Basic Plant Nutrition and Soil Fertility

Basic NRCCA Training
Competency Areas 1 and 2

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Soil fertility & nutrient management

Six Competency Areas:

1: Basic Concepts of Plant Nutrition
2: Basic Concepts of Soil Fertility

3: Soil Testing and Plant Tissue Analysis
4: Nutrient Sources, Analyses, Application Methods
5: Soil pH and Liming
6: Nutrient Management Planning

Essential Nutrients

There are 18 nutrients essential for plant growth:

1. Structural elements C, H, and O
2. Macronutrients
   - Primary Nutrients N, P, and K
   - Secondary Nutrients Ca, Mg, S
3. Micronutrients Fe, B, Cu, Cl, Mn, Mo, Zn, Co, Ni

	Nutrient	Macro/micro	Uptake form	Mobile in plant?	Uptake*
1	Carbon	Macro	CO_2,H_2CO_3		
2	Hydrogen	Macro	H^+,OH^-,H_2O		
3	Oxygen	Macro	O_2		
4	Nitrogen	Macro	NO_3^-,NH_4^+	Mobile	170
5	Phosphorus	Macro	HPO_{4-}^{+2},$H_2PO_4^-$	Mobile	35
6	Potassium	Macro	K^+	Mobile (very)	175
7	Calcium	Macro	Ca^{+2}	Immobile	35
8	Magnesium	Macro	Mg^{+2}	Moderately mobile	40
9	Sulfur	Macro	SO_4^-	Moderately mobile	20
10	Boron	Micro	H_3BO_3,BO_3^-	Immobile	0.2
11	Copper	Micro	Cu^{+2}	Immobile	0.1
12	Iron	Micro	Fe^{+2},Fe^{+3}	Immobile	1.9
13	Manganese	Micro	Mn^{+2}	Immobile	0.3
14	Zinc	Micro	Zn^{+2}	Immobile	0.3
15	Molybdenum	Micro	MoO_4^-	Immobile	0.01
16	Chlorine	Micro	Cl^-	Mobile	
17	Cobalt	Micro	Co^{+2}	Immobile	
18	Nickel	Micro	Ni^{+2}	Mobile	

*Lbs/acre nutrient assuming an average yield of 150 bu/acre

Nitrogen

N availability limits the productivity of most cropping systems in the US.

Use:

- Amino acids

  Proteins, Protoplasm, Alkaloids, Hormones

- Chlorophyll

Plant available forms

- Ammonium- NH_4^+
- Nitrate – NO_3^-

Nitrogen

Mobile in soil as NO_3^-
Mobile in the plant

Excess:

- Very dark green leaves
- Excessive vegetative growth.
- Lodging and delayed maturity.

Deficiency:

- Little new growth.
- Yellowing (chlorosis) of older leaves
- Earlier fall leaf drop.
- New shoots may be red to red-brown.
- Low protein content.

Nitrogen

Mobile in soil as NO_3^-
Mobile in the plant

Phosphorus

Use:

- Energy (ADP ATP)

  Membrane transport, photosynthesis, protein synthesis, lipid synthesis, DNA and RNA synthesis

Plant available forms:

Orthophosphate ions ($H_2PO_4^-$ and HPO_4^{2-})

Phosphorus

Not mobile in soil
Mobile in the plant

Excess:
- Induces Zn deficiency

Deficiency:
- Purple or reddish leaves
- Poor growth and yield
- Premature fruit drop
- Delayed maturity
- Poor root growth

Potassium

Use:

- Maintains ionic strength of solutions within plant cells

Enzyme activation for cell division, grain filling, nitrogen fixation, water uptake and drought tolerance, stomata functioning, ATP synthesis…

Plant available Form: K^+

Potassium

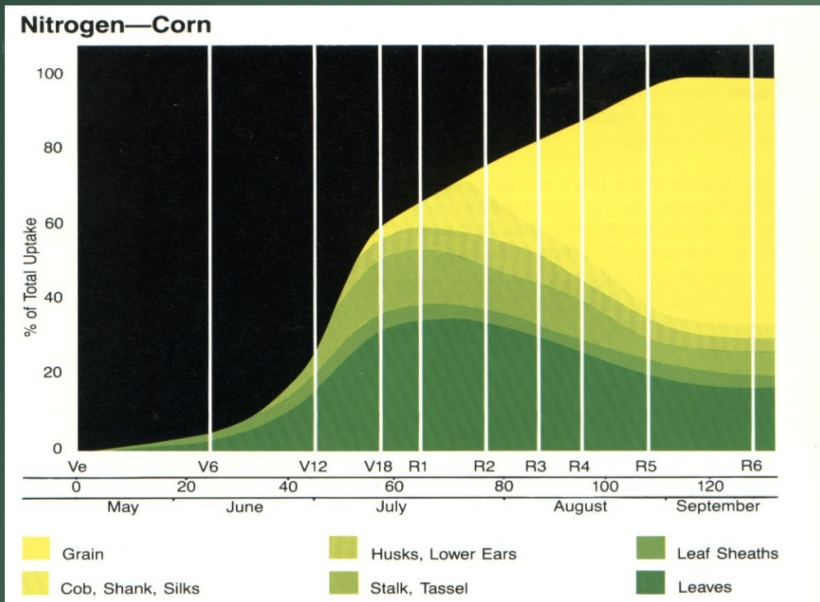
Mobile in the soil
Very mobile in the plant

