Introduction to Soil Biology

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the in-house research arm of the U.S. Department of Agriculture

Living Soils

- Soil is organic (i.e. living) and filled with millions of different organisms.
- A handful of soil contains more organisms than the total number of people that have ever lived on earth.

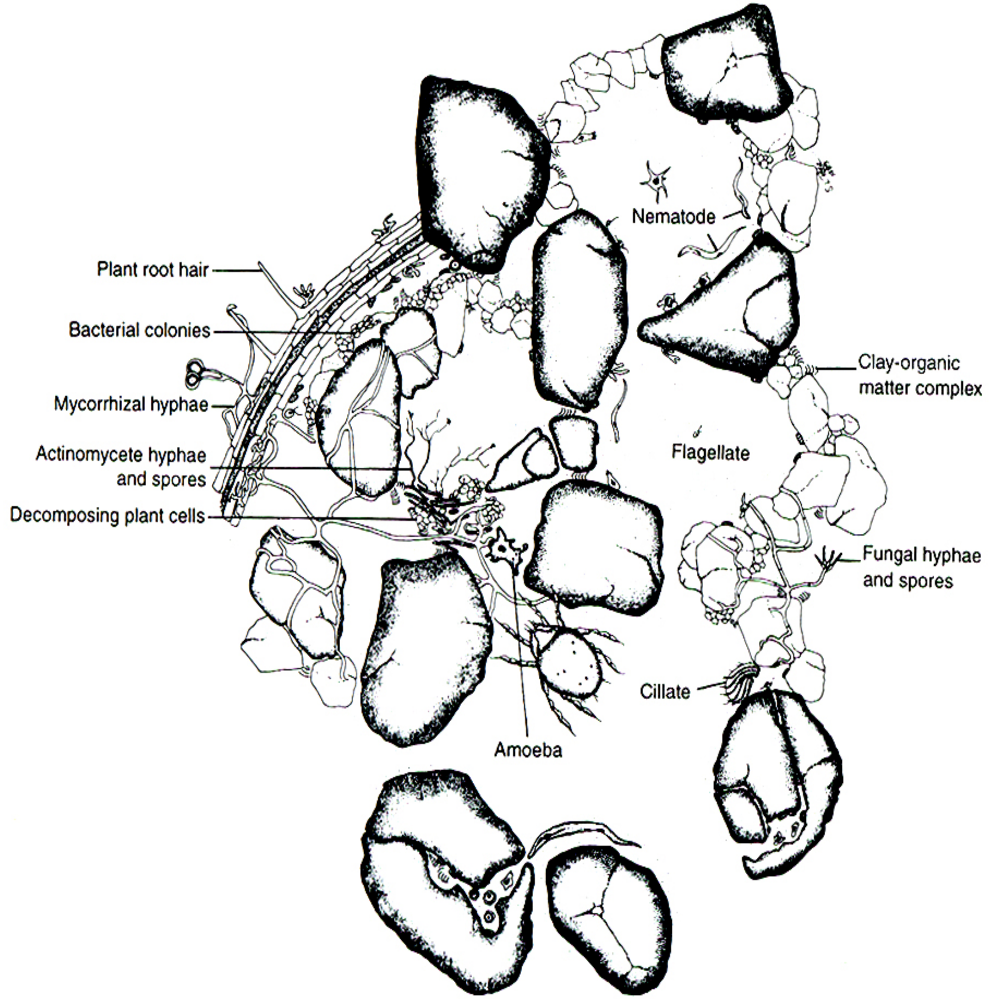


FIGURE 5.2 Diagrammatic representation of a plant root and associated biota approximately 1 cm^2 of a surface grassland horizon associated with a plant root. (Adapted from S. Rose and T. Elliott, personal communication.)

Why Do You Care About Soil Biology?

"A cloak of loose, soft material, held to the earth's hard surface by gravity, is all that lies between life and lifelessness."

- Wallace H. Fuller, in <u>Soils of the Desert Southwest, 1975</u>

"Essentially, all life depends upon the soil .... There can be no life without soil and no soil without life; they have evolved together."

- Charles E. Kellogg, <u>USDA Yearbook of Agriculture, 1938</u>

"Land, then, is not merely soil; it is a fountain of energy flowing through a circuit of soils, plants, and animals."
- Aldo Leopold, <u>A Sand County Almanac, 1949</u>

Why Do You Care About Soil Biology?

You Need to Make More MONEY!!!

HOW?????

- **Get more money for your product**
  - This cannot be controlled unless you grow specialty or organic crops or sell directly to the public.
- **Reduce costs to make product**
  - Work with soil biota to provide nutrients and reduce pest problems.
- **Increase productivity**
  - Work with soil biota for improved nutrient cycling and water usage, and increases above- and belowground diversity.

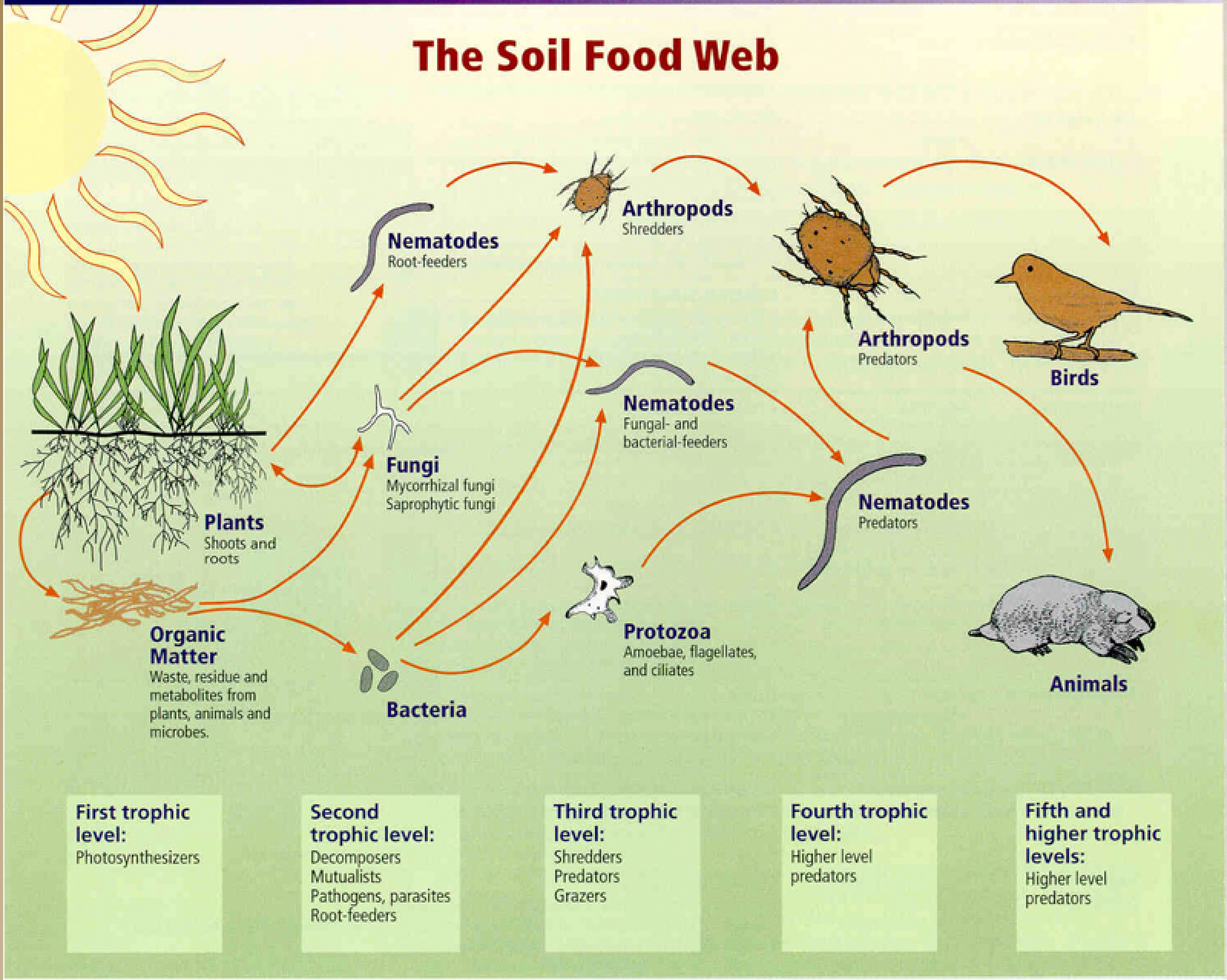
Soil Food Web Structure

- **Definition**
  - The interactions of producers, consumers, and decomposers in the soil – each organism is both predator and prey at the same time.

- **Why is it important?**
  - Sustains life in the soil
  - Essential for nutrient cycling by helping to decompose crop residue and build organic matter
  - Assists in controlling plant diseases and weed invasion
  - Improves aeration, water infiltration, water holding capacity, and root growth
  - Mitigates wind and water erosion

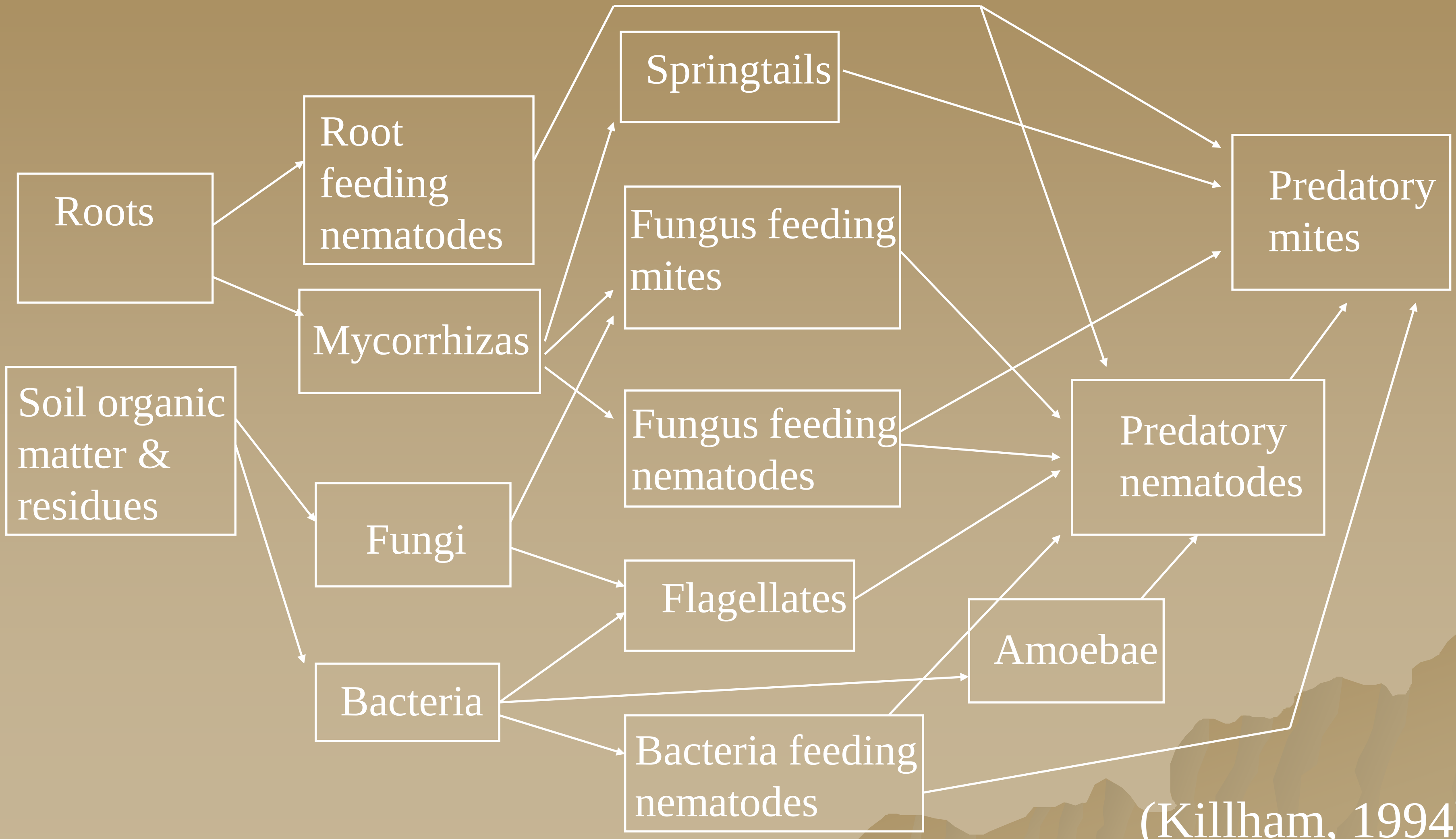
Soil Food Web Members

- Bacteria
- Fungi
  - Mycorrhizae
- Nematodes
- Protozoa
- Microarthropods
- Earthworms, Moles, etc.



Relationships between soil food web, plants, organic matter, and birds and mammals
Image courtesy of USDA Natural Resources Conservation Service
http://soils.usda.gov/sqi/soil_quality/soil_biology/soil_food_web.html.

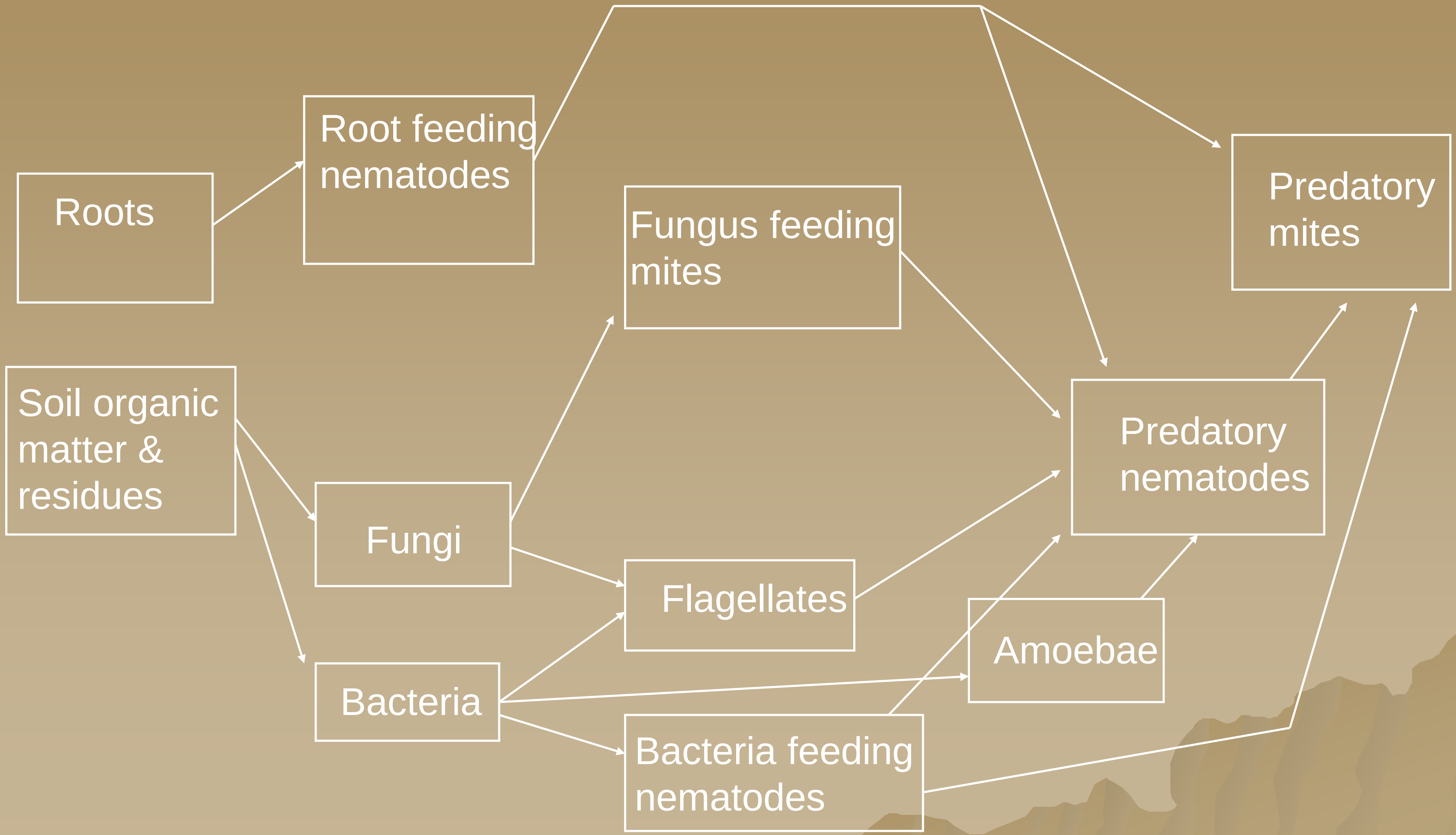
Microbial Foodweb of Grassland Soil



(Killham, 1994)

