesofauna (0.2–2.0 mm) such as mites and springtails, and macrofauna (>2.0 mm) such as spiders, beetles, centipedes, and millipedes (Figure 1, grey boxes). All these animals organize around what we call **food webs**, in which predator-prey relationship take place governed by the rule that "big fish eats little fish;" that is, larger species prey (kill and feed) on several smaller ones, while small species prey on even smaller species or on the offspring of larger ones (Figure 1, black arrows). This interdependence among species means that food webs are fragile systems, in which the extinction of one species can cause the extinction of others, making the entire food web to crumble as a "house of cards" (**Video 1**). Therefore, studying the functioning of food webs is crucial for soil health monitoring.

LEAF-LITTER

The top soil layer of dead leaves (1 cm–1 m depth) in terrestrial ecosystems, such as forests and scrublands, which provides habitat and food to a large diversity of organisms.

FOOD WEB

A natural network of connections (interactions) among organisms that feed on each other.

VIDEO 1

An illustrative video of a crumbling food web as a "house of cards."

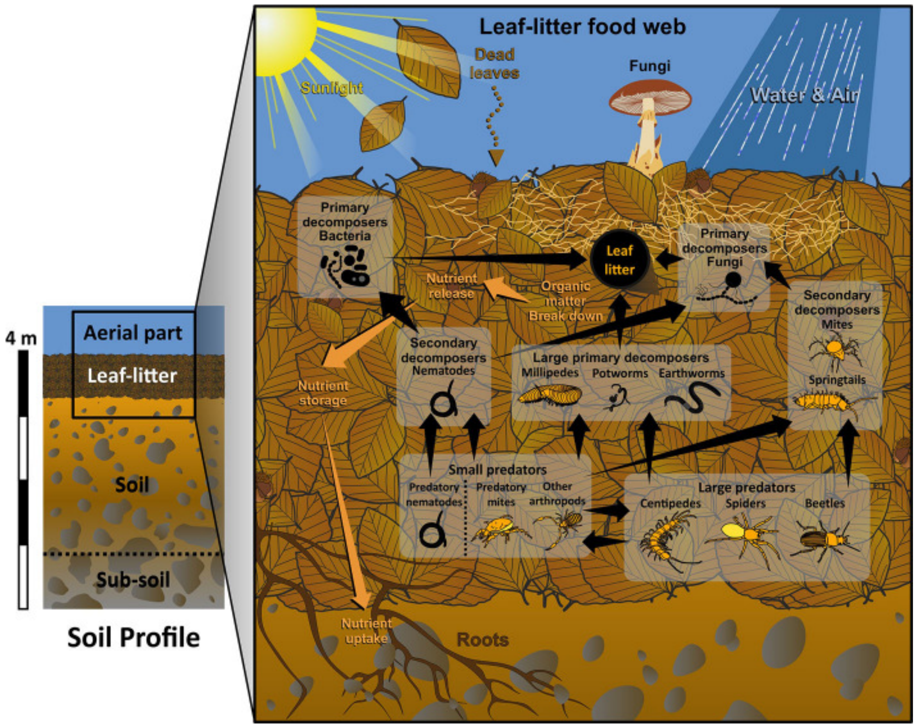

Figure 1

Figure 1

The leaf-litter food web. The abundance and diversity of soil fauna is critical for soil health. Black arrows show "who eats whom," and organisms can be classified into: (1) primary decomposers that directly feed on the leaf-litter; (2) secondary decomposers that feed on primary decomposers; (3) small predators that feed on primary and secondary decomposers; and (4) large predators that feed on small predators and large decomposers. Orange arrows show the decomposition process, by which dead matter is transformed into food from which plants feed upon. To complete the decomposition process of the falling leaves (brown arrow), sunlight, rainfall and a good airflow are also necessary.

USING TRAPS TO MEASURE THE ACTIVITY OF LEAF-LITTER ARTHROPODS

Not all soil animals search food at the same time, nor for the same amount of time, which determines which animals encounter and interact with each other in the soil. Therefore, predator-prey interactions in food webs could be influenced by the activity patterns (e.g., diurnal or nocturnal) of different animals. Our main goal is to study the **activity** of leaf-litter arthropods using different types of traps. The use of traps for measuring animal activity may be an appropriate approach to monitor the functioning and health of soils. Even so, it is still unclear if trap catches are an estimate of activity, abundance, or a mixture of both [3]. This is because traps in a location with more arthropods will catch a larger number of them if they are more abundant, but also if they move around for longer time (that is, because they are more active). Since the early 1900s, the standard method for collecting soil fauna and measuring the abundance and/or diversity of soil arthropods has been the use of pitfall traps. These traps consist of cups buried in the soil in which fauna crawling through the leaf-litter fall. The cups are usually partially filled with a liquid to kill and preserve the trapped organisms. Besides pitfall traps, there are other methods of sampling abundance and/or diversity of soil arthropods [4]. In our study, we were interested in assessing the activity—not just the abundance—of soil arthropods. Therefore, we used pitfall traps without preservative liquid, which allowed collecting live specimens that could be returned to the leaf-litter.

ACTIVITY

The amount of animal movement per unit of time (minutes, hours, etc.).

However, pitfall traps have many problems, including the fact that animals that are too small or too large do not fall into them, either because they are longer than the trap entrance or so small that they detect the edge of the trap and move away from it. Some animals can even walk on the trap walls without falling in. This means that pitfall traps might not give us good estimates of the entire leaf-litter community, which could lead to improper conclusions about predator-prey interactions when using pitfall traps [3]. Thus, we developed two new trapping devices to improve the monitoring of animal activity, small mesh fabric bags in the shape of a sock named "cul-de-sac" traps, and square baskets made of wireframe similar to a box with holes without a lid named "basket" traps [5], in which the transition between the edge of the trap and the surrounding litter is less noticeable to soil animals than in pitfall traps.

DISTINGUISHING ACTIVITY FROM ABUNDANCE

Our main goal was to find which traps were better at monitoring animal activity, by means of distinguishing abundance (how many animals are there) from activity (how much do they move). We use traps to estimate activity; that is, animals that fall inside a trap while it is placed in the field should reflect how much they move. However, things are not this simple. For instance, the number of animals directly captured in the leaf-litter is an estimate of their abundance; that is, the quantity of animals present regardless of the moment. Hence, differently than activity, abundance is not affected, for instance, by the weather conditions of the day of the experiment in which we capture the animals. And this is when things get tricky: animal abundance affects how many animals are caught in the traps regardless of their activity. Therefore, in order to differentiate activity from abundance, we had to count and classify the arthropods inside the traps (activity) and within the leaf-litter outside the traps (abundance). This distinction is very important because the measure of soil arthropod activity cannot be done without knowing the abundance. Imagine one location in the soil inhabited by 2 individuals of a species (Sp1) of very active beetles that move around a lot, and by 20 beetles of a very abundant but sedentary species (Sp2); i.e., that do move very little. If our traps collected 2 beetles of each species in that location, we would conclude that the activity of both species was similar. However, in reality the 2 individuals of the former species (Sp1) would be caught by their high activity, while the second two (Sp2) would be caught because this species is much more abundant. Just because Sp2 is present in large numbers two are caught in the traps, even though these beetles move much less. An independent measurement of abundance serves the researchers to correct for these differences and have accurate measurements of activity.

SETTING UP OUR MESOCOSM EXPERIMENT

In the spring of 2013, we conducted an experiment in 4 beech forests (*Fagus sylvatica* L.) from the Cantabrian Mountains, Spain (Figure 2A). Beech trees have relatively large leaves that fall in autumn, forming a leaf-litter layer often deeper than 10 cm, which is shelter to large numbers of arthropods [6]. Working in soils with leaf-litter offers a great advantage: animals live and are active in superficial layers of the soil during most of the time, while in the soils of other terrestrial ecosystems the fauna is mostly active in deeper layers, from which it is difficult to trap live animals.

All traps used in the study were handmade. Pitfall traps (Figure 2C, left) consisted of a plastic cup with the base cut and a fabric attached at the bottom to prevent small animals from escaping while allowing water to drain out. This fabric was very fine, with a mesh of about 200 μm. In addition, to minimize the entry of sunlight as to mimic the dark conditions within the litter, a wooden square cap was placed on top of each pitfall trap in the leaf-litter. Cul-de-sac traps (Figure 2C, center) were made firm by sewing an oval-shaped wire around the mouth trap. The fabric of these bags was the same as that used for the pitfall traps. Basket traps (Figure 2C, right) consisted of 20 $\times$ 20 $\times$ 7 cm wireframe baskets of 1 $\times$ 1 cm mesh. Once we built all traps, we placed several square shaped metal enclosures buried in the forest leaf-litter, named **mesocosms** (Figure 2B). We then collected leaf-litter in the surroundings of each mesocosm, removed all fauna from this litter in the laboratory, filled all traps with this litter free of fauna, and finally placed all traps in the field. Cul-de-sac and basket traps were embedded in the litter layer within the mesocosms, and pitfall traps were buried in the mesocosm soil (Figure 2D). In total, 4 mesocosms were placed in each forest, each with 4 pitfalls, 2 cul-de-sac, and 2 basket traps (Figure 2E). To begin our observations with similar moisture conditions in the traps and the surrounding litter, we placed roofs on the mesocosms to block all rainfall 15 days in advance. This procedure provided with uniform moisture conditions within the mesocosms, ensuring that animals were not moving to seek for, or to avoid humidity.

MESOCOSM

A device, normally placed outdoors, that encloses part of an ecosystem and allows scientists to control parameters, such as rainfall, more realistically than in laboratory experiments.

After collecting the samples from the traps and the leaf-litter outside the traps, five steps were then followed in the laboratory: (1) we weighed the leaf-litter of each sample (wet weights); (2) we removed and counted the arthropods; (3) using a dissecting microscope we classified the arthropods according to their size (macrofauna vs. mesofauna), diet (predators vs. prey) and main group (mites, springtails, spiders, centipedes, millipedes, or beetles); (4) we dried the leaf-litter of each trap and weighed it again (dry weights); and (5) we calculated the water content within each trap from the difference between wet and dry leaf-litter weights. We used statistical tools to reach conclusions from the numerical data that we obtained from the field. We needed to use these tools for including a correction

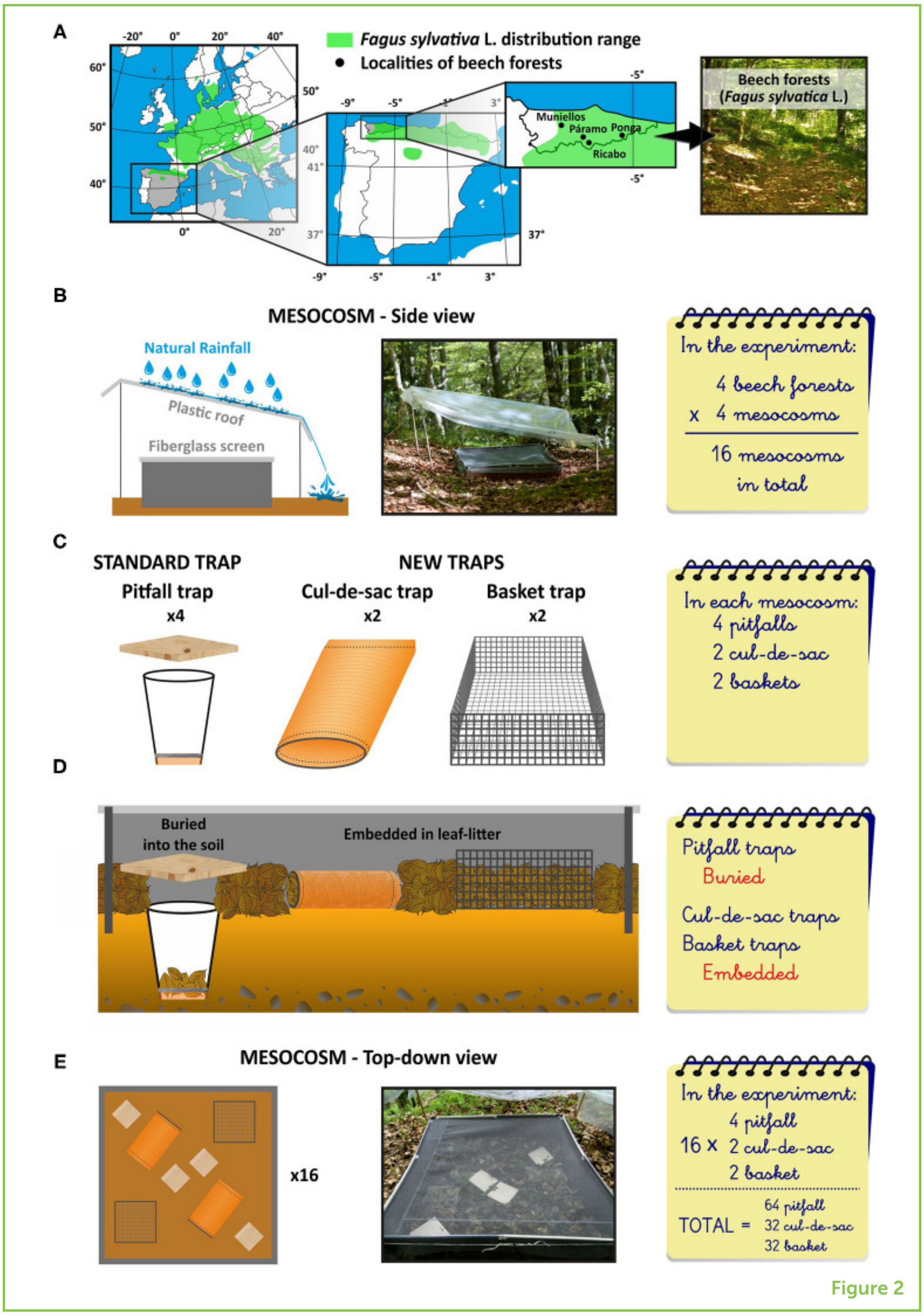

Figure 2

Our experimental setup. **(A)** Our study was conducted in 4 beech forests in Asturias, Spain. **(B)** We set up mesocosms that were partially buried in the soil, each with a fiberglass screen on top to prevent the escape of arthropods and a plastic roof to block rainfall. **(C)** Each mesocosm contained "pitfall" traps and the new "cul-de-sac" and "basket" traps. **(D)** Pitfall traps were buried in the soil, whereas cul-de-sac and basket traps were embedded within the leaf-litter layer. **(E)** Top-down view of a mesocosm with 4 pitfall, 2 cul-de-sac and 2 basket traps (photographs and some drawings were reused from the Original Source Article).

for abundance (see the above section), ensuring that we were testing for differences in activity and not in abundance [7]. In summary, we tested the activity of each group and if some trap types captured some groups more than others. For instance, we compared the catches of large (macrofauna) vs. small (mesofauna) animals, as well as those of predators vs. prey. With this set of comparisons, we could assess what kind of trap works better for studying arthropod activity.

WHAT TYPE OF TRAP BEST MEASURES ACTIVITY?

Through our experiments, we found that cul-de-sac and basket traps performed better than pitfalls trap. First, pitfall traps retained almost twice the amount of water than cul-de-sac and basket traps, which could result in attraction for some animals or repulsion for others. Additionally, the litter in these new traps had similar water content than that in the surrounding litter outside the traps (Figure 3A). Second, cul-de-sac and basket traps caught around 3–5 times more animals per unit time, for example per hour, than pitfall traps. Thus, the latter underestimated the activity of leaf-litter fauna (Figure 3B). Third, pitfall

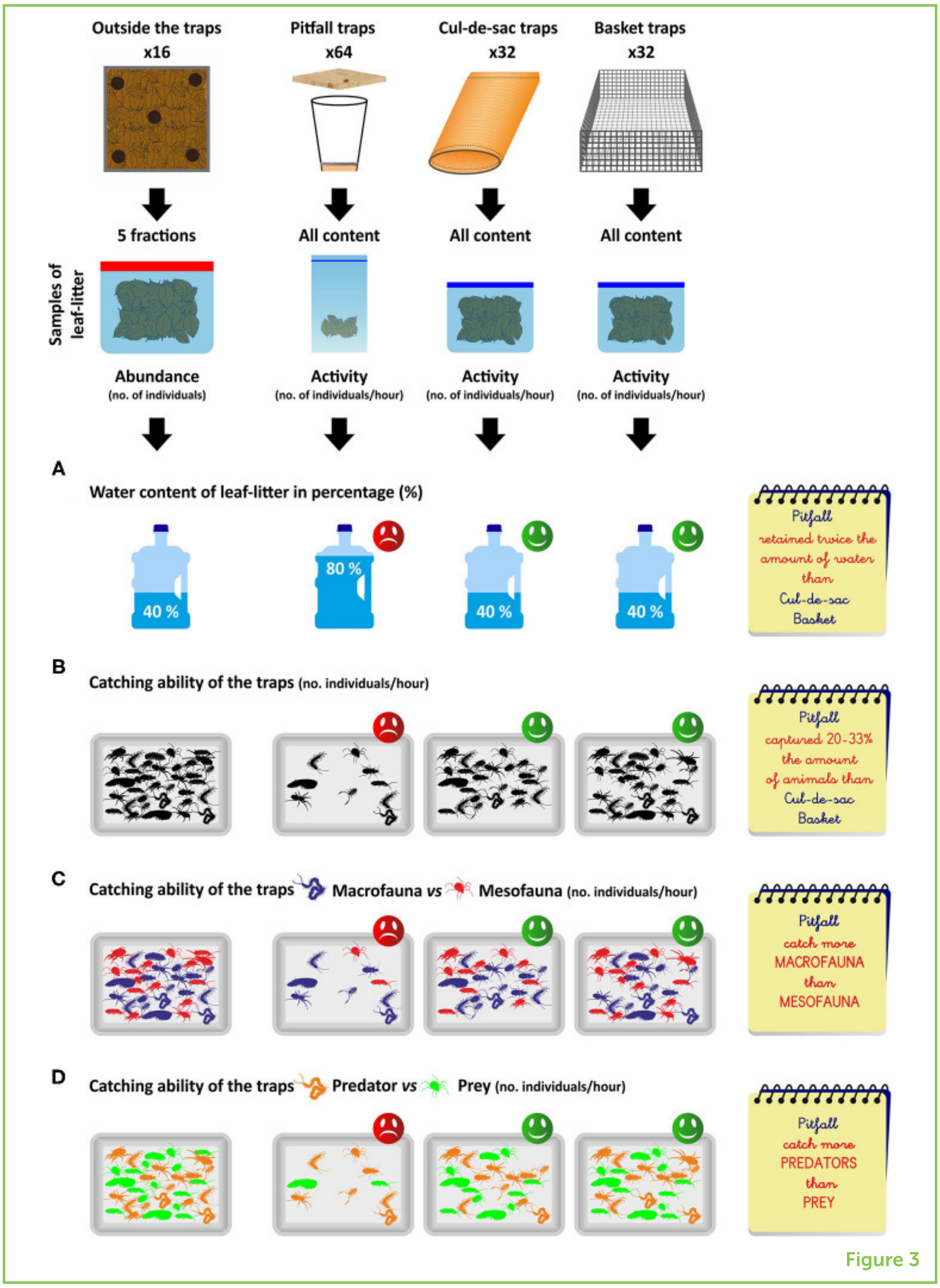

Figure 3

What type of trap best measures the activity of leaf-litter fauna? To estimate the natural abundance of arthropods, we collected 5 samples of leaf-litter from each mesocosm. We also collected pitfall, cul-de-sac and basket traps to estimate arthropod activity. Compared to the new traps, pitfall traps: **(A)** retained twice the amount of water as the other two traps; **(B)** captured 20–33% the amount of animals per unit of time; for example, per hour, than the new traps; **(C)** caught more macrofauna than mesofauna; and **(D)** caught more predators than prey. This told us that the new traps are better measuring the activity of soil arthropods (photographs and some drawings were reused from the Original Source Article).

traps captured more macrofauna than mesofauna and more predators than prey. This means that the predators that fell into the pitfall traps could have eaten some of the smaller fauna before we collected the traps (Figures 3C,D). Therefore, we concluded that cul-de-sac and basket traps performed much better than pitfall traps.

WHY DO THESE NEW TRAPS MATTER?

Our new cul-de-sac and basket traps are promising tools for soil ecologists, since they perform much better than pitfall traps, which have been widely used to assess abundances over the last century. These new traps will help scientists to more accurately estimate the activity of soil arthropods, which will improve our knowledge of terrestrial ecosystems with leaf-litter. Besides these are cheap devices that one can easily build him/herself (with fabric, wires, plastic, and/or metal meshes of different sizes, some glue, and leaf-litter), allowing one to learn more about soil animals and, therefore, about the health of ecosystems. These new traps capture animals more efficiently, minimize the predation on small ones and do not attract/repel animals because of differences in moisture between trap and the surrounding leaf-litter. In addition, these traps can not only be used in soils with a deep leaf-litter layer (like forests or jungles), but also in any ecosystem that has a well-defined leaf-litter layer, such as under shrubs in scrubs and savannas. This work is also very important because we need to understand how climate change may negatively affect food webs (feeding interactions among species) and the important functions and benefits that soil ecosystems provide. We are already working on it, through tools like these new traps and field experiments in which we modify rain or predators. Thus, we should not miss this opportunity and get to know the wonderful but hidden soil fauna. Because it is everyone's heritage and because it protects us all, now more than ever we have to study and preserve the soils and the life they host.

ACKNOWLEDGMENTS

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ORIGINAL SOURCE ARTICLE

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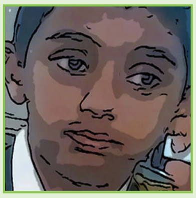

SASYAK, AGE: 12

Sasyak is a 12-year old student from India. He is an avid reader of several genres of books. He is a keen participant in quiz contests and olympiads, and is a spell bee champion. He attends football classes and enjoys cycling.

AUTHORS

DOLORES RUIZ-LUPIÓN

I started my academic career with two bachelor degrees one in Marine Sciences and another in Environmental Sciences, and later I received a Master degree in Evaluation of Global Change. Afterwards, I completed my PhD in Evolutionary Ecology at the Estación Experimental de Zonas Áridas, Consejo Superior de Investigaciones Científicas (EEZA-CSIC). My scientific interest is the study of terrestrial and aquatic food webs through field and laboratory experiments, as well as theoretical approaches using mathematical models and computer simulations. I am very enthusiastic about scientific illustration and I design figures for other researchers. *loli.ruiz@eeza.csic.es; loli.ruizlupion@gmail.com [†]Dolores Ruiz-Lupión, Laboratory of Arid Zones and Global Change, Department of Ecology, Instituto Multidisciplinar para el Estudio del Medio "Ramón Margalef" (IMEM), Universidad de Alicante (UA), Spain

MARÍA PILAR GAVÍN-CENTOL

I am a pre-doctoral student at the Estación Experimental de Zonas Áridas, Consejo Superior de Investigaciones Científicas (EEZA-CSIC). Since I was a child, animals have always amazed me, but even more since I learned that nematodes (tiny worm-shaped animals) can "wake up" after spending about 40,000 years on ice! That is why, after my studies in Biology, a master's degree and two internships, I began to investigate the mechanisms by which these and other soil animals are affected by increased droughts and how their drought-driven inactivity affects ecosystem functioning, both in natural and human-modified ecosystems.

JORDI MOYA-LARAÑO

I have been live-collecting and observing bugs in nature since I was a child. I am passionate about wilderness and I consider myself a naturalist. As a consequence I also adore my job as an evolutionary ecologist. In our group, we conduct both field and laboratory experiments to understand the role of water in soil food webs. We also perform computer simulations that recreate both ecology and evolution in food webs, and my dream is to achieve realistic simulation scenarios that match our field experiments.

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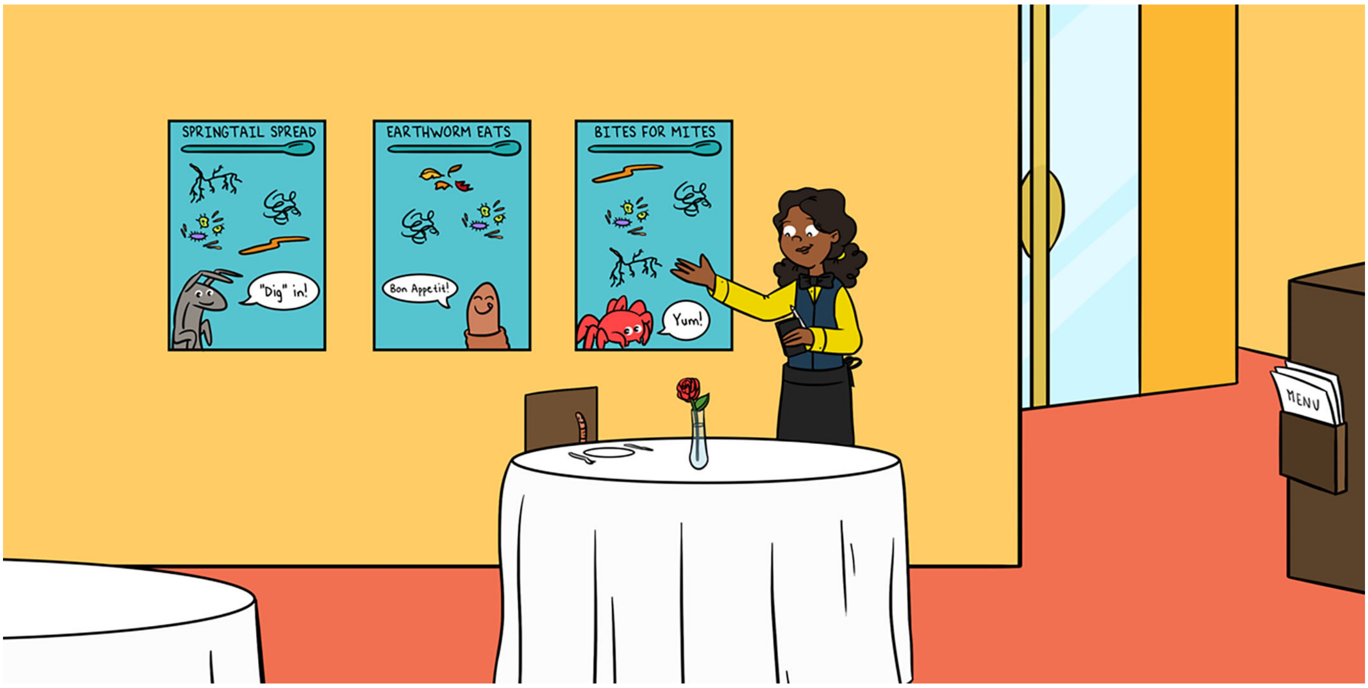

SOIL ECOLOGISTS AS DETECTIVES DISCOVERING WHO EATS WHOM OR WHAT IN THE SOIL

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[2] *Centre of Biodiversity and Sustainable Land Use, University of Göttingen, Göttingen, Germany*

YOUNG REVIEWERS:

CECÍLIA

AGE: 9

NYNKE

AGE: 12

Did you ever notice that dead leaves never accumulate in forests? For that service, we can thank a cleaning team of tiny recyclers living in the soil. Dead organisms are their food source, and they recycle them by just eating them. Knowing who eats what or whom in soils is essential to understand this recycling machinery. But that is hard to know, because many soil animals are tiny, hidden in the soil, and unable to tell us what they ate! To bypass these difficulties, soil ecologists have developed a special method. They track specific markers of bacteria, fungi, and plants in the fat of animals and hence can identify what they fed on. Some animals consume a large variety of food sources, others are more specific. Remarkably, many organisms have developed amazing strategies to feed in soil, because finding food in such a dark maze is not that easy!

WHY IS IT IMPORTANT TO UNDERSTAND WHO EATS WHOM OR WHAT IN SOILS?

Have you ever noticed that we never see huge piles of dead leaves accumulating in the forest? It is also very rare to encounter a dead animal lying on the forest floor. That should encourage us to ask the question, "who is cleaning the forest floor?" In cities, city workers remove all the dead leaves. In the forest, the work is done by a team of tiny recyclers living in the soil. For these small soil animals, dead organisms are a food source and they recycle leaves and other dead things by just eating them. When the soil animals defecate (meaning poop) they release nutrients that can be used by plants to grow. Or, small soil animals are eaten by larger animals, and that allows the bigger animals to grow. This process allows the recycling of nutrients and is essential to help plants grow. It is also very important for humans, as plants provide us with plenty of goods, such as foods like vegetables, cereals, and fruits, and also wood to build furniture and houses. Understanding who consumes what in soil is essential to understand this precious recycling machinery.

WHAT KIND OF FOOD IS IN SOIL … AND WHAT IS A SOIL FOOD WEB?

What kind of food is in the soil? If you dig in soil in the forest, you would not find a plate with spaghetti Bolognese! We are not talking about this kind of food, of course! In soil, the basic food sources are dead tissues from plants and other organisms (dead leaves or dead soil organisms of any size), and plant roots (Figure 1A). These basic food sources are mainly consumed by bacteria and fungi, which are called **primary consumers**. Fungi and bacteria themselves are the main food source for larger organisms, such as protists, nematodes, springtails, and mites (about 0.1–2 mm; Figure 1). These organisms again are eaten by larger predators (a few millimeters in size), such as centipedes and spiders (Figure 1B). Earthworms also mainly eat bacteria and fungi, but in a special way, they eat them together with soil (Figure 1B). This is a bit like if you ate the food on your plate together with the plate!

PRIMARY CONSUMER

Organisms directly consuming the dead plant material.

Although some soil animals, such as springtails or nematodes, mainly eat tiny living creatures like bacteria and fungi, they can also eat plant tissue, notably the roots or the nutritious liquid roots release. Altogether, there are many food sources in soil, ranging from plant to animal tissues and from dead to living organisms, and most soil organisms consume several of these food sources. All the links of who consumes what or whom is called a **soil food web** (Figure 1A).

SOIL FOOD WEB

All the links indicating who consume whom or what in soil.

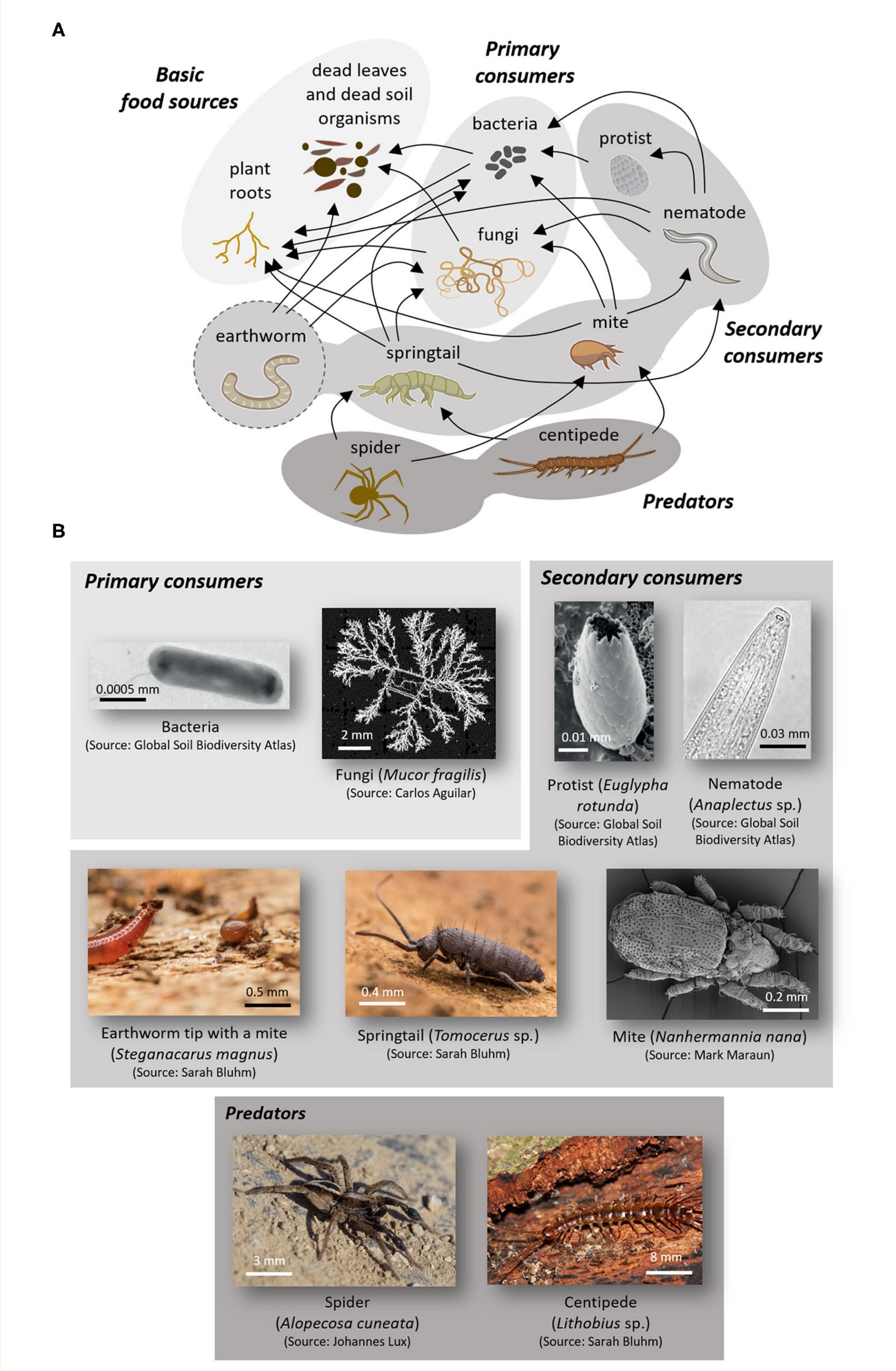

Figure 1

Organisms in a typical soil food web. **(A)** A food web contains basic food sources, like plant roots and dead organisms, as well as primary and secondary consumers and a selection of predators. Arrows indicate who consumes what or whom. Note that primary consumers are a food source for secondary consumers, which themselves are a food source for predators. **(B)** Here you can see examples of soil primary and secondary consumers as well as predators.

HOW DO WE STUDY SOIL FOOD WEBS?

Despite all the research that has happened in the last decades, researchers still know little about who consumes what or whom in soil. This lack of knowledge is because soil animals are tiny, hidden

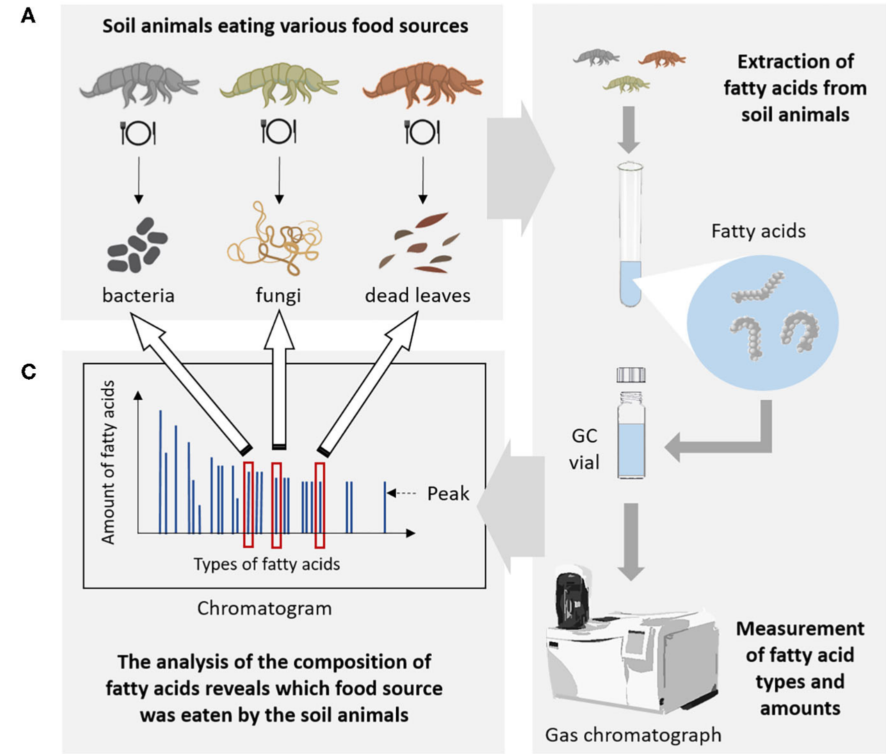

Figure 2

Figure 2

Determining what soil organisms eat by looking at fatty acid markers. **(A)** Soil animals have different types of fats in their bodies, depending on the food sources they eat, such as bacteria, fungi, or dead leaves. **(B)** The fats can be extracted (removed) from these animals in the form of fatty acids. **(C)** Those fatty acids can then be analyzed using a piece of equipment called a gas chromatograph. The data from the gas chromatograph allows researchers to identify which foods the soil organisms ate.

in the soil, and cannot tell us what they ate! To know who consumes what in the soil, researchers must act as detectives. They developed a curious method: they study the fat of soil animals (Figure 2). When you eat something, the food serves as a source of energy, so you can grow and be active. However, you cannot use all the energy at once, so your body must store it for later use. How is energy stored? When we eat more than we need at that moment, the body builds up fat as an energy-storage tissue. The fat will later be "burned" for energy when we need it. For both humans and animals, it is even easier for the body to take up and store the fat that is already in the food, instead of making new fat. Now, the trick is that not all fat is the same! Bacteria, fungi, and plants have different types of fat, and researchers can track these so-called **fatty acid markers** in the animals that consumed these food sources [1]. So, in the end, we can identify if the fat stored in an animal has come from bacteria, fungi, or plants—and thus know what they ate.

FATTY ACID MARKERS

Molecules of fat which are specific from a food source, namely bacteria or fungi.

FOOD GENERALISTS VS. FOOD SPECIALISTS

By studying the fat of soil animals, researchers discovered that many springtails preferably feed on fungi, but can also eat bacteria or plants. Because they can eat different food sources, they are considered **food generalists** [2]. This means that they are not difficult to satisfy if you invite them for dinner! Some other organisms are **food specialists** and tend to eat only one thing. For example, some nematodes prefer

FOOD GENERALIST

Soil organisms consuming many types of food resources.

FOOD SPECIALIST

Soil organisms consuming specifically one or a few types of food resources only.

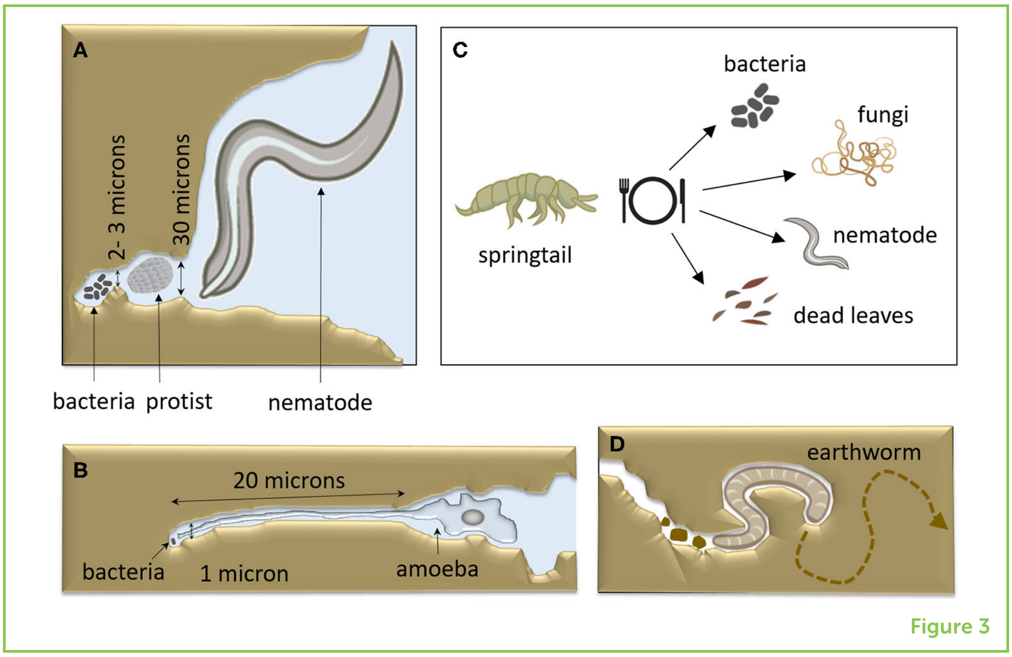

Figure 3

Animals have developed ways to deal with the difficulty of feeding in the dark soil. **(A)** Small holes in the soil provide a place for tiny soil organisms (nematodes, protists, and bacteria) to hide from the animals that eat them. **(B)** To reach its prey, an amoeba (a type of protist) can extend an arm 20 microns long and 1 micron thin to catch bacteria hidden in small soil holes. **(C)** Springtails are flexible in the food sources they consume, allowing them to have something to eat each day. **(D)** Earthworms ingest soil along with their food and digest the bacteria and fungi contained in the ingested soil. This also creates a path through the soil maze, making it easier for them to travel through it. Remember 1 micron is 1,000 times smaller than 1 mm.

eating bacteria, while others prefer fungi. There are even predatory nematodes that eat other nematodes! Each class of nematode has a different mouth shape, specific for eating a certain type of food.

WHY IS IT SO SPECIAL TO FEED IN THE SOIL?

Soil is dark. Have you ever tried to eat your dinner in the dark? It is not that easy to find where the food is. Soil animals have the same problem. Eyes do not work in the soil, so many soil animals do not even have them. By contrast, most soil animals have very fine "noses." For example, nematodes, springtails, and earthworms are very efficient at smelling their food. They can detect the location of food and move toward it. Nematodes can "smell" bacteria up to 50 cm away and reach them in 2 weeks [3]. This is a considerable distance for a nematode, as these little worms are usually only a few hundred microns long (1 micron= 0.001 mm; for comparison, the width of a human hair is 100 microns). This would be like humans being able to smell food from about 70 km away!

Soil is not only dark, it is also a maze, through which soil organisms cannot freely move. Soil is like a sponge with larger holes and smaller holes. The smaller organisms, such as the bacteria, typically measure 1–2 microns and can "hide" in small holes. For example, we know that protists (Figure 1) cannot reach bacterial prey if the bacteria are located in holes smaller than 2–3 microns [4] (Figure 3A). The same applies to nematodes, which cannot eat bacteria located in holes with openings smaller than 30 microns [4] (Figure 3A). The smaller the holes in soil, the more the bacteria can hide in them and avoid being caught and eaten by predators. But predators have developed strategies to feed despite these problems. For example, amoebae (the plural of "amoeba") are protists with soft bodies that can adopt any shape (Figure 3B). Amoebae can extend a very thin and long "arm" into small soil holes to catch hidden bacteria [5]. Springtails have a different strategy: they are simply not very picky about the food sources they consume—they are food generalists. They can eat bacteria and fungi, but also dead leaves and nematodes (Figure 3C). Depending on what is available in the small holes of the soil they are crawling through, they eat one food source or another. This flexibility helps them to have something to eat every day. Earthworms are less affected by the difficulties of accessing food in the soil. These animals directly ingest soil, enabling them to search for and access food easily in the soil maze (Figure 3D). Moreover, they can digest bacteria and fungi, as well as dead plant material that is ingested with the soil. When earthworms poop, the undigested leftovers typically form small bowls of soil.

A NEW LOOK INTO FEEDING IN A DARK MAZE

Feeding in soil is like finding food in a dark maze. To understand who eats whom in the soil darkness below our feet, soil ecologists have to act as real detectives and using all sorts of complicated techniques, either in the forest or in the laboratory. Now that you know what it is like to feed in soil, you will never look at soil animals in the same way!

ACKNOWLEDGMENTS

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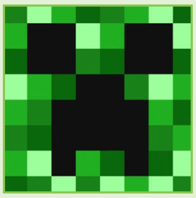
YOUNG REVIEWERS

CECÍLIA, AGE: 9
Cecília is a bright young lady that loves to play chess and is very curious about all kind of random things. She just wants to know how everything works and likes to later show off all the facts that her brain collected.



NYNKE, AGE: 12
Hi, my name is Nynke.

AUTHORS

AMANDINE ERKTAN
I am a post-doc at the University of Göttingen in Germany. I am interested in understanding how living organisms shape the soil structure, and vice-versa. I first worked on plant roots and studied how they structure the soil. I quickly realized that roots are not the only engineers of the soil. There are countless microbes and animals in the soil and their roles are crucial to determining the soil structure. I am now acquiring new skills studying soil animals and hope to shed light on how plant roots, microbes and soil animals interact in the soil matrix. *aerktan@gwdg.de

MELANIE M. POLLIERER

I am a post-doc at the University of Göttingen, Germany. My main interest concerns soil animal food webs. Since it is hard to observe what soil animals really eat, I use indirect methods to find out more. In my Ph.D. thesis, I analyzed fatty acids in soil animals and followed the fate of labeled carbon from plants to animals. Now, I use another new method: I analyze stable forms of carbon and nitrogen in amino acids, allowing even more detailed insights into the diet of consumers.

STEFAN SCHEU

While studying biology in Tübingen and Göttingen between 1979 and 1986, I was fascinated by the enormous diversity and important role of soil invertebrates. Ever since, I have investigated the structure and functioning of soil animal communities, first during my Ph.D. at the University of Göttingen and later as a post-doc in Calgary and Göttingen. In 1997, I established my own research group as Professor of Zoology and Ecology at Darmstadt University of Technology, and in 2008 back at the University of Göttingen as Chair of Animal Ecology. Here, we investigate the structure, function, and evolution of soil animal species and communities.

frontiers FOR YOUNG MINDS

BIODIVERSITY
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LOOKING FOR EARTHWORMS IN DEADWOOD

Frank Ashwood[1*], Elena I. Vanguelova[1], Sue Benham[1] and Kevin R. Butt[2]

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[2] Earthworm Research Group, University of Central Lancashire, Preston, United Kingdom

YOUNG REVIEWER:

MARIA

AGE: 14

Fallen branches, logs, and tree stumps are a valuable habitat in forests, giving food and shelter to many organisms, including earthworms. Unfortunately, deadwood is often removed from forests because its value is not fully appreciated. We wanted to overcome this by developing a sampling method for earthworms living in deadwood in forests. By testing our new sampling method in oak forests, we found that including deadwood in earthworm surveys improves our knowledge of forest earthworm populations. We also found a greater number of young earthworms in deadwood, where conditions were warmer and moister than in the soil. By surveying deadwood for invertebrates, such as earthworms, we can better understand the important role that deadwood in forests plays in maintaining biodiversity.

EARTHWORMS IN TREES?

Earthworms are important for maintaining healthy ecosystems: their burrows help air and water enter soil, and they break down dead

Figure 1

Figure 1

An epigeic earthworm found in deadwood. The pale band (or "saddle") toward the head end (to the right) tells us this is an adult earthworm.

plant material, recycling its nutrients back into the environment. But earthworms do not just live in the ground, they can be found in all sorts of unexpected places—even up in trees and inside logs! Logs and fallen trees are called **deadwood** and are an important habitat for many different types of earthworm, giving them shelter and food (Figure 1). There are three main groups of earthworms: **epigeic** (living above-ground), **endogeic** (shallow-burrowing in soil), and **anecic** (deep-burrowing in soil) [1]. Earthworm populations in a forest can affect how fast deadwood decays, with different groups and species more important at different stages [2]. This decaying wood is a source of nutrients and **organic matter** (organic compounds that are the remains of organisms, such as plants), and its decomposition is important for maintaining healthy forest soils.

DEADWOOD IS AN IMPORTANT BUT UNDER-STUDIED HABITAT

Despite being a key source of soil organic matter and an important habitat, deadwood is often removed from forests when trees are cut down for timber and firewood, putting many species of animals at risk of going extinct [3]. Protecting forest **biodiversity** is important. Biodiversity is the variety of life in a habitat, and we depend on the services that healthy and highly biodiverse forests provide, such as storing carbon and protecting soil. The more information we can learn about the amount of biodiversity present in deadwood, the better we can understand the importance of keeping it in forests. We do not have a full idea of which earthworms live inside deadwood, because we do not currently have a scientific way of looking for them there. Earthworm surveys normally only look in the soil and may miss earthworms living in other places. By developing a way to survey deadwood for earthworms, we can learn more about earthworm lifecycles and perhaps show how important it is to keep deadwood

DEADWOOD

In forests, woody material that is no longer living, including fallen branches, logs, stumps, and standing dead trees.

EPIGEIC

Earthworms that live on the surface of the soil in organic matter-rich habitats, like leaf litter.

ENDOGEIC

Earthworms that make shallow, horizontal burrows, and feed on the soil.

ANECIC

Earthworms that build deep vertical burrows and feed on organic material on the soil surface.

ORGANIC MATTER

Matter composed of organic compounds that have come from the remains of organisms, such as plants and animals.

BIODIVERSITY

The variety of life in a habitat, a high level of which is usually desirable.

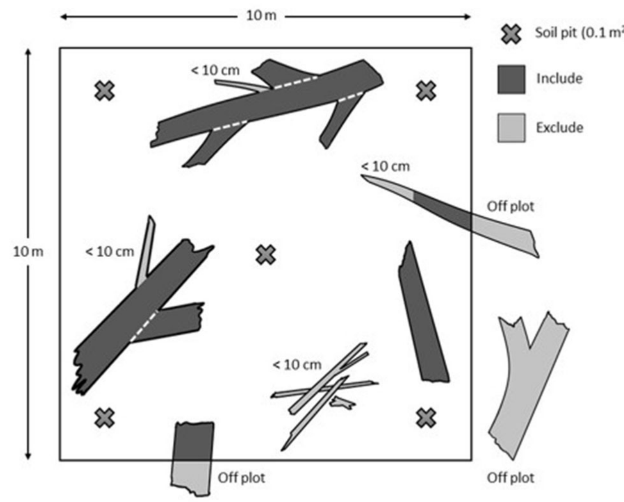

Figure 2

Figure 2

Earthworm sampling in an oak forest plot. Dashed white lines within deadwood indicate sections divided into separate pieces. All deadwood within the plot and >10 cm in diameter (dark gray) was measured for total length and midpoint diameter, and five randomly selected pieces of mid- to late decay were sampled for earthworms. All deadwood <10 cm in diameter or outside the plot was excluded from the survey (light gray). Five 0.1 m^2 soil pits (indicated by crosses) were sampled for soil-dwelling earthworms.

in forests. The main aim of our project was to develop and test a method for surveying deadwood for earthworms. To test whether our method worked, we compared our deadwood results with those from a standard soil-based earthworm survey.

SURVEYING DEADWOOD FOR EARTHWORMS

To try out our method, we visited 12 forests of common oak trees (*Quercus robur*) in Surrey, UK, and in each forest, we marked out a 10 × 10 m square plot (Figure 2). In each plot, the total volume of deadwood was recorded and we tried to determine which tree species the deadwood belonged to. We also estimated how decayed the deadwood was, based on a 1-to-5 ranking system, in which 1 is least decayed (freshly fallen) and 5 is most decayed (deadwood completely broken down into the soil). Since small branches have very few earthworms in them, we selected five pieces of deadwood that were larger than 10 cm in diameter, and of mid- to late-decay stage (loose bark and wood beginning to soften). We analyzed the deadwood by placing it onto a sheet and measuring its length and diameter, so we could calculate its volume. Deadwood temperature was measured by inserting a digital kitchen thermometer beneath any loose bark. We then removed any moss and loose bark and inspected it for earthworms, and the remaining wood was taken apart and inspected. Once all earthworms were collected, the deadwood was then returned to its original location, with moss and loose bark replaced as best possible.

