Mycorrhizae are the rule, not the exception, for most plant species.

**Symbiosis Example: Mycorrhizae**

- Mycorrhizae (fungus) - riza (root)

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**Table 2. Nutrients taken in by plants that are infected and not infected with AMh:**

<table>
<thead>
<tr>
<th>Element</th>
<th>No Mycorrhizae</th>
<th>With Mycorrhizae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Potassium</td>
<td>4,000</td>
<td>9,300</td>
</tr>
<tr>
<td>Calcium</td>
<td>1,200</td>
<td>1,600</td>
</tr>
<tr>
<td>Magnesium</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Zinc</td>
<td>25</td>
<td>95</td>
</tr>
<tr>
<td>Copper</td>
<td>10</td>
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<td>Manganese</td>
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Although mycorrhizae don’t make humus, it is difficult to start the humification process without them. They bring large quantities of soluble C into the soil from plant roots, which feeds the microbes involved in the complex process. Photo: Jill Clapperton.

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**Rhizobia Bacteria**

Forms a symbiotic relationship with the leguminous plant. The plant supplies all the necessary (C) energy for the bacteria. The bacteria fixes nitrogen into the plant.
Mycorrhizae are the rule, not the exception, for most plant species.

**Symbiosis Example: Mycorrhizae**

- **Mykós (fungus)- riza (root)**

- Plants use 5-20% of C from photosynthesis to ‘feed’ fungi
- Fungi increase adsorptive root surface area at least 10x
- Fungi increase nutrient uptake especially P and Zn
- Fungi suppress pests and diseases
- Fungal networks build soil aggregates

Although mycorrhizae don’t make humus, it is difficult to start the humification process without them. They bring large quantities of soluble C into the soil from plant roots, which feeds the microbes involved in the complex process. Photo: Jill Clapperton.

Table 2. Nutrients taken in by plants that are infected and are not infected with AM when no phosphorus is added to corn (8).

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<td>1340</td>
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</tr>
<tr>
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</tr>
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<td>Magnesium</td>
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Dr. K. Grover (NMSU)

Rhizobia Bacteria
Forms a symbiotic relationship with the leguminous plant.
The plant supplies all the necessary (C) energy for the bacteria.
The bacteria fixes nitrogen into the plant.
Ways To Increase Mycorrhizal Fungi:
Reduce/Eliminate Chemical Use
Reduce/Eliminate Tillage
Reduce/Eliminate Synthetic Fertilizers
Living Plant Roots As Long As Possible

Indication: High-input agriculture and excessive tillage select for less effective AM Fungal and microbial Communities

Schubert and Hayman (1986) found mycorrhizae was no longer effective when 100 mg or more of P was added per kilogram of soil (100 ppm).
Johnson 1993; Corkidi et a. 2002; Ryan & Graham 2002; Anderson & Carney 2004

Fungi Retain Nutrients

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

- Assists with P uptake from soil
- Moves P from the non-legume plant to the legume plant
- Moves N from the legume plant to the non-legume plant
- Increases area roots can reach.

At hyphal tips- bacteria produce enzymes that make unavailable plant nutrients available. I.e. bacteria and fungi make nutrients available to plants that plants cannot access or extract.

MF- extends the reach of roots, small to us, but huge to a root. MF – like nutrient pipelines.

Mycorrhizal fungi - powerhouse of the soil - Dr. Christine Jones
This is what it looks like in the soil system when roots are trying to gather available nutrients. Plant roots are not very efficient at absorbing moisture and nutrients on their own. They need help.

Collaboration between root fungus and roots

Mycorrhizae assist with Organic Nitrogen Uptake

- Need aerobic conditions - 5 to 6 mg oxygen per liter
- In low oxygen conditions anaerobic bacteria attack and eat fungi
- Disease causing fungi benefit under anaerobic conditions

Collaboration between roots and fungi in the soil increase surface area for nutrient absorption.

Amino Acids inside mycorrhizal hyphae

Amino Acids have entered the root From mycorrhizal hyphae
Fungal hyphae binding soil particles together into aggregates. Arbuscular Mycorrhizal fungi produces Glomalin that glues soil particles together.

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Table 2. Nutrients taken in by plants that are infected and are not infected with AM when no phosphorus is added to corn (8).

There would be sufficient length of mycorrhizal hyphae in the top 10 cm of just four square metres of healthy grassland soil to stretch all the way around the equator (Leake et al, 2004)

Although mycorrhizae don’t make humus, it is difficult to start the humification process without them. They bring large quantities of soluble Carbon in to the soil from plant roots, which feeds the microbes involved in the complex process. Photo: Jill Clapperton

What tillage does to the soil
- Destroys aggregates
- Exposes organic matter to decomposition
- Compacts the soil
- Damages soil fungi
- Reduces habitat for the Soil Food Web
- Disrupts soil pore continuity
- Increases salinity at the soil surface
- Plants weed seeds

Although mycorrhizae don’t make humus, it is difficult to start the humification process without them. They bring large quantities of soluble Carbon in to the soil from plant roots, which feeds the microbes involved in the complex process. Photo: Jill Clapperton