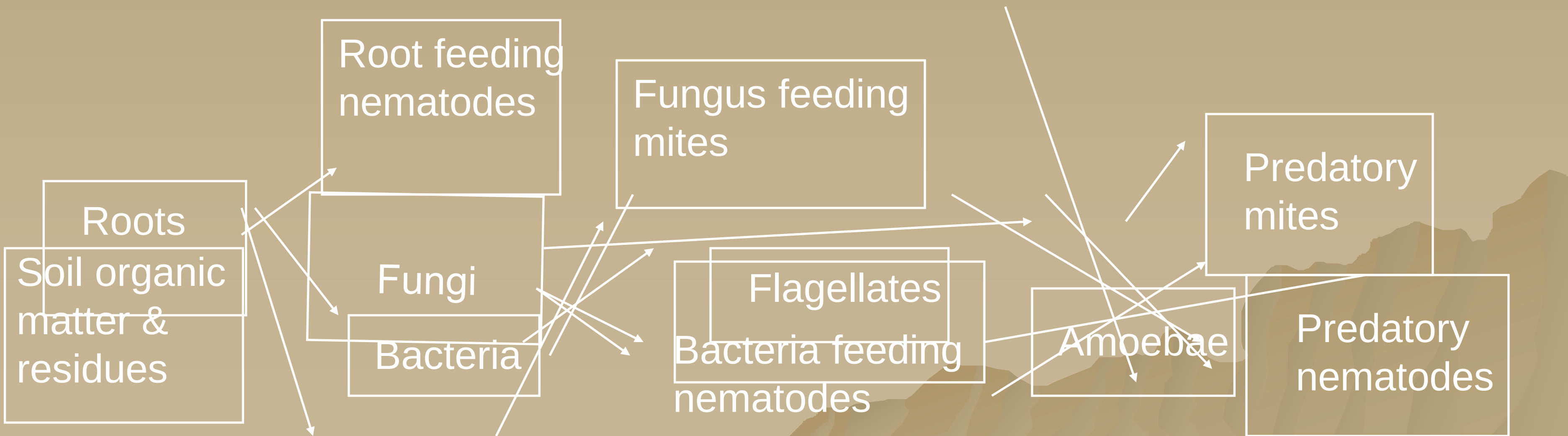
Microbial Foodweb of Grassland Soil

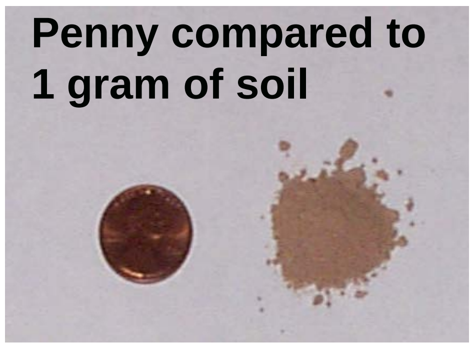
If you remove a group of organisms from the web, such as mycorrhizal fungi,



Microbial Foodweb of Grassland Soil

… the web will collapse and soil productivity is reduced.





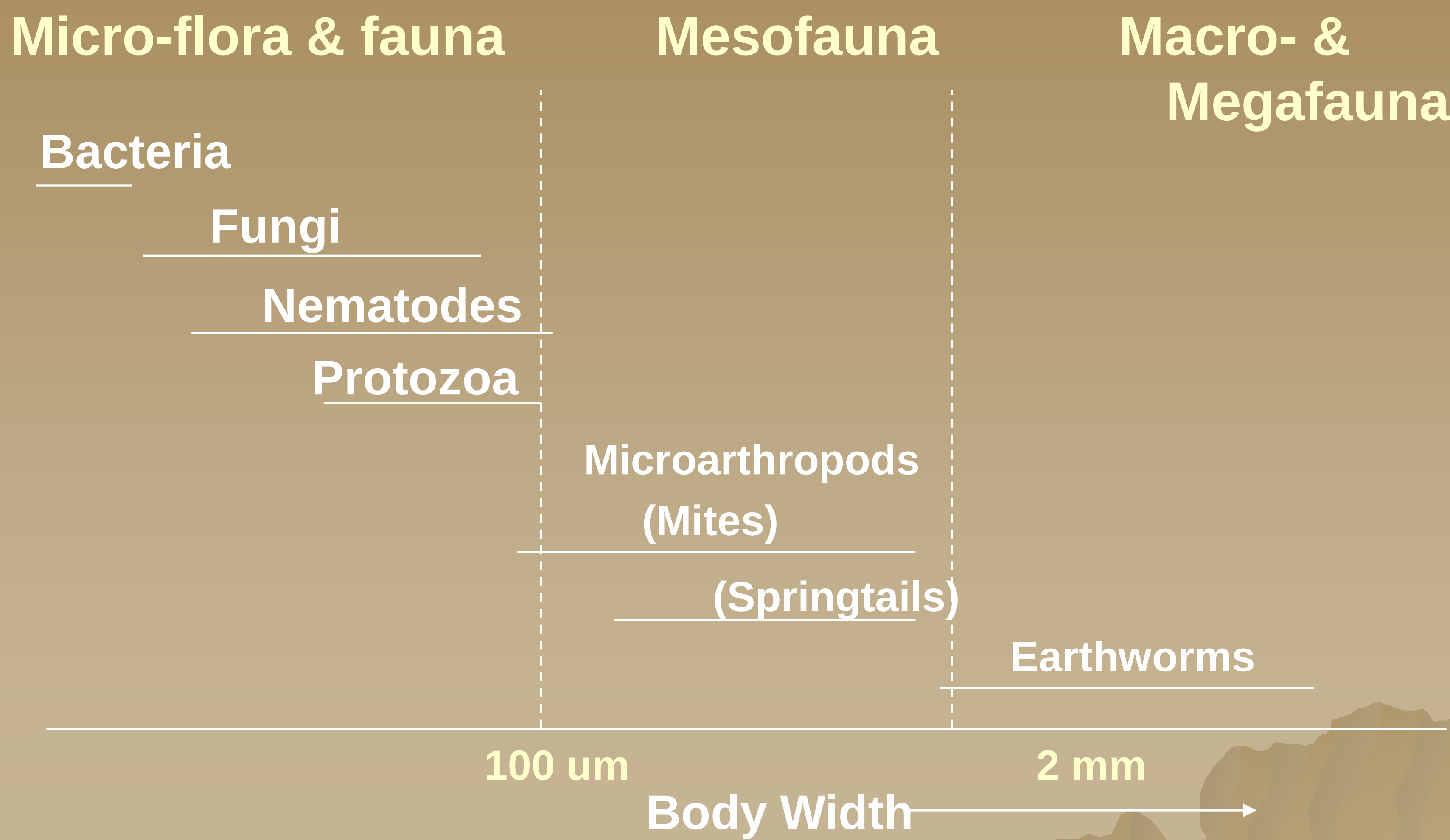
Faunal Biomass

- Weight of microbial C per gram of soil
  - bacteria-- 1 billion
  - actinomycetes-- several hundred million
  - Fungi-- 10 — 20 million
  - algae-- 10,000 — 3 million
  - protozoa-- up to 1 million
  - nematodes-- 50 or more

(Stevenson, 1994)

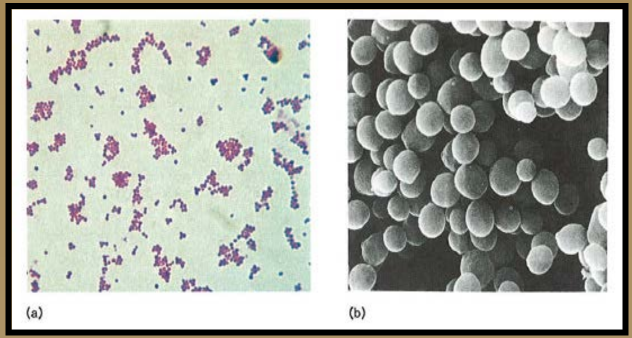
Size Classification

(by body width)



(Swift et al., 1979)

Bacteria



Staphylococcus aureus
(a) X1,500, (b) x34,000
- Prescott, Harley, and Klein 1993

- Bacteria include many different types which are single-celled, have different shapes, may or may not be mobile, and may grow in clusters
- Feed on organic matter that is easy to break down
- Store and cycle nitrogen
- Contribute to soil stability
- Decompose pesticides

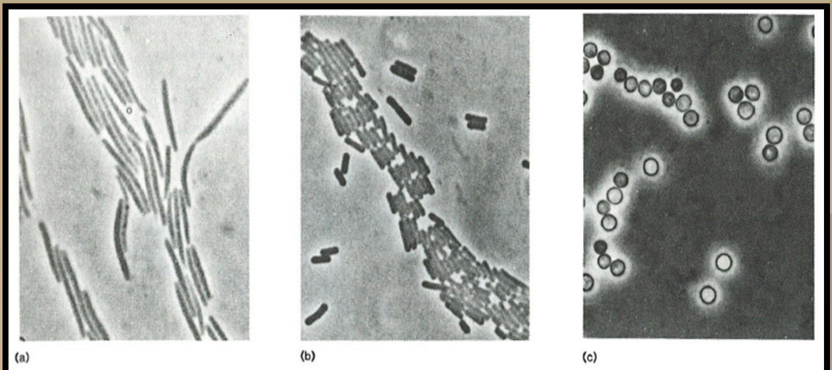
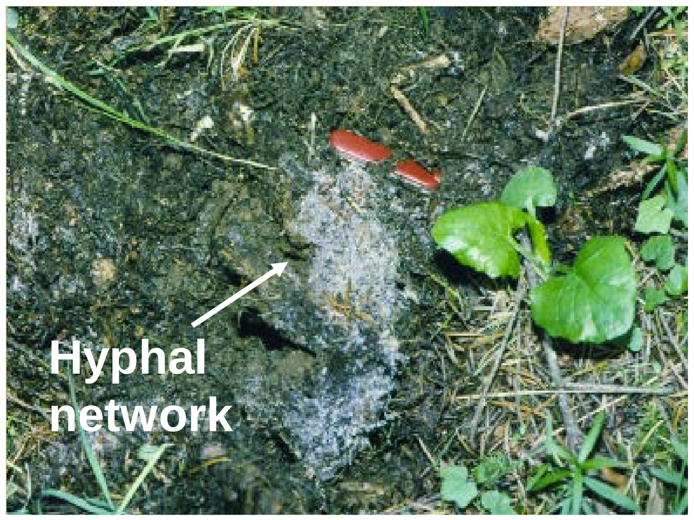


Figure 23.24 **Gliding, Fruiting Bacteria (Myxobacteria).** Myxobacterial cells and myxospores. (*a*) *Stigmatella aurantiaca* (×1,200). (*b*) *Chondromyces crocatus* (×950). (*c*) Myxospores of *Myxococcus xanthus* (×1,100). All photographs taken with a phase-contrast microscope.

-Prescott, Harley, and Klein 1993

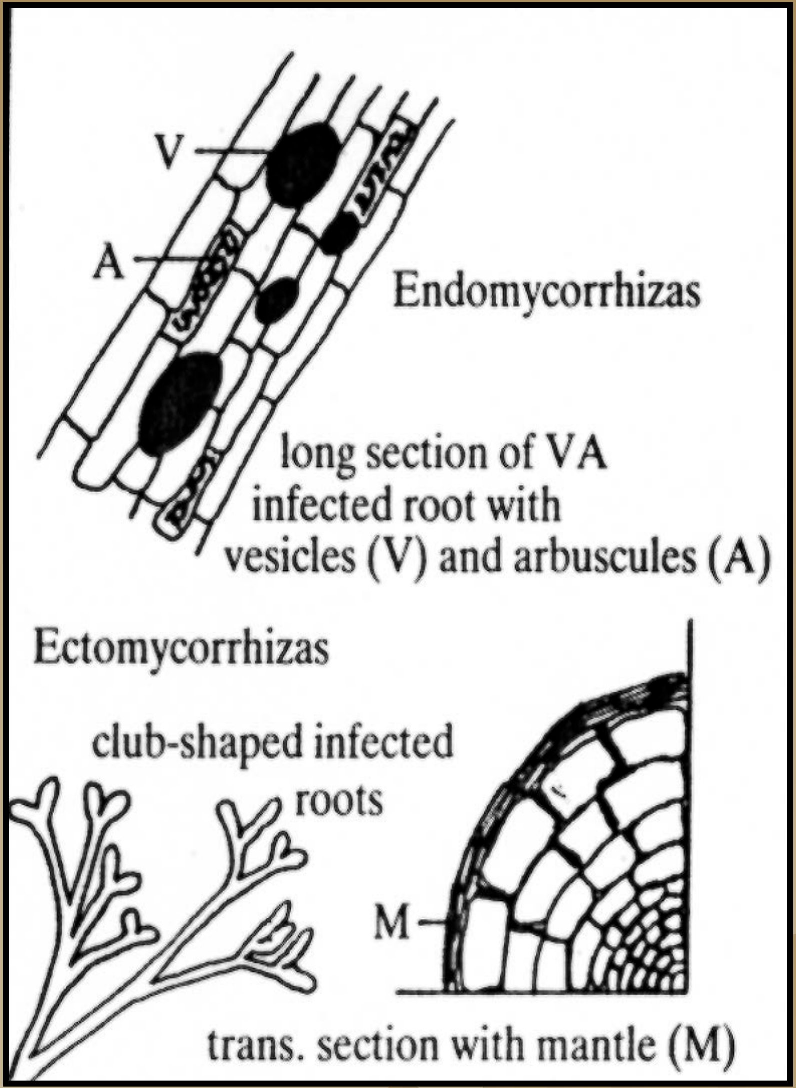
Fungi

- Fungi include two main types: saprophytes (i.e. decomposers) and mutualists (i.e. work with other organisms, like the plant, to trade food for nutrients)
- Saprophytes feed primarily on residue but will consume organic matter especially after tillage
- Store nitrogen
- Contribute to soil stability
- Are harmed by tillage, which destroys hyphal networks (i.e. nets in the soil that look like fine threads)



Mycorrhizal Symbiosis

- There are two major types of mycorrhizal fungi – endomycorrhizas and ectomycorrhizas.
- The endomycorrhizas or arbuscular mycorrhizal fungi penetrate the root cell walls of about 80% of all vascular plants including most crop and forage species.
- The ectomycorrhizas surround the root mantle to form club-shaped roots and are associated with many tree species, especially conifers.

