Life Belowground on the Range

An Introduction to the Soil Communities that Support California's Rangelands

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COVER: Example of a diverse rangeland soil ecosystem.

Notice the annual flowers and grasses, native perennial purple needlegrass, and blue oak tree that bring carbon into the system; the dung beetles, centipede, and fungi who help to decompose dead organic material and recycle nutrients; the gopher and earthworms that help to mix the soil; and the western toad and grub that seek shelter underground.

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Introduction

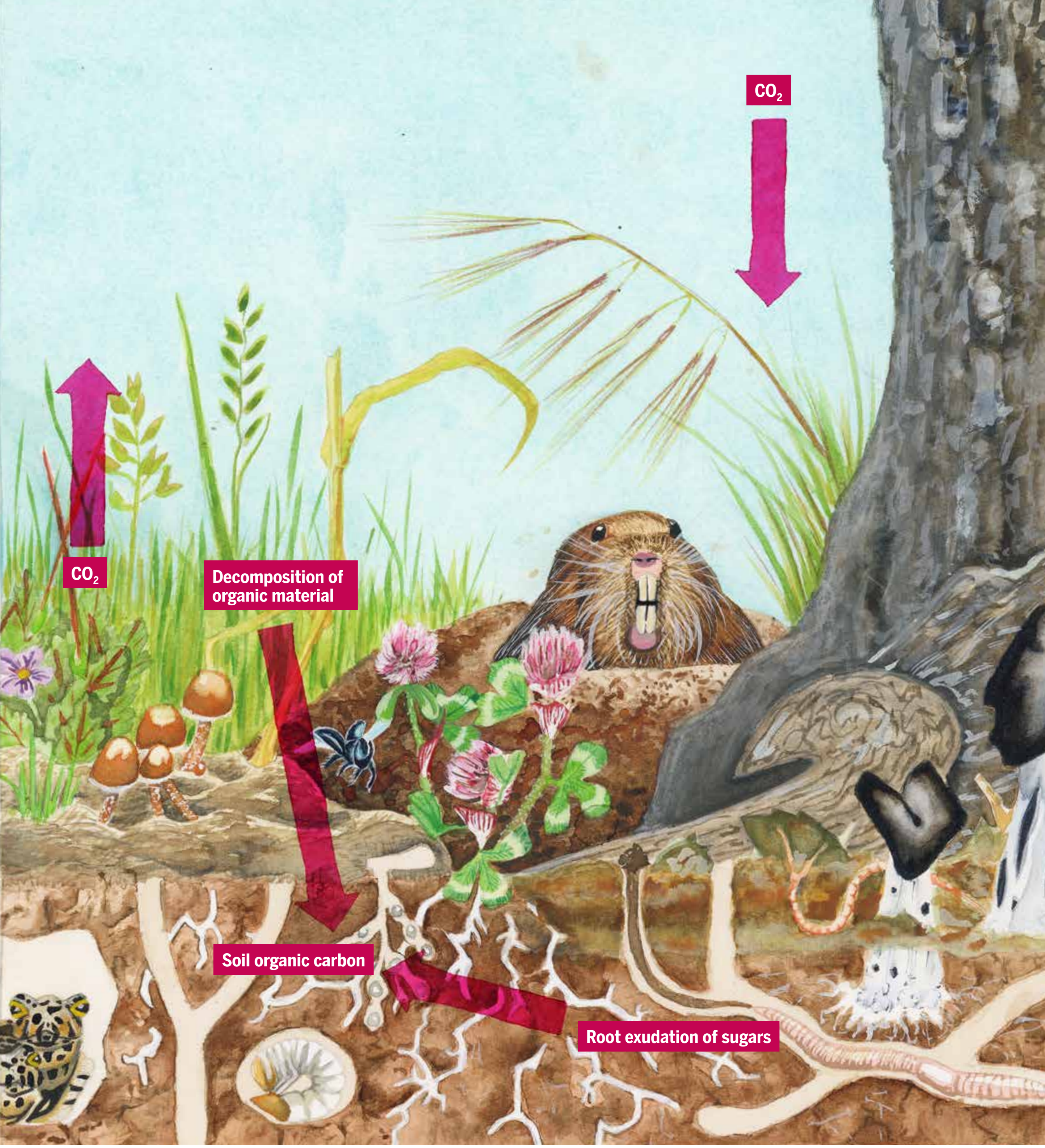
When we walk through California's rangelands, the biodiversity is striking: wildflowers, grasses, butterflies, and birds flood your senses. Patterns through space and time quickly become apparent. Migratory birds arrive and depart; plants germinate, bloom, and die back; herbivores graze and move on; and a keen observer recognizes that some plants and animals are more likely to be found in some places than others. What is less obvious is that there is a rich abundance of belowground diversity in California's rangelands that mirrors the complexity we find aboveground.

This document aims to capture some of this belowground diversity, providing introductory information that will hopefully spark wonder and curiosity and have you seeking more. We cover five major groups of soil organisms—earthworms, nematodes, protozoa, fungi, and bacteria—giving a brief overview of how diverse they are, where you might find them, and what they do. We also highlight five other notable groups, providing a peek into their ecology and importance on our rangelands. While our primary focus is on soil organisms, many of these organisms (such as dung beetles, plants, and some fungi) live both above- and belowground, reminding us of the intimate connection between these two worlds.

In our illustrations, you'll notice we have made use of bright colors that you wouldn't necessarily expect to see in rangeland soils (pink, blue, yellow, orange). We did this to draw your attention to particular groupings or ideas, as a way to help convey the greatest amount of information. Keep an eye out for the meaning of these colors described in each illustration's caption. We hope you enjoy, and feel free to share.

Why should I care about the life below my feet?

Although you wouldn't know it just by looking, there are more organisms in a handful of soil than there are people on Earth. These organisms help to drive carbon, nutrient, and water cycles and are therefore critical for the functioning of any ecosystem—including California's rangelands. How much forage you produce, the quality of your feed, and whether you have desirable or undesirable plants in your pasture all depend, at least in part, on the organisms that live belowground. Whether your soil is capturing and storing water, building soil organic matter, sequestering carbon, or resisting erosion similarly depends on the presence and activity of these organisms. While a "healthy" rangeland soil may look and function differently depending on your context and goals[1], the soil organisms belowground invariably play a key role in helping you to achieve these goals and sustainably steward your land for generations to come.



