COLORADO SOIL HEALTH FUNDAMENTALS

PRIMER 5: SOIL BIOLOGY & FUNGAL NETWORKS

PRIMER 5 SUMMARY

The goal of the Colorado Soil Health Primer series is to demonstrate the core principles related to soil health management as practiced and researched within the boundaries of the State of Colorado. Colorado scientists studying the effects of management practices and the state's farmers and ranchers implementing and measuring the changes on the land participated in this project.

This series is not about instructing the exact tactics a farmer or rancher would need to improve soil health. The individual tactics and strategies must change from property to property — or even field to field — depending on the goals of the land manager, and the available natural and financial resources. This series of information will give readers the resources to understand and evaluate practical and proven ideas to explore and adapt into a new or existing operation.

In this primer, readers will learn why it's important to understand soil biology and discover strategies to enhance the biology of the soil of their operation.

For a land manager in the state Saving Tomorrow's Agriculture Resources (STAR) program, biology is a big topic. Whether you are managing a small greenhouse, or establishing a system for thousands of acres, the need to understand the role of biology is significant. The term "biology" here is used to include the smallest of microbial life, responsible for replenishing a plant's nutrition, to larger biological life like earthworms and dung beetles.

Biology is responsible for helping break down organic matter and turning it into available nutrients for your crops. "Soil biology" describes a vast underground network of complex biodiversity. Scientists and producers now understand and embrace the concepts of biodiversity and biological complexity as foundational to seeing how soil biology is a cornerstone driver of agricultural systems that create healthy ecosystems. These concepts underlie strategies to enhance resilience to increasingly erratic weather events and historic drought, and ultimately, help sustain successful farming operations, because the more that a producer focuses on soil biology, the healthier and more productive the soil biology becomes. It is a virtuous cycle: long-term management plans that are designed to support healthy soil biology will create higher yields and healthier, more resilient soils that will effectively sustain profitable agricultural operations over the long run.

Here are a few common concepts to know:

Rhizosphere: The rhizosphere refers to the area both comprised of – and in close radius to - a plant's root system. The root structure of a single sideoats grama (Bouteloua curtipendula) plant might measure 12- to 18-inches wide and 2- to 4-feet deep. The rhizosphere is the stage for soil-food-web activity, and plays host to the root exudates, microbial life, fungal associations, nutrient cycling, and soil aggregate building that occurs as a result of soil biology relationships. If you imagined an entire rangeland of native, perennial grasses spanning thousands of acres, and were able to peek underground at the vast network of root systems, fungal networks, microbiology, and insects, you would find it easy to understand how critical rhizosphere communities are to building healthy soil.

Soil Organisms: Keystone species,

COMMON TERMS

Cover Crops: The act of keeping the ground covered and maintaining living roots are two principles of soil management, and cover crops are a key tool to help farmers transition and measure the gains.

Pasture: Fields for grazing, wildlife passage or soil remediation are common across the state of Colorado.

Soil Biology: The life in the soil, from the smallest microbes to earthworms and dung beetles. The biology is responsible for helping break down organic matter and turning it into available nutrients for your crops.

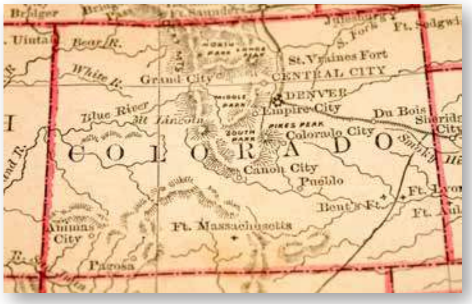
Soil Chemistry: The ratios of elements in the soil are important and go beyond N-P-K.

Soil Health: The concept of maximizing an ecosystem's ability to feed soil microorganisms, leading to efficient nutrient cycling and turnover, which creates more nutrient availability for plants, increases soil water storage, and improves ecosystem sustainability and resiliency.

Soil Testing: The process of quantifying certain attributes of soil, including macro- and micro-nutrients, soil organic matter, cation exchange capacity, soil biology, water and/ or air.