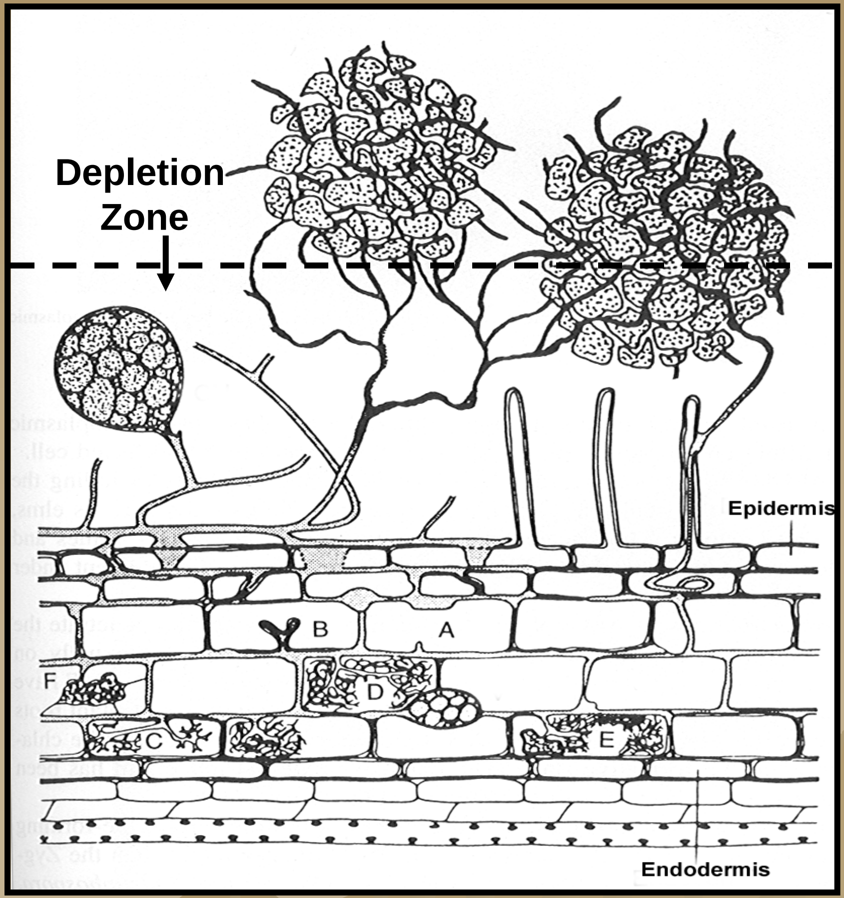


(Killham, 1994)

Arbuscular Mycorrhizal Fungi

(literally translated as tree-like fungus-root fungi)

- Plants quickly absorb the nutrients that are right next to the root or root hairs.
- Mycorrhizal fungal hyphae (i.e. fine threads) grow out into the soil, typically 1 to 2 in., to obtain nutrients which are exchanged with the plant for carbon

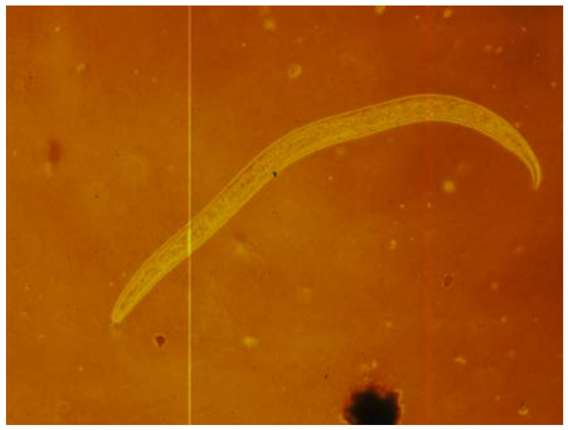


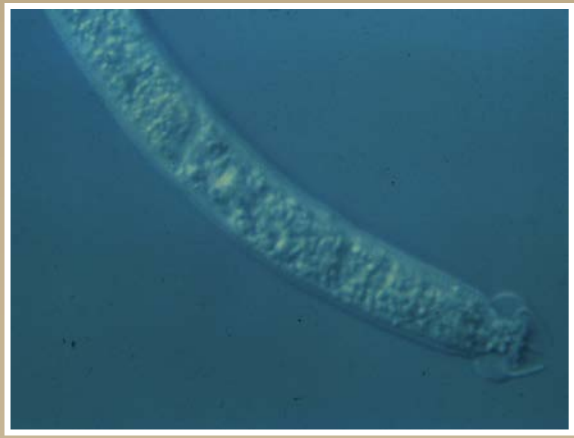
Hyphae extends out of these corn roots to efficiently acquire nutrients from outside of depletion zones and deliver these nutrients to the plant in exchange for carbon. The distance that the hyphae can extend into the soil is 25 to 51 thousand times the diameter of the hypha.

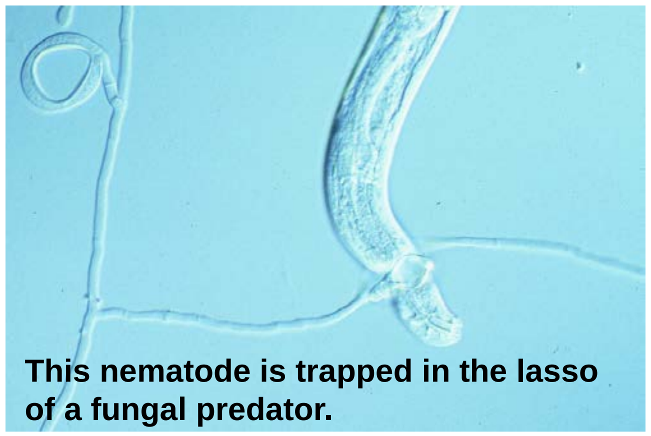
High magnification (1000X) picture of arbuscules (tree- or shrub-like blue-stained structures) within root cell wall. Nutrients scavenged from the soil by mycorrhizal fungi are traded for carbon at the arbuscules.

Nematodes

- Include fungal feeders, bacteria feeders, root feeders, predators and omnivores
- Are an important part of the nitrogen cycle
- Number about 10-20 nematodes per gram of soil
- Are impacted by management: pesticides, food source, tillage



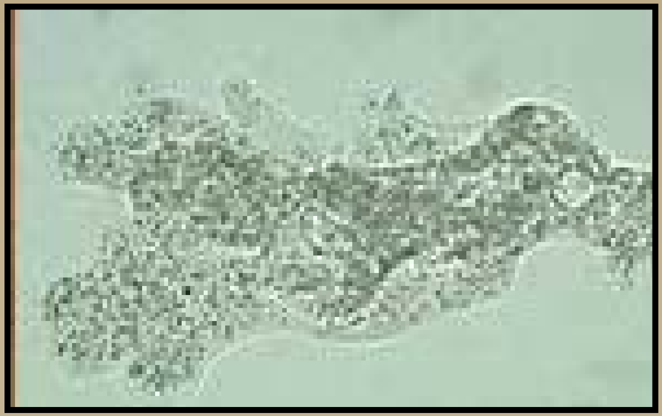




This nematode is trapped in the lasso of a fungal predator.

Protozoa

- Protozoa include: amoebae, ciliates, flagellates
- Are an important part of the nitrogen cycle because they consume bacteria and release nitrogen



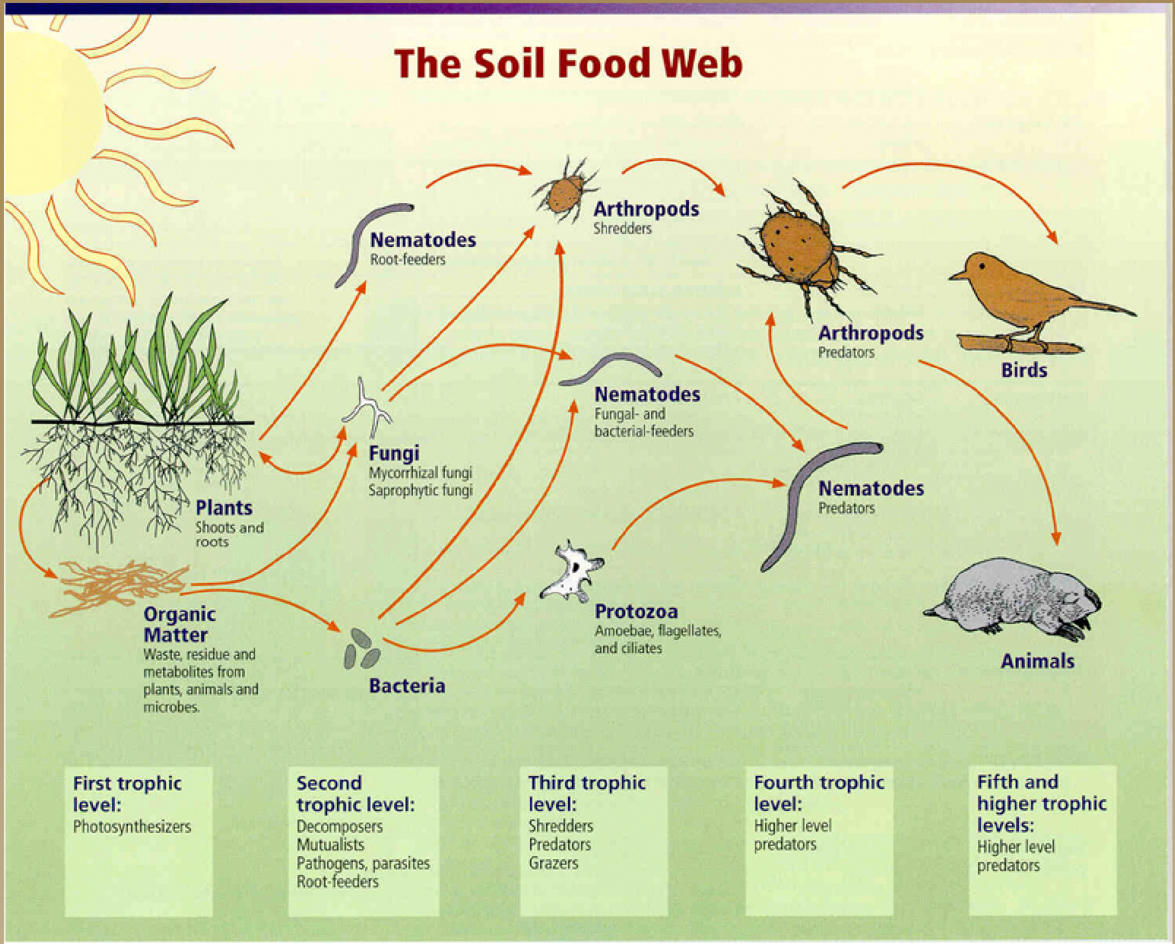
Microarthropods

- Microarthropods include: mites, collembola (or springtails)
- Decompose & shred organic matter
- Are an important part of the nitrogen cycle
- Are harmed by tillage and pesticides

Microarthropods

Earthworms

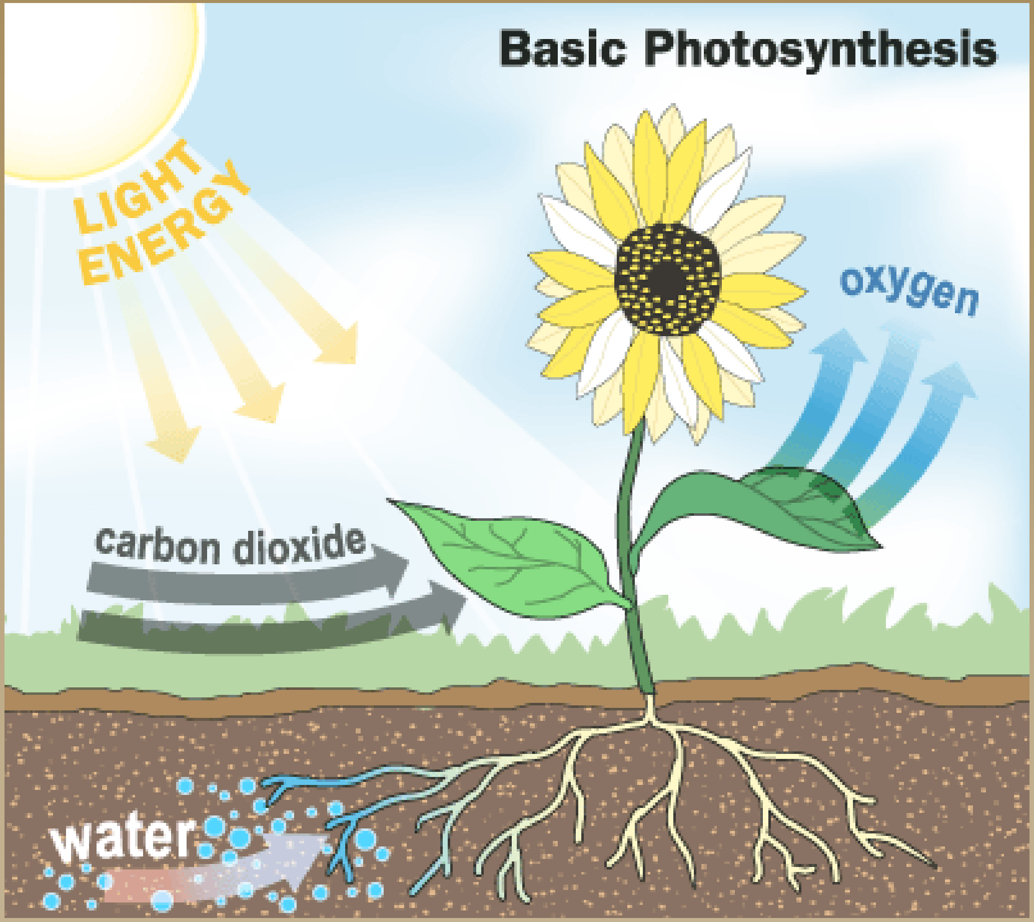
- In many regions the most abundant species are non-native
- Native species are displaced
- For nutrient cycling and stability functions, these exotics are good
- For maintaining biodiversity, they are not



Relationships between soil food web, plants, organic matter, and birds and mammals
Image courtesy of USDA Natural Resources Conservation Service
http://soils.usda.gov/sqi/soil_quality/soil_biology/soil_food_web.html.

Note that in the Soil Food Web, the first trophic level begins with plants. The web illustrates the flow of carbon from the plant, where carbon compounds are made by photosynthesis.