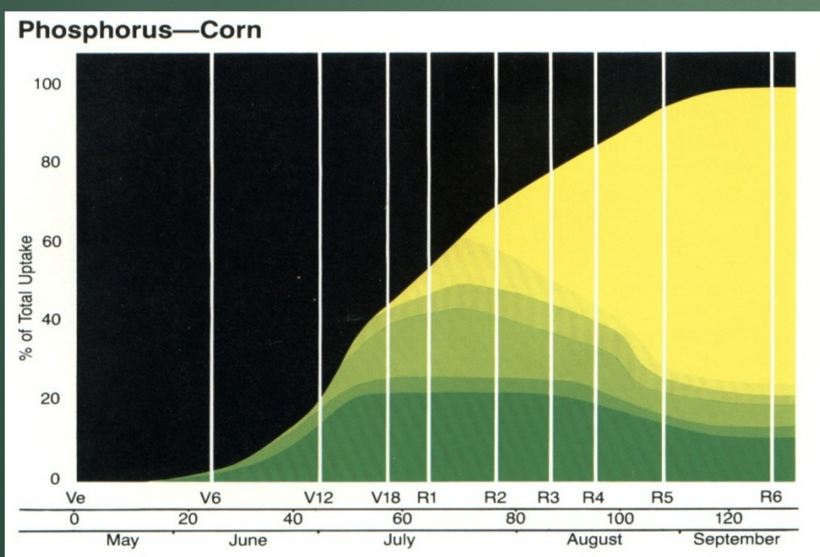
Excess:
- Reduced uptake of Mg

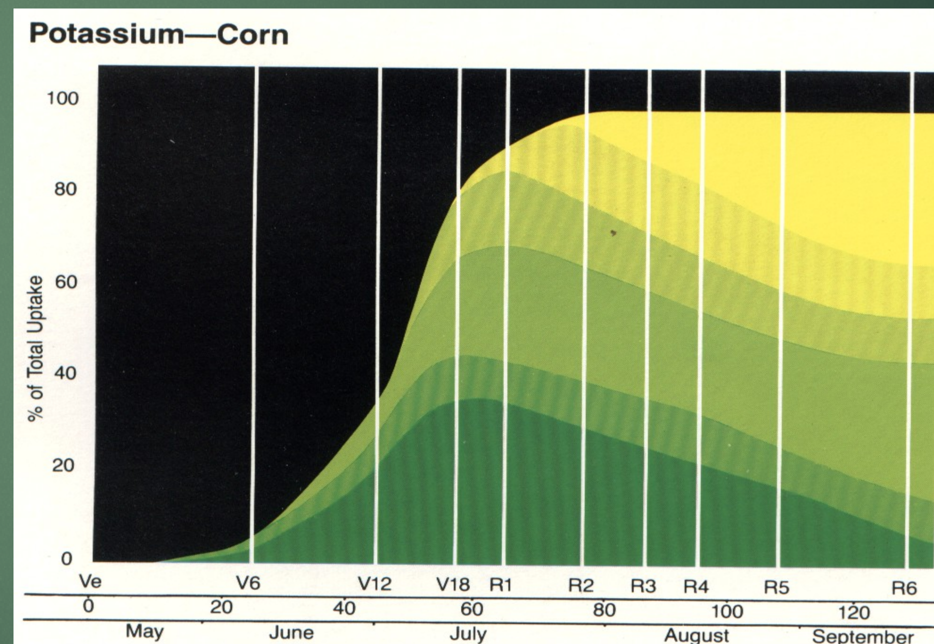
Deficiency:
- First seen in older leaves
- Leaves showing marginal and interveinal yellowing
- Leaves may crinkle and roll upwards
- Yield reduction usually occurs before symptoms are seen

Potassium

Nutrient Demand Depends on Growth Stage







Secondary Macronutrients

Secondary macronutrients are those that less often limiting, and less often added to soils as fertilizers.

Calcium and magnesium are often supplied by mineral weathering, either of natural soil materials or of aglime.

In the past Sulfur was often added in sufficient quantities to soil with atmospheric deposition (associated with air pollution) and impurities in fertilizers, particularly common P fertilizers.

Calcium:

Somewhat mobile in the soil
Immobile in the plant

Use:

- Membrane permeability, translocation of carbohydrates and amino acids, catalyst for enzymes

Excess:

- Causes B or Mg deficiencies

Deficiency:

- Seldom occurs if pH is ok
- Deficiency shows in young leaves
- Young leaves are small and distorted with curled back leaf tips
- Shoots may be stunted and show dieback
- Blossom end rot on tomatoes

Crop: Corn • **Image:** Img007 • **Source:** R. G. Hoeft
Nutrient: Calcium
Caption: Calcium deficiency in corn, with leaves failing to unfold.

Crop: Tomato • **Image:** Img180 • **Source:** G. E. Wilcox
Nutrient: Calcium
Caption: Blossom-end rot of tomato caused by Ca deficiency.

Calcium:

Somewhat mobile in the soil
Immobile in the plant

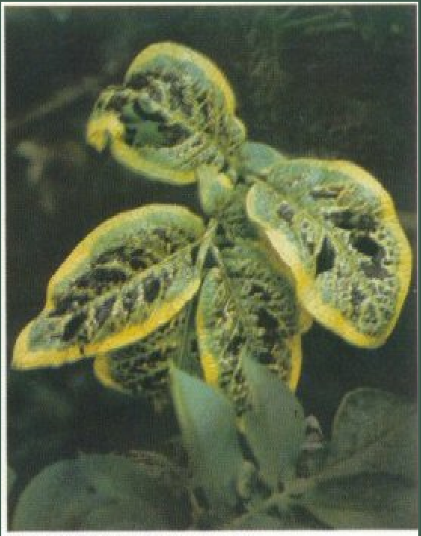
Use:

- Build soil structure
  - Sodic soils (sodium saturated soils)
    - Sodium (Na) reduces soil structure
    - Calcium displaces sodium in the soil and improves structure (decreases bulk density)
  - Clay soils
    - Function in flocculating clay particles to decrease bulk density
    - Questionable economic benefit in eastern U.S.

- Gypsum (Calcium Sulfate, $CaSO_4$)
  - Readily available in recent years
  - Great source of calcium and sulfur
  - pH neutral – does not increase pH!

Magnesium: Somewhat mobile in the soil Moderately in the plant

Maize (*Zea mays*)



Potato (*Solanum tuberosum*)

Use:

- Chlorophyll, catalyst for enzymes

Excess:

- May cause K deficiency.
- Poor growth.
- Mg should never exceed Ca in soils.

Deficiency:

- Chlorosis (green-yellow stripes on older leaves).
- Deficiencies usually first seen in the older leaves.
- May occur on acid soils or at high pH soils with lots of Ca.

Sulfur:

Mobile in soil
Moderately mobile in the plant

Use:

- Chlorophyll production, constituent of amino acids, and vitamins, catalyst for enzymes

Excess:

- Necrotic areas on leaves.

Deficiency:

- Looks like Mg deficiency but is usually first seen in *youngest* leaves and then the plant becomes uniformly chlorotic.


Corn


Oil Seed Rape


Sugar Beet

Sulfur:

Following the passing of the Clean Air Act in 1970 and the introduction of sulfur (S)-free phosphorus fertilizer and pesticides, incidental addition of S to fields through atmospheric deposition has decreased drastically in NYS.

