Nitrogen-Fixing Legumes

Phenomenon/Problem:

How can a relationship between legumes and bacteria help plants grow and change the availability of nitrogen in an agricultural system?

Essential Questions:

- Why do plants need nitrogen, and where do they normally get it?
- If nitrogen is abundant in the atmosphere, why can't plants use it directly?
- What is happening inside the nodules found on legume roots?
- How do nitrogen-fixing bacteria make atmospheric nitrogen available to plants?
- How do legumes and nitrogen-fixing bacteria each benefit from their relationship?
- How do matter and energy move between a legume and the bacteria living in its root nodules?
- How does access to usable nitrogen affect plant growth and biomass production?
- What happens to the nitrogen contained in a plant after the plant dies or is harvested?
- How can nitrogen fixed by bacteria eventually become available to other organisms?
- How can growing legumes change the movement and availability of nitrogen within an agricultural system?
- Why might a crop grown after a legume require a different amount of nitrogen fertilizer?
- How do environmental conditions and agricultural management affect nitrogen fixation and cycling?
- How can farmers manage plant–microbe interactions to support crop production while managing nitrogen resources?

Stimuli: How will students experience and/or observe the phenomenon/problem?

Two soybean plants are grown under similar conditions with little available nitrogen in the soil. One develops numerous nodules on its roots and grows well; the other develops few or no nodules and shows poorer growth.

Soybean Plant with Roots



From Adobe Stock: 1080924181

Soybean Roots

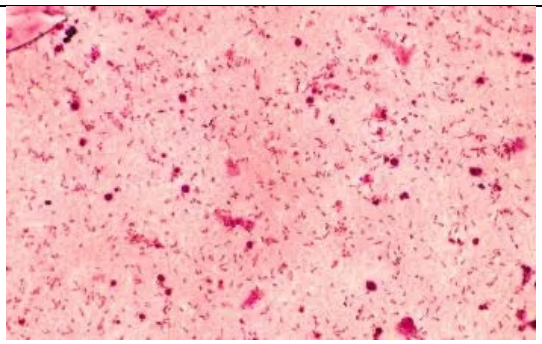


From: https://extension.psu.edu/evaluating-nodulation-in-soybeans

A small bacterium known as Rhizobium colonizes the roots of legume plants.

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Rhizobium bacteria at 1000x magnification

Image from:
https://www.elmdirt.com/blogs/news/rhizobium-nitrogen-fixing-bacteria?srsltid=AfmBOooOXVrC0-gfz_Dl_PMjUnXTJQuREcmL72Shd0p1_a6i6UnCYK8N

Legume plants grown with and without compatible nitrogen-fixing bacteria show differences in plant growth, biomass, leaf color, or nitrogen content.



Soybean field not previously planted to soybeans. Dark green strips were inoculated with rhizobia.

Image from:
https://www.pioneer.com/us/agronomy/soybean-nodulation-biology.html

Related Phenomena/Problems:

- Soybean plants with many root nodules grow differently from soybean plants with few or no nodules.
- Legumes can grow in nitrogen-poor soils where some non-legume plants struggle.
- Soybeans inoculated with compatible rhizobia may develop more nodules and grow differently than uninoculated plants.
- Cutting open an active legume root nodule can reveal a pink or reddish interior.
- Clover or other legumes are sometimes planted as cover crops between other crops.
- Farmers sometimes inoculate legume seeds with bacteria before planting.
- Different legume species form associations with particular types or strains of nitrogen-fixing bacteria.
- Nitrogen contained in legume residues changes form as the residues decompose.
- Removing a legume crop at harvest versus leaving plant residues in the field changes how much fixed nitrogen remains in the agricultural system.
- Soil nitrogen levels and forms change throughout a growing season even when no fertilizer is added.
- Waterlogged, drought-stressed, acidic, or otherwise unfavorable soil conditions can reduce nitrogen fixation even when legumes and bacteria are present.

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- Two fields growing the same legume can show different levels of nodulation and nitrogen fixation.
- Farmers must balance biological nitrogen fixation, crop rotation, fertilizer inputs, and crop nitrogen needs when developing a nutrient-management plan.