Photosynthesis



Soil organisms create contribute to soil formation by utilizing carbon derived from photosynthesis and mineral soil components – clay, sand, and silt.

$$6CO_2 + 6H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6O_2$$

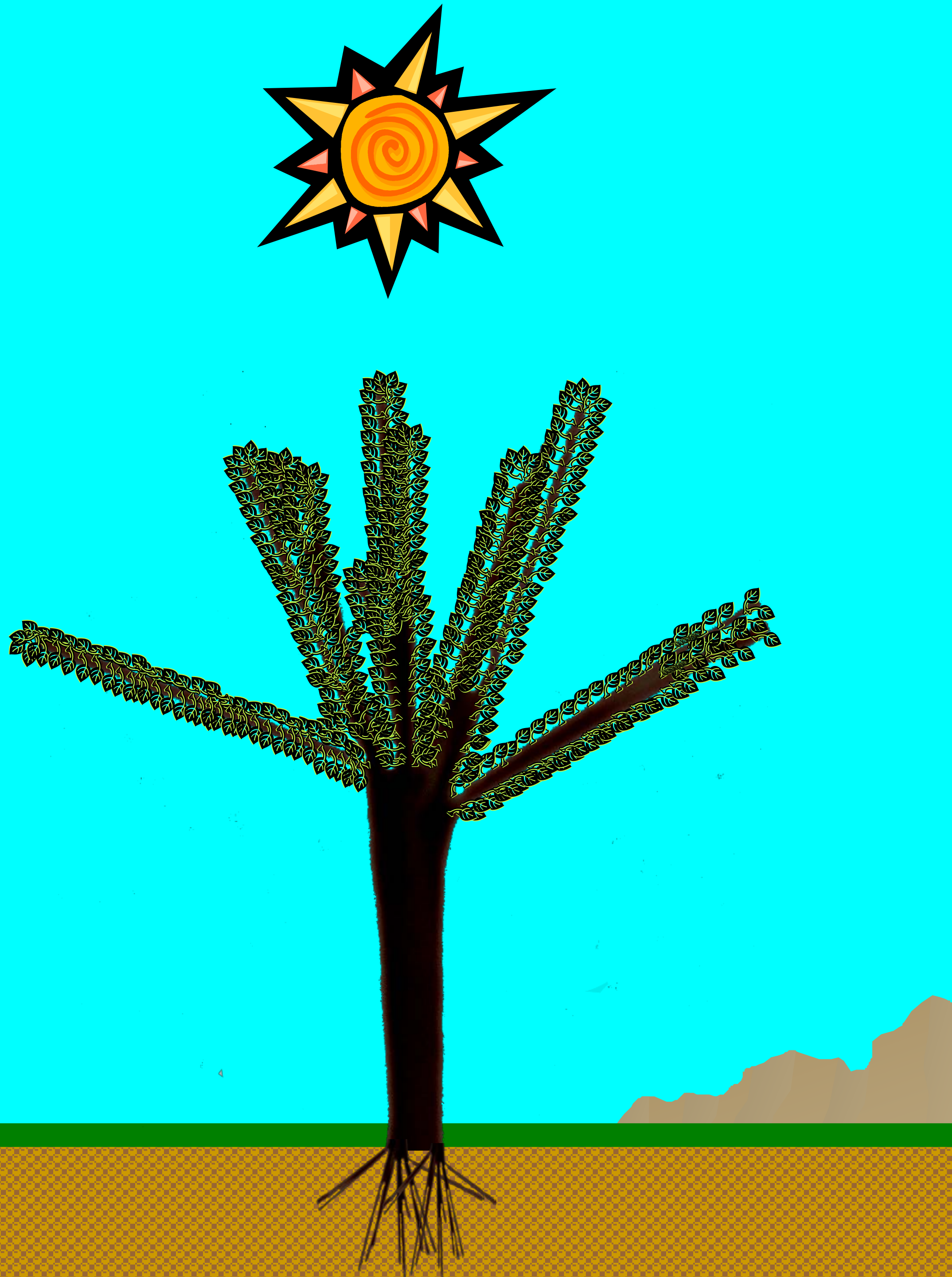
The Carbon Allocation Equation

- Carbon belowground comes from photosynthetically-derived carbon aboveground.
- To have a soil healthy biological community this carbon must come from different plant sources. Different plant sources have different carbon to nitrogen ratios which then feed different organisms.
- Living roots keep soil organisms growing and healthy.

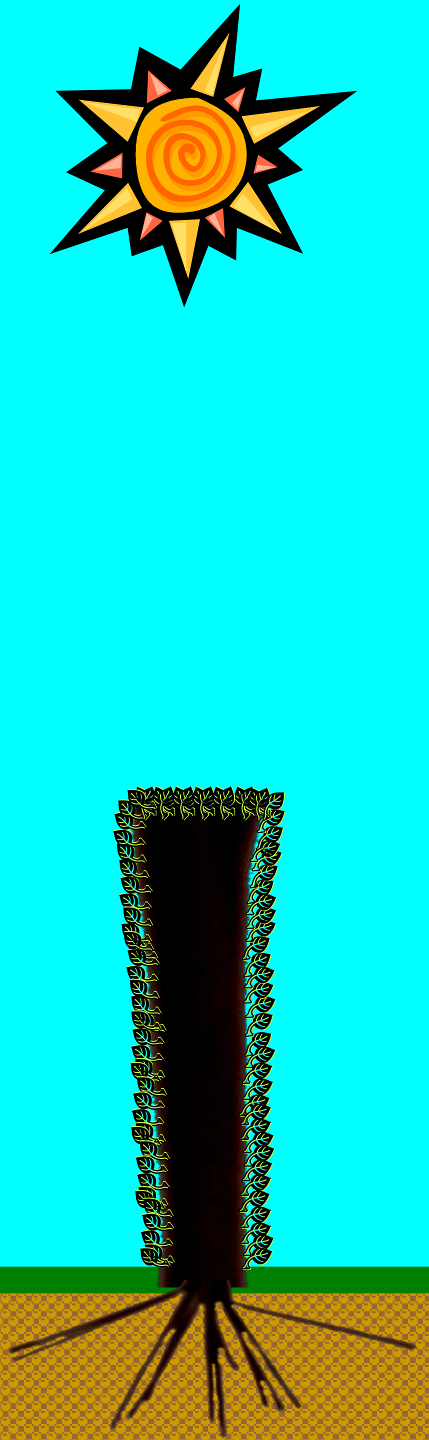
The Carbon Allocation Equation

The following slides will demonstrate how carbon from aboveground via photosynthesis is allocated belowground and the importance of that carbon to belowground processes.

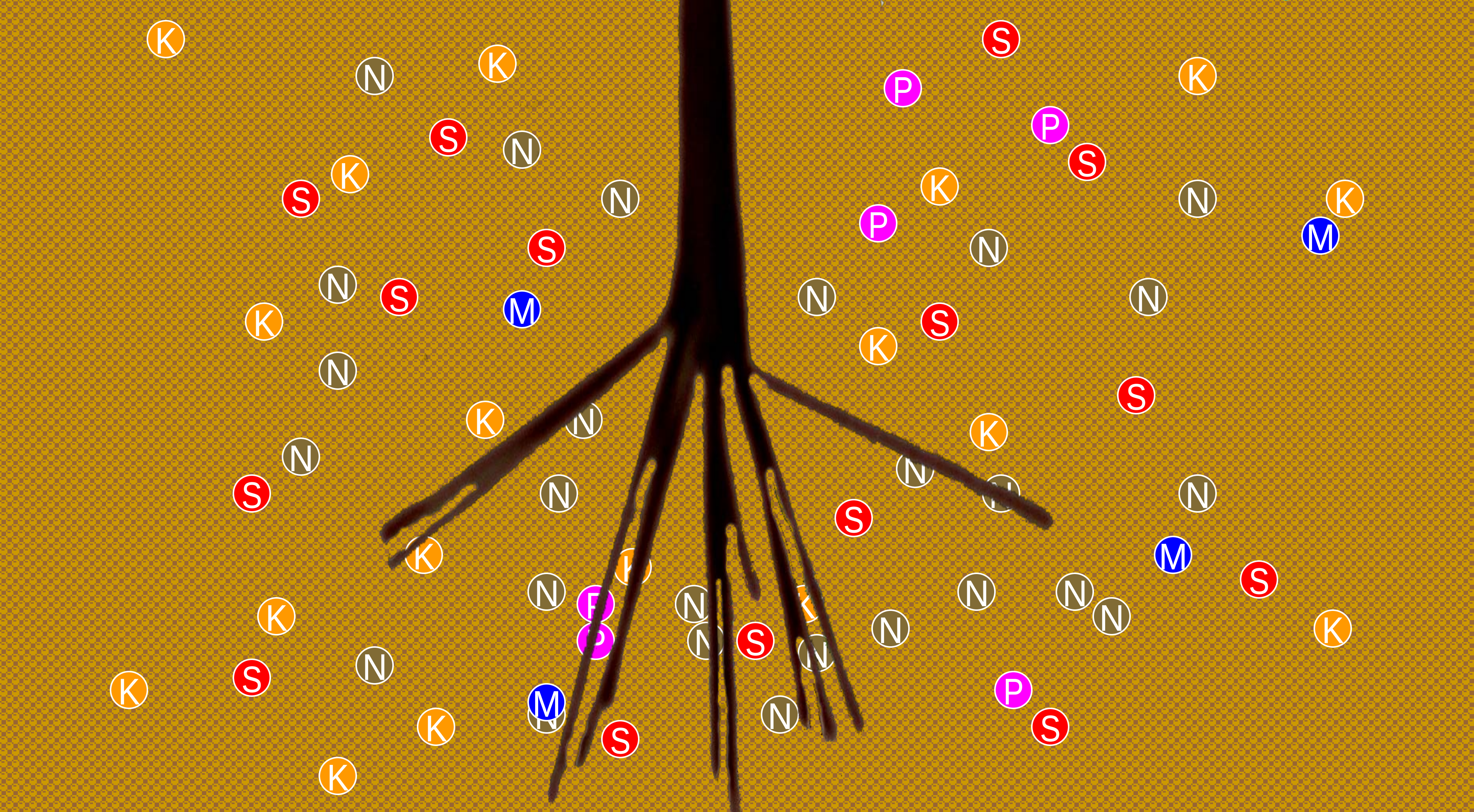
- The sun passes overhead
- Leaves on the branches absorb sunlight
- Sunlight provides energy for photosynthesis
- Photosynthesis makes sugars
- Sugars provide carbon for:
  - energy to grow
  - leaf, branch, trunk, and root formation
  - root exudates



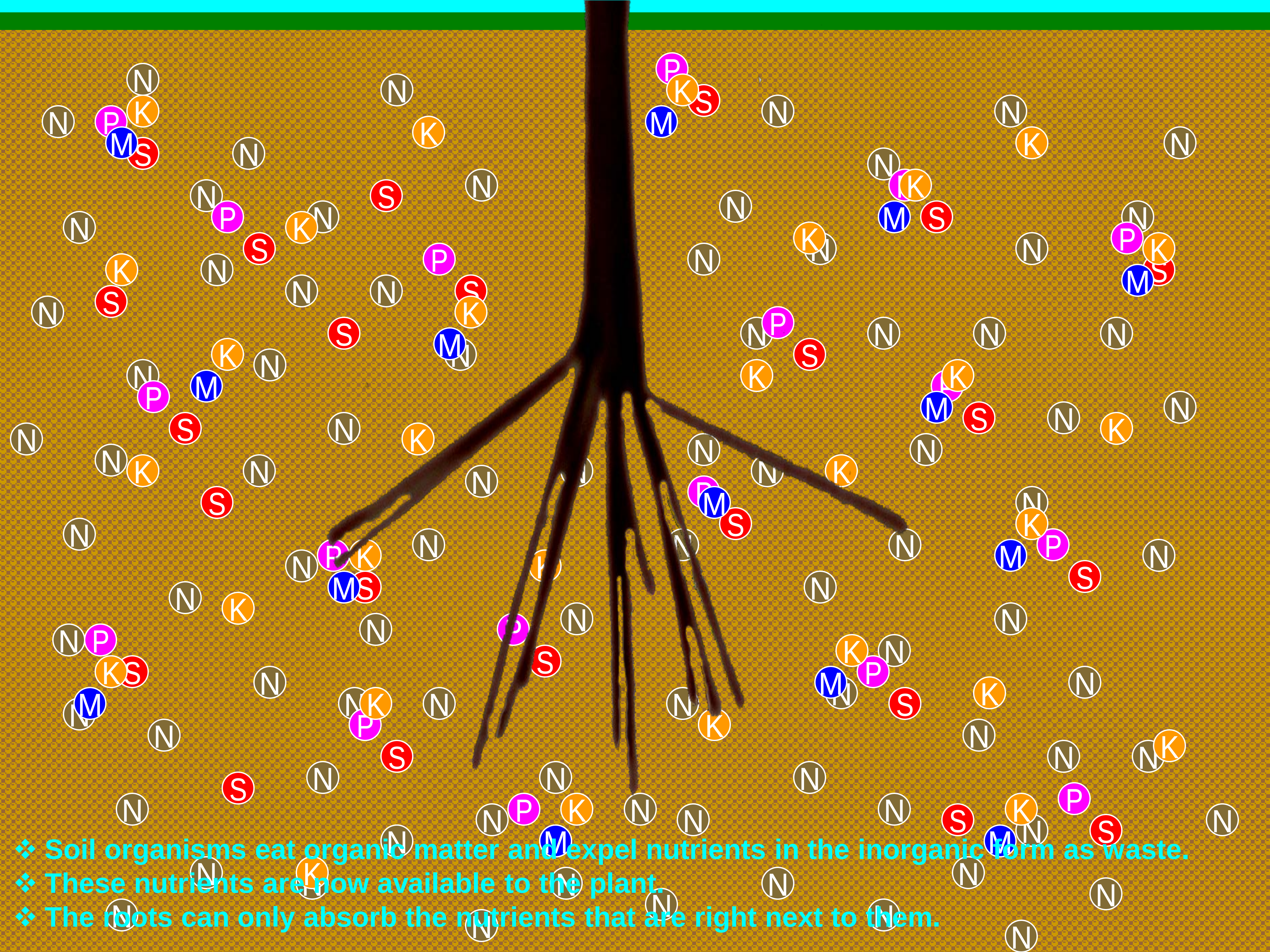
- If leaves were just on the trunk, the leaves could not fix enough carbon to keep the tree alive.
- Branches are thinner than trunks and provide a greater surface area for more leaves.
- Having branches is the most efficient mechanism to obtain the carbon need to support growth.



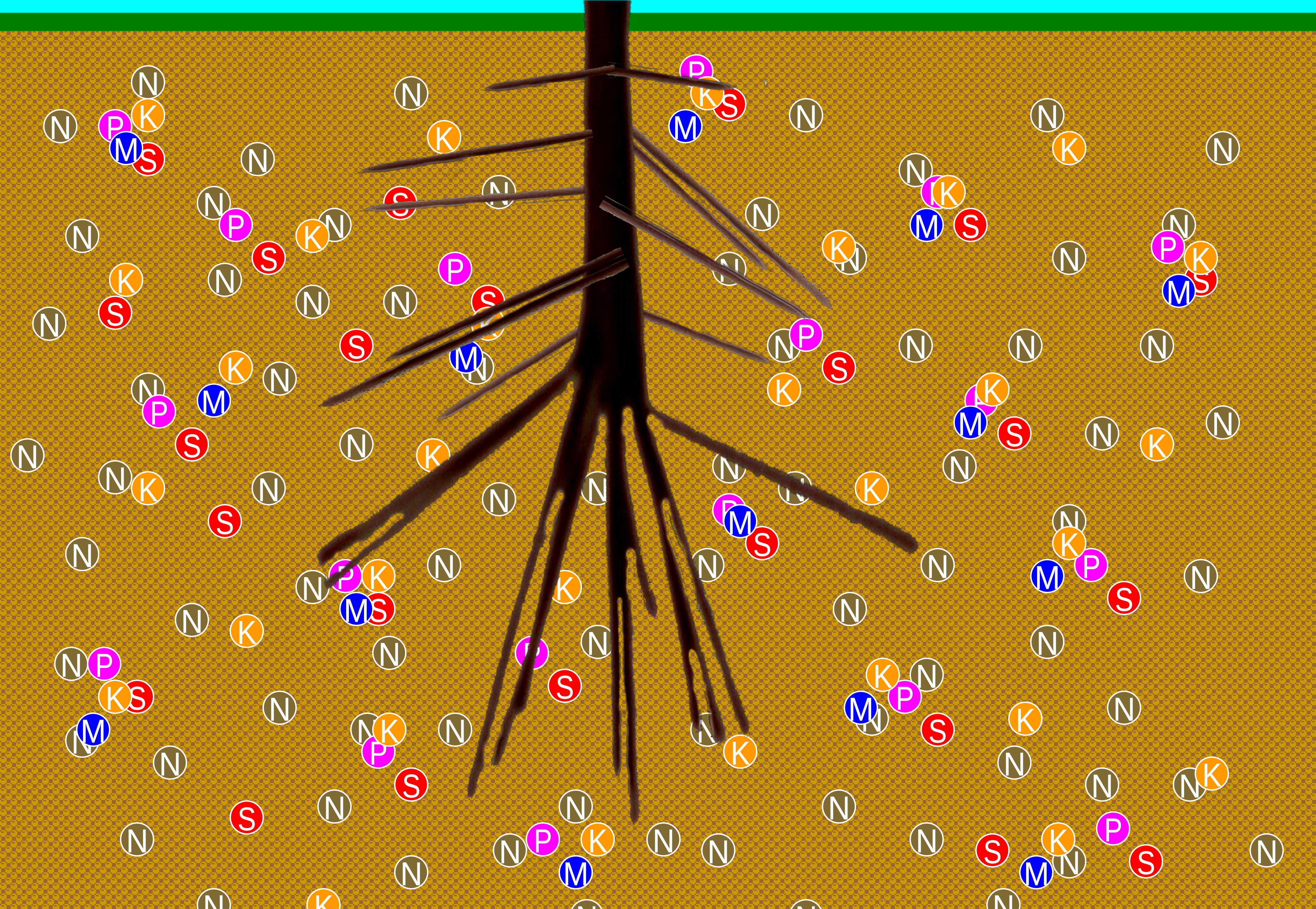
Does this process of efficiency get repeated by the roots below ground?