Simplified diagram of the carbon cycle.

Plants "fix" carbon dioxide (CO_2) through the process of photosynthesis, turning it into plant biomass. Some of the carbon that is "fixed" by plants is released by plant roots as exudates, which becomes food for microbes. Dead plant biomass decomposes over time as it feeds the belowground food web. Through this process, most of the dead organic matter returns back to the atmosphere as carbon dioxide, but some is also stored in the soil, contributing to carbon sequestration.

Did you know? Levels of serotonin in your brain increase in response to the soil bacterium, *Mycobacterium vaccae*. This helps to create a sense of happiness or well-being for those interacting closely with soil.

What influences the presence and activity of soil organisms?

The services provided by a soil community are affected by the amount and kinds of organisms present, the activity level of each individual, and the surrounding physical, biological, and chemical environment. In order to better understand soil biology and how to steward it, it's helpful to know what controls the presence and activity of these organisms across space and time. The following factors, many of which are intertwined, are known to be influential: soil aggregation, water availability, acidity, organic matter content, nutrient availability, temperature, dispersal, and interactions between organisms.

Most soil organisms have the same basic requirements. To begin, all need food that provides carbon, energy, and nutrients for growth and reproduction.

Symplified diagram of the elements of the soil system that relate to aggregation and soil structure.

LEFT: Soil mineral particles are made of sand, silt, clay. Sand is the largest particle (tan), clay is the smallest (tiny dark brown speck), and silt is in between (medium-sized dark brown). The proportion of sand, silt, and clay determines a soil's texture and the ability of a soil to hold water, carbon, and nutrients. It also influences the susceptibility of a soil to compaction, with clay-dominated soils being easier to compact.

MIDDLE: In an uncompacted soil, soil particles (tan) should make up approximately 45% of the soil volume, soil organic matter (dark brown) should make up 5%, and pore space (blue) should make up the last 50%. Half of the pore space will be filled with water (dark blue), providing this essential resource to plants and soil organisms while maintaining aerobic conditions. Compacted soils will have reduced pore space.

RIGHT: Mineral particles (tan), organic matter (dark brown), and pore spaces (light and dark blue) organize to form soil aggregates. These aggregates, which vary in size, provide critical habitat for organisms in the soil. Roots (black) and mycorrhizal fungi (pink) intertwine throughout, helping to glue the aggregates together.

The majority of organisms in the soil get this by consuming other organisms (i.e., organic matter made up of dead plant litter, living microorganisms, etc). In fact, it is now recognized that plant roots and their exudates[2] are a very important source of food that fuels the belowground world. In addition to needing food, most soil organisms require—or prefer situations with—oxygen and adequate soil moisture, which is promoted, in part, by good aggregation and soil structure.

Despite these common basic requirements, soil organisms have diverse ecological preferences and optimal conditions. Just like the aboveground wildlife on our rangelands, organisms belowground differ from one another in the exact kinds of foods and environments they prefer and in the company they like to keep. In fact, the diversity of preferences and tolerances in a handful of soil may be as varied as you'll find in wildlife from rangelands across the globe. For both wildlife and belowground organisms, one species may like it hotter, or wetter, than another; one may prefer to hang out among trees, another among grass; one may like eating shrubs, another not so much. These differences—combined with an astoundingly variable soil environment that changes with bedrock, topography, vegetation, climate, soil age, and management—affect the distribution of soil organisms across space and time, and ultimately help to promote biodiversity belowground.

Together, this belowground diversity interacts to make up the soil food web. Similar to what happens aboveground, as soil predators consume their prey, they influence the presence and activity of the organisms they eat and contribute to the cycling of energy and nutrients.[3] At the end of this guide—after we've learned a little bit more about who these organisms are that make up the soil food web, and what they do—we will discuss how we can use the information presented in this section to help steward the life belowground.

Did you know? While the majority of organisms in the soil food web make their living by eating plant material or other soil organisms, some have found more unusual ways to get by. For instance, one group of bacteria rely on carbon dioxide and inorganic nitrogen to get their carbon and energy. We can thank these bacteria for the important nitrogen cycling process called *nitrification*.

1 Soil health can be defined as the capacity of the soil to function as a vital living ecosystem that maintains biodiversity and maximizes provision of multiple ecosystem services in a sustainable way. The same soil may be deemed healthy in one context and unhealthy in another. For example, serpentine soils, which have inherently low nutrient availability and high concentrations of heavy metals, are healthy in the sense that they support unique and diverse plant communities. However, these soils also support inherently low plant biomass, such that they would be considered unhealthy as measured by the ecosystem service of forage production. Therefore, whether or not serpentine sites are targeted for management activities that try to improve soil health would depend on the management goals at hand.

2 Plant root exudates are simple sugar and sugar-like carbon compounds that plants release from their roots. You may have heard root exudates described as the "liquid carbon pathway" in other contexts.

3 While it was historically thought that the soil food web was composed of distinct parts or channels, one fueled by bacteria and the other by fungi, we now know that the system is much more interconnected with many groups of organisms showing versatility in feeding preferences.

Earthworms

Earthworms enhance soil fertility by incorporating plant material into the soil, redistributing nutrients in the upper soil layers, aerating the soil, and increasing water infiltration.

While there are approximately 7,000 known species of earthworms, some scientists think that number may account for only 23% of all earthworm species in existence. Earthworms can be grouped into categories based on where they live in the soil and what they eat. *Epigeic* earthworms live amongst plant litter or at the soil surface and eat litter and microorganisms. *Endogeic* earthworms inhabit the soil—some in the upper 8 inches, some all the way down to 30 inches—and eat soil with varying levels of organic matter in it. *Anecic* earthworms eat surface litter and soil and create permanent burrows from the surface down into the soil profile. As a result of their foraging and feeding, earthworms produce casts that are enriched with microbes, plant-available nutrients, and even plant-growth-promoting hormones.