SURVEYING SOIL FOR EARTHWORMS

We also sampled the soil for earthworms using a standard method. This involved digging soil pits (30 × 30 cm wide and 10 cm deep)

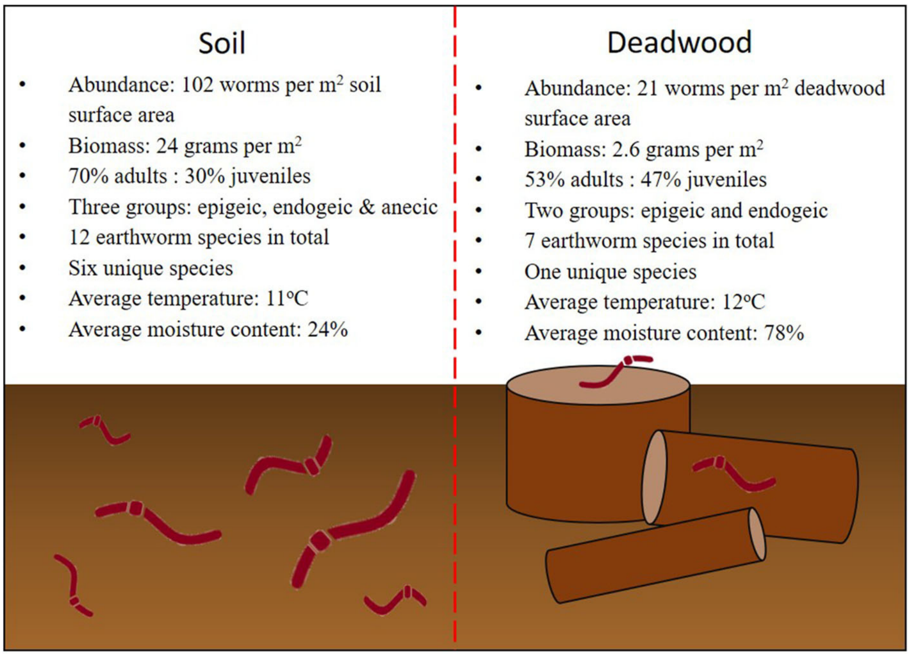

Figure 3

Figure 3

Summary of the results from the earthworm surveys of soil and deadwood in oak forests.

at five locations in the plot (Figure 2). First, we placed the soil onto a sheet to hand-sort for earthworms, and then we poured 5 L of mustard water (25 g of table mustard powder mixed with 5 L of water) into each soil pit, to extract deep-burrowing earthworms, some of which can dig 2 m deep! This mustard powder irritates the earthworms' skin and encourages them to come up to the surface. Soil moisture and temperature measurements were also taken. Once all earthworms were collected, the soil was placed back into the holes. All earthworms from deadwood and soil were preserved in alcohol and were weighed, then each species was identified using a microscope and an earthworm identification guide [4].

WHAT DID THE SURVEYS REVEAL?

Overall, we found a total of 1,012 earthworms and 13 different earthworm species. The number of earthworm species was different between soil and deadwood, with seven species found in deadwood, and twelve species found in soil (Figure 3). One species, *Eisenia fetida*, was found only within deadwood. This is an epigeic earthworm that is often found in compost heaps. Six species were found only in the soil: two epigeic, three endogeic, and one anecic species. All other earthworm species were found in both deadwood and soil. Many more juvenile (young) earthworms were found in deadwood than soil, and deadwood was much moister than the soil and warmer by around 1°C.

ABUNDANCE

The number of a species or community in an ecosystem, such as the number of individuals per area.

BIOMASS

The mass of an organism or community of organisms in an area or ecosystem.

Total earthworm **abundance** (number of individuals) and **biomass** (mass of all earthworms) was much greater in soil than in deadwood (Figure 3). On average, the deadwood surveys contributed an additional 81 earthworms and 209 g earthworm biomass per 10 m^2 forest plot.

THE BENEFITS OF DEADWOOD SURVEYS

By adding deadwood to our forest earthworm surveys, we found both a greater abundance of earthworms and more earthworm species than we would have found by doing only soil surveys. There was a much greater proportion of juvenile earthworms inside deadwood, where temperature and moisture conditions were more favorable. Earthworms are very sensitive to temperature and moisture extremes, so being protected in decaying wood allows earthworms to stay active throughout the year, especially during summer drought and freezing winter conditions. Removing deadwood from forests may therefore have a negative effect on the many earthworm species that rely on it for shelter and food. Based on our results, we can say that forest-based earthworm research that does not include deadwood is likely to underestimate earthworm populations, and forests without deadwood will have fewer earthworms. With more development, our survey method could be used for studying other important invertebrates that live in deadwood, such as insects [3]. Hopefully we can use this information to improve forest management practices, to make sure that deadwood is left in place to protect forest biodiversity.

ORIGINAL SOURCE ARTICLE

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YOUNG REVIEWER

MARIA, AGE: 14

Hi, my name is Maria and I am from Poland. I absolutely love biology, especially solving tasks in genetics and cell metabolism. In my spare time I enjoy reading books and playing with my cat Roxi. I am keen on ballet. I train regularly at the Dance Conservatory. I really love it!

AUTHORS

FRANK ASHWOOD

A passion for nature encouraged me to study Biology at university, where I volunteered for research projects on invertebrate ecology in Scotland and Mexico. After working as an environmental consultant for a few years, I went back to Uni and did a Ph.D. studying earthworms on reclaimed landfill sites. I now have a great job as a soil ecologist for Forest Research, where I study soil biodiversity in UK woodlands. In my spare time I am a soil biology tutor and do macrophotography (taking photos of the tiny animals living in soil). *francis.ashwood@forestresearch.gov.uk

ELENA I. VANGUELOVA

I have always been an outdoorsy person, spending lots of time in the mountains in Bulgaria as a child. At University I studied Forest Engineering but was not entirely happy until I did my Ph.D. in atmospheric pollution impacts on forest ecosystems. Then I realized that what I really like is the environmental side of forestry and soil. I work at Forest Research as a biogeochemist (a little bit of everything:

biology, geology, and chemistry), and investigate the effects of afforestation, forest management, and environmental changes on forest soil biogeochemistry.

SUE BENHAM

I have always loved nature and spent my childhood climbing trees and watching the natural world in the woods around my home. Now I am a scientist at Forest Research and I get paid to do the same thing! I spend my time working to understand how our forests grow and what effect the changing climate is having on their condition. For this I study all aspects of a tree's environment, from the soil around its roots to the air around its leaves and the animals that rely on it.

KEVIN R. BUTT

Kevin is an ecologist at the University of Central Lancashire. He has studied earthworms for more than 30 years and is interested in how these ecosystem engineers are able to assist humankind through their everyday activities, such as burrowing and eating organic matter. He has studied earthworms throughout Britain and undertaken research across Europe and in the USA. One of his current projects is examining the action of earthworms on Charles Darwin's estate, recreating experiments of the great scientist, whilst another is investigating giant rainworms in the mountains of Germany.

BIODIVERSITY
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THE WAY SOIL ORGANISMS LOOK CAN HELP US UNDERSTAND THEIR IMPORTANCE

***Pierre Ganault*[1*]*, Léa Beaumelle*[2] *and Apolline Auclerc*[3]**

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[2] *INRAE, UMR SAVE, Bordeaux, France*

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YOUNG REVIEWER:

GIULIA

AGE: 13

There is a multitude of life forms on our planet. This is especially true under our feet, in the soil. Earthworms, spiders, and millipedes are only a few examples of the vast number of soil organisms. Once you look what lives in soils, you realize the tremendous diversity of shapes and colors. But what if we take the time to describe all their characteristics: color, size, shape, number of legs, type of wings, lifespan, and climate preferences? All these characteristics, called traits, help us to understand what types of organisms can be found in a particular ecosystem, what they feed on, and how far they can travel. Scientists use this information to understand the different roles of organisms in soils, and to restore degraded soils. Analyzing traits can reveal the importance of soil organisms and the fundamental roles they play for human societies.

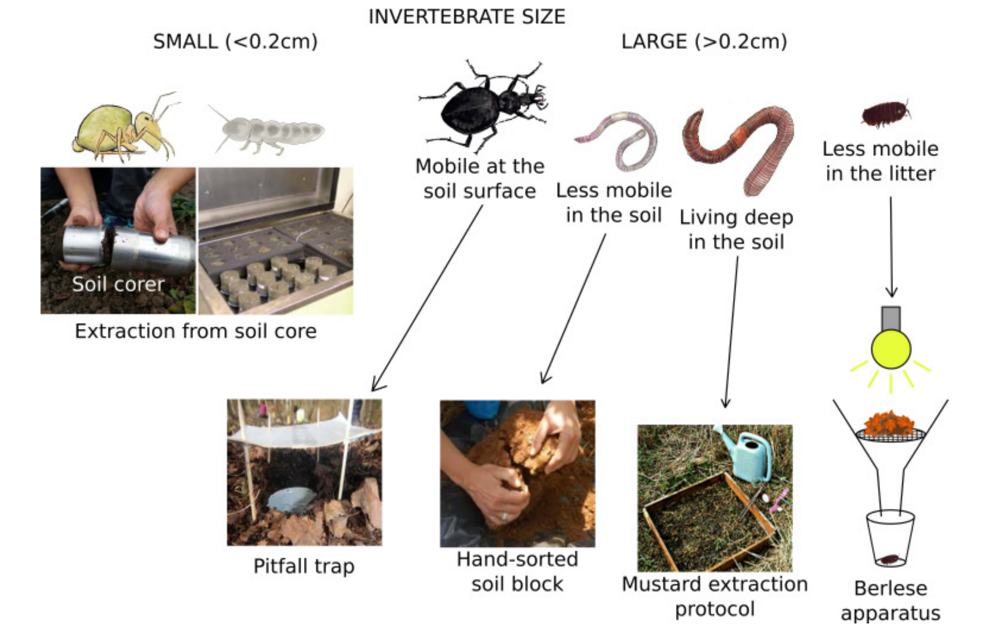


Figure 1

Figure 1

Methods of sampling and studying soil invertebrates. Small organisms are extracted from a small soil core by drying the soil and collecting the individuals that fall out of the sample. Large, fast-moving organisms living in leaf litter are collected when they fall into pitfall traps. Less-mobile organisms are extracted from a soil block of soil with a shovel and then sorted by hand. Earthworms living deep in the soil are extracted by pouring a mustard solution into their burrows. Less-mobile organisms living in the leaf litter can be isolated using a Berlese apparatus, which dries the litter and traps the organisms in a jar (Drawing credits: www.lesbullesdemo.fr. Picture credits: Apolline Auclerc, EcoBioDiv lab).

INVERTEBRATE

A small animals with no internal skeleton, such as insects, worms, or molluscs.

SOIL BIODIVERSITY

The variety of life forms in soils. It can be measured by the number of species, traits, or genes of these organisms.

SOIL ECOLOGIST

A scientist investigating soil organisms, their interactions with their environment, and their role in soil functioning.

THE SOIL: A WONDERFUL BUT POORLY KNOWN WORLD

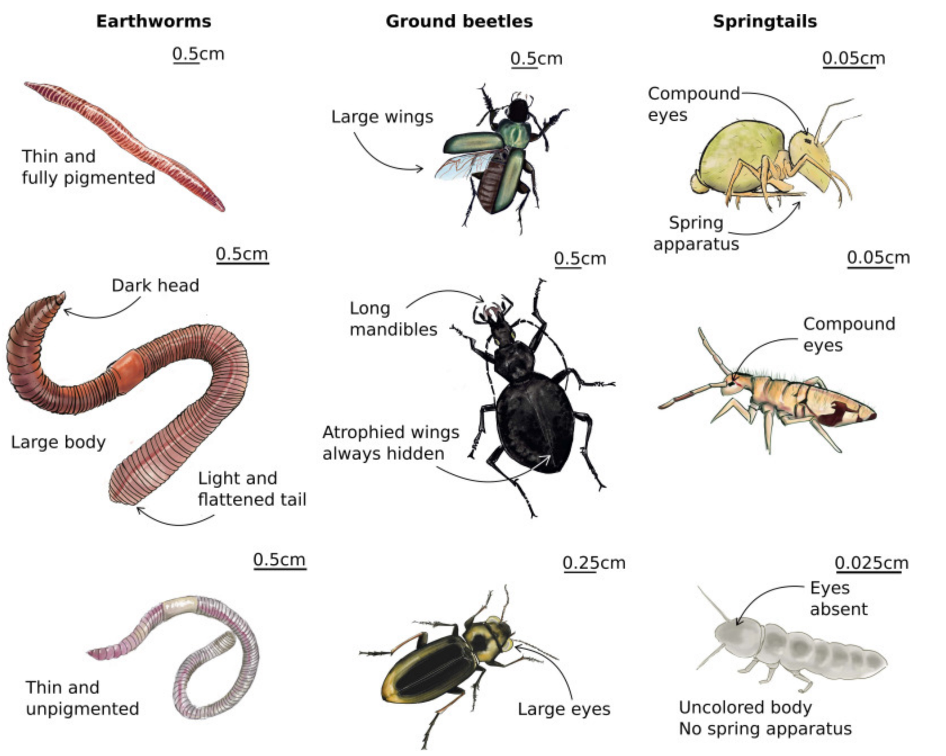
Under our feet, millions of organisms live in the soil [1]. These organisms span from the microscopic (called microorganisms) to **invertebrate** organisms (such as earthworms) more than 1-m long. The variety of organisms in the soil is called **soil biodiversity**. Biodiversity means the variations in all the life forms on the planet.

Soil ecologists are scientists who study the diversity of soil organisms. They usually sample the soil organisms living in various places, like tropical rainforests or agricultural fields. They use shovels, traps, or corers to remove soil samples, depending on whether the organisms of interest live within the soil or on its surface (Figure 1). Then, the scientists catch the organisms they can see in their samples by hand or with tweezers. To catch the smallest soil invertebrates, soil ecologists often use a technique called the **Berlese method**. In the laboratory, they place the soil sample in a funnel, with a heating lamp above the sample and a jar below it. The light and heat make the tiny organisms go down through the funnel into the jar. After a few days, scientist can study the organisms in the jar.

When all the soil organisms are collected, the long and meticulous work starts. Soil scientists count and closely observe each individual organism, to identify which **species** it belongs to. To do so, they use various types of microscopes along with identification keys and books. The total number of species found in one particular ecosystem represents that ecosystem's biodiversity. Soil scientists have a lot of work to do, because soils are among the most diverse and highly

Figure 2

Differences in morphological traits between nine species of soil invertebrates belonging to three groups: earthworms, ground beetles, and springtails (Drawing credits: www.lesbullesdemo.fr).



BERLESE METHOD

A procedure to extract small-size organism from leaf-litter and soil sample by drying it and collecting organisms that migrate through the sample and fall in a jar.

SPECIES

Individual organisms that belong to the same species can produce fertile offspring. It is the most commonly used unit to describe life on Earth. All human beings belong to the same species but there are many, many species of soil organisms.

TRAIT

Any characteristic that can be measured on an individual to describe its shape, movement capacity, diet, behavior, or reproduction strategy.

human-impacted ecosystems on Earth. In addition, many soils in the world have not yet been studied, so many species of soil organisms have still not been discovered.

SOIL ORGANISMS ARE EXTREMELY DIVERSE

Soil biodiversity is so large that it is almost impossible to describe the **traits** of all soil organisms at once. We will give you an idea of soil diversity by describing the appearance and behaviors of three well-studied types of soil organisms: earthworms, springtails, and ground beetles (Figure 2).

Body Size

An important structural difference between earthworms, springtails, and ground beetles, and between species within these groups, is their body size. Size is an example of a morphological trait. The smallest earthworm measures several cm long, while the largest, found in tropical forests, can be 2 m long. In Europe, ground beetles measure between 2 mm and 8 cm from the top of the head to the last segment of the abdomen. Springtails are much smaller, with an average body size of only 2 mm, but their size varies depending on where they live. Some springtail species living in dead leaves are bigger than other species that live deeper in the soil.

Movement

To find a habitat with enough food, other organisms with which to reproduce, and a low number of predators, soil organisms have developed numerous techniques for moving, both at the surface and within the soil. Earthworms do not have legs, but some species have strong muscles and small hairs that they use to burrow between soil particles. With their six legs, ground beetles can run on the soil surface to catch their prey. Many species of ground beetles have wings, allowing them to rapidly escape from a predator or other disturbance, or to move to a place where they can find more prey or mates. Springtails also move on their six legs, but thanks to a special appendage that acts like a spring, some springtails can jump several centimeters into the air to escape predators!

Color

Soil organisms can be colorful. Some earthworms that live in the few first centimeters of soil, in the dead leaves, or in compost or manure are reddish-brown, which enables them to camouflage from their predators against orange-brown dead leaves, but which also protects them from **UV light** [2]. Other earthworms live deeper in the soil and often have pale colors, such as pale pink, gray, or green. In the dark soil, pigmentation is not necessary because UV light does not penetrate. Still other earthworms live mostly in the soil, but they put their heads out of the soil to feed on dead leaves; consequently, only their heads are pigmented. Springtails show almost the same color patterns as earthworms: pigmented species live on top of the soil and unpigmented ones live within the soil [3]. Finally, ground beetles can have many wonderful color patterns, especially those of the *Carabus* genus. The vivid colors might discourage their bird predators or might help them to camouflage in their environments.

UV LIGHT

Part of the sun's rays that are invisible to the naked eye and can cause sunburn.

Mouth Types

Another stinking difference between our three groups is their mouth type. Ground beetles have strong mandibles (jaws) that can have different shapes and sizes depending on what they eat the most. For example, some species have very long mandibles, projected forward, to reach inside the shells of snails. Springtails have small mouths that allow them to eat fungi growing on leaves and small pieces of the leaves themselves, creating beautiful, skeletonized dead leaves. Earthworms do not have mandibles, but their muscular stomachs are strong enough to crush the soil and the leaves they eat.

THE TRAITS OF SOIL ORGANISMS ARE CLUES TO THEIR IMPORTANT ROLES

Careful observations of the traits of soil organisms can tell soil ecologists a lot about what the organisms eat, where they live, and how they interact with their environments (Figure 3). The actions of soil

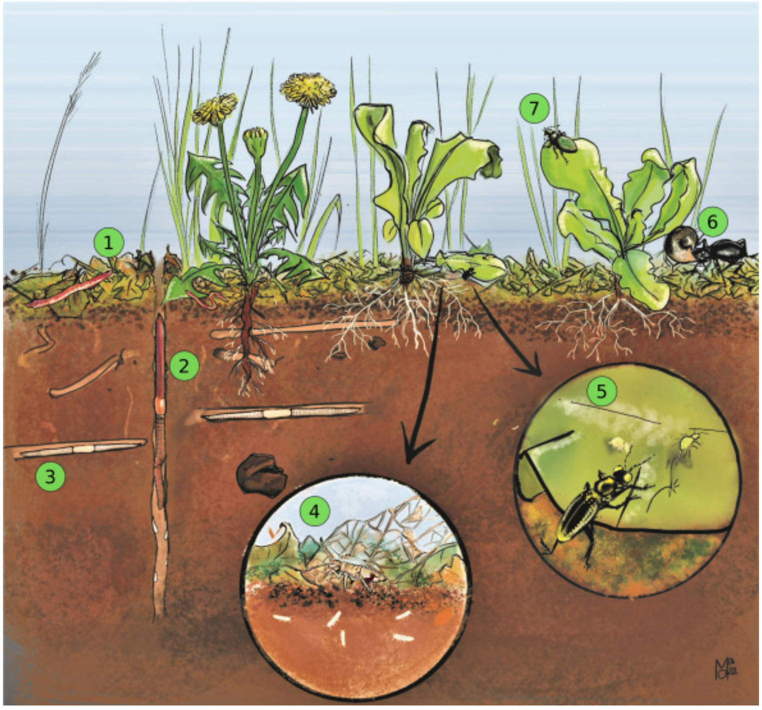


Figure 3

Figure 3

Soil organisms in action. (1) Earthworm living and feeding on dead leaves. (2) Earthworm reaching the soil surface through its large, deep burrow. (3) Earthworms living in the soil and digging many burrows. (4) Different springtail species transforming dead leaves into fecal pellets. (5) Springtail escaping from a predator by jumping with its spring-like appendage. (6) Ground beetle feeding on a snail. (7) Ground beetle ready to fly (Drawing credits: www.lesbullesdemo.fr).

organisms are extremely important for maintaining healthy soils. These organisms can change the physical organization of soil by creating burrows, can add nutrients to the soil through the breakdown of dead leaves, and can help to control the populations of other soil organisms, [4]. Let us look at the important roles played by our three example organisms.

Earthworms play a crucial role in maintaining healthy soils by their intense burrowing activity. The earthworm species that live in the soil move through it, eating the food they find there and mixing the soil particles with pieces of dead leaves. As they move, they create a lot of burrows through which air and water can circulate more easily [5], helping other soil organisms to drink and breathe, and helping plant roots to grow. Some large earthworms create long, wide, vertical burrows (very much like chimneys). Others make thinner burrows, but still contribute strongly to mixing the soil. Earthworms therefore are quite important to reduce flooding and soil erosion, and to improve soil health.

Springtails also play crucial roles in soils, especially by recycling nutrients from dead leaves, which helps with plant growth. In some cases, springtails can reach densities of 10–100,000 individuals per m^2! They can eat very large amounts of leaf litter and microorganisms (like fungi and bacteria). After eating, they produce many small fecal pellets composed of very tiny pieces of dead leaves mixed with some water. Fecal pellets are the perfect meal for microorganisms, which will continue to transform the dead leaves into nutrients that the plants can use. This nutrient recycling performed by springtails and microorganisms is extremely important for ecosystems and plant growth.

Ground beetles have diverse diets, but can be predators feeding on a wide range of prey, from small aphids to larger snails. Ground beetle species are specialized for the prey that they eat; for instance, the species *Cychrus caraboides* only feeds on snails. Some ground beetles catch tiny springtails, thanks to their well-developed eyes (Figure 3). Ground beetles are important for regulating the populations of other animals. For example, in crops, they feed on the pests that would otherwise damage the crop plants. Farmers can therefore use ground beetles instead of chemicals to fight against pests. This is called biological control, because it uses natural predator-prey interactions between organisms to control pests. It is important to maintain a high diversity of ground beetles in an ecosystem because not all species feed on the same prey. Ground beetles vary in body size and mostly eat prey that is smaller than they are. Therefore, a high diversity of ground beetle species allows a better regulation of pests [6].

Body size, mouth type and size, hunting strategies, and type of prey are important traits that soil ecologists commonly consider to better understand the relationships between soil invertebrates and their environments.

CONCLUSION

Soil organisms are incredibly diverse in shape and behavior. Soil ecologists explore the wonderful world of the soil and have the chance to discover new species and new traits. By looking at the characteristics of the species they find, soil scientists can better understand the interactions between organisms and ecosystems. Taken together, the numerous roles played by the wide variety of soil organisms are complementary and fundamental to maintaining healthy soils. It is thus very important for us to maintain and conserve soil biodiversity, which is facing the increasing impacts of human activities, such as intensive agriculture and climate change. Raising public awareness of the importance of soil organisms and improving our knowledge of soil biodiversity will be key to decreasing our impacts on the amazing ecosystems under our feet.

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YOUNG REVIEWER

GIULIA, AGE: 13

I am Giulia. I am 13 years old. I like going to school and my favorite subject is English. In my free time, I love playing with my dog, playing tennis, and going to ride horse. In the summer, I like playing in my little swimming pool with my friends and going around my city, all together, by bike. Instead, in the winter, I like very much skiing with my parents and our neighbors.

AUTHORS

PIERRE GANAULT

At each walk in nature, I cannot help myself from flipping logs and rocks over or searching into the dead leaves to see what wonderful animal I will find hiding there. This curiosity led me to study soil biodiversity and do a Ph.D. on the response of tree species mixture for soil invertebrates and the role of these animals for soil processes. I also work with associations to bridge the gap between scientist and citizen so we can work all together to study, better understand and protect the creatures living in the soil. *pierre.ganault@gmail.com

LÉA BEAUMELLE

I am a post-doc at the French National Institute for Agriculture of Bordeaux. My research aims to better understand the impacts of human activities on soil biodiversity and functioning. During my Ph.D. in Versailles, I was studying the response of earthworms to heavy metal pollution. I have expanded my research during my post-docs in France and Germany, by investigating the effects of multiple pollutants, the response of entire soil communities, and the consequences of biodiversity changes for ecosystem processes.

APOLLINE AUCLERC

I am an Assistant Professor in soil ecology, biology at University of Lorraine in France, Nancy. My research is focused on understanding how the urban and industrial soil ecosystems can host a surprising high level of biodiversity by assessing how invertebrates, such as earthworms, insects, spiders, millipedes... are adapted to the special features of these human-impacted soils. I also develop tools to help citizens to raise their awareness on the soil quality and its unknown biodiversity.

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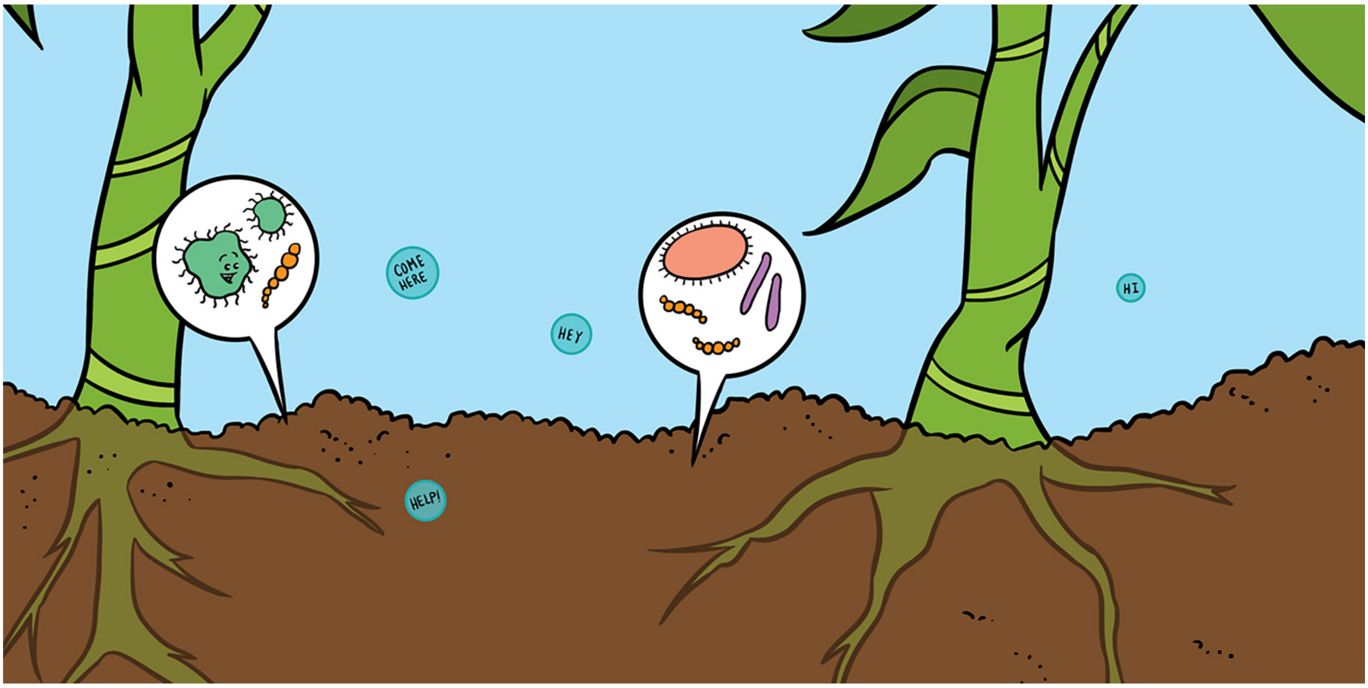

THE FASCINATING WORLD OF BELOWGROUND COMMUNICATION

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YOUNG REVIEWER:

SHASHI PREETHAM

AGE: 13

If you are a microbe in soil, how do you say something to your neighbors? Well, speaking English, French, or Italian would not do you any good underground. Instead, you would have to use molecules as words! Soil microbes like bacteria and fungi communicate with each other and with other organisms, such as animals or plants, by producing different kinds of molecules. Many organisms use these molecules as chemical words. These molecules can be volatile molecules, which means that they are like gases, just like the air. They can travel easily through small pockets of air in the soil and can also travel really far. It is like long-distance communication. Other molecules are soluble so they can dissolve in water, allowing the communication between organisms close to each other. The organisms that receive this communication can respond in different ways, such as by growing faster or producing other molecules in response. In this article, we will explore the exciting and mysterious world of belowground chemical communication and its role in the interactions occurring between microbes and plants.

LIFE IN THE SOIL

ECOSYSTEM

The set of different organisms (plants, animals, and microbes) that interact with the non-living matter in a specific area.

The soil is one of the most fascinating and complex **ecosystems** on Earth. It is not only the outer surface of our planet where plants grow, but it is also a spectacular and hidden world where many kinds of organisms live. The soil is composed of irregular pieces of rocks, small air-pores, and organic matter (dead plants and animals). This environment is a wonderful place for microbes, insects, and plants to live. Can you believe that soil is so full of life? Depending on the soil characteristics (size of the rocks, types of food, amount of water, etc.), different organisms can live in it. These different organisms build a specific community, which is a unique set of different organisms living together.

RHIZOSPHERE

The portion of the soil surrounding the roots where plants and microbes talk to each other by using molecules.

Do you know what soil microbes are? They are very tiny organisms that live attached to soil particles or other living things. There are fungi that have a shape similar to very thin roots, so that they can touch and exchange information with their neighbors. There are also bacteria, which are organisms that consist of a single cell that you can usually see only by using a microscope. If these organisms live in the **rhizosphere** (the portion of soil surrounding the plant roots), they are called rhizosphere microbes. They can also live on the root surface or inside the roots [1]. In the rhizosphere, you can find beneficial (good) microbes, which help plants to survive and grow, or harmful (bad) microbes, which attack plants and make them sick.

HOW DO SOIL MICROBES AND PLANTS COMMUNICATE?

CHEMICAL COMMUNICATION

The communication that occurs between two or more different organisms (plants, animals, and microbes) by using molecules.

SOLUBLE

A substance that dissolve in water, like salt and sugar.

VOLATILE

A substance that tents easily to become gas and spread in the air, like the smell of a flower.

What is particularly exciting is the ability of soil microbes to communicate amongst themselves as well as with other organisms, including plants and animals. The communication between microbes and plants has been studied by many scientists. This communication is based on the use of molecules as words, and it is called **chemical communication**. You can imagine a molecule as a group of many little balls (that we call atoms), connected to each other. These atoms are important chemical pieces, like carbon (C), hydrogen (H), oxygen (O), and nitrogen (N), that join together (like a puzzle) to form molecules like water (H_2O) or carbon dioxide (CO_2). The specific combination of atoms creates molecules that have different properties.

Soil microbes can produce many types of molecules, which can be divided into two main categories: **soluble** molecules and **volatile** molecules. Soluble molecules dissolve in water, like a sugar cube in tea, and they can be transported by water in the soil. They are used to talk with plants that grow close to the microbes. Volatile molecules, also

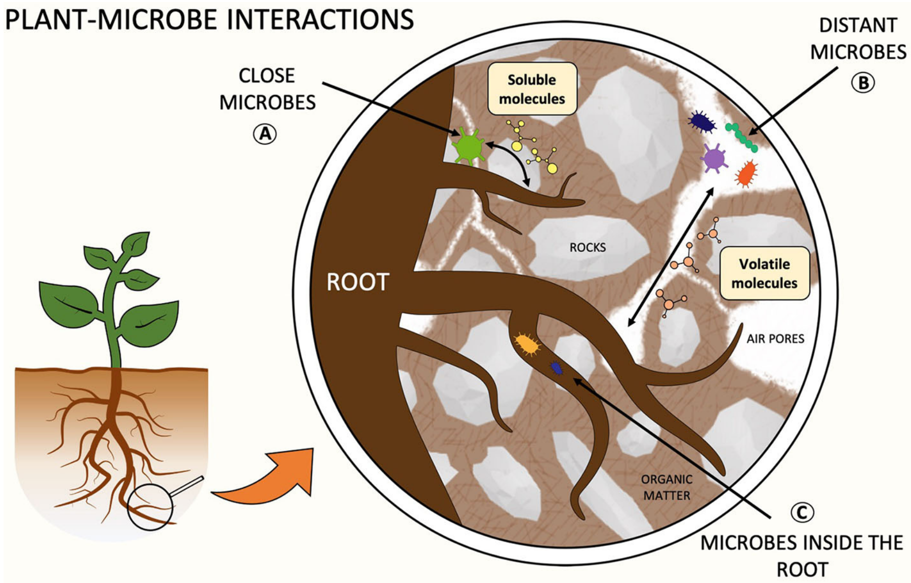

Figure 1

Plant-microbe interactions in the rhizosphere. The picture shows three types of interactions: **(A)** interactions between plants and microbes living on the root surface or near the roots, with the help of soluble molecules; **(B)** interactions between plants and microbes living far away from the roots, with the help of volatile molecules; and **(C)** interactions with microbes living inside the roots, directly in contact with root cells. These interactions take place in the soil, which is composed of rocks, air pores, and organic matter.

VOCS

The volatile organic compounds that are produced by different organisms, like plants and microbes, to communicate with each other by distance.

called **volatile organic compounds (VOCs)**, are used to communicate over long distances (Figure 1). These volatile compounds are gases, which travel easily through the air-pores of the soil. Plant roots can smell these gases, like your nose can smell a flower or freshly baked bread [1]. Chemical communication does not happen only in one direction (from the microbes to the plants), but in two directions—plants also produce molecules that can be understood by microbes.

WHAT ARE THE EFFECTS OF COMMUNICATION MOLECULES?

Here are some examples of what happens between microbes and plants when they start to talk to each other.

Plants and Microbes Help Each Other to Get Food

Many soil microbes can help plants grow, because the microbes make necessary nutrients more available for the plants. For example, a bacterium called *Rhizobium* can transform the nitrogen in the air (N_2) into a different molecule: ammonia (NH_3). This transformation is called nitrogen fixation and it happens in the soil. Nitrogen fixation is really important for plants because they need nitrogen to grow and they are only able to get NH_3 from the soil. By transforming N_2 into NH_3, *Rhizobium* helps plants to grow and makes them stronger!

What is even more interesting is that *Rhizobium* can talk with a specific group of plants, including beans and peas. But how does this dialogue work? First, the plant releases molecules called isoflavones into the rhizosphere, which can attract *Rhizobium.* The bacteria “hear” the

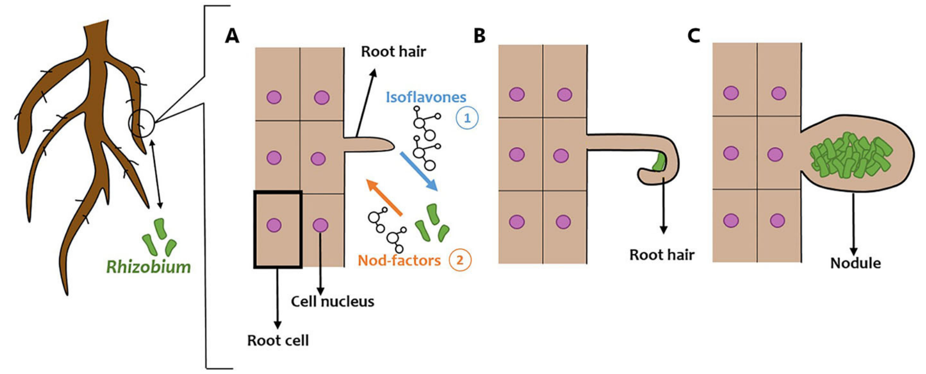

Figure 2

Figure 2

The effects of plant-*Rhizobium* interactions on root structure. **(A)** Normal root structure and the beginning of chemical communication. First, the plant produces isoflavones (1), then *Rhizobium* responds by producing nod-factors (2). **(B)** *Rhizobium* goes toward the root and sticks to a root hair, which then changes its shape to hug the bacteria so that the bacteria can enter into the root. **(C)** Formation of the root nodule, which is the space where the bacteria multiply and sugar and nitrogen are traded.

plant "talking" and go toward it. On their journey toward the plant, the *Rhizobium* start to produce other molecules, known as nod-factors, which tell the plant to create a space in the roots, called root nodule, where the *Rhizobium* can live. In exchange for a place to live and food (sugar) from the plant, the *Rhizobium* gives the plant a lot of NH_3 (Figure 2). As a result, plants that allow *Rhizobium* to live with them grow much more. For both the plant and the *Rhizobium*, living together is an advantage, because both organisms have more food to eat than when they live alone, and thus they can grow better [2].

Microbes Can Help Protect Plants From Pathogens and Pests

BIOTIC FACTORS

The living components of an environment, like plants, animals, and microbes.

Biotic factors are the living parts of an environment, such as plants, animals, and microbes (Figure 3). Biotic stress is stress felt by an organism, like a plant, that is damaged by biotic factors like bad microbes, called pathogens, or by bad insects, called pests. Good microbes can help plants to fight against pathogens and pests in two ways. First, the microbes can push the pathogen/pest away or kill it. For example, some good microbes produce VOCs that can stop a pathogen's growth or a pest's attack on the plant. The second way good microbes can help plants to fight pathogens is by telling the plant to prepare itself to fight by increasing its defenses. Probably also your mum, during the winter, tells you to eat oranges because they contain an important molecule, the vitamin C, which is able to increase your immune defenses protecting you from illnesses. The mechanism is the same for microbes and plants! For example, the molecules produced by the bacterium *Pseudomonas fluorescens* allow the plants to better resist the pathogen attack [3].

Microbes Can Help Plants Survive in Difficult Areas

ABIOTIC FACTORS

The non-living components of an environment, like rocks, sunlight, and water.

Abiotic factors are the non-living parts of an environment, which include sunlight, temperature, and water (Figure 3). Abiotic stress is the negative effect of such factors on a living organism. Examples of abiotic stresses that weaken plants are low water availability and high levels of salt. Good microbes can help plants to live in difficult areas with bad living conditions. For example, the bacterium *Pseudomonas*

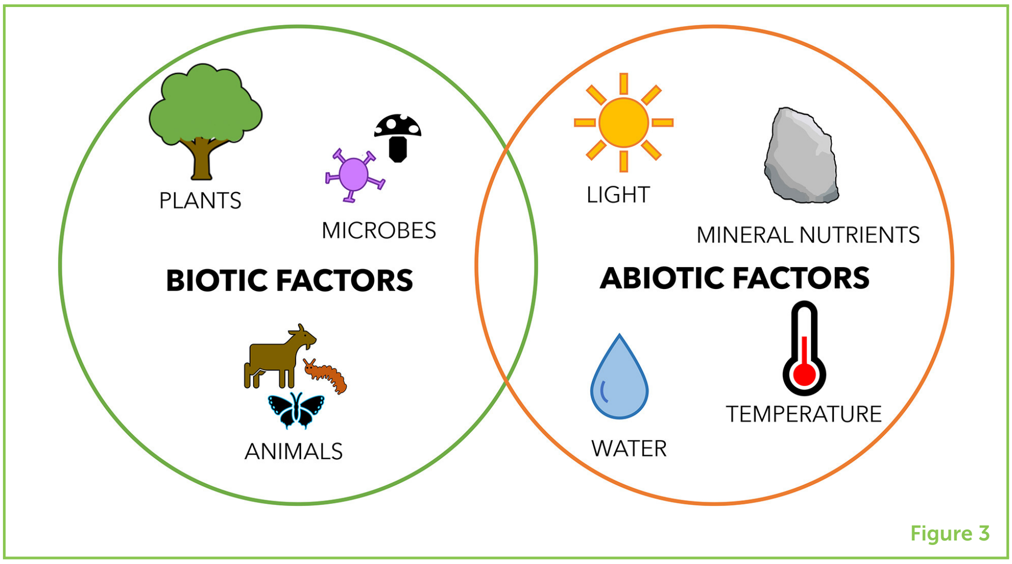

Figure 3

Important biotic factors and abiotic factors that interact in the environment. They have an impact on plants growth and they can influence the chemical communication between plants and microbes in the soil. Mushroom icon is from Flaticon.com.

chlororaphis O6 allows some plants to survive when there is not enough water [4]. Other microbes, like the bacterium *Bacillus subtilis*, help plants to survive in soil where there is a high concentration of salt, by reducing the amount of salt that enters the plant's roots [5].

WHY IS IT IMPORTANT TO UNDERSTAND CHEMICAL COMMUNICATION?

Chemical communication between microbes and other organisms started evolving millions of years ago. Four hundred and fifty million years ago, plants moved from the sea and started to live on the land. Scientists believe that soil fungi first helped plants to make this move to land. The fungi helped the plants to use important nutrients so that the plants could survive [6]. So, for millions of years, chemical communication among soil organisms has been important for plant well-being and growth. In this article, we explained how plant-microbe interactions can give a plant more food or help plants to fight against pathogens or to live in difficult areas. Unfortunately, these interactions are in danger! The high use of antibiotics, pesticides, and fertilizers in agriculture can change the soil and in doing so can also change the soil community, causing some soil organisms to die and others to grow. Changes in the microbial community can have terrible effects on plants; for example, the microbes that grow might be pathogens!

The human population is still growing, and since people need food to survive, new methods of increasing plant growth and food production must be found [2]. Microbes are increasingly used as natural helpers to improve plant growth and food production. The study of microbe-plant communication is necessary to understand which microbes can be used to help plants grow. We must pay close attention to choose the correct microbes! For example, you could think that the use of the fungus *Fusarium culmorum* would be a good idea, because it helps certain plants to grow in difficult areas that are rich in salt. However, *Fusarium culmorum* is a bad organism for maize—it is a pathogen! For these reasons, researchers want to understand as much as possible about chemical communication, to increase our knowledge about soil ecosystems, to understand how organisms interact in these ecosystems, and to help us use plant-microbe interactions to increase plant growth for food while protecting soil ecosystems.

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YOUNG REVIEWER

SHASHIPREETHAM, AGE: 13

Hello, my name is Shashi, I am 13 years old and I go to Penglais School. I enjoy playing football and basketball. My favorite subjects are Maths and computers. I am currently studying year 8. I am a four times Guinness World Records holder in a game called Rocket League and my name is in 2018 Guinness World Record Gamers Edition.

AUTHORS

CRISTIANA ARIOTTI

I recently graduated from the University of Turin with a degree in Environmental Biology. I am now a Ph.D. student at the University of Turin where I study the communication between plants and soil microbes growing in iron-deficient conditions. In my free time, I love climbing mountains (I live near the Alps!) and singing in choirs.

ELENA GIULIANO

I recently graduated in Environmental Biology from the University of Turin. I would like to apply for a Ph.D. in plant science. I am interested in plant-microbe interactions and plant protection against biotic and abiotic stress. I like sharing knowledge and ideas with people from different cultures and I love reading and taking photos in my spare time.

PAOLINA GARBEVA

I am group leader in the Department of Microbial ecology at NIOO in Wageningen. The focus of my current research is to understand the fundamental mechanisms of microbial chemical interactions and communication.

GIANPIERO VIGANI

I am researcher at University of Turin (Italy). The focus of my research is to understand how plants take up nutrients and water from the soil and how plant-microbe interactions belowground occur. *gianpiero.vigani@unito.it

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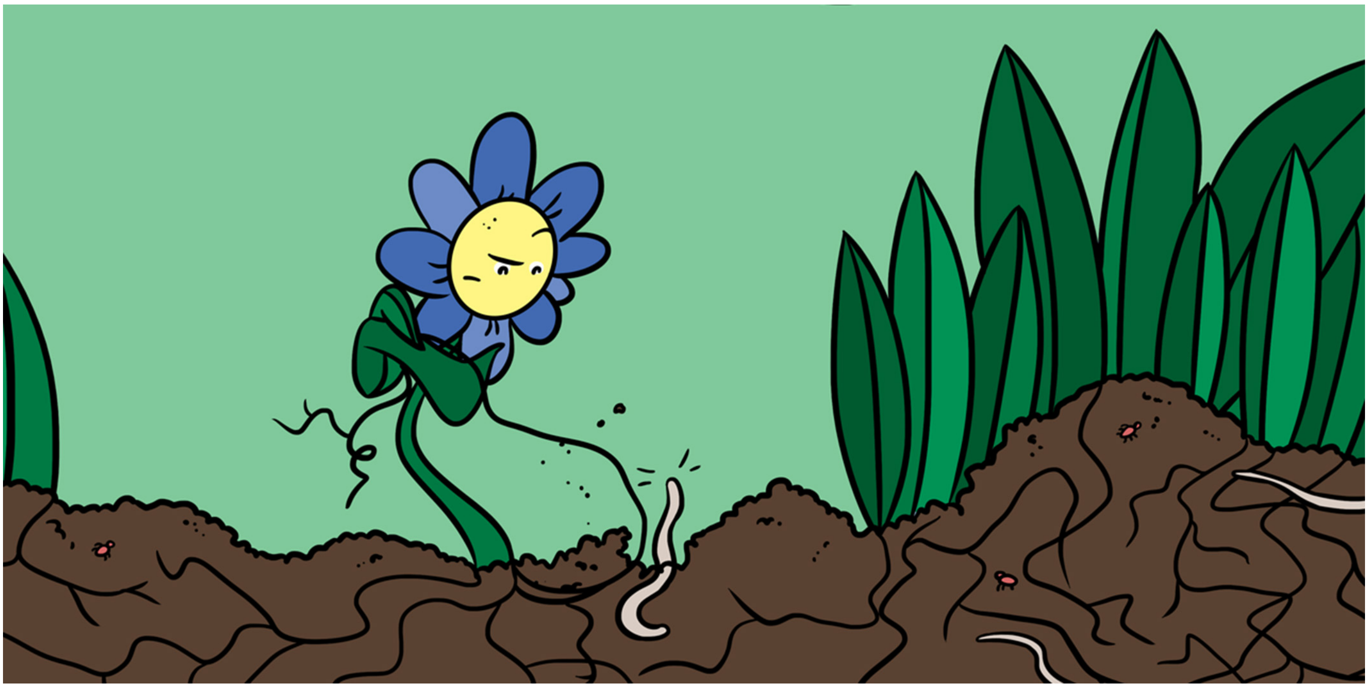

HOW DO PLANTS DEFEND THEMSELVES FROM ROOT-EATING CREATURES?

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YOUNG REVIEWERS:

AVANI
AGE: 10

CATHERINE
AGE: 15

HARRISON
AGE: 11

The belowground world is full of creatures that depend on plants as a food source. Belowground plant eaters, or herbivores, feed on roots and can cause considerable damage to plants. Roots are very important because they help plants take up water and nutrients from the soil. These are important resources that plants need for growth. To protect their roots, plants produce chemical defenses. The production of these defenses is costly because nutrients and energy used to make defenses cannot be used for growth or the production of flowers and seeds. Plants, therefore, must be efficient with their defenses. Scientists are very interested in understanding how plants defend themselves efficiently, because this can help us to develop more environmentally friendly ways of growing fruits and vegetables. In this article, we explain how plants defend themselves efficiently, and how plant defenses affect herbivores in the soil.

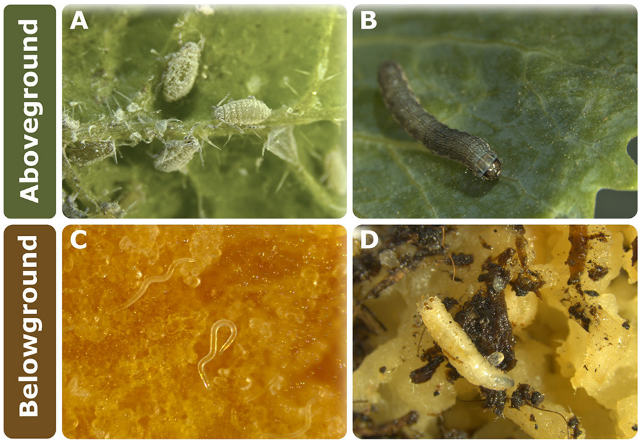

Figure 1

Figure 1

Examples of aboveground and belowground herbivores. **(A)** Cabbage aphids, **(B)** the caterpillar of the beet armyworm, **(C)** a plant-eating nematode, and **(D)** the larvae of the cabbage root fly. (Photo credits: Axel Touw).

PLANTS: SURVIVING IN A DANGEROUS WORLD

Plants are an important food source for many creatures, including humans. Plant eaters, or **herbivores**, can be large mammals like cows, sheep, or horses, but most of them are actually much tinier, such as caterpillars or aphids (Figure 1). Because these tiny herbivores usually occur in large numbers, they can cause a lot of damage. Insects, for example, are the most diverse group of animals on Earth. There are around 1 million known species of insects, of which about half are herbivores. In comparison, there are only around 5,500 mammal species living on Earth. In addition to the large and small herbivores aboveground, there are many plant feeders living belowground as well. The soil is filled with many kinds of herbivores that feed on plant roots, including insect larvae, tiny worms called **nematodes**, and spider-like creatures called mites (Figure 1).

HERBIVORE

An animal that eats plants.

NEMATODES

Tiny, wormlike animals that mostly occur in the soil, but also in seas or lakes, in the intestines of animals, and even in the guts of insects.

There are usually high numbers of herbivores present in the soil, just like there are aboveground. For example, there are 30,000 known nematodes species, of which around 10% are plant eaters. One single female nematode produces up to 200 eggs. This means that a single plant can be attacked by thousands of nematodes at the same time. Chewing insects are another danger. They may chew through the water transport system of plant roots, which can cause the leaves to droop and the plant to die from lack of water.

HOW DO PLANTS DEFEND THEMSELVES?

With so many creatures trying to attack them, you can imagine that plants have a hard time surviving. Since plants cannot flee from their attackers, they had to evolve ways of defending themselves. Plants have developed several defenses against herbivores [1]. Some **plant defenses** are easy to see, like the thorns of a rose, the hairs on the leaf of a stinging nettle, or the thick skin of beetroots. Other defenses,

PLANT DEFENSES

Features of a plant that affect the behavior, growth, or survival of herbivores.

such as chemical defenses, are less visible. Each plant produces thousands of different chemicals, all involved in essential processes. Some chemicals, like sugars, provide energy to the plant. Other groups of chemicals help to defend plants against attackers. These chemical defenses can make the plant taste bad, which prevents herbivores from eating plant tissues. In some cases, the chemicals can even be toxic. Chemical defenses can affect humans too. There are many plants that would make you feel very sick if you ate them, for example the berries of black nightshade. Some plants, such as poison ivy or hogweed, can give you a rash and even cause burns when you touch them. Most chemical defenses are not that bad, though. In fact, chances are high that you have been exposed to plant chemical defenses yourself.

We have grown to like the taste of some chemicals that plants produce. Have you ever put mustard on your hotdog or sausage, or enjoyed a nice Indian curry with mustard seeds? The sharp-bitter taste of mustard is caused by defense chemicals called **glucosinolates**. In the wild, glucosinolates help plants to defend themselves against insects, fungi, and bacteria. The caffeine in coffee, which helps people to wake up in the morning, is not made by coffee trees to please humans. In reality, coffee trees produce caffeine to protect their seeds—the coffee beans—from insect attacks. Caffeine not only gives coffee beans their bitter taste, but it can also paralyze or kill insects trying to feed on them.

GLUCOSINOLATES

Defense substances responsible for the sharp bitter taste of mustard and wasabi. Although most humans enjoy their taste, they are toxic to most insects, nematodes and bacteria.

These examples illustrate that chemical defenses are an effective way for plants to protect themselves against herbivores in their environments. Nevertheless, most plants are not completely defended by these chemicals. If you take a good look at the plants around you, you will notice that most plants show some damage, such as holes in their leaves. This is because the production of chemical defenses comes at a cost. Plants do not only have to worry about defending themselves, but they must also put energy into growth, producing flowers, and making seeds. So, the energy plants can spend on producing defenses is limited. Plants must make use of this limited amount of energy in an efficient way.

HOW DO PLANTS DEFEND THEMSELVES EFFICIENTLY?

Fossils of herbivore-damaged leaves show that plants and herbivores have been living together on Earth for more than 400 million years. During this time, plants have developed several ways to produce defenses in a cost-efficient manner. One way is to produce defenses only when necessary, for example, when insects start eating them [2]. By only producing defenses when under attack, plants save energy when no dangers are present. The disadvantage of this strategy is that defense production will only begin after the herbivore starts eating. Because defense production takes time, the plant can suffer significant damage before the herbivore leaves or dies.

Another strategy is to always have some defenses at hand but in limited amounts. In this case, the plant moves most defenses to the plant parts that are most important for survival and are vulnerable to attack by herbivores [3]. This would be like defending a castle by putting the soldiers on the outer wall, where the first attack would occur and where the castle is most vulnerable. Clearly, the treasure in the castle would be well guarded too, as this is the most valuable. Aboveground, such valuable plant parts include young leaves, flowers, and seeds, which play essential roles in energy production or in producing the next generation.

TAPROOT

Main root from which lateral roots arise. Collects water and nutrients from the rest of the root system and distributes them aboveground. In carrots and beetroots, it stores starch and nutrients.

Belowground, various parts of the root system also have different values. The root systems of plants like tomato or cabbage consist of three parts: the **taproot**, lateral roots, and fine roots (Figure 2). Lateral and fine roots help the plant take up valuable nutrients and water from the soil. The taproot is the main root that collects all the water and nutrients absorbed by the lateral and fine roots and distributes them to the aboveground parts. Simultaneously, sugars and other substances produced in the leaves move through the taproot in the other direction. The important role of the taproot in transport of nutrients and water makes it an essential part of the root system. When herbivores damage the taproot, the essential transport routes are broken, and the plant will die. In plants like beets, the taproot stores energy in the form of sugar. This is like the treasure in the castle. The taproot is therefore considered the most valuable root part and is defended the most, followed by the lateral and fine roots [4] (Figure 2).