- Aurora Research Farm
- Total S Deposition estimated at:
  - 14 lbs/acre in 1979-1981
  - 6 lbs/acre in 2008

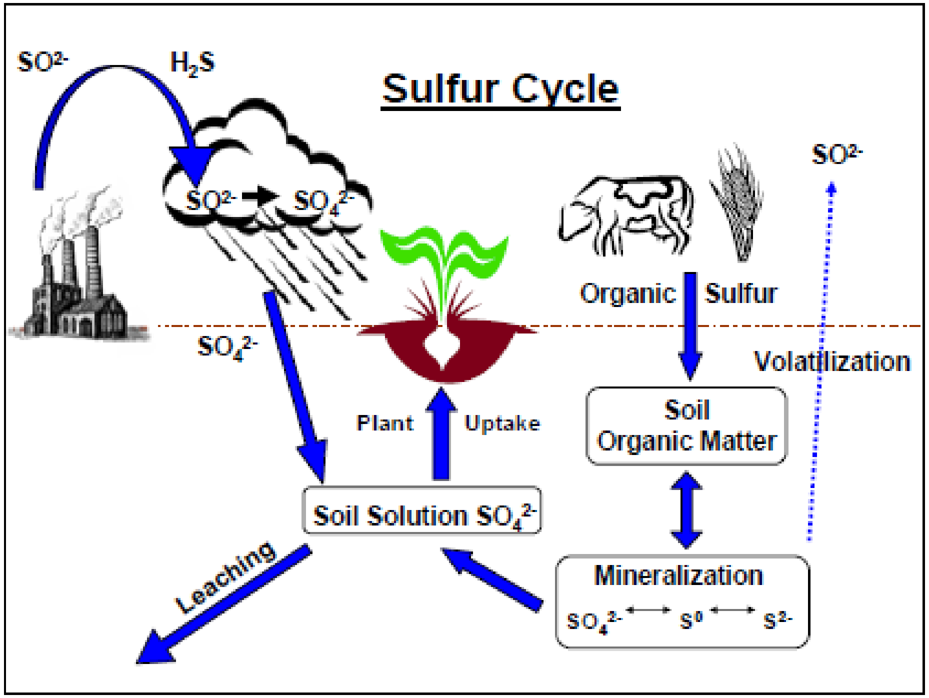


Figure 2: Schematic of the sulfur cycle.

What's Cropping Up? Vol. 22, No. 2

Greater Concern of S deficiencies in non-manured fields.

Micronutrients

Micronutrients are plant nutrients that are required in relatively small quantities, usually a few ounces for plant growth.

Include:

B, Cu, Fe, Mn, Zn, Mo, Cl, Co, Ni

Micronutrients

Important to know:

- Leaf symptoms are only guides to the source of the trouble.
- Symptoms tend to be complicated because under field conditions more than one nutrient may be deficient.
- Diseases may enhance nutrient deficiencies and visa-versa.
- Stress can produce/enhance deficiency symptoms

The only way to be sure is to tissue sample!

Micronutrients

Boron (B)

Immobile in the plant

- Boron becomes less available as pH increases especially above 6.
- Easily leached from soils.
- Excess leads to necrosis.

Micronutrients

Copper (Cu)

Immobile in the plant

- Copper is bound primarily to the organic matter in soils. Soils very high in organic matter are most likely to be Cu deficient.
- Excesses are deadly.
- Small leaves with necrotic spots and brown areas near the leaf tips. Rosetting of the leaves and dieback of terminal shoots.

Copper Deficient Wheat.

Leaf tips are dying back and curling. Most often seen on muck soils.

Micronutrients

Iron (Fe)

Immobile in the plant

- Iron is held on CEC and complexed by organic matter. The Fe^{2+} form is
- important for plant uptake.
- Iron deficiencies show first in the youngest leaves.
- Excess causes Mn and P deficiencies.
- Yellow leaves with green veins leading to marginal scorching. Fruits have poor color. Shoot diameter is small.

Micronutrients

Immobile in the plant

Manganese (Mn)

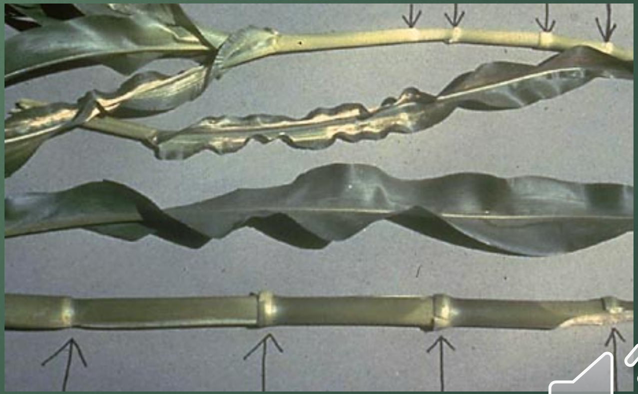
- Manganese is held in soils by CEC of clays and chelated by organic matter.
- Deficiency symptoms similar to N deficiency: leaves display marginal scorching, rolling
- and reduced width.
- Sources:
  - Manganese sulfate 24% Mn
  - Manganese chelates 8-12% Mn

Micronutrients

Zinc (Zn)

Immobile in the plant

- Zinc becomes less available as soil pH increases, especially above 6.
- Deficiency can be induced by high P levels.
- If deficient: leaves are small, yellow, narrow and older leaves may drop. Small shoots may show rosetting followed by dieback. Stripes appear like in Mg deficiency.
- Sources:
  - Organic matter
  - Manure
  - Zinc oxide 19% Zn
  - Zinc chelates 10 - 12 % Zn
  - Zinc sulfate 35% Zn



Micronutrients

Molybdenum (Mo) Immobile in the plant

- Molybdenum is is very important to rhizobia infections on legume roots; however, the plant also has a requirement. More deficient in acid soils.
- Deficiency shows as N deficiency.

Chlorine (Cl) Mobile in the plant

- Chlorine is associated with chlorophyll and photosynthesis. It is mobile in the plant.
- Deficiencies show as wilting and stubby roots. Field deficiencies are unknown.
- Excess is called salt injury.

Cobalt (Co)

Immobile in the plant

- Essential for N-fixing microorganisms.
- Excess produces similar symptoms as Fe and Zn.

Nickel (Ni)

Mobile in the plant

- Is the lates nutrient to be added as an essential nutrient (1984) since Cl in 1854.
- Is the metal component of urease, an enzyme that catalyzes urea. Thus it is important for plants that produce urea through N metabolism such as legumes– without it urea accumulates to toxic levels in the plants

Soil Fertility

Understand how field characteristics impact plant-soil processes which drive nutrient uptake.