In California, earthworm communities are relatively diverse and densities commonly range from 1 to 4 individuals per liter of soil. Both native and non-native species occur here. Native earthworms dominate in habitats that are undisturbed by human activity, including grasslands, oak woodlands, and chaparral soils that have not been plowed, heavily fertilized, or irrigated. In contrast, non-native earthworms dominate in croplands, orchards, urban soils, and irrigated, fertilized pastures. Both native and non-native species help to decompose plant litter, enhance fertility, and create macropores within the soil. In fact, some species can ingest an amount of soil and organic matter equivalent to 30% of their body weight daily! However, non-native earthworm species differ from natives in how active they are and where they burrow, and can therefore influence the soil and aboveground plant communities in different, perhaps even undesirable, ways. While more research is needed on the ecological effects of earthworms in California rangelands, it may be a good idea to avoid management activities like plowing, bulldozing, or fertilizing should you want to keep the native species.

Did you know? Some earthworms produce "signaling molecules" that directly stimulate plant growth. These molecules can even help plants to fight off harmful parasites.

Example of the three different earthworm lifestyles and known species exhibiting them in California.

Epigeic earthworms (yellow) include the non-native Redworm (*Eisenia fetida),* a popular choice for worm-compost bins. Endogeic earthworms (blue) include the non-native Grey worm (*Aporrectodea caliginosa*) and native *Argilophilus marmoratus*. Like many native earthworms, *A. marmoratus* is transparent, so its lymphatic system shows blue. Its clitellum turns coral-red during the mating season, complementing the blue background. Anecic worms (pink) include larger *Apporectodea* species and the Nightcrawler (*Lumbricus terrestris*), a species known to many because of its popular use as fishing bait.

Nematodes

While some nematodes are parasitic to plants, many are not. Instead, they make a living by eating soil microorganisms, a process that enhances soil fertility by releasing nitrogen into the soil where it can be taken up by plants.

Nematodes are the most abundant animal on Earth. Only 2.5%, or 25,000, of the estimated 10 million nematode species have been described to date. Nematodes are roundworms that live in water films surrounding soil particles, and are therefore sensitive to soil water availability. When conditions are harsh, nematodes have the ability to enter a dormant state, which can be reversed when conditions become more favorable. Like hibernation in bears, dormancy is a strategy that allows organisms to persist through periods when resources are scarce and environmental conditions are harsh.

Nematodes feed on a wide range of food and are typically classified by their feeding behavior. Some nematodes eat bacteria, while others eat fungi. Still others feed on plants, protozoa, or even other nematodes. Omnivorous nematodes also exist that can change food sources as needed. The mouth structures of nematodes are used to identify feeding preferences. The ratio of fungal-feeding to bacterial-feeding nematodes can be one indicator of prior cultivation, with bacterial-feeding nematodes often predominating in previously cultivated soils.

Soil nematodes are important for forage productivity and quality, as they help make nitrogen available for plants to use by eating bacteria, fungi, and protozoa. In doing so, they convert previously bound-up nitrogen into a plant-available form (a process called nitrogen mineralization) while also stimulating growth of these microbial populations. Evidence suggests that nematodes are responsible for up to 40% of nitrogen mineralization in some soils.

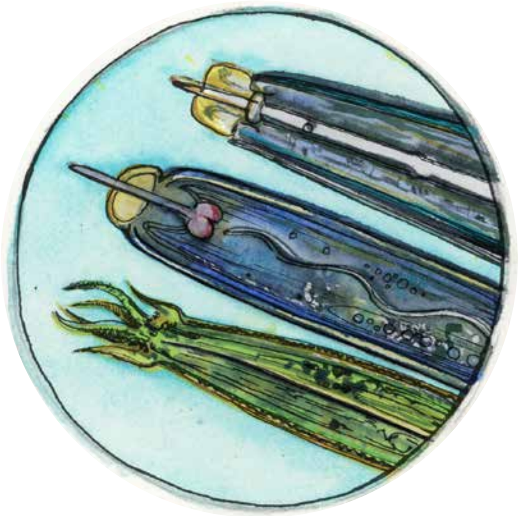
Nematodes serve other important roles as well. For example, bacteria can "hitchhike" on or inside nematodes, moving farther distances in the soil than they would otherwise be able to. Some nematodes can also be parasitic and infect pasture plants, both above- and belowground.

As with most other soil organisms, we still have much to learn about nematodes across California's diverse rangelands. However, these animals are likely abundant and very important. Indeed, in just one liter of soil, grasslands in the Sacramento Valley contain between 1,000–4,000 nematode individuals. There is some evidence that non-native plants like Barb goatgrass (*Aegilops triuncialis*) and Medusahead (*Elymus caput-medusae*) decrease these numbers. On the Central Coast, the nematode *Heterohabditis marelatus* suppresses lupine ghost moths, which feed on lupine roots. In doing so, *H. marelatus* decreases damage caused by these moths and increases growth and survival of lupine. Another nematode on the Central Coast, the aboveground gall-forming nematode *Cynipanguina danthoniae,* directly infects California oatgrass (*Danthonia californica*)—although it is unclear whether this infection has any negative impacts on plant health.

Did you know? Two nematode species in your soil can be as genetically different as a mouse and a tiger.

Illustration of *Cynipanguinea danthoniae*, a nematode species that forms galls on California oatgrass (*Danthonia californica*).

The left side of the illustration shows the galls on the leaf blade, and the right side shows a microscopic view of some of the nematodes living inside them. These galls provide the nematodes with food and shelter for up to two years. While they look a lot like "plant tumors," only in rare cases do galls result in the death of their plant host. Can you see any anatomical differences between individual nematodes on the right?



Examples of mouth parts for three different nematode feeding groups.

The top-most nematode is omnivorous, meaning it can eat algae, protists, other nematodes and even fungi and bacteria. The middle one feeds on plants, using its spear to pierce the root, and the bottom nematode feeds on bacteria.