White areas indicating presence of glomalin (Dr. Kris Nichols, USDA/ARS Mandan, ND)

Undisturbed prairie

Tilled farm soil

Fig. 2. Glomalin is extracted from soil with high heat. After removal of glomalin, soil is transformed from a rich brown color to a grey mineral color.
Factors affecting Nutrient Cycling & Soil Health:
- Temperature
- Oxygen
- Soil Moisture
- Soluble Organic Carbon
- C:N ratio
- Salinity
- pH
- Predation/Competition
- Nutrients
- Diverse Soil Food Web
- F:B ratio

Healthy Soil have Ideal Carbon, Nutrient & Water Cycles

Macroaggregate (2.0 – 5.0 mm dia.)

Microaggregate (< 0.3 mm dia.) Consisting of Clay, silt, humus, particulate organic matter, very fine sand, precipitated minerals, microorganisms & other organic compounds.

White areas indicating presence of glomalin-related proteins (Dr. Kris Nichols)

Healthy soil has optimum biological, physical & chemical properties

Soil Solution
(the Soil Solution is held within & between the Macroaggregates & Microaggregates)

Dissolved Oxygen & Carbon Dioxide

Oxygen (O_2 gas in macro pores)

Carbon Dioxide (CO_2 gas in macro pores)

Mineralization ↔ Immobilization

C:N Ratio

Soluble Nutrients (e.g., OC, ON, OP, NH_4^+, NO_3^-, other: K^+, Ca_2^+, etc.)

Fungal:Bacterial Ratio

Higher Carbon-Use Efficiency

Bacteria (other: protozoa, nematodes, etc.)

Mycorrhizal hyphae

Root hair
Without biology, you are stuck with pH as the sole arbiter of what is available to plant roots. Add microbes, and plant nutrition is no longer ruled by pH alone. Microbes can use enzymes to solubilize plant nutrients.
Healthy soil allows for Straight Roots

Compacted Layers

What do Your Roots Say?

Roots run laterally on top of a compacted layer

Healthy Roots
• Uninhibited root growth
• Lots of fine roots
• White (no root pathogens)

Unhealthy Roots
• Restricted root growth
• Few fine roots
• Short thick roots
• Discolored & Lesions (root pathogens present)

• Roots are a great indicator of soil conditions, especially related to compaction.
• Roots should grow uninhibited into the soil profile, generally they hit a compacted layer at varying depths.
• Compacted layers that exceed 300 psi will restrict root growth
• Roots need a pore space greater than 0.1 mm
Grazing (Adaptive Grazing; take 1/3)

Ungrazed vs Grazed

The difference in land management techniques
Adjoining paddocks March 2010

Planned grazed and Pasture Cropped
Continuously grazed and fertilised annually

Stubble/Pasture Health

Grazing Period
Short Long Continuous

Recovery Allowed
Long Short None
Root development is strongly related to frequency and extent of leaf removal

Cut to 2” every week

Cut to 2” every 4 weeks

Rhizosphere Biology

The Rhizosphere is the area:

- Immediately surrounding (about 0.5-1 inches) the plant roots
- Of highest biological activity due to the high concentration of photosynthetically-derived carbon (approx. 70%) – Juma, 1993
- Has some of the greatest impact on soil structure
- Of the majority of the nutrient cycling activity
- Most impacted by aboveground management

Dr. Kris Nichols
Biological Disturbance

- No diversity in the crop rotation
  - Growing single species or few crops in rotation
  - Lack of diversity limits diversity of plant root exudates
  - Hampers the development of a diverse soil biota
- Overgrazing
  - Plants are exposed to intensive grazing for extended periods of time, without sufficient recovery periods
  - Many pasture have single species grasses

Impact of Biological Disturbance from Overgrazing

1. Disturbance stimulates weeds populations
2. Diminishes Fungal biomass and spores
3. Reduces infiltration - inefficient water cycle
4. Increases soil temperature
5. Diminishes the habitat of the soil engineers and other diverse soil organisms
6. Increases the usage of chemical inputs
(II) **Aggregates**: Water-stable surface macro-aggregates, which provide ideal soil structure (crumbly/granular & cottage cheese appearance). There is no surface or subsurface compaction (ideal bulk density/porous soil). Saline & sodic conditions are easier to manage.
Healthy soils are held together by soil glues, or glomalin, that are produced by fungi. Soils rich in soil biota hold together, while soils devoid of soil life fall apart and form a layer of sediment in the bottom of the jar. Pictured above, the soil on the left is from a field that has been managed using no-till for several years. The soil on the right is from a conventionally-tilled field.

Water-Stable Aggregates have minimal slaking
Healthy Soils are well aggregated

Importance of Stable Aggregate:

- Ultimate ‘home’ of soil microbes (spaces in between)
- Increases pore space and sizes of space (decrease density and compaction)
- Large pores important for infiltration, drainage, aeration
- Small pores important for water storage and protection of organic matter and microbes

Soil Food Web Benefits:
Formation & Stabilization of Aggregates

- Chemical interactions
  - Polysaccharides (sugars) released by bacteria act like glues to bind particles
  - Glycoproteins (glomalin-related soil proteins and other proteins) act like glues

How do soil aggregates form?