HOW DO PLANT DEFENSES AFFECT SOIL HERBIVORES?

Herbivores decide which root part to eat based both on its nutritional value and on how well it is defended [5]. Most herbivores would prefer to feed on the taproot since it is the most nutritious part of the root system. However, as mentioned earlier, the taproot is also the best-defended part. Not all herbivores can overcome these chemical defenses. Some herbivores, like the larvae of the cabbage root fly, can deactivate chemical defenses and feed on the taproot [4]. Other herbivores, like the larvae of the European June beetle, cannot deal with the high defense levels in the taproot and instead eat the lateral and fine roots (Figure 2). The distribution of chemical defenses across the root system and the ability of herbivores to overcome these defenses can therefore have a strong influence on where herbivores can be found in the soil.

HOW CAN SCIENTISTS USE THIS KNOWLEDGE?

The knowledge gained by studying the defense systems of plants helps us to understand how plants interact with herbivores and other

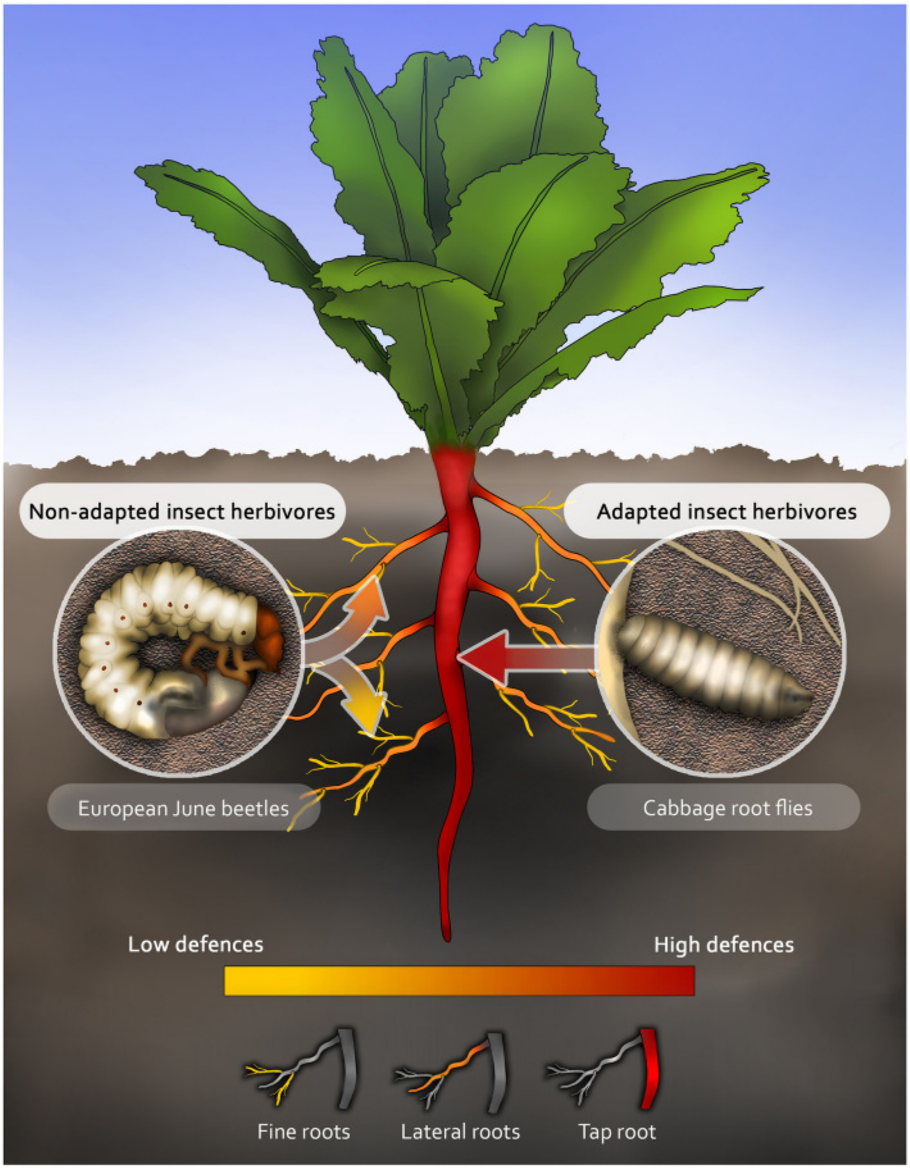

Figure 2

Figure 2

The distribution of chemical defenses over a root system, and how this affects belowground herbivores. Red indicates the highest defense level in the root system and yellow indicates the lowest level. Chemical defenses are generally highest in the taproot (red), followed by the lateral roots (orange) and the fine roots (yellow). Some insect herbivores, like the cabbage root fly, can deactivate a plant's chemical defenses and can eat the taproot where defenses are highest. Other herbivores, like the European June beetle, cannot deactivate plant defenses and therefore they eat the fine roots, where chemical defense levels are lower. (Image credit: Jennifer Gabriel).

animals in their environments. In addition, knowing how plants defend themselves can help us to develop more environmentally friendly ways of growing crops. **Plant breeding** can create new crop varieties, such as plants with nicer colors, more interesting tastes, or bigger fruits. Similarly, plant breeders can create crops that are better defended against attackers. To do so, plant breeders must understand how plants produce defenses, and which attackers those defenses are effective against. Scientists who study plant defenses using lab experiments and field studies collect this kind of information. By creating crops with better defenses, we can help farmers to reduce the amounts of chemical pesticides they use. This is good news for both human health and the health of our environment.

PLANT BREEDING

The science of creating new plant varieties with desirable characteristics like taste, smell, color, or resistance to herbivores or certain environmental conditions like drought.

ACKNOWLEDGMENTS

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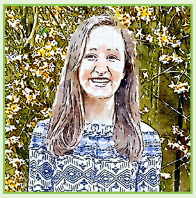
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

AVANI, AGE: 10

Hello, I am Avani. I enjoy running and swimming. I am also a dancer. I love going on walks with my dog, or collecting stones. I love math, science and I love sports. I enjoy playing video games, and calling friends. I love nature and cold windy weather.



CATHERINE, AGE: 15

I love music and singing, I play the violin and guitar and I also enjoy writing! I am part of a highland dance troup and volunteer with children at local kids clubs and guides. I enjoy attending youth events at my church and doing fitness. I hope that by reviewing these articles I could learn about new and interesting stuff!

HARRISON, AGE: 11

I love playing sports such as hockey and go running and chasing my dog! I also love discovering new things, but not new food! Because I currently go to primary school I am excited to start my new secondary school and try lots of new subjects. My favorite subject at the minute is maths.

AUTHORS

AXEL J. TOUW

Axel has been fascinated by nature since he was young. At that time, he was mostly interested in dinosaurs, cats, dogs, lizards, and frogs, but particularly in birds. Actually, the first thing he ever drew was an owl (with some imagination). While studying biology, he became interested in how plants communicate, especially with insects. Today, Axel studies how plants defend themselves against microbes, nematodes, and insects. In his free time, he likes to be outside, play football, read, and cook. He also tries to use the knowledge gained during his research in his garden, with varying degrees of success. *axel.touw@idiv.de

NICOLE M. VAN DAM

Nicole was born and grew up in the Netherlands with her parents and two younger sisters. As a kid, she liked to experiment with insects. For example, she tested whether ants can swim by putting them in puddles (in case you are wondering, they do quite well). She studied biology in Wageningen, the Netherlands. There she became interested in how plants can defend themselves and how farmers can use this knowledge to reduce pesticide use. After doing a lot more experiments with insects and plants in various places in the world, she became a professor. In her free time, she likes to do yoga and to watch movies with her two sons (19 and 21). Together with her husband, she likes to grow organic fruits and vegetables in her garden. There she also finds inspiration for new research projects.

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BIODIVERSITY
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BACTERIA IN SOIL KEEP YOUR HAMBURGER “HEALTHY”

Stephanie D. Jurburg *

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YOUNG REVIEWERS:


MADDIE
AGE: 15


MATÍAS
AGE: 14


TACY
AGE: 13

In 1993, an outbreak of the bacterium *Escherichia coli* made over 700 people ill across the United States. A special kind of *E. coli,* called strain O157:H7, inhabits the guts of cattle and spreads to water and compost through cow manure. The strain O157:H7 can survive for many months in the water or compost, until it reaches humans through meat or vegetables, causing disease. However, *E. coli* survives a much shorter time in the soil because it must compete with the many kinds of bacteria already present there. To soil bacteria, strain O157:H7 is an invader, and invaders depend on the “leftovers” of the native organisms to survive. In more diverse communities, fewer resources are left behind, and it is harder for organisms to invade. This is why *E. coli* O157:H7 is least successful in soil, the most diverse environment on Earth, and it is one of many reasons why soil bacteria are important for our health.

ESCHERICHIA COLI ATTACKS!

In 1993, an outbreak of the bacterium *Escherichia coli* caused over 700 people to become seriously ill across the United States. The culprit was uncooked beef patties. Thirteen years later, another *E. coli* outbreak caused massive recalls of prepackaged spinach across the country. This time, the source was a cattle ranch next to a spinach farm. Since then, *E. coli* outbreaks have started from the consumption of cheese, onions, soy, and most recently, romaine lettuce. These outbreaks were always caused by the same bacterium: *E. coli* **strain** O157:H7. Who is this bacterium and why is it still causing disease outbreaks? Keep reading to learn more!

STRAIN

A subtype of a bacterial species that has slight differences in its genes from other strains in the same species.

THE HISTORY AND TRAITS OF *E. COLI*

Most of the bacteria we know about today were discovered in the last 10 years. However, *E. coli* is the exception. This bacterium was discovered in the colon of healthy humans in 1885, by pediatrician Theodor Escherich, after whom the bacterium is named. *Coli* refers to their habitat, the colon. Because it grows so well in the laboratory, microbiologists have continued to study *E. coli* to understand how bacteria grow and respond to their surroundings.

Many of the characteristics that make *E. coli* so attractive as a study organism also make this bacterium stand out. First, *E. coli* grows very well if it is given the right food sources—and there are many food sources that are "right" for this bacterium. With enough food, *E. coli* can grow very quickly: from a single cell to a million cells within 7 hours! Second, bacteria can change their **genes**, and *E. coli* is especially good at this (Figure 1). Genes are the cell's instruction manual, and unlike larger organisms like animals, bacteria can trade genes with each other, receive genes from a virus, or pick up genes from the environment. When a bacterium changes its genes, its behaviors and abilities change too, and its descendants, which inherit the same new genes, become members of a specific strain—much like you are a member of your family and share many characteristics with them. Instead of family names, strains are usually identified by a code name of letters and numbers, like O157:H7.

GENE

A DNA segment containing instructions for building a protein.

THE SUPER STRAIN O157:H7

Thousands of *E. coli* cells from different strains live in the healthy human gut and protect us from other pathogenic, or disease-causing, bacteria like *Salmonella*. But that is not what strain O157:H7 does. First discovered in 1983, *E. coli* strain O157:H7 now infects ∼73,000 people a year in the United States alone [1]. What makes this strain unique is the set of genes it has acquired: one set of genes gives strain O157:H7 the ability to produce Shiga toxin, which is the poisonous substance

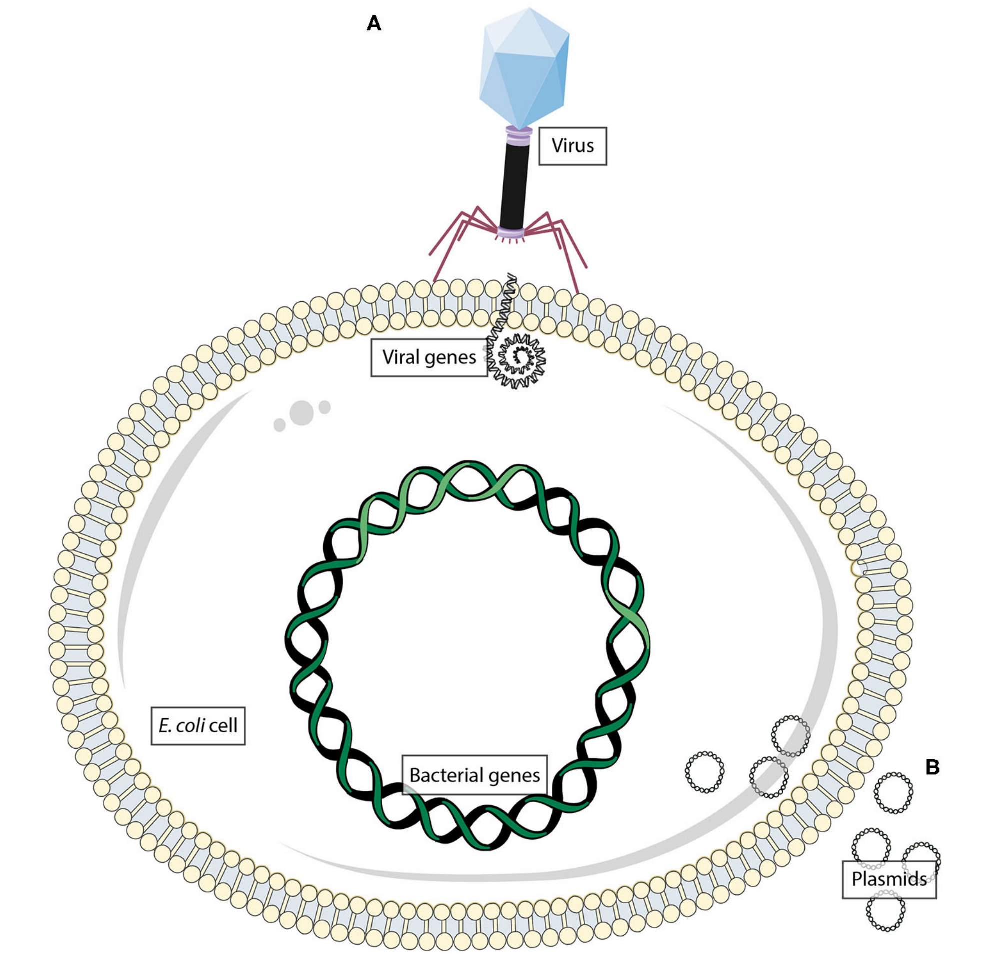

Figure 1

Figure 1

Bacteria, unlike most other organisms, can change their genes. **(A)** *Escherichia coli* strain O157:H7 has genes that were left behind by a virus that infected it. **(B)** O157:H7 has also taken up genes from the environment. Bacteria can also get genes from other bacteria.

that makes infected people sick. Producing poison is not quite enough to become a threat to our health. Strain O157:H7 also behaves in a way that makes it a **pathogen**: it actively tries to spread. Not all *E. coli* strains do this. This spreading behavior is also a result of genes picked up from the environment (Figure 1).

PATHOGEN

An organism that can cause disease.

Since 1993, there have been almost yearly outbreaks of disease caused by O157:H7. Why do they still happen? The simple answer is that there are too many ways that *E. coli* can reach your food. If the beef used to make your hamburger came from an infected cow, your burger is probably contaminated, but this is not a problem, because hamburgers are never eaten raw. When you cook your hamburger, the *E. coli* in it is killed by the heat, and the meat is safe to eat. But vegetables like lettuce are often eaten raw, and in that case, the bacteria may be alive when you eat them.

E. coli normally lives in the guts of cattle for weeks to months, where it does not cause disease (Figure 2). The feces of these animals contain many *E. coli* cells: a single gram of feces from an infected cow can contain over 50 million *E. coli* cells, and it is extremely difficult to get

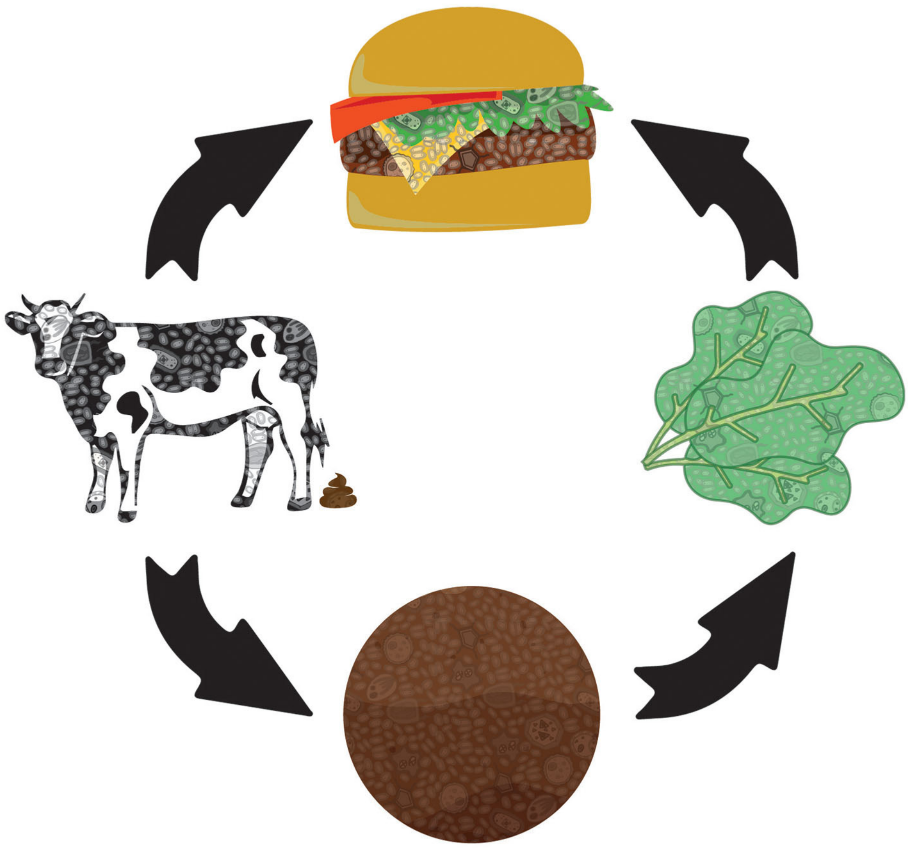

Figure 2

Figure 2

Many pathways to a hamburger. Beef from infected cows ends up in in raw hamburger patties, and *Escherichia coli* is shed from the cow gut onto the soil as manure, where the native bacteria compete with it. If *E. coli* persists and can grow in the soil, then it may contaminate crops like lettuce, spinach, and onions.

rid of them once they leave the cow as manure. Manure can host these bacteria for over 21 months, giving the bacteria plenty of opportunity to reach the soil. If the manure reaches the water, then the bacteria may survive there for more than 8 months, and during this time, they may also get into the soil, when the water is used to irrigate crops. Once in the soil, *E. coli* may contact crop plants, result in contaminated fruits and vegetables.

SOIL BACTERIA, A SOLUTION

Given how long these bacteria can live and how easily they spread, why is *E. coli* relatively rare? The answer: soil bacteria. To contaminate our vegetables, *E. coli* must survive in the soil, but its ability to do so is limited. In soil, *E. coli* can only survive for 3 months. Scientists think that the **diversity** of soil bacteria, or the number of different kinds of bacteria naturally living there, make all the difference [2]. No environment is more diverse than soil. A single handful of soil can contain 10,000 different bacteria [3], and very often, many of them are non-infectious strains of *E. coli.* In several experiments, scientists have shown that the more diversity a soil has, the harder it is for dangerous bacteria to successfully invade it. The reason for this seems to be the availability of resources that the invading

DIVERSITY

The number of different species in a community.

bacteria need to survive [4]. Resource consumption for bacteria is similar to food preferences in animals, and different strains of bacteria consume different resources. When an environment like the soil has a high diversity of natural bacteria, the bacterial community consumes a wide range of resources, leaving nothing behind. When *E. coli* lands on this environment, it is not able to feed or grow, and so it dies. Less diverse groups of bacteria cannot consume all the resources, leaving "leftovers," which *E. coli* can use to grow and spread.

HOW ANTIBIOTICS HELP *E. COLI*

So, now you know that the diversity of bacteria in soil is important because it ensures that there are few resources left for disease-causing bacteria to use. Unfortunately, soil bacteria are constantly threatened by antibiotics. Humans use antibiotics to combat diseases in animals and in themselves, but soils are exposed to antibiotics in ways we did not initially expect. Consider how soil can become contaminated with the pathogenic *E. coli* strain: cattle feces. To prevent disease outbreaks, cows often receive large amounts of antibiotics. These are not fully used up by their bodies and can be released into the environment through the cow's urine and feces. But that is just the beginning. Sewage contains lots of antibiotics released in the same way by humans and by the water from fish farms, which is also high in antibiotics. These waters mix into rivers, which are then used to irrigate soils for agriculture. Once the antibiotics reach the soil, they kill most of the good soil bacteria, leaving behind resources that pathogenic bacteria can use to grow and multiply, potentially spreading disease. A growing group of countries around the world have created laws to limit the use of antibiotics on animals like cattle, as a way to reduce the spread of antibiotics in the environment and to improve the health of their citizens but also of wildlife.

BACTERIA: THE TINY ROAD AHEAD

Humans have known that bacteria cause diseases since the 1800s, but we are still learning the ways in which bacteria can prevent diseases. In fact, we have only started to see the full extent of bacterial diversity over the past 20 years. We used to think that a clean environment was a sterile one, without any bacteria. As we gather more and more information about the bacterial world, our definition of what is "clean" is changing, from an emphasis on the lack of bacteria to a focus on having the "right" bacteria who can prevent the pathogenic bacteria from successfully invading. We now know that bacteria are everywhere, and it is not possible to live without them. Our research is shifting from trying to keep our world free of bacteria, to learning how to select the right ones: those that help our environments and our bodies to stay healthy. There are still many unanswered questions. For example, who are the "right" bacteria, and what makes them so special?

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YOUNG REVIEWERS

MADDIE, AGE: 15
My name is Maddie. I am 15 years old, and live near San Francisco.

MATÍAS, AGE: 14

I am a 14 years old who loves science, programming, Vikings, mythology, Jiu-Jitsu, rock and roll, singing, and playing drums.

TACY, AGE: 13

Hi I am Tacy. I am 13, and live near San Francisco. I like drawing, videogames, and playing guitar.

AUTHOR

STEPHANIE D. JURBURG

Stephanie Jurburg is an enthusiast of all things tiny. For nearly a decade, she has studied how the bacteria living in and around us shape our world, making us healthy or unhealthy and keeping our soils fertile. She is particularly interested in how communities of bacteria change over time, and how they recover when they are disturbed. Currently, she is a researcher at the German Centre for Integrative Biodiversity Research (iDiv), where she studies how the bacterial communities in different environments are alike. *s.d.jurburg@gmail.com

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DUNG BEETLES HELP KEEP ECOSYSTEMS HEALTHY

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YOUNG REVIEWERS:

FDR-HB_ PERU IGEM TEAM

AGES: 14–17

Dung beetles are a group of insects that primarily use the dung (poop) of mammals for feeding and nesting. These beetles are important for the breakdown and recycling of dung into the soil, enabling the nutrients in the dung to cycle through the ecosystem. Dung beetles provide many benefits for the health and functioning of both natural and human-modified ecosystems, such as dispersing seeds, reducing livestock parasites, and promoting plant growth. In this article, we will explore the basic life history of dung beetles. We then dig a little deeper into the importance of dung beetles within tropical forests and agricultural ecosystems.

DUNG BEETLE BASICS

Many readers will be familiar with dung beetles from nature documentaries. Once you have seen a beetle skillfully roll away a ball of dung (animal poop), the sight is hard to forget. Readers might be surprised to learn that dung beetles are found across most of the world (Figures 1A–D), on all continents except Antarctica! This group

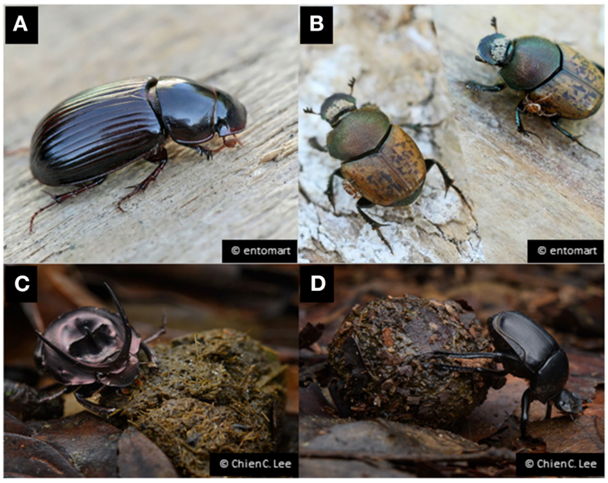

Figure 1

Figure 1

Examples of dung beetles in temperate and tropical environments. **(A)** The dweller *Aphodius rufipes* is a nocturnally active species found in high abundance in agricultural ecosystems. It is an important food source for bats. **(B)** The tunneller *Onthophagus coenobita* occurs in agricultural ecosystems, and often carries tiny mites that use dung beetles to transport them between dung pats. **(C)** Male *Proagoderus watanabei*, a tunneling species found in Sabah, Malaysia, feeding on dung. **(D)** *Paragymnopleurus maurus*, a rolling species found in Sabah, Malaysia, pushes a dung ball to safety using its back legs.

of beetles is named for its habit of using the dung of mammals for food and nesting. Although, some species of dung beetles opt for decaying flesh, fungi, fruits, and even dead millipedes and ants! Like all beetles, dung beetles have two sets of wings: a flexible interior pair used for flight, and a tough exterior pair that serves as armor. All dung beetles have antennae that widen at the ends into a club, and the males of some species have impressive horns that they use when fighting for females (Figure 1C). There are more than 7,000 different species of dung beetles, and new species are discovered each year.

Dung beetles can be classified into three main groups based on their feeding and nesting habits (Figure 2). The first group are the dweller dung beetles. Dwellers arrive at a pile of dung and quickly take up residence. Inside the dung, they mate and lay eggs. Once hatched, the larvae (the immature form of the beetles) spend the entirety of their development feeding within the pile of dung that serves as a home and a food source (Figure 2A). The second group are the tunnellers. Female tunneller beetles arrive at the dung and begin digging a tunnel in the soil. They drag small pieces of dung into the tunnel, forming the pieces into lumps called brood balls. The males then compete for a female and her tunnel, which they defend until the female is mated and lays her eggs in the dung (Figure 2B). Then there are the rollers. A male arrives at the dung and sculpts it into a ball using his hind legs. If the dung ball is to the female's liking, he rolls it away and begins burying the dung in the soil. Once buried, the female lays an egg inside the ball and the larva feeds on the dung ball for the entirety of its development—safe and sound in the soil (Figure 2C). Whichever method a dung beetle uses for feeding and nesting, its activities add and mix **organic matter** into the soil. This is extremely important for other soil animals and microbes and provides a boost of nutrients to plant roots.

ORGANIC MATTER

Compounds that have come from the remains of dead organisms, such as plants, fungi, and animals.

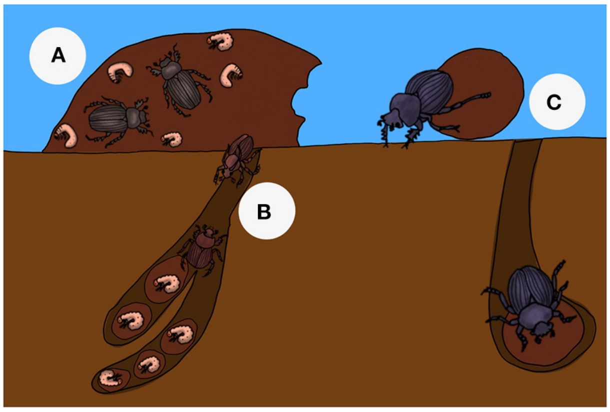

Figure 2

Figure 2

Three different nesting strategies used by dung beetles. **(A)** Dweller beetles lay eggs directly into the dung where the larvae spend the entirety of their development. **(B)** Tunneller beetles dig tunnels in the soil where they form small balls of dung known as brood balls. The female lays eggs into those brood balls, where the larvae will feed. **(C)** Roller dung beetles sculpt a ball of dung and roll it away to safety, before burying it into the soil and laying eggs.

DUNG BEETLES IN TROPICAL FOREST ECOSYSTEMS

Dung beetles form networks of interactions with the mammals whose dung they feed on. Both mammals and dung beetles have interactions with the fruiting plants whose seeds they disperse in the dung (Figure 3A). However, if some mammals become extinct, this may affect the dung beetles that feed on their dung and the distribution of the plants whose seeds they help disperse [1] (Figure 3B). We have been studying the interactions among mammals and dung beetles in the tropical forests of Brazil, Singapore, and Malaysia. These tropical forests have lost **biodiversity** because of deforestation, **fragmentation**, and hunting. We expect that as the forests become more disturbed and fragmented into smaller patches, the number of mammal species would decline, and we would also see fewer dung beetles. We predict that the complex interactions between mammals, dung beetles, and fruiting plants would be simpler in disturbed areas and isolated forest patches compared to large and healthy tropical forest.

BIODIVERSITY

The variety of life on Earth.

FRAGMENTATION

The process of being split into smaller patches.

To test our prediction, we set up traps baited with dung from different mammals in habitats ranging from forests to oil palm plantations. We looked at large areas of continuous forest and small forest patches. We then counted and identified the beetles that were attracted to each dung type in each habitat. We found that tropical forest dung beetle-mammal networks are fairly **resilient**, meaning they do not change very much in response to logging and fragmentation. We think this is because dung beetles are not very fussy about what kind of dung they eat. While many beetles have a preferred food type, few specialize only on a single dung type. So, if one mammal species is lost from an area, most dung beetles can simply switch to the dung of another mammal species for their next meal (Figure 3B). We discovered that some dung beetles even feed on python dung! However, although networks were resilient in moderately disturbed habitats, we found that in heavily disturbed sites, such as oil palm plantations and small isolated forest patches, the networks did become simplified, with

RESILIENT

Able to withstand changes in the environment.

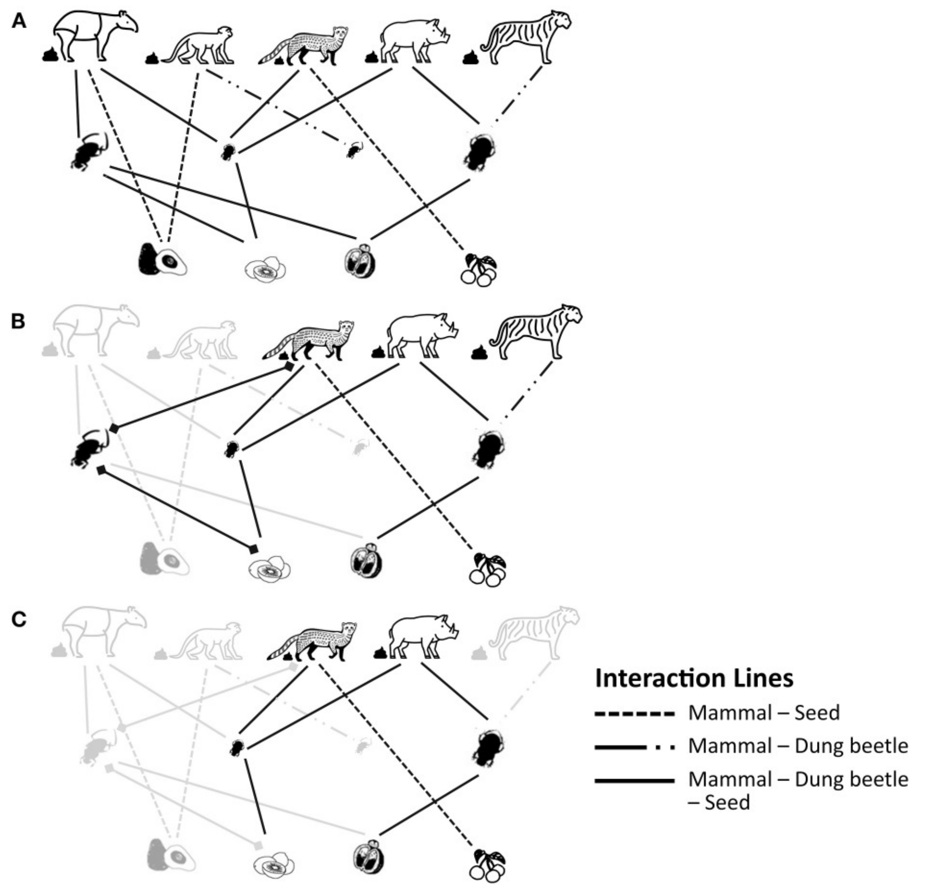

Figure 3

Simplified interactions among mammals, dung beetles, and seeds in **(A)** an undisturbed ecosystem, **(B)** a moderately disturbed or fragmented ecosystem, and **(C)** a heavily disturbed or fragmented ecosystem. The loss of species and interactions are shown in gray. Three types of interactions are possible: (1) mammal-seed—only the mammals disperse the seeds; (2) mammal-dung beetle—there is no seed dispersal; (3) mammal-dung beetle-seed—both mammals and dung beetles disperse seeds. In moderately disturbed or fragmented ecosystem **(B)**, dung beetles can switch their feeding preferences to a different dung. This does not happen in heavily disturbed or fragmented ecosystem **(C)**, so the beetle and its interactions are lost.

fewer dung beetle species and fewer interactions between beetles and mammals [2] (Figure 3C).

Using traps baited with dung to catch beetles only tells us if the beetles are attracted to the dung, but not if those beetles actually feed on that dung type. We could only bait traps with dung from mammals that we could easily find, like animals kept in zoos. Luckily, new laboratory methods are allowing us to know exactly which mammal dung the beetles have been feeding on. So, in our current work, we are dissecting the guts of beetles to analyze the genetic material of the beetle gut contents. This method allows us to identify which mammal dung the beetles were feeding on before they were captured. We hope that this will allow us to document more complete networks, including rare or difficult-to-study mammal species, and the interactions between mammals and dung beetles that live in the forest canopy—yes, there are canopy dung beetles too!

DUNG BEETLES IN AGRICULTURAL ECOSYSTEMS

ECOSYSTEM

A community of animals, plants, bacteria, and fungi living in a particular location along with the non-living components of that environment.

Dung beetles are important members of agricultural **ecosystems**, and many researchers have explored how dung beetles help support the production of food [3]. For example, flies that bite and disturb cows and other farm animals, lay their eggs in dung and the immature fly larvae then feed on dung when they hatch. Dung beetles help to keep farm animals like sheep, cows, and horses healthier by burying farm animal dung, so that it is not available for the flies to breed in.

Dung beetles also help to reduce parasite infections of farm animals. Parasitic **nematodes**, which are tiny worms, are eaten by animals grazing in the pastures. The nematodes then multiply in the animals and their eggs are excreted in the dung. When the eggs hatch, the larvae migrate to the grass and are ingested by grazing animals, like cows or sheep, which quickly increases the infection rates. When dung beetles tunnel through dung, they cause it to dry out. This kills the eggs, and reduces the numbers of parasitic nematodes in the pasture, which leads to fewer infected animals. This tunneling action also helps with the recycling and mixing of the soil, which aids the movement of nutrients through the soil so they can be available by plants. Because dung beetles are relatively small and often secretive, many farmers may not even recognize that dung beetles live on their farms. However, despite their small size, dung beetles save the cattle industry in the United Kingdom alone about £367 million per year [4]!

NEMATODES

A group of worms, also known as roundworms, found in soil and aquatic environments that can be parasites in plants and animals.

Dung beetles are sensitive to how pastures are managed. In one study, scientists collected beetles from a series of cattle farms in Ireland [5]. They compared conventional farms that used artificial fertilizers and insecticides to organically managed farms, which used neither. The researchers found that organic farms had a greater abundance of dung beetles and more dung beetle species than the other type of farms. We then discovered that having more dung beetle species increases plant growth, but has no benefit for improving the number of air pockets in the soil [6].

Parasiticides are also a serious threat to dung beetles living in agricultural ecosystems. These are chemicals given to farm animals to protect them against parasites, such as ticks, fleas, and nematodes. Parasites harm the animals by feeding on their blood and sometimes transmitting diseases. Parasiticides are generally excreted in animal dung, so the same chemicals that kill the parasites can also affect dung beetles when they then feed on the dung. Sadly, we discovered that a parasiticide commonly used to treat farm animals can kill dung beetles or stop them from breeding. This reduces the health and number of dung beetles and the amount of dung they bury [6]. Farmers can help protect their dung beetles by using fewer parasiticides, by treating only those animals with high numbers of parasites, or choosing treatments that are less toxic to dung beetles.

PARASITICIDES

Drugs given to animals to kill their parasites.

THE PRECIOUS AND FASCINATING DUNG BEETLE

As you can see, dung beetles are precious. As you now know, they have many important ecological roles in natural and agricultural ecosystems, and can help us understand more about the health of ecosystems. For example, because dung beetles are linked to mammals, if we notice that some dung beetle species disappear from our forests, this suggests that the forest mammals might be disappearing too. Healthy soils and plants need nutrients, which dung beetles and other soil animals help provide. The disappearance of dung beetles and other soil animals due to chemical and environmental disturbances would lead to our soils becoming infertile, and the seeds of many plants would not be dispersed or grow. The many different behaviors that dung beetles exhibit have put them in the spotlight of numerous fascinating behavioral studies. Findings have included beetles navigating using the milky way, and others dispersing the seeds of a plant that have tricked the beetle by evolving to look and smell like antelope dung! Keep an eye open for these fascinating creatures wherever you find yourself, you never know what discoveries you might make.

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

FDR-HB_PERU IGEM TEAM, AGES: 14–17

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

AUTHORS

PAUL MANNING

Paul is a post-doctoral fellow at the Faculty of Agriculture at Dalhousie University. He holds a B.Sc. in agriculture from the Nova Scotia Agricultural College, and a D.Phil. in Zoology from the University of Oxford. He has been working on dung beetle ecology and toxicology since 2013. His research aims to understand how insect communities support ecosystem functions (like dung decomposition) in agricultural ecosystems. Paul is also interested in elevating public understanding and appreciation of insects through speaking to community groups, working with youth, and conducting research through participatory citizen science. *paul.manning@dal.ca

XIN RUI ONG

Xin Rui is a Ph.D. student at the Asian School of the Environment in Nanyang Technological University. She graduated from the National University of Singapore with a B.Sc. in Life Sciences, specializing in Environmental Biology. Xin Rui was first introduced to the fascinating world of dung beetles during her undergraduate years and is now studying the diversity of dung beetles and their interactions with mammal communities in Southeast Asia.

ELEANOR M. SLADE

Eleanor is an Assistant Professor at the Asian School of the Environment. She holds a B.Sc. in Zoology from the University of Leeds, a M.Sc. in Ecology from Aberdeen University, and a D.Phil. in Zoology from the University of Oxford. Eleanor is an ecologist whose research focuses on the conservation, management, and restoration of tropical forest landscapes and agricultural systems. She is particularly interested in invertebrates and has been studying dung beetles and their importance for healthy ecosystems for 17 years. Eleanor is also interested in using science to help inform policy and best practices in the oil palm industry.

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PLANT-EATING NEMATODES AND THE KEY TO FIGHTING THEM

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YOUNG REVIEWERS:


MARIE
AGE: 13


MEHA
AGE: 15


NIVEDITA
AGE:14


SHREEYA
AGE: 11


SHRIYA
AGE: 13

Plant roots interact with many bacteria, fungi, and microscopic organisms within the soil that can impact how well the plants grow. Some of these microscopic organisms are animals called nematodes, and they are an especially important part of the life in the soil. Nematodes can be good, bad, and neutral for plants. Some scientists called nematologists study nematodes and how to prevent the bad ones from damaging important crops, like carrots. Nematologists and other scientists partner up to help farmers manage these pests and grow healthy crops.

LITTLE ORGANISMS CAN CAUSE MIGHTY PROBLEMS

A handful of soil contains thousands of animals that are so small we need a microscope to see them. Tiny as these animals may be, some of them have a worldwide impact on the successful growth of food crops. **Nematodes** (Figure 1) are tiny roundworms that live in the soils of our gardens, crop fields, and landscapes. While some nematodes are helpful for plants, others are enemies of the

Figure 1

Figure 1

A male root-eating nematode of the *Pratylenchus* species, collected from carrot roots. For scale, 100 µm is 10 times smaller than 1 mm and is roughly the width of a human hair!

plant world. These dangerous nematodes feed on plant roots, which ultimately damages the plant and severely impacts plant growth. While feeding, nematodes create wounds on the roots, which can leave the plant's roots vulnerable to infection by other disease-causing organisms in the soil [1]. Nematodes that damage plant roots are often called **parasites**.

NEMATODE

A group of animals (Phylum: Nematoda) that have a worm-like shape that is long and cylindrical. They can be found on all seven continents (even Antarctica!), as well as in oceans and lakes.

PARASITES

An organism that relies on another host organism to steal food and nutrients.

PLANT-EATING NEMATODES: A THREAT TO ROOT CROPS

Some garden plants have roots that we eat, like carrots, beets, parsnips, and potatoes. Nematodes can damage these important food crops along with many others. Nematodes possess a straw-like mouth part that injects a mixture of **enzymes** into the plant, which breaks down the plant cells into a plant-cell soup. After the cells are broken down, the nematodes eat up this soup [2]. When nematodes feed on carrot roots during the early stages of the plant's life, this can cause serious damage or even the plant's death. When some plant-parasitic nematodes feed on carrots and parsnips early in the growing season, they damage the roots so much that farmers cannot sell them. If certain nematodes of the genus *Pratylenchus* feed on very young carrots, the root damage causes the carrots to develop forked roots (Figure 2). When there are many of plant-parasitic nematodes in the soil, large crop losses can result.

ENZYMES

Biological molecules that induce chemical reactions within cells.

Nematologists are scientists who study nematodes. Nematologists who research plant-parasitic nematodes can work with farmers to test

NEMATOLOGISTS

Scientists who study nematodes.


Figure 2

Figure 2

Carrots damaged by root-eating nematodes, resulting in forking of the main root.

the effectiveness of products that can kill dangerous nematodes, to find the best ways to combat these pests. Nematodes that eat root vegetables are particularly difficult to manage because sometimes farmers cannot see the symptoms of nematode infestation until the end of the season, when the roots are harvested.

HOW IS A NEMATODE INFESTATION DIAGNOSED?

Unlike insect pests, nematodes cannot be seen by the naked eye, so confirming a nematode infestation requires laboratory testing. If a farmer is concerned that he has plant-parasitic nematode damage, he can send a soil sample collected from his field to a nematology laboratory. In the laboratory, the soil is mixed with water and shaken through mesh sieves, in a process like sifting flour. The goal is to remove any large chunks of sand or other debris from the soil and capture only the nematodes. The mixture is transferred to tubes, which are put into a centrifuge—a large machine that spins extremely quickly to collect denser particles at the bottom of the tubes. The nematodes float in the water while heavier sand and mud particles stay in the bottom of the tube. Then, a sugar solution is added to the tube that causes the nematodes to float to the top of the tube. Scientists can collect the tiny animals and view them under a light microscope and identify which species of nematodes are in the farmer's field. {Jenskins} However, some species of nematodes look so much like other species that they need to be identified by analyzing their **DNA**.

DNA

The instructions required to make up cells that is stored in every organism.

HOW CAN FARMERS MANAGE NEMATODES?

Nematologists and other scientists work together to tackle the issues that farmers face with nematodes. There are some chemicals, called **nematicides**, that are currently used to treat nematode infestations. These chemicals are toxic to nematodes but can also be dangerous for the person applying them, and they are also expensive. Nematologists are researching other effective ways for farmers to manage these pests. Some types of **bacteria** and **fungi** [3] present in soil have nematocidal qualities, meaning they can kill or inhibit nematodes, and some are so specialized that they only attack the bad nematodes [4]. Many current studies are trying to identify and grow these beneficial species, so they can be applied to farmers' fields to lower the populations of bad nematodes in the soil. The most desirable nematicide would only be harmful to plant-parasitic nematodes, to ensure that soil resources and other helpful microscopic organisms in the soil are protected.

NEMATICIDE

A substance or organism that is effective at killing nematodes.

BACTERIA

A group of organisms that are prokaryotic, meaning that they lack a nucleus and only have one cell.

FUNGI

A group of organisms that are eukaryotic (cells contain a nucleus) and feed on organic matter. This group includes mushrooms and yeasts that we eat, as well as mildews and molds.

FUNGI AND BACTERIA: A POTENTIAL KEY TO FIGHTING PLANT-PARASITIC NEMATODES

Plant-parasitic soil nematodes are dangerous pests that can damage plant roots and cause farmers to lose a lot of money due to unsellable crops. Thus, it is important to find effective ways to manage plant-parasitic nematodes. Ideally, these treatments should be safe for the environment and other soil-living species and should also be easily affordable for the farmer. This is a considerable challenge for nematologists, but the future is bright! The potential key solution is finding types of soil fungi or bacteria that can control plant-parasitic nematodes to develop new, effective, and environmentally friendly products for farmers to use. In addition, using nematode DNA to identify the different species of nematodes in soil has helped to advance the field of nematology. Sometimes molecular science like DNA analysis can be expensive but, by working together, scientists can make advances in molecular techniques that will make the process cheaper for future scientists and farmers. These techniques will pave the way for teams of nematologists and their partner scientists to help find the best ways to control these harmful pests.

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YOUNG REVIEWERS

MARIE, AGE: 13
I study in 8th grade right now and I like biology and chemistry. Actually, I want to be a geneticist for life. I like sports too, my favorite one is acrobatics. I also like trampoline jumping, it is really fun.

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

NIVEDITA, AGE: 14
Hi I am Nivedita, my pronouns are she/her/hers, and I am excited to start this year off! A little about me, I love listening to music in my free time (Frank Ocean is a favorite→) and I like to draw when I can. I like hanging out my friends, and my favorite subject is chemistry!

SHREEYA, AGE: 11

Hi my name is Shreeya. I live with my sister and my parents. In my free time I like to walk with friends, play board games, and doing karate. During this time, I have been keeping myself busy by talking with my friends, reading Harry Potter books, and finishing a 3D Hogwarts Puzzle.

SHRIYA, AGE: 13

Hi, my name is Shriya. I live in the U.S. I am in eighth grade, and my favorite subjects are science and math. In my free time, I like to dance and do art. I just started working with Frontiers for Young Minds, and am very excited to continue!

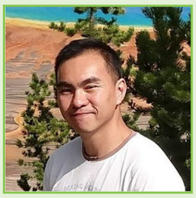
AUTHORS

ELISABETH DARLING

I am Ph.D. student at Michigan State University in the Department of Entomology. My co-advisors are Drs. Marisol Quintanilla and Henry Chung. My research project focuses on how different plant-feeding nematode species impact carrot plants. These nematodes are called root lesion nematodes, and they are really damaging to many different crops! I am also really interested in learning about how and to what extent plant feeding nematodes impact other specialty crop systems, like parsnip and hop plants. I love learning about different aspects of nematology.

MARISOL QUINTANILLA-TORNEL

Marisol Quintanilla is the Nematologist in the Entomology department in Michigan State University. Her nematology helps to evaluate management practices to reduce plant parasitic nematodes in Michigan crops. She obtained Ph.D. from Michigan State University. *marisol@msu.edu



HENRY CHUNG

Henry is a biologist working at Michigan State University. He is fascinated by how life works at the molecular level. Henry studies insects and nematodes to understand how these organisms can adapt to different environments or feed on different host plants.

BIODIVERSITY
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THE BIZARRE ROLE OF SOIL ANIMALS IN THE DECOMPOSITION OF DEAD LEAVES

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YOUNG REVIEWER:

JUAN DIEGO
AGE: 15

When plant leaves die, they fall and accumulate on the soil where an important process occurs: they decompose. Decomposition is essential for recycling nutrients and returning them to the soil. It is mainly done by an army of creatures called microbes, invisible to the naked eye, that slowly make the dead leaves rot. But larger creatures, like millipede and snails, also eat dead leaves. These large creatures do not digest these leaves very well and return most of the leaf matter to the soil as poo, which is further decomposed by microbes. Does this transformation of dead leaves into poo affect the recycling process? By collecting poo from many soil animals feeding on dead leaves, we found that they decomposed faster than intact dead leaves. This means that soil animals help the decomposition of dead leaves, not by digesting them, but by transforming them into poo.

WHY STUDY DEAD LEAVES?

Plants are the basis of all life on Earth. Thanks to their leaves, plants can use the energy from the sun to capture carbon dioxide from the air and transform it into sugars. This process, called **photosynthesis**, is absolutely essential to life on Earth. The sugars are used to grow more plant parts (leaves, stems, roots), which can then be eaten by many different creatures. But a plant's leaves only live for several months to a few years. When the time comes for plants to shed them, dead leaves accumulate on the soil where another important process begins: dead leaves decompose. This **decomposition** process is just as critical as photosynthesis, as it allows the carbon that the leaves are made of to return to the atmosphere as carbon dioxide, which can be used again by other plants. Through decomposition, nutrients contained in the dead leaves also return to the soil, where they can be used again by plants to form new leaves. It is only thanks to this fragile balance between photosynthesis and decomposition that the cycle of life continues.

PHOTOSYNTHESIS

The process by which plants capture the energy from sunlight with their leaves to transform carbon dioxide and water into sugars.

DECOMPOSITION

The process by which complex plant or animal matter is broken down into a simpler form, producing carbon dioxide, and nutrients.

MICROBES DECOMPOSE DEAD LEAVES

How does decomposition happen? This crucial process is mainly carried out by one group of soil organisms: **microbes**. Microbes consist of fungi—the same organisms that form mushrooms—and bacteria. Microbes are so tiny that they are mostly invisible to the naked eye, yet they are extremely abundant in the soil. Just 1 g of soil can contain 10 billion microbes. These microbes use dead leaves as their food. They digest leaves by releasing many different **enzymes** into the soil around them. These enzymes are like scissors, cutting the large dead leaves into microscopic bits. Microbes can then digest these leaf bits to get energy and grow. Then, the microbes release the carbon back to the atmosphere as carbon dioxide. The cycle of life can continue.

MICROBES

Tiny living things, invisible to the naked eye, such as bacteria or fungi. Also called "microorganisms."

ENZYME

Proteins that can break down large and complex molecules into smaller and simpler molecules.

But microbes cannot decompose all dead leaves at the same speed. Some plants, like pines or beeches, form leaves that are sturdy, quite thick, and poor in nutrients. These leaves are not very good at photosynthesis, but they can survive even in difficult conditions. Consequently, when dead, these dead leaves decompose slowly because they offer few nutrients and little surface for microbes to grow on. On the other hand, plants like ash trees or clover form leaves that are much thinner and have more nutrients. These leaves are less resistant to damage but are better at photosynthesis. When these thinner, more nutritious leaves die, they offer a lot more nutrients and more surface area for microbes, and therefore they decompose faster.

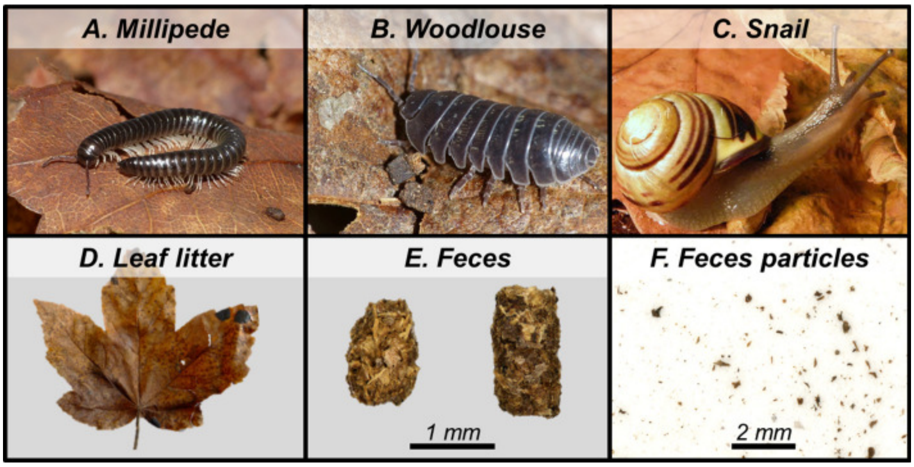

Figure 1

Figure 1

(A–C) Examples of soil animals that eat dead leaves and transform them into feces. **(D)** Example of dead leaves that these animals can eat. **(E)** Examples of feces from animals that eat dead leaves. **(F)** The feces of leaf-eating animals are made up of many small leaf particles.