Considerations for Instructional Design:

- Develop and revise a model tracing nitrogen from atmospheric N_2 through nitrogen-fixing bacteria, the legume, plant biomass, decomposers, soil, and potentially a subsequent crop. Use the model to identify where nitrogen changes form and where it moves within or leaves the agricultural system. (MOD, Energy & Matter)
- Analyze data comparing legumes with and without effective bacterial inoculation or nodulation, using measures such as plant biomass, leaf nitrogen, nodule number, or nitrogen content to identify patterns connecting the plant–bacteria relationship to plant growth. (DATA, Patterns)
- Plan and carry out an investigation comparing legume growth or nodulation under different conditions, such as inoculated versus uninoculated seeds or different levels of available soil nitrogen. Use evidence to determine which factors influence the relationship between legumes and nitrogen-fixing bacteria. (INV, Cause & Effect)
- Construct an explanation for how the interaction between legumes and nitrogen-fixing bacteria benefits both organisms. Account for the movement of nitrogen-containing matter to the plant and carbon-containing compounds/chemical energy to the bacteria. (CEDS, Energy & Matter)
- Use mathematical or computational representations to account for nitrogen moving into, through, and out of an agricultural system—for example, nitrogen fixation, fertilizer inputs, harvested nitrogen, crop residues, and soil nitrogen. Use the representation to determine whether nitrogen is conserved as it changes form and location. (MATH, Energy & Matter)
- This is particularly well aligned with HS-LS2-4, which emphasizes using mathematical representations to describe matter cycling and specifically identifies nitrogen as an example.
- Analyze crop-rotation data comparing crop growth, yield, or fertilizer requirements following legumes versus non-legumes. Use patterns in the evidence to explain how an interaction occurring at the scale of a root nodule can produce effects at the scale of an agricultural ecosystem. (DATA, Scale, Proportion & Quantity)
- Develop a systems model comparing what happens to fixed nitrogen when a legume is harvested, grazed, terminated as a cover crop, or left to decompose. Identify system boundaries and predict how changing one pathway affects nitrogen available elsewhere in the system. (MOD, Systems & System Models)

Explanation:

Plants require nitrogen to build important biological molecules, including amino acids and proteins, nucleic acids such as DNA and RNA, and chlorophyll. Although Earth's atmosphere contains abundant nitrogen gas (N_2), plants cannot directly use atmospheric N_2 as their nitrogen source. Plants generally absorb nitrogen through their roots in biologically available forms such as ammonium and nitrate.

Legumes such as soybeans, peas, beans, clover, and alfalfa can form a mutualistic relationship with nitrogen-fixing bacteria, including bacteria commonly referred to as rhizobia. The bacteria infect legume roots and stimulate the formation of specialized structures called root nodules. These nodules create conditions that support the exchange of matter and energy between the plant and bacteria.

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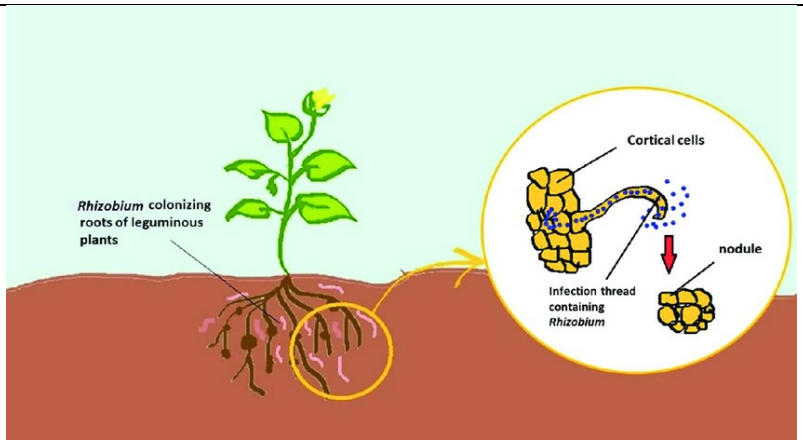


Image from: https://www.researchgate.net/figure/Nitrogen-fixation-in-leguminous-plants-by-rhizobium_fig3_369525343

Inside the nodules, the bacteria carry out biological nitrogen fixation. Using the enzyme nitrogenase, they convert atmospheric nitrogen gas into ammonia, which can be incorporated into biologically useful nitrogen-containing compounds. This gives the plant access to a source of nitrogen that would otherwise be unavailable to it.

The relationship also benefits the bacteria. Through photosynthesis, the plant captures light energy and stores it as chemical energy in carbon-containing molecules. The plant supplies carbon compounds to the bacteria, which provide the energy needed to support the energetically expensive process of nitrogen fixation. In return, the bacteria provide the plant with biologically available nitrogen. The interaction is therefore an exchange in which matter cycles and energy flows between organisms.