Field Characteristics

- Cation Exchange Capacity
- Soil Organic Matter
- Soil Minerals
- Plant Residue
- Soil Texture
- Soil Structure
- Drainage/Aeration
- Soil Moisture
- pH
- Temperature

Plant-Soil Processes

- Nitrogen Cycle Processes
- Phosphorus Cycle Processes
- Potassium Cycle Processes
- Soil Solution Concentrations
- Nutrient Mobility in the Soil
  Mass Flow
- Diffusion
- Root Interception

Soil Minerals

Types of minerals:

- Primary minerals
  - Persisted with little change in composition.
  - Examples: quartz, micas and feldspars
- Secondary minerals
  - Formed by the breakdown and weathering of primary minerals
  - Examples: **clay minerals**, iron and aluminum oxides, dolomite, calcite and gibbsite

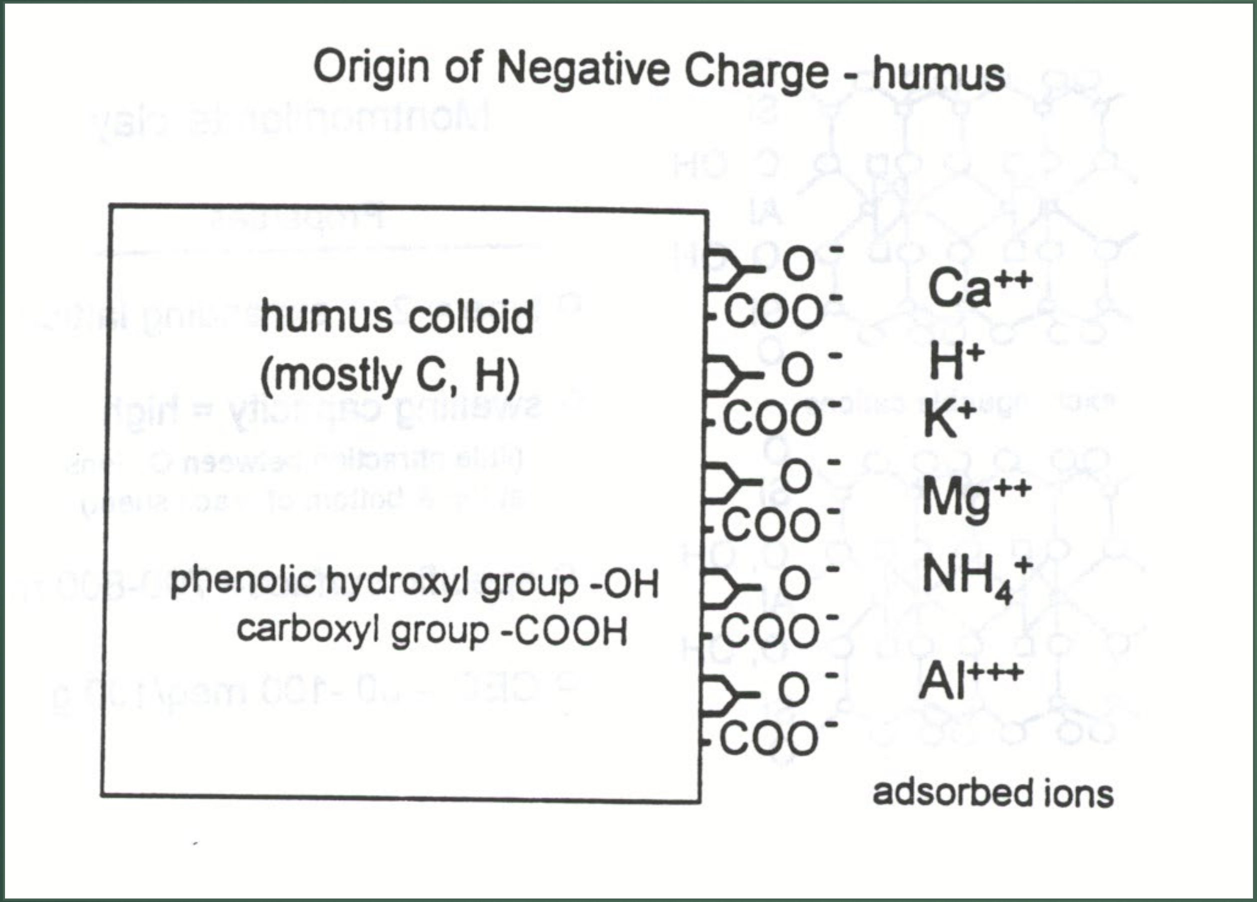
Cation Exchange Capacity (CEC)

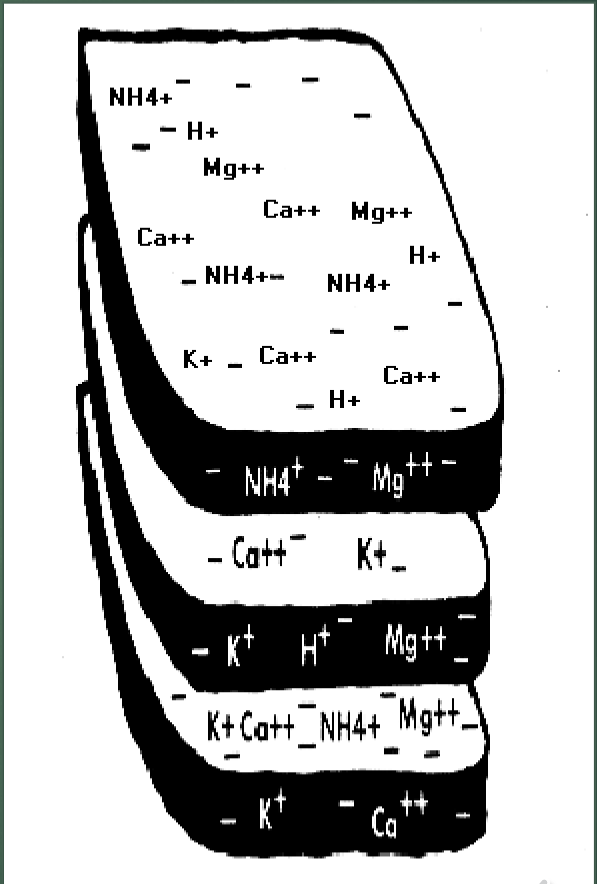
- Defined by measurement of the amount of positive charged ions (cations) which can be bound by a given weight of soil.
- Created by negatively charged clay minerals and soil organic matter
- <u>Cation examples:</u>

  K^+, Ca^{2+}, Mg^{2+}, NH_4^+

  Cu^{2+}, Fe^{2+} or Fe^{3+}, Mn^{2+}, Al^{3+}, Zn^{2+}

Cation Exchange Capacity (CEC)





Cation Exchange Capacity (CEC)

- Larger CEC = greater capacity to retain K^+, Ca^{2+}, Mg^{2+}, NH_4^+
- CEC increases with pH (due to variable charge on the OM)
- CEC is seldom measured in a soil testing lab (it is estimated from exchangeable cations)
- If the CEC is measured at the pH of the soil, it is called the effective CEC.