Protozoa

Like nematodes, soil protozoa enhance soil fertility by releasing nitrogen into the soil as they eat their prey.

There are approximately 1,600 known species of protozoa who make soil their home. It is estimated that up to 80% of species remain to be documented. Protozoa are extremely diverse, but can be categorized into three general groups based on body type and method of movement: flagellates, amoeba (testate or naked), and ciliates. Flagellates propel forward by a whip-like organ, whereas amoeba ooze around by extending parts of their bodies called pseudopods. Testate amoeba have a protective shell, while naked amoeba do not. Ciliates are covered with many tiny hair-like structures that help them wiggle about.

Protozoa live in water films surrounding soil particles and have primarily been thought to eat bacteria. However, we now know that they also feed on fungi, algae, nematodes, and even other protozoa. In doing so, protozoa play an important role in the nitrogen cycle, converting previously bound-up nitrogen into a plant-available form, just like nematodes! Some protozoa are also important pathogens on our rangelands. One obvious example is *Cryptosporidium parvum,* a livestock pathogen that can be transferred to waterways through fecal deposits and cause human health concerns.

The amount and kinds of protozoa inhabiting rangeland soils varies widely across the state. Previously cultivated, restored grasslands of the Central Valley harbor approximately 400,000 protozoa in a tablespoon of soil, with the community being dominated by flagellates. In contrast, rangelands on the Central Coast average 5 million protozoa in a tablespoon of soil, with a dominance of amoeba. Fungal-dominated soils tend to have more testate amoeba, while bacterial-dominated soils tend to have more flagellates. Naked amoeba thrive in many different conditions, from agricultural to forested soils.

Did you know? Protozoa live in water films lining soil particles and can withstand dry periods by forming resistant structures called cysts. When favorable conditions return, the protozoa emerge from these cysts and continue their business as usual.

Illustration of the four groups of protozoa.

The topmost protozoa is a ciliate; the middle is a flagellate; the bottom left is a testate amoeba, and bottom right is a naked amoeba.

Fungi

Fungi influence forage productivity, plant community composition, and carbon sequestration by decomposing plant material, consuming root exudates, providing growth-limiting nutrients to plants, and enhancing soil structure and water retention.

There are approximately 97,000 known species of fungi, with millions more unidentified. In fact, only 6.5% of fungi are estimated to have been described to date! Some have aboveground fruiting bodies, i.e. mushrooms, while others reside entirely belowground. One of the primary roles of fungi on rangelands is to decompose dead organic material, recycle nutrients, and transfer carbon into stabilized forms in the soil. Some fungi also cause diseases (e.g., Valley Fever), while many, such as mycorrhizal fungi, form intimate relationships with plants that benefit both parties involved (a mutualism). Mutualisms are an important part of the plant-soil system, so keep an eye out for other examples highlighted in this guide!

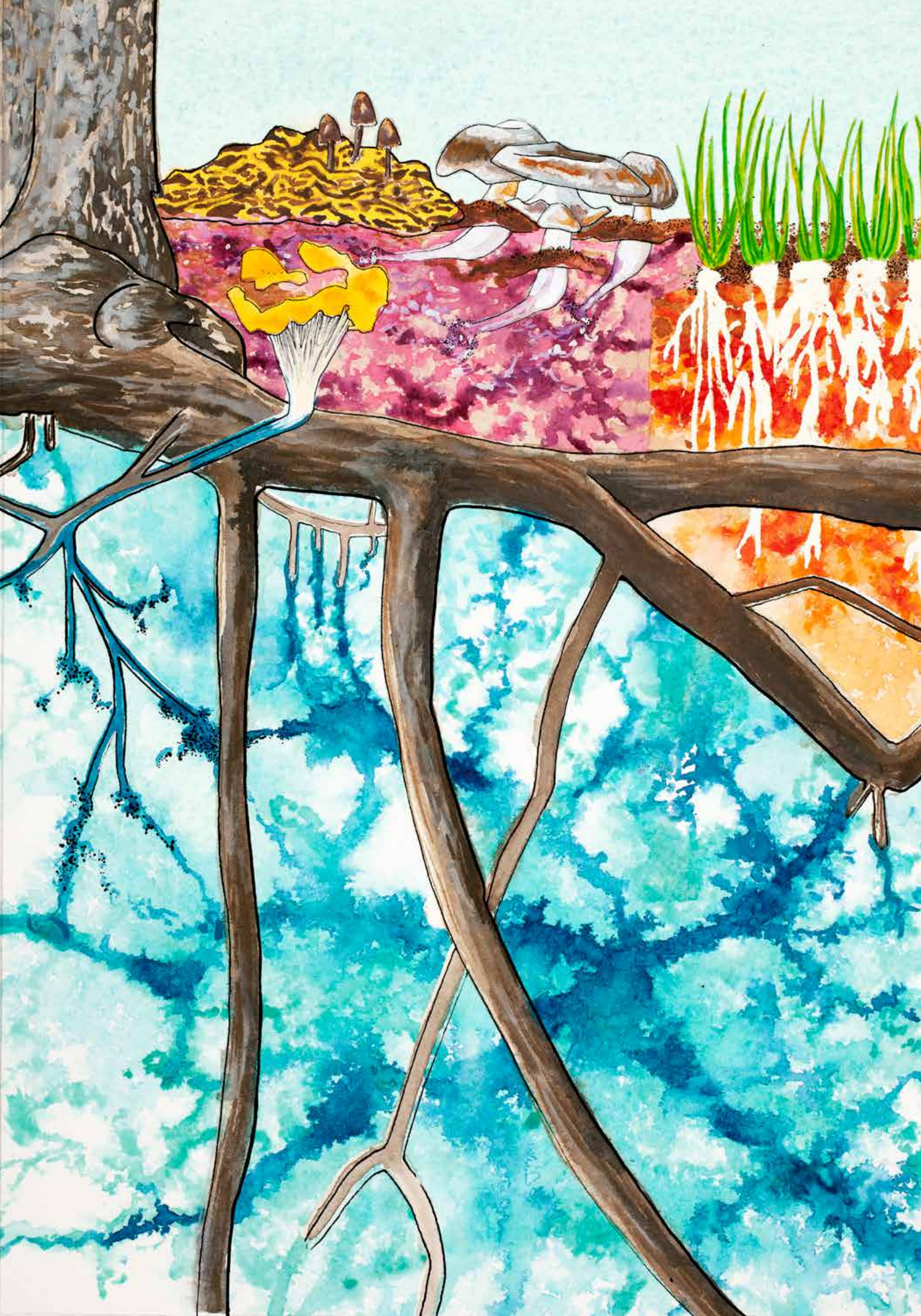
Mycorrhizal fungi link with the roots of most plants, providing the plants with phosphorus, nitrogen, and water in exchange for carbon. These fungi also help to protect plants against soil-borne parasites and pathogens. The two kinds of mycorrhizal fungi that occur on California's rangelands are *arbuscular mycorrhizal* fungi (AMF), which mostly associate with herbaceous plants (but also with coyote brush [*Baccharis pilularis*]), and *ectomycorrhizal* fungi (ECM), which associate with many kinds of trees such as oaks and douglas fir. AMF live exclusively belowground, meaning they do not form mushrooms. In contrast, ECM fungi do form mushrooms that you can find beneath a host tree at the right time of year. One example is the distinctive ECM fungi, Oak-loving Elfin Saddle (*Helvella dryophila*), which you can find beneath oak trees in the winter or spring.