NRCS: The Natural Resources Conservation Service.

Source: Jim Ippolito & Megan Machmuller, Colorado State University



USDA-NRCS
Soil Management Principles

1. Limit disturbance
2. Keep soil covered
3. Strive for biodiversity
4. Maintain living roots
5. Integrate animals

in any habitat, are fundamental to ecosystem balance, and soil ecosystems are no exception. Microorganisms and macrofauna living in the soil are critical drivers of above ground plant health and can broadly be considered keystones to rhizosphere dynamics.

Bacteria: Bacteria are the most abundant and the smallest organisms found in soil. Bacteria play an important role in building soil health as decomposers, disease suppressors, and nutrient cyclers. Throughout this primer, as we explore the role of soil organic matter (SOM), soil/water dynamics, and soil structure, we will revisit the importance of bacteria and their relationship to building soil health. Particular species of importance include:

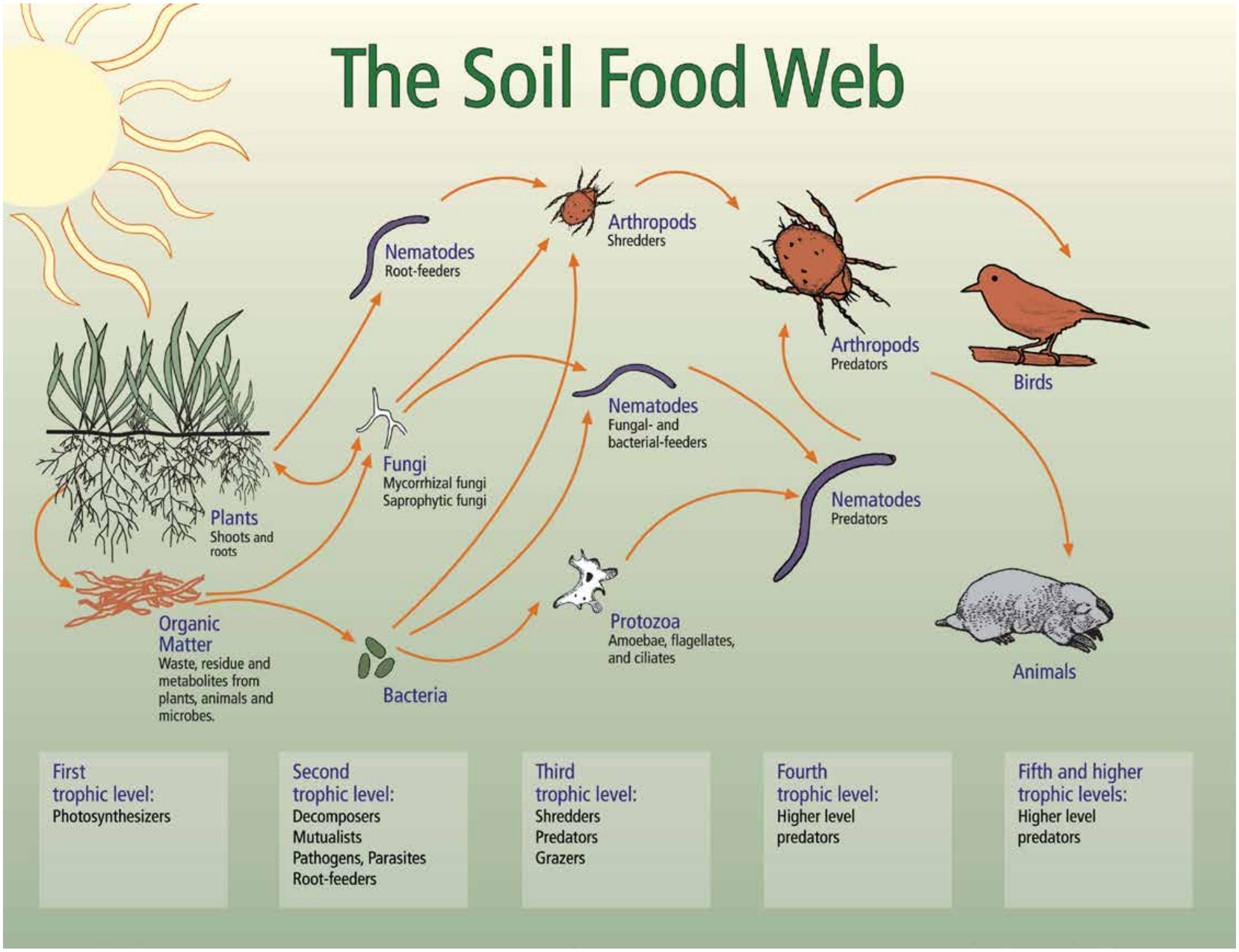
Actinomycetes: These are an abundant species of bacteria in the soil, designated as plant-growth promoting microbes due to a highly filamentous structure allowing for strong bonds with both plants and soil particles.