Cation Exchange Capacity (CEC)

- **CEC increases with:**
  - OM
  - Clay content
- **Low CEC means:**
  - More frequent nutrient additions needed
- **Impacts**
  - Soil solution concentrations
  - Nutrient availability for plant uptake

Soil Solution

- Soil water contains dissolved solids and gases
- Medium through which most nutrients are obtained by plant roots
- Setting for 3 nutrient transport processes
  - Mass flow
  - Diffusion
  - Root interception

Mass Flow

- Movement of dissolved nutrients with plant absorption of water for transpiration
- Responsible for most transport of nitrate, sulfate, calcium and magnesium

Diffusion

- Movement of nutrients to the root surface in response to a concentration gradient (from where you have a lot to where you have little)
- Important for transport of phosphorus and potassium

Root Interception

- Root growth causing contact with soil colloids containing nutrients
- Important mode of transport for calcium and magnesium

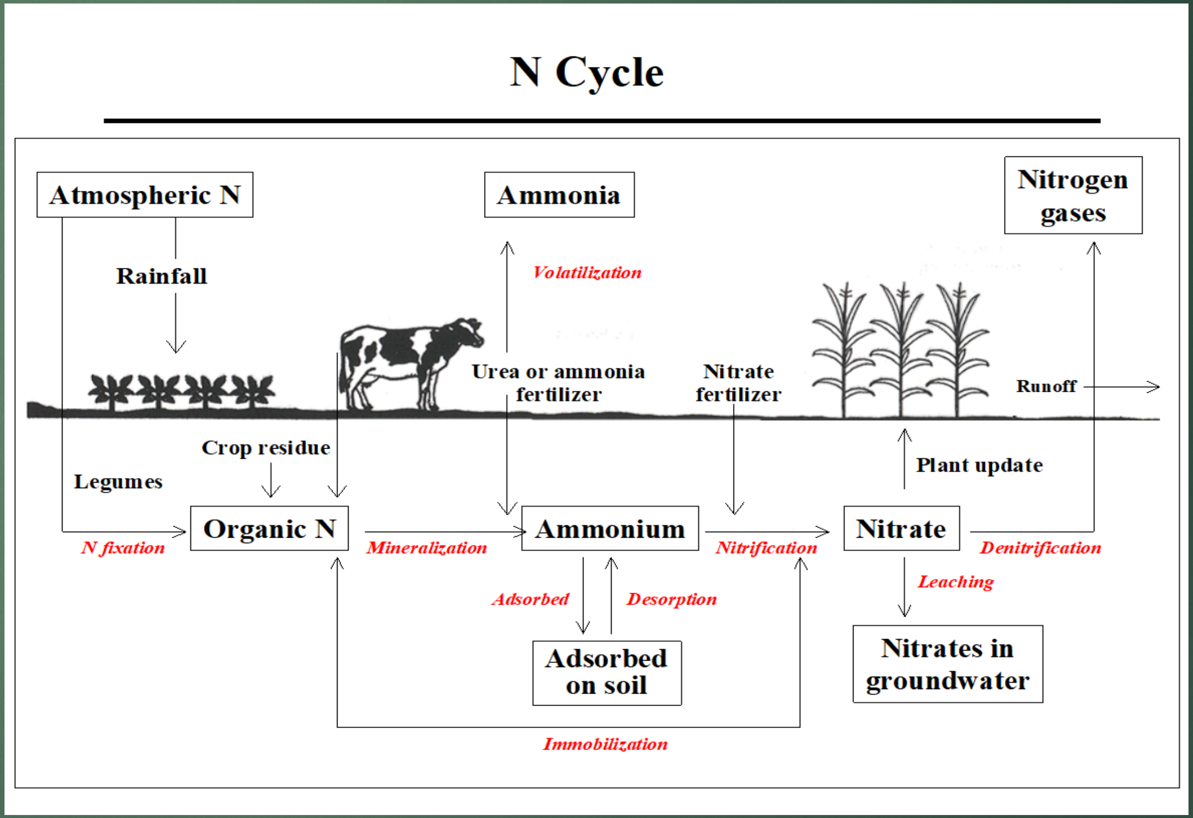
Nutrient Transport Processes

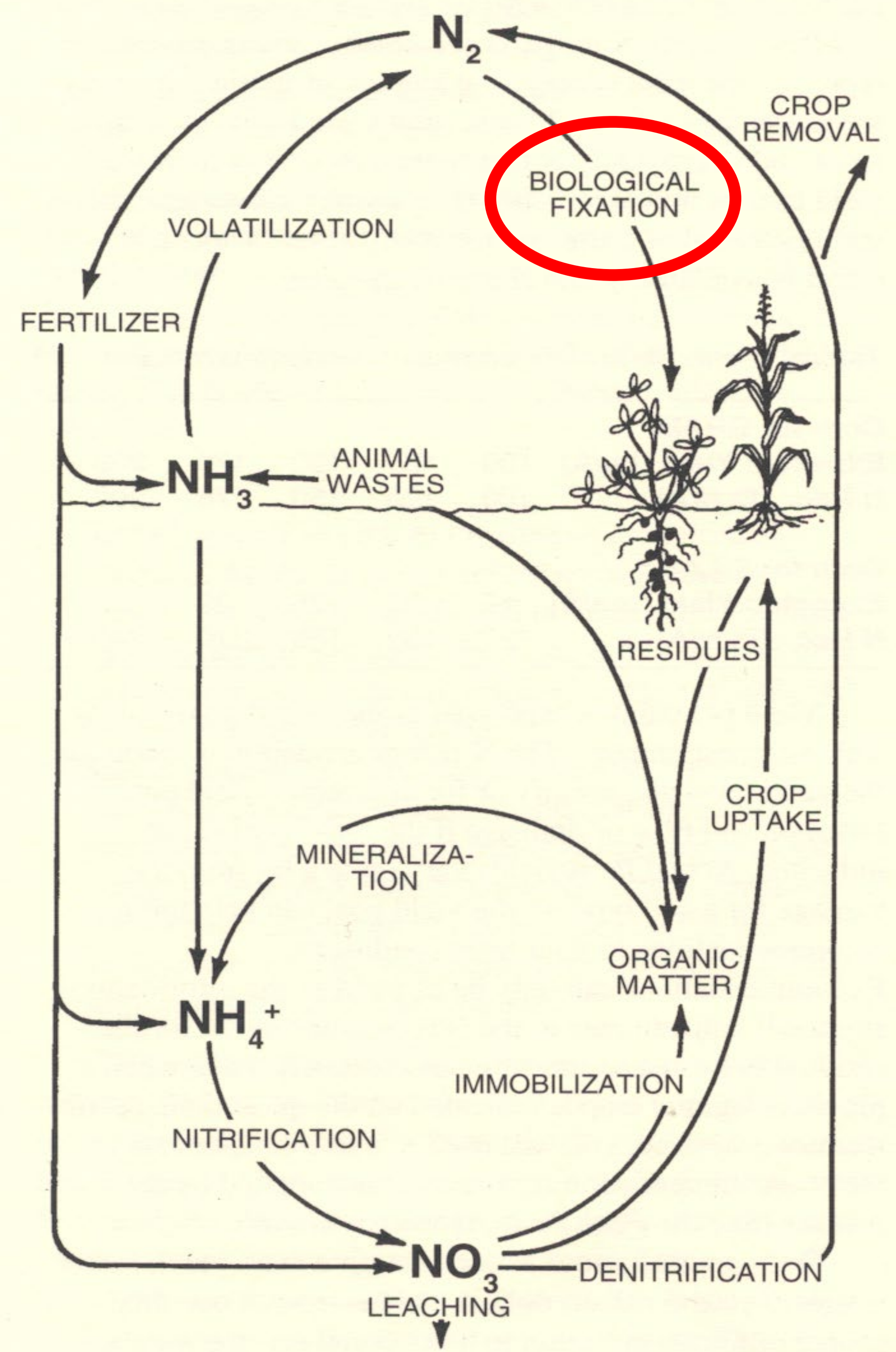
	Nutrient	Major Supply Path to Plant
1	Carbon	
2	Hydrogen	
3	Oxygen	
4	Nitrogen	Mass Flow
5	Phosphorus	Diffusion
6	Potassium	Diffusion, Mass Flow
7	Calcium	Mass Flow, Root
8	Magnesium	Mass Flow, Root
9	Sulfur	Diffusion, Mass Flow
10	Boron	Mass Flow
11	Copper	Mass Flow
12	Iron	Mass Flow, Diffusion, Root
13	Manganese	Mass Flow, Root
14	Zinc	Mass Flow or Diffusion or
15	Molybdenum	Mass Flow
16	Chlorine	
17	Cobalt	
18	Nickel	