There are also many fungi who, instead of forming mutualisms with plant roots, make their living as saprotrophs. These fungi break down dead organic material and eat simple sugars and other compounds exuded by plant roots. In your pastures, keep an eye out for mushrooms on wood, in plant litter, and emerging from dung—these will be your "free-living" saprotrophs.

Whether plant mutualists or "free-living" saprotrophs, all fungi are important for forming soil organic matter and sequestering carbon from the atmosphere. For example, mycorrhizal fungi help plants to capture more carbon dioxide (CO_2) by providing increased access to water and limiting nutrients. There is also some evidence that during decomposition of plant litter and consumption of root exudates, saprotrophic fungi "eat" the carbon more efficiently than bacteria. This means they retain more of the carbon they consume and minimize the amount that is released as carbon dioxide back to the atmosphere. In addition, fungi enhance soil aggregation by producing glue-like substances such as glomalin, which helps infiltrate water and protect carbon that enters the soil.

Illustration of four different kinds of fungi.

Saprotrophic fungi can live in dung (yellow) or plant litter and the soil (pink). Arbuscular mycorrhizal fungi (red-orange) associate primarily with grass roots. Ectomycorrhizal fungi (blue) associate with tree roots such as this blue oak. All of these fungal groups, except arbuscular mycorrhizal fungi, form mushrooms that can be seen aboveground.



Fungal biomass differs greatly across land-use types, with forests being dominated by fungi, agricultural systems having very few fungi, and grasslands falling somewhere in between. Promoting fungal biomass in rangeland soils has been proposed as a means to build soil organic matter and sequester carbon. A popular proxy for fungal dominance is the ratio of fungal biomass to bacterial biomass, with a higher number indicating more fungi. While there is unfortunately no magic fungi:bacteria ratio for managers to shoot for, measuring this ratio over time can help you determine if you're moving in the desired direction. And, looking at the range of values observed in California rangelands can help provide an idea of what's possible. Reported ratios across the state vary by site and season, ranging from 0.01 to 5.5 with an average of 1.8. However, it's important to note that fungi:bacteria ratios and subsequent ecological interpretation will depend on the methodology used, and likely more important than the ratio itself is the total biomass of both fungi and bacteria in your soil.

Did you know? The encroachment of non-native plant species can change AMF communities to the detriment of native plants like purple needlegrass (*Stipa pulchra*).

Did you know? Spores from dung fungi are ingested by livestock and deposited with the cow pies themselves.

Illustration of some mushrooms found on California's rangelands.

Note that many of these mushrooms are toxic, and one is deadly poisonous.

Ectomycorrhizal mushrooms, outlined in blue, from left to right: California Golden Chanterelle (*Cantharellus californicus*), Oak-loving Elfin Saddle (*Helvella dryophila*), Death Cap (*Amanita phalloides*, deadly poisonous), California Satan's Bolete (*Rubroboletus eastwoodiae*), Barometer Earthstar (*Astraeus hygrometricus*), and Russula "Ocher Oaks" (*Russula* species).

Saprotrophic mushrooms found on wood, outlined in pink, from top left to bottom right of the log: Western Artist's Conk (*Ganoderma brownii*), Turkey Tails (*Trametes versicolor*), Oyster Mushrooms (*Pleurotus ostreatus*), and Giant Oak Polypore (*Pseudoinonotus dryadeus*).

Saprotrophic mushrooms found in litter, also outlined in pink, from left to right: Elephant-skin Puffball (*Calvatia pachyderma*), Oak Leaf Pinwheel (*Gymnopus quercophilus*), Crocodile Agaricus (*Agaricus crocodilinus*), and Sunny Side Up (*Bolbitius titubans*).

Saprotrophic mushrooms found on dung, outlined in yellow, from bottom left to top right of the manure: Dung-loving bird's nest (*Cyathus stercoreus*), Orange Dung Disc (*Cheilymenia granulata*), Dung-loving Inky Cap (*Coprinopsis stercorea*), Dung-loving Deconica (*Deconica coprophila*), and Bell-capped Paneolus (*Paneolus papilionaceus*).

Bacteria

Bacteria decompose plant material, play a central role in the nitrogen cycle, consume root exudates, and form mutualisms with plants. In this way, like fungi, bacteria influence forage productivity, plant community composition, and carbon sequestration.

