Chapter 37

Soil and Plant Nutrition

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

Neil Campbell and Jane Reece

Lectures by Chris Romero, updated by Erin Barley with contributions from Joan Sharp

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Overview: “The Nation that Destroys Its Soil Destroys Itself”

• Farmland productivity often suffers from chemical contamination, mineral deficiencies, acidity, salinity, and poor drainage

• Healthy soils improve plant growth by enhancing plant nutrition

• Typically, plants obtain carbon dioxide from the air, and water and minerals from the soil
Concept 37.1: Soil is a living, finite resource

- Plants obtain most of their water and minerals from the upper layers of soil
- Living organisms play an important role in these soil layers
- This complex ecosystem is fragile
Soil Texture

• Soil particles are classified by size; from largest to smallest they are called sand, silt, and clay

• Soil is stratified into layers called soil horizons

• Topsoil consists of mineral particles, living organisms, and humus, the decaying organic material
Fig. 37-2

A horizon

B horizon

C horizon
• After a heavy rainfall, water drains from the larger spaces in the soil, but smaller spaces retain water because of its attraction to clay and other particles.

• The film of loosely bound water is usually available to plants.

• **Loams** are the most fertile topsoils and contain equal amounts of sand, silt, and clay.
Topsoil Composition

- A soil’s composition refers to its inorganic (mineral) and organic chemical components
Inorganic Components

- Cations (for example $K^+$, $Ca^{2+}$, $Mg^{2+}$) adhere to negatively charged soil particles; this prevents them from leaching out of the soil through percolating groundwater.
During **cation exchange**, cations are displaced from soil particles by other cations.

Displaced cations enter the soil solution and can be taken up by plant roots.

Negatively charged ions do not bind with soil particles and can be lost from the soil by leaching.

Animation: How Plants Obtain Minerals from Soil
Soil particle

\[
\begin{align*}
\text{K}^+ & \quad \text{K}^+ \\
\text{Ca}^{2+} & \quad \text{Mg}^{2+} \\
\text{H}_2\text{O} + \text{CO}_2 & \rightarrow \text{H}_2\text{CO}_3 \\
\text{H}_2\text{CO}_3 & \rightarrow \text{HCO}_3^- + \text{H}^+ \\
\end{align*}
\]

Root hair

Cell wall
Organic Components

- Humus builds a crumbly soil that retains water but is still porous
- It also increases the soil’s capacity to exchange cations and serves as a reservoir of mineral nutrients
- Topsoil contains bacteria, fungi, algae, other protists, insects, earthworms, nematodes, and plant roots
- These organisms help to decompose organic material and mix the soil
Soil Conservation and Sustainable Agriculture

• In contrast with natural ecosystems, agriculture depletes the mineral content of soil, taxes water reserves, and encourages erosion.

• The goal of sustainable agriculture is to use farming methods that are conservation-minded, environmentally safe, and profitable.
Irrigation

- Irrigation is a huge drain on water resources when used for farming in arid regions.
- The primary source of irrigation water is underground water reserves called aquifers.
- The depleting of aquifers can result in subsidence, the settling or sinking of land.
Land subsidence in California

Sinkhole in Florida
Land subsidence in California
Sinkhole in Florida

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- Irrigation can lead to *salinization*, the concentration of salts in soil as water evaporates.
- Drip irrigation requires less water and reduces salinization.
Fertilization

- Soils can become depleted of nutrients as plants and the nutrients they contain are harvested

- **Fertilization** replaces mineral nutrients that have been lost from the soil

- Commercial fertilizers are enriched in nitrogen, phosphorus, and potassium

- Organic fertilizers are composed of manure, fishmeal, or compost
Adjusting Soil pH

- Soil pH affects cation exchange and the chemical form of minerals
- Cations are more available in slightly acidic soil, as H\(^+\) ions displace mineral cations from clay particles
Controlling Erosion

- Topsoil from thousands of acres of farmland is lost to water and wind erosion each year in the United States.
- Erosion of soil causes loss of nutrients.
Erosion can be reduced by

- Planting trees as windbreaks
- Terracing hillside crops
- Cultivating in a contour pattern
- Practicing no-till agriculture
Preventing Soil Compaction

- Soil compaction from heavy equipment reduces pore space between soil particles
- Soil compaction slows gas exchange and reduces root growth
Phytoremediation

- Some areas are unfit for agriculture because of contamination of soil or groundwater with toxic pollutants

- **Phytoremediation** is a biological, nondestructive technology that reclaims contaminated areas

- Plants capable of extracting soil pollutants are grown and are then disposed of safely
Concept 37.2: Plants require essential elements to complete their life cycle

- Plants derive most of their organic mass from the CO$_2$ of air, but they also depend on soil nutrients such as water and minerals.
Macronutrients and Micronutrients

- More than 50 chemical elements have been identified among the inorganic substances in plants, but not all of these are essential to plants.