The Nitrogen Cycle

Field characteristics that impact the N cycle:

- CEC
- Soil organic matter
- Plant residue
- Soil texture
- Soil structure
- Drainage/aeration
- Soil moisture
- Temperature





Nitrogen conversion processes:

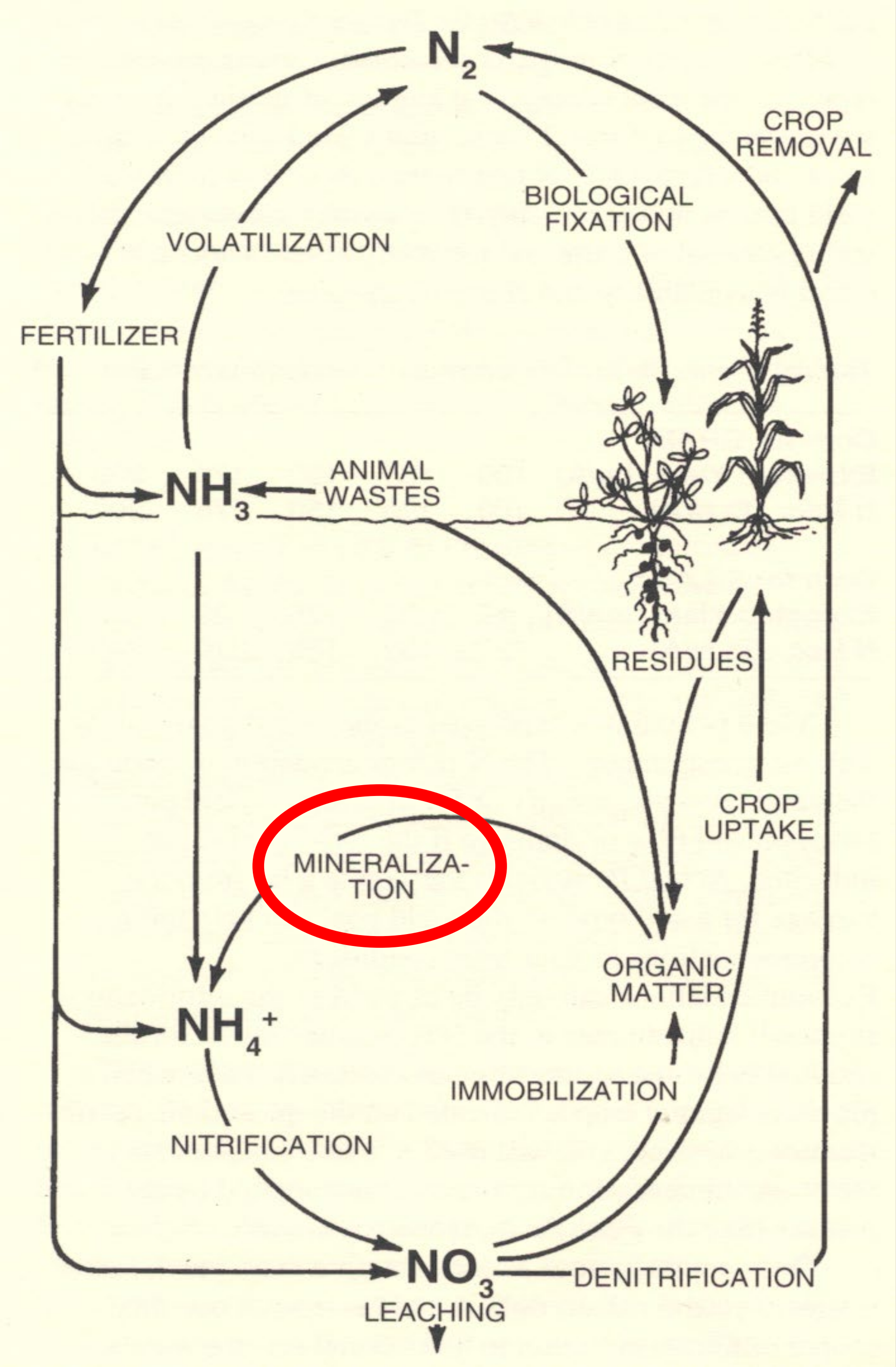
1. N fixation
2. Mineralization
3. Nitrification
4. Denitrification
5. Ammonia volatilization
6. Immobilization

From Penn State Agronomy Facts 12

Nitrogen Fixation

$N_2 \rightarrow NH_3 \rightarrow$ amino acids $\rightarrow$ proteins

- ✓ Conversion of N_2 from the atmosphere to plant protein.
- ✓ This nitrogen becomes available when N fixers die.
- ✓ Process carried out by microorganisms.
- ✓ Requires energy and the enzyme nitrogenase (Fe, Mo, P, S).