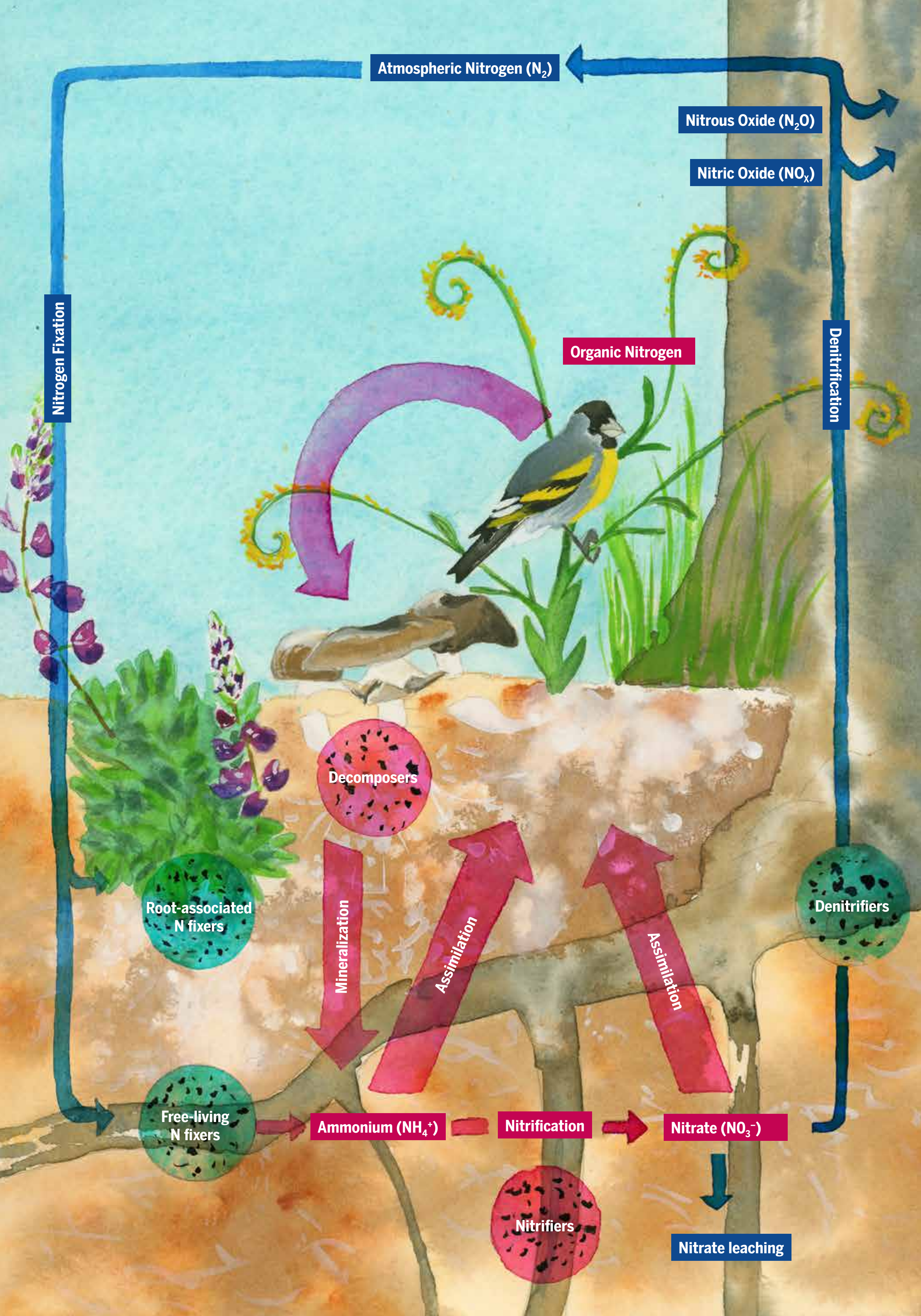
There are approximately 15,000 described species of bacteria, which is estimated to be only 1.5% of bacterial species that exist. In California's rangelands, there can be more than 1,500 unique kinds of bacteria in less than ½ a teaspoon of soil! Like fungi, many of these bacteria decompose organic matter, recycle nutrients, and form mutualisms with plants. In addition, some bacteria have the unique ability to fix nitrogen from the atmosphere, making this nutrient available for plants to use. These nitrogen-fixing bacteria, along with some archaea, are the only organisms on the planet that can do this naturally! In fact, bacteria play a central role in the entire nitrogen cycle, which is very important for California rangelands because plant growth in these systems is often limited by this nutrient.

In addition to cycling nitrogen, bacteria perform a number of other key functions in our rangelands. For example, by eating plant root exudates bacteria, like fungi, help to build soil organic matter and sequester carbon from the atmosphere. In addition, some bacteria consume methane, a critical greenhouse gas—and it's likely that bacteria from groups such as *Pseudomonas* produce hormones that can stimulate the growth of pasture plants, as has been shown elsewhere. While most bacteria in the environment are not harmful, some key microbial pathogens that enter

Simplified diagram of the nitrogen cycle.

Plants need nitrogen to survive, but nitrogen is generally not supplied when rocks turn to soil, and plants cannot use the form that makes up 78% of the atmosphere (N_2). Plants therefore rely on bacteria to pull N_2 out of the atmosphere and transform it into a form they can use (ammonium; NH_4^+). This process is called nitrogen fixation. Once that step is complete, the "fixed" nitrogen effectively becomes part of the rangeland ecosystem, where it can experience many fates. Much of the nitrogen that is brought into the rangeland system through "fixation" will continue to cycle through the bodies of plants and animals, back into the soil when these organisms die and decompose (mineralization), only to be taken up once again by plants (this internal cycling is shown with large pink arrows). For example, ammonium can be incorporated into plant and microbial biomass, or converted to another plant available form (nitrate; NO_3^-) by a small group of bacteria known as nitrifiers. However, some of the "fixed" nitrogen is lost from the boundaries of the rangeland system over time, either back to the atmosphere via microbial denitrification or by leaching into the soil profile and into adjacent waterways (inputs and outputs of nitrogen from the plant-soil system are shown with blue arrows).

In California rangelands, nitrogen mineralization and nitrification generally peak twice a year: once in the fall just after wet-up, and once again in the spring as temperatures begin to rise. In the fall, this corresponds to litter and thatch being incorporated into the soil; in the spring, it is mirrored by plants "taking off," or reaching peak biomass.