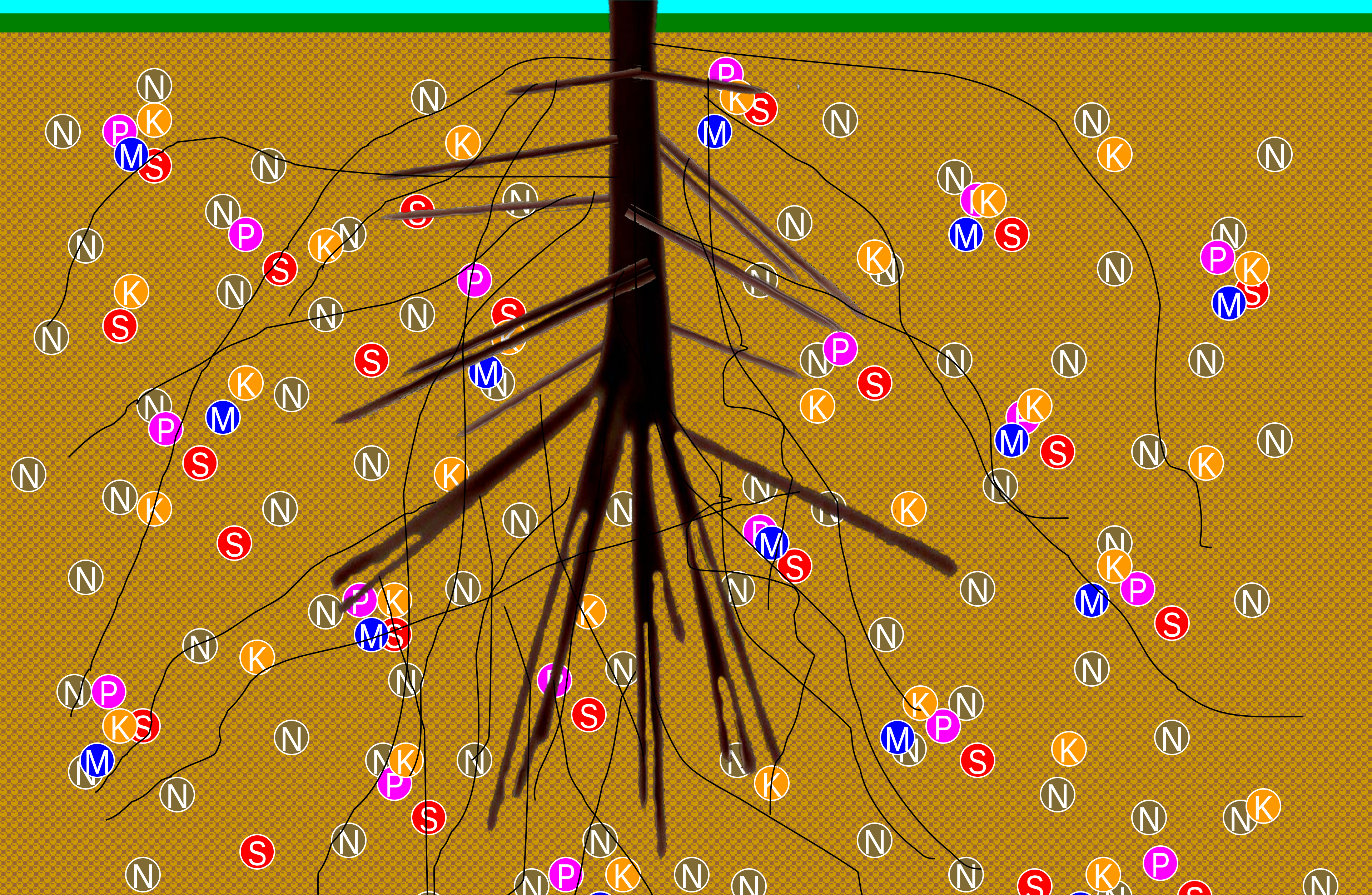
- Plants need nutrients to be in the inorganic form.
- Most of the soil nutrients are locked up in organic matter.
- Some inorganic nutrients, such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and micronutrients (M) including iron, aluminum, zinc, calcium, etc., may be present.
- This a small amount of nutrients compared with what is in the organic matter.



- Soil organisms eat organic matter and expel nutrients in the inorganic form as waste.
- These nutrients are now available to the plant.
- The roots can only absorb the nutrients that are right next to them.

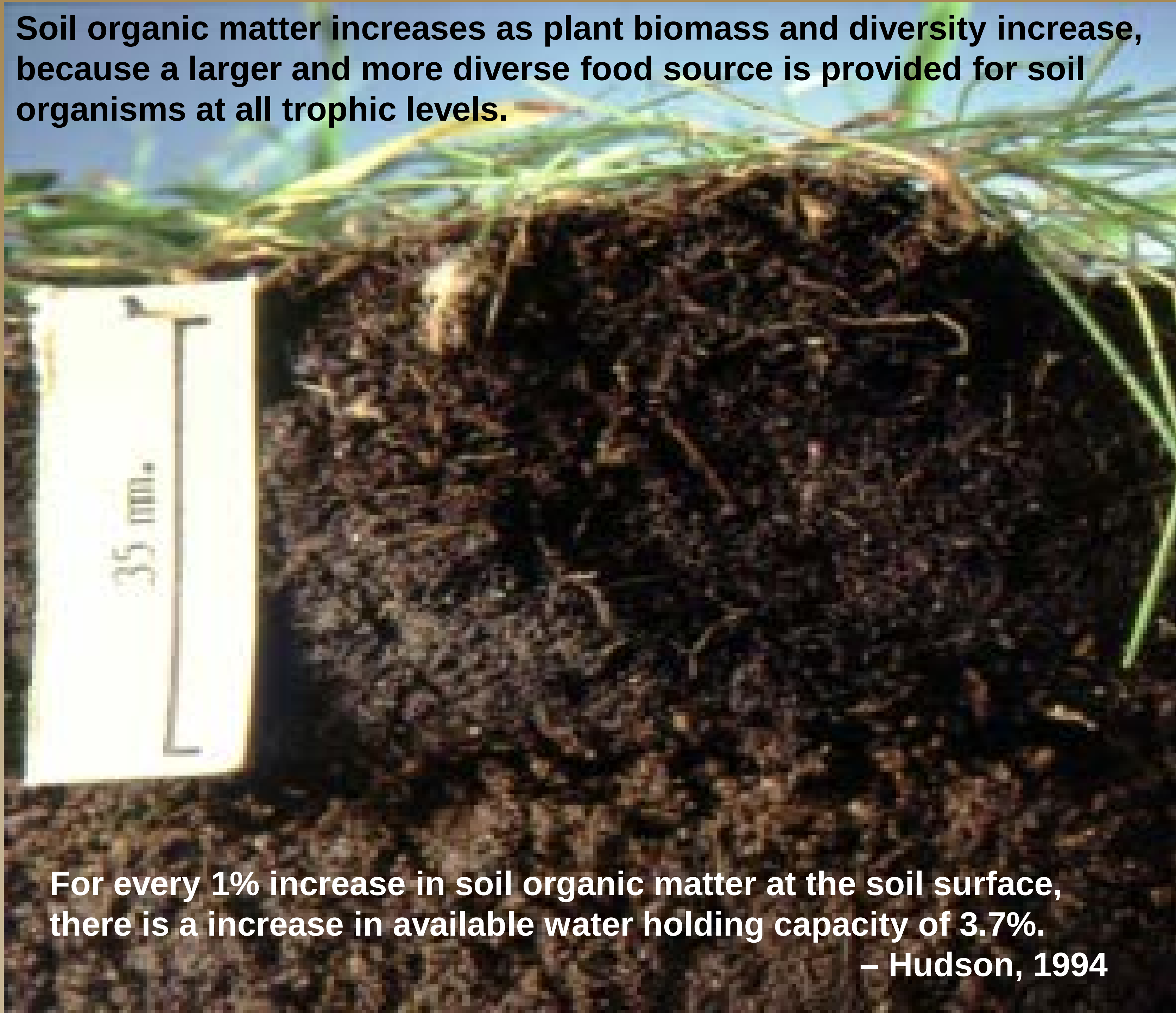


- More branches from the tap root will give the plant access to more nutrients.
- This is more efficient than forming more tap roots.



- To increase the efficiency even more and use less carbon, plants form a mutually beneficial relationship with arbuscular mycorrhizal fungi.
- The fungal hyphae has a greater surface area than fine root branches to access more soil and obtain even more nutrients.

Soil organic matter increases as plant biomass and diversity increase, because a larger and more diverse food source is provided for soil organisms at all trophic levels.



For every 1% increase in soil organic matter at the soil surface, there is a increase in available water holding capacity of 3.7%.

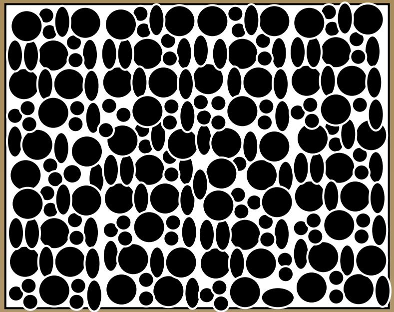
– Hudson, 1994

Organic matter (i.e. carbon) and soil organisms form soil aggregates

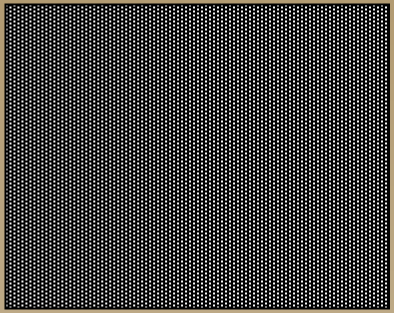
Soil aggregates are pellets of different shapes and sizes that are formed by soil organisms. Many aggregates were formed on switchgrass roots grown for 3 months in a pot in the greenhouse using a 1:1 sandy loam soil to sand mix (A). Despite the high sand content, you can see that with active soil biota, aggregates will form (B). Aggregates (1 to 2 mm) may be separated from the sandy loam soil where Russian wild rye was grown for at least 3 years (C).

Why are aggregates important?

- **Improve Soil Structure**
  - ✓ **Porosity**
    - **Root penetration**
    - **Aeration**
    - **Water infiltration**
    - **Water holding capacity**
  - ✓ **Erosion control**



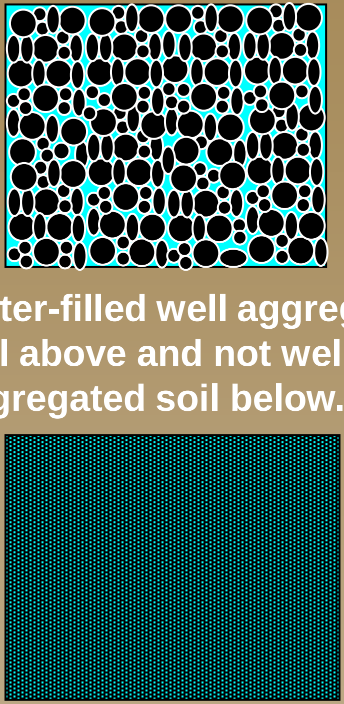
Well Aggregated Soil



Not Well Aggregated Soil

Why are aggregates important?

- ❖ **Improve Soil Structure**
  - ✓ **Porosity**
    - Root penetration
    - Aeration
    - Water infiltration
    - Water holding capacity
  - ✓ **Erosion control**
- ❖ **Improve Nutrient Cycling**
  - ✓ Increasing the growth of soil organisms by providing a protected habitat which contains a food source
  - ✓ Increasing plant growth by providing food from the work of soil organisms and a habitat to grow into and throughout
  - ✓ Increasing the protection of soil organic matter (i.e. carbon) from rapid decomposition



Water-filled well aggregated soil above and not well aggregated soil below.

What Makes Soil Aggregates?

Biological Components

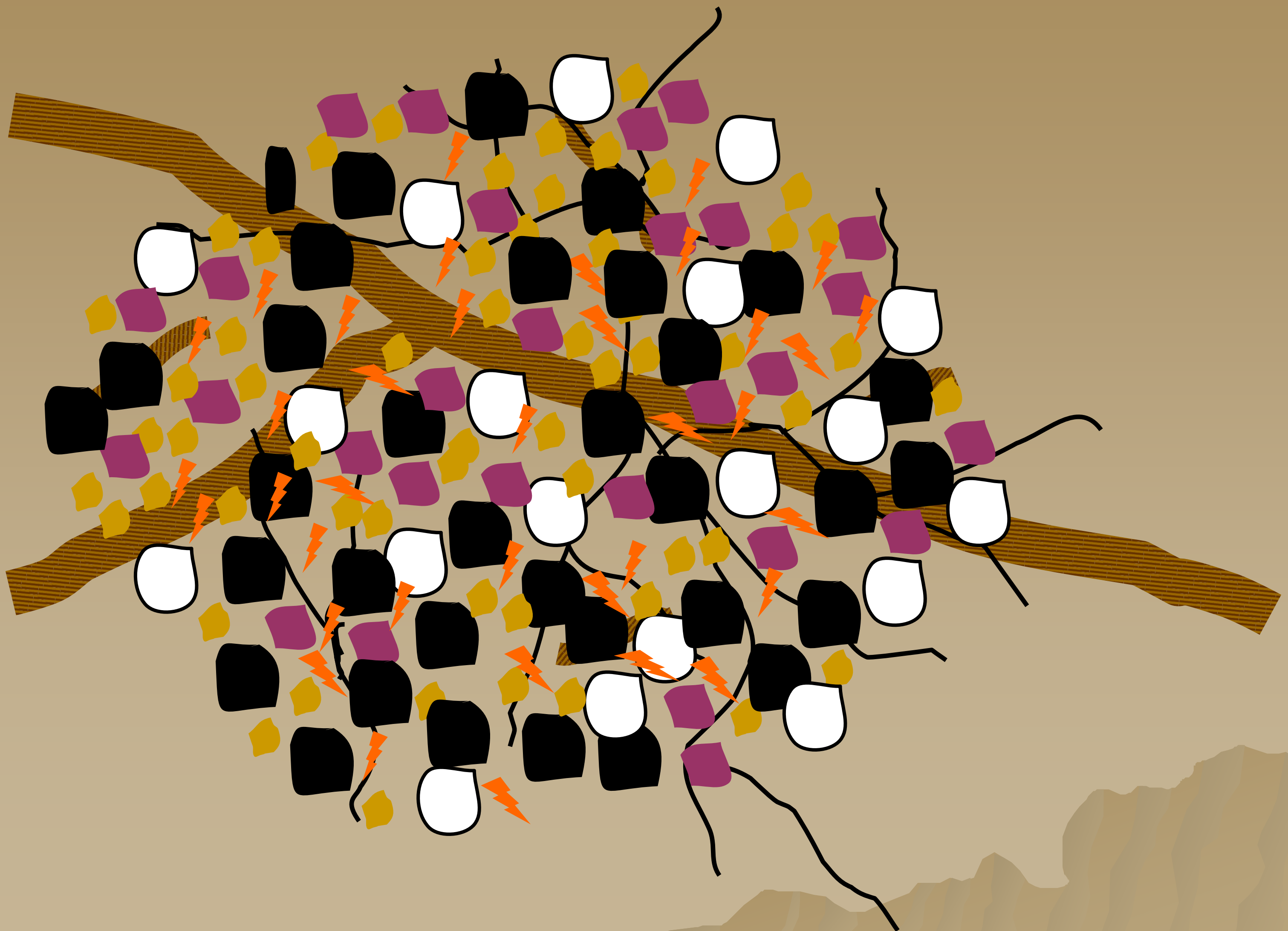
- Plant roots
- Mycorrhizal hyphae
- Bacteria and other microbes
- Organic matter (Humus)
- Sugar exudates from roots and bacteria
- Glomalin
- Particulate Organic Matter