Glycoproteins on soil aggregates
Dr. Nichols, USDA-ARS

Bacteria (ovals) with ‘sticky’ polysaccharides (red arrows)
SEM photo source: Eckhorst, Thula & Tippkoetter, Rolf
Micropedology – The hidden world of soils. University of Bremen, Germany
Healthy Soils are well aggregated

Soil Food Web Benefits: Formation & Stabilization of Aggregates

- Physical interactions
  - Plant roots enmesh soil particles
  - Earthworms (casts) and termites (mounds)
  - Soil fungi and some Actinobacteria produce filaments that physically enmesh soil particles together

How do soil aggregates form?

Stabilization of soil structure by actinomycete (bacterial) filaments

Netlike fungal mycelia stabilize micro-aggregates

Why Are Stable Aggregates Important?

- Aggregates are comprised of mineral particles, organic matter, biological ‘glues’ and ‘nets’, and pore space
- These pores allow water to infiltrate, drain, and be stored for future plant use
Building Aggregates means improving biological functioning through physical and biological methods

Reduce tillage, increase fresh organic matter availability to decomposers, improve environment for plants and soil organisms

Brady and Weil, 2002
Creating a **Soil Habitat** is the first step to managing **soil biota** for long-term soil quality, soil health, and productivity.

Soil biological processes are responsible for supplying approximately 75% of the plant available nitrogen and 65% of the available phosphorus in the soil. Like all organisms, those inhabiting your soil need **food** and a **favorable environment**. Adequate organic matter content, ample aeration, moderate moisture, neutral **pH**, and warm temperatures all favor increased microbial activity.

### Soil Food Web (Soil Livestock)

**Soil Food Web** (Soil Livestock) Photos: Soil Biology Primer

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### Rhizosphere

- **Narrow region of soil directly around roots.**
- Living roots release many types of organic materials.
- These compounds attract **Bacteria** that feed on the proteins & sugars.

### Soil Health

**Soil Health** is an attempt to **bring together** different aspects of the soil with the understanding that they are **inter-related** and that they must **operate in synergy** for optimum and sustainable functioning of the soil media.

### What Do They Weigh?

- **Bacteria**: 2,000 - 2,500 Lbs/Acre
- **Fungi**: 1,000 - 15,000 Lbs/Acre
- **Protozoa**: 20 - 300 Lbs/Acre
- **Nematodes**: 10 - 300 Lbs/Acre
- **Microbes in Humans**: 3 Lbs/Person

Source:

The zone of greatest microbial activity usually occurs within the top couple of inches of the soil surface where optimal temperature, moisture, oxygen and nutrient conditions exist.
Aggregate stability will only regenerate biologically.

Colonizing mycorrhizal fungi and aerobic microbes (e.g. rhizobium) build soil structure and cycle nutrients.

Soil Glue (polysaccharides, proteins and root exudates): form water stable aggregates that are nutrient rich.

Healthy soil is like a Sponge: It can hold a lot of water.

For every 1% that you increase SOM, waterholding capacity increases 20,000-25,000 gallons per acre.
Does your Soil have a Living Skin?

Good Soil Structure (Crumbly/Granular)

Granular Structure: similar to Cottage Cheese in structure

Healthy Soil

Ideal Soil Composition

Compacted Soil

Crumbly structure of surface soil is associated with adequate organic matter content.
Fields outside the project area: Typical no-till field without cover crops and diversity: Small detritusphere other spheres diminished. Notice the color and horizontal compaction.

Fields inside the project area: Ecological farming- no-till with diverse covers (less than 2 years): Notice all 5 well defined spheres present, dark humic color and increased earthworms populations.

Healthy soil has Crumbly/Granular structure

Soil Crusts
Ref.: NRCS Soil Quality Indicators

Shovel:
A Tool to determine soil health

Left: Note the surface crust on this soil. The field was in tall fescue sod for 11 years. It was cleared and plowed using conventional tillage methods. Photo courtesy Bobby Brock, USDA NRCS (retired). Right: Collected from a no-till field in Georgia’s Southern Piedmont, good structure and aggregation are evident in the soil on the right. The same soil formed a structural crust under conventional tillage. Note the sunlight reflectance of the crusted soil. Photo courtesy James E. Dean, USDA NRCS (retired).
An electron micrograph of Soil Aggregate, held together by carbon. Soil aggregates are a storage place for water, nutrients and soil micro-organism (Winger, 2014).

Good Soil Structure (Crumbly/Granular)

An Aggregate is like a House
The interesting stuff is going on in the “empty” spaces!

- **An electron micrograph of Soil Aggregate, held together by carbon.** Soil aggregates are a storage place for water, nutrients and soil micro-organism.
- **Poor Soil Structure (unstable aggregates/collapsed; consisting of micro-aggregates)**