Atmospheric Nitrogen (N_2)
Nitrous Oxide (N_2O)
Nitric Oxide (NO_x)
Nitrogen Fixation
Denitrification
Organic Nitrogen
Decomposers
Root-associated N fixers
Mineralization
Assimilation
Assimilation
Denitrifiers
Free-living N fixers
Ammonium (NH_4^+)
Nitrification
Nitrate (NO_3^-)
Nitrifiers
Nitrate leaching

waterways through livestock waste are bacteria, including certain strains of *E. coli* and *Salmonella*. To minimize the transfer of these microbial contaminants, think about moving supplement and watering sites away from streams, and perhaps even consider whether your riparian areas could be restored (e.g., through plantings or managed grazing)! Wooded riparian areas can act as great filters for microbial pathogens.

Did you know? A group of soil bacteria known as Actinobacteria are responsible for the earthy smell that lingers after a rain event. Some members of this group release the molecule Geosmin when they die, which creates the distinct scent most of us know and love.

Did you know? In addition to legumes, woody plants like mountain mahogany (*Cercocarpus* species), California lilac (*Ceanothus* species), and pacific wax myrtle (*Myrica californica*) also form associations with nitrogen-fixing bacteria.

Illustration of legume nodules where biological nitrogen fixation occurs.

Nitrogen-fixing bacteria can be free-living, but bacteria fix the most nitrogen when they form special associations with certain kinds of plants such as legumes (e.g. clovers, vetches, trefoil, lupines, and others). These specialized bacteria bring nitrogen into the rangeland system, giving nitrogen to the plant in exchange for carbon and a protected environment inside the plant root. In California rangelands, nitrogen fixation rates range from 0.5–11 lbs/ac/yr in grass-dominated sites, and 45–178 lbs/ac/yr in legume-dominated sites. To give some context to these numbers, plants require 60–106 lbs/ac/yr of nitrogen in an average California grassland.

Other Notable Organisms

Archaea: Archaea do not play a large role in most rangeland soils. Still, they constitute an important group of micro-organisms, and are worthy of note. Archaea resemble bacteria in many ways, but unlike bacteria are often found in extreme environments like hot springs. In rangeland systems, they are responsible for producing methane in the rumen of livestock and also from any wetlands or slurry lagoons that may be present on the landscape. They also take part in the nitrogen cycle, although their contribution to nitrogen cycling appears to be minimal under conditions typical of California rangelands.

Biocrusts: Biocrusts are communities of cyanobacteria, algae, mosses, lichens, liverworts, fungi, and bacteria that form blankets on arid and semi-arid range-lands across California. These communities protect the soil from erosion and pump carbon into the system through photosynthesis. They play a critical role in places like the Mojave desert, but can also be found throughout other semi-arid regions of California, from the Central Valley to the Central Coast. They are sensitive to animal impacts, so should be managed with care.

Arthropods: Arthropods are invertebrates with hard shells and jointed limbs, including beetles, spiders, centipedes, and ants. They constitute an important part of the soil food web and help to decompose plant litter, recycle nutrients, and form aggregates. One iconic arthropod on rangelands is the dung beetle. Dung beetles burrow into cow pies, helping to accelerate decomposition and recycle nutrients from these waste piles. This process has an added side benefit of helping to minimize livestock intestinal parasites.

Phytophthora: Contrary to popular belief, *Phytophthora* are not fungi—they are oomycetes (water molds). These pathogens are responsible for damaging plants throughout California, and perhaps most conspicuously are responsible for Sudden Oak Death (SOD). Recently, soil and water-borne *Phytophthora* species have been recovered from restoration sites in northern California. This is a concern since *Phytophthora* can spread to new plant hosts quickly upon introduction. While new techniques are rapidly being developed to detect the presence of *Phytophthora* in soil, for now it is probably a good idea to test for *Phytophthora* using a pear baiting method if you are planning to create a microbial inoculant from soil on your ranch. And if you suspect that trees on your ranch may be infected by SOD, seek assistance from your local cooperative extension office or other resource management agencies to prevent the spread of this disease to new plants.

Viruses: While not technically alive, viruses play a natural and important—but not well understood—role in soils. Viral abundance can range from undetectable levels in deserts to over 1 billion per gram of soil in wetlands. These

Illustration of two species of dung beetles and their brood chambers.

The Bull Headed Dung Beetle, *Onthophagus taurus*, is outlined in pink (female on the left, male on the right) and the European Dung Beetle, *Aphodius fimetarius*, is outlined in blue. Both species were introduced to California from other places and can still be found on our rangelands today. In particular, the Bull Headed Dung Beetle was imported from its homeland in Australia and introduced to California's rangelands by researchers at the University of California Cooperative Extension in the mid 1970s, with the goal of reducing pest fly populations and improving nutrient cycling. Each species uses dung differently. The European Dung Beetle is a "dweller," meaning it mostly lives on top of the manure pile and its young are raised inside it (see its brood chamber, outlined in blue). In contrast, the Bull Headed Dung Beetle is a "tunneler," meaning it builds chambers in the earth below the dung, where it lays its eggs in "brood balls," which are composed of manure (see its brood chamber, outlined in pink). Unusual in the insect world, this species invests a lot of time and energy into rearing its young. Because they use the manure differently, each species plays a different role in decomposition and nutrient cycling. You would not expect to find dung beetles in the manure of livestock that have been given dewormers such as ivermectin, since they pass through into the manure and remain toxic to many organisms including dung beetles.

viruses can infect all organisms in the soil, including plant roots, with largely unknown consequences for nutrient cycling and microbial growth. In aquatic systems, viruses are responsible for up to 10-50% of bacterial deaths; this phenomenon stimulates nitrogen cycling and the growth of bacteria in a similar way to predation by nematodes and protozoa. In California, Barley and Yellow dwarf viruses are transmitted aboveground by aphid insects and can erode the health of pasture plants, affecting native bunchgrasses more severely than annuals like soft brome (*Bromus hordeaceus*). In this way, the presence of these viruses may shift grassland community composition by influencing interactions between native and non-native grasses. Unfortunately, it is hard to detect whether most grasses are infected with the naked eye, although some may develop red, purple, or yellow coloring on their leaves.