- A chemical element is considered an essential element if it is required for a plant to complete its life cycle.

- Researchers use hydroponic culture to determine which chemical elements are essential.
Control: Solution containing all minerals  Experimental: Solution without potassium
<table>
<thead>
<tr>
<th>Element</th>
<th>Form Available to Plants</th>
<th>% Mass in Dry Tissue</th>
<th>Major Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Macronutrients</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>CO₂</td>
<td>45%</td>
<td>Major component of plant's organic compounds</td>
</tr>
<tr>
<td>Oxygen</td>
<td>CO₂</td>
<td>45%</td>
<td>Major component of plant's organic compounds</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂O</td>
<td>6%</td>
<td>Major component of plant's organic compounds</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>NO₃⁻, NH₄⁺</td>
<td>1.5%</td>
<td>Component of nucleic acids, proteins, hormones, chlorophyll, coenzymes</td>
</tr>
<tr>
<td>Potassium</td>
<td>K⁺</td>
<td>1.0%</td>
<td>Cofactor that functions in protein synthesis; major solute functioning in water</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca²⁺</td>
<td>0.5%</td>
<td>Important in formation and stability of cell walls and in maintenance of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>membrane structure and permeability; activates some enzymes; regulates many</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>responses of cells to stimuli</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg²⁺</td>
<td>0.2%</td>
<td>Component of chlorophyll; activates many enzymes</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>H₃PO₄⁻, HPO₄₂⁻</td>
<td>0.2%</td>
<td>Component of nucleic acids, phospholipids, ATP, several coenzymes</td>
</tr>
<tr>
<td>Sulfur</td>
<td>SO₄²⁻</td>
<td>0.1%</td>
<td>Component of proteins, coenzymes</td>
</tr>
<tr>
<td><strong>Micronutrients</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl⁻</td>
<td>0.01%</td>
<td>Required for water-splitting step of photosynthesis; functions in water balance</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe³⁺, Fe²⁺</td>
<td>0.01%</td>
<td>Component of cytochromes; activates some enzymes</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn²⁺</td>
<td>0.005%</td>
<td>Active in formation of amino acids; activates some enzymes; required for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>water-splitting step of photosynthesis</td>
</tr>
<tr>
<td>Boron</td>
<td>H₂BO₃⁻</td>
<td>0.002%</td>
<td>Cofactor in chlorophyll synthesis; may be involved in carbohydrate transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>and nucleic acid synthesis; role in cell wall function</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn²⁺</td>
<td>0.002%</td>
<td>Active in formation of chlorophyll; activates some enzymes</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu⁺, Cu²⁺</td>
<td>0.001%</td>
<td>Component of many redox and lignin-biosynthetic enzymes</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni²⁺</td>
<td>0.001%</td>
<td>Cofactor for an enzyme functioning in nitrogen metabolism</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>MoO₄²⁻</td>
<td>0.0001%</td>
<td>Essential for symbiotic relationship with nitrogen-fixing bacteria;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cofactor in nitrate reduction</td>
</tr>
</tbody>
</table>
Nine of the essential elements are called **macronutrients** because plants require them in relatively large amounts.

The macronutrients are carbon, oxygen, hydrogen, nitrogen, phosphorus, sulfur, potassium, calcium, and magnesium.
• The remaining eight are called **micronutrients** because plants need them in very small amounts.

• The micronutrients are chlorine, iron, manganese, boron, zinc, copper, nickel, and molybdenum.
Symptoms of Mineral Deficiency

• Symptoms of mineral deficiency depend on the nutrient’s function and mobility within the plant.

• Deficiency of a mobile nutrient usually affects older organs more than young ones.

• Deficiency of a less mobile nutrient usually affects younger organs more than older ones.

• The most common deficiencies are those of nitrogen, potassium, and phosphorus.
Fig. 37-7

Healthy

Phosphate-deficient

Potassium-deficient

Nitrogen-deficient
Improving Plant Nutrition by Genetic Modification: Some Examples

• Genetic engineering can improve plant nutrition and fertilizer usage
Resistance to Aluminum Toxicity

- Aluminum in acidic soils damages roots and greatly reduces crop yields
- The introduction of bacterial genes into plant genomes can cause plants to secrete acids that bind to and tie up aluminum
Flood Tolerance

- Waterlogged soils deprive roots of oxygen and cause buildup of ethanol and toxins
- The gene *Submergence 1A-1* is responsible for submergence tolerance in flood-resistant rice
Smart Plants

• “Smart” plants inform the grower of a nutrient deficiency before damage has occurred.