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Nitrogen Mineralization

- ✓ Process that converts organic N in manure, crop residues and soil organic matter to ammonia and ammonium.

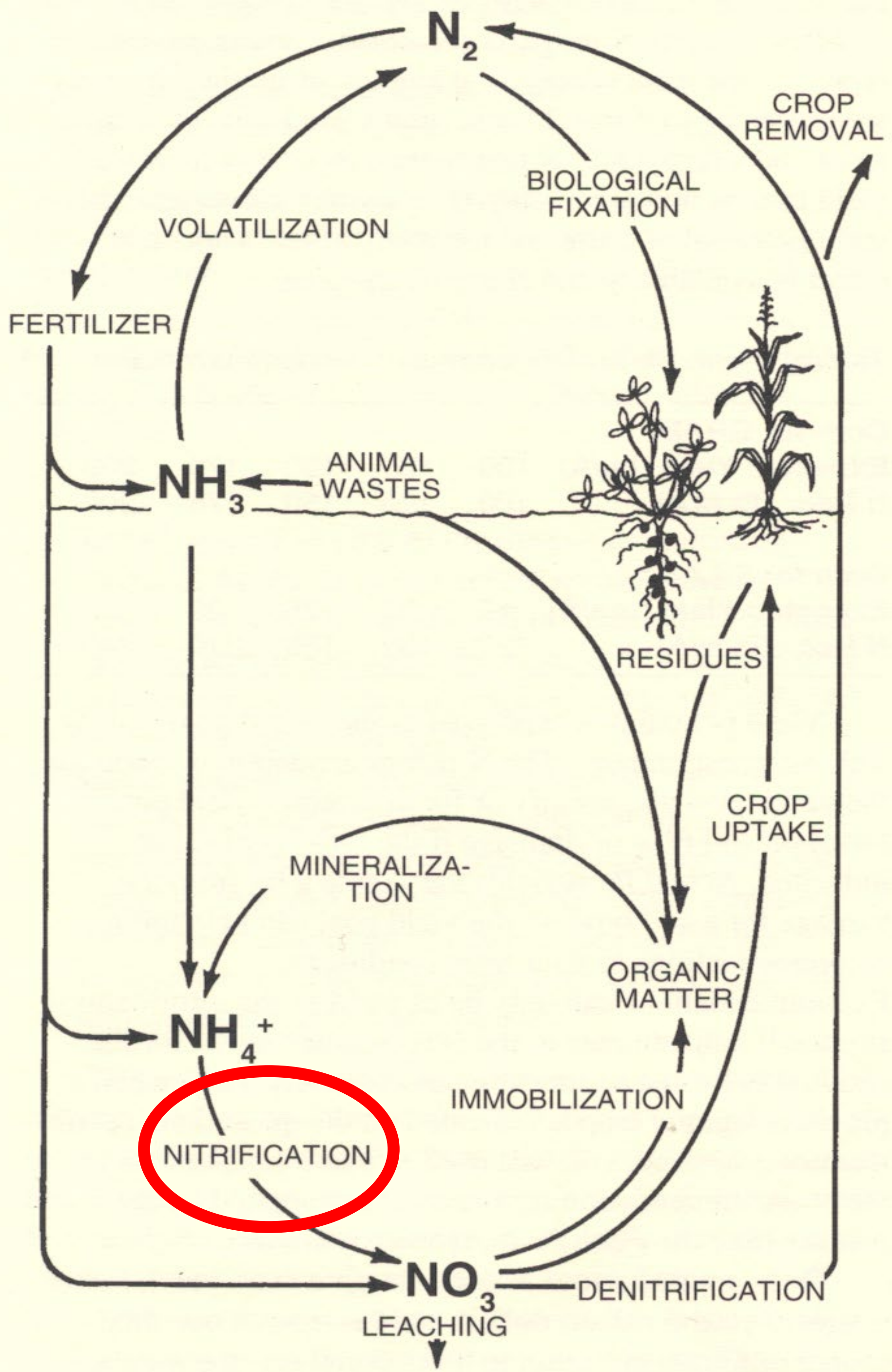
$R\text{-}NH_2 \rightarrow NH_3 \rightarrow NH_4^+$

Organic N Ammonia Ammonium

Nitrogen Mineralization

✓ Annual mineralization rates vary:

- 1.5-3.5% of the organic nitrogen in the soil.
- Exact rates depend on soil temperature, moisture and aeration status.
- Most rapid mineralization in hot climates, well-aerated soils and moist soils.