Illustration of "shepherd's crook" on a tanoak twig infected by *Phytophthora ramorum*.

While most members of its group are root pathogens, *Phytophthora ramorum,* the organism that causes Sudden Oak Death (SOD), is a leaf pathogen. Some tanoaks infected with SOD show symptoms of a shepherd's crook, which is when new leaves wilt, turn pale, and die. Not pictured here, "bark bleeding," or dark sap oozing from cankers on the tree trunk, is another common symptom of SOD.

As the name suggests, SOD is a disease of oak trees. However, the *P. ramorum* organism that causes SOD can live in many different host plants, often without any visible damage. In California, one primary non-oak host is the California bay laurel (*Umbellularia californica*). *P. ramorum* incubates in these trees and then spreads to neighboring oaks through wind and water. Oaks that are particularly susceptible to SOD include tanoaks (*Notholithocarpus densiflorus*), coast live oaks (*Quercus agrifolia*), interior live oaks (*Quercus wislizeni*), and black oaks (*Quercus kelloggii*). Interestingly, other oak species such as blue oaks (*Quercus douglasii*) and valley oaks (*Quercus lobata*) do not appear to be affected.

Observing Life Belowground

Interested in knowing more about these organisms on your ranch? Below are some ways that you can observe and track them in the field and using service laboratories.

Earthworms: To look for earthworms, simply grab a shovel and explore your soil with your hands and eyes. Or, mix 4 liters of water with 40 grams of ground oriental mustard seed powder in an empty milk jug. Pour on your soil and wait. The earthworms will emerge from the soil, and the amount of time it takes them to surface depends on how deep they were to start. Non-native earthworms like nightcrawler (*Lumbricus terrestris*) burrow up to 8 feet deep and can take 5-10 minutes to emerge.

Nematodes: You can keep an eye out for leaf galls on your California oatgrass (*Danthonia californica*) by looking for light green to yellow spheres speckling the blades of this grass. In addition, these commercially-available tests can tell you more about the nematodes in your soil:

- Direct microscopy—the occurrence of nematodes to the genus level
- PCR-RFLP—genetic identification of plant parasitic nematodes

Protozoa: While you can't see them with your naked eye, these commercially-available tests can tell you more:

- Direct microscopy—the occurrence of protozoa, enumerated as ciliates, flagellates, and amoeba
- Phospholipid fatty acid analysis—biomass of total protozoa

Fungi: Take a walk during the rainy season to hunt for mushrooms! You'll be surprised what you can find. One note of caution though: never eat a wild mushroom unless it has been positively identified by an expert. Many poisonous species occur in California, including several deadly ones. In addition to mushroom hunting, these commercially-available tests can tell you more about fungi in your soil:

- Direct microscopy—the amount of total and active fungi
- Phospholipid fatty acid analysis—the amount of total fungi, saprotrophs, arbuscular mycorrhizal fungi, plus the fungi to bacteria ratio
- Root health bio-assay—a measure of fungal disease pressure
- Mycorrhizal spore count and inoculum potential—an estimate of arbuscular mycorrhizal fungi potential
- Mycorrhizal percent colonization—percent of roots colonized by arbuscular mycorrhizal fungi
- Soil respiration—a measure of the activity of soil microorganisms participating in organic matter decomposition

Bacteria: Find some nitrogen-fixing plants, dig up their roots, and look for nodules. If they're pink, it's an indication that nitrogen fixation is occurring. In addition, these commercially-available tests can tell you more about bacteria in your soil:

- Direct microscopy—the amount of total and active bacteria
- Phospholipid Fatty Acid Analysis—biomass of total bacteria, free-living nitrogen-fixing bacteria, and a fungal-like bacteria called Actinobacteria
- Soil respiration—a measure of the activity of soil microorganisms participating in organic matter decomposition

Arthropods: Keep an eye out for dung beetle activity in cow pies across your landscape. Or, construct a pitfall trap or Berlese funnel to catch and identify various arthropod species.

Stewarding Life Belowground

Now that we know more about the organisms below our feet and what influences their abundance and activity, we can begin to understand how to steward them. For example, the soil food web is driven by plant inputs, including roots and root exudates. Maintaining or increasing the amount and diversity of organic matter inputs entering the soil will help to ensure food supply is abundant and that the needs of a variety of soil organisms are met. In addition, most soil organisms do best in well-structured soils with a mixture of air and water.

It follows then, that leaving adequate amounts of plant material behind after you graze, minimizing soil compaction or disturbances such as tillage, and potentially increasing the diversity of functional groups within your plant community may be some actions to consider. Other actions may center around maintaining or improving the amount of living roots in your soil, both in space (horizontally, vertically) and time (extending the growing season where possible)—or reducing the amount of dewormers or other biocides used, which pose risks to soil organisms. To maximize belowground diversity at the ranch scale, you could also consider embracing and fostering the diversity of habitat types within your property boundary.

It's important to emphasize that the resource concerns you have on your property, along with broader goals of your operation, should guide if and how you decide to steward the organisms in your soil. There is still much to learn about the ecology of soil communities, including how different practices will affect them, and whether these practices create trade-offs for other ecosystem outcomes. Because of this, we recommend using a data-informed adaptive management framework where carefully chosen indicators of soil biology are tracked over time and management practices are first implemented on small scales and modified according to your goals. You can use the techniques above to track indicators, from in-field observations to laboratory measurements. It doesn't have to be fancy, just keeping a notebook to record your observations in the field is a great start. Along the way, we hope you have fun!

Did you know? At any given time, greater than 95% of microorganisms in soil are inactive—waiting to "turn on" when conditions become favorable.

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Additional Resources

Soil Biology Testing Laboratories (not an endorsement):

1. University of Florida Soil Microbial Ecology Laboratory. **2.** Cornell University Soil Health Laboratory. **3.** Earthfort Laboratory. **4.** Ward Laboratory. **5.** Trace Genomics. **6.** CDFA Plant Pest Diagnostic Center.

Websites and Other Resources:

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