ANIMALS HELP MICROBES WITH DECOMPOSITION

Microbes are not the only soil creatures that decompose dead leaves. Many larger soil creatures, such as millipedes, earthworms, woodlice, and snails, also feed on dead leaves (Figures 1A–C). In some types of forests, and even in deserts, the majority of the dead leaves that fall every year are eaten by these animals [1–4]. However, of all the leaves that these animals eat (e.g., Figure 1D), only a small part is actually digested and used by the animals. The majority is returned to the soil as **feces—** in other words, poo (Figure 1E). This means that, in ecosystems where these animals are abundant, the main sources of organic matter for bacteria and fungi are not dead leaves, but feces. Regardless of the type of dead leaves eaten, these feces are always much smaller than dead leaves, and they are made of tens of thousands of tiny leaf pieces (Figure 1F). This transformation from large, intact dead leaves into tiny pieces provides a lot more surface area for microbes to grow on and to decompose.

FECES (FEE-SEEZ)

Remains of eaten food that is not digested by animals. In other words, poo.

The importance of converting dead leaves into feces is not well-understood. Are feces more easily decomposed by microbes than intact dead leaves are? If so, is this effect more important for thick, sturdy leaves than for the thin leaves that are already easily degraded by microbes? Do all animals that feed on dead leaves help microbes to break the leaves down? In this study, we aimed to provide answers to these questions [5].

THE FECES FACTORY: STUDYING DECOMPOSITION IN THE LAB

To study the importance of converting dead leaves into feces, we needed to find and collect tens of thousands of fresh feces from various soil animals that eat different kinds of dead leaves. This is an impossible task in the wild, because feces are very small and

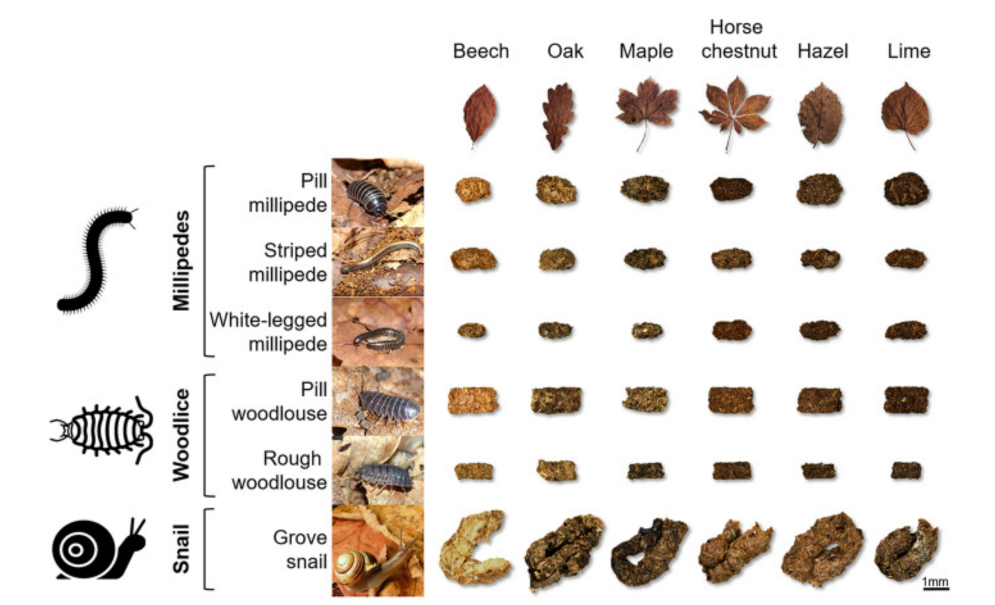

Figure 2

Figure 2

Feces collected from six different soil animals that were feeding on six different types of dead leaves. Feces are drawn to scale but leaves and animals are not to scale. You can see that the color of feces depends on the dead leaves that were eaten, with light color when animal ate beech leaves and darker color when they ate lime leaves. Instead, the shape of feces depends on the animal, with oval feces for millipedes, rectangular feces for woodlice, and cylinders for snails (Image credit: adapted from [5]).

it is impossible to determine the species of animals that produced the feces, or the type of dead leaves that the animal ate. So, we invented a new, special type of experiment: a feces factory. We started by wandering in various forests and grasslands of the Scottish Lowlands, where we collected thousands of soil animals from six species, including three millipede species, two woodlouse species, and one snail species. We also collected dead leaves from six tree species known to decompose at different speeds: oaks, beeches, hazelnuts, maples, horse chestnuts, and limes (Figure 2). We brought all the samples back to the laboratory and, using plastic boxes, we paired each species of animals with each type of dead leaves. In total, we had 36 leaf/animal combinations. We then let the animals eat and, twice a week for 1 month, we collected their feces. These feces were very diverse: they varied in color depending on the dead leaves that were eaten, and they varied in shape depending on the type of animal (Figure 2).

After the feces collection step, we measured how fast these feces decomposed, compared to the intact dead leaves. We wanted to measure this under conditions that other researchers across the world could repeat to verify our results or to compare our findings to those using different animal or leaf species. To do so, we created small, artificial soil systems in the laboratory. We filled small jars with soil from a local field and placed a small amount of feces or dead leaves on top of this soil, separated from the soil surface by a fine mesh. The mesh allowed us to retrieve the remaining pieces of feces or dead leaves easily, but it still allowed the microbes from the soil to move through it and decompose the feces or dead leaves. We placed the jars in a dark, warm, humid room for 6 months. Every week, we added water to the jars to keep the soil moisture optimum for microbes. After 6

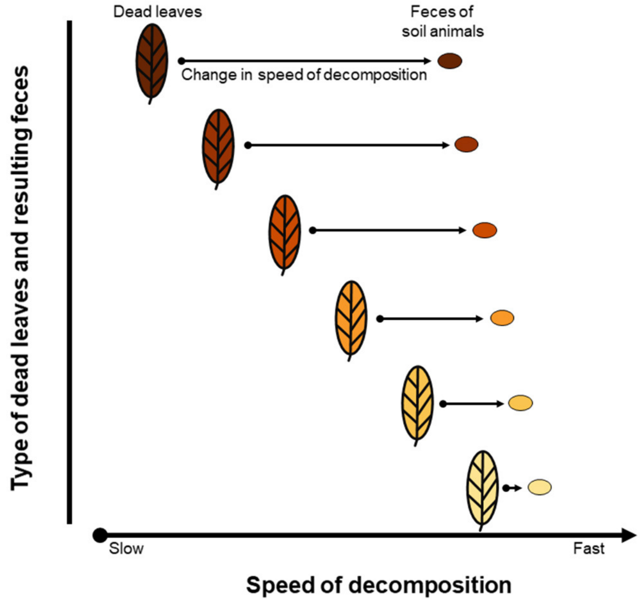

Figure 3

Figure 3

By transforming dead leaves into feces, soil animals affect the speed at which dead leaves decompose. On average, the feces of soil animals decomposed 38% faster than the intact dead leaves did. This effect depends on the type of dead leaves. When animals ate dead leaves that were easy for microbes to decompose (shown in light yellow), their feces did not decompose much faster than dead leaves. However, when they ate dead leaves that were difficult for microbes to decompose (shown in dark brown), the resulting leaf fragments in the feces decomposed much faster.

months, we retrieved the remaining feces and dead leaves. We dried them, weighed them, and compared the mass of the samples to their starting masses, to tell us how much of the leaves and feces had been decomposed by the microbes during those 6 months.

WHAT DID WE FIND?

Our experiments led to two very interesting discoveries. First, for all the animal species we studied, we found that the feces decomposed 38% faster on average than the dead leaves did (Figure 3). These results were very consistent even though snails, millipedes, and woodlice are very different species. We think that feces decomposes faster because the animals transform the large dead leaves into thousands of small pieces, which are easier for microbes to grow on and decompose. Our second important discovery was that the increased speed of decomposition was not the same for all types of dead leaves. When animals ate dead leaves that were easy for microbes to decompose, their feces did not decompose much faster than the dead leaves themselves. However, when animals ate dead leaves that were difficult for microbes to decompose, their feces decomposed much faster than the uneaten leaves did. Because of this, the big differences in the speed of decomposition between various types of dead leaves nearly disappear once the leaves are eaten by animals and transformed into feces.

SOIL ANIMALS CONTRIBUTE TO THE CYCLE OF LIFE

In summary, by transforming dead leaves into feces, soil animals speed up the decomposition carried out by microbes. This is the reason why we do not see dead leaves piling up on top of the soil, particularly under plants with slow-decomposing leaves. More importantly, by transforming dead leaves into feces, soil animals help the carbon from the leaves return to the atmosphere as carbon dioxide, and help the nutrients return to the soil, where these critical substances can be used again by plants. Thus, soil animals help to maintain the critical balance between photosynthesis and decomposition that sustains plants—and that therefore sustains all life on Earth!

ORIGINAL SOURCE ARTICLE

Joly, F.-X., Coq, S., Coulis, M., David, J.-F., Hättenschwiler, S., Mueller, C. W., et al. 2020. Detritivore conversion of litter into faeces accelerates organic matter turnover. *Commun. Biol*. 3:660. doi: 10.1038/s42003-020-01392-4

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YOUNG REVIEWER

JUAN DIEGO, AGE: 15

Hi, my name is Juan Diego, I just turned 15. I am from Ecuador but I grew up in the United States. I have many hobbies. My favorite pass time is playing video games because it allows me to play with my friends now that I am locked in because of the pandemic. I enjoy animals and nature. That is why as part of a school project, currently, I am working on a small stickers book about endangered species of Ecuador.

AUTHORS

FRANÇOIS-XAVIER JOLY

François-Xavier Joly is a French soil ecologist working at the University of Vienna, in Austria. His research focuses on understanding how soil organisms contribute to the decay of dead plants, and how this process may change due to global changes, such as biodiversity loss and climate change. *joly.fx@gmail.com

JENS-ARNE SUBKE

Jens-Arne Subke is an ecosystem ecologist at the University of Stirling, and is interested in the interactions of plants, soil, and the environment. He tries to answer questions about the way carbon taken from the atmosphere by plants can be stabilized in soils, to reduce atmospheric CO_2 concentrations.

BIODIVERSITY
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DECOMPOSITION IN PEATLANDS: WHO ARE THE PLAYERS AND WHAT AFFECTS THEM?

Carlos Barreto*† and Zoë Lindo†

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YOUNG REVIEWERS:

ADAM

AGE: 14

ALEXANDER

AGE: 12

All soils store carbon. As plants grow, they take up carbon from the atmosphere and this carbon enters the soil when they die. This dead plant material slowly decomposes as organisms, such as bacteria, fungi, and tiny animals called mites and springtails use this carbon as a food source. Decomposition is very slow in peatlands, and as a result, much of the carbon from dead plants remains in the soil, which can help slow climate warming. Decomposition in peatlands depends on how wet the soil is, and the different types of plants and soil organisms. We discovered that, in a peatland in northern Canada, dead plant material of different plant types decomposed at different rates, and more mites and springtails aiding in decomposition were found in wetter areas. Because peatlands are important for carbon storage, understanding who the players of decomposition are is important for understanding how to slow climate warming.

INTRODUCTION

DECOMPOSITION

Break-down of dead plants and animals which is measured as loss.

ORGANISM

An individual plant, animal, bacteria, or fungi.

PEATLANDS

Peatlands are a type of wetlands. The term "peatland" refers to the peat soil and the wetland habitat growing on its surface.

Decomposition is the natural process of breaking down dead plants and animals. During decomposition, the chemical composition of dead plants and animals changes, and carbon is released into the atmosphere. Decomposition results from the activities of different types of **organisms** like fungi (Figure 1D), bacteria (Figure 1E), worms (Figure 1F), oribatid mites (Figure 1B), and springtails (Figure 1C). For example, bacteria and fungi directly breakdown dead plant material and are considered primary decomposers. Fungi and bacteria (primary decomposers) are eaten by oribatid mites and springtails (secondary decomposers). In turn, predatory mites (Figure 1A) consume secondary decomposers. Therefore, oribatid mites and springtails indirectly affect how fast decomposition happens.

Peatlands are important ecosystems that accumulate partially decomposed vegetation (Figure 1G), and thus store carbon contained in the decomposing plant material [1] (Figure 2A). Their main plant type is mosses (Figure 2E). Mosses are small, slow growing plants that need a lot of water to survive because they do not have real roots. They also decompose very slowly in peatlands after they die.

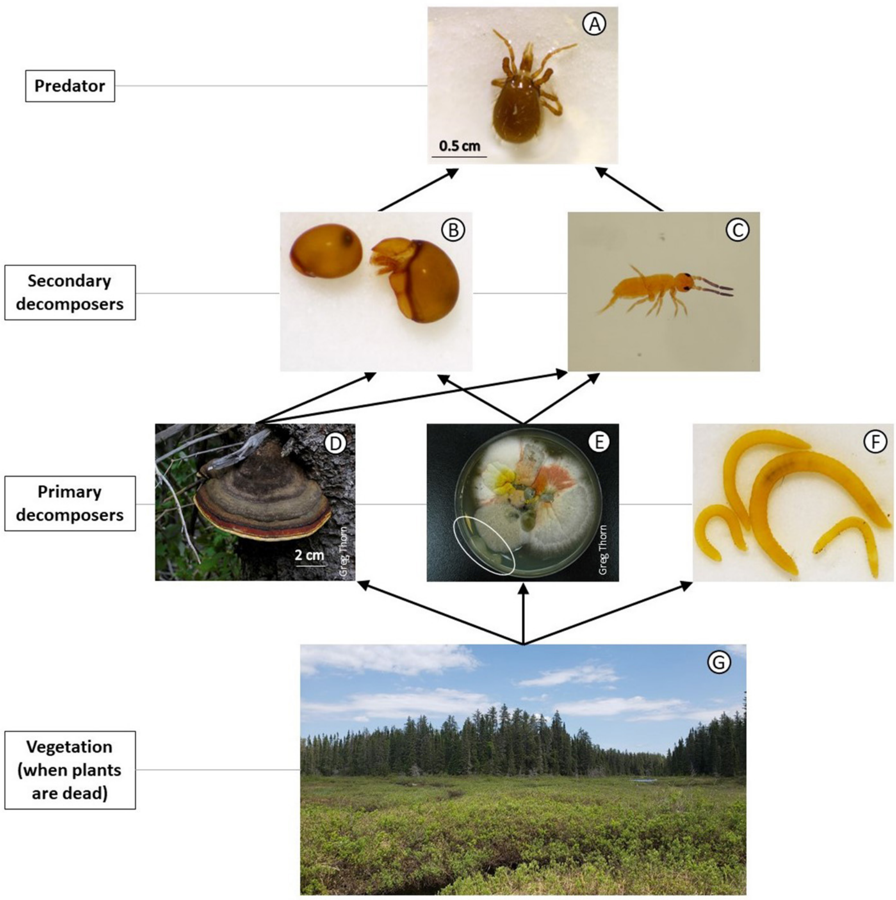

Figure 1

Figure 1

Example of simplified soil food web: Example of a predator **(A)** Predatory mite; Secondary decomposers. **(B)** Example of oribatid mites. **(C)** Example of springtail; Primary decomposers. **(D)** Fungi. **(E)** Fungi with bacteria at the bottom of the picture (ellipse). **(F)** Earthworms. **(G)** Vegetation in the peatland (only dead plants undergo decomposition). Arrows represent feeding links and point in the direction of the energy flow.

Figure 2

Figure 2

(A) Peatland. **(B)** Hummock in front of a tree behind it. **(C)** Hollow with litterbags being deployed. **(D)** Litterbags (10 × 7 cm and the holes were 1 mm). **(E)** Moss (species *Sphagnum* sp.). **(F)** Shrub (species *Chamaedaphne calyculata*). **(G)** Sedge (species *Carex* sp.). **(H)** Tullgren funnel (fauna extractor).

Peatlands are very wet, and decomposition is slow compared to other ecosystems like forests or grasslands which are drier. As a result, more dead plants accumulate, which means less carbon is released to the atmosphere from peatlands than from many other ecosystem types. In other words, more carbon enters and is held within peatland soils than is released back to the atmosphere as carbon dioxide. Carbon dioxide is a greenhouse gas that traps heat in the Earth's atmosphere, and therefore, peatlands can help slow or reverse climate warming. Peatlands could help reverse **climate change** by stocking more carbon in their soil.

CLIMATE CHANGE

Climate change is the warming of the entire world, mostly caused by increasing levels of carbon dioxide in the atmosphere. The main source of carbon dioxide is human activities.

Different factors can influence decomposition in peatlands; for instance, how wet the soil is, the different types of dead plant material present, and the soil **community**–the types of different organisms found in soil. Because we wanted to know what influences decomposition in peatlands, we went to the Boreal forest in northern Ontario, Canada to study the mites and springtails living in a beautiful peatland. We studied mite and springtail communities living in different areas of that peatland for two reasons: first because it is still not well-known what **species** of mites and springtails are found in peatland communities, and second because we also wanted to know how much they could help decompose leaves.

COMMUNITY

A group of different species living in the same area and that interact with each other.

SPECIES

Organisms that share the same physical and genetic features; for example, all humans comprise a species, as do all dogs, all cats are considered a species too.

WHAT DID WE DO?

A group of researchers from Western University (London, Ontario, Canada) have been working in a peatland in northern Ontario (Canada) in collaboration with Ontario Provincial government scientists at the Ontario Forest Research Institute. We are trying to answer different questions about peatlands by studying the plants, mites, insects, mercury, carbon, and water at this site. This peatland site is mostly covered in *Sphagnum* mosses that create raised areas called hummocks (Figure 2B) and depressions called hollows (Figure 2C). Hummocks are an accumulation of mosses and other plants, and they are dry at the surface. On the other hand, hollows, as depressions on the ground, are generally very wet at the surface. For this study, we wanted to know whether mite and springtail communities (secondary decomposers), as well as decomposition rates (how fast dead plants decompose) differed between hummocks and hollows at our peatland site.

What Did We Do in the Peatland?

One way to study decomposition is to use litterbags [2]. Litterbags are small bags made of a mesh material that can be filled with dead plants; the holes in the mesh allow tiny organisms to come and go. We filled the litterbags (Figure 2D) with leaves of three different plants: moss (Figure 2E), shrub (Figure 2F) (these are small bushes), or sedge leaves (Figure 2G) (these are grass-like plants), and we weighed them to know the initial amount of dry leaves in each litterbag.

In June 2015, we placed one litterbag of each plant type (three litterbags) on five different hummocks (dry raised areas) and in five different hollows (wet depressions). Litterbags were pinned to the soil surface and left there for a whole year so that organisms had enough time to colonize the litterbags and help decompose the leaves. After 1 year, we went back to the peatland site, collected the litterbags, and brought them back to our laboratory at Western University, in southern Ontario (Canada).

What Did We Do in the Laboratory?

In the laboratory, we placed each litterbag onto a special piece of equipment called a Tullgren funnel (Figure 2H) that has a light bulb inside of it, and when it is on, it warms the whole litterbag so that it forces the organisms to move out of the litterbags into a small vial where we can observe them. Afterwards, we cut the litterbags open and dried the leaves in an oven, and then weighed them with a scale. We observed the organisms we collected from the litterbags using a microscope and separated them into different species based on what they looked like. We also counted how many of each species we found in each litterbag. This part of the work took two researchers about 5 days working all day long. Finally, we compared the weight of the plant leaves left at our peatland site for 1 year, to the initial weight of the

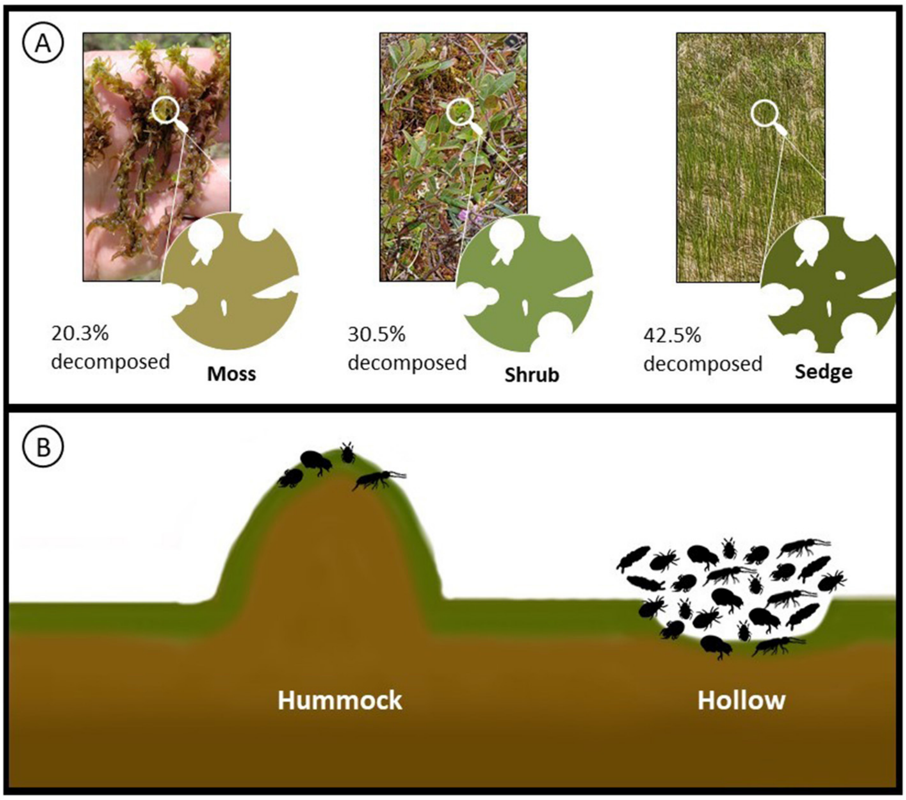

Figure 3

Figure 3

(A) Different levels of decomposition on different leaf types; sedges decomposed more within the 1 year experiment. **(B)** Hollows had more species and individuals of oribatid mites and springtails. Pictures are not to scale.

leaves before they went to our peatland site. The difference in weight told us how much of the leaves had decomposed over the course of 1 year, in other words, how much the animals had eaten.

WHAT DID WE FIND?

Leaves from the different plants decomposed at different rates. The sedge leaves, that resemble grasses (reduction of 42.5%), decomposed more than the shrub leaves (reduction of 30.5%), which in turn decomposed more than the moss (reduction of 20.3%) in the litterbags (Figure 3A). However, it did not matter whether the litterbags were on the hummock surface or in the hollow, as we found a similar amount of decomposition in both cases. This was because even though hollows are wetter than hummocks, neither were fully saturated in a way that decomposition would slow significantly in our sites, compared to other submerged parts of the peatland.

A single litterbag had between zero and 203 individual mites and between zero and 123 individual springtails. We found more individual mites and springtails from our litterbags placed in hollows (wet depressions) than on hummocks (dry raised areas) (Figure 3B). But the tiny animals did not have a preferred leaf type, meaning they were found in similar numbers in litterbags that contained sedges, shrubs, or mosses. Certain mites called oribatid mites (Figure 1B) were the dominant group in the litterbags (53.6% of the total number of individuals) followed by springtails, representing 40%. Other groups of mites that were not numerous, a few spiders, and a few insect larvae, were also collected, but altogether were only 6.4% of the animals in the litterbags. Besides having more individuals, hollows (wet depressions) also had more species collected. In total, we found 20 species from 506 individual oribatid mites and seven species from 378 individual springtails (Figure 1C). The communities of oribatid mites were more similar to one another in hollows and had the most species present. The species of oribatid mites found in hummocks seemed to be random.

WHY IS THIS IMPORTANT?

Few studies have been done for mites and springtails in peatlands, so the first reason we did this study was to gain information on what species of oribatid mites lived in our peatland. Also, understanding how the tiny animal communities differ provides us with an idea on how fast or slow decomposition naturally happens on leaves in peatlands.

Although in most cases, oribatid mites and springtails are considered secondary decomposers [3] because they feed on fungi and bacteria, understanding who they are, where they live, and how much they contribute to decomposition processes is important for predicting the amount of carbon released to the atmosphere from soils. Peatland soils are a special case because peatlands only occupy a small portion of the world, but their slow decomposition means peatlands can store very high amounts of carbon [1].

Increases in global temperatures due to climate change are expected to change the plant types we observe in peatlands. Specifically, warmer temperatures will allow sedges to take over where mosses were previously found [4]. In our study, we found that sedges decomposed faster than mosses, and this means that a change in the type of plants in peatlands from mosses to sedges may increase the amount of carbon being released through decomposition.

Even though we did not collect bacteria and fungi in this specific study, other studies by our research group in the same peatland found that communities of fungi [5] and bacteria [6] also varied between hummocks and hollows. Mites and springtails are understudied, so we chose to focus on them. Results for fungi and bacteria also suggest that climate change may change the carbon storage ability of peatlands. In other words, increases in temperature may speed up the overall decomposition of leaves, releasing more carbon dioxide into the atmosphere, and making climate change even more pronounced. Nonetheless, we must engage in the conservation of peatlands, as these are important ecosystems for our life in a future where more carbon dioxide will likely be present in the atmosphere. The time for conservation actions is now!

AUTHOR CONTRIBUTIONS

CB and ZL wrote the manuscript and CB created the figures.

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ORIGINAL SOURCE ARTICLE

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

YOUNG REVIEWERS

ADAM, AGE: 14

Hi, my name is Adam. I live with my parents, older brother, dog, fish, and two birds. I am a big fan of Science and History. I like to draw, write, and read. My favorite sport is soccer (or football). I enjoy swimming in the ocean and playing video games.

ALEXANDER, AGE: 12

I am a 12 years old boy in the seventh grade and my favorite subject is mathematics. I like to play the guitar and am learning how to play drums.

AUTHORS

CARLOS BARRETO

Since a very young age I realized that I liked animals, maybe too much. Science in school was always my favorite discipline, all the way through to high school. It is then that I decided that I wanted to do something that involved science and animals. I tried to be a vet; it did not work out. No regrets. So, I became an Ecologist a few years later,

and since then, I have worked with little animals (mostly insects and mites) in tropical forests, iron ore and limestone caves, boreal forests, urban fields, and peatlands on three continents; South America, North America, and Europe. *cbarreto@uwo.ca
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ZOË LINDO

Dr. Zoë Lindo is an expert on soil biodiversity and ecosystem function. She has worked extensively in Canadian forests including the mixed-wood boreal of Alberta, the subarctic taiga of Quebec, the coastal temperate rainforest of British Columbia, and the black spruce/peatlands of Ontario. "The overall focus of my research aims to mitigate biodiversity loss in association with human-induced environmental change and maintain ecosystem functioning in Canadian forest and soil ecosystems. I describe myself as a biodiversity scientist to encompass the breadth of my research in the areas of community ecology, soil ecology, and taxonomy." †orcid.org/0000-0001-9942-7204

THE EARTH AND ITS RESOURCES
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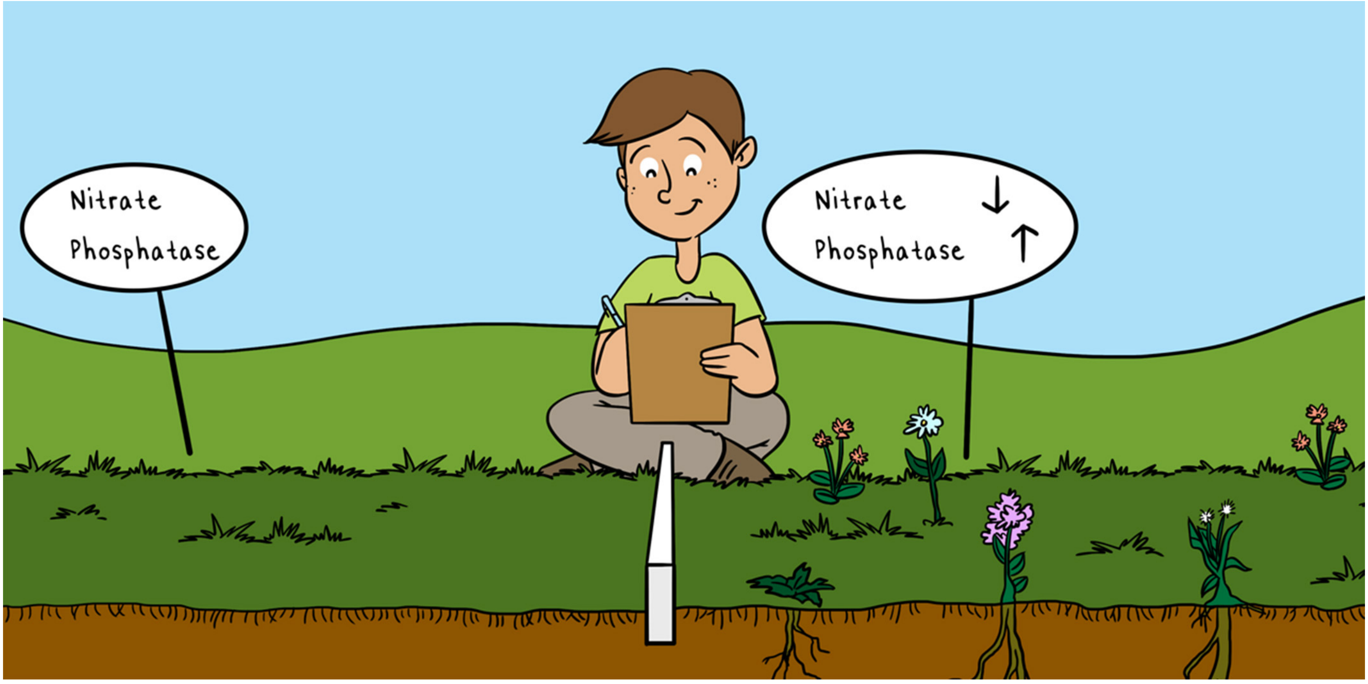


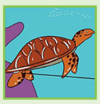
DOES PLANT BIODIVERSITY INFLUENCE NUTRIENT CYCLES?

Eva Koller-France[1], Wolfgang Wilcke[2] and Yvonne Oelmann[1]*

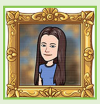
[1] *Department of Geography/Geoecology, University of Tübingen, Tübingen, Germany*

[2] *Institute for Geography and Geoecology, Karlsruhe Institute of Technology, Karlsruhe, Germany*

YOUNG REVIEWERS:



MACKENZIE
AGE: 14



ROSE
AGE: 14

All living things, like humans, animals, plants, and even microbes, need to take up the same nutrient elements to live, most importantly nitrogen and phosphorus. Understanding the cycling of these elements through the ecosystem is one key to understanding why ecosystems work the way they do. One of the questions we are asking is if the diversity of organisms, like plants or insects, is related to these nutrient cycles. When plant communities are made up of many different plant species, they seem to make better use of the available soil nutrients than plant communities made up of fewer species. This may be because of something called complementarity, which means different plant species access the available nutrients in different ways, for example from different soil depths. In this article, we will describe the connections between plant biodiversity and soil nutrient cycling and discuss the implications for the functioning of the whole ecosystem.

WHY DO WE CARE ABOUT BIODIVERSITY EFFECTS ON NUTRIENT CYCLES?

All living things on earth need certain nutrient elements. In natural ecosystems, these nutrients, most importantly nitrogen and phosphorus, are taken up by plants from the soil. Plants may then be eaten by animals or people. The nutrients are returned to the soil through animal droppings and when plants and animals die, and then can be taken up again by new plants. Because everything repeats on and on, we call this the nutrient cycle.

In different ecosystems and under different environmental conditions, the cycling of nutrients can work faster or slower, and nutrients can be used and recycled by different parts of the system in more or less complete ways, which may cause imbalances. For example, sometimes there are more available nutrients than are needed because farmers add too much fertilizer to the soil, or because there is a warm day in winter when tiny organisms in soil recycle and release nutrients from dead material which are not needed by plants during their inactive phase. If there are excess nutrients in the soil, those nutrients may be washed out into the groundwater or into lakes and streams. From there, they are transported to bigger rivers and finally to the sea. If these water bodies receive too great an amount of nutrients, there can be rapid growth of algae, which damages freshwater ecosystems. In this case, too much of a good thing can definitely be a big problem. This is why studying the nutrient cycles of ecosystems under different conditions is not just a good way of learning how ecosystems work, but also helps us with practical considerations, such as how to protect our supply of clean water.

BIODIVERSITY

Simply put, the number of species in an ecosystem.

We know that the **biodiversity**, the richness of species, of an ecosystem plays a role in many of its functions, and we also know that biodiversity is decreasing on a global scale. For example, some species of bees and rare flowers are going extinct, and therefore many ecosystems are now less diverse than they previously were. This is one of the reasons we are interested in how the nutrient cycle responds to changes in biodiversity.

WHAT EFFECT DOES BIODIVERSITY HAVE ON NITROGEN IN SOIL?

A connection between biodiversity and nitrogen (in the form of nitrate, one form of nitrogen that is taken up by plants) in soil has been fairly well-established in experiments studying the effects of biodiversity on ecosystems [1]. In these experiments, plant diversity is studied by creating small model ecosystems (often grasslands, where this is easiest to do) with a known number of species growing under the same environmental conditions, for example in the same field. This is done by sowing a specific mixture of seeds into a square of ground, called the experimental plot. These small plots are regularly checked for plants that were not sown into them, which are removed. Results from experimental plots with higher or lower diversity can be compared to each other quite well, since the only difference between plots should be the number of species growing on them.

In these experiments in grasslands, we find that the higher the number of plant species, the lower the concentration of nitrogen in soil, which is fairly easy to explain. If plants take up more nitrogen, this means that less is "left over" in the soil. In ecosystems that are reasonably rich in nutrients, this also means less nitrogen is washed out into ground water, which protects ground water quality and freshwater ecosystems.

To understand these results, we must consider one of the other important effects of plant biodiversity on unfertilized ecosystems, which is an increase in plant growth. When there is higher plant biodiversity, there is generally more plant **biomass**, for example more hay on meadows, being produced. More nitrogen is needed to build this greater amount of biomass. Of course, another way of looking at it is that this greater biomass can only be built if the plants can access more nitrogen (and all other necessary nutrients). This is where something called complementarity comes into play.

BIOMASS

The total amount of mass present in components of the ecosystem, such as plants or animals. For example, plant biomass, which we talked about in this article, can be defined as all the living matter contained in the plant roots, shoots, leaves, flowers, and fruits. In temperate climate, biomass is not constant but usually increases from spring to late summer and decreases in autumn.

DIFFERENT SPECIES WORK TOGETHER TO ACCESS NUTRIENTS

Complementarity describes a mechanism by which different parts of an ecosystem (such as different species) use different essential (and limited) resources from different locations or at different times. The use of this resource by one species "complements" that of the other species. In this way, the plant community uses the available resources more completely. In our example, the resource used is soil available nitrogen. You probably know that plants take up nutrients from the soil with their roots. But not all roots are the same. Some plants have strong, long roots that can access deeper parts of the soil, but do not branch out much on their way there. Others have roots that only reach shallower parts of the soil. If you combine even just these two types, you can see that one plant species takes water and nutrients out of the shallow soil, and the other takes the same resources out of the deeper soil (Figure 1). The two types of root systems complement each other, and this means that the nutrients that would have gone unused in a system that only contained one or the other of these plants are now being used to produce more plant biomass, which serves as food for microbes and animals. These two plants use different niches in space, which we call spatial niches. Similarly, not all plants develop and grow at the same time. If one species develops early in the spring and another only starts growing in summer, then these two species will not take up most of their nutrients at the same time. They use

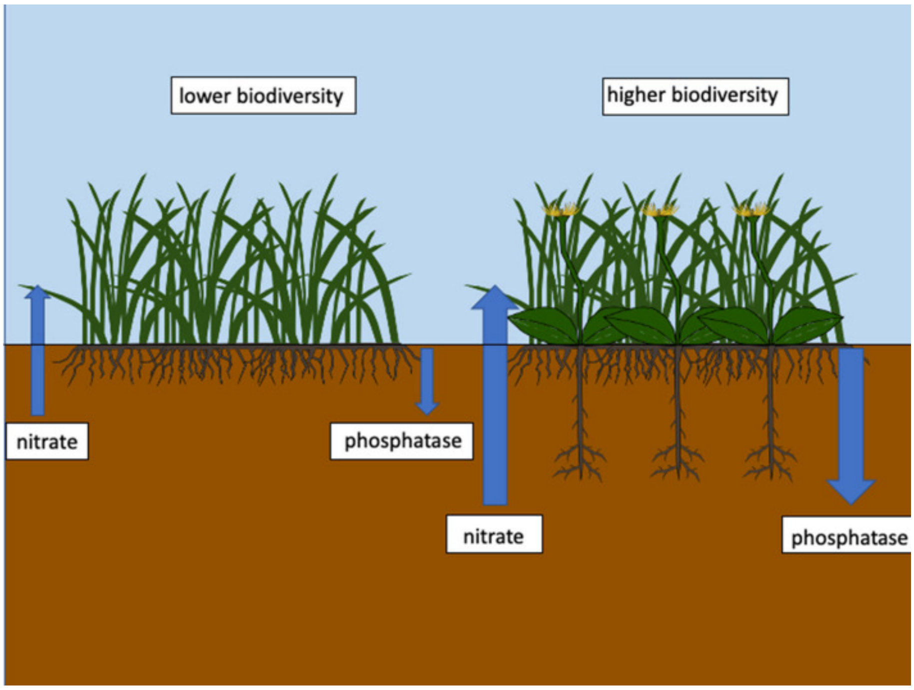


Figure 1

Figure 1

Complementarity between rooting systems in soil systems under higher biodiversity leads to more efficient nutrient cycling. Broad arrows represent greater uptake of nitrate or higher phosphatase activity in more diverse ecosystems; narrow arrows represent less uptake of nitrate or lower phosphatase activity in less diverse ecosystems. While nitrate is being taken up by the roots and transported into the above-ground parts of the plant, phosphatase is released downwards into the soil to make phosphate available for uptake by roots.

two temporal niches, or niches in time, and they too access nutrients and other resources much more completely together than they would alone. So, when not only two but many plants grow together using different spatial and temporal niches, the nitrogen in soil is used more completely, and therefore, less is left in the soil for us to measure.

PLANT BIODIVERSITY AND SOIL PHOSPHORUS

It would be logical to assume that the effect of biodiversity we have just described for soil nitrogen is the same for soil phosphorus. Both are essential nutrient elements, and both can be limiting to biomass production. However, perhaps surprisingly at first, this is not something we find in biodiversity experiments, in which we control the species richness of single ecosystems to study biodiversity effects on these ecosystems. Often, concentrations of readily available phosphate, the chemical form of phosphorus that is taken up by plants, are so low in the soils of the systems we study that there simply cannot be any "leftovers" as is sometimes the case with nitrogen. So, does plant diversity have any effect on phosphorus cycling at all?

The short answer is yes, probably. We know that there is more phosphorus in the plant biomass of more diverse systems and this effect—similar to nitrogen—is caused by the greater amount of biomass that comes from a greater phosphorus uptake by plants [2]. The question is how more diverse ecosystems can take up more phosphate, even though we cannot see the results of this in the soil.

ENZYME

Small molecules that speed up a (bio-)chemical reaction in or outside of cells.

To access phosphate in the soil, both plants and microbes use **enzymes** (substances that facilitate certain chemical reactions) to split phosphate from more complex chemical molecules that exist in soil humus, the organic part of the soil you likely know as compost. We can measure the speed and function of phosphatase, the enzyme responsible for making phosphate accessible in this way, which allows us to estimate how much phosphate is being released from the soil for plant or microbial use. In ecosystems where plant biodiversity is higher, we find more activity in soil phosphatases (Figure 1) [3]. This indicates that, while we cannot see the higher uptake of phosphorus from soils with higher plant biodiversity the same way we can for nitrogen, we can see that there is more efficient access to phosphorus in soils through higher phosphatase activity. This is one way plant biodiversity can influence phosphorus cycling through the ecosystem.

THE IMPORTANCE OF BIODIVERSITY FOR ECOSYSTEM FUNCTION

ECOSYSTEM PRODUCTIVITY

The amount of organic material, such as plant biomass, produced by the ecosystem in a given time. A good example for this would be how much wheat or hay is harvested in the course of 1 year from a field.

So, what does all this mean? The general assumption is that with continued global changes, more species will be lost from ecosystems and biodiversity will continue to decline. With the decline of biodiversity, it is likely that both nitrogen and phosphorus cycling will become less efficient, that is, ecosystems will be less capable of keeping and recycling nitrogen and phosphorus than they are now. This is a big change in the ecosystem and may be one factor leading to a reduction of **ecosystem productivity**. Declining biodiversity may also lead to nutrients being lost from the system, such as nitrate being washed out into the groundwater. Excess nitrate is a pollutant if it gets into our drinking water and it can also have negative effects on the aquatic ecosystems it is transported to, for example through the excessive growth of algae. And at the other end, these nutrients are then not available to plants, microbes or animals in the original ecosystem, leaving a system that is likely poorer in nutrients and less capable of sustaining the organisms living in it.

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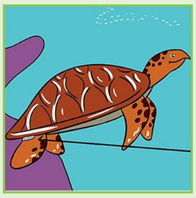
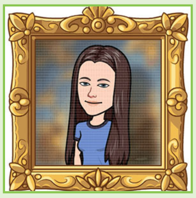
YOUNG REVIEWERS



MACKENZIE, AGE: 14

My name is Mackenzie, and I enjoy music (both playing and listening), books (fantasy in particular), and sports (my favorite is tennis). I also enjoy science, math, and language, but the thing I enjoy most is backpack camping.



ROSE, AGE: 14

Hello. I am 14 years old and live in Canada. I like knitting, crocheting, and reading.

AUTHORS

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Eva is an ecosystem ecologist interested in the effects of all kinds of global changes on ecosystem carbon and nutrient cycling. She spent her formative Ph.D. years wandering the Arctic to study the effects of environmental change on the links between carbon and nutrient cycles, and she is now a post-doctoral researcher for the Jena Experiment (http://www.the-jena-experiment.de/), studying the long-term effects of plant species richness on nitrogen and phosphorus cycling. *ekoller@gmail.com

WOLFGANG WILCKE

Wolfgang Wilcke studied Geoecology at the University of Bayreuth and is now Professor of Geomorphology and Soil Science at the Karlsruhe Institute of Technology (KIT) after research and teaching stations at the TU Berlin, the Johannes Gutenberg University Mainz and the University of Berne. His research interests focus on the effects of environmental change, including climate change, land-use change, nutrient deposition, pollution, and biodiversity loss, on the element cycling between soils and plants. He uses soil chemical analyses, long-term observations of element fluxes, and stable isotope approaches.

YVONNE OELMANN

Yvonne is a soil scientist working on ecosystem carbon and nutrient cycling. She did her Ph.D. at the TU Berlin on the effects of plant diversity on nutrient cycling in grassland soils (http://www.the-jena-experiment.de/). As a Post-Doc, she broadened her perspective on this issue by focusing on complex forest ecosystems and by including the impact of mankind. She was appointed a professorship at the University of Tübingen in 2011 and since then has been working on carbon and nutrient cycling in grasslands and forests around the globe.

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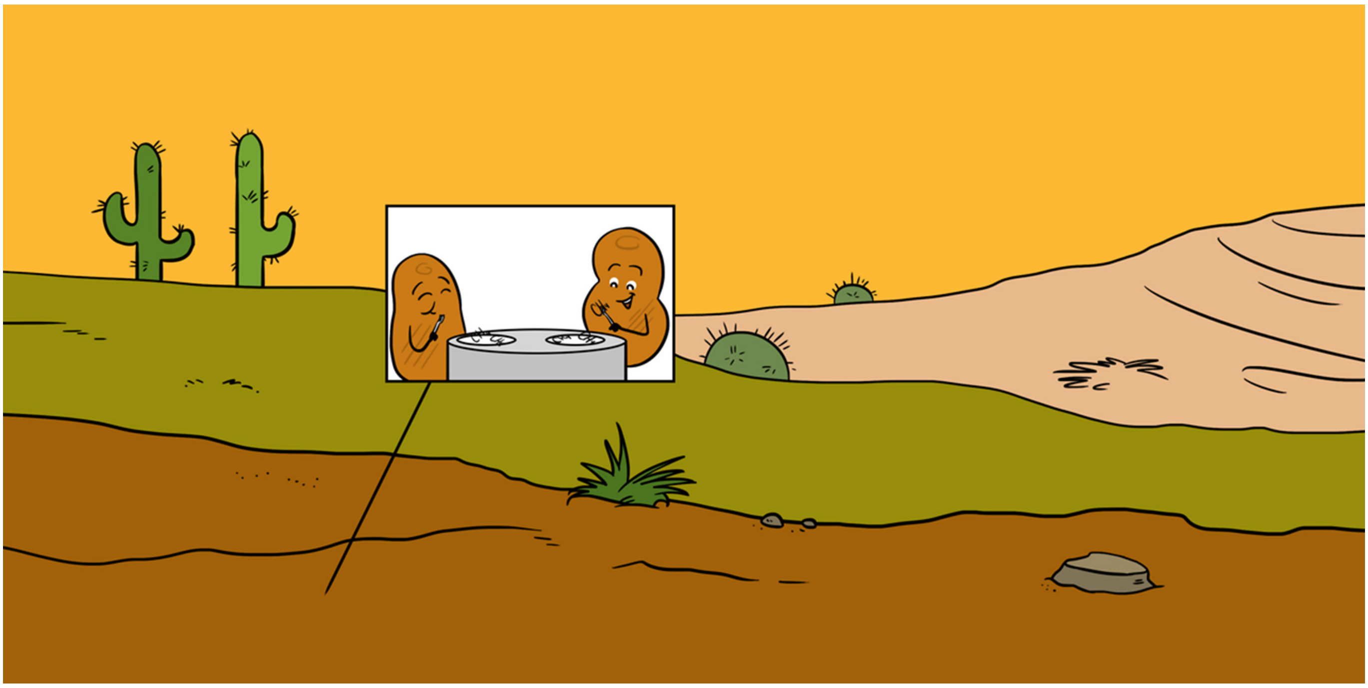

CAN METHANE-EATING BACTERIA IN DRYLANDS HELP US REDUCE GREENHOUSE GASES?

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YOUNG REVIEWER:

SEBASTIAN
AGE: 10

What is a dryland? The first thing that may come to your mind is a desert-like place where nothing can live or grow. Despite the scarcity of water, dryland ecosystems are diverse and will expand due to global climate change. The main cause of global warming is the increase of greenhouse gases in our atmosphere. To solve this, we obviously need to reduce the emission of greenhouse gases, but the study of microorganisms in nature also gives us exciting clues for how to address the problem of global warming. Microorganisms live in all possible Earth environments, and luckily some of them can even take greenhouse gases from the air as their food! In this article, we describe our search of the global soils for bacteria that can consume one of the most powerful greenhouse gases, methane (CH_4). Contrary to what was expected, we found that these bacteria live in drylands all over the world!

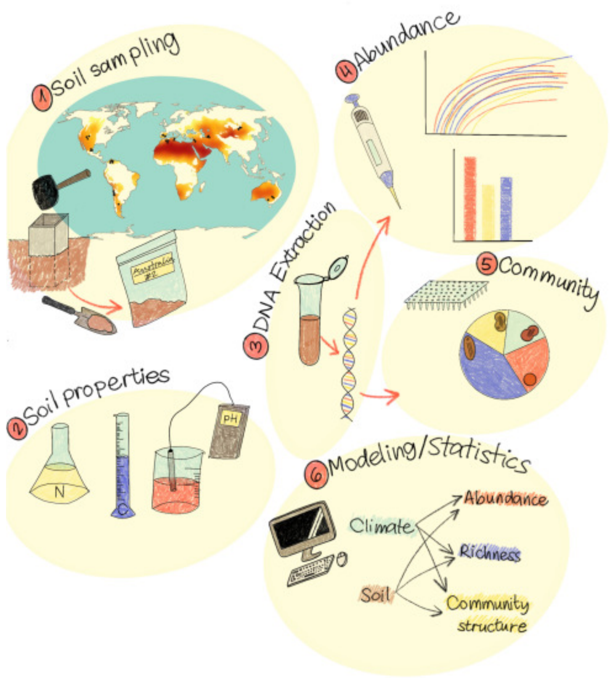

Figure 1

Figure 1

Methods that we follow to find and study soil methanotrophs. We selected drylands all around the world and took soil samples **(1)**. We analyzed the properties of those soils, such as organic matter content and pH **(2)**. We extracted the genetic information (DNA) of the bacteria present in the soil **(3)**. Studying the DNA, we obtained information about the abundance, richness, and community structure of the methanotrophs from each soil sample **(4,5)**. Then we used mathematics to figure out which are the most relevant soil or climate conditions for methanotrophs **(6)**.

THE LARGEST TERRESTRIAL ECOSYSTEM ON EARTH: DRYLANDS

Drylands are characterized by scarce rainfalls and consequently do not have lush vegetation. However, drylands cover a whole range of different ecosystems, from the driest place on Earth, the hot desert of Atacama in Chile, to the leafy eucalyptus forests in Australia where Koalas live (Figure 1.1). Dryland ecosystems also contain huge numbers of organisms, many of which are plants and animals that live only in drylands and have adapted to the harsh conditions. Drylands are the biggest terrestrial ecosystem, occupying almost half of the Earth's land surface (45%) and are home to more than 40% of the human population. So, you can see why drylands are extremely important areas of the earth to research.

Living beings and non-living substances in the environment, like plants and water, are intimately connected in by cycles in nature. These non-living substances are called **abiotic** factors. Water is crucial for all processes that are related to life, from plant growth to the development of communities of soil microorganisms. Therefore, water is the most important abiotic factor in an ecosystem. We measure the availability of water in an ecosystem with a measurement called **aridity**, a mathematical relationship between the amount of precipitation (rain, fog, or snow) and the evaporation of water. The less available water there, the more arid a place is (Figure 1.1).

ABIOTIC

Non-living abiotic factors in an environment include temperature, water, and light.

ARIDITY

Mathematical relationship between the amount of precipitation (rain, fog, or snow) and the evaporation of water. It describes how deficient water is in an ecosystem.

In drylands, where water is not always available, the natural cycles between living beings and non-living substances are hugely affected. When there is no water from rain and the humidity goes down, this affects the carbon (C) and nitrogen (N) cycles, reducing the **abundance** of these elements in soil, which impacts plants, animals, and microorganisms. All this makes drylands extremely vulnerable to ongoing climate change.

ABUNDANCE

The number of individuals of a certain type present in an environment.

SOIL BACTERIA AND METHANE

The Earth is surrounded by a gaseous layer called the atmosphere, which protects us form solar radiation and helps maintain the overall temperature of the Earth. The principal components of the atmosphere are nitrogen (78%) and oxygen (21%), but there are many other gases in the atmosphere as well. Some atmospheric gases, such as carbon dioxide (CO_2) and water vapor, are the greenhouse gases, so called because they trap the Sun's heat, working like the glass in a greenhouse. The greenhouse gases let the Sun's light reach the Earth's surface but prevent heat from leaving the atmosphere. This trapping of heat contributes to global warming.

The most abundant human-produced greenhouse gas in the atmosphere is CO_2, released from burning fossil fuels. However, the second most important gas contributing to global warming is methane (CH_4). Methane is a simple molecule formed by one atom of carbon (C) and four atoms of hydrogen (H). The warming effect of one molecule of methane is equivalent to 25 molecules of CO_2, making it a super-powerful greenhouse gas. Methane is produced by **methanogens**, a group of microorganisms that do not need oxygen to survive and therefore can live in oxygen-free environments like rice fields, lake sediments, and wetlands. Methanogens also live in the digestive tracts of animals, such as the stomachs of cattle and even in humans! Methanogens are responsible for animal burps and farts! Methanogens also produce methane while decomposing organic matter, such as leaves or wood fragments. In addition to agriculture, other human activities, such as the oil and gas industries also release large amounts of methane into our atmosphere [1] (Figure 2).

METHANOGENS

Group of microorganisms that do not need oxygen to survive and therefore can live in oxygen-free environments. They produce methane while decomposing organic matter, such as leaves or wood fragments.

The methane released into the atmosphere is greatly contributing to climate change and there is only one group of organisms that can consume it, the **methanotrophs**. This group of microorganisms is capable of using up methane as their source of carbon and energy. These microorganisms basically eat methane (Figure 2)! In drylands, methane production is low because of the scarcity of water (remember, methanogens typically live in flooded soils and other oxygen-free environments). However, due to the large extent of drylands and the global increase of methane in the atmosphere, dryland ecosystems could be of great interest if methanotrophs are also present and abundant there.

METHANOTROPHS

Group of microorganisms that are capable of using up methane as their source of carbon and energy. They are methane eaters.

Figure 2

Main methane (CH_4) sources and sinks.