Rhizobium: This is a specialized nitrogen-fixing bacteria which forms symbiotic relationships with legume family crops, such as alfalfa, hairy vetch, and clover. Rhizobia infect the roots of host plants and convert atmospheric nitrogen into plant-available nitrogen.

Protists: Protozoa are world-class micro grazers and in turn, powerhouse nutrient cyclers. Like flocks of hungry sheep, protozoa consume soil bacterial biomass and as a result, produce plant-available nutrients - such as nitrogen - in the rhizosphere to support plant growth.

Fungi: Fungi orchestrate soil health. Fungi are keystone decomposers and thus, leading contributors to nutrient cycling. Using root-like strands of branching filaments called hyphae, fungi create essential symbiotic relationships with plant roots: the hyphae and the plant roots work together to mobilize the availability of plant nutrients.

▼ Soil biology plays a critical role in plant health and an ecosystem's water-holding capacity. *Source: Colorado Department of Agriculture and Adrienne Barclay*

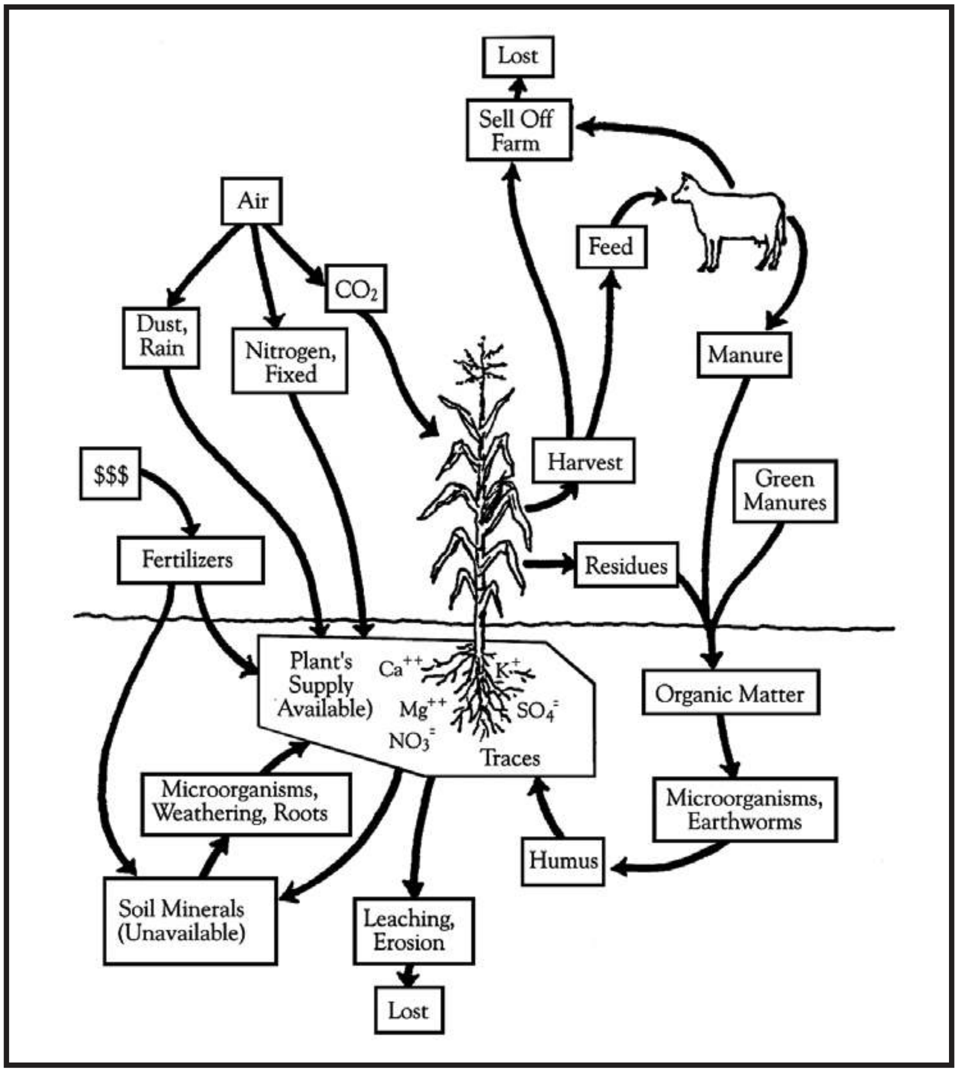


▲ Relationships between soil food web, plants, organic matter, and birds and mammals. *Source: USDA*

The North American prairie biome, the second most biologically diverse ecosystem on Earth (behind the Brazilian rainforest), owes a large portion of that diversity to soil biology. And generally speaking, the development of this landscape spanned about 5 million years. This long-game, so to speak, of natural activity, is something that farmers know, in their bones. Colorado farmer Lowell King can speak to this knowledge. Lowell grew up on a dairy farm and presently runs his own cash crop operation in Loma, Colorado, which covers 900 acres in hay, wheat, and corn production, along with cattle.

King speaks of his appreciation for soil biology and changes in soil ecology: "A question I like to ask myself when I consider management decisions is, 'Is this going to create more life than it destroys?'" he says. "And so, we have a large focus on having living roots all the time. Our hay fields are a perennial system, so there's living roots. When we aren't in hay production, there's a cover-crop going. As soon as we harvest corn, we plant a crop of wheat or rye in the fall. When wheat is harvested in July, we plant a diverse cover-crop in July, and we try to have livestock grazing at each part of the farm at least once a year to stimulate biology in the soil and to cycle nutrients back into the soil."