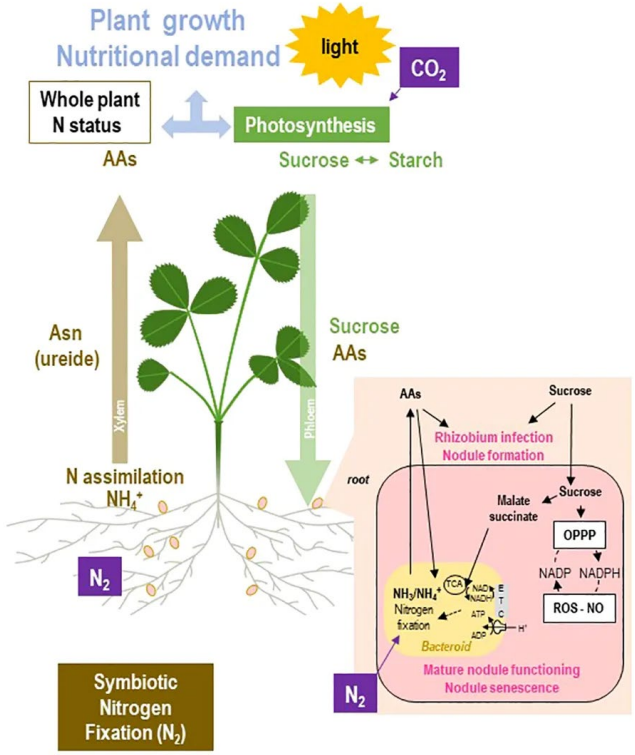


Image from: https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1114840/full

This relationship can directly influence plant growth. When usable nitrogen in the soil is limited, legumes with effective nitrogen-fixing bacteria can continue obtaining nitrogen needed to synthesize proteins, nucleic acids, chlorophyll, and

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other cellular materials. Legumes without an effective bacterial partnership may experience nitrogen limitation, which can restrict photosynthesis, growth, and biomass production. The effects can also extend beyond an individual plant. Nitrogen fixed through the plant-bacteria relationship becomes incorporated into plant tissues and other organic matter. When roots, nodules, leaves, or other plant residues die and decompose, microorganisms break down this organic matter, returning some nitrogen to the soil in forms that can eventually become available to other organisms. Some nitrogen leaves the agricultural system in harvested crops, and some may be lost through leaching, runoff, or gaseous pathways. Farmers work to reduce these losses through practices such as cover crops, no-till, buffer zones, and careful timing and rates of fertilizer application.

For this reason, including legumes in crop rotations can influence the amount and form of nitrogen moving through an agricultural system. A crop grown after a legume may sometimes require less supplemental nitrogen fertilizer because the previous crop and its associated microorganisms have altered the system's nitrogen inputs and cycling. However, nitrogen fixation does not simply "add fertilizer to the soil." How much nitrogen ultimately becomes available to a following crop depends on the legume species, amount of nitrogen fixed, how much nitrogen is removed during harvest, decomposition of remaining plant material, soil conditions, microbial activity, weather, and management practices.

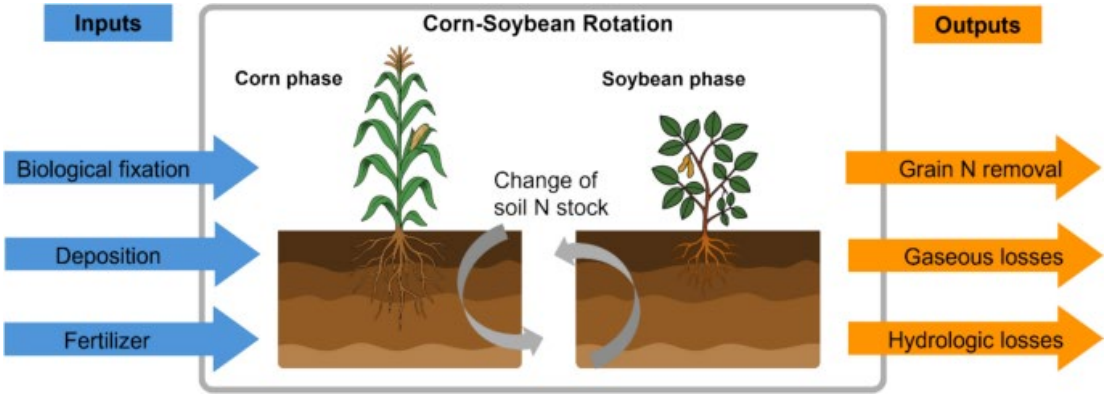


Image from: https://link.springer.com/article/10.1007/s10533-026-01325-z

In addition to the life cycle of certain crops, there may be economic factors to consider when rotating crops. At the end of the day, farming is a business. Crop rotation does not replace the use of fertilizers, and based on market prices, a farmer may not be able to use crop rotation on every acre of land every year. For example, in a year where bean or wheat prices are low, a farmer may have to plant a crop like corn or cotton on a larger scale in order to maintain cash flow and meet required payments.