• A blue tinge indicates when these plants need phosphate-containing fertilizer.
Fig. 37-8

No phosphorus deficiency

Beginning phosphorus deficiency

Well-developed phosphorus deficiency
Concept 37.3: Plant nutrition often involves relationships with other organisms

- Plants and soil microbes have a mutualistic relationship
  - Dead plants provide energy needed by soil-dwelling microorganisms
  - Secretions from living roots support a wide variety of microbes in the near-root environment
Soil Bacteria and Plant Nutrition

- The layer of soil bound to the plant’s roots is the **rhizosphere**

- The rhizosphere has high microbial activity because of sugars, amino acids, and organic acids secreted by roots
Rhizobacteria

- Free-living rhizobacteria thrive in the rhizosphere, and some can enter roots

- Rhizobacteria can play several roles
  - Produce hormones that stimulate plant growth
  - Produce antibiotics that protect roots from disease
  - Absorb toxic metals or make nutrients more available to roots
• Inoculation of seeds with rhizobacteria can increase crop yields
Bacteria in the Nitrogen Cycle

- Nitrogen can be an important limiting nutrient for plant growth
- The **nitrogen cycle** transforms nitrogen and nitrogen-containing compounds
- Most soil nitrogen comes from actions of soil bacteria
Fig. 37-9

Atmosphere

Nitrogen-fixing bacteria

Soil

Nitrogen-fixing bacteria

Soil

H⁺ (from soil)

Ammonifying bacteria

Ammonia (NH₃)

Ammonium (NH₄⁺)

Nitrifying bacteria

Nitrifying bacteria

Nitrate (NO₃⁻)

Denitrifying bacteria

Organic material (humus)

Nitrate and nitrogenous organic compounds exported in xylem to shoot system

Root
Nitrogen-fixing bacteria

Ammonifying bacteria (ammonia)

Organic material (humus)
Nitrogen-fixing bacteria

Atmosphere

Soil

Nitrogen-fixing bacteria

Ammonifying bacteria

NH$_3$ (ammonia)

NH$_4^+$ (ammonium)

Nitrifying bacteria

NO$_3^-$ (nitrate)

Denitrifying bacteria

Nitrate and nitrogenous organic compounds exported in xylem to shoot system

Root

Copyright ©2006 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.
• Plants absorb nitrogen as either NO$_3^-$ or NH$_4^+$

• Bacteria break down organic compounds or use N$_2$ to produce NH$_3$, which is converted to NH$_4^+$

• *Nitrification* is carried out by bacteria that convert NH$_3$ into NO$_3^-$
Nitrogen-Fixing Bacteria: A Closer Look

- $\text{N}_2$ is abundant in the atmosphere, but unavailable to plants

- **Nitrogen fixation** is the conversion of nitrogen from $\text{N}_2$ to $\text{NH}_3$

- Symbiotic relationships with nitrogen-fixing bacteria provide some plant species with a built-in source of fixed nitrogen

- Key symbioses occur between nitrogen-fixing bacteria and plants, including those in the legume family (peas, beans, and other similar plants)
• Along a legume’s roots are swellings called **nODULES**, composed of plant cells “infected” by nitrogen-fixing *Rhizobium* bacteria.

• Inside the root nodule, *Rhizobium* bacteria assume a form called **bacteroids**, which are contained within vesicles formed by the root cell.

• The bacteria of a root nodule obtain sugar from the plant and supply the plant with fixed nitrogen.
(a) Pea plant root

(b) Bacteroids in a soybean root nodule

Nodules

Roots

Bacteroids within vesicle

5 µm
(a) Pea plant root
(b) Bacteroids in a soybean root nodule
• Each legume species is associated with a particular strain of *Rhizobium*

• The development of a nitrogen-fixing root nodule depends on chemical dialogue between *Rhizobium* bacteria and root cells of their specific plant hosts
**Fig. 37-11**

1. Chemical signals attract bacteria
2. Bacteroids form
3. Nodule forms
4. Nodule develops vascular tissue

- Infected root hair
- Infection thread
- Rhizobium bacteria
- Bacteroid
- Dividing cells in root cortex
- Dividing cells in pericycle
- Developing root nodule
- Bacteroid
- Nodule vascular tissue

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**Nitrogen Fixation and Agriculture**

- **Crop rotation** takes advantage of the agricultural benefits of symbiotic nitrogen fixation

- A non-legume such as maize is planted one year, and the next year a legume is planted to restore the concentration of fixed nitrogen in the soil
• Instead of being harvested, the legume crop is often plowed under to decompose as “green manure” and reduce the need for manufactured fertilizer

• Non-legumes such as alder trees, certain tropical grasses, and rice benefit either directly or indirectly from nitrogen-fixing bacteria
Fungi and Plant Nutrition

- **Mycorrhizae** are mutualistic associations of fungi and roots.
- The fungus benefits from a steady supply of sugar from the host plant.
- The host plant benefits because the fungus increases the surface area for water uptake and mineral absorption.
- Mycorrhizal relationships are common and might have helped plants to first colonize land.
The Two Main Types of Mycorrhizae

- In **ectomycorrhizae**, the mycelium of the fungus forms a dense sheath over the surface of the root.