Mary Ellen Cannon, a Resource Soil Scientist with the USDA Natural Resources Conservation, based out of Greeley, Colorado, has more than 30 years of soil science experience, and she reminds soil health advocates that Colorado soils are wide-ranging in diversity, and there isn't only one correct way to approach soil health building. Cannon sees the five basic principles of soil health encouraged by the state Saving Tomorrow's Agriculture



◀ This shows the cycle of nutrients and biology in a plant's ecosystem. *Source: Acres U.S.A./Biological Farmer*

Resources (STAR) program (living roots, soil cover, biodiversity, minimized disturbance, and livestock conservation) as supporting soil biology across our diverse soils.

"Colorado soil is very diverse—we have so many precipitation zones and altitude zones, geology and climate zones—and all of that contributes to diverse soil origins. We have gypsum here and granite there…different parent materials will host different microbial communities that align with different plant communities. That is what is unique about Colorado soil."

There is a common thread that connects Colorado soil ecoregions; and this is the fact that all soil is alive. It does not matter the parent material, management approach, or microclimate. Soil is a natural resource and a habitat teeming with life. The vigor and fertility of unique soil sites will vary based on stewardship and management approaches, but taking a closer look at soil biology helps us to better understand how agricultural systems can foster optimal soil ecology, which in turn, supports crops—by increasing favorable physical and chemical conditions.

King credits healthy soil biology with increases in crop health, drought resilience, and increased available nutrients. "For 20 years, I farmed just like the generations before me. Then, I made the switch when I noticed less irrigation needs after a season of paying attention to the root zones of my crops."

As a farmer explores soil biology in agricultural systems and learns about living relationships (soil biology), soil structure (soil physics) and nutrient cycling (soil chemistry), they will also discover the soil-food-web and basic concepts associated with energy cycling.