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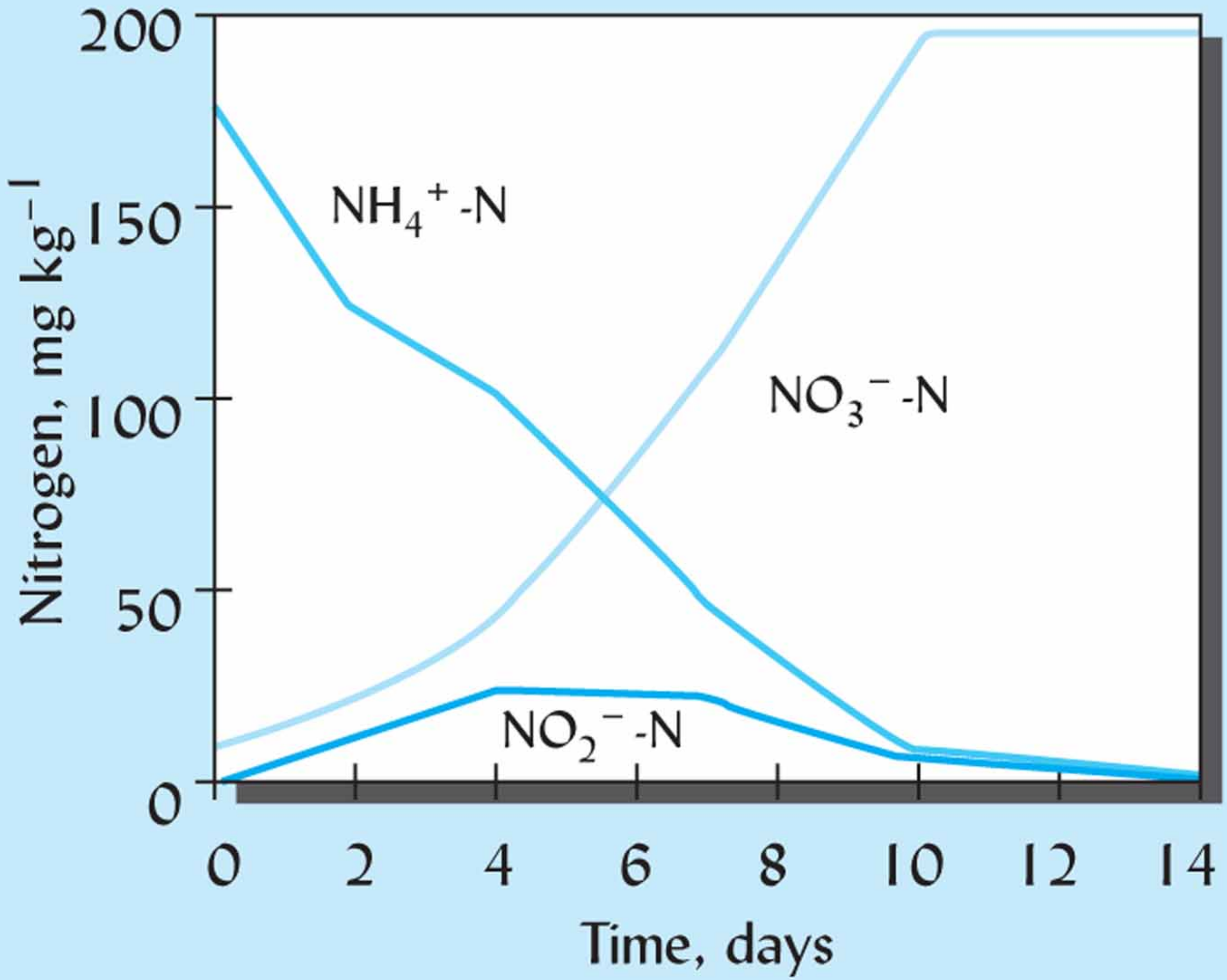
Nitrification

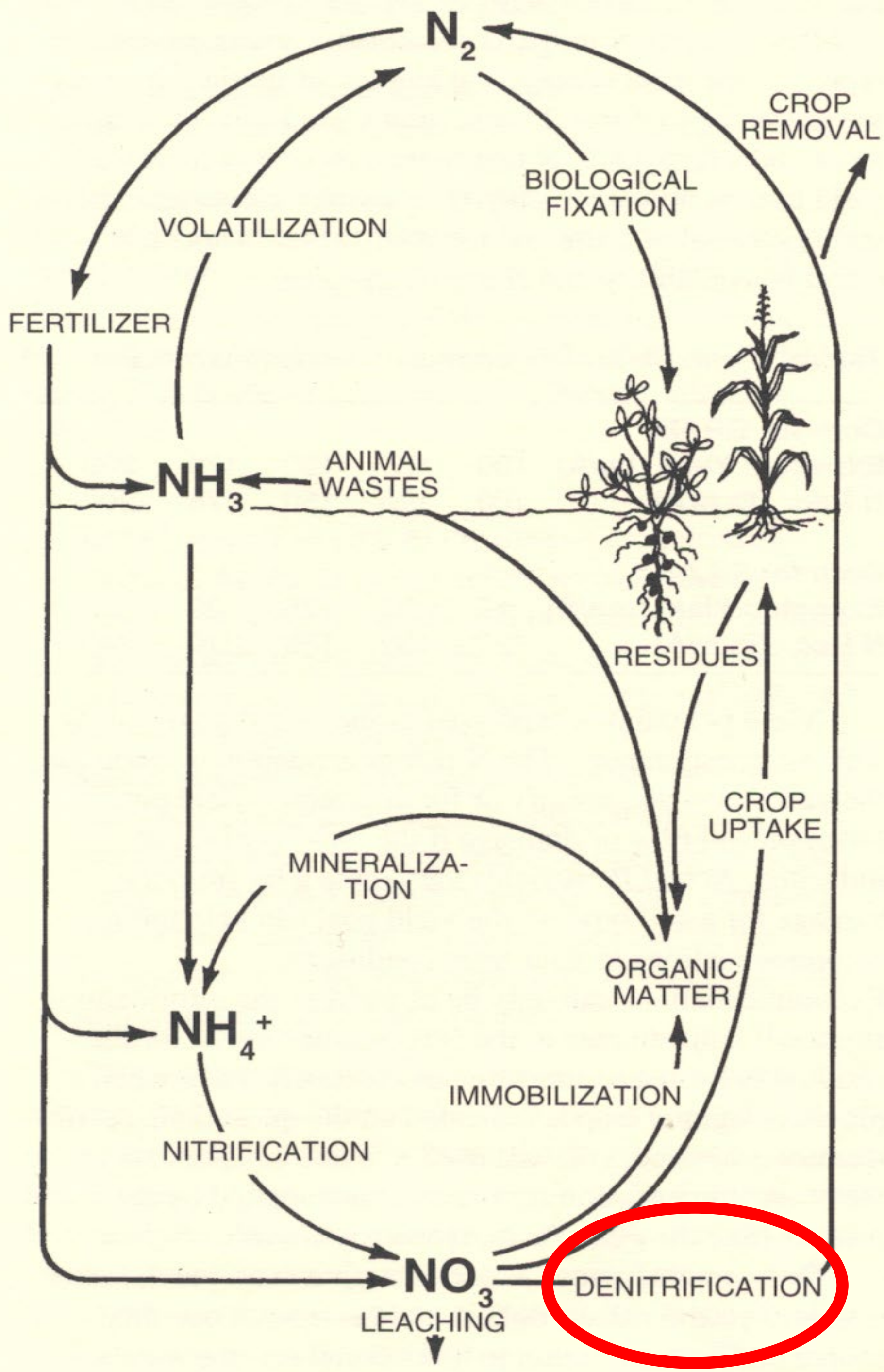
- Microbes use enzymes to convert ammonium (NH_4^+) to nitrate (NO_3^-) to obtain energy.
- Nitrate is most readily available and the preferred N form.
- Rapid when soil is warm, moist, well aerated (late May, June).
- Nitrification lowers soil pH.

NH_4^+ (ammonium) → NO_2^- (nitrite)

NO_2^- (nitrite) → NO_3^- (nitrate)



PEARSON Education *The Nature and Properties of Soil*, Fourteenth Edition
By Nyle C. Brady and Ray R. Weil



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From Penn State Agronomy Facts 12