Student and teacher questions about this phenomenon/problem that could be instructionally productive:

- What evidence suggests that the nodules and bacteria are connected to the differences we see aboveground?
- What is the plant getting from this relationship—and what might the bacteria be getting?
- If nitrogen is all around the plant in the atmosphere, why does the plant need bacteria to access it?
- Can we trace a nitrogen atom from the atmosphere into the soybean plant?
- Where does the energy needed for this relationship ultimately come from?
- What happens to that nitrogen when the plant dies, decomposes, or is harvested?
- How can something happening inside a small root nodule produce the field-scale pattern we observed?

Explaining the phenomenon/problem or related phenomena could lead students toward developing the following DCIs:

HS-LS2.B: Cycles of Matter and Energy Transfer in Ecosystems (Nitrogen Cycling, Ag Ecosystems)

- Photosynthesis and cellular respiration (including anaerobic processes) provide most of the energy for life processes. (HS-LS2-3)

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HS-LS2.A: Interdependent Relationships in Ecosystems (Symbiosis)

- Ecosystems have carrying capacities, which are limits to the numbers of organisms and populations they can support. These limits result from such factors as the availability of living and nonliving resources and from such challenges such as predation, competition, and disease. Organisms would have the capacity to produce populations of great size were it not for the fact that environments and resources are finite. This fundamental tension affects the abundance (number of individuals) of species in any given ecosystem. (HS-LS2-1, HS-LS2-2)

HS-LS1.C: Organization for Matter and Energy Flow in Organisms (Plant Growth)

- The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen. (HS-LS1-5)
- As matter and energy flow through different organizational levels of living systems, chemical elements are recombined in different ways to form different products. (HS-LS1-6, HS-LS1-7)

HS-LS2.C: Ecosystem Dynamics, Functioning, and Resilience (Ag Ecosystems)

- A complex set of interactions within an ecosystem can keep its numbers and types of organisms relatively constant over long periods of time under stable conditions. If a modest biological or physical disturbance to an ecosystem occurs it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability. (HS-LS2-2, HS-LS2-6)

Notes about relevance and authenticity (funds of knowledge, interests, identity)
Why might students be engaged?

- It presents a hidden biological mystery. Plants growing in seemingly similar conditions can look very different depending on whether particular bacteria are present, prompting students to wonder what is happening belowground.
- Root nodules provide a surprising observable feature. Seeing nodules on legume roots—and discovering that they contain bacteria performing an important function—gives students something tangible to investigate.
- It challenges an intuitive idea about plant nutrition. Students may know that plants need nitrogen but be surprised to learn that, although the atmosphere is mostly nitrogen gas, plants cannot directly use that nitrogen. This creates a productive puzzle: How does atmospheric nitrogen get into a plant?
- It involves a mutually beneficial partnership. Students can investigate what two very different organisms—the plant and bacteria—each contribute and receive, making symbiosis more mechanistic than simply labeling the relationship as "mutualism."
- Students can follow matter through a real biological system. Nitrogen can be traced from the atmosphere → bacteria → plant → soil → other organisms, allowing students to investigate something invisible through models, data, and evidence.
- A microscopic interaction can have field-scale consequences. Something happening inside tiny structures on a plant's roots can influence plant growth, soil nitrogen cycling, crop rotations, and management decisions.
- It connects biology to an authentic agricultural problem. Farmers must ensure crops have enough nitrogen to grow while managing fertilizer inputs, soil conditions, and crop rotations. Biological nitrogen fixation provides a real example of organisms influencing how nutrients move through an agricultural system.

Resources/References

Biological Nitrogen Fixation

Legume Life Cycles and Characteristics

Legumes and Soil Quality - USDA

Giving Proper Nitrogen Credit for Legumes in Corn and Milo Rotations

National Agronomy Manual

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Rhizobial-Host Interactions and Symbiotic Nitrogen Fixation in Legume Crops Toward Agriculture Sustainability

Rhizobium: The Nitrogen-Fixing Bacteria Every Gardener Needs to Know

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