Roy Pfaltzgraff manages the day-to-day operations for Pfaltzgraff Farms, a 2,000-acre dryland operation, and farms alongside his wife and parents. Pfaltzgraff Farms is located in the northeast corner of Colorado. This area averages 16 inches of precipitation a year. Roy has seen some seasons with as low as three-quarters of an inch of rain. When asked how he turned around production and yields on his family farm over the last several years, Roy points to building soil biology as a crucial piece of the puzzle, "The most important thing for soil health is to have a living root, in the soil, continuously, year after year." And with living roots, come living soil organisms.

Fungal Networks, Soil Building, and Soil/Water Interface

Arbuscular mycorrhizal fungi (AMF) play an integral role in fostering plant health by orchestrating chemical exchanges, resistance to abiotic and biotic stressors, physical structuring, and nutrient cycles in the soil. AMF belong to the phylum Glomeromycota, an ancient fungi, and create a mutualistic symbiotic relationship with up to 80 percent of terrestrial plants (though commonly cultivated food crops in the Brassicacea family are excluded).

When AMF enters the soil, it first colonizes the roots of compatible plant species with structures called arbuscules. Once established, AMF serves as a conduit between a plant and the substrate surrounding the rhizosphere. The host plant supplies AMF with up to 20 percent of plant-fixed carbon in exchange for water and nutrients, such as phosphorus, delivered to the plant via an ingenious network of branching structures known as hyphae.

Hyphae are the filamentous extensions, analogous to root hairs, of AMF. As AMF colonizes a plant root, hyphae rapidly reproduce and spread outward into the rhizosphere. As the body of hyphae expands, its role is to absorb nutrients and water from the soil and transport them back to its host plant. While this dance of exchanges is occurring between fungi and plant, something quite fascinating is also happening, which is the development and dispersal of a glycoprotein called glomalin. Glomalin is the glue that holds soil together. In the vast world of soil ecology, glomalin is the must-have, molecular tool for engineering tilth, stability, and resilience.

Ryan Ericson in Fort Collins owns and operates Well Fed Farmstead and raises 3.5 acres of mixed vegetables, fruits, herbs, and flowers. Ericson describes his soil building practices and appreciation for soil microorganisms:

"I try to rotate my fields through the broad families of annuals to help with pest and insect pressure, as well as to keep the nutrient content of the soil relatively balanced. I am also working on rotating a cover crop through every field at least once every two years (the goal being that each field could rest and recuperate a full season every other year)."