Non-Biological Components

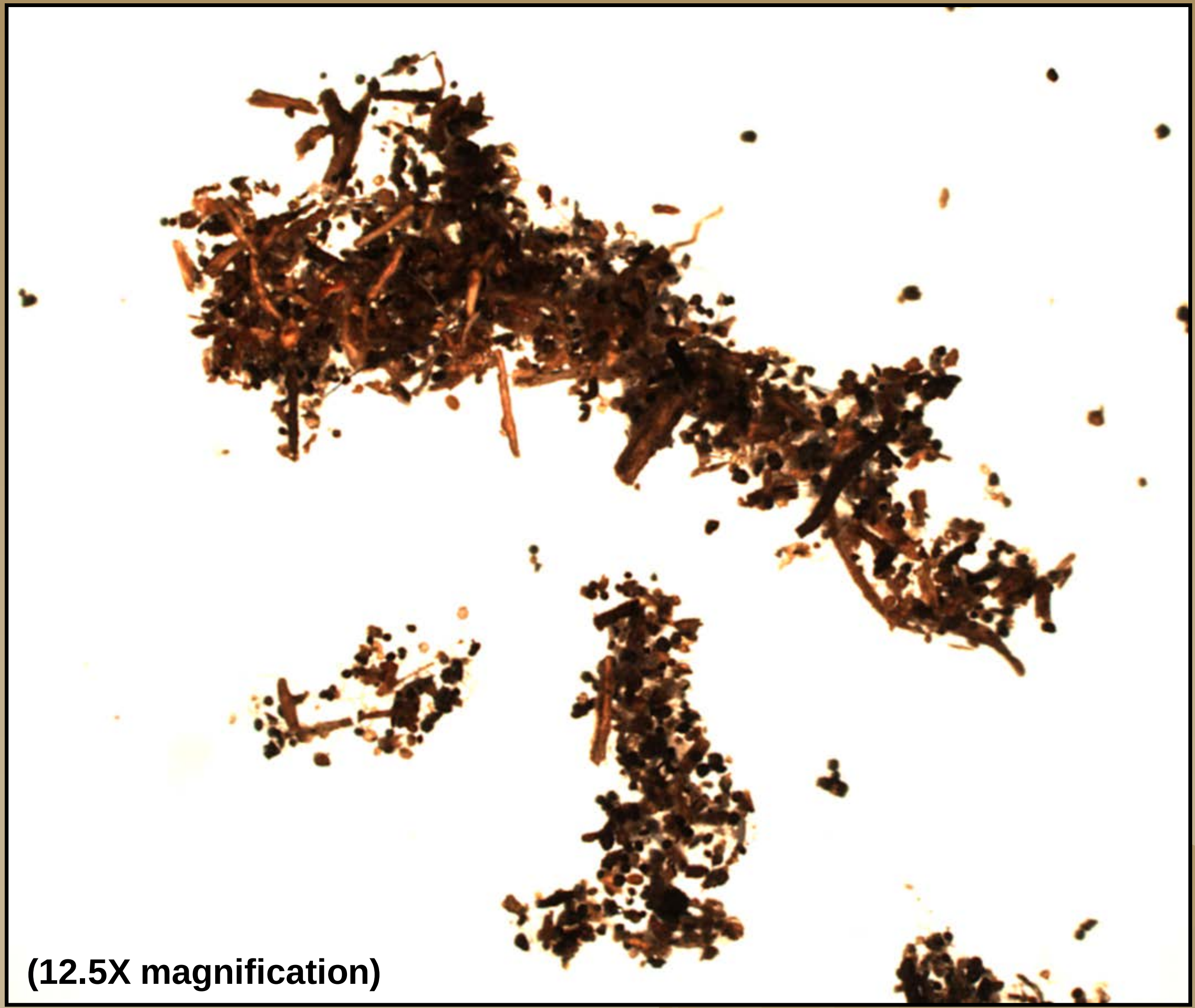
- Clay minerals
- Sand
- Cations – Fe, Al, Ca
- Silt
- Pore Space

Aggregate formation begins with the plant root and fungal hyphae acting as a net in the soil.

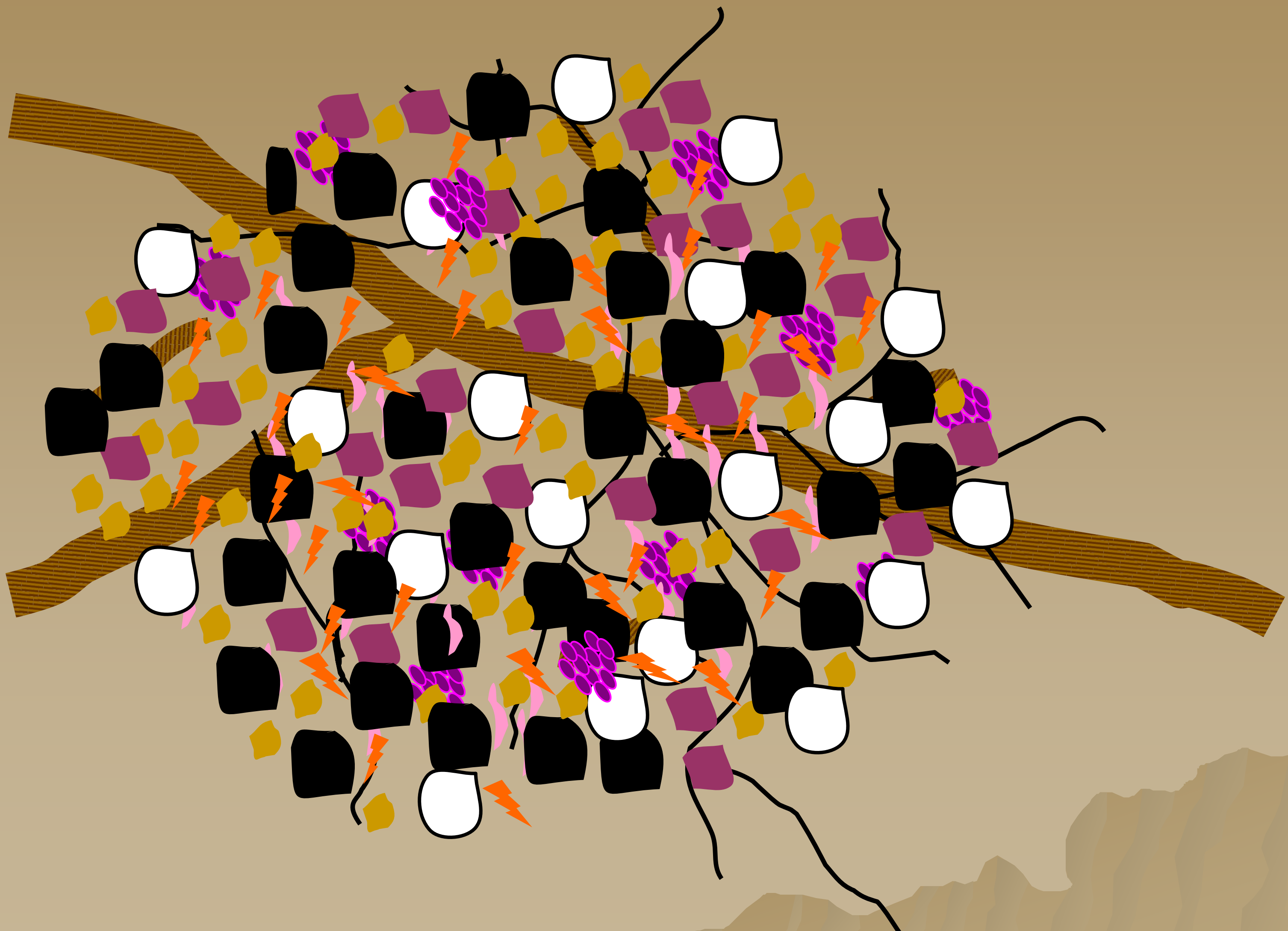
Organic matter, sand, and other debris in the soil are enmeshed by the root-fungal net.



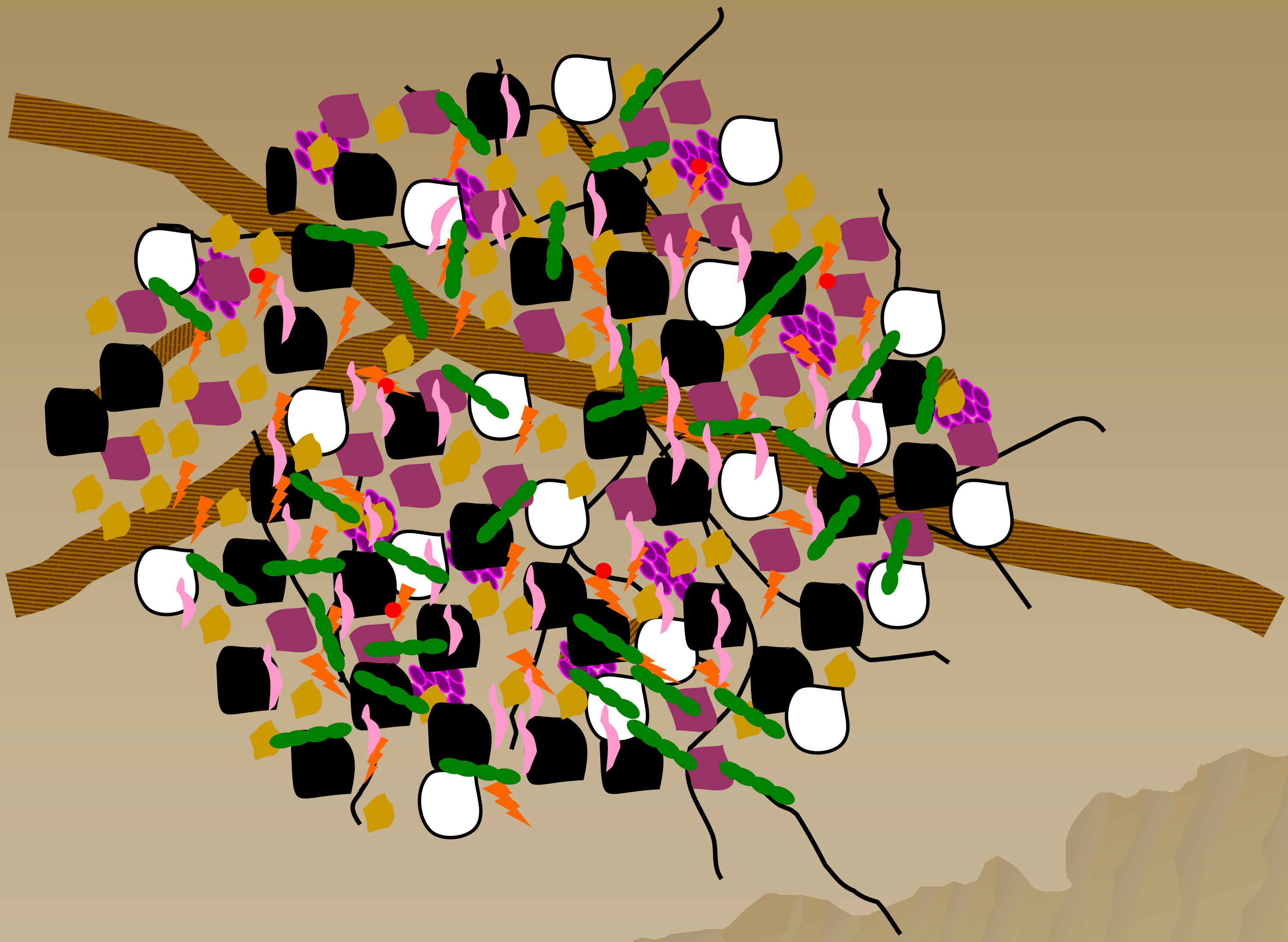
This picture demonstrates how the root-fungal net entraps soil particles to begin aggregate formation.



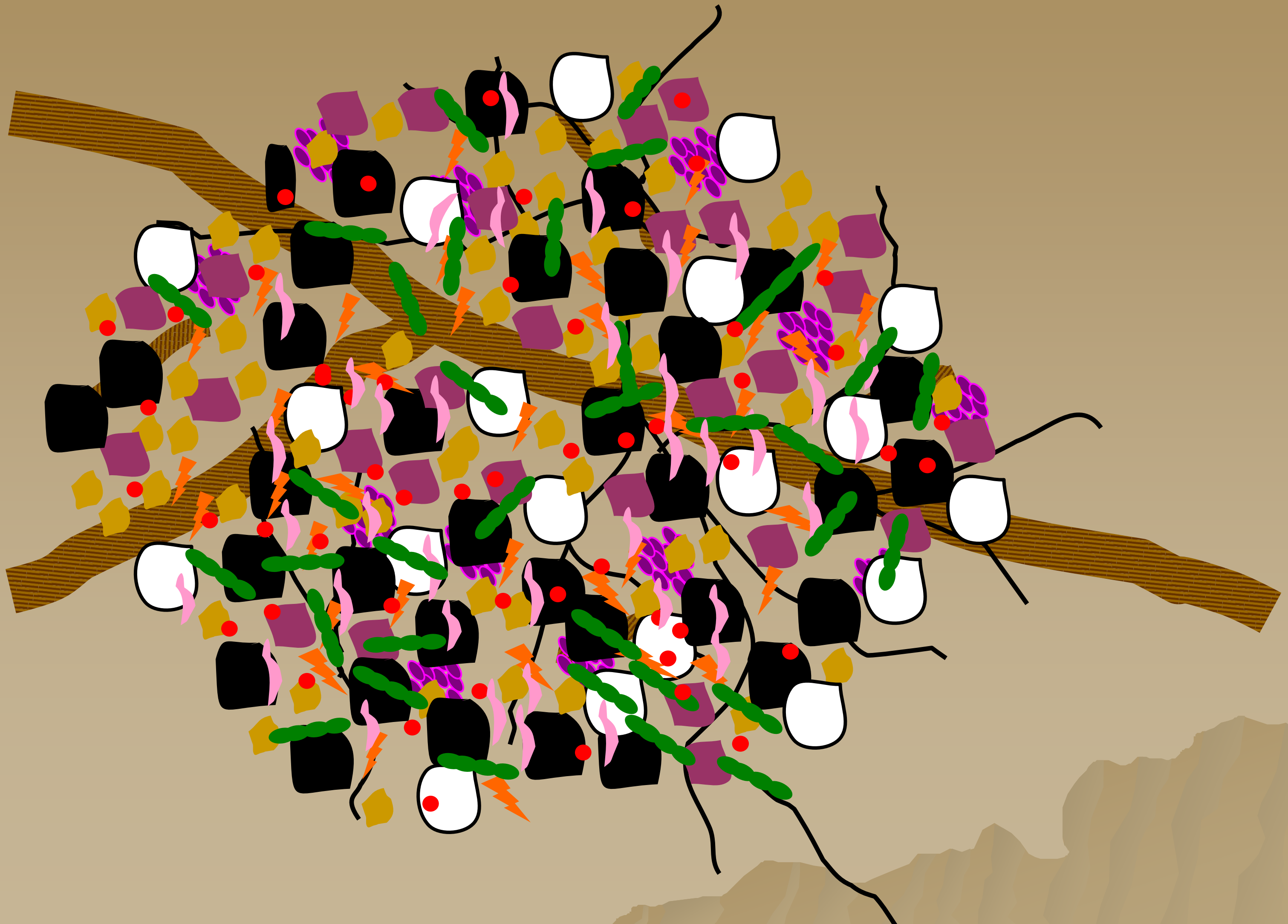
The debris in the root-fungal net attracts bacteria and other microorganisms to feed on the organic matter and sugars exuded from the roots and bacteria.