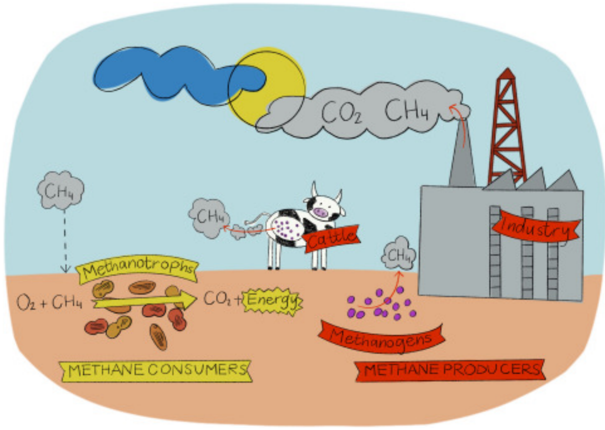

Figure 2

HOW TO FIND AND STUDY METHANOTROPHS

In our research, we were interested in learning if methanotrophs are common in the soils of drylands worldwide, and if they are sensitive to climate conditions and soil properties, like most soil microorganisms. First, we selected 80 dryland sites all around the world (Figure 1.1). At each site, we collected climate information, such as mean annual temperature, annual precipitation, and aridity. We also took soil samples and analyzed properties, such as the amount of organic matter (Organic Carbon), pH, and sand content (Figure 1.2). High soil organic matter indicates the soil is fertile, meaning it has the nutrients that plants, soil animals and microorganisms need to grow. pH analysis tells us how acidic the soil is. pH is one of the most important factors regulating soil bacteria growth. For example, when soils are very acidic like vinegar, only specific acid-tolerant bacteria can live there. Soil grains are very close to each other but also leave spaces for air and water to enter. The amount of sand, the largest type of particle in the soil, tells us how big these soil spaces are. This way, a high sand content means there are big spaces, so that air can enter the soils easily, but water and nutrients can also drain easily.

DNA EXTRACTION

Laboratory procedure in which cells are broken open to release the genetic material (DNA) they contain inside, without damaging the DNA.

To study the methanotrophs in our soil samples, we need the genetic information (DNA) of these bacteria [2]. First, we obtain all the DNA present in our soil samples, through a process called **DNA extraction** (Figure 1.3). This process is done in the laboratory using powerful enzymes that break the cells open without damaging the genetic information. We then analyse the extracted DNA for a specific region that is present only in methanotrophs. This stretch of DNA is a gene called *pmoA*. The p*moA* gene contains the instructions for the protein that allows methanotrophs to eat atmospheric methane. Knowing the concentration of the *pmoA* gene in each soil sample tells us how many methanotrophs were living in that sample (Figure 1.4). There are several closely related species of methanotrophs that all have similar

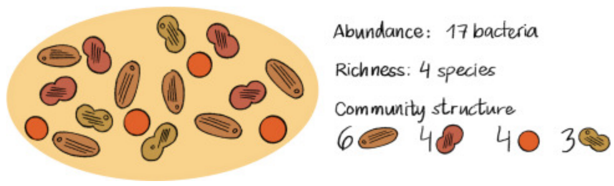

Figure 3

Figure 3

Microbial communities can be described using three properties. Abundance is the total number of bacteria of a certain type present. Richness is the number of different kinds of bacteria present in an environment. Community structure describes how many different kinds of bacteria there are and how abundant each kind is.

DNA information, but different species have tiny genetic differences in their DNA, so we can use DNA to identify different methanotrophs, like a fingerprint (Figure 1.5).

Our DNA studies help us to obtain information about the abundance (total number of bacteria of a certain type present), **richness** (the number of different kinds of bacteria present), and **community structure** (the different kinds of bacteria and the abundance of each kind) of the methanotrophs from each soil sample (Figure 3). Then, we use mathematics to figure out which soil or climate conditions are the most important for methanotrophs (Figure 1.6).

RICHNESS

The number of species (different kinds) of organisms present in an environment.

COMMUNITY STRUCTURE

The combined richness and abundance in the community.

WHERE THE METHANOTROPHS LIVE

We were not sure if we would find methanotrophs in drylands, since these microorganisms need methane to live and drylands are not the typical ecosystem for methane production. So, finding methanotrophs in all our dryland soil samples was an extraordinary finding! We can now say that methanotrophs are widely distributed in global drylands. Surprisingly, we even found some methanotrophs that are usually found in humid places, such as Denmark, Scotland, or New Zealand.

We also found that, in drylands, the average annual temperature and aridity are not the main conditions influencing the abundance and richness of methanotrophs. Abundance and richness may be driven by other factors, such as rainfall. However, climate conditions like mean annual temperature, rainfall, aridity, and soil properties, such as organic matter, pH, and sand content did affect the community structure of methanotrophs. For example, higher temperatures increased the abundance of certain methanotrophs that are heat-resistant. In other words, those drylands with higher temperatures, the methanotroph communities may contain more heat-resistant methanotrophs. Climate conditions can also affect soil properties, for example by favoring the breakdown of rocks, which increases sand content, or by modifying soil pH and organic matter. These soil properties affect the amount of air that can get into the soil, which we found to be very important for the community structure of the methanotrophs.

WHAT WE LEARNT FROM METHANOTROPHS IN DRYLANDS?

As we found, methanotrophs are abundant and widely distributed in drylands worldwide. Both climate and soil affect the communities of methanotrophs. Moreover, we found the community structure of methane eating bacteria was highly dependent on climate conditions, such as amount of rainfall and temperature, and soil characteristics as soil organic content.

Because we found that climate influences the methanotrophs, we expect that ongoing climate change will modify methanotroph communities in the coming years, affecting the consumption of atmospheric methane. To date we knew methanotrophs lived on cold and humid places, which will be surely affected by climate change. The vast amount of land that drylands cover and the many methanotrophs they contain may make these areas extremely important for consuming atmospheric methane in the future. In other words, dryland bacteria can help us reduce greenhouse gases! Taking good care of drylands now and continue studying the hidden marvels they contain is important to deal with our future warmer planet. Methane-Eating Bacteria in Drylands can help us!

ORIGINAL SOURCE ARTICLE

Lafuente, A., Bowker, M. A., Delgado-Baquerizo, M., Durán, J., Singh, B. K., and Maestre, F. T. 2019. Global drivers of methane oxidation and denitrifying gene distribution in drylands. *Glob. Ecol. Biogeogr.* 28:1230–43. doi: 10.1111/geb.12928

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YOUNG REVIEWER

SEBASTIAN, AGE: 10
I like sports, reading, math, and animals.

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CONCHA CANO-DÍAZ
I am a biologist finishing my Ph.D. at Universidad Rey Juan Carlos (Spain). My research is focused on the distribution and ecological preferences of soil cyanobacteria. I am currently studying the effects of climate change and soil formation processes on cyanobacterial communities around the world. I love to make scientific illustrations and in my free time I enjoy playing music with the ukulele and singing in the choir.

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EARTHWORMS AND THEIR ROLE IN GREENHOUSE GAS EMISSIONS

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GWEN
AGE: 13

The mass of all earthworms living on our planet is greater than the mass of any other terrestrial animal species. There are over 7,000 species of earthworms, and they are involved in many processes that keep soils healthy and help plants to grow, which makes them extremely important organisms to study. The activity of earthworms also stimulates the growth of bacteria, both in the soil and in their guts. Some studies have suggested that these bacteria might increase greenhouse gas emissions, particularly the gases carbon dioxide and nitrous oxide that contribute to global warming. So, are earthworms good or bad for the environment, overall? This article will describe the experiments that can be used to study the links between earthworms and greenhouse gas production, as well as the limitations of these experiments. The effects of earthworms on soil processes are very complex and therefore scientifically challenging, important, and exciting.

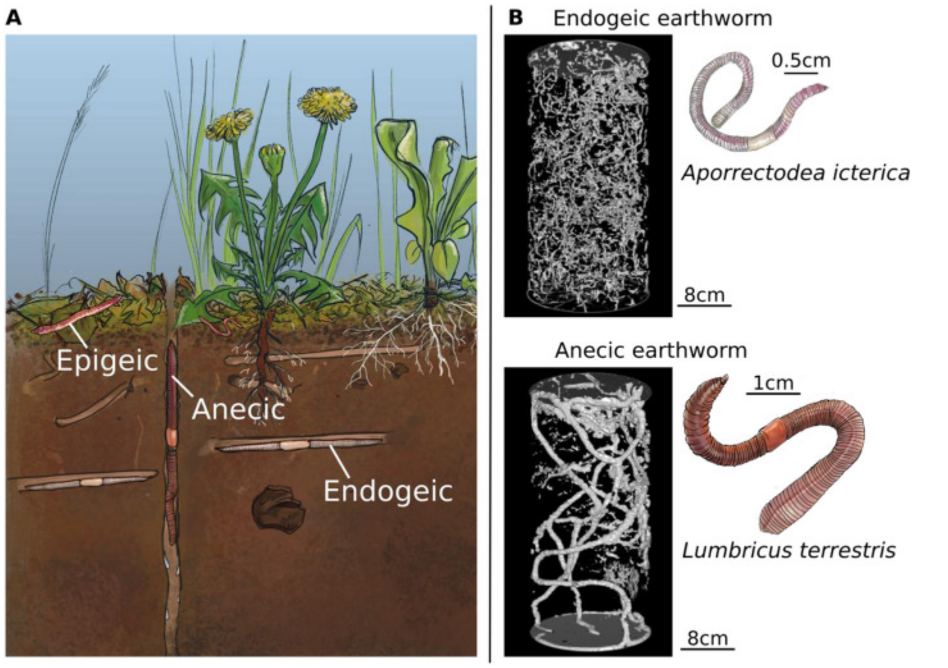

Figure 1

Figure 1

(A) The three main groups of earthworms, epigeic, anecic, and endogeic. Illustration credits: www.lesbullesdemo.fr. **(B)** X-ray 3D reconstruction of the burrow systems of one endogeic species called gray worm (*Aporrectodea icterica*) and one anecic species called nightcrawler (*Lumbricus terrestris*). X-ray image credits: Yvan Capowiez.

EARTHWORMS, THE UNDERGROUND ENGINEERS

Under our feet, thousands of animals live in the soil, including the famous earthworms. The term "earthworms" actually refers to many species. Scientists have described around 7,000 earthworm species worldwide, but some areas are poorly studied, and scientists expect that there are more than 30,000 earthworm species yet to be described [1]. Earthworms are invertebrates, so they do not have bones. Unlike insects, earthworms also lack an external skeleton and they do not have eyes, but they have strong muscles. Earthworms can move through the soil, and even eat it, along with some dead leaves. Although most earthworm species look fairly similar, they have various lifestyles, which fall into three main **ecological groups** (Figure 1A) [2].

The first group, called **epigeics,** are small earthworms (3–10 cm) with a red color, and can be used in vermicomposting. Epigeic earthworms live in dead leaves. Their color protects them from UV radiation and camouflages them from surface predators. Without digging into the soil, they eat dead leaves and transform them into small pieces of **organic matter** in their feces, which are called **casts**. **Endogeic** earthworms are larger (5–15 cm) and completely unpigmented. They only live in soils and create numerous burrows (Figure 1B). In an experimental pot, four endogeic earthworms dug 2.2 km of burrows of 3.5 mm width per cubic meter of soil in only 6 weeks [3]! As they dig, they also eat many very small pieces of dead leaves that are in the soil, and they mix organic matter within the soil (Figure 2). The third group is called **anecic** earthworms. They are the largest, they can

ECOLOGICAL GROUP

Earthworms differ regarding where they live in the soil, what they eat, and what color is their skin. There are three main groups: **epigeics** (pronounced "ep-i-jEE-ik"), **endogeic** (pronounced "en-d-oh-jEE-ik"), and **anecic** earthworms (pronounced "an-e-c-ik").

ORGANIC MATTER

It is matter composed of organic compounds that comes from the remains of organisms, such as plants and animals and their waste products in the environment.

CASTS

It is earthworm poo. Depending on the earthworm ecological group, they can be deposited at the soil surface or within the soil, in their burrow.

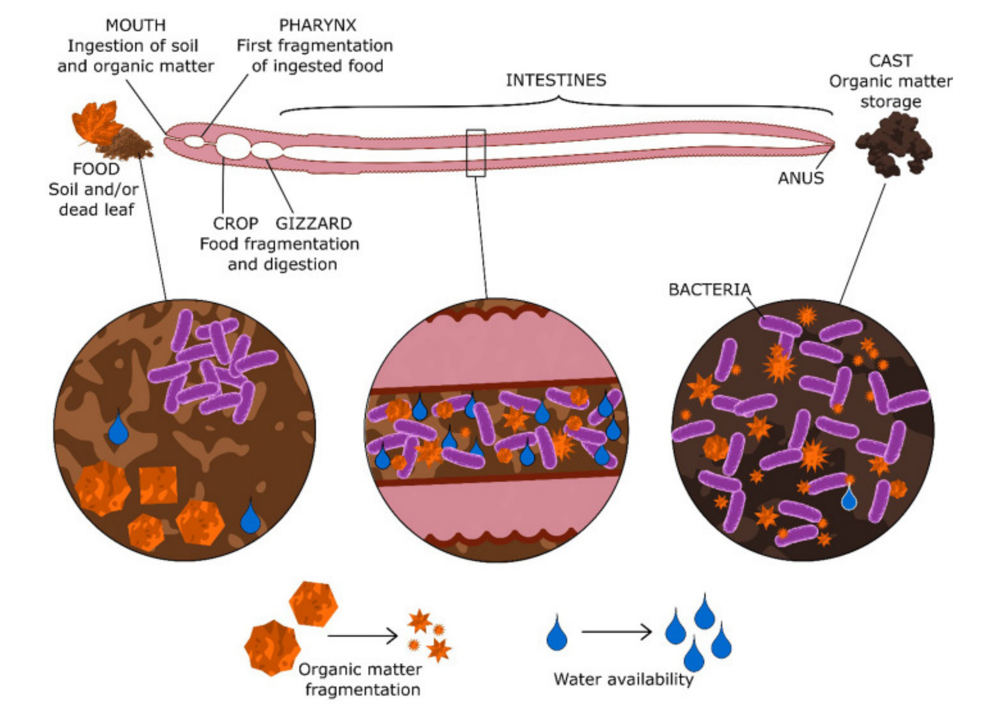

Figure 2

Figure 2

Organic matter passes through the earthworm's digestive tract, is broken into smaller pieces, digested, and the remainder exits as feces called casts. Casts then help to feed bacteria. Bacteria are also present within the digestive tract of earthworms. Bacteria need the right mix of organic matter, water, and air to be active. Image inspired by Drake and Horn [4].

grow as big as 10 cm and up to 1 m! They dig deep vertical burrows (Figure 1), that can exceed 1 meter in depth. During the night, they stick their heads out to grab dead leaves on the surface and bring them to deeper soil layers. Since only their heads leave the soil, only their heads are pigmented.

Eating or burying dead leaves and moving through the soil by creating burrows are the two main actions of earthworms. These actions are good for the soil, the other soil organisms, and the entire **ecosystem**, which has earned earthworms the name "**ecosystem engineers**."

ECOSYSTEM ENGINEER

They are organisms that modulate the availability of resources to other species. Termites, ants, and earthworms are the major ecosystem engineers.

HOW EARTHWORMS ARE CHANGING THE SOIL AND GROWING BACTERIA

Earthworm burrows profoundly change soil structure by creating large spaces in the compact soil. The burrows are the habitat of many organisms like small invertebrates, bacteria, and plant roots. Burrows also act as pipes that increase water and oxygen flow between the surface and deeper soil layers. Earthworms of different ecological group build burrows that affect water and gas fluxes differently. In the experiment of Capowiez et al. [3], done in PVC tube (16 cm diameter, 30 cm height, Figure 1B), the endogeic earthworms' burrows allowed a water infiltration rate of 5.2 L per minute, while this rate reached 12.4 L per minute in the anecic earthworm' burrows as they are larger, more continuous, and vertical.

In ecosystems where earthworms are abundant, dead leaves disappear quite quickly and do not accumulate on the soil surface. Epigeic earthworms transform dead leaves into smaller pieces repacked in their casts and anecic earthworms bury dead leaves in deeper soil layers. Endogeic earthworms then eat small dead leaves or root particles along with the soil and excrete it behind them wherever they go. These actions of earthworms result in the redistribution of organic matter throughout the soil. Instead of accumulating at the soil surface, the organic matter is more spread out and available for plant roots and other soil inhabitants.

The changes of the soil made by earthworms affect another important group of soil organisms, like bacteria. Bacteria need the right balance of food, water, and air to live. They transform the small pieces of organic matter into even smaller particles, breaking them down into carbon and nitrogen. These particles are so small that plant roots can easily absorb them and use them to grow. To break down their food, bacteria use **oxygen** (they breath, even without having lungs) and produce **carbon dioxide** as a waste product. If there is too much water around, such as during a flood or in rice fields, the bacteria instead produce **nitrous oxide** as a waste product. Carbon dioxide and nitrous oxide are **greenhouse gases** that increase the atmosphere's temperature, so contributing to climate change.

In some soils, bacteria may lack organic matter, air, or water, and be less active. Earthworms can "wake up" bacteria by making organic matter, water, and air more available. This effect is even stronger for the bacteria living in the earthworm's gut (Figure 2). In the gut, organic matter and soil are perfectly mixed in an environment saturated with water. This is heaven for bacteria that produce nitrous oxide [4]. Since earthworms stimulate bacteria that produce carbon dioxide and nitrous oxide, this makes us wonder if earthworms serve to increase or decrease greenhouse gases emissions.

OXYGEN

This is a gas constituting 21% of the air we breathe. Plants produce oxygen from carbon dioxide, water and sunlight while animals use oxygen and produce carbon dioxide.

CARBON DIOXIDE

It is a colorless gas composed of one atom of carbon and two of oxygen. Its atmospheric concentration raised from 0.028 to 0.042% since 1850 causing an increase of 1° of global temperature.

NITROUS OXIDE

It is a colorless gas composed of two atom of nitrogen and one of oxygen. It is in very low concentration but one nitrous oxide molecule warms the atmosphere as 270 carbon dioxide molecules.

GREENHOUSE GASES

It is a gas that absorbs and emits solar energy causing the greenhouse effect, i.e., warming the atmosphere.

STUDYING THE IMPACT OF EARTHWORMS ON GREENHOUSE GASES EMISSIONS

To study how earthworms affect bacteria and the greenhouse gases they produce, scientists can run experiments. In one type of laboratory experiment, scientists use pots filled with soil that is sifted to remove rocks, all animals, and roots. Then earthworms are added, usually a few individuals of the same species, ideally in numbers close to what would be found in nature. Some pots are kept without earthworms, for comparison. Then, greenhouse gases emissions are measured at the soil surface and the bacteria in the pots are studied, to see whether greenhouse gases emissions are higher in the presence or absence of earthworms.

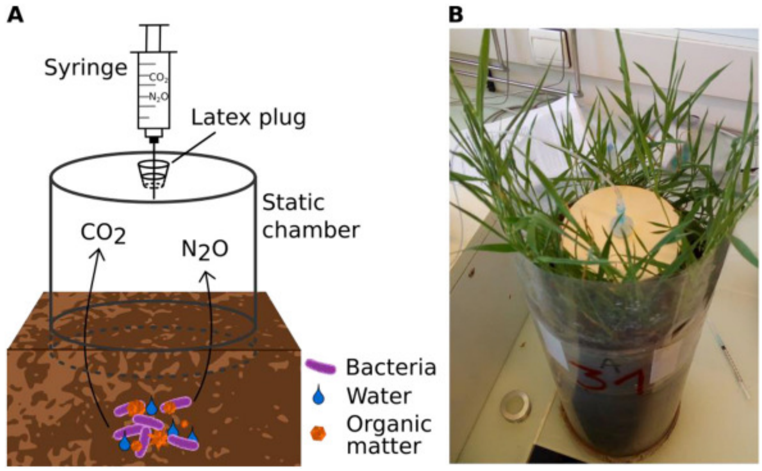

Figure 3

Figure 3

(A) An experimental chamber can be used to measure GHG emissions in natural environments. Gases produced by bacteria accumulate in the sealed chamber, and then are sampled with a syringe through the latex plug to measure the levels of carbon dioxide (CO_2) and nitrous oxide (NO_2). **(B)** Example of a chamber placed on the soil surface of an experimental pot with earthworm and plants. Credits: Pierre Ganault.

Another method scientists use is to measure greenhouse gases in nature. In this case, cylindrical chambers are pushed into the ground to measure gases like carbon dioxide and nitrous oxide (Figure 3). The earthworms in the soil are also studied so that scientists can try to relate greenhouse gases emissions to the abundance and number of species of earthworms present. Scientists can also measure other soil characteristics important for bacterial activity, including water content, availability of organic matter, and **pH**.

pH

In chemistry, pH is a scale used to specify the acidity or basicity of an liquid solution. Acidic solutions are measured to have lower pH values than basic or alkaline solutions.

Another way to know the effect of earthworms on greenhouse gases emissions is to gather information from all the existing studies. So, it was found that, on average, earthworms increase carbon dioxide emissions by 33% and nitrous oxide emissions by 42% [5]. This seems to tell us that, although they are beneficial for soil health, earthworms may be detrimental for the environment because they increase bacterial activity and related greenhouse emissions.

THESE EXPERIMENTS HAVE LIMITS

This seems like a real dilemma: earthworms improve soil health, but at the same time they appear to increase greenhouse gases emissions! Before we draw this conclusion, however, it is important to recognize that the experiments we have described all have drawbacks that make it difficult to be completely certain of the role earthworms play in greenhouse gases emissions. The interactions between earthworms, bacteria, soil, plants, and water that result in greenhouse gases emissions are extremely complex. These factors vary tremendously in the natural environment and are very difficult to recreate accurately in scientific experiments.

The first important factor limiting our full understanding of the role of earthworms in greenhouse gases emissions is the great diversity of soil properties, such as sand content. Most earthworms generally prefer soils with a low sand content because sandy soils dry faster, and sand particles can be abrasive for their skin. Soil pH can also strongly affect earthworms, and many may not survive in soils with a pH below 4.5. It would be extremely difficult to make experimental pots for the thousands of different soil types that exist in nature, so our knowledge is currently limited to certain common types of soil.

A second limitation is that very few studies included plants in the experiments. Plants absorb water and nutrients with their roots, reducing the availability of water and nutrients for earthworms and bacteria. However, plants and bacteria also help each other. Plant roots produce sugar in the surrounding soil that bacteria can eat in exchange for providing minerals that plants need. Unfortunately, it is very difficult to set up an experiment that could test all the possible positive and negative interactions happening at the same time in the soil.

The third limitation is that most studies kept the soil water content constant. This is generally done to optimize earthworm activity. In nature, soils are constantly drying out and being remoistened by rainfall. Earthworms can be completely inactive if the soil gets too dry. This means that experiments in which the soil has a constant water content might overestimate the negative effects of earthworms on greenhouse gases emissions. In a lab experiment in which scientists used more realistic drying-rewetting cycles, the presence of earthworms actually reduced nitrous oxide emissions [6]. The scientists reasoned that earthworm burrows increased water flow to lower soil layers and aerated the soil, which sped up soil drying and reduced bacteria activity. The effects of drying-rewetting cycles are very important to study, especially since these cycles are expected to be more frequent and extreme with the on-going climate change.

CLIMATE CHANGE—DO NOT BLAME THE EARTHWORMS

We showed you just how complex it is to study greenhouse gases emissions from the soil. Earthworms modify the distribution of organic matter and the availability of water and air in the soil. All these change the activity of soil bacteria. However, soil bacteria also depend upon the properties of the soil, on drying-rewetting cycles, and on the plants that grow there. We are far from having enough studies with realistic experiments to understand the true role of earthworms in greenhouse gases emissions. On the other hand, human activities, notably agriculture, produce large amount of greenhouse gases and we need to keep thinking in innovative ways to improve the health of our planet and all living creatures.

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

YOUNG REVIEWER

GWEN, AGE: 13

Hi, my name is Gwen, I live in the U.S. and play piano and volleyball. I just finished seventh grade, and my favorite subjects are science, math, art, and Spanish. I love to read, particularly Sci-Fi novels and series (I am also a huge fan of Harry Potter). I am very excited to be working with Frontiers for Young Minds!

AUTHORS

PIERRE GANAULT

At each walk in nature, I cannot help myself from flipping logs and rocks over or searching into the dead leaves to see what wonderful animal I will find hiding there. This curiosity led me to study soil biodiversity and do a Ph.D. on the effect of tree species mixture on soil invertebrates and the role of these animals for soil processes. I also work with associations to bridge the gap between scientists and citizens so we can work all together to study, better understand, and protect the creatures living in the soil. *pierre.ganault@gmail.com

SACHA DELMOTTE

My passions for nature, humans, science, and the transmission of knowledge led me to pursue 7 years of university studies in ecology, biology, and geology. I am also an animator in the plains of nature for audiences ranging from 3 to 18 years old to awaken them to the things that fascinate me.

AGNÈS DUHAMET

Agnès is a Ph.D. student in marine biology. She obtained her bachelor's degree in biology at the University of Avignon and her master's degree in ecology and evolutionary biology at the University of Montpellier. She is passionate about nature and likes to transmit knowledge about natural sciences.

GAËLLE LEXTRAIT

I have always been passionate about microorganisms, whether pathogenic or mutualistic. I turned to the interactions between small animals living in soils (insects) and their symbionts. I am currently a Ph.D. student in microbiology at the CNRS of Gif-sur-Yvette (University Paris-Saclay), where I am continuing my observations on the symbiotic interactions between stinkbugs and their symbiotic bacteria.

YVAN CAPOWIEZ

Yvan Capowiez is a Senior Research Scientist at the French Agronomy Institute (INRAE), Avignon, France. His research is focused on earthworm ecology and behavior. He has extensive experience studying how earthworms burrow in the soil and how the resulting burrows will influence important soil functions, such as water transport and organic matter burial.

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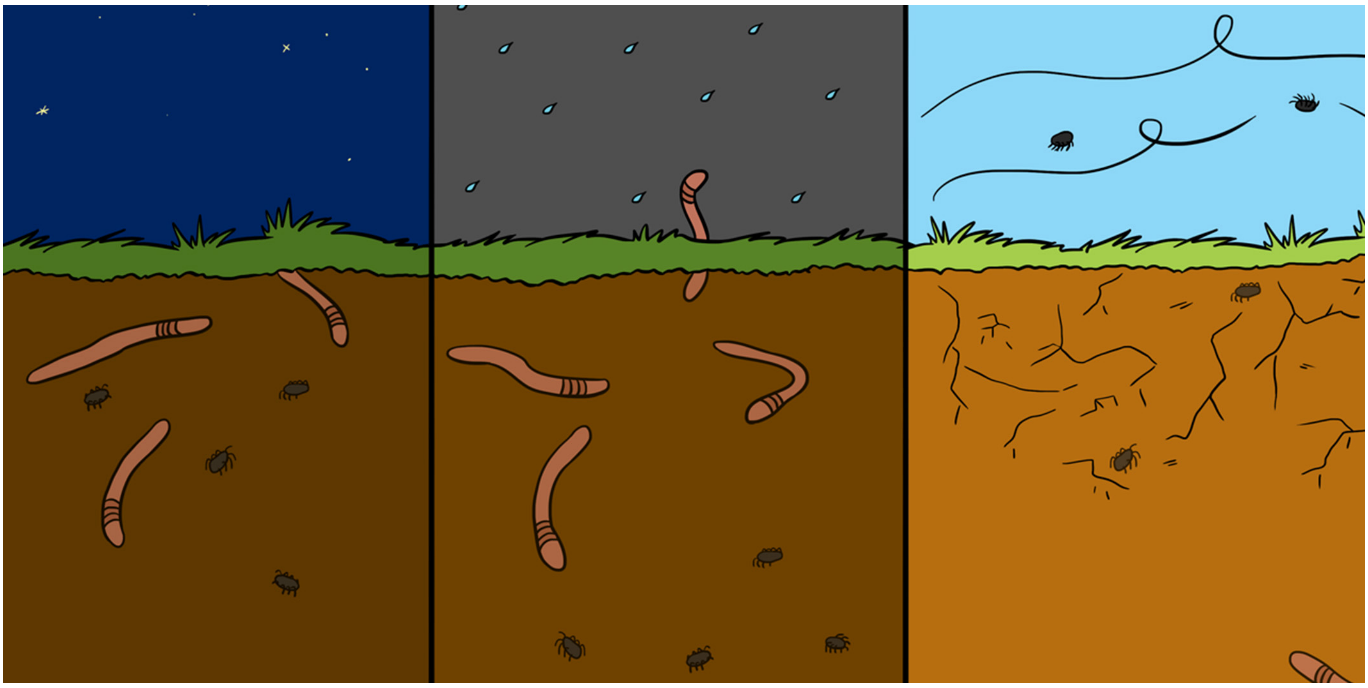

SOIL ECOSYSTEMS CHANGE WITH TIME

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CREAF, Bellaterra (Cerdanyola del Vallès), Barcelona, Spain

YOUNG REVIEWERS:

RUTENDO
AGE: 14

NOKUTENDA
AGE: 14

All the animals living below our feet are not still. They can move (to a lot of places because the soil is a 3D space) and to change (for example, from a cocoon to an active state). Therefore, the same soil below a given piece of field may not contain the same living communities in winter as in summer, or even during a sunny day compared to a cold night. For example, research on soil beetle larvae showed seasonal vertical movements, as the larvae searched for better living conditions. Moreover, the soil varies a lot during its formation, and consequently its inhabitants also change. In the case of oribatids, a minuscule but diverse group of soil mites, scientists observed changes in the community over dozen to hundreds of years! Many studies showed a basic but powerful principle: ecosystems are not still photographs, but instead are constantly changing environments.

ECOSYSTEMS ARE NOT STATIC PHOTOGRAPHS

When we imagine ecosystem diversity, we often picture ecosystems as mostly stable and unchanging, like photographs in a book, with all the plants and animals existing in a frozen state of balance. In our heads (and in many book pictures), plants are readily available for herbivores to eat, and herbivores are waiting to be eaten by carnivores, all under wonderful daylight. But reality is not like that! Most of the animals in an ecosystem move during the day and some of them only appear at night. Plants produce different edible parts depending on the season. The entire ecosystem can even change due to catastrophes like forest fires. Not to mention, we rarely even imagine the diversity that happens in the soil under our feet.

HOW CHANGE WORKS UNDER OUR FEET

Of course, **soil biodiversity** also changes with time, although not necessarily the same way changes happen aboveground. First, movement is certainly more difficult in the soil. Earthworms, insect larvae, mole crickets (also moles, but we are going to focus on small **invertebrates**), and many other tiny creatures must dig with their mouths, claws, or legs. Smaller creatures move throughout the soil mainly using tiny air-filled spaces called **soil pores**.

Soil inhabitants are not limited to the typical horizontal movements of surface animals. Soil invertebrates can also move up and down beneath the same surface area, which is called **vertical migration**. Vertical migrations can occur during a single day, or across seasons. Enchytraeids, very tiny worms, are one of the few types of soil-dwelling animals that have been observed to migrate during the day. Enchytraeids move deeper into the soil to escape from dry surface conditions at midday and return from the deep in the evening, when their favorite moist conditions are reestablished. This migration is the basis of one of the most-used methods to study **soil mesofauna**. This method consists of drying a soil sample in a funnel with a light bulb at the top, so the creatures "escape" by falling to a collection container in the bottom (Figure 1).

Many soil invertebrates can exist in resistant forms that allow them to survive harsh conditions for a long time. Ground pearls, small, rounded, and very interesting insects, are a perfect example. They can secrete a pearly covering around themselves, forming a spherical cyst or "resting" stage, in which they can remain for decades! But when delicious roots are available, the cysts develop and become voracious adults. If conditions are really good, many ground pearl species can clone themselves to profit as much as possible from favorable conditions. An unlucky vineyard farmer may not see the tiny ground pearls 1 year, but find his crops infested with adults the next.

At the soil surface, many small animals can be carried by the wind, water, and even by other animals. Some surface-dwelling creatures travel this way as well, but the so-called **passive dispersal** of soil

SOIL BIODIVERSITY

The total variety of living creatures inhabiting soils.

INVERTEBRATES

Animals with no bones. In the soil, that means mainly worms and arthropods (centipedes, woodlices, insects, spiders...).

SOIL PORES

Extremely small (<0.075 mm) spaces in the solid structure of the soil, filled mainly with air and water [1].

VERTICAL MIGRATION

Vertical migration is typical of soil and aquatic environments, where mobile organisms are not limited to move over a (horizontal) surface. Like any other migration, it is normally guided to find resources or better environmental conditions.

SOIL MESOFAUNA

Soil inhabitants, smaller than 2 mm, such as springtails, mites, and tiny worms [2].

PASSIVE DISPERSAL

Mobile organism can move actively (using their legs or appendices to go through the territory) or let themselves "go with the flow" (of water, wind or even other animals), which is call passive movement or dispersal.

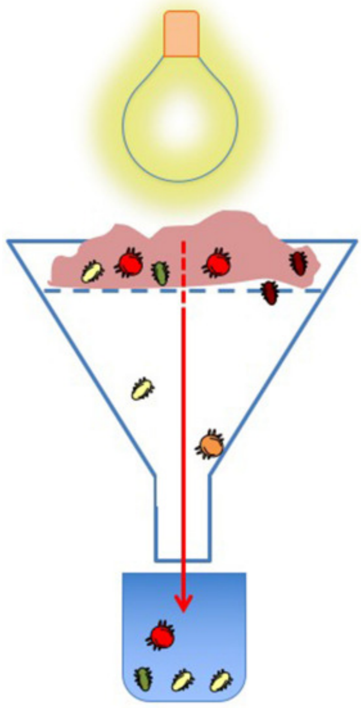

Figure 1

Figure 1

Isolating soil invertebrates for study. A typical Tullgren or Berlese funnel trap, named after its inventors. The soil is placed in the top of a funnel, held up by a layer of mesh. A light bulb heats and dries the soil, forcing the soil organisms to go down. When they drop from the sample, they fall into a collection container, usually filled with a substance that keeps them alive. The organisms can then be studied.

fauna has gained a lot of research attention lately, as it may explain movements of soil organisms across large distances.

SEASONAL CHANGES

During my early years as a researcher, movements of soil organisms were not as understood as they are today and every discovery was very exciting, including the discovery that some soil-living insect larvae perform seasonal vertical migrations [3]!

Soil was sampled in multiple locations every month for 2 years, in a desert-type shrubland in Southern Spain. Soil samples were collected at different depths, from the surface litter down to 50 cm deep. For each sample, all the **macroinvertebrates** were counted and identified. After analyzing all the samples, from every season and soil depth, scientists found that the larvae of one abundant beetle family called Tenebrionidae, which eat organic debris, made the same movement each year. They were more abundant at the soil surface in winter than they were in summer (Figure 2).

In the studied area, summers are very hot and dry. However, Tenebrionidae's favorite dish, litter debris, is found in exposed soil-surface "restaurants," like shrubs and ant mounds. Therefore, these beetle larvae prefer to devour surface litter debris during the winter's gentle weather, but enjoy other, deeper "restaurants," such

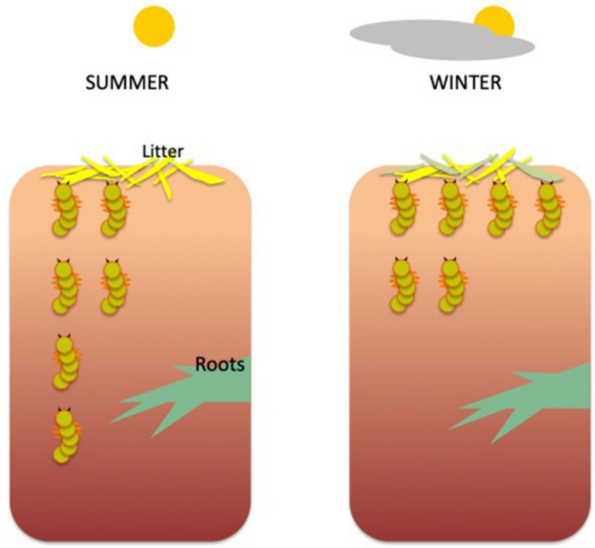

Figure 2

Figure 2

Vertical migration of beetle larvae, depending on soil depth and season. In summer, the larvae are equally abundant at the surface and in the deeper levels of the soil, but in the winter they are much more abundant at the surface, where they can feed on leaf litter and not be damaged by the hot, dry conditions present in summer.

as decaying roots, in summer. When the larvae perform this vertical migration, they are also doing a great service for the entire ecosystem. Like earthworms in more humid ecosystems, these tough larvae move the soil in arid environments, so air, water, and organic materials are mixed in the soil, which is highly beneficial for soil health.

ECOSYSTEMS CAN GROW… AND EVEN AGE!

ECOSYSTEM SUCCESSION

The process by which ecosystems are "born" and "grow" after the creation of new surfaces, like a new coral island or the soil revealed after glaciers melt, or how ecosystems "regrow" after disturbances like forest fires.

CHRONOSEQUENCE

A group of ecosystems studied at the same time, which are similar in origin, plant species, and geographical area, but have different ages. Studying ecosystems in chronosequence is necessary because we cannot wait decades to sample one ecosystem over the course of its development.

Changes in weather conditions and food availability are not the only changing features of ecosystems. In fact, an entire ecosystem can change during a process called **ecosystem succession**. Scientists have studied how the diversity of soil animals changes during ecosystem succession, focusing on a group of soil mites called oribatids. Oribatids are tiny, abundant, and diverse, which means that you can find an entire community of them in a small sample of soil. There are also many resources available to help identify various oribatid species, so they are a perfect organism to observe to study changes in soil ecosystem diversity. Also, the mobility of oribatids is relatively limited, since they exist in the deep soil are restricted to moving through soil pores and can occasionally move by passive dispersal. Therefore, oribatid communities mainly develop through the process of ecosystem succession.

In a recent study, scientists carried out in a **chronosequence** of forests that are re-growing after cropland abandonment. They wanted to know if similar forests of different ages have the same soil communities. Scientists hypothesized that croplands probably had only a few oribatid species in low abundances, but that complex communities with high diversity would develop in older forests. Comparing current aerial photographs with others from the 1950s,

Figure 3

Ecosystems change and grow over time. In the 1950s (top), there were more abundant and rich communities of oribatids in the forest than in croplands. After crop abandonment (middle), individuals of some species from the forest arrived in the connected croplands mainly by passive dispersal (arrows). Finally, the disappearance (dashed arrow) of a few species, which probably needed a more developed soil, created the current differences among the three kinds of forests (bottom).

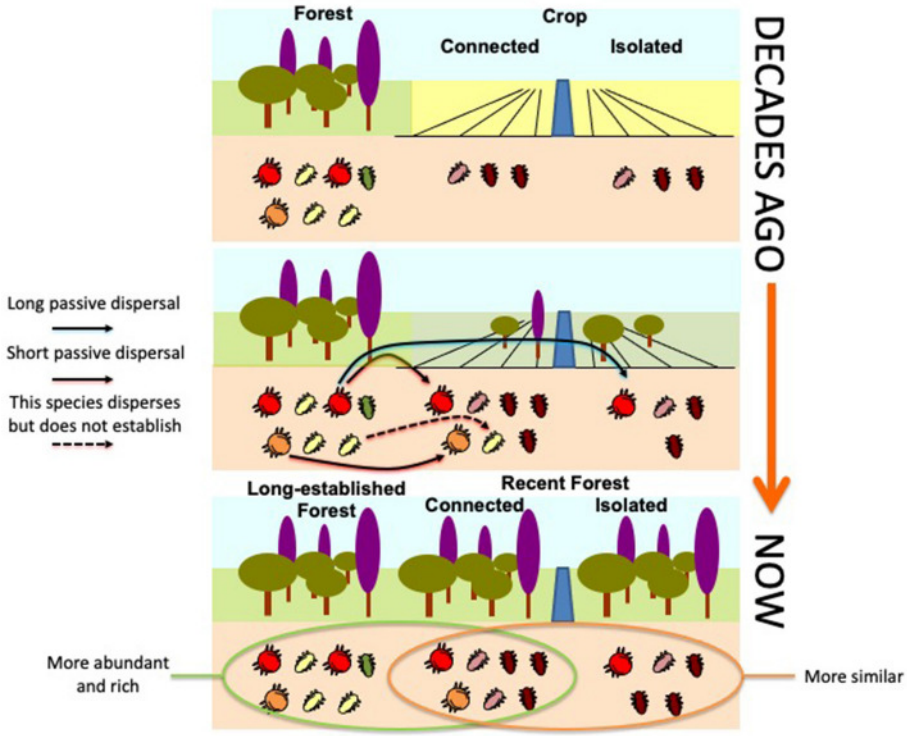

Figure 3

scientists determined which areas had been forests in the 1950s (long-established forests), and which had been croplands (recent forests). Among the recent forests, we also distinguished between isolated forests (surrounded mainly by croplands and most likely showing oribatid communities similar to those found in croplands) and those connected to other forests (probably with oribatid communities similar to those found in old forests).

Scientists observed two important results. First, long-established and recent but connected forests showed similar numbers of oribatids and similar numbers of species, which were higher than what was seen in the isolated forests. Second, oribatid communities in isolated and connected recent forests shared more species than they did with long-established forests (Figure 3, bottom). Likely, oribatids arrive mainly by passive dispersal early in ecosystem development. That is probably why recent forests connected to long-established forests quickly establish oribatid communities similar to those in the long-established forests. But as the recent forest ecosystem continues to develop, lack of refuge availability and access to food may prevent some oribatid species from permanently settling there. This could explain why oribatid communities in recent and connected forests are more like those of isolated forests and thus to those of croplands (Figure 3).

Ecosystems not only "grow," but can also "age" if no major disturbance occur, such as fires. Scientists studied ecosystem aging in Canadian boreal forests [4]. They sampled oribatids in a chronosequence based on the time since the last forest fire, which was estimated from 100-year-old maps, tree rings from trees up to 200 years old, and chemical dating of deep soil, which was up to 700 years old! Although oribatid abundance was drastically reduced during the first 200 years of forest development after the last fire, the number of different species was not really affected until the later stages of forest aging. This means that the progressive diminution of nutrients as phosphor and nitrogen could not maintain abundant populations, and later on, not even entire populations of some species. Scientists also studied soil samples beneath tree logs and exposed soil and found that oribatids beneath logs were less abundant than those living in exposed soil, although maintained their populations stable. This led lead scientists to conclude that oribatids living on exposed soil were more affected by aging, probably because of a reduction in the availability of leaf litter as the forest aged.

ECOSYSTEMS ARE LIKE PRECIOUS MOVIES

I hope that now, when you imagine ecosystem diversity in a forest, you have more than just a still picture in your head, since all these living creatures change and move, appear and vanish…and I hope that you also imagine the creatures inhabiting the soil beneath our feet! Ecosystems, as living scenarios, are not static but are highly dynamic over time. The tiny, diverse creatures living in the soil change with the ecosystems, using many different and amazing strategies. Soil-living creatures are especially important for the ecosystem, as they maintain soil health and are a critical part of the recycling of dead leaves and roots, a process that actually helps to reduce global warming and contributes to the health of our entire planet.

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YOUNG REVIEWERS

RUTENDO, AGE: 14
I was born in Zimbabwe and I have two brothers and one sister. I love maths, reading books, and listening to music. When I grow up I want to be either a doctor, scientist, psychologist, or archaeologist.

NOKUTENDA, AGE: 14
My hobbies are mostly cooking and drawing (anime at most). I have my heart set on being a chef when I am older. I love creative arts. In my spare time I love drawing what my mind expresses. Other times I try and find the time to read a fiction fantasy novel.

AUTHOR

ENRIQUE DOBLAS-MIRANDA
Enrique has a Ph.D. in biology and is a researcher at CREAF. He is also interested in international cooperation and was the head of the Euro-Mediterranean project called MENFRI, from which he founded an organization that forges partnerships to overcome complex challenges to development and the environment. Enrique has contributed to research on landscape resilience and management in the face of global change, and he also continues his principal line of research about variations in the biodiversity of ecosystems over time. Using several soil invertebrate communities, Enrique has studied the dynamics of forests and croplands in Spain, New Zealand, and Canada. *e.doblas@creaf.uab.cat

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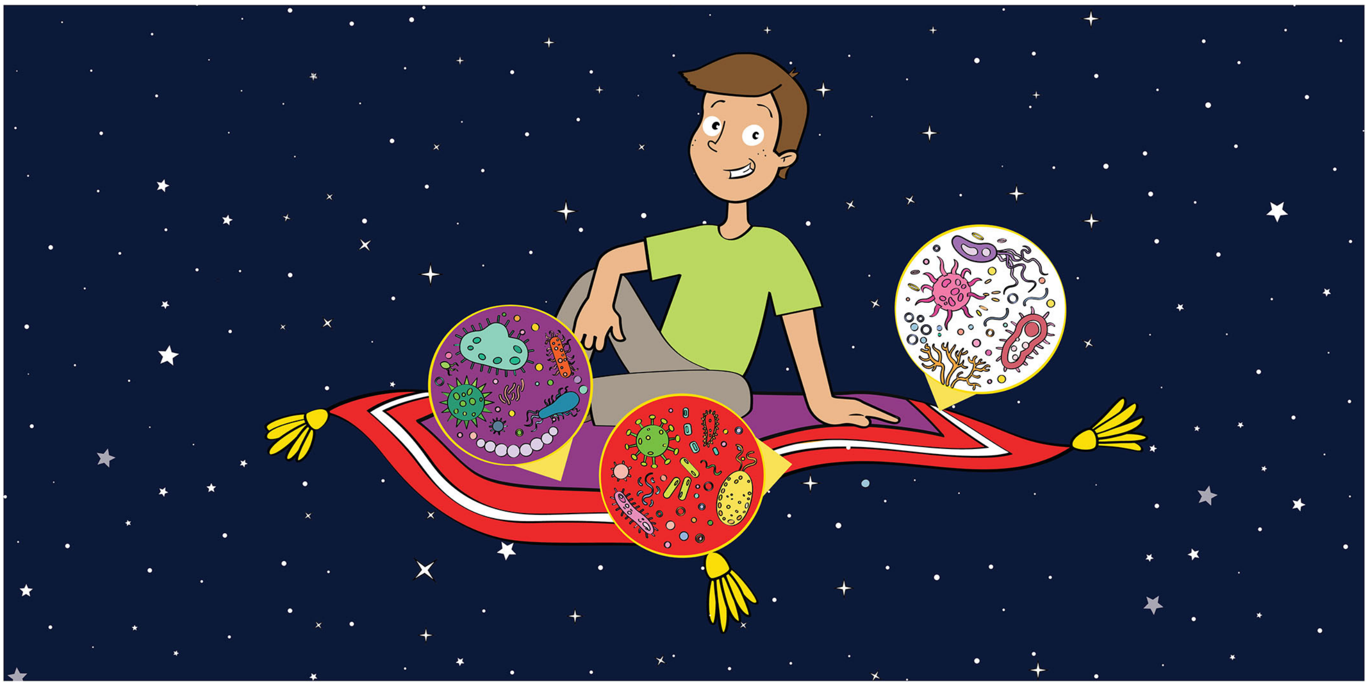

MICROBIAL MATS: PRIMITIVE STRUCTURES THAT COULD HELP US FIND LIFE ON OTHER WORLDS

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YOUNG REVIEWERS:


ANHAD
AGE: 12


AVANI
AGE: 10


SANSKRITI
AGE: 15

Some microscopic organisms grow together to build structures known as microbial mats. These mats are formed from several layers with different colors, and their structure depends on environmental conditions such as sunlight, humidity, and available food. Microbial mats are found in oceans, lakes, and coastal lagoons, as well as in extreme environments like deserts, polar regions, and hot springs. The study of fossils indicates that microbial mats were a common form of life on early Earth, and they have persisted on our planet ever since! Therefore, the study of modern mats helps us to understand microbial life in the past, and how they might help to regulate the Earth's climate. Scientists believe that microbial mats can prosper on rocky planets like Earth, so they are studying mats in different terrestrial environments to help them to recognize evidence indicating the presence of mats on other worlds.

MICROORGANISMS CAN FORM LARGE STRUCTURES!

Microorganisms are tiny living things that cannot be seen with the naked eye, as most of them are made up of only one cell. We need to use a microscope to see them. They live in and on our bodies, and in our surroundings, including the soil, water, and air. Sometimes microorganisms work together to build big structures that are observable without microscopes. Lichens, for example, look like plants, but they result from an interesting relationship between algae and fungi, which form flakes or leafless branches on trees or rocks. Yogurt, vinegar, cheese, and bread are produced by fermentation processes, which are performed by groups of particular microorganisms. Some plants built small structures called root nodules, where microorganisms can live. Thanks to the microorganisms in these nodules, the plants can obtain more food from the environment and thanks to the plants, the microorganisms have a place to live and a lot of sugar to feed on. Commonly, when your food spoils in the refrigerator, you can observe a layer of microorganisms known as a **biofilm** growing on it.

BIOFILM

A layer of microorganisms that are stuck to one another and stuck to (or floating on) a surface.

In nature, many microorganisms live in the ground. Using soil, water, and minerals these microorganisms can form big, solid structures. When high-quality food is present, some microorganisms can reproduce by the millions, attached to grains of soil or sand, creating structures that look like normal rocks or mud, but that are actually living structures built by multitudes of microscopic organisms. There are different types of rocky microbe structures. They have names like microbialites, endoevaporites, oncolites, and stromatolites (Figure 1) [1]. These structures can have diverse shapes and colors, which are strongly influenced by the environmental conditions present during their formation. **Microbial mats** are a specific example of a structure built by microorganisms.

MICROBIAL MAT

A large structure build by microorganisms, that grow on the top of sediments. It is usually composed by grands of soil, minerals, nutrients, and microbes.

WHAT ARE MICROBIAL MATS AND WHAT DO THEY DO?

Microorganisms need energy and water to build a microbial mat. Water can be provided by hot springs, lagoons, or a coastal shoreline, and many microorganisms use solar light as their main energy source. With enough energy and water, microorganisms can flourish on a surface, sticking together with food and grains of sand or soil, and building mats that can be up to a few centimeters thick (Figure 1C). In some cases, a new living mat grows on top of an older, dead mat, creating thick layers (Figures 1G,H). As the name suggests, mats resemble carpets or rugs, in the way that they cover surfaces of various sizes. When seen up close, mats also have interesting vertical layering (Figure 2). Microorganisms can be distributed in green, orange, red, and purple layers, with each layer representing a different community of microorganisms that needs different amounts of sunlight and oxygen (Figure 1I). All the

Figure 1

Figure 1

Examples of structures made by microorganisms using soil, water, rocks, and minerals. **(A)** Oncolites from Casey Falls locality, Canning Basin, Western Australia (photograph credit: Heidi Allen). **(B)** Endoevaporite. **(C)** Microbial mat. **(D,E,G,H)** Microbial mats in the Yucatán Peninsula in Mexico. **(F)** Microbial mats from the Middle Island Sinkhole, Lake Huron in North America (photo credit: John Bright, NOAA Thunder Bay National Marine Sanctuary). **(I)** A cross-section of a microbial mat from Guerrero Negro, Mexico.

microorganisms in the mat work together to sustain themselves and to interact with their surrounding environment.

Studies have shown that microbial mats are important for the functioning of **ecosystems**. For example, when mats colonize the ground, they contribute to the health of soils and sediments, producing nutrients that enrich them. Mats participate in the recycling of some chemical elements, including carbon, nitrogen, and sulfur. They can also clean the water and they both take up and release gases from the atmosphere, such as oxygen, hydrogen, carbon dioxide, and methane. Mats are also a food source for animals. Some flies, snails, worms, crabs, and birds feed on small pieces of microbial mats, and larger organisms can then feed on those smaller ones [2]. Because they are continuously eaten, mats often do not grow much, except in extreme environments[1].

ECOSYSTEM

A community of organisms living in a certain area, and the non-living components of their environment (weather, landscapes).

[1] If you want to explore deeper into microbial mats, watch this video: https://youtu.be/VpCkgvb41Ag

MICROBIAL MATS AROUND THE WORLD

Nowadays, microbial mats can be found in tropical coastal lagoons, estuaries, and bays, but they may be difficult to spot because they can only grow large when they have enough food and when they are protected from grazing organisms. However, mats are found extensively in the **fossil record**, indicating that, billions of years ago, these structures were abundant on the early Earth. Just think about it! Dinosaurs originated 0.245 billion years ago (BYA), fishes 0.530 BYA and aquatic plants 1.2 BYA, but microbial mats were present on Earth

FOSSIL RECORD

The history of life on Earth, documented by fossils, remains, or imprints of organisms that lived many years ago.