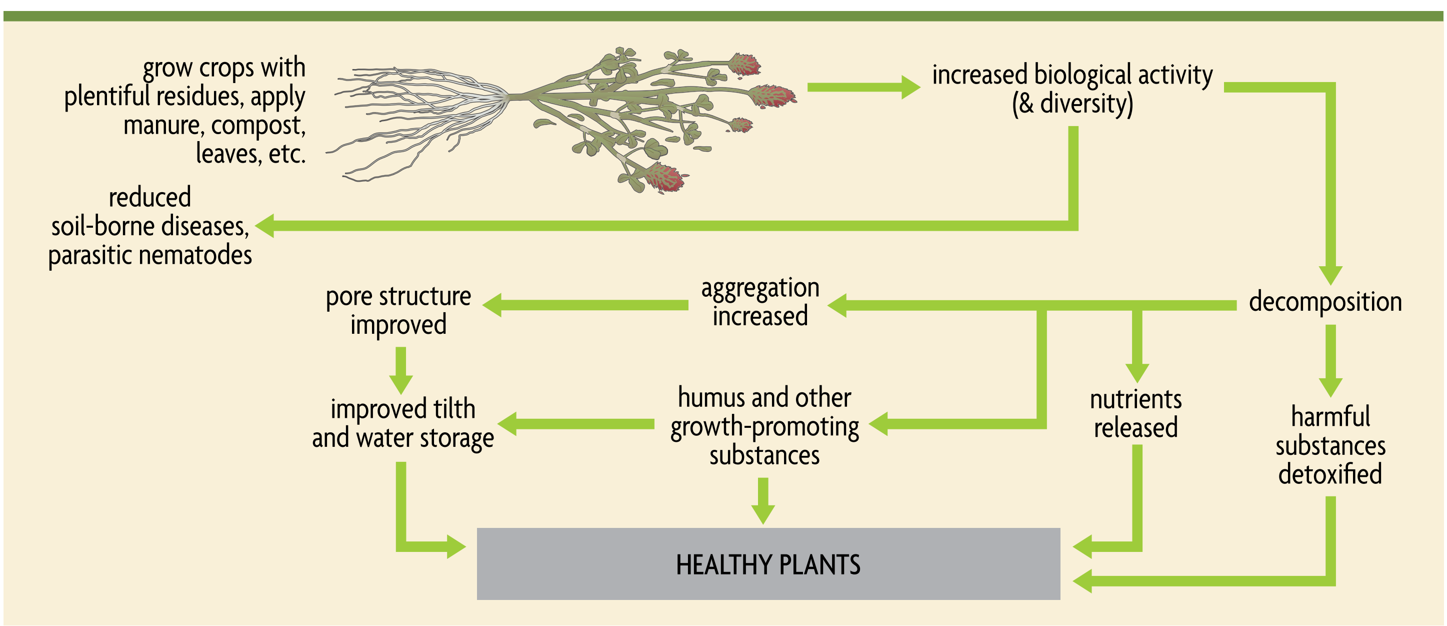
Ryan sees the results of his management strategies first-hand:, "I have seen the impacts of my practices…how tilling has changed the aggregate size and has caused compaction in certain areas, but also how the incorporation of so much organic matter (through compost and cover cropping) has revitalized it in ways I couldn't have imagined seeing in Fort Collins soil. I've seen long strands of mycorrhizae form around the roots of plants only 4 weeks old and earthworms in almost every scoop of soil."

Within every scoop of soil, we can expect to find the following composition: 45 percent mineral, 5 percent organic matter, 20 to 30 percent water, and 20 to 30 percent air. These figures are relative, of course, as landscapes do vary across the globe. But, if we assume the above numbers are an average estimation for Colorado soils, then let's examine how to form highly sought after, tilth-y, stable, water-affirming, nutrient dense, and microbially active soil in situ.

Consider a tract of annually cultivated agricultural land that has been under decent crop-rotation and managed with a concerted effort to maintain living roots and above-ground plant material. The rhizosphere beneath the surface exhibits a healthy population of bacterial and fungal activity, along with earthworms, nematodes, and other soil-borne fauna. These soil organisms are teeming around living roots that exude sugary-rich, carbonaceous excretions and as they surround the roots, the organisms efficiently cycle nutrients that were otherwise plant-unavailable: they literally make these macro and micronutrients accessible for plant use.

While these symbiotic organisms are cycling through these natural processes, AMF (Arbuscular mycorrhizal fungi) is spreading hyphae projections throughout the rhizosphere of both single individual plant specimens as well as throughout the entire subterranean living area. Imagine acres of hyphae—as webbing—that is weaving under the ground. And inside the hyphae cell walls, glomalin is being produced.

▼ Adding organic matter results in many changes. *Modified from Oshins and Drinkwater (1999).*



Glomalin is a soil-borne protein that contains carbon—referred to as a glycoprotein. It is resistant to decay and is not easily dissolved in water. As older hyphae cease to transport nutrients, glomalin sloughs off into the surrounding soil and begins to capture particulates in the soil, like fibers that are drawn to Velcro. Glomalin is a sticky, adhesive-like substance—and in gluing soil particulates together (sand, clay, organic matter)—glomalin is forming soil aggregates. And soil aggregation is the driver behind soils that will stand up to the epic drought and sparser, but still periodic, deluge conditions—that Colorado endures.