- These hyphae form a network in the apoplast, but do not penetrate the root cells.
Fig. 37-12

(a) Ectomycorrhizae

- Epidermis
- Cortex
- Mantle (fungal sheath)
- Fungal hyphae between cortical cells
- Endodermis
- Fungal vesicle
- Casparian strip
- Arbuscules
- Plasma membrane
- Root hair

(b) Arbuscular mycorrhizae (endomycorrhizae)

- Epidermis
- Cortex
- Cortical cells
- Endodermis
- Fungal vesicle
- Casparian strip
- Arbuscules
- Plasma membrane

(colorized SEM)
(a) Ectomycorrhizae
Mantle (fungal sheath)

(a) Ectomycorrhizae
Mantle (fungal sheath)

Fungal hyphae between cortical cells

(colorized SEM)
• In **arbuscular mycorrhizae**, microscopic fungal hyphae extend into the root

• These mycorrhizae penetrate the cell wall but not the plasma membrane to form branched arbuscules within root cells
(b) Arbuscular mycorrhizae (endomycorrhizae)
Fig. 37-12b-2

Cortical cells

Arbuscules

(LM, stained specimen)

10 µm
Agricultural and Ecological Importance of Mycorrhizae

- Farmers and foresters often inoculate seeds with fungal spores to promote formation of mycorrhizae

- Some invasive exotic plants disrupt interactions between native plants and their mycorrhizal fungi
**EXPERIMENT**

**RESULTS**

![Graph showing increase in plant biomass and mycorrhizal colonization.](image)

### Increase in plant biomass (%)

- **Invaded**: [Graph data here]
- **Uninvaded**: [Graph data here]
- **Sterilized invaded**: [Graph data here]
- **Sterilized uninvaded**: [Graph data here]

### Mycorrhizal colonization (%)

- **Invaded**: [Graph data here]
- **Uninvaded**: [Graph data here]

**Soil type**

- Mycorrhizal colonization (%): [Graph data here]
  - Sugar maple
  - Red maple
  - White ash

**Seedlings**

- Sugar maple
- Red maple
- White ash
RESULTS

Increase in plant biomass (%) Mycorrhizal colonization (%)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Invaded</th>
<th>Uninvaded</th>
<th>Sterilized invaded</th>
<th>Sterilized unininvaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invaded</td>
<td>0</td>
<td>300</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Uninvaded</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>Sterilized invaded</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Sterilized unininvaded</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Soil type

Seedlings
- Sugar maple
- Red maple
- White ash
Epiphytes, Parasitic Plants, and Carnivorous Plants

- Some plants have nutritional adaptations that use other organisms in nonmutualistic ways

- An **epiphyte** grows on another plant and obtains water and minerals from rain
Fig. 37-14a

Staghorn fern, an epiphyte

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.
• Parasitic plants absorb sugars and minerals from their living host plant
Mistletoe, a photosynthetic parasite

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Dodder, a nonphotosynthetic parasite
Fig. 37-14c-3

Host’s phloem

Dodder

Haustoria
Indian pipe, a nonphotosynthetic parasite
Carnivorous plants are photosynthetic but obtain nitrogen by killing and digesting mostly insects.
Venus flytrap
Pitcher plants
Sundews
Nitrogen-fixing bacteria

Denitrifying bacteria

Nitrifying bacteria

Ammonifying bacteria

Organic material (humus)

Nitrogen (N₂)
(from atmosphere)

Nitrogen (N₂)
(to atmosphere)

H⁺
(from soil)

Ammonium (NH₄⁺)

Ammonia (NH₃)

Nitrate (NO₃⁻)

Root
You should now be able to:

1. Define soil texture and soil composition
2. Explain why plants cannot extract all of the water in soil
3. Define cation exchange and describe how plants can stimulate the process
4. Discuss the problems of topsoil erosion and farm irrigation in arid regions; suggest actions that can help mitigate these problems
5. Distinguish between and list the macronutrients and micronutrients
6. Explain how a nutrient’s role and mobility determine the symptoms of a mineral deficiency

7. Summarize the ecological role of each of the following groups of bacteria: ammonifying, denitrifying, nitrogen-fixing, nitrifying

8. Describe the basis for crop rotation

9. Distinguish between ectomycorrhizae and arbuscular mycorrhizae

10. Describe the adaptations for nutrition of parasitic, epiphytic, and carnivorous plants