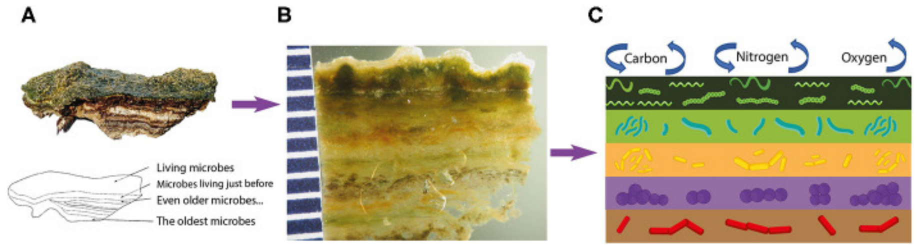

Figure 2

Figure 2

Zoom to the top first centimeter of a microbial mat. **(A)** Structure of a classic microbial mat. Living microbes are found in the top layer, while older mat is below. **(B)** A close-up look at a cross-section of the first centimeter of a mat, showing the different layers formed. **(C)** Different types of microorganisms live in the different layers of a microbial mat. Important elements such as carbon, nitrogen, and oxygen are recycled by microorganisms.

even 3.5 BYA, long, long before any other forms of life existed. On early Earth, these microbial structures proliferated on rocky or sandy surfaces worldwide. Imagine that! Today, microbial mats usually get eaten by other organisms, but billions of years ago, those higher lifeforms had not yet evolved, so the mats just kept growing! Microbial mats are one of the oldest forms of organized life and the study of today's mats helps scientists to understand their contribution to ecosystems on both modern and early Earth.

Geological data and laboratory studies have revealed the importance of microbial mats in the history of Earth. It is believed that, in the past, the abundance and high activity of mats created the atmosphere that we breathe today. Furthermore, as ancient mats released carbon dioxide and methane, they also contributed to the regulation of Earth's climate, helping to create the warm atmosphere that made the Earth a habitable planet [3].

MATS AS MODELS FOR EXTRATERRESTRIAL LIFE

Microbial mats have been observed in extreme ecosystems, such as in extremely salty areas around coasts and in deserts soils. Also, they can form in the polar regions attached to permafrost, which is soil that never thaws. Mats have been discovered at high temperatures, close to volcanoes and hot springs. They have also been found in the deep ocean, under harsh conditions of light and pressure.

Since mats can grow under extreme variations of sunlight, water, temperature, and salinity, scientists believe that microbial mats might exist beyond Earth, growing on other rocky planets or moons. Most planets and moons in our solar system are not suitable places for life, due to the high amounts of ultraviolet light or cosmic radiation they receive, and their lack of a life-supporting atmosphere. But evidence suggests that some planets and moons in the solar system may have water, sometimes protected by ice layers. If there is life in those remote places, it is likely to be microbial life, not big animals, or plants. Therefore, by studying the characteristics of microbial mats, scientists can discover the microbial mats' **biosignature**. A biosignature is like an identification card that suggests the presence of life. For example, the

BIOSIGNATURE

Any feature, molecule, substance, or characteristic that strongly suggest evidence of life.

gases produced by microorganisms or the structures they built in rocks and sand could be their biosignatures. Using cameras and instruments on spacecrafts, large structures produced by microorganisms would be far easier to detect than would microorganisms themselves. If we observe the biosignature of microbial mats on another planet using a spacecraft's cameras, it will indicate that microorganisms could be living on that planet.

Currently, scientists are looking for live or fossilized mats in our solar system. The planet Mars and two moons of the planet Saturn (Titan and Enceladus), have geological characteristics that are promising for the formation of microbial mats. Mars has a rocky, dry surface but recently, NASA's Mars Reconnaissance Orbiter provided strong evidence of liquid water on the planet [4]. The Cassini-Huygens and Voyager spacecraft missions studying Saturn and its moons found evidence of water and polar ice on Titan and Enceladus, probably similar to the ice and water found in the polar ice caps on Earth [5]. There is no evidence yet of any kind of life prospering beyond our planet, but the study of extreme ecosystems on Earth helps us to predict the conditions needed for microbial life elsewhere in the Universe, and to design strategies and devices that will help us to find it. For example, we must know which instruments to send on space missions to detect gases produced by microorganisms, and we must know how to identify microbial mats in photographs.

HOW ARE MICROBIAL MATS STUDIED?

Microbial mats are everywhere on Earth, in both mild and extreme environments, and in both accessible and hard-to-reach places. Some of the most famous microbial mats are found at Yellowstone National Park, California (USA), where they grow near hot springs and geysers. However, you can find mats on some shallow coasts, where seawater rises and falls with the tides. For example, mats can grow in mangrove forests, salt marshes, wetlands, or at the edges of rivers and lakes. Sometimes, in other places where the water is not cleaned regularly, bits of biofilm or small mats can grow—for example, in birdbaths, fountains, or fish tanks (Figures 3A–H).

Current microbial mat research is conducted through field trips and expeditions that investigate the ability of mats and microorganisms to survive in various ecosystems, under diverse environmental conditions. This information helps scientists to understand the role of mats in ecosystems, and the limits of sunlight, water, temperature, and other conditions under which these microorganisms can function. In addition to studying mats in their natural locations, pieces of mats are transported to laboratories, where long-term experiments can be performed, and various laboratory tools can be used to learn about the lives of the microorganisms. For example, we can grow mats in the laboratory and use instruments to measure how much

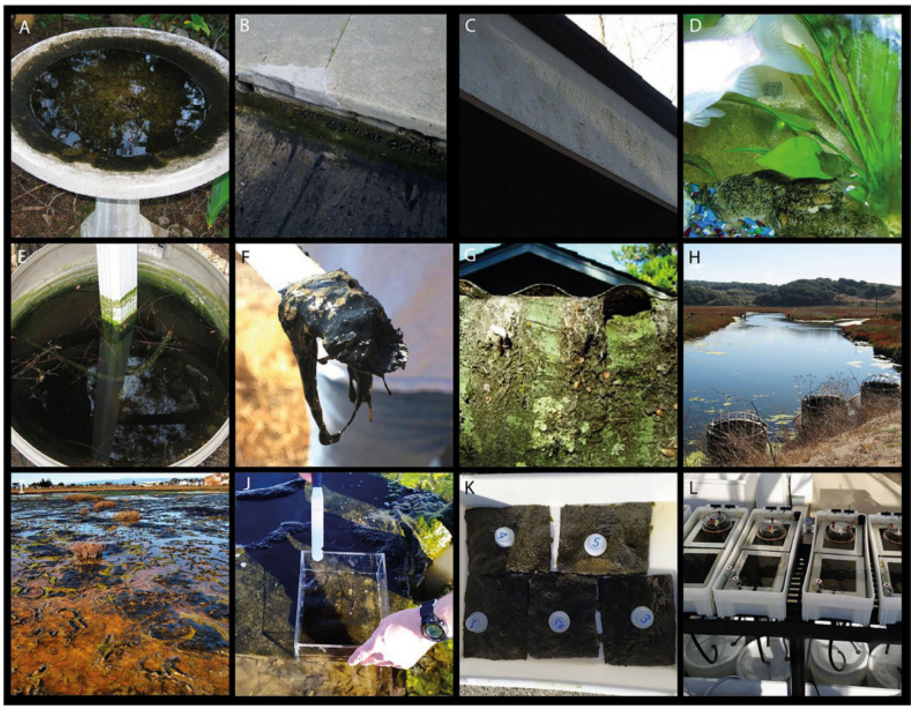

Figure 3

Figure 3

Algae and mat-like biofilms growing in familiar places, such as **(A)** a bird bath, **(B)** a street gutter, **(C)** an exterior roof board, **(D)** the bottom of a fish tank, **(E)** a water collector from a roof drain, **(F)** the waters of an estuary, and **(G)** a board found under a shed. **(H)** Floating algae in an upstream area of Elkhorn Slough, California. **(I)** A view of the microbial mat collecting area. **(J)** Sampling microbial mats. **(K)** Transporting mats from the field site. **(L)** Mats incubating in a greenhouse at NASA's Ames Research Center.

oxygen they produce and how much carbon dioxide they consume (Figures 3I–L).

CONCLUSION

In conclusion, microbial mats are complex systems that provide an excellent opportunity to study microbial diversity, ecology, and evolution. Mats are found all over Earth in many kinds of ecosystems, and they come in a wide variety of shapes and sizes. Just like the mats themselves, scientist interested in studying microbial mats can be found all around the world. Do you know, or have visited any place where mats would grow?

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

YOUNG REVIEWERS

ANHAD, AGE: 12

Hello my name is Anhad and I like writing about topics (sometimes). I also love watching tv and playing video games on my console and also love hanging out with my friends and family. I like waching netflix in my free time and cooking.

AVANI, AGE: 10

Hello, I am Avani, I like to play a lot of games of every type. I also like playing with my puppy and video games. I like animals and nature a lot! So, in warm weather, I go outside and look at my beautiful surroundings and nature around me! And in cold weather, I ski and play in the snow! Those are some things about me!

SANSKRITI, AGE: 15

Hello, my name is Sanskriti. I am 14 years old and am going into 9th grade. I love Computer Science and hope to see more girls showing interest in that field in the next few years.

AUTHORS

SANTIAGO CADENA

I am a marine biologist dedicated to the study of marine and hypersaline microorganisms. I am very interested in geomicrobiology, astrobiology, and biotechnology. I have experience in the study of the methane and sulfur cycles in microbial mats. Also, we are studying the microorganisms living in mangrove forests. In brief, I am interested in studying the role of microorganisms in nature and their potential use for biotechnological purposes.

PAULA MAZA-MÁRQUEZ

I am a postdoctoral researcher in the Exobiology Branch at NASA's Ames Research Center. I study the structure and function of microbial mats. I am particularly interested in genes that control nitrogen cycling, to explore the hypothesis that key features of the modern biological nitrogen cycle evolved in microbial mat systems.

SANDRA I. RAMÍREZ JIMÉNEZ

I am an astrobiologist at Centro de Investigaciones Químicas, Universidad Autónoma del Estado de Morelos, interested in microorganisms from extreme ecosystems, specifically, bacteria living in high salt concentrations. I study the adaptation strategies bacteria use in environments mimicking the salty water of the satellite Europa or the subsurface of the planet Mars, to understand the limits of terrestrial life and the potential for life on other bodies in the solar system.

SHARON L. GRIM

I am a postdoctoral fellow at NASA's Ames Research Center. I study cyanobacteria, which are photosynthetic microorganisms that have shaped Earth's atmosphere for billions of years by producing oxygen. I use computational tools to understand the genes and biogeochemistry of cyanobacteria and other microorganisms in extreme microbial mats.

JOSÉ Q. GARCÍA MALDONADO

I am a research scientist working at the Marine Resources Department in the Center for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV), in Mexico. My investigations are mainly related to the ecology and biotechnology of complex microbial communities in marine and extreme environments. *jose.garcia@cinvestav.mx

LESLIE PRUFERT-BEBOUT

I am a microbial ecologist and geobiologist. I am interested in how the sedimentary mineral environment characteristics affect colonization by different populations of microorganisms. I focus on cyanobacterial species and how they distribute themselves in their environments. I am also very interested in how much and what colors of light exist inside of sands and rocks.

BRAD M. BEBOUT

I am a scientist at NASA's Ames Research Center now, but I have been studying microbial mats since I was a graduate student; that was 30 years ago! I am mostly interested in how mats help recycle carbon and nitrogen in the environments where we find them, but also in the biosignatures that they produce so that we, at NASA, can see if they occur in places other than Earth.

BIODIVERSITY
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HOW SOIL INVERTEBRATES DEAL WITH MICROPLASTIC CONTAMINATION

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YOUNG REVIEWERS:

ASTÈRE
AGE: 8

JUNIE
AGE: 10

Small animals living in soils, called soil invertebrates, represent a very diverse group of soil inhabitants. They include earthworms, woodlice, spiders, springtails, mites, and some insects. Soil invertebrates feed on dead plants, on fungi and bacteria, or on other soil invertebrates. The many ways soil invertebrates interact with each other, and the large number of different species, make life in soils complex and difficult to understand. Unfortunately, soil invertebrates have been dealing with soil pollution, including contamination with tiny particles of plastic called microplastics for decades now. But are microplastics harmful to these organisms? Can microplastics be passed between soil invertebrates when one feeds on another? Most questions about microplastics and soil invertebrates have been investigated using earthworms, but a few studies on others, like

springtails, mites, and nematodes, also exist. In this article, we summarize the effects of microplastics on soil invertebrates.

WHO ARE THE HIDDEN SUPERHEROES IN THE SOIL AND WHAT ARE THEIR JOBS?

SOIL INVERTEBRATES

Small, soil-dwelling animals without backbones or bony skeletons.

Many animals live in soils, but... why can we not see them all? The tiny animals living in soils are called **soil invertebrates**, and they vary greatly in size. Some species are even smaller than the diameter of a human hair! We can classify soil invertebrates into three main groups based on their sizes [1] (Figure 1). Macroinvertebrates are big invertebrates like earthworms, woodlice, spiders, millipedes, centipedes, and some insects like beetles. They are bigger than 2 mm and can create their own living spaces in soils. Mesoinvertebrates have an intermediate size (0.1–2 mm) and live in air-filled pore spaces in soils. Examples include springtails [2], mites, and potworms. Microinvertebrates are <0.1 mm, so small that we cannot see them without the help of a microscope. They live in the water that is present around soil particles. Examples include nematodes, rotifers, and water bears.

Each soil invertebrate group likes different foods [3]. In general, some soil invertebrates, like spiders, feed on other soil invertebrates. Others, like springtails, feed on microbes like fungi and bacteria; and still others, like earthworms, feed on dead plants. These feeding relationships are part of a complex food web that is composed of many species (Figure 2) and many interactions.

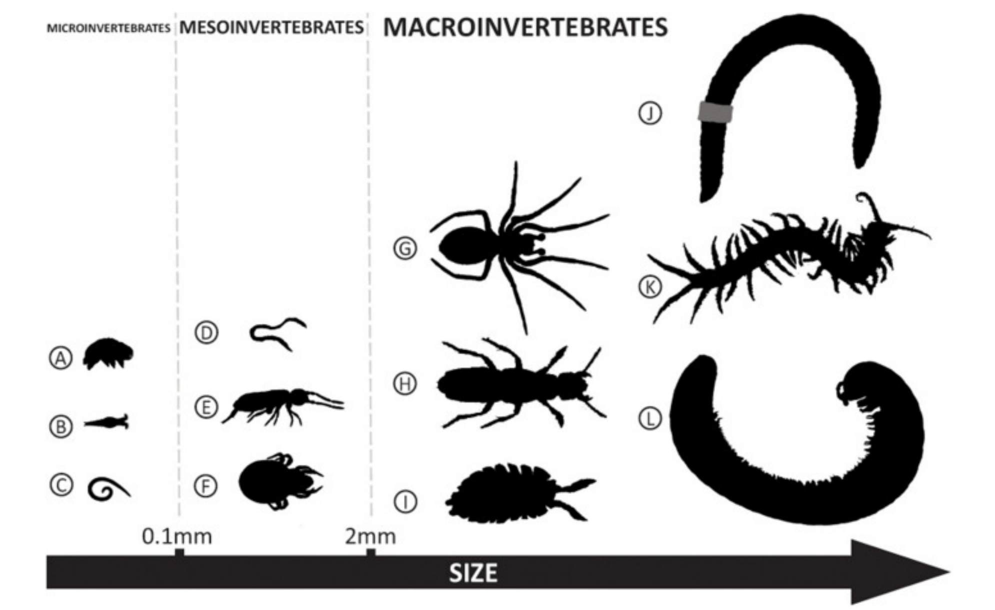

Figure 1

Figure 1

Examples of soil invertebrates of different size. **(A)** water bear, **(B)** wheel animal, **(C)** nematode, **(D)** potworm, **(E)** springtail, **(F)** mite, **(G)** spider, **(H)** beetle, **(I)** woodlouse, **(J)** earthworm, **(K)** centipede, and **(L)** millipede. Illustrations do not represent the actual size of the soil invertebrates.

Figure 2

Figure 2

Examples of soil invertebrates. Microinvertebrates (<0.1 mm) include **(A)** water bears and **(B)** nematodes; mesoinvertebrates (between 0.1 and 2 mm) include **(C)** potworms, **(D–G)** springtails, and **(H,I)** mites; macroinvertebrates (>2 mm) include **(J)** woodlice, **(K)** beetles, **(L)** earthworms, **(M)** millipedes, **(N)** centipedes, and **(O)** spiders (photo credits: **A,C–O**: Frank Ashwood; **B**: Devdutt Kamath).

All soil invertebrates are important for the environment. For example, water bears can colonize new environments and serve as food for other organisms. Nematodes can help cycle nutrients through the soil, with the help of springtails, mites, woodlice, and earthworms. Woodlice, springtails, and some mites [4] help decompose leaves and other formerly living materials in the soil [5], and they also help trap carbon from the atmosphere in the soil. Earthworms help rainwater to infiltrate into the soil. Some soil invertebrates may feed on organisms that cause plant diseases, protecting plants from these pests. Each in their own way, these creatures help to keep the soil healthy, which is also necessary to ensure the quality of our food.

MICROPLASTICS

Small plastic particles (<5 mm) which can be harmful to soil and aquatic life.

THE THREAT OF MICROPLASTICS

Unfortunately, the homes of many soil invertebrates have been invaded by pollutants such as **microplastics**. Microplastics are small particles (<5 mm) that are created in many ways (Figure 3; Box 1). For example, when cars are driven on roads, their tires wear out and

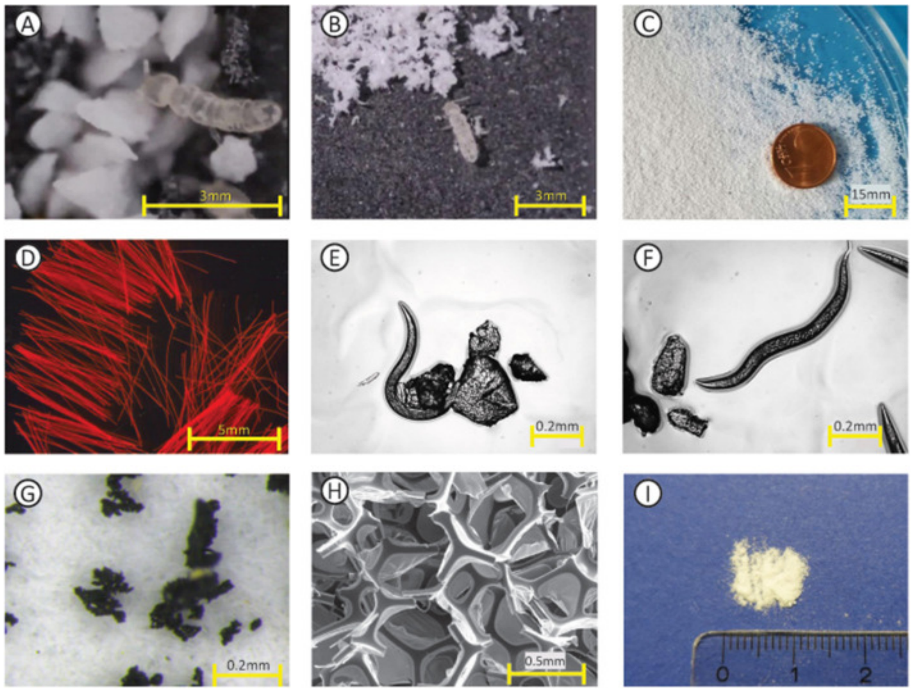

Figure 3

Figure 3

Examples of microplastics. **(A)** Springtail and urea-formaldehyde particles. **(B)** Springtail and plastic scraped off a pop bottle. **(C)** Polypropylene microbeads. **(D)** Polypropylene microfibers. **(E,F)** Adult nematodes with fragments of polystyrene. **(G)** Particles formed by tire abrasion. **(H)** Close-up of a polyurethane sponge. **(I)** Powder-like polypropylene (photo credits: A,B: C. Reinhart and D. Daphi, C,I: Stefanie Maaß, D: Carlos Barreto, E,F: Shin Woong Kim, G: Eva Leifheit, H: Walter Waldman).

lose microplastics, which can be picked up by the wind and end up in soils. Also, when we do laundry, plastic fibers are released from the clothes into the water. One fleece coat alone can release up to one million fibers per wash cycle! Many of these plastic fibers end up in the sewage, which is a problem because treated sewage can be used to fertilize the soil that crops are grown in. Microplastics can also enter the soil through plastic trash and rainwater.

Microplastics have a huge range of chemical and physical properties. Plastic materials often contain **additives**. These additives can make microplastics even more harmful to the environment, especially once the microplastic particles start to undergo **degradation**. Plastic particles become increasingly brittle due to sunlight, water, and the surrounding soil particles that rub on them. Over time, microplastic particles fall apart into even smaller particles, called nanoplastics. During degradation, the additives slowly start to **leach** out of the microplastics, into the soil. The particles can also leach into the tissues of organisms if they are eaten. Unfortunately, we still do not know much about the effects that leaching of additives from plastics can have on the environment.

ADDITIVES

Chemicals that make the plastic more colorful flexible, or less flammable.

DEGRADATION

The breakdown or separation of something into simpler/smaller parts.

LEACHING

When a liquid substance is released away from its solid source.

So, microplastic particles can clearly affect the soil, but how do they affect soil invertebrates? [6] If we look at earthworms, with their constant appetite for dead leaves and their intense digging activities, we can easily imagine that they regularly ingest microplastic particles and transport them deep into the soil. Not only by feeding, but also on their skin, they can transport these particles. The same has

Box 1 | Sources of microplastics in soils.

Object	Plastic (formal names)	Comment
Paints	Epoxy and alkyd resins	Microplastics are formed from sanding painted surfaces and when paint peels off walls or other structures.
Plastic bags	Low-density polyethylene (LDPE)	When plastic bags are discarded improperly, they might end up on the ground and get degraded by the sun, eventually forming microplastics.
Mulching films	Low-density polyethylene (LDPE)	Some farmers use plastic mulching films to protect plants from water loss. These plastics will break down from sun exposure and form microplastics.
Tires	Polyisoprene (natural rubber)	Although tires are made primarily of natural rubber, they also contain additives and their toxicity is currently being tested.
Foam	Polystyrene (PS)	Foams are widely used in house insulation and in packaging to protect products during transport and storage. Damage and breakdown of foams produce microplastics.
Glitter	Polyethylene terephthalate (PET)	Glitter spreads easily and can detach from makeup and toys and contaminate soil.
Water bottles	Polypropylene (PP)	Breakdown of improperly disposed water and soft drink bottles can contaminate the soil.
Soft drink bottles	Polyethylene terephthalate (PET)	
Clothes	Polyesters and polyamides	Synthetic fibers release microfibers during washing, and they end up in the soil *via* fertilizers prepared from sewage.

been shown for springtails. What does this mean? On the one hand, the microplastic particles will become more degraded as they pass through the guts of soil organisms. But on the other hand, once particles are carried deeper into the soil, degradation slows down due to the absence of sunlight and reduced microbial activity. In other words, the deeper the particles move into the soil, the longer it takes for them to totally degrade.

MICROPLASTICS CAN AFFECT THE HEALTH OF SOIL ORGANISMS

Soil organisms feel sick when they eat microplastics, and this is has been reported for earthworms and springtails. After feeding on microplastic particles, earthworms suffered from several health problems, including inflammation and damage to the gut [7]. Additionally, ingestion of microplastics put the immune system of the earthworms on higher alert than usual. Springtails that ingested microplastics suffered changes in the helpful bacteria living in their digestive systems [8]. Both earthworms and springtails grew more slowly, had fewer offspring, and died more often after they ingested microplastics.

This sounds like bad news for nematodes, but here is the good news: scientists have not seen a build-up of microplastic particles in organisms over time, which means that they might not suffer that much harm after all. However, it is likely that microplastic particles can be passed on along through the soil food web, from microbes like fungi, to springtails, to predatory mites; or from microbes to earthworms, and then to chickens [9]—and maybe also to humans! We still do not know much about how microplastics move through the soil food web, but research is progressing quickly on that topic. Despite these concerns, scientists have found a gleam of light! One research group reported that certain bacteria in the guts of earthworms can digest ingested microplastics, leading to high degradation rates [10]. This means that bacteria might be able to speed up the destruction of microplastics in soil. Can other soil invertebrates do the same? We simply do not know yet.

WHAT CAN WE DO TO PROTECT SOIL INVERTEBRATES?

You might wonder why scientists have not made more progress answering important questions about the effects of microplastics on soils and the organisms that live there. Unfortunately, these studies face numerous difficulties. For example, we do not yet have a reliable method for measuring the amount of all types of microplastics in all types of soil. Also, many studies consist of short-term experiments that are done in the lab, instead of long-term studies done outdoors in the soil. The huge diversity of plastic types and additives makes it impossible to test everything under real-world conditions. Lab experiments are only informative to a certain degree. Lab experiments are also difficult because not all soil organisms will survive in the laboratory environment. But rest assured: scientists are doing their best to solve these problems. In the meantime, there are ways that *you* can help!

We should all try our best to minimize the future addition of plastics of any type and size into the environment. You may already know some of the most important ways! Avoid single-use plastic items like plastic cups or straws. Choose your favorite metal or reusable plastic cup, and a metal straw, and keep them handy in your lunch bag! It is also important to put plastic waste in the correct recycling container: This can help reduce the amount of plastic that ends up in the water and soil. Additionally, avoid beauty products that have microplastics in their ingredients, like some conditioners! There are alternative products that are free of microplastics, and some smartphone apps can help you choose the best ones for you. To reduce the number of plastic fibers released into the environment, try not to throw away old clothes just because you do not want them anymore! Instead, try to sell, donate, or reuse them in a creative way. Let's join forces and save our tiny soil superheroes from further microplastic pollution. It is worth every effort!

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YOUNG REVIEWERS

ASTÈRE, AGE: 8
My age is 8. I like reading, doing DIY, drawing, coloring, art, maths, writing, and history. My favorite books are Harry Potter and Percy Jackson.

JUNIE, AGE: 10
I have many hobbies but the ones that I do the most are cooking, reading, drawing, and sewing. I go to a primary school in a big city in the UK and my age is 10. My favorite books are Percy Jackson, books by Judy Blume, Scarlet and Ivy, and North child.

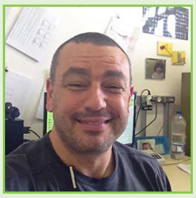
AUTHORS

CARLOS BARRETO

At a very young age, Carlos realized that he liked animals, maybe too much. In school, science was always his favorite discipline, all the way through to high school. That is when he decided that he wanted to do something that involved science and animals. He tried to be a vet; it did not work out. No regrets. So, he became an ecologist a few years later, and since then, he has been working with little animals (mostly insects and mites) in tropical forests, iron ore and limestone caves, boreal forests, urban fields, and peatlands on three continents: South America, North America, and Europe. *cbarreto@uwo.ca; †orcid.org/0000-0003-2859-021X

MATTHIAS C. RILLIG

Matthias likes soil and all the critters in it, not just the animals. Actually, his favorite are the fungi. His favorite soil process is soil aggregation, the formation of the little crumbs of soil. Matthias is a professor at Freie Universität Berlin and gets to think about soil and what is going on in there all day. Currently he is very interested in how soils are being affected by a wide range of factors, including microplastics. †orcid.org/0000-0003-3541-7853



WALTER R. WALDMAN

Walter is a proud Brazilian chemist who loves music, chemistry, food, cinema, and polymers. His first experiment involved chewing gum and the hair of an ex-friend. The experiment did not end well for all the participants, but the adhesive power of polyisoprene was confirmed, and a polymer scientist was born that day. Now he tries to understand the role of polymer degradation on the impact of microplastics. When he has some free time, you can find him reading something about chemistry and polymers. And eating... †orcid.org/0000-0002-7280-2243

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Stefanie wanted to become a make-up artist or costume designer but due to lack of art skills, she moved on to something completely different: biology. When she was introduced to tropical insects and mites of tree bark during her studies, she became fascinated by their beauty and diversity. She then worked on soil insects and mites and has become a passionate and curious soil ecologist who wants to understand the feeding relationships, reactions to pollutants (like microplastics), and distribution patterns of her beloved soil creatures. †orcid.org/0000-0003-4154-1383

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DIRT IS NOT DEAD: HOW LAND USE AFFECTS THE LIVING SOIL

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YOUNG REVIEWER:

KONSTANTIN
AGE: 14

Humans use land to grow crops for food, and the farming methods we use can influence the organisms that live in the soil. Soil organisms do important work, like decomposing organic matter and releasing nutrients for plant growth. By adding more pesticides and fertilizers to farmland, we can produce more crops in a smaller space. But those methods can also harm soil organisms and the work that they do. In contrast, we can use gentler methods to grow crops, which are better for soil animals, but those methods require more land. People in all countries need food from crops to live healthy lives. Because we all share one land surface, when we decide how to use land, we need to remember how agriculture influences soil animals.

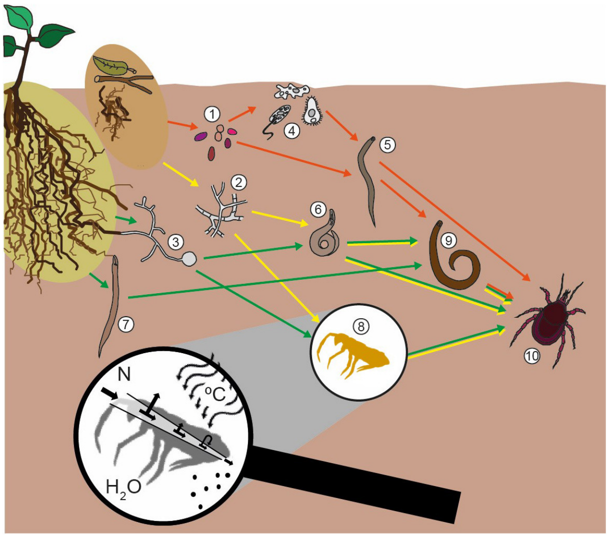

Figure 1

Figure 1

The soil food web is composed of many kinds of soil organisms: (1) bacteria, (2) fungi, (3) arbuscular mycorrhizal fungi, (4) protozoans, (5) bacteria-feeding nematodes, (6) fungal-feeding nematodes, (7) root-feeding nematodes, (8) collembolans, (9) predatory nematode, and (10) predatory mites. Arrows point from the organisms that are eaten to the organisms that eats them. Interaction pathways form three main energy channels: bacteria-based channel (orange arrows), fungal-based channel (yellow arrows), and root-based channel (green arrows). The magnifying glass shows that nutrients and energy flow through each soil organism when it eats and respires.

7.8 BILLION PEOPLE, AND COUNTING, EAT FOOD THAT GROWS IN SOIL

There are 7.8 billion people and all of them need to eat healthy food. Vegetables and other crops are part of a healthy diet. But producing food for so many people comes with a cost to the environment. First, we need enough farmland and then we need farming practices that keep the environment healthy. The organisms that live in soil can tell us if our farming practices are good or bad for the environment.

In the soil, there are billions of organisms, such as bacteria, fungi, nematodes, and isopods that live in soil (Figure 1). They all eat, and grow, and use oxygen and release carbon dioxide, just like we do. When **soil organisms** carry out these life processes, they release nutrients from their food that are useful for plant growth (Figure 1, inset). They also mix organic matter (i.e., dead plants and organisms) throughout the soil. They improve the structure of the soil, which improves water availability for plants. Soil organisms supply the resources that help plants grow the food that humans like to eat. Soils provide important **ecosystem services**, such as water filtration and nutrient recycling, that help keep humans alive and healthy.

SOIL ORGANISMS

All of the types of life forms that live below ground. This includes single celled organisms like bacteria, and multi-cellular organisms like earthworms, protozoa, nematodes, and mites.

ECOSYSTEM SERVICES

The important things environments do for people. In soils ecosystems, examples include recycling nutrients, retaining and draining water, and mixing organic matter.

SOIL ORGANISMS FORM A FOOD WEB UNDER YOUR FEET

The organisms in the soil do not work alone; they are connected with each other in a network of interactions called the **soil food web**. Changes in the abundance of one species can affect the abundance of their predators and prey, in a chain of interactions called an **energy channel** (Figure 1). Soil food webs have three main energy channels: one fueled by bacteria, another fueled by fungi, and a third fueled by

Land use practices	Extensive land use	Medium-intensity land use	Intensive land use
Fertilizers	(-)	(+)	(++)
Pesticides	(-)	(+)	(++)
Ploughing	(-)	(+)	(++)
Harvesting	Grazing or mowing by hand	Light machinery	Heavy machinery
Plants grown	Mixture of naturally occurring species	Rotation of species planted by humans	Human planted single plant species (i.e. monoculture)

Figure 2

Figure 2

Three common ways that natural environments are used. Extensive land use does not involve much plowing and harvesting or the addition of lots of fertilizers and pesticides, and it produces diverse ecosystem services. Medium-intensity land use needs some plowing and harvesting and yields intermediate harvests. High-intensity land use requires lots of work plowing and harvesting, as well as lots of chemical use, to produce a lot of crops from a smaller area. In high-intensity land use, some ecosystem services are reduced in favor of high-output of crop production.

plant roots. Bacteria and fungi eat organic matter, such as dead roots and leaves, and later they are eaten by other organisms. There are also organisms that feed directly on living roots, such as root-eating nematodes (tiny worms), which are also eaten by other animals. When humans use the land in a way that disrupts these energy channels (such as by **tilling** the soil or adding fertilizers), they may alter the ability of soil food webs to provide their usual ecosystem services. But how many species are affected by humans and how strong is our effect on the processes soil organisms normally perform?

AN EXPERIMENT TESTING THE EFFECTS OF LAND USE ON SOIL FOOD WEBS

Scientists hypothesized that different types of **land use** would affect the structure of the soil food webs (Figure 2) [1]. They thought that intensive land use, such as tilling the land, would reduce the number of soil organisms and limit the ecosystem services provided by soils [1]. Scientists also thought that soil organisms would be more abundant when farmers applied extensive land use practices (such as hay meadows and pasture). In extensive land use, there is less plowing and less fertilizer added, but more land area is needed to produce the same amount of food. They thought that soil organisms would do best in natural grasslands, where farmers do not use the land to grow crops [1].

With the goal of using sites exposed to a broad range of environmental conditions (temperature, precipitation, soil texture, etc.), a team of scientists went to four countries across Europe: Sweden, Czechia, United Kingdom, and Greece. In each country, they went to sites with three types of land use: high-intensity agriculture, medium-intensity agriculture, and natural grasslands [1] (Figure 2). At

SOIL FOOD WEB

The network of feeding interactions among soil organisms. The interactions start from three main resources (roots, fungi, bacteria) that form energy channels.

TILLING

Preparing soil for agriculture by plowing or digging. Tilling buries weeds and makes it easier for crop roots to enter the soil.

LAND USE

How the natural environment is managed and modified. Examples in text include Intensive land use, extensive land use, and natural areas.

each site, they measured a variety of soil organisms, including fungi, bacteria, protozoa, nematodes, earthworms, enchytraeids, mites, and collembolans. To find out how the ecosystem services differed between the land uses, they also measured some of the important processes performed by soil organisms.

INTENSIVE FARMING REDUCES BIODIVERSITY IN THE SOIL

The scientists found that the type of land use was important for the numbers and types of organisms that they found in the soil. They found that more intensive land use reduced the biodiversity of the soil food web: there were fewer groups of organisms present, and within these groups, there were also fewer species [2]. They also found that the total weight of most groups of soil organisms was lower where there was high- and medium-intensity land use. The organisms that are fueled by plant roots were the most reduced, and organisms that eat bacteria and fungi were affected less. This is probably because tilling the soil has strong effects on plant roots in medium- and high-intensity land use, which has extended effects on the organisms that are fueled by plant roots. But how much of the change was due to the direct effects of the tilling on the soil, and how much was due to changes in the soil food webs?

PROCESSES CARRIED OUT BY SOIL ORGANISMS

To evaluate the question above, the scientists looked at relationships between groups of soil organisms and the processes that these organisms carry out. The scientists focused on two processes: respiration and the cycling of nitrogen. When we are talking about tiny organisms, **respiration** is the name of the process that uses oxygen and releases carbon dioxide, to produce the energy that the organisms need to grow and perform their functions. Nitrogen is an essential element for all life, including plants. It cycles through the environment in several steps. **Mineralization** is the process by which nitrogen is released from organisms into the soil (Figure 3), usually when they decay. Nitrogen in the soil can be lost through **leaching**, which means being flushed out of the soil by water, or by **denitrification**, in which the nitrogen is turned into a gas called nitrous oxide (NO_2) produced by bacteria and escapes from the soil into the atmosphere.

NATURAL GRASSLANDS ENHANCE SOIL RESPIRATION

First, scientists found that the respiration of soil organisms was higher in natural grasslands and where there were more earthworms in the soil. Earthworms mix the soil, and by doing this, they stimulate the activity of other soil organisms. Just like us, when soil organisms

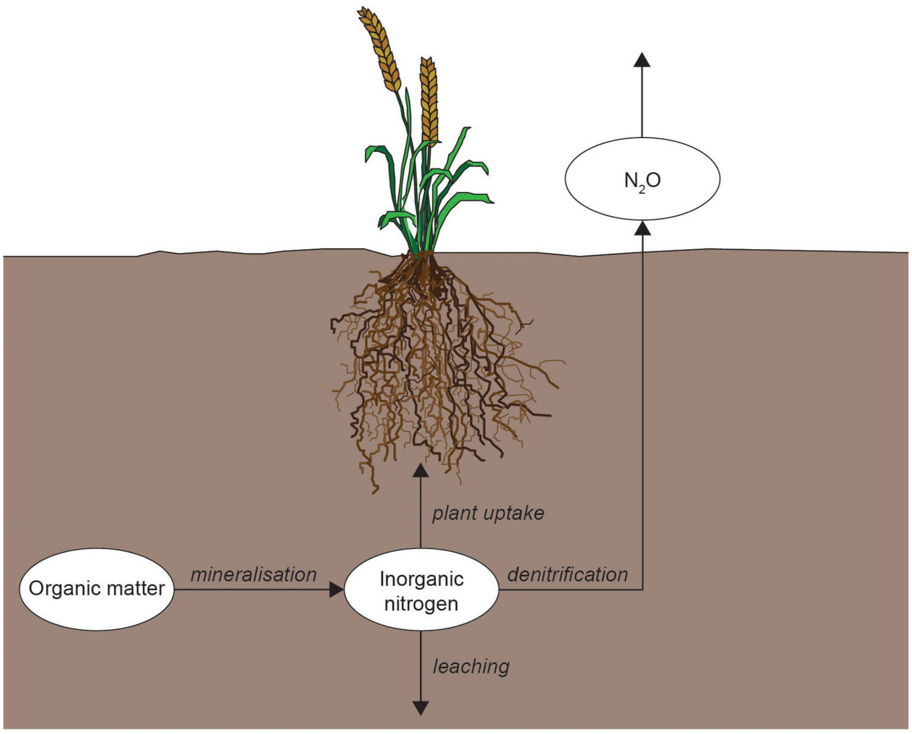

Figure 3

Nitrogen is transformed by soil food webs so that it can move through plants, water, or air. Soil organic matter (dead plants and animals) is mineralized to inorganic nitrogen by the feeding activity of soil organisms. Inorganic nitrogen in soil can be taken up by plants and fungi, or it can be lost from the soil by either leaching into ground water or by conversion to N_2O gas by bacteria, in a process called denitrification.

become more active, they need to eat more and respire more. When there is more organic matter available as food, there will be a greater number of active soil organisms. Because natural grasslands have higher organic matter than the fields used for medium- and high-intensity agriculture, respiration was higher in these sites.

MORE NITROGEN FLOWS INTO AND OUT OF INTENSIVELY MANAGED FARMS

When scientists looked at the cycling of nitrogen, they found that nitrogen mineralization was higher in food webs with a stronger bacterial energy channel (see soil food web in glossary). Bacteria are often very abundant in areas with intensive land use, where they grow quickly and die quickly, releasing the nitrogen from their tissues into the soil.

After they measured the mineralized nitrogen that was released into the soil, the scientists wanted to know how land use affected where the nitrogen went next. They found that, in areas with less intensive land use where there were a lot of arbuscular mycorrhizal fungi, there was less leaching of nitrogen into the water, meaning that more nitrogen stayed in the soil where plants could use it. Farmers want to limit the amount of nitrogen leaching, so that most of the nitrogen can be used by crop plants instead of flowing out of the fields. Arbuscular mycorrhizal fungi are a special group of fungi that attach to plant roots and help the plant take up nutrients, including nitrogen. These fungi might take up nitrogen from the soil and prevent it from being lost through leaching. So, the presence of arbuscular mycorrhizal fungi could be a good indicator of reduced leaching across different types of land use.

To evaluate the amount of denitrification, scientists measured the concentration of nitrous oxide gas (N_2O). They found lower N_2O concentrations where there was an increased number of flagellates—tiny creatures that use a tail to propel themselves forward in the water that is within the soil and that eat bacteria. Importantly, denitrification is not actually done by flagellates, but by a specific group of bacteria. Because flagellate increased in areas where denitrifying bacteria were not abundant, we may be able to use flagellate abundance as an important indicator of other processes (e.g., denitrification) and soil organisms (e.g., denitrifying bacteria). Understanding what is happening in soil food webs with low concentrations of denitrifying bacteria is important because, when nitrogen leaves the soil as N_2O, it can make climate change worse. N_2O is a greenhouse gas that is 314 times stronger than CO_2!

INCREASE SOIL BIODIVERSITY TO MINIMIZE THE IMPACTS OF INTENSIVE FARMING

The question of the “right” way to use land to grow vegetables and other crops is an ongoing scientific and social debate. How can humans produce healthy and enough food for billions of people with the minimal impact to the planet? Scientists are learning that soil organisms are sensitive to changes humans make to the environment. Farming practices do not just influence individual organisms, they influence a complex network of species interactions. Changes in this interaction network affect how energy flows through an ecosystem, which nutrients are retained, which nutrients are lost, and how farmers will have to rely on fertilizers and pesticides. While intensive land use takes up less land area, which is positive, it also causes many negative impacts since it decreases soil biodiversity and increases losses of nutrients and carbon. In opposition, lower intensity land use produces fewer crops but is more environmentally-friendly. So, one solution is to restore soil biodiversity in intensive land use areas to make them less dependent on fertilizers and pesticides, which is good for the environment and therefore for humans. So, if you have the possibility to grow your own vegetables you will be protecting the environment because you will not be producing them through intensive agriculture practices. If you cannot plant your vegetables, you can still protect the environment if you can buy vegetables and other crops that are not produced in intensive farmland. Little by little we can make our planet healthier and healthier.

ORIGINAL SOURCE ARTICLE

de Vries, F. T., Thébault, E., Liiri, M., Birkhofer, K., Tsiafouli, M. A., Bjørnlund, L., et al. 2013. Soil food web properties explain ecosystem services across European land use systems. *Proc. Natl. Acad. Sci. U.S.A.* 110:14296–301. doi: 10.1073/pnas.1305198110

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YOUNG REVIEWER

KONSTANTIN, AGE: 14

Hi I am Konstantin, your nearby Young Mind! I am from Rousse, Bulgaria and since I was little I had questions like: what is the point in recycling etc. Now, as an adolescent, I really got into ecology and decided to help bring awareness of some of the problems in our world has like the air pollution, species extinction, and deforestation. If I, an ordinary student, can make a difference you can too-so what are you waiting for my young reader!

AUTHORS

JES HINES

Jes is an ecologist working at the German Centre for Integrative Biodiversity Research (iDiv). Her research focuses on how biodiversity responds to changes in the environment. She is interested in how complex systems grow and how species influence the flux of nutrients, energy, and information through ecosystems. *jessica.hines@idiv.de

FRANCISKA T. DE VRIES

Franciska de Vries is a professor at the University of Amsterdam. Her research focusses on understanding how interactions between plants and soil microbes respond to climate change, and how this affects the functioning of the ecosystem.

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DOUBLE WHAMMY FOR LIFE IN SOIL? THE EFFECTS OF DROUGHT AND FERTILIZER USE

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YOUNG REVIEWER:

JEDIDIAH

AGE: 14

For the last two centuries, humans have been changing the Earth through their way of life. Our actions are not only causing climate change and leading to prolonged periods of drought, they are also leading to an overaccumulation of nutrients in soil, due to burning of fossil fuels and fertilization of agricultural fields. Both factors are threatening the world beneath our feet: the soils. They may look rather boring and lifeless, but soils are actually home to many organisms—from tiny bacteria to agile millipedes and slimy earthworms—all of which contribute to processes that are indispensable to life on Earth. For example, the activity of these organisms promotes decomposition of plant material, which ensures that the farmlands on which we grow our food remain fertile. As almost all soil organisms are very sensitive to changes in their environments, we wanted to know what would happen if drought and over-fertilization occurred together.

HUMAN ACTIVITIES CHANGE ECOSYSTEMS

Over the last 200 years, human activities have changed the world tremendously. Human-induced climate change is causing the planet to warm up, coupled with ever-longer periods of drought (prolonged periods with little rainfall) in some regions. At the same time, the farming of fields and meadows has changed dramatically in recent decades. The world's population is growing steadily, and all these many people need to eat. Therefore, large amounts of fertilizers are applied on agricultural fields today, resulting in much higher crop yields [1]. While they may provide enough food for several billion people, these practices come with a significant drawback: similar to drought, excess fertilization affects not only the plants visible aboveground, but also the complex **ecosystem** belowground—the soil and the organisms living in it.

ECOSYSTEM

A community of plants, bacteria, animals, and fungi in a certain location, along with the non-living components of that environment.

THE IMPORTANCE OF THE SOIL ECOSYSTEM

Soils are an important part of terrestrial ecosystems. Although we are often unaware of them, soils are teeming with living things. There are microorganisms, such as bacteria and fungi that are so tiny that they are not visible to the naked eye. What they lack in size, however, they compensate for in number: just one teaspoonful of soil can contain several million soil microorganisms. Even many of the somewhat larger creatures, such as mites and springtails, can only be seen with a magnifying glass. Among the biggest soil animals are woodlice, centipedes, and earthworms. All the somewhat larger soil creatures are united by the fact that they do not have backbones, which is why they are referred to as **invertebrates**. These creatures live together in the soil and interact in various ways: some feed on each other, while others work together.

INVERTEBRATES

Animals lacking spines, such as centipedes, woodlice, and earthworms.

The soil invertebrates perform numerous tasks that are necessary for our existence. One of the most important of these **ecosystem functions** is **decomposition**, which requires the cooperation of a multitude of creatures. Soil organisms are responsible for the breakdown of dead plant material. Withered leaves, dead roots, and seeds are their food resources. They break down these dead plant materials into smaller and smaller pieces. The resulting tiny compounds, in turn, provide an excellent food source for soil microorganisms like bacteria and fungi. Eventually, these resources are converted back into a form that plants can use for their growth, namely CO_2 and nutrients.

ECOSYSTEM FUNCTIONS

Natural processes that occur in an ecosystem.

DECOMPOSITION

After death, living organisms are broken down into smaller and smaller pieces. This releases nutrients, which in turn are needed for plant growths.

All these soil creatures, like almost all life on earth, are highly dependent on water for drinking, for breathing, or even as a means of transportation. Increasingly long and frequent periods of drought are therefore a problem for many small organisms. And even worse, what happens if other harmful factors occur at the same time? Excessive

Figure 1

Figure 1

In half of the experimental plots in our study, we used roofs to simulate drought. The other half of the plots received "fake" roofs with rain panels put upside-down to account for the potential side effects of these roof structures (like changes in wind speed and light). ©Julia Siebert.

PH VALUE

A scale indicating whether a solution has an acidic or basic character. The lower the value, the more acidic the solution is.

use of fertilizer, for example, can be harmful to soil organisms, as it changes the **pH value** of the soil to make it more acidic. Many soil organisms cannot tolerate acidic soil conditions. Could fertilization add a further stress factor, making it even harder for soil organisms to withstand dry conditions? And how exactly can we learn whether drought and fertilization are harmful to soil organisms and interfere with their functions?

HOW DID WE STUDY SOIL MICROORGANISMS?

To understand the effects of drought and fertilization on soil organisms, we started an experiment that simulated these two common factors that humans change [2]. We chose a meadow in Central Germany where we selected small areas called experimental plots and treated the plots in different ways. One-fourth of the experimental plots were treated with drought using roofs (Figure 1), another fourth was treated with fertilizer, and yet another fourth was treated with a combination of drought and fertilizer. The last fourth was not treated at all, which was our control plot. Control plots are important because they allow us to compare the treatments to normal conditions.

To understand how drought and fertilization affect soil organisms, we looked at soil invertebrates and soil microorganisms separately. We examined the activity of soil invertebrates in each of our plots. To do this, we used narrow plastic strips with several small holes in them, called bait lamina test strips. Every hole was filled with a bait mixture, which soil invertebrates like to eat—imagine invertebrate cereal. We stuck some bait lamina test strips completely into the ground of our plots (Figure 2). After 3 weeks, we observed the amount of the bait that had been eaten by the soil animals. Soil ecologists use this method to assess how much soil invertebrates eat, which is a very good indicator of their activity in general.

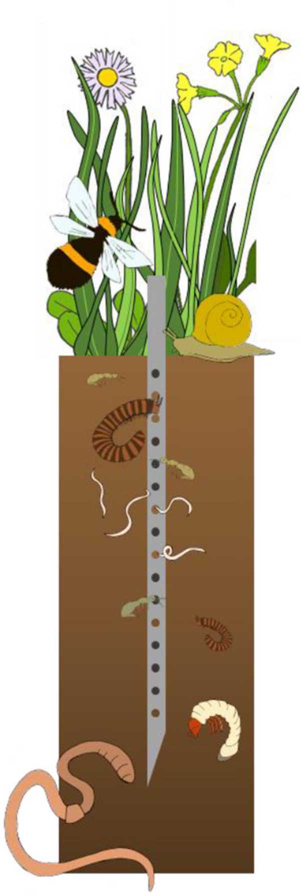

Figure 2

Figure 2

To determine the activity of soil invertebrates in our experimental plots, we used bait lamina strips. The strips were completely inserted into the ground for soil invertebrates to feed on. After 3 weeks, we checked how many of the little holes containing the bait were full, empty, or half-empty. The more active and hungrier the soil invertebrates, the more of the bait was eaten. ©Gottschall/Siebert.

To examine the soil microorganisms more closely, we took a small amount of soil from each of our plots back to the lab. We determined the microbial activity in these samples by measuring their respiration. Just like humans, soil organisms breathe in oxygen (O_2) and exhale carbon dioxide (CO_2), so the more respiration that is happening in a sample, the more active are the microorganisms (think of yourself exercising). To measure microbial respiration, we used a device with a special sensor that can measure the amount of oxygen used by the microorganisms, and these data were then transferred to a computer for storage. By knowing the activity of the soil microorganisms, we were then able to calculate their **biomass**, which is a measure for the amount of all microbes that live in a defined amount of soil, for example on a teaspoon.

BIOMASS

Measure for the amount of all microbes that live in a defined amount of soil.