Lowell King describes how he sees soil aggregation, through soil organic matter, helping his farm stand-up to drought: "We are tracking about a quarter-percent increase in soil organic matter per year. If you've got a 1 percent increase in organic matter, that translates to ~27,000 gallons of water holding capacity increase. So, I'm increasing about 7,000 gallons of water holding capacity per acre while I'm increasing my farm profitability. We are also building free reservoirs on our farm. If you take the 900 acres that we farm and put 7,000 gallons of holding capacity per acre, it's a pretty substantial little reservoir that we build each year in our soil— without costing us a penny. And our farming becomes more and more profitable as we do it."

Soil aggregation, as described above, is a process, dependent upon microorganism health, that results in stable soil units that are bound together. Soils with living roots, whether through managed cover-crop cultivation or as natural, perennial rangeland, have been studied and shown to exhibit higher soil aggregate stability as a result of high glomalin levels. Soils with favorable levels of aggregate stability demonstrate resistance to erosion and extreme weather events, withstand nutrient leaching, promote microbial activity, and very critically—specific to moisture-deficits as experienced in Colorado—promote drought-resilient soils.

"I like to think that we could resolve the crisis on the Colorado River in the southwest if all the millions of acres that are irrigated (agriculture uses 80 percent of the water on the river) — if 100 percent of those acres would implement the six soil health principles and use 10 percent less water," King said. "Problem solved. I've seen it on my farm. I know it's not simple, but there it is. We have moisture sensors on my farm, and I've recorded water usage since 2017, and we have diverted somewhere around 10 to 20 percent more water than six years ago."

A different perspective:

SOM Category	Soil Benefit	Applications in Colorado Agriculture
Microorganisms and Macrofauna	**Consuming root exudates, cycling through the rhizosphere, tunneling in soil**	**Ryan Ericson of Wellsted Farm, utilizing cover crops to build an ideal environment for soil organisms**
Living roots and cover-crops	**Preventing soil erosion, feeding microorganisms, capturing water and sunlight**	**Roy Pfaltzgraff maintaining dutch white clover in otherwise fallow fields**
Green (decaying) residue	**Providing fodder for soil organisms, building habitat for soil organisms, capturing moisture, releasing nutrients**	**Steve Ela of Ela Family Farms green-chopping alfalfa tops in orchard alleys and allowing to decompose into the topsoil**
Perennial systems	**Building soil aggregates, preventing erosion, fostering fungal networks and drought resilience**	**Lowell King maintaining perennial hay fields; Ela maintaining orchard health**

▲ SOM supplies food for the soil organisms that are responsible for unlocking nutrients, building soil aggregates, and increasing water infiltration—all in order to grow healthy plants. *Source: Colorado Department of Agriculture and Ryan Kanode*

Soil Organic Matter (SOM) and Building Soil

Soil organic matter (SOM) refers to material originally sourced from living plants or animals that is undergoing decomposition or is completely decayed. Dr. Francesca Cotrufo is a world-renowned expert on soil organic matter and associate department head of soil and crop sciences at Colorado State University. Dr. Cotrufo's research demonstrates marked improvements in soil health indicators as a result of SOM increases in soil.

SOM supplies food for the soil organisms that are responsible for unlocking nutrients, building soil aggregates, and increasing water infiltration and also includes those soil organisms themselves. University of Minnesota researchers have stated that, "Soil biological processes are responsible for supplying approximately 75 percent of the plant-available nitrogen and 65 percent of the available phosphorus in the soil." The fuel for those biological processes is SOM.

Examples of Soil Organic Matter (SOM) in Colorado Agriculture:

- Living organisms cycling through life-cycles in a field's living rhizosphere (microorganisms, macrofauna)
- Freshly mown/chopped cover-crop residue beginning to decompose
- Earthworms tunneling through hospitable soil (cool temps) via the above green residue
- Leaving corn stubble after

harvest

- Drilling cover-crop seed after mid to late summer harvest to establish winter cover
- Establishing perennial cover-crop strips within managed fields
- Ensuring that all soil is covered with mulch, crop residue, or living cover-crops

Research around the country confirms what growers are seeing in Colorado. From a recent SARE (Sustainable Agriculture Research and Education) report: "A study of soils in Michigan demonstrated potential crop-yield increases of about 12 percent for every 1 percent increase in organic matter. In a Maryland experiment, researchers saw an increase of approximately 80 bushels of corn per acre when organic matter increased from 0.8 percent to 2 percent."