Glomalin forms a protective coating on hyphae and acts like a glue to stick the aggregate together along with root- and bacteria-derived sugars.

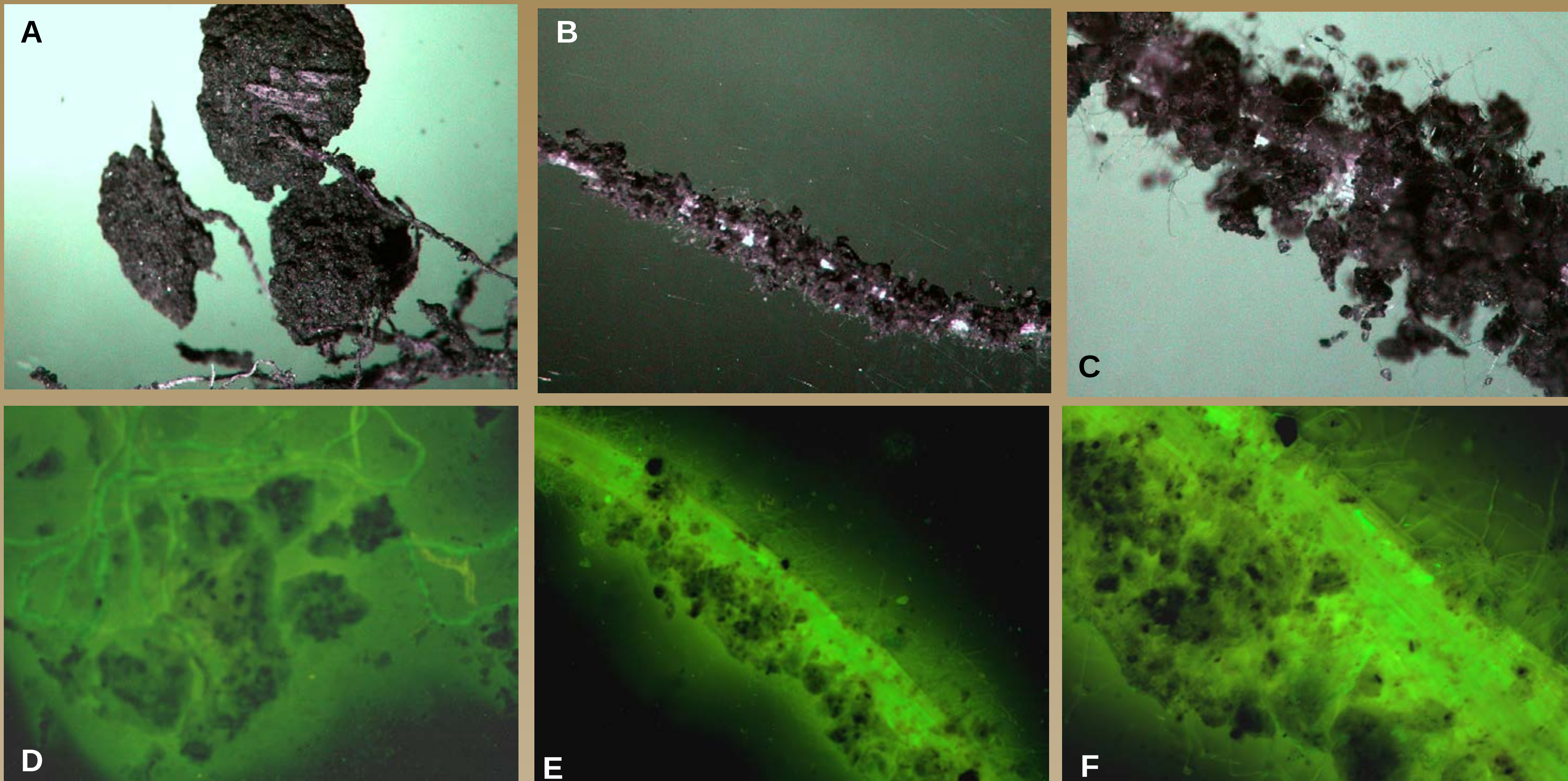


Cations, such as iron aluminum, and calcium, form chemical bridges between clay particles and organic matter to hold the aggregate together.



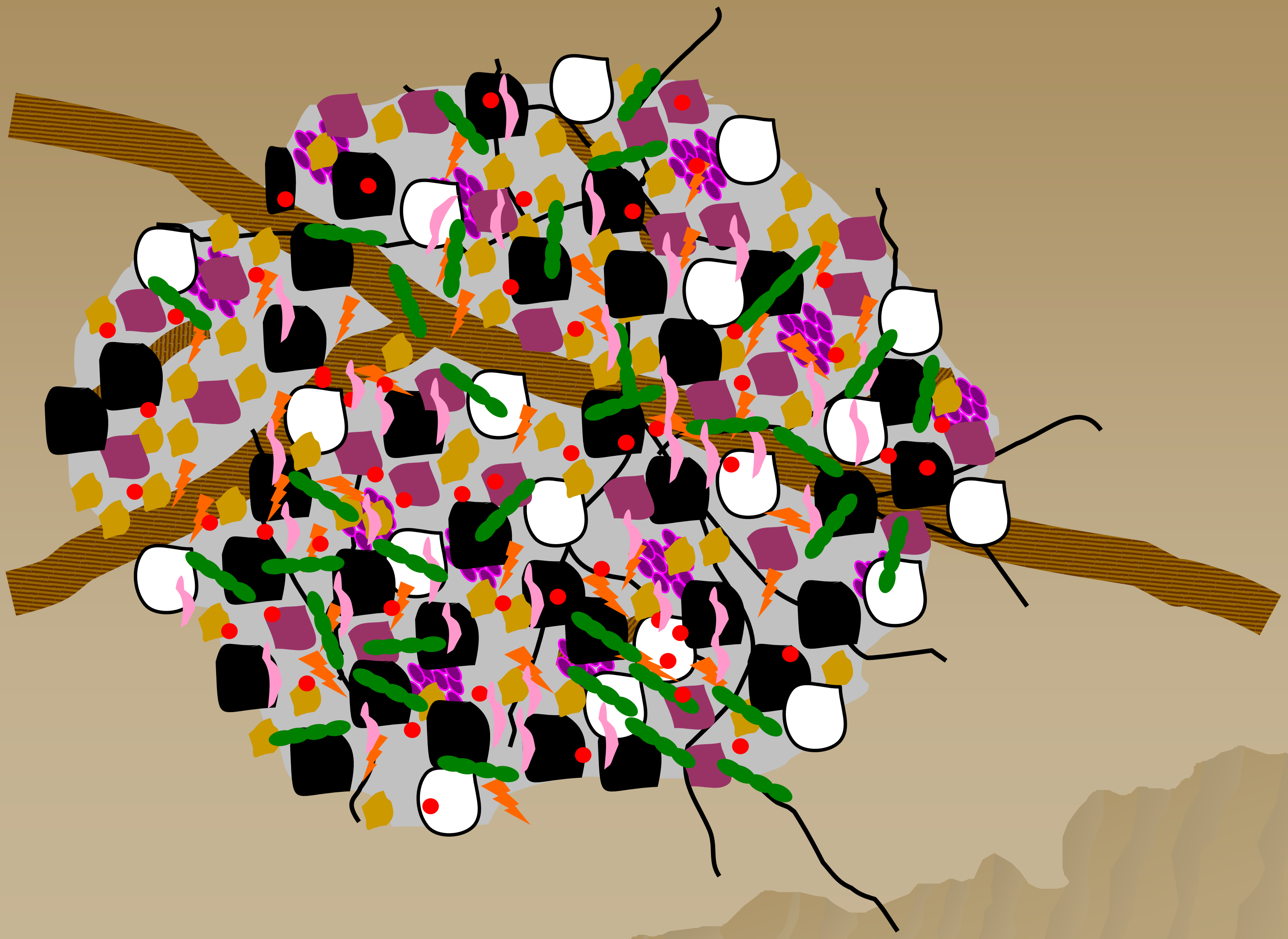
Mycorhizosphere (i.e. fungus surrounding the root) at work

(Samples collected on August 30.)



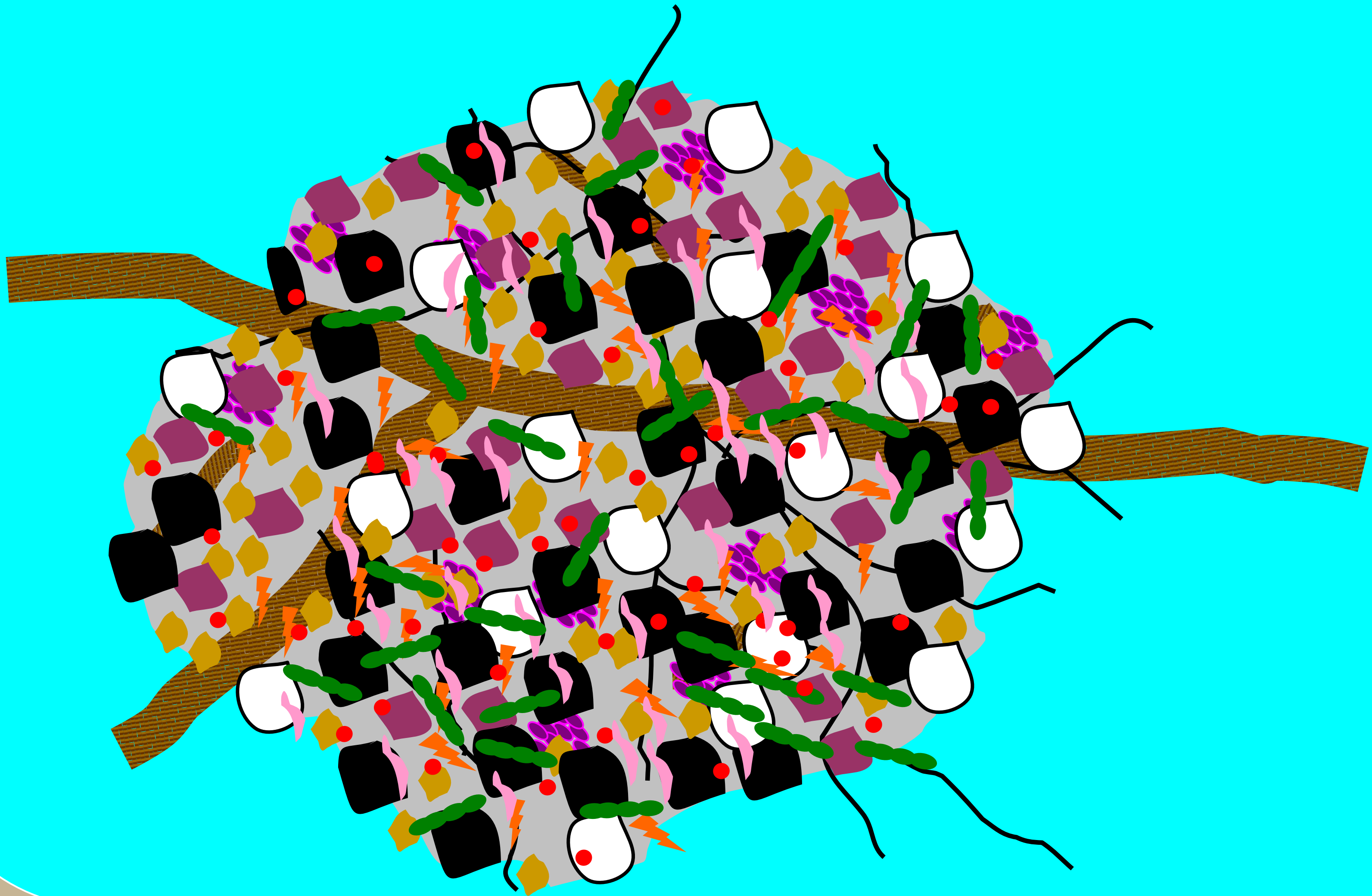
Soil aggregates were formed near the roots of a millet, which was part of a cover crop cocktail planted in a Lihen loamy fine sand soil on July 7 following a forage pea crop (A). The fungal hyphae surrounding the root has attached soil particles to the root forming small aggregate-like structures that the root is barely visible (B). A high magnification picture of the root shows the fungal hyphae and attached material very clearly (C). Following a laboratory procedure, the presence of glomalin is readily visible on one of the soil aggregates (D), and the root surrounded by fungal hyphae and soil particles (E and F). The material in E and F remains attached to the root even after 3.5 hrs of incubation in various water-based solutions.

The space remaining between the roots, hyphae, soil particles, organic matter, bacteria, other microbes, sugars, glomalin, and cations is open pore space that is filled with a combination of air and water depending on the soil moisture content.



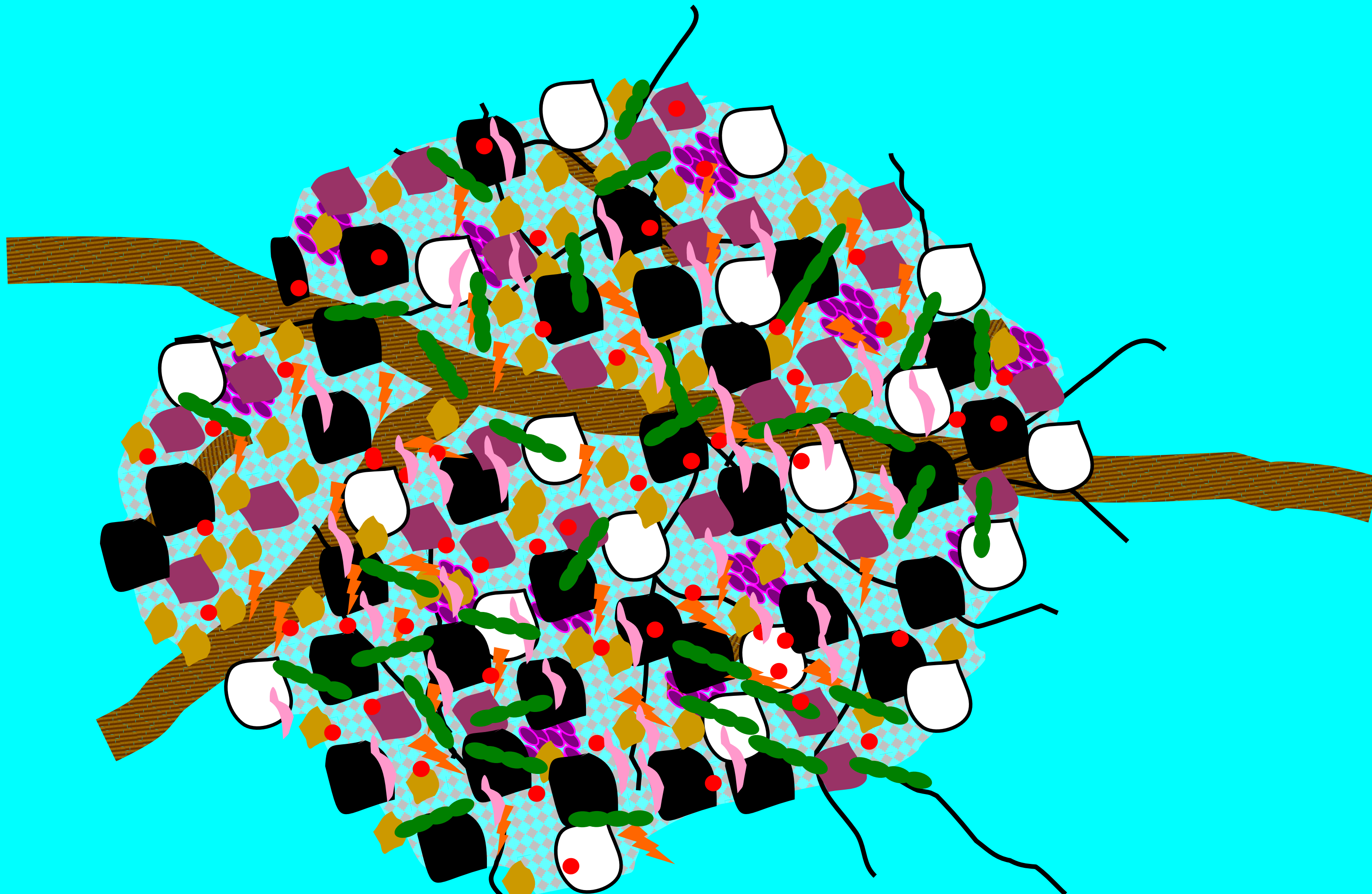
Aggregate Stabilization Model

A dry aggregate will have its pore space filled with air. When it rains water will move into this pore space.