DROUGHT AND FERTILIZATION CAN AFFECT SOIL INVERTEBRATES

We used statistical tests on our data to find out how the microbial and invertebrate soil communities reacted to drought and fertilization. We found that both drought and fertilization severely disrupt the activity of soil invertebrates. Although the factors on their own had strong

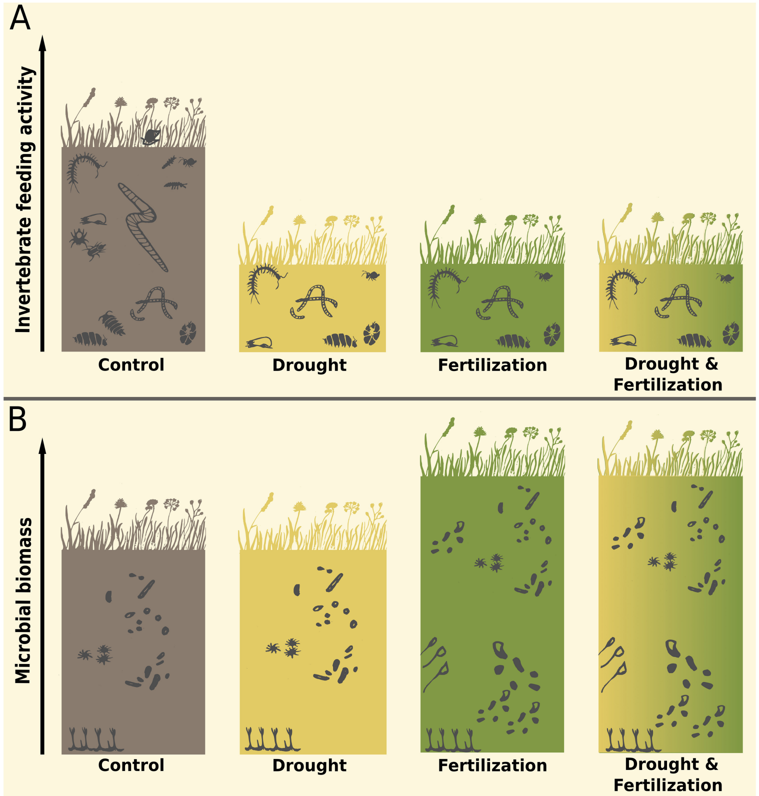

Figure 3

Figure 3

What did we find? **(A)** Drought, fertilization, and both together strongly reduced the feeding activity of soil invertebrates. **(B)** Soil microorganisms were not disturbed by the drought treatment. Fertilization caused an increase in the soil microbial biomass.

negative effects, their combination did not reduce invertebrate activity any further (Figure 3A). Soil microbes, however, reacted completely differently. Drought could not harm them, and additional fertilization even increased their biomass (Figure 3B).

Why do drought and fertilization harm invertebrates much more than microorganisms? Usually, both groups are highly dependent on soil moisture and have trouble coping with droughts. Among other things, their food becomes so dry that they have difficulty digesting it [3]. Imagine eating old toast without jam all day, without drinking anything with it. To avoid drought conditions, invertebrates may travel to deeper, moister soil layers that we did not reach with our tests. However, why did fertilization lower their activity as well? The reason is that fertilization leads to an acidification of soils, which means that the pH value falls below five. Earthworms and many other soil invertebrates do not like to live in low-pH conditions, which can be damaging to their delicate skin. A lemon, for example, has a pH value of 2. Have you ever had a cut on your finger and then gotten lemon juice on it? Not very pleasant.

The drought treatment did not harm soil microorganisms. This took us by surprise, because our treatment reduced the annual rainfall by half, which naturally led to extremely dry soils. However, we think it is possible that bacteria and fungi that normally live in the upper layer of the soil are constantly exposed to the temperature and humidity cycles of the seasons. For this reason, they must be able to survive even the driest periods [4]. One way that they do this is by building themselves a sugary protective shell that prevents their surfaces from drying out. Alternatively, they can create a very resistant form that allows them to survive, called a spore. Spores are in a dormant state and can outlive extreme heat and drought for up to 1,000 years. This is why we believe the drought conditions of our experiment hardly harmed the soil microorganisms. But it is also possible that our experiment was too short to see any negative effects of the drought.

Fertilization, on the other hand, was even beneficial for the microorganisms. This is because the additional nutrients from the fertilizer strongly promoted plant growth. Not only did the plants respond with longer shoots, larger flowers, and many more leaves, they also released more resources into the soil via their roots and the microorganisms could feed on all these extra food sources.

We were happy to find that drought and fertilizer did not reinforce each other's effects, which means that both factors together do not seem to do more harm than either does on its own. This may mean that ecosystems have some great coping mechanisms to use against harmful environmental attacks. But in this study, we only measured the activity of soil organisms after 1 year. We should examine the soil after many years of drought and fertilization, to see if the results are still the same.

WHAT WILL THE FUTURE HOLD FOR OUR SOILS?

To sum up, larger soil invertebrates seem to be much less well-equipped for future environmental changes than microorganisms are. What does this mean for our soils in the future? The decline in the activity of soil animals has several consequences for ecosystems and therefore for humans. As we have already learned, all organisms in the soil are necessary to keep the process of decomposition running. The decomposition process is divided into several steps, which are indispensable for one another. While invertebrates are mostly responsible for breaking down larger pieces of dead animals and plants, microorganisms digest the smaller pieces in the next step and release a range of nutrients. Together, the soil organisms form a large feeding community, in which each species has its own special place, fulfilling their specific tasks. However, if one link in this chain is missing, the whole system is likely to lose its balance [5]. This could mean that soils could lose their fertility in the long term. The result would be that not only grasses but also the wheat and maize in our fields would no longer grow so luxuriantly, and we would eventually have problems feeding all the people on Earth. We are therefore dependent on the well-being of all soil creatures and should keep their importance in mind as we make future decisions that could affect our soils.

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ORIGINAL SOURCE ARTICLE

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

YOUNG REVIEWER

JEDIDIAH, AGE: 14

Jedidiah is interested in science and math, particularly in how the environment impacts his daily life. He spends time working in the family garden, making money by selling eggs and vegetables he helps produce. In his spare time, Jed likes to play baseball and play video games.

AUTHORS

MARIE SÜNNEMANN

When she was 6 years old, her best friend challenged her to a dare: to eat an earthworm. Even though she would not do that today, her curiosity about everything that creeps and crawls belowground has never waned. Today, as a doctoral student, she studies the reactions of soil organisms to climate change in meadows and agricultural fields. In her free time, she does combat sports and enjoys being outside. *marie.suennemann@idiv.de

JULIA SIEBERT

Julia has been fascinated by nature since she was a child. She spent as much time as possible outdoors, built moss houses in the forest, and searched for all kinds of animals. She followed this passion by studying biology and communication science and was always keen on finding ways to transfer knowledge to different audiences. Her scientific studies focused on how changing climate conditions affect soil organisms and the ecosystem functions they drive. Furthermore, she explored ways to engage school students in biodiversity science. In her free time, she enjoys horse-riding, traveling, birdwatching, mountain biking, and all sorts of outdoor sports.

NICO EISENHAUER

Nico has been interested in nature since his early childhood. He dug for earthworms, caught frogs and fish, and helped lizards survive the winter months. He has always been fascinated by the beauty of nature and driven by the question of why a specific plant or animal species occurs in one place, but not in another. During his study of biology, he discovered his interest in soil animals and their important activities that are crucial for the functioning of ecosystems. When not at work, Nico likes playing soccer and badminton, running, and spending time with his family and friends.

BIODIVERSITY
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SOIL ORGANISMS HAVE FAVORITE FORAGE PLANTS

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YOUNG REVIEWERS:

JACK
AGE: 13

SOPHIA
AGE: 15

Cows and sheep eat plants known as forages. Forage plants can include grass, chicory, and clover. Forage plants vary in nutrients and tastiness. These plants can also change the ecosystem belowground for soil animals. Soil animals may move to eat or live beneath different forages. Earthworms mix up the soil and food, improving the soil habitat. Fungi break down dead plants, and organisms that eat fungi speed up this breakdown process, which creates more food for other plants and soil animals. We tested which forage plants soil animals preferred. Large numbers of earthworms were found under white clover. Tiny fungal-feeding worms and springtails (insect-like creatures) were found in greater numbers under clover and chicory. Plant-eating soil animals compete with cows and sheep for food. These plant-eaters were found in larger numbers below ryegrass. Growing plants that increase the numbers of helpful soil animals can lead to healthier soils.

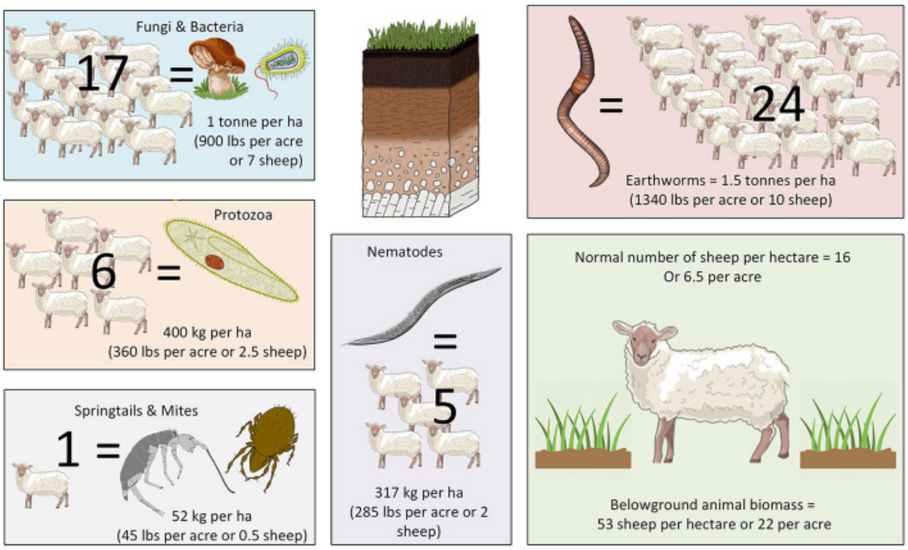

Figure 1

Weight of soil animals per hectare (ha), measured in sheep. Adult sheep weigh around 60 kg [1]. The soil organisms in one hectare weigh around 53 sheep [2]. The standard for farming is around 16 sheep per hectare so, added up, the weight of soil organisms is more than the weight of sheep above ground, per hectare.

SO MANY SOIL ANIMALS!

Cows and sheep eat a wide-ranging diet that depends on the types of plants growing within a field, which are called **forage plants** or simply **forages**. The most common forage plant is grass (ryegrass), but others include clover and chicory. These plants vary in their tastiness and nutrient content, which gives cows and sheep a choice of food and provides a healthy, varied diet. In addition, forage plants provide **ecosystem services**. For example, clover creates its own nitrogen fertilizer to help itself (and other plants) to grow. Chicory has a deep **tap root** that helps increase the airflow within the soil.

Taken together, the soil animals that live below ground weigh more than the sheep and cows above them (Figure 1)! These soil animals eat lots of different foods, and they choose to live in different places because of the plants growing there. Imagine living in a city: in some areas there are lots of people living close together, while in other areas there are fewer people. Some people like to be close to resources like schools, work, and shops. However, some may prefer to live in less crowded areas. The same is true for soil animals. When resources are limited or poor, soil animals may move to find more or better ones. Soil animals also provide important ecosystem services within the soil. For example, they break down dead plant material, recycle nutrients, and improve soil structure.

Forage plants provide a stable habitat for **soil organisms**. After they are planted, forages grow and are grazed for many years, without disturbing the soil. There is a large diversity of soil animals that all have different roles within the soil. Earthworms are the superheroes of the soil, or "ecosystem engineers." They change the whole soil habitat, mixing soil, and moving air and food within it. Springtails and mites

FORAGE/FORAGE PLANTS

Plant material eaten by grazing animals, like cows and sheep.

ECOSYSTEM SERVICES

The important things environments do for people and animals. In soil ecosystems, examples include recycling nutrients, retaining and draining water, and mixing dead plant material into the soil.

TAP ROOT

A large, wide, main root, tapering in shape and growing directly downwards (similar to a carrot).

SOIL ORGANISMS

All the organisms that live below ground, including tiny microorganisms like bacteria, fungi, protozoa and nematodes, medium-sized organisms like springtails and mites, and large organisms like earthworms.

help to break down dead plant material, making the soil stick together properly, and disperse fungi. Nematodes (tiny worms) eat fungi and bacteria, speeding up **nutrient cycling**. The number of organisms that live within the soil can be an indicator of soil health. Increasing the number of soil organism can lead to better soil health and can help plants grow.

NUTRIENT CYCLING

Movement and exchange of various nutrients between the living and non-living parts of an ecosystem. Nutrient cycling helps plants grow.

DO SOIL ORGANISMS HAVE FAVORITE FORAGE PLANTS?

Since there have not been many studies looking at the effects of forage plant species on soil organisms, we decided to do an experiment. We grew forages of ryegrass, chicory, red clover, and white clover in separate plots. These plots were next to each other in the same field. There were four plots for each forage. The plants grew for 3 years, during which the forages were cut regularly, to simulate grazing by sheep and cows. After 3 years, soil animals (earthworms, springtails, mites, insects, and nematodes) were measured within each plot, to see which forage plants they preferred.

Different sampling methods were used to count the soil animals. For earthworms, we dug up a square cube of soil and sorted through it, picking out all the earthworms we could find. Earthworms were then sorted into groups, based on their size and color. To collect springtails, mites, and other small insects, we took small soil samples and placed them on **Tullgren funnels**. You can make your own Tullgren funnel at home by following instructions in Barreto and Lindo [3]. We had to identify these soil animals with a microscope because they are so small. Nematodes were collected by placing soil within tissue paper and resting it in a tray of water. The nematodes swam out of the soil into the water, where we collected them and identified them under a microscope.

TULLGREN FUNNEL

Device in which the soil is warmed up and the small soil animals move away from the heat and light, falling into a collection pot under the funnel.

WHITE CLOVER INCREASES THE NUMBER OF SOIL ANIMALS

Our results are summarized in Figure 2. The most earthworms were found in the white clover plots, and the fewest in the ryegrass plots. Earthworm numbers in the soil below the chicory and red clover forage plots were in-between. The deep-burrowing (**anecic**) earthworms showed the most plant preferences compared to other kinds of earthworms. Dividing the nematodes into feeding groups, showed some had favorite forages. Larger numbers of fungal-feeding nematodes were found below the clovers compared to the ryegrass. Plant-eating nematodes were found in larger numbers below the ryegrass compared to the clovers or chicory. Thousands of springtails and mites were found per square meter of soil. Two groups of springtails were found in different numbers in the soil below the

ANECIC

Group of large earthworms that create deep vertical burrows that go up and down through the soil, moving dead plant material around to eat later.

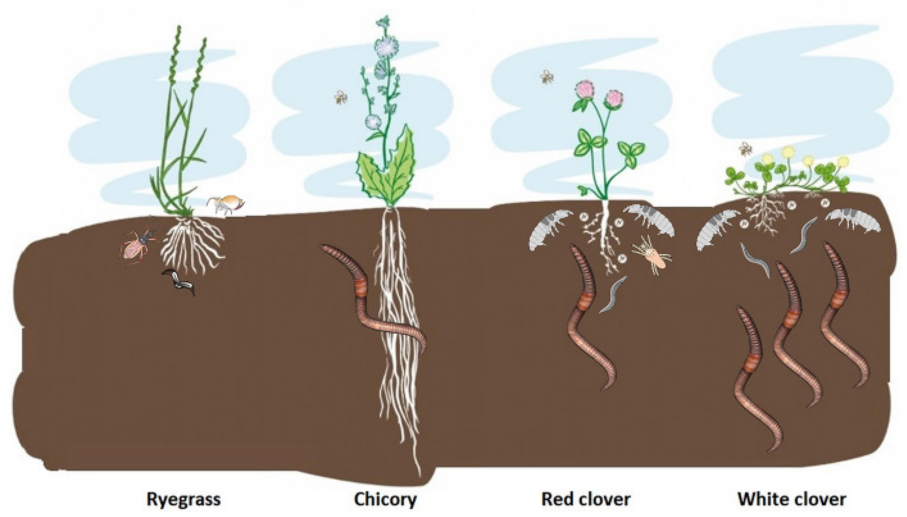

Figure 2

Differences in soil animal numbers below ryegrass, chicory, red clover, and white clover forage plants. Ryegrass had the most plant-eating soil animals (true bugs, thrips, and plant-feeding nematodes). White clover had the most earthworms, fungal-feeding nematodes, and Poduromorpha springtails. Red clover had in-between numbers of earthworms, fungal-feeding nematodes, and Poduromorpha springtails. Red clover had a larger number of predatory mites than the other forages. Chicory had in-between numbers of earthworms but fewer of the other organisms than the clovers (Plant pictures adapted from Cotswold Seeds).

PODUROMORPHA

Group of springtails that look fat and have a small springing tail, mostly eat fungi, bacteria, and dead plant material.

forage plants. A group of springtails called **Poduromorpha**, which eat fungi, bacteria, and dead plant material, were found in larger numbers below the clovers. Plant-eating springtails (Symphypleona) were found in larger numbers below the ryegrass. Greater numbers of predatory mites were also found below the red clover plants. "Other" invertebrates were found to differ in numbers in the soil below the forages. The ryegrass plants had many more "other" invertebrates in the soil than either red clover or chicory. There were large numbers of bugs and thrips (tiny plant eating insects) below the ryegrass plots compared to the other forages.

We calculated the *total* soil animal biodiversity for each forage and found that the lowest animal diversity was found in the ryegrass soil and the highest was in the soils of the two clovers. The diversity of soil animals below chicory was in-between.

HEALTHY SOIL ORGANISMS = HEALTHY AGRICULTURE

Large and diverse populations of soil organisms are thought to improve soil health, which could lead to increased crop growth. It is important to monitor soil animal numbers to see if they are affected by the types of forages grown by farmers. This will tell us whether changes in the types of plants farmers choose to grow might affect the health of the soil. Our findings show that soil animal numbers change depending on the type of forage plants grown. This means that changes in plant species can influence the biodiversity of the soil animals living under those plants.

All plants were located next to each other within the same field, so the soil animals could move to live below whichever forage plants they preferred. Three years of plant growth led to changes in the soil habitats, because the four forages had different root structures and changed the nutrient availability in the soil. The moving speeds of soil animals vary. For example, earthworms can move more than 1 m per day, but some species of mites only move 1–8 m per year [4, 5]. The earthworms found below white clover had time to move there during the three-year experiment. However, some of the other animals may not have had enough time to reach their favorite forage crop to live below it. Earthworm numbers reflect how much food is available. The larger numbers found under white clover suggest there is more food there. Since earthworms can improve soil structure, larger numbers of earthworms could improve soil health [6]. Plants can use the deep burrows of anecic earthworms as ready-made channels for their roots to grow into. Forage plants that draw large numbers of anecic earthworms could therefore improve other plants growth.

Maintaining a high diversity of soil animals is important. If soils experience a loss in soil animal biodiversity due to poor soil management, this could reduce the ability of the soil to grow plants, store water and cycle nutrients. Our research showed that changing the type of forage plants being grown could help to maintain soil animal biodiversity and therefore help to keep soils healthy. Healthy soils are important because they support the growth of crop plants. This means that choosing the right forage plants could ultimately help farmers grow enough food to feed the growing human population!

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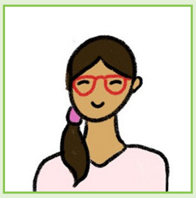
YOUNG REVIEWERS

JACK, AGE: 13

My name is Jack. I am interested in coding, programming, and cybersecurity. I participate in science and math competitions like Science Olympiad and Math League. I am an avid basketball player. I love to travel and have visited 4 of the 7 continents so far.



SOPHIA, AGE: 15

My name is Sophia. I am on the pre-med pathway in high school. I compete in Science Olympiad, Quiz Bowl, and the Science Fair. I have a love for spelling. I won my school spelling bee multiple years and competed in the Scripps national spelling bee. For relaxation, I enjoy doing art projects and baking culinary treats for my friends and family. I also love to travel. One of my favorite places is Tokyo.

AUTHOR

FELICITY V. CROTTY

Dr. Felicity Crotty is a senior lecturer in soil science and ecology at the Royal Agricultural University. She has been researching soil biology and soil health for the last 14 years, focusing on understanding the linkage between sustainable agriculture and soil health, within both the animal and crop sectors. *felicity.crotty@rau.ac.uk

frontiers FOR YOUNG MINDS

BIODIVERSITY
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HOW INTRODUCED EARTHWORMS ALTER ECOSYSTEMS

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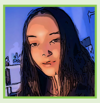
YOUNG REVIEWERS:

LILU
AGE: 10



MICHELLE
AGE: 16

We all know earthworms as important friends in our garden: they help plants to grow better by providing nutrients, water, and air in the soil. However, in some cases, earthworms have more negative effects. This is because other organisms need to be used to the activities of earthworms to benefit from their presence. Some regions of the world have developed without earthworms for over thousands of years. For example, in northern North America, earthworms have been absent for more than 10,000 years and have only been re-introduced over the past ∼400 years. In many cases, introduced earthworms find a perfect environment, because no other organisms have been able to use the resources that these earthworms now consume. As so-called ecosystem engineers, earthworms dramatically alter many ecosystem characteristics. In this article, we summarize the known consequences of earthworm invasion, report on how scientists study these, and highlight remaining knowledge gaps that you might help solving should you decide to become an ecologist.

INTERACTING ORGANISMS HELP ECOSYSTEMS PROVIDE SERVICES TO HUMANS

Within an ecosystem, different species interact, for example by eating, helping, or providing habitat for each other. Every species consumes its resources and is eaten by other species. They all have their unique roles in nature. Some species have particularly important roles in ecosystems because they eat dead leaves or animals. These species recycle materials and provide them back to the ecosystem. Other organisms help plants to produce flowers and seeds. All organisms carry out **ecosystem functions**, such as decomposition, pollination, and many others. We humans rely on the functions and services that intact ecosystems provide to us. However, these services depend on the diversity and interactions of the species present. **Perturbations** to an ecosystem can alter its **biodiversity** and the interactions of species within it. Changing climate (e.g., higher temperature), altered land use (e.g., transforming forests into agricultural fields), or species invasions (the introduction of new species to an ecosystem) all have the potential to disrupt ecosystems in ways that can alter their functions and the services they provide.

INVASIVE SPECIES CHANGE ECOSYSTEMS

An invasive species is a species that arrives in a new environment, establishes itself, substantially increases in abundance, and forms novel interactions there, significantly altering the invaded ecosystem. Species invasions are one of the most important causes of global biodiversity change. Invaded ecosystems are changed by things like the establishment of new feeding relationships, the replacement of natural plants by dominating invasive plants, the disappearance of previously-established species, or the facilitation of further invasions. The effects of species invasions are strongest if the invasive species differs a lot from the species already living in the ecosystem [1]. Differences could include resource use, robustness to stressors, growth speed, or the ability to eat food that the other species cannot digest. Some invasive species have particularly strong effects because they actively alter their environment by creating or modifying habitats. Such species are called **ecosystem engineers**. Examples are beavers, which build dams and temporarily turn terrestrial habitats into freshwater ones, and earthworms, which alter soils by **burrowing** (building tunnels), **casting** (building small piles of their droppings on and in the soil), and **mixing** dead plant material on the ground with the soil below [2].

ECOSYSTEM FUNCTION

A process that takes place in an ecosystem and either represents, or is driven by, the activity of organisms. Examples include the decomposition of organic material, nutrient cycling, or water retention.

PERTURBATION

A disturbance, in ecology usually a disturbance to an equilibrium state, or any level of biological organization (individual, population, community, ecosystem).

BIODIVERSITY

The variety of life on earth, usually measured as variability at the genetic, species, or ecosystem level.

ECOSYSTEM ENGINEER

An organism that modifies its environment by redistributing material and energy via non-feeding interactions with living and dead components of its ecosystem.

BURROWING

Tunnel-building activity of earthworms.

CASTING

The activity of building small piles of earthworm droppings on the soil surface and in the soil.

MIXING

The activity of redistributing different parts of the soil with each other and organic material from the soil surface.

EARTHWORMS ARE VERY IMPORTANT FOR SOIL ECOSYSTEMS—IN A GOOD OR BAD WAY

Earthworms naturally occur in most terrestrial ecosystems around the globe. They constantly structure the soils that they live in. Their burrowing activities mix the soil and improve the flow of air and water through the underground world. By eating dead organic material from the soil surface, dragging it down into the soil, digesting it, and then leaving their droppings, they redistribute nutrients throughout the soil. These activities affect other life below and above the ground. The altered air, water, and nutrient availability changes how other organisms can use their resources, where they can live, and how well they can grow and reproduce. Through these activities, earthworms influence bacteria, fungi, springtails, mites, beetles, plants, and even animals that live above the soil surface, such as aphids. Consequently, earthworms are very important soil organisms[1] with impacts beyond the belowground world. This is fine in areas where the other organisms are used to having earthworms around, but it can become problematic where they are not used to these squishy neighbors.

[1] Clay video by Maxwell Helmberger: https://www.youtube.com/watch?v=3a7lFGOYL7s&list=PLB9tSz89_6_qBS8RRF0h5YzhyC31KJHoc&index=5

INVASIVE EARTHWORMS ARE A GLOBAL ISSUE

In many places, earthworms are considered “the gardener’s best friend.” They commonly improve soil quality in gardens, fields, meadows, and forests. Other organisms have shared these ecosystems with the earthworms for a very long time, and are used to their presence and activity. Hundreds of earthworms and up to a dozen earthworm species per square meter can be found in these ecosystems, but this is not the case everywhere in the world. Some places have a low number of earthworms, and in other areas earthworms are completely absent [3]. In areas where earthworms are naturally rare or absent, introduced earthworm species can become a big problem [4]. This is because, in these places, microbial, plant, and animal species are not used to having earthworms around. The native species may not be able to deal with the changes the earthworms make to the soil’s water, air, and nutrient availability. It is important to study the effects of earthworm invasion on ecosystems and predict their future impact because it is impossible to remove earthworms from areas where they have established without killing other animals and plants.

NORTHERN NORTH AMERICA IS BEING INVADED BY EARTHWORMS

Huge parts of the northern USA and Canada were covered by vast ice sheets during the last glaciation period (Figure 1). Under these ice sheets, earthworms could not survive. Thus, at least since the ice disappeared about 12,000 years ago, most of North America has been

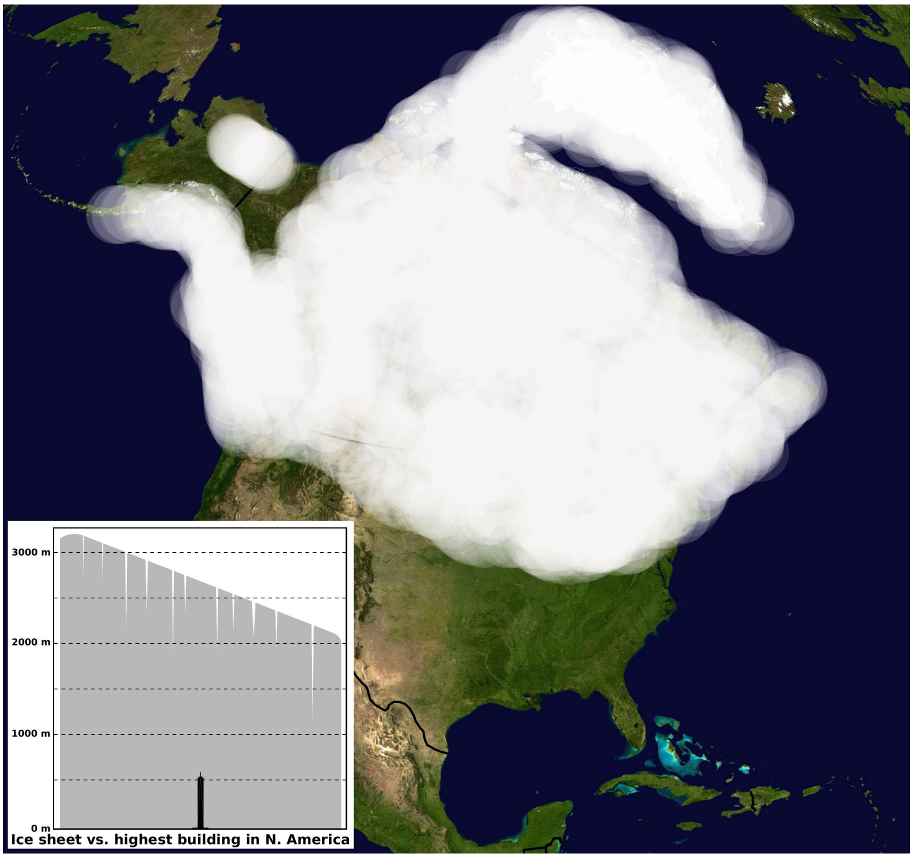


Figure 1

Figure 1

Approximate extent of the northern North American ice shield during the last glacier period. The graph at the lower left shows the approximate maximum thickness of the ice sheet in comparison to the highest building in North America (546 m, One World Trade Center, New York City, USA). The thickness of the ice sheet varied across time and space during the glaciation. Original satellite image by NASA, from wikipedia.org.

naturally earthworm-free. Natural reintroduction of earthworms takes a long time, because they spread slowly into new habitats (<10 m per year). However, when the European settlers arrived in North America, they accidentally and/or intentionally brought earthworms with them[2] . Once introduced, the earthworms liked many of these areas a lot. The forests had thick layers of not-yet-decomposed organic matter (dead remains of formerly living stuff), which was a great feast for the earthworms (Figure 2). They made themselves at home and their numbers grew rapidly. By building roads, moving soil, moving plants, and similar activities, the settlers actively distributed earthworms throughout the northern part of the continent much faster than the earthworms could have traveled on their own. In some areas, earthworms were likely introduced by fishermen, who may have dropped their unused bait close to lakes, streams, or fishing cabins. As a result, the spread of earthworms was helped by humans who did not know or did not care what ecosystem-scale effects these newcomers would have.

[2] MinuteEarth video: https://www.youtube.com/watch?v=icGV8bJRkkg

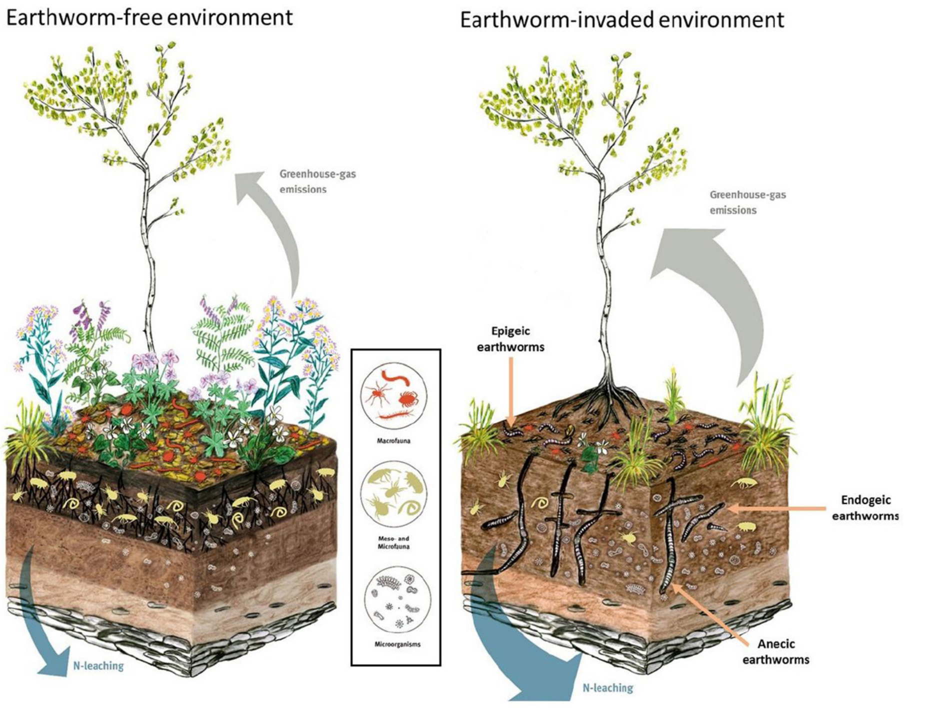


Figure 2

Figure 2

Illustration of how invasive earthworms alter previously earthworm-free ecosystems. By burrowing, feeding on leaf litter, and mixing soil, earthworms affect the soil properties causing changes in soil layers, vegetation, and soil organisms. These changes affect ecosystem processes, such as greenhouse-gas emissions and loss of nitrogen (N leaching) from the soil. Increasing atmospheric levels of greenhouse-gases, e.g., carbon dioxide or nitrous oxide, are an environmental issue. Different functional groups of soil animals, shown in the black center box (size groups from large to small: macrofauna—e.g., spiders and woodlice; mesofauna—e.g., springtails and mites; microfauna—e.g., nematodes, and microorganisms—e.g., bacteria and some fungi), are affected by the three ecological groups of earthworms (epigeic—live in leaf litter and on the soil surface, endogeic—build mostly horizontal burrows in upper soil layers, and anecic—build deep, vertical burrows; see right panel). What changes can you spot? Originally published in Ferlian et al. [5], reproduced with the permission of the original publisher.

RESEARCHERS STUDY HOW EARTHWORMS CHANGE ECOSYSTEMS

Scientists have been studying earthworm invasions for many decades, using three different approaches: First, in field observation studies, researchers compare uninvaded to similar, already invaded ecosystems. Second, in field experiments, researchers compare small areas without earthworms to areas nearby where they experimentally release earthworms. Alternatively, they first measure ecosystem properties, then release earthworms there and then measure the same properties again. Another approach is to keep small patches of soil and plants in laboratories under controlled conditions, with light, water, and temperature controlled by researchers. Some patches then receive earthworms and others do not so that they can be directly compared. In all these approaches, researchers can assess the ways that earthworms change ecosystems, such as how earthworms alter the **physical**, **chemical**, and **biological properties** of soils, and various ecosystem functions. All these different approaches and measurements help us to better understand how invasive earthworms change their new homes.

WHAT DO WE ALREADY KNOW?

We already know quite a lot about how earthworms change the chemical and physical properties of the soil. Earthworms create soils that are warmer, drier, and less acidic, and they alter the availability

Figure 3

Figure 3

Extreme example of the potential consequences of earthworm invasion in a maple forest in Minnesota, USA. The upper panel shows an uninvaded forest area, the lower panel shows a forest area invaded by European earthworms. Photo credit: Ulrich Pruschitzki (top) and Olga Ferlian (bottom), altered after [6].

PHYSICAL SOIL PROPERTY

Soil properties related to matter, energy, or force. For example, the water or air content.

CHEMICAL SOIL PROPERTY

Soil properties related to elements and compounds of atoms, molecules, and ions. For example, the availability of different nutrients and elements, or acidity.

BIOLOGICAL SOIL PROPERTY

Soil properties related to living things. For example, the number of species present, their biomasses, or interactions.

of soil nitrogen and carbon, two very important chemical elements. In addition, earthworm invasion often reduces the number of other soil organisms and the number of different animal and plant species (Figures 2, 3). Not all organisms are negatively affected though. For example, oribatid mites and springtails are often reduced, but prostigmatid mites are increased where earthworms have invaded. Also, some species locally disappear, but other species, particularly those that are used to the presence of earthworms, might follow the earthworms' example and become invasive. Earthworm invasion can cause a cascade of ecosystem consequences that are also relevant to humans, such as altered water quality and the likelihood of forest fires [6]. We know that invasive earthworms reduce the number of plant species, but they increase the importance of grass-like plants and the number of non-native plants. Earthworms also influence large animals, such as salamanders and birds that nest on the soil surface. While some salamanders can use earthworm burrows to hide and feed on earthworms, the nests of ground-nesting birds can be destroyed by earthworms burying leaf litter, which is the primary nest-building material.

EARTHWORM INVASION RESEARCH CONTINUES ...

It takes time to study ecosystem responses to perturbations—studies often need to run for many years. This is why, despite decades of research on the effects of invasive earthworms on their new homes, there is still a lot that we do not know [7][3] . We know more about how earthworm invasion affects the physical structure, other organisms, and ecosystem functions below the ground than above. We also do not know a lot about how earthworm invasion changes the way above- and below-ground systems interact, or how energy flows through the networks of organisms eating each other. While we know how earthworm invasion alters the plant community as a whole, we do not know much about how it influences the characteristics of individual plants, such as the size of their leaves, which is very important for plant life and function (e.g., photosynthesis). Most of our knowledge is based on observational studies and laboratory experiments because field experiments are often difficult to run and require special care to make sure the worms cannot escape and invade previously uninvaded areas. Finally, you probably know that our planet's climate is rapidly changing. Higher temperatures and changing intensity of rain can interact with earthworm invasions. It is therefore important to study what happens when organisms in an ecosystem must simultaneously cope with a combination of higher temperature, changing precipitation patterns, and their new squishy neighbors. Curious young minds like you can help answering these questions and further unravel the secret details of life below the ground, especially in response to species invasions and their impacts on the ecosystems of our ever-changing planet.

[3] EcoWorm project introduction video: https://www.youtube.com/watch?v=Au_-VYDUhAw&list=PLJFvA_Py3UkyUbNO48W7bY2KoVuSYIlec&index=10&t=0s

AUTHOR CONTRIBUTIONS

MJ drafted the text and figures and NE contributed to the writing and discussion of the content.

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

YOUNG REVIEWERS

LILU, AGE: 10

I love polar bears and I am fighting against Climate Change to save them! I love guinea pigs too.

MICHELLE, AGE: 16

I am a Spanish girl who wants to be a pilot. At school, my favorite subjects are Biology and Maths. My hobbies are aviation and playing tennis.

AUTHORS

MALTE JOCHUM

Malte studied biology because, as a teenager, he built a small pond in his parents' garden and realized that this subject would never cease to amaze him. As a community ecologist, he is very interested in how human activities affect plant and animal communities and their functioning. His work has focused on aquatic and terrestrial ecosystems across temperate and tropical areas and mainly involves macroinvertebrates. When not at work, he likes to explore nature with his two daughters, do rock climbing, cycling, or canoeing, and more recently, has discovered an interest in beginner-level triathlon. *malte.jochum@idiv.de

NICO EISENHAUER

Nico has been interested in nature since early childhood. He dug for earthworms, caught frogs and fish, and helped lizards survive the winter months. He has always been fascinated by the beauty of nature and driven by the question of why a specific plant or animal species occurs at one place, but not at another place. During his study of biology, he discovered his interest in the distribution of biological diversity, particularly in the soil, and how it affects the functioning of ecosystems. When not at work, Nico likes soccer, badminton, running, and spending time with his family and friends.

BIODIVERSITY
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CAN WE SAVE THE BEAST BY CONSERVING THE BEAUTY?

***Felix Gottschall*[1,2*]*, Erin K. Cameron*[3]*, Inês S. Martins*[4]*, Julia Siebert*[1,2] *and Nico Eisenhauer*[1,2]**

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YOUNG REVIEWERS:

ANHAD
AGE: 11

ASHIMA
AGE: 12

Because having a wide variety of species on earth is essential for human health and our economy, conservation areas have been established worldwide. These conservation efforts mostly focus on "beauties," such as pandas or tigers. Many other species are not as charismatic and thus merely considered "beasts." Many "beasts" live invisible lives in the soil but are extremely important for mankind. We asked whether current conservation efforts based on saving the "beauties" can help to automatically protect the "beasts." In other words, is there high biological diversity in the soil at locations with high aboveground biodiversity? We mapped aboveground and belowground biodiversity across the world and found that there are many areas where aboveground biodiversity is high and belowground biodiversity is low, or the other way around. Our results suggest that conserving the "beauties" may not be enough to protect the

"beasts." We need to consider life belowground when planning new conservation areas.

WHAT NATURE PROVIDES AND WHY WE NEED IT

When going for a hike in nature or a walk in a park, there are many different animals and plants to discover. Singing birds, buzzing bees, and pretty flowers are beautiful by themselves and something we enjoy. Furthermore, they provide important functions to our ecosystem and services for us as humans (which are called **ecosystem services**). For instance, birds can control pests like aphids, and plants provide us with necessary oxygen while also producing food, with the help of bees that spread pollen. The amount and extent of these functions and ecosystem services strongly depends on the variety of different plant and animal species. This variety is referred to as **biodiversity** [1].

ECOSYSTEM SERVICES

Functions and processes of an ecosystem that in some way benefit humans. For example, production of fruit, timber, and oxygen, or the purification of water.

BIODIVERSITY

Biodiversity describes the variety and variability of life. Depending on the context it can refer to different measures. Most common is the number and variety of different species in a given location.

Many plant and animal species worldwide are threatened by human activities. Increasing agriculture, deforestation, and climate change due to excessive use of fossil fuels have pushed many species to **extinction** [2]. This loss of species is not only worrying in terms of the **intrinsic value** of nature, but also because we depend on nature's services. With ongoing loss of species, we will not only lose parts of the beauty of nature, but also many of its functions that are essential for human life on earth [3].

EXTINCTION

The permanent disappearance of a species. Extinction can be caused by a natural incidents (dinosaurs) or human actions (dodos).

INTRINSIC VALUE

A value that is coming from within. Valued for what it is, rather than for what it is worth.

THE PROTECTION OF NATURE'S BEAUTY AND SERVICES

By actively protecting certain areas of the world [4], we support threatened species, preserving them and their services for us and for future generations. When deciding which areas to protect, we often chose regions with especially charismatic and noticeable "beauties," like pandas, tigers, or golden eagles. These species often need a large, high-quality living area and live in regions that contain a high diversity of other species. By protecting these "beauties," it is assumed that a lot of other, smaller animals and plants are also automatically protected and cared for. People are more willing to invest money in "beauties" because everybody knows and loves them. Who does not like to watch a panda rolling around in the forest?

THE BEASTS BELOW US AND WHY THEY ARE OFTEN OVERLOOKED

However, everybody who has done some gardening work or explored the soil below their feet knows that nature provides shelter to more species than we can see at first glance. Below our feet and the feet of the panda lies a hidden community of earthworms, ants, spiders, springtails, centipedes, and beetles. If we look even closer (e.g., with a microscope) there are tiny bacteria and fungi in the soil as well. Like birds, flowers, and bees, all these belowground species fulfill important functions and services. For example, fungi and springtails digest wood and leaves, providing nutrients to the soil and plants. Earthworms loosen the soil and allow air to enter the ground, making it more productive. Centipedes and spiders control pests and thereby prevent pest species from taking over.

Although belowground species fulfill vital roles and provide important services, they are often overlooked. Scientists are just starting to understand how many species there are in the soil and how these species work together in different ways to shape belowground processes. There are several reasons for this lack of knowledge. Soil is not easy to access (or to see through), which makes experiments, monitoring, and observational studies hard to plan and conduct. Furthermore, many important players in belowground systems are tiny and do their work in secret. Some people even consider soil animals as "beasts." Worms, insects, spiders, bacteria, and fungi are rarely considered "beauties," although their alien appearances and ways of life hold their own kind of charm. During the establishment of new protected areas, however, these issues lead to belowground species being left out of consideration.

CAN WE SAVE THE "BEAST" BY PROTECTING THE "BEAUTY"?

In our research, we asked whether we would automatically protect the important belowground "beasts" like earthworms by choosing protected areas based on aboveground "beauties" like the panda. Can we save the "beast" by protecting the "beauty"?

This question is very important because it helps us to understand whether the current way of choosing protected areas is good enough, or if it has to be adjusted to include ecosystem services that may have been overlooked so far, but are essential for human well-being.

HOW DID WE APPROACH THIS QUESTION AND WHAT DID WE FIND?

PUBLIC DATABASE

An organized collection of data that can be accessed by scientists or the general public from all over the world.

To determine whether protecting aboveground species also automatically protects belowground species, we assembled big sets of data about the presence and diversity of aboveground species (mammals, birds, amphibians, and plants) and belowground species (bacteria, fungi, and soil animals). Most of the data was already collected and published by collaborating scientists and some information was extracted from **public databases** [5]. We then used

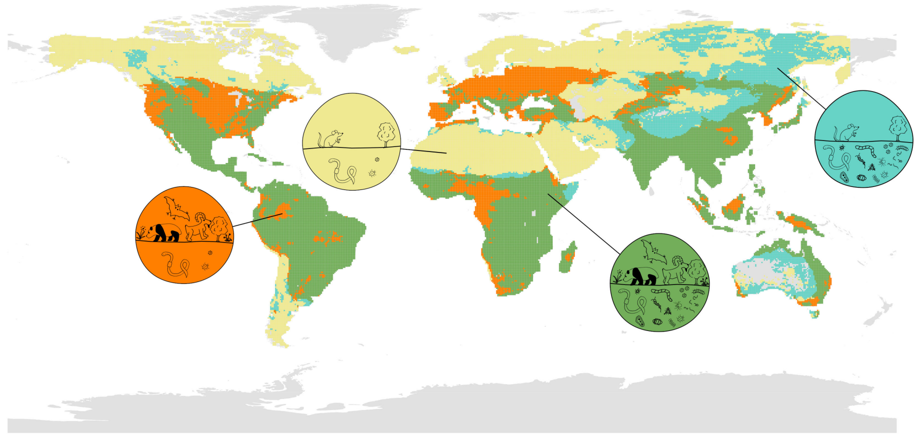

Figure 1

Figure 1

Global map showing the distribution and overlap of aboveground (mammals, birds, amphibians, and plants) and belowground (fungi, bacteria, insects, and worms) biodiversity. Colors indicate different combinations of above- and belowground biodiversity. Orange: high aboveground biodiversity and low belowground biodiversity; beige: low aboveground biodiversity and low belowground biodiversity; green: high aboveground biodiversity and high belowground biodiversity; turquoise: low aboveground biodiversity and high belowground biodiversity; and gray: no data available. From this map, you can see that there are big areas of mismatch (orange), where it is not possible to protect the "beasts" by protecting the "beauties."

special computer techniques (ArcGIS: a software used to create maps and analyze geographic information) to create maps to show patterns in the data around the globe. By analyzing and comparing these maps, we were able to answer our question.

What is the answer? With the help of our maps (Figure 1), we saw that there are many areas where both aboveground biodiversity and belowground biodiversity are high ("match"), such as in many tropical regions of the globe (Figure 1—green areas). However, we also saw that there are many areas where aboveground biodiversity is high and belowground biodiversity is low (Figure 1—orange areas), or the other way around (Figure 1—turquoise areas) ("mismatch"). One example of high belowground biodiversity but low aboveground biodiversity is the northern regions of the earth, like the vast tundra and boreal regions in the northern hemisphere. The overall area of mismatch, where it is not possible to protect the "beasts" (belowground diversity) simply by protecting the "beauties" (aboveground diversity) spans roughly one third of the land surface of the Earth.

WHAT ABOUT THE FUTURE?

Given our results, we strongly suggest that we need to adapt the way experts decide which regions to declare as protected areas (Figure 2). While it is very important to protect the habitat of "beauties" like the panda or tiger, we have to be careful not to overlook the "beasts" in the soil that are so important for our well-being. If we only focus on the areas containing "beauties," we risk losing many soil species and their services (examples: soil carbon storage, water purification, nutrient cycling), because these soil species may be very diverse in regions of the world where "beauties" are less diverse.

The results of this study only mark the beginning of new approaches to nature conservation. Since soil is not easily accessible, we still

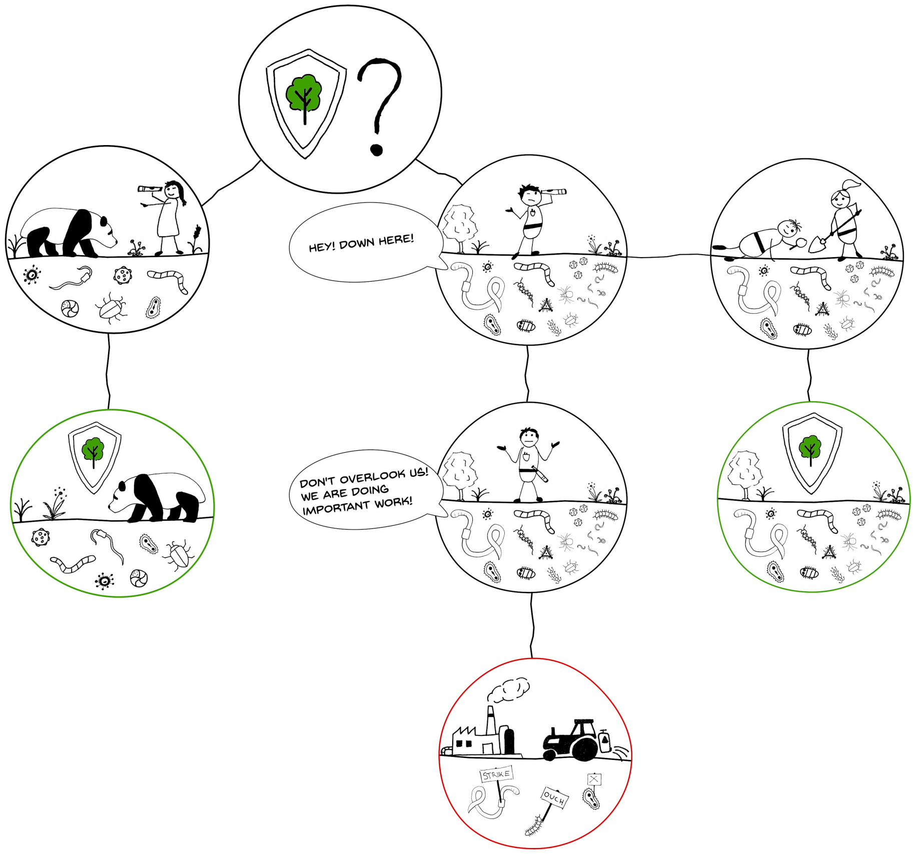

Figure 2

Figure 2

How do we decide which areas to protect? Left: A scientist checks aboveground to see if the area is worth protecting. The decision is based on diversity of aboveground species and occurrence of "beauties". A positive outcome leads to the protection of the area and ecosystem. Middle: A scientist checks and finds low aboveground diversity and is unaware of belowground diversity. The area does not get protected. Soil organisms are overlooked and threatened by industry and agriculture. Important functions and services of soil life are lost. Right: In addition to the aboveground check, scientists also consider soil organisms. The area will be protected based on the positive results for soil diversity. The ecosystem and the soil functions and services are preserved.

need much more information on threats to belowground processes and soil organisms, as well as on the roles, needs, and behaviors of these organisms. This will help to make recommendations for areas to protect and a general adjustment of common industrial and agricultural practices outside of conservation areas. Therefore, an important next step is to increase the overall knowledge about soil species worldwide, by conducting surveys and monitoring programs. Basically, that means that we have to "dig deeper"! To enable scientists to do this important work, it is essential to raise awareness among both the general public and governments about the importance of the curious "beasts" below our feet.

ORIGINAL SOURCE ARTICLE

Cameron, E. K., Martins, I. S., Lavelle, P., Mathieu, J., Tedersoo, L., Bahram, M., et al. 2019. Global mismatches in aboveground and belowground biodiversity. *Conserv. Biol.* 33:1187–92. doi: 10.1111/cobi.13311

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YOUNG REVIEWERS

ANHAD, AGE: 11

Hello my name is Anhad and I like writing about topics (sometimes). I also love watching TV and playing video games on my console and also love hanging out with my friends and family. I like watching netflix in my free time and cooking.

ASHIMA, AGE: 12

Hi, I am Ashima. I like to read fiction books and swim. I love to study. My favorite subject is mathematics. Quadratic functions are my favorite topic in mathematics.

AUTHORS

FELIX GOTTSCHALL

Already as a kid, Felix was fascinated by dinosaurs and all kinds of extinct animals. After memorizing all his children's books, he spent a lot of time in museums and imagined how it would be to search for long-lost animals himself. Over time, his interest switched to living animals, like birds (which basically are dinosaurs!), and he began to study biology. As a scientist, he has worked on many different topics, from glowing snails over thirsty treetops to life below ground. Instead of digging for dinosaurs, he is now digging for soil bacteria and still sees the adventure in it. *fgottschall@gmail.com

ERIN K. CAMERON

Erin enjoyed playing outside as a child but did not consider becoming a biologist. Eventually, she started helping with research examining how human activities affect songbirds and she found it fascinating. Once she started to work on soil organisms and saw how much is still unknown about them, she was convinced that she wanted to study biology. Now she investigates how human activities affect soil biodiversity and the functioning of ecosystems. Erin also enjoys cross-country skiing, bicycling, and kayaking in her free time.

INÊS S. MARTINS

Inês always loved learning how things are created, where they came from, and how they are changing. Nothing holds more questions like that than nature, so it is not surprising Inês choose to pursue biology in school. While studying, she became particularly interested in looking at how humans have been influencing organisms by changing their habitats. Now, she spends her days trying to model and understand how biodiversity responds to past and possible future environmental changes across vast areas of the world. Outside work, Inês likes to play sports, go to the cinema, and to simply enjoy time with friends and family.

JULIA SIEBERT

Julia has been fascinated by nature since she was a child. She spent as much time as possible outdoors, built moss houses in the forest, and searched for all kinds of animals. She followed this passion by studying biology and communication science and was always keen on finding ways to transfer knowledge to different audiences. Her scientific studies focused on the effects of global change on soil organisms and their ecosystem functions in agroecosystems. Furthermore, she explored ways to engage school students in biodiversity science. In her free time, she enjoys horse-riding, traveling, birdwatching, mountain biking, and all sorts of outdoor sports.