"It's all about soil biology," King said. "I just go back to that is what drives the system. Anything we can do to stimulate biology will make any of those nutrients that are tied up in the soil. What we are supposed to be doing as stewards is multiplying life. We have the potential to create and add life or to destroy and degrade. And so, as producers, we have the responsibility to steward life. Every part of my farm: I have one goal, to promote life. I want my cattle alive and reproducing. I want my soil biology alive and reproducing, I want my plants alive and reproducing. I want my family alive, happy, and promoting life. It's all part of the whole cycle of life."

As farmers tackle changing weather patterns, dwindling water supplies, and increased supply costs, a focus on the living soil biology becomes even more important to build soil security. There are well-researched and demonstrated benefits to establishing living cover on managed lands, including fostering soil microbial communities and enhancing water infiltration - all leading to an increase in drought resilience.

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Endnotes

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The STAR program was originally developed by Champaign County Soil and Water Conservation District (CCSWCD) in Illinois and is now also administered in four other states: Colorado, Indiana, Iowa, and Missouri. The Colorado STAR Plus program grew out of a stakeholder process launched by the Colorado Department of Agriculture and other partners in 2019 that was facilitated by the Colorado Collaborative for Healthy Soils, involved more than 250 stakeholders and resulted in passage of HB21-1181 and SB21-235, which authorized and funded the launch of a state soil health program based around STAR. This state stimulus funding and additional grant funding received from the Gates Family Foundation, Colorado Department of Public Health and the Environment, Colorado Water Conservation Board, NFWF, and NRCS have enabled the launch of the first round of the STAR Plus program.

Getting Involved with Colorado STAR

In the summer of 2021, legislation was passed in the Colorado House of Representatives funding the Agricultural Soil Health Program for 2022. The Colorado Soil Health Program is built around the framework of an Illinois program called STAR, which stands for Saving Tomorrow's Agriculture Resources. STAR was developed to be a free resource for farmers and ranchers, helping them evaluate their current land practices, and particularly focusing on nutrient and soil loss. The STAR program encourages best soil health practices, and rewards producers with recognition, a high rating, and a field sign. While the STAR rating system is a useful metric for farmers to measure their own conservation efforts, it is also a tool for consumers interested in a farmer's soil health practices.

The program was originally created in the Champaign County Soil & Water Conservation District in 2017, with the assistance of the Illinois Department of Agriculture, as a means to facilitate specific environmental and agricultural goals that were outlined in the state's Nutrient Loss Reduction Strategy. Colorado, as well as Iowa and Missouri, have adopted this program framework.

Best management practices for agricultural land use have been developed since the 1930s by the United States Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS). The STAR program utilizes these best practices, and also relies on a panel of experts, including university researchers and scientists, to establish appropriate ranking systems based on different resource factors. STAR Plus is an additional level of producer support that "facilitates capacity building by providing matching state funds towards the cost of these projects and activities within each district". This means that the state provides technical and financial assistance to producers over the course of three years, through grants and services like soil testing that are facilitated through the state's conservation districts.

Any farmer or rancher can visit the STAR website and fill out these forms in order to receive this rating. The first 100 participants in a year also receive a free soil test.

To participate, the only requirement is that the farmer or rancher fill out a form to the best of their knowledge, describing their farm practices in detail for a specific field chosen by the producer. The forms include questions about cropping practices, tillage regimes, fertilizer and nutrient applications, and other management practice information. The producer then receives a STAR rating from 1-5 that demonstrates their incorporation of the five principles of STAR: Soil Armor, Minimize Soil Disturbance, Plant Diversity, Continual Live Plant/Root, and Livestock Integration in their cropping system. Earning five stars in a field means that a farmer or rancher is implementing all five soil health principles on that field, while earning one star means that they are following only one.

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SAVING TOMORROW'S S.T.A.R. AGRICULTURE RESOURCES