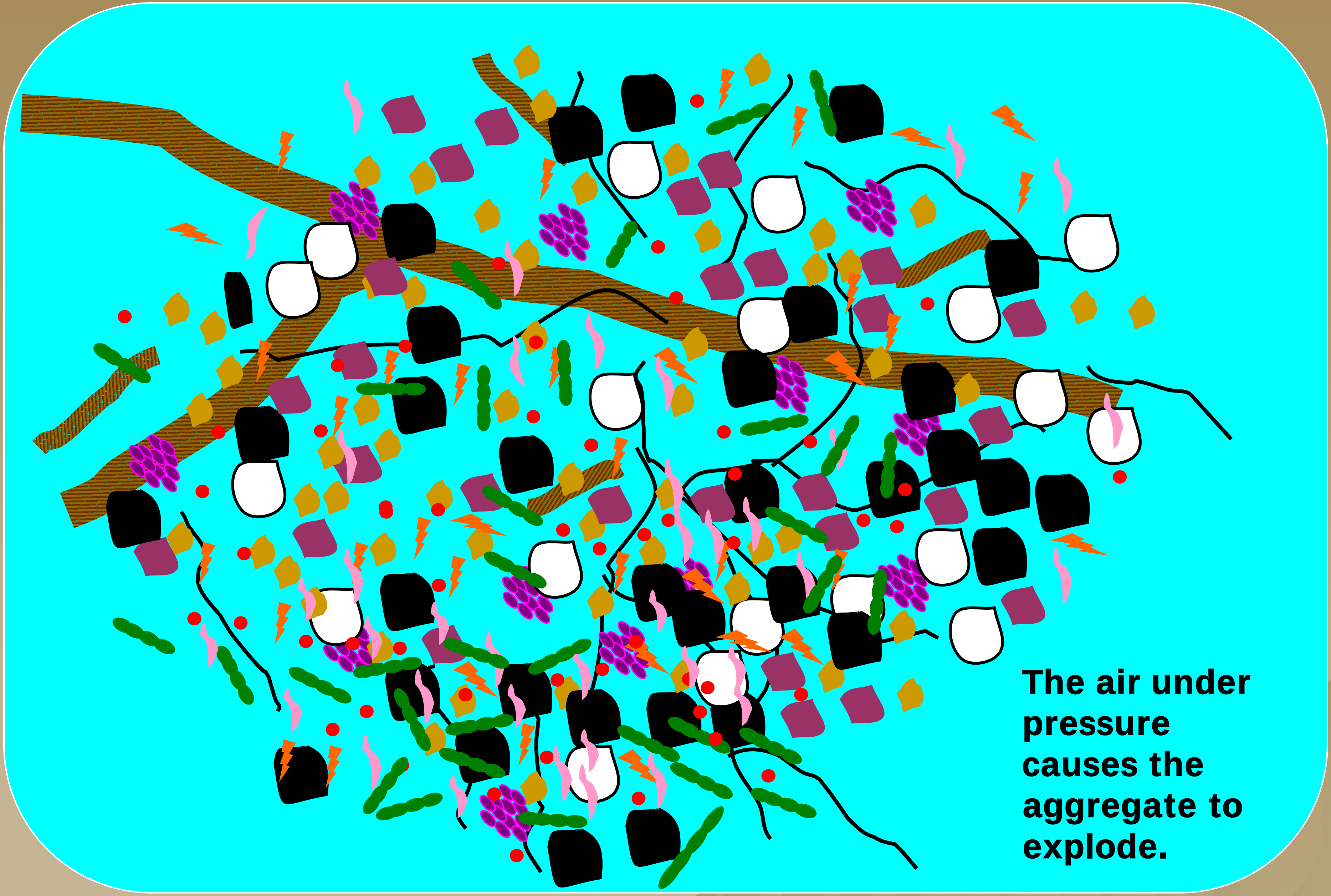


Aggregate Stabilization Model

As the water moves in, the air becomes trapped and condenses into the diamond-shaped figures, where air-pressure builds.

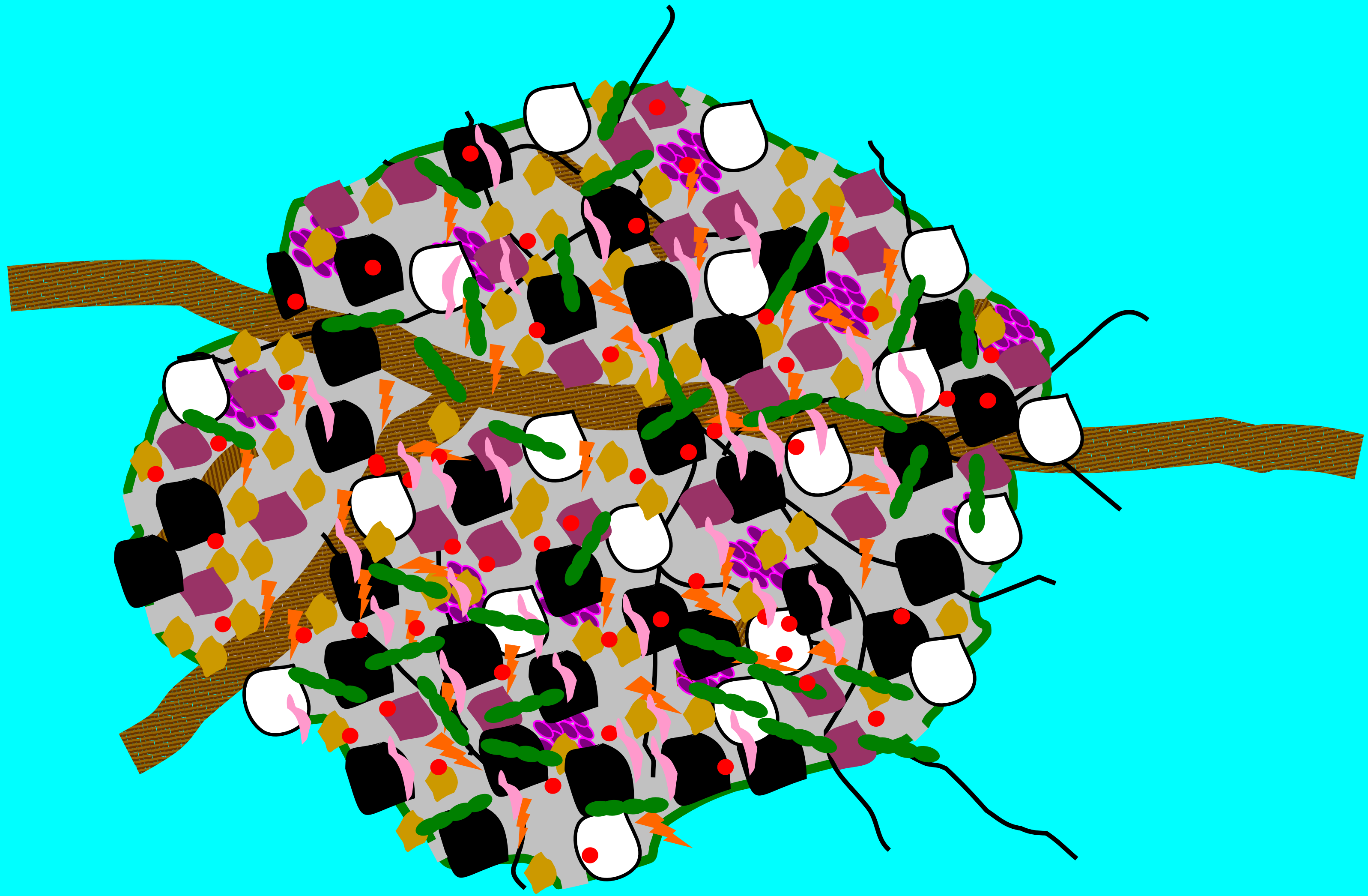


Aggregate Stabilization Model



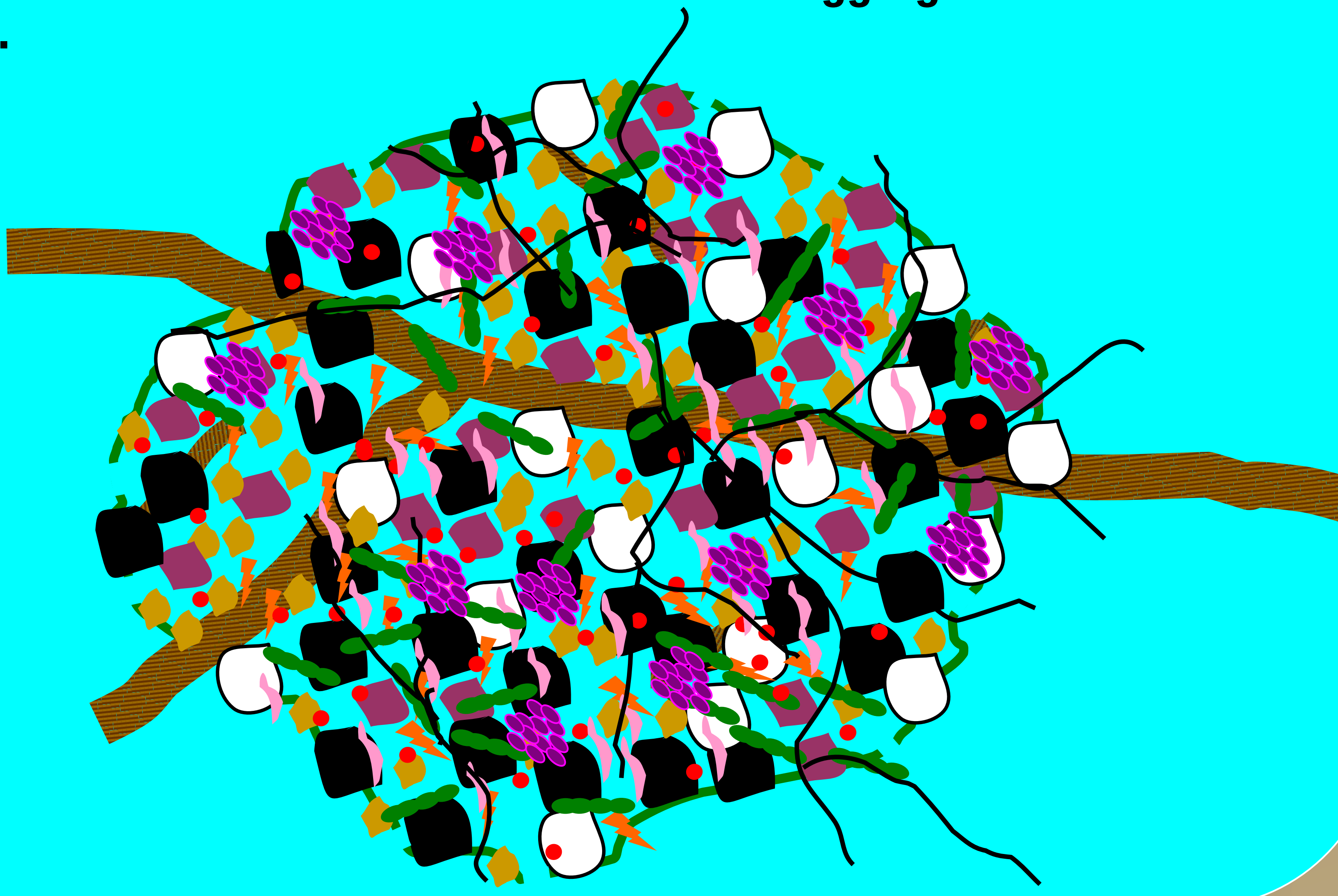
Aggregate Stabilization Model

Glomalin forms a lattice-like coating on the surface of aggregates so water can only enter the aggregate through tiny holes.



Aggregate Stabilization Model

Because the water enters the pore space in the aggregate more slowly when there are only a few tiny points of entry, air molecules have time to dissolve into the water and the aggregate remains stable.



How do we know that GLOMALIN helps to stabilize aggregates?

- **Laboratory Analyses**
  - Glomalin extraction from soil and quantification
  - Water stable aggregation measurements
  - Comparison of glomalin quantities with water stable aggregation measurements
  - Using a laboratory procedure to indicate the location of glomalin on hyphae and aggregates
- **Visual Observation of Glomalin 'Scum'**
  - Submerging soil samples in water and observing scum on the water surface indicates how much glomalin is on stable aggregates – Scum Test

Demonstration of Aggregate Stability

The samples below are 1 to 2 mm aggregates separated by dry sieving from Wilton silt loam soils under different management.

Conventional Till, Spring Wheat-Fallow

No-Till, Spring Wheat-Winter Wheat-Sunflower

Moderately-grazed pasture

Water-stable aggregation = 14%, Total Glomalin = 2.4 mg g^{-1}

Water-stable aggregation = 47%, Total Glomalin = 3.2 mg g^{-1}

Water-stable aggregation = 93%, Total Glomalin = 7.9 mg g^{-1}

Glomalin on Water Stable Aggregates

Following a laboratory procedure in which a 1 to 2 mm aggregate is incubated for at least 3.5 hours in various solutions. The location of glomalin, which forms a lattice-like protective coating, on the aggregate is visible as green spots under blue light.

Scum Test

Scum floating on the water surface after placing soil in water contains glomalin. When very little scum is present, as in the case of big bluestem, most of the glomalin, i.e. scum, is on stable aggregates in the soil at the bottom of the bucket.

Switchgrass

Switchgrass – Immediately After Placing in Water

Switchgrass – After Minimal Manual Disruption

Switchgrass

Big Bluestem

Alfalfa

Compaction Impacts on Root Growth

In poorly aggregated soil, or where zones of compaction exist due to poor aggregation, roots will grow where there is no compaction (left) or will bend to avoid compacted zones (above).

BUILD SOIL BIOTA

- To cultivate soil organisms, they need:
  - Food
    - Diverse crop rotation
    - Consistent source from continuous cover provided by perennials, cover crops, or long-season crops
  - Habitat
    - Stable aggregates that are not destroyed by tillage
- The benefits of cultivating soil organisms are:
  - Increased soil organic matter
  - Increased fertility
  - Increased profitability
  - Long-term sustainability

To be a successful farmer one must first know the nature of the soil.

- Xenophon, Oeconomicus, 400 B.C.

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