NICO EISENHAUER

Nico has been interested in nature since his early childhood. He dug for earthworms, caught frogs and fish, and helped lizards survive the winter months. He has always been fascinated by the beauty of nature and driven by the question of why a specific plant or animal species occurs at one place but not at another place. During his study of biology, he discovered his interest in soil animals and their important activities that are crucial for the functioning of ecosystems. When not at work, Nico likes to play soccer and badminton, to run, and to spend time with his family and friends.

frontiers FOR YOUNG MINDS

EARTH AND ITS RESOURCES
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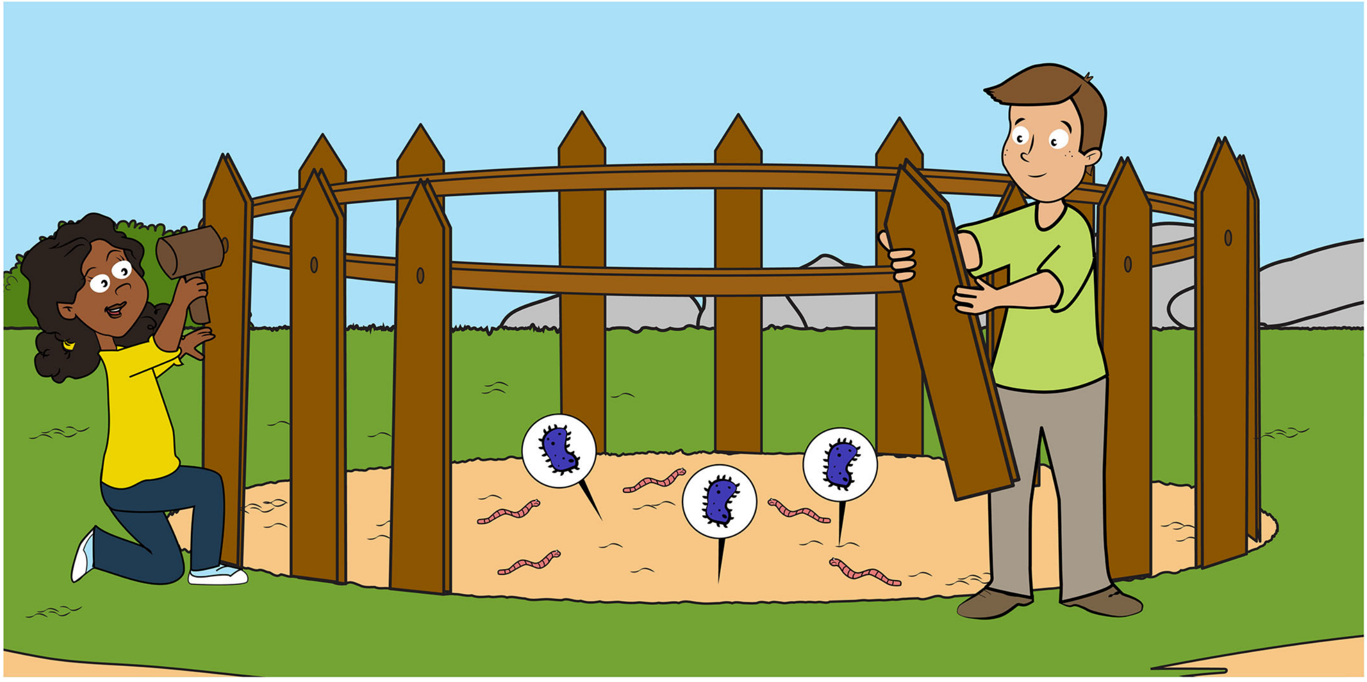

PROTECTING SOIL BIODIVERSITY: A DIRTY JOB, BUT SOMEBODY'S GOTTA DO IT!

Alberto Orgiazzi*

European Commission, Joint Research Centre, Ispra, Italy

YOUNG REVIEWERS

KAYSVILLE JUNIOR HIGH

AGES: 12–13

Soil biodiversity means the range of creatures, of various shapes and sizes, living in the soils—from microorganisms to animals. Soil diversity is extremely important and, to protect it, we need to know where potentially endangered soil organisms live. Unfortunately, we do not have data on the distribution of most soil species. However, we do know the potential threats to soils and soil inhabitants. Therefore, we identify areas where risks are high and try to reduce those risks, which allows us to indirectly protect soil organisms. Following this path, we mapped the risk to soil microorganisms and animals in 27 countries of the (pre-Brexit) European Union. Our results highlight the urgent need to act, as organisms living within more than 40% of soils are at high risk in most countries.

SOIL BIODIVERSITY MATTERS

An estimated one quarter of the life on our planet lives under our feet, in the soil. The vast range of organisms living in the soil is

SOIL BIODIVERSITY

All the living creatures that inhabit the soil.

called the **soil biodiversity**. Organisms living in the soil provide many essential services to humankind. They support food production by helping plants to grow, and they play a key role in controlling nutrient cycles (especially carbon and nitrogen), and thus in regulating the Earth's climate. Other less obvious but still crucial services include water purification, which makes water drinkable, and the production of substances that have important medical uses. For example, most of the antibiotics that we currently use come from soil organisms.

Despite its importance, soil biodiversity is generally not considered when people think about how to protect the Earth's biodiversity. Most of the current plans for biodiversity protection only target organisms that live above ground. It is also not that easy to protect soil biodiversity—it is a dirty job, but one that needs to be done!

HOW TO PROTECT SOIL BIODIVERSITY

Imagine you are a superhero with a new, challenging mission: you must save a group of mammals, plants, reptiles, and insects that will disappear in a few days. If the target group lives above ground, you can easily identify where your endangered community lives. This allows you to create a protected area—maybe a kind of a fence surrounding the space where your endangered group lives. Mission accomplished: you are protecting biodiversity.

SOIL MICROORGANISMS

Organisms living in the soil that can be seen only through a microscope. Soil microorganisms include archaea, bacteria, fungi, and protists.

SOIL FAUNA

Organisms living in the soil that belong to the kingdom Animalia. These range from tiny worms called nematodes (<0.1 mm) to larger animals like moles.

However, often the job is not that easy. If you need to safeguard organisms living below ground, you might not have much information about who they are or where they live. This is because most of the species living beneath our feet are yet to be discovered [1]. Furthermore, soil biodiversity is extremely complex and ranges from **soil microorganisms**, which are invisible to the naked eye, to **soil fauna**, including animals like earthworms and moles. Therefore, pinpointing exactly where soil organisms live is an extremely difficult, sometimes impossible task. Luckily, there is another, indirect way to protect soil biodiversity. Even if you do not know where a group of organisms lives, you can figure out the areas where soil organisms might be in danger from potential risks. Once you have mapped those high-risk areas, you can work to reduce the threats that potentially affect your target organisms. But it is not quite as easy as it sounds...

IDENTIFYING RISKS TO SOIL BIODIVERSITY

Of course, every mission faces difficulties. Indirect protection of soil biodiversity needs to overcome three main obstacles. First, we must understand the main threats to soil biodiversity. Many things can affect soil organisms, but we need to identify current threats that can be measured and that are actually *known* to be dangerous to life in the

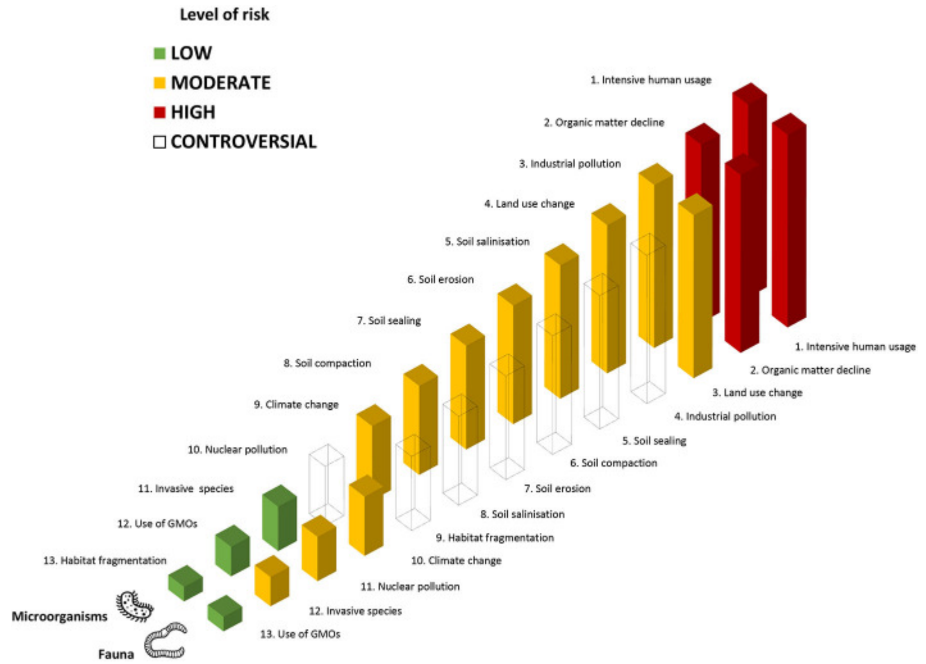

Figure 1

Figure 1

Level of risk associated with 13 potential threats to soil microorganisms and fauna. Numbers indicate the position of each threat based on scientists' rankings, from least risky (smallest numbers) to most risky (largest numbers). Transparent bars indicate threats on which experts cannot agree, so they remain controversial and require more research. You can see that, for both microorganisms and soil fauna, the biggest risk to soil biodiversity is intensive human usage.

soil. Over the years, scientists have worked to find out what puts soil life at risk. Therefore, as a superhero, your first step should be to read all the available literature on this topic. Even though we are not superheroes, that is what we did in our study mapping at-risk soils in the European Union [2]. We identified 13 potential threats to soil organisms, from pollution and use of **genetically modified organisms (GMOs)** to increasing **aridity** (dryness) and soil loss due to extreme weather events (Figure 1).

GENETICALLY MODIFIED ORGANISM (GMO)

An organism that has had its DNA modified to give it new abilities, such as pest resistance or the ability to grow in the presence of weed-killing chemicals.

ARIDITY

A condition characterized by limited-to-no water availability in an environment, mainly due to scarce precipitation.

Once we have a list of the threats to soil organisms that we want to map, our second obstacle becomes clear: soil biodiversity is immense. Are we sure that, for instance, increasing aridity has the same negative effect on *all* soil organisms? Increased aridity will likely be a big problem for earthworms (which love wet, moist soils), but may be less of an issue for microorganisms that can better tolerate harsh conditions. Furthermore, not all earthworm or bacterial species are affected in the same way by the same threat. In an ideal situation, we would try to create a risk map for each species of soil organism, but that would lead to millions of maps, which would be impossible even for superheroes to manage. We need a compromise. As a first step, we decided to create maps for two main groups: soil microorganisms (including bacteria and fungi) and soil fauna (including earthworms, insects, springtails, and mites [1]).

Now we have a list of threats to map and of target groups to be considered. A third obstacle emerges. To what extent does each threat affect the different groups of organisms? Aridity can cause earthworms to die, so this has a high level of risk for them. However, some bacteria can recover quickly from a dry period, so aridity poses a low level of risk to them. To assess these differences, we called on the knowledge of soil scientists who have been working on risks to soil organisms for a long time. We knew that these experts could help us by providing accurate information about the risk levels our threats pose for various species. We contacted over 100 researchers and asked them to rank our 13 threats to soil biodiversity based on the level of risk (low, moderate, high) to the soil microorganisms and fauna they studied. This information helped us to pinpoint the most accurate level of risk associated with each of the proposed threats and groups of organisms.

RISKS TO SOIL BIODIVERSITY IN THE EUROPE UNION

Now you are part of a team of superheroes; you have all you need to accomplish your mission. You have pooled all the information to identify your most dangerous enemies, combined expert opinions on groups of soil organisms, and ranked the threats to soil microorganisms and fauna (Figure 1). When we did these things, our findings suggested that, for both soil microorganisms and animals, the most dangerous threat is intensive human use of soil, which mainly means agriculture through intense physical (high cattle density, heavy machinery) and chemical (pesticides and fertilizers) inputs [3]. This is not surprising because no soil organism can do well when strange machines come to break up or destroy its home on a regular basis. At the opposite end of the scale, the use of GMOs in agriculture was ranked as being the least risky. GMOs are agricultural plants whose DNA has been modified by humans to make them grow better and produce more food [4]. The use of GMO plants in agriculture is controversial. Our findings suggested that, while the use of GMOs is not completely risk-free, other threats are more dangerous to soil biodiversity.

Scientists often disagree and, in our case, sometimes the level of disagreement was so high that it was impossible to classify the level of risk for some threats (Figure 1). For example, biodiversity experts could not agree on the effect of pollution on soil animals and the effect of climate change on soil microorganisms. These "controversial threats" were expected. An interesting side-product of our analysis has been the identification of those threats about which we still do not know enough to say how risky they are. These threats require further investigation in the future, so there is plenty of work to keep soil scientists busy!

FINDING THE ENEMIES

The next step of your mission: find out where the enemies are, by combining threat rankings with some geographical data. For instance,

Figure 2

Maps of risk to soil microorganisms and fauna in 27 countries of the European Union, based on data collected from 2016. In more than half of the countries studied, 40% of the soils posed high levels of risk to soil microorganisms and soil fauna.

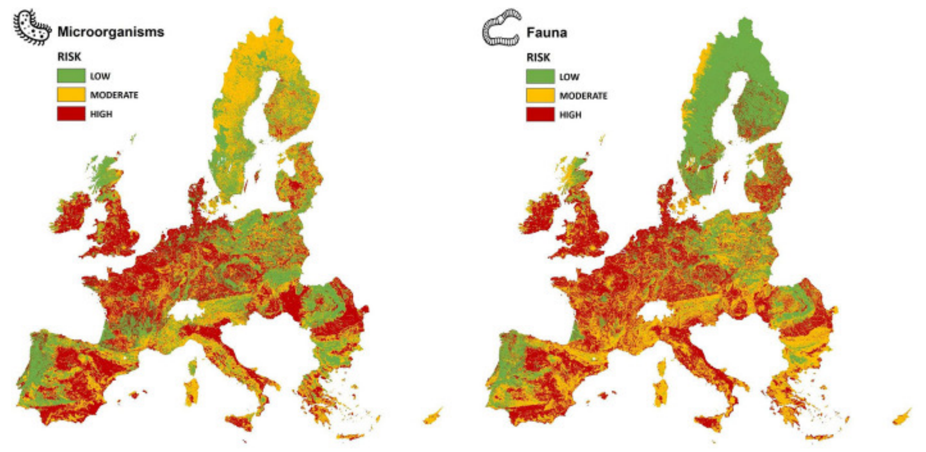

Figure 2

for the threat "use of GMOs in agriculture," we combined a map of the European countries in which GMO cultivation is allowed (Spain, Portugal, Romania, Czechia, and Slovakia) with a map of the agricultural areas in those countries. This allowed us to identify soils where GMOs might be grown. For the threat of "intensive human usage," we made a map showing fertilizer application (the more fertilizers used, the more intense the human usage) and number of cattle (the more cattle, the greater the impact on the soil).

Once all our geographical data were collected, thanks to supercomputers, we brought all the data together to produce maps showing the risk to soil biodiversity in the European Union (Figure 2). As we looked closely at the risk distribution in each of the 27 European countries, we found an alarming situation. In more than half of the countries studied (14 out of 27), 40% of the soils posed high levels of risk to soil microorganisms and animals. Only five countries showed that more than 40% of their soils posed low risks to soil life.

The maps we produced not only allowed us to identify the areas with higher levels of risk in each country, but they also gave us information about the activities affecting soils in those regions. All these data are fundamental to ensure the proper protection of soil biodiversity.

WHAT NEXT?

We have mapped the risks to soil biodiversity and discovered areas where help is needed to preserve soil organisms. Does this mean we can say, "Mission accomplished! Life belowground is safe!"? Not really. But here is the best part: we must now identify real-life actions that will reduce the risks to soil organisms in the high-risk areas. For instance, maybe protected areas (like national parks) can be set up to avoid, or at least reduce, human interference. However, in many cases this may not be enough. For example, extreme weather events do not have boundaries; they also occur in national parks. To reduce the impacts of severe weather on soil organisms, we need wider measures that will help to slow or reverse climate change. That is another story—a true superhero mission!

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ORIGINAL SOURCE ARTICLE

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YOUNG REVIEWERS

KAYSVILLE JUNIOR HIGH, AGES: 12–13

The students that reviewed this article were selected from Mr. Lanford's Science 7 classes at Kaysville Jr High. Students that live in the area come from strong communities that also know how to appreciate and enjoy nature in the Western US. A lot of the families make a habit to go hiking, fishing, camping, rock hounding, river rafting, biking, and too many other hobbies to mention.

AUTHOR

ALBERTO ORGIAZZI

When he was a child, Alberto wanted to become a helicopter pilot. However, life is full of surprises, and instead he has gone the way of the ostrich, putting his head in the ground. Switching from the sky to the soil, he is now a soil researcher at the European Commission's Joint Research Center. His current mission focuses on the creation of detailed maps of life in European soils. *alberto.orgiazzi@gmail.com

BIODIVERSITY
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TINY FUNGI IN THE SOIL ARE LIKE MEDICINE FOR NATURE

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YOUNG REVIEWERS:


JOVENA
AGE: 9


KAVIN
AGE: 9


TANISHKAA
AGE: 8


THUVISHA
AGE: 13


VETRIVEL
AGE: 12


YUTHIGA
AGE: 8

Like humans, plant and animal species have a specific type of place, called an ecosystem, where they prefer to live. If the ecosystem changes too much, some species will disappear, much the same way people avoid living in the desert because it is too hot and dry. Humans modify many ecosystems, sometimes so severely that almost no plants or animals can live there anymore. To help damaged ecosystems recover, we often start by planting trees or other plants. Biologists found that mycorrhizal fungi, tiny fungi living in the soil and inside plant roots, could speed up ecosystem recovery by making plants grow back faster and stronger. In this article, we describe how the recovery of ecosystems can be enhanced by mycorrhizal fungi, and when mycorrhizal fungi are especially helpful.

DEGRADED ECOSYSTEMS NEED OUR HELP

Natural **ecosystems**, such as forests, grasslands, or bogs—provide many functions and serve as homes for native plants, animals, and tiny microorganisms in the soil. Some ecosystems also filter and store water, keep excess carbon out of the atmosphere, and preserve a healthy soil layer where plants can grow and produce fruits and vegetables for us to eat. Ecosystems provide these functions if they are healthy and intact, but sometimes ecosystems become disturbed and stop functioning well. Such disturbances include fires, floods, or tree fall after storms. Fortunately, healthy ecosystems can usually recover easily from these disturbances. However, if disturbances occur frequently over a long period, or if they are very intense, ecosystems have more difficulty recovering and might change. For example, a forest might become a grassland after a very intense storm pulls all the trees over. As another example, after a long period of drought (when there is not enough water for plants to survive) plants may have a hard time growing back even when water is available again. If, after disturbances, ecosystems change to become less complex and have fewer species living in them, we call them **degraded ecosystems**.

ECOSYSTEM

An environment colonized by different organisms that are living together and interacting with each other.

DEGRADED ECOSYSTEM

An ecosystem that has been damage or destructed, which also negatively affects the organisms living in the ecosystem and hampers the functioning of the ecosystem.

ECOLOGIST

A scientist that studies how ecosystems function, and how the organisms in an ecosystem interact with each other and the environment.

Humans use ecosystems to create space for cities, to produce food in agricultural fields, or to mine for stones, sand, or metals for building or manufacturing. These human activities often disturb ecosystems so severely and for so long that the ecosystems are pushed over the edge from where they can no longer recover without help. **Ecologists**, which are scientists who study how ecosystems function and can be home to many species, can help restore degraded ecosystems, helping them to regain their health and their functions. When ecologists restore ecosystems, they might plant trees to help forest recovery after trees are cut down for timber production, or sow seeds to help grasslands recover after they have been used as agricultural fields. Even with this help, sometimes the new plants do not grow well, or the ecosystem looks different after restoration than it did before the disturbance. Why does restoration sometimes not work as well as other times? Recently, ecologists have begun to understand that successful ecosystem restoration needs to take care of both the plants and animals aboveground and the organisms that live belowground, in the soil.

WHY ARE THE SMALL CREATURES LIVING IN THE SOIL SO IMPORTANT?

Because plants cannot move, they use their roots to look for nutrients and water in the soil. The soil is an important part of the ecosystem and is the habitat of many small creatures [1]. One teaspoon of soil is inhabited by more organisms than there are people on earth—around 7.5 billion [2] (Figure 1A)! All these small creatures interact with each other and contribute to the functioning of the ecosystem, so the health

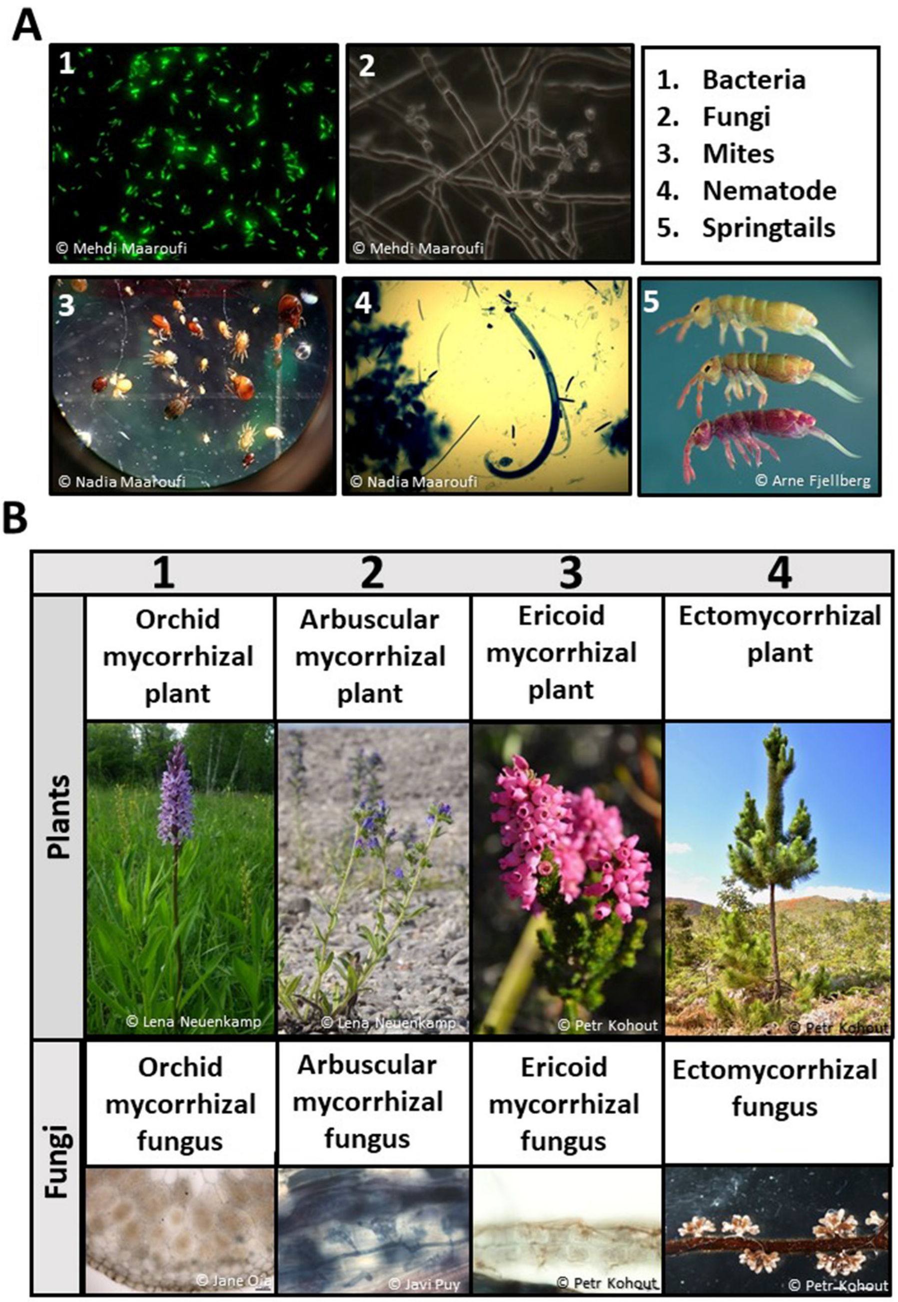

Figure 1

Figure 1

The small creatures inhabiting the soil. **(A)** Microscope pictures of bacteria, fungi, mites, nematodes, and springtails. Nematodes are small roundworms, mites look a bit like mini spiders, and springtails are tiny insects that sometimes can jump (Photo credits: Mehdi Maaroufi, Nadia I. Maaroufi and Arne Fjellberg). **(B)** Pictures of different types of mycorrhizal fungi and their host plants. (1) An orchid and the orchid mycorrhizal fungi inside the plant root. (2) Arbuscular mycorrhizal fungi inside a blueweed plant. (3) A heather plant and ericoid mycorrhizal fungi inside the plant root. (4) A pine tree and ectomycorrhizal fungi on the surface of the plant root (Photo credits: Lena Neuenkamp, Petr Kohout, Jane Oja, Javi Puy).

of these soil organisms is likely to be quite important for ecosystem restoration. The most abundant soil organisms are bacteria and fungi. Some of them, called **decomposers**, feed on dead plants and help to break down the plant material until it becomes soil again [3]. Some soil organisms, called **pathogens**, can attack plant roots and make plants sick. Other soil organisms, called **symbionts**, cooperate with plants by exchanging nutrients with them. **Mycorrhizal fungi** are one group of symbionts that researchers believe may help with ecosystem restoration [4, 5] (Figure 1B).

DECOMPOSERS

Organisms that feed on dead plant and animal material, and by that break this material down into the different nutrients it is made off until it becomes soil again. Plants, in turn, take up the nutrients in the soil as food. Many decomposers are fungi.

PATHOGENS/ PATHOGENIC FUNGI

Organisms that cause diseases for example a pathogenic fungus that makes plant leaves turn brown and incapable of doing photosynthesis.

MYCORRHIZAL FUNGI ARE LIKE POWERFUL MEDICINE FOR PLANTS

Mycorrhizal fungi can help plant roots to collect more nutrients and water from the soil, therefore helping the plants to grow better. So, let us call them helper fungi from now on. In addition, these helper fungi can protect plants against pathogens that can cause plant diseases! In return for the benefits helper fungi provide, plants give helper fungi some of their carbon—a nutrient that plants produce with the help of sunlight during photosynthesis. So, the partnership between plants and fungi is a win-win situation for both partners, called **symbiosis**. Ecologists tested the effects of the helper fungi for assisting ecosystem restoration (Figure 2). The process of adding helper fungi to the soil is called **soil inoculation**. Studies testing the effects of soil inoculation on ecosystem restoration showed that replanted tree seedlings and grasses grew better when helper fungi were added to the soil [4]. In addition, the studies showed that grasslands restored by adding helper fungi were richer in plant species.

SYMBIONTS/ SYMBIOTIC FUNGI

Organisms that live together and help each other. For example, symbiotic fungi, such as mycorrhizal fungi that live in plant roots and help plants with nutrient uptake from the soil in exchange for carbon produced by plants in their leaves.

MYCORRHIZAL FUNGI (*MI-CO-RYE-Z-ALL FUN-GUY*)

A group of fungi that live in the soil and the roots of plants. Mycorrhizal fungi help the plants with nutrient uptake and resistance against drought or disease caused by other fungi, and in return fungi get food from the plants.

SOIL INOCULATION

Adding soil organisms (for example, mycorrhizal fungi or bacteria) to the soil to make plants grow better.

THE POWER OF HELPER FUNGI VARIES

Different types partnerships exist between helper fungi and plants, depending on which species of fungi are most abundant in a specific ecosystem (Figure 1B). Plants and helper fungi differ in when and how much they need each other and how fairly they trade resources and benefits with each other. So, restoration of ecosystems with plants that depend strongly on helper fungi might need mycorrhizal fungi as a medicine more than other ecosystems in which the plants are more independent from helper fungi [5]. When scientists looked through all ecosystem restoration experiments that used helper fungi, they actually did find that the benefits of adding helper fungi varied between studies [4]. So, helper fungi are a good medicine for plants, but when they are most powerful depends on the plants and the ecosystem.

The scientists concluded that helper fungi were the most helpful in the following three conditions:

- for plants that give shelter to bacteria in their roots, making the plants hungry enough for two—themselves and the bacteria (like pea or bean plants);
- for plants that have trouble finding nutrients because their roots are too big to reach into the small soil pores where many nutrients are sitting (like some grasses); and
- for plants growing on soils that are both severely disturbed and nutrient-poor.

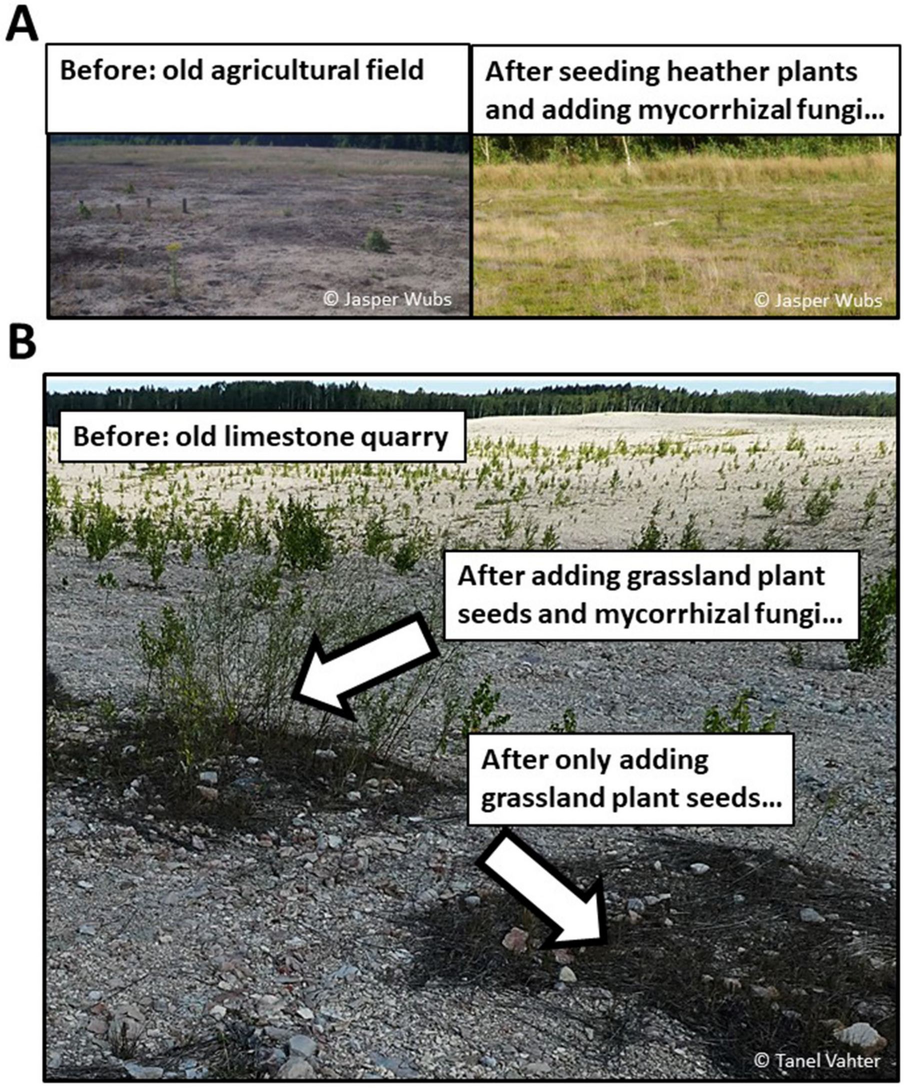

Figure 2

Figure 2

Examples of results of ecosystem restoration projects using mycorrhizal fungi. **(A)** Heathland restoration in the Netherlands, with the aim of re-establishing a heathland on an old agricultural field with the help of heather plants and ericoid mycorrhizal fungi. **(B)** Limestone quarry restoration in Estonia, with the aim of speeding up revegetation of an abandoned limestone quarry with the help of grassland seeds, hay, and arbuscular mycorrhizal fungi (Photo credits: Jasper Wubs, Tanel Vahter).

WANT TO HELP YOUR OWN HOUSE PLANTS?

About 80% of all plants—even your potted plants at home—have a symbiosis with one type of helper fungi, called arbuscular mycorrhizal fungi. You can keep your plants healthy by making your own arbuscular mycorrhizal fungal inoculum (Figure 3). Many gardeners already do this! You will need a shovel, a 10-liter bucket to mix the soil, 3–5 l of sand, seeds of grass and clover plants, and 4–6 flowerpots.

The steps:

- **Plant selection:** Select one or two plants from your garden that form arbuscular mycorrhizal symbioses (maybe a grass and a clover plant) and dig them out together with a good portion of soil around the roots.

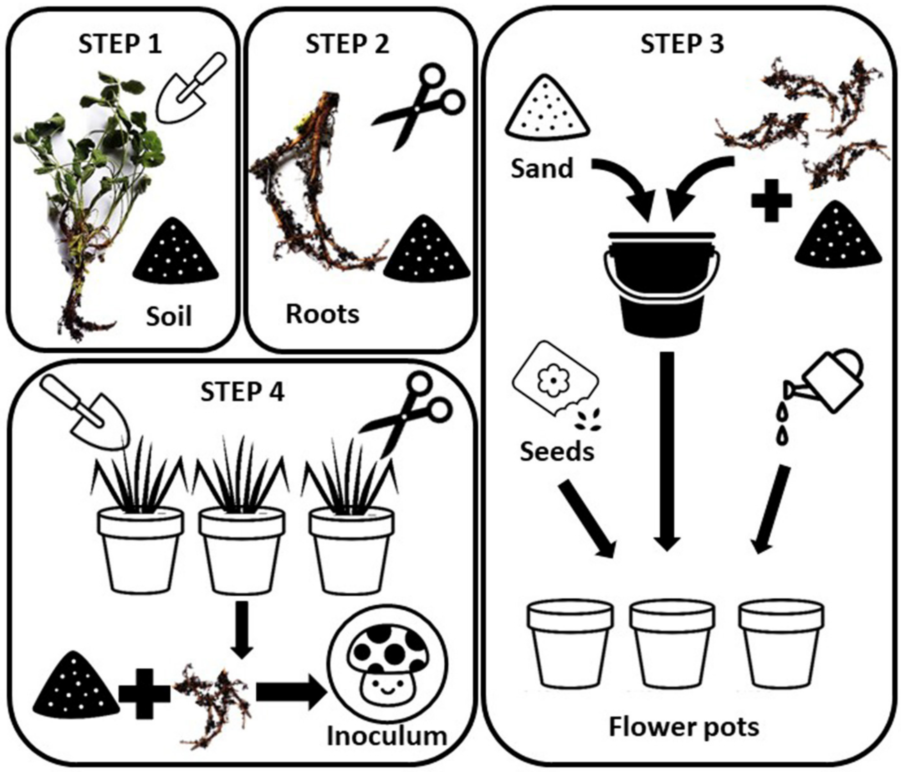

Figure 3

Figure 3

Do-it yourself mycorrhizal inoculum. The most important steps for producing your own mycorrhizal inoculum (Based on the instructions given here: https://orgprints.org/35308/1/symanczik-etal-2018-Mycorrhizal-fungi-as-natural-biofertilizer_technical_note.pdf).

- **Source inoculum:** Remove the leaves and stems of both plants, cut their roots into small pieces, and mix all roots and soil well. This is your source inoculum, which we will multiply so that we do not have to dig out too many garden plants to create the inoculum.
- **Inoculum multiplication:** Mix the source inoculum with sand (1 part of inoculum with 1 part of sand, or even 1 of part inoculum with 2 parts of sand) and put it into the flowerpots. Add the grass and clover seeds to the pots, water them, and let them grow for 2–4 months. The seeded species are called **bait plants** because they attract the arbuscular mycorrhizal fungi. When the bait plants start growing, the arbuscular mycorrhizal fungi will colonize their roots and the fungal population will grow. The longer the plants grow, the more fungi will be in the soil.
- **Inoculum harvest:** After 2–4 months, remove all leaves from the bait plants, cut their roots into small pieces, and mix them with the soil. The inoculum is now ready to be added in small amounts to your potted plants—either dry or mixed with water.

BAIT PLANTS

Plants used as a lure to attract mycorrhizal fungi in their roots, where mycorrhizal fungi reproduce and grow. The multiplied fungal material in the roots and the surrounding soil can then be used to produce a fungal inoculum.

TAKE HOME MESSAGE

Human activities can degrade ecosystems so severely that they need help to recover. Mycorrhizal fungi are helper fungi for plants that could support ecosystem recovery, because they can increase plants' nutrient uptake and protect plants against diseases or drought. Different types of helper fungi exist with different properties, thus when and which helper fungi are most powerful for ecosystem recovery depends on the plants and the ecosystem.

AUTHOR CONTRIBUTIONS

LN and NM conceived the original idea and wrote the first draft of the manuscript. All authors gave final approval for submission.

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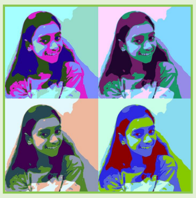

JOVENA, AGE: 9

I like reading a lot. I usually read magical books like Harry Potter books. They are my favorite series to read. I also like to read mystery books. I love animals. I like playing Roblox. I enjoy playing with my friends. I like skate boarding and roller-skating. My dream is to 1 day be a pro skateboarder. Hasta Luego Baby!

KAVIN, AGE: 9

Science is important and interesting.

TANISHKAA, AGE: 8

I have been interested in learning science since my childhood. I would like to explore every part of science. My favorite part of science is learning about the human body. I like science very much because it is very very interesting. I want science to be a part of my whole life.

THUVISHA, AGE: 13

I like Science because it is something new and makes us discover a lot of things that are related to our daily life. It is always interesting. We need science in our world.

VETRIVEL, AGE: 12

I like to make paper airplanes and do simple experiments. I like to learn about scientists. I like to do many experiments and am exploring more and more ideas.

YUTHIGA, AGE: 8

I am interested in painting and playing chess. I won third prize and got trophy at district level chess tournament. My favorite subjects are English, Science, and Mathematics. I spend my holidays exploring new things.

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I am a plant ecologist, and I started to investigate the soil because it could help me to understand plants. Well, I then became fascinated by mycorrhizal fungi and how they interact with plant roots. I am working as a researcher at the University of Bern in Switzerland. I am interested in understanding how human disturbances and climate change influence plant and soil communities, as well as the interactions between plants and soil organisms. I would like to use that knowledge to predict how well ecosystems can function and provide services to humans, in the face of current human disturbances and climate change. *lena.neuenkamp@ips.unibe.ch

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I am a soil ecologist interested in the small creatures inhabiting the soil. I am working both at the University of Bern in Switzerland and at the Swedish University of Agricultural Sciences, Uppsala in Sweden. I am particularly interested in understanding how soil organisms are impacted by human and natural disturbances, and how these disturbances affect forest and grassland ecosystem functioning.

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LEARNING MORE ABOUT EARTHWORMS WITH CITIZEN SCIENCE

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Have you ever wanted to conduct scientific research? Citizen, or community science involves non-scientists in assisting scientists with research. The term covers a huge variety of projects: from online-only where you can classify galaxies, to practical outdoor activities, and even helping with scientific expeditions. Ideally, citizen science benefits everyone—scientists collect more data, and over larger geographic areas than they could on their own. Non-scientists benefit by learning something new and experiencing how science works, and hopefully having fun! The small size of most soil organisms is challenging for citizen science. However, earthworms are easy to recognize and relatively large, so there have been several citizen science projects focused on them. In this article, we discuss earthworm citizen science from its origins with 18th and 19th century natural historians, to the modern day. Discover what non-scientists have contributed to earthworm science and how you can design your own earthworm investigations.

WHY CITIZEN SCIENCE?

Science is not only carried out by scientists. When other people, like students or families, collect scientific data and help with research, it is called **citizen science**. Citizen science, also known as community science, allows anyone to participate in research, and its popularity has been increasing. Scientists benefit because this helps them to gather data that would have been difficult, expensive, or impossible for them to collect on their own. On the other hand, citizen scientists gain the opportunity to be directly involved in research and learn about science.

CITIZEN SCIENCE

Scientific studies carried out in whole or part by volunteers rather than paid scientists, also known as community science.

TYPES OF CITIZEN SCIENCE

There are many kinds of citizen science. Some projects borrow the power of personal computers to search for alien life[1] or to find cures for diseases[2]. Some online citizen science projects ask people for help with identifying wildlife or galaxies, translating documents, and many more tasks[3]. Other citizen science projects need people to go outside to survey wildlife[4] or to measure water pollution[5]. There are even expedition-style projects, in which volunteers help scientists with research on volcanoes and rainforests.

1 setiathome.berkeley.edu/

2 foldingathome.org/

3 www.zooniverse.org/

4 www.birdcount.org

5 freshwaterwatch.thewaterhub.org/

WHY STUDY EARTHWORMS?

Healthy soils are important for all life on Earth, as they recycle nutrients, filter water, and help plants to grow. As earthworms feed and burrow, they mix the soil and provide the nutrients that most plants need. Depending on the location of a study, the scientific questions addressed by earthworm research differ. In some places, like the United Kingdom, earthworms are considered beneficial and scientists want to find out more about where they are, to improve soil health. But in other areas of the world, like most of Canada and the northern United States, the last ice age wiped out the earthworms. Now the only earthworms living there are those that were brought into the region by people, often accidentally, with soil or plants that were imported from Europe. Scientific research in these areas often tries to determine where earthworms are found and how they are spreading, to try to reduce their impacts in forests. Even where earthworms are invasive, they are still usually considered beneficial in gardens and for composting and are only a problem when they escape into wild areas.

CITIZEN SCIENCE FOR EARTHWORMS

Earthworms were some of the first soil animals to be studied by early scientists and they continue to be studied by scientists today, with

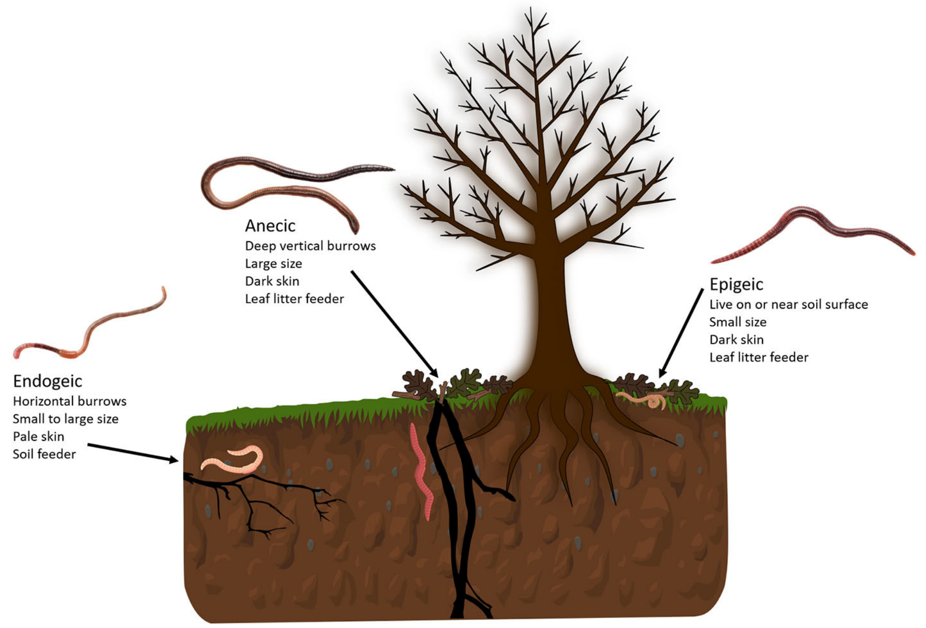

Figure 1

There are three main types of earthworms, called ecotypes: endogeic, anecic, and epigeic. Some of their characteristics are described here (Credits: earthworm clipart from Vecteezy.com Earthworm photographs © Trustees of the Natural History Museum/Harry Taylor).

the help of farmers, gardeners, students, and many others. Most soil organisms are small and require special equipment and knowledge to study them, which makes it difficult to include them in citizen science. Earthworms are a happy exception, as they are relatively large and easy to find and observe without special equipment. The usual method for finding earthworms is to dig out a cube of soil from the ground and then search through it by hand, picking out any earthworms. Another method uses a mixture of hot mustard powder and water poured on the soil. If the mustard water touches any earthworms in the soil, they move to the surface where they can be captured, but the mustard does not do permanent harm.

Although the species of most earthworms cannot be identified without a microscope, they can be grouped into different categories according to their lifestyle. These categories are called **ecotypes**. The three ecotypes—**endogeic**, **anecic**, and **epigeic** (Figure 1)—can usually be distinguished by citizen scientists.

ECOTYPE

Groups of earthworms based on their burrowing and feeding habits.

ENDOGEIC

An earthworm that creates horizontal burrows in soil, feeding on soil as it burrows. Usually pale in color.

ANECIC

A type of earthworm that builds deep vertical burrows and comes to the surface to feed on leaf litter. Often large and red in color.

EPIGEIC

Earthworms that feed and burrow on or near the soil surface, feeding on leaf litter. Usually small and red in color.

EARLY EARTHWORM CITIZEN SCIENCE

The earliest natural scientists, such as John Ray (1627–1705) and Carolus Linneaus (1707–1778), grouped all long, wiggly animals together as "worms" and many still have common names that reflect this. Some moth caterpillars are called inchworms, legless lizards are called slow worms, and glowing beetle larvae are known as glow worms. John Ray was the first to record the phrase "the early bird catches the worm" in his book "A Handbook of Proverbs," published in 1670. Linneaus developed rules for naming organisms and named the common earthworm *Lumbricus terrestris*—the same name it has today.

The English pastor Gilbert White (1720–1793) was the first to observe and write about how earthworms live. He described that earthworms seem to promote plant growth and are an important part of the food chain. Inspired by White's writing, Charles Darwin (1809–1882) was also fascinated by earthworms. Darwin's book *The Formation of Vegetable Mould Through the Action of Worms, with Observations on their Habits* [1] is the result of his 40-years study of earthworms and it was the final book he published, in October 1881. It was very popular, selling 6,000 copies in the first year.

WHAT DID DARWIN DISCOVER ABOUT EARTHWORMS?

Darwin found that earthworms have no sense of hearing. He discovered this by shouting at earthworms and playing them various musical instruments including a piano, a bassoon, and a tin whistle. However, earthworms in pots placed on a piano hid in their burrows when notes were played, showing that they can sense vibrations through the soil. Darwin also investigated earthworms' sense of smell by blowing tobacco smoke and perfume at them, and they did not react. They can smell their favorite foods though—Darwin experimented with giving captive earthworms many different foods and noted which they preferred. He found that wild cherry leaves were preferred over lime and hazel leaves. Cabbages, horseradish, carrot, and celery were also liked, but herbs, such as sage, thyme, and mint were barely touched.

Darwin observed the way that large stones and ancient buildings are slowly buried, including making a journey to Stonehenge to examine buried stones there. Darwin placed a large stone on the soil surface of his garden and, over 29 years, recorded how long it took the stone to be buried by earthworms. Using this experiment, Darwin estimated that earthworms move 34,000 kg of soil (the weight of five and a half African elephants) per hectare (about one and quarter soccer pitches) to the surface each year—this process is called **bioturbation**.

BIOTURBATION

The movement of soil by living animals or plants.

EARTHWORM CITIZEN SCIENCE TODAY

Despite the long history of research involving earthworms, we still do not know enough about where they are most common and how they are affecting other species. Citizen science is helping scientists answer these questions. There are increasing numbers of programs in different parts of the world that involve earthworm sampling (Figure 2 and Table 1). The data citizen scientists collect is mailed to scientists or sent in through smartphone apps. Some of the programs are designed for use in schools and include suggestions for how they fit with

Figure 2

Figure 2

Examples of earthworm citizen science projects in various countries. OPVT, L'Observatoire Participatif des Vers de Terre.

course material, while other programs are designed so that anyone can participate.

DISCOVERIES FROM EARTHWORM CITIZEN SCIENCE

A lot of the research from citizen science projects is still underway, but there have already been some exciting discoveries. And Citizen Scientists have been extremely important! For example, in the United States, citizen scientists have helped to detect the spread of new species, such as jumping worms (*Amynthas* species), which were introduced from Asia. In Finland, citizen scientist helped showing that the number of earthworm species decreases moving from the south to the north of the country. In the north, most of the places surveyed had no earthworms or only one species, likely because of the cold temperatures. In the United Kingdom, the OPAL Soil and Earthworm Survey discovered that citizen scientists find it quite difficult to identify earthworm species but can tell ecotypes apart correctly 70–90% of the time.

The project "What is Under Your Feet?" confirmed that earthworm numbers change with the seasons, with the most found in spring and autumn [3]. There were also more earthworms found after rain. The project #60minworms counted earthworms from farm fields and found that plowing the soil reduced the number of earthworms [4]. Some farms had no epigeic or anecic earthworms, which may mean the fields are plowed too often. The "Earthworm Watch" project found that gardens that use organic fertilizer, such as manure and compost, have 20% more earthworms than gardens that added no fertilizers.

Table 1

Past and present earthworm citizen science projects around the world.

Country	Project name	Aimed at	More information	Year
United States	Great Lakes Wormwatch	Anyone	https://www.k-state.edu/cecd/partnerships/EarthwormsAcrossKansas.htm	2006–today
	Earthworms across Kansas	School students	https://www.k-state.edu/earthworm/	2010–2012
Canada	Alberta Worm Invasion Worm Tracker	Anyone	https://worms.educ.ualberta.ca/	2013–today
	WormWatch	Anyone	https://www.naturewatch.ca/wormwatch/	2014–today
United Kingdom	Open Air Laboratory (OPAL) Soil and Earthworm Survey	Anyone	https://www.imperial.ac.uk/opal-soil	2009–2020
	What is Under Your Feet?	School students	https://jointhepod.org/teachers/other/information-pack-whats-under-your-feet	2018–today
	#60minworms	Farmers	https://www.rothamsted.ac.uk/news/earthworm-research-spurs-farmers-act	2018
	Earthworm Watch	Anyone	https://earthwormwatch.org/	2016–2018
	Earthworm Society of Britain	Anyone	https://www.earthwormsoc.org.uk/	2009–today
France	L'Observatoire Participatif des Vers de Terre (OPVT)	Anyone	https://ecobiosoil.univ-rennes1.fr/OPVT_accueil.php	2011–today
Australia	Earthworms Downunder	School students	[2]	1992
Finland	Matoseuranta	School students	http://matoseuranta.it.helsinki.fi/fi	2016–2018
Norway	Forskningskampanjen 2010—Meitemark	School students	https://www.miljolare.no/aktiviteter/land/natur/ln6/	2010

Table 1

DOING YOUR OWN EARTHWORM RESEARCH

Whether earthworms are helpful for harmful for soil health depends where in the world you are, but they are always important. Using citizen science, scientists, students, families, farmers, and anyone else interested, can work together to find out more about earthworms. There are still many unanswered questions about earthworms that you can investigate. Here are a few suggestions if you want to start your own project on earthworms:

- Recreate one of Darwin's experiments—how long do earthworms take to bury a stone in your garden? Does this vary depending on where the stone is in your garden?
- How does season affect the number of earthworms found in your garden, or the number of different types of earthworms?
- How does the number and types of earthworms vary across different **habitats** (like your garden compared with a forest)?
- Start a compost bin in your yard—how long does it take for earthworms to arrive?

HABITATS

The home environment of animals, plants or other organisms, providing food, shelter, protection and mates.

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YOUNG REVIEWER

AYA, AGE: 9

Aya wants to study marine biology. She wants to specialize in sharks and rays. Her favorite subjects in school are reading, writing, math, and music. In her free time she likes to read books, try out challenging puzzles, training for track and cross country, experimenting with different art techniques, and roller skating.

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VICTORIA J. BURTON

I spent my childhood playing outside, making nature journals, and learning how to identify plants, birds, and insects in the woods. I did not like school but always wanted to be a scientist, so I studied for a degree with The Open University. I have just finished my Ph.D. with Imperial College London, where I researched how soil and leaf-litter invertebrate communities respond to human activities. In my free time I enjoy looking after my pets and plants and helping run the Bug Club for young people interested in insects. *v.burton@nhm.ac.uk

ERIN K. CAMERON

I enjoyed playing outside as a child and loved science but did not consider becoming a biologist until I was in university. Eventually, I started helping with research examining how human activities affect songbirds and found it fascinating. Once I started to work on soil organisms and saw how much is still unknown about them, I was convinced that I wanted to study ecology. Now I investigate how human activities affect soil biodiversity and the functioning of ecosystems. I enjoy cross-country skiing, bicycling, and kayaking in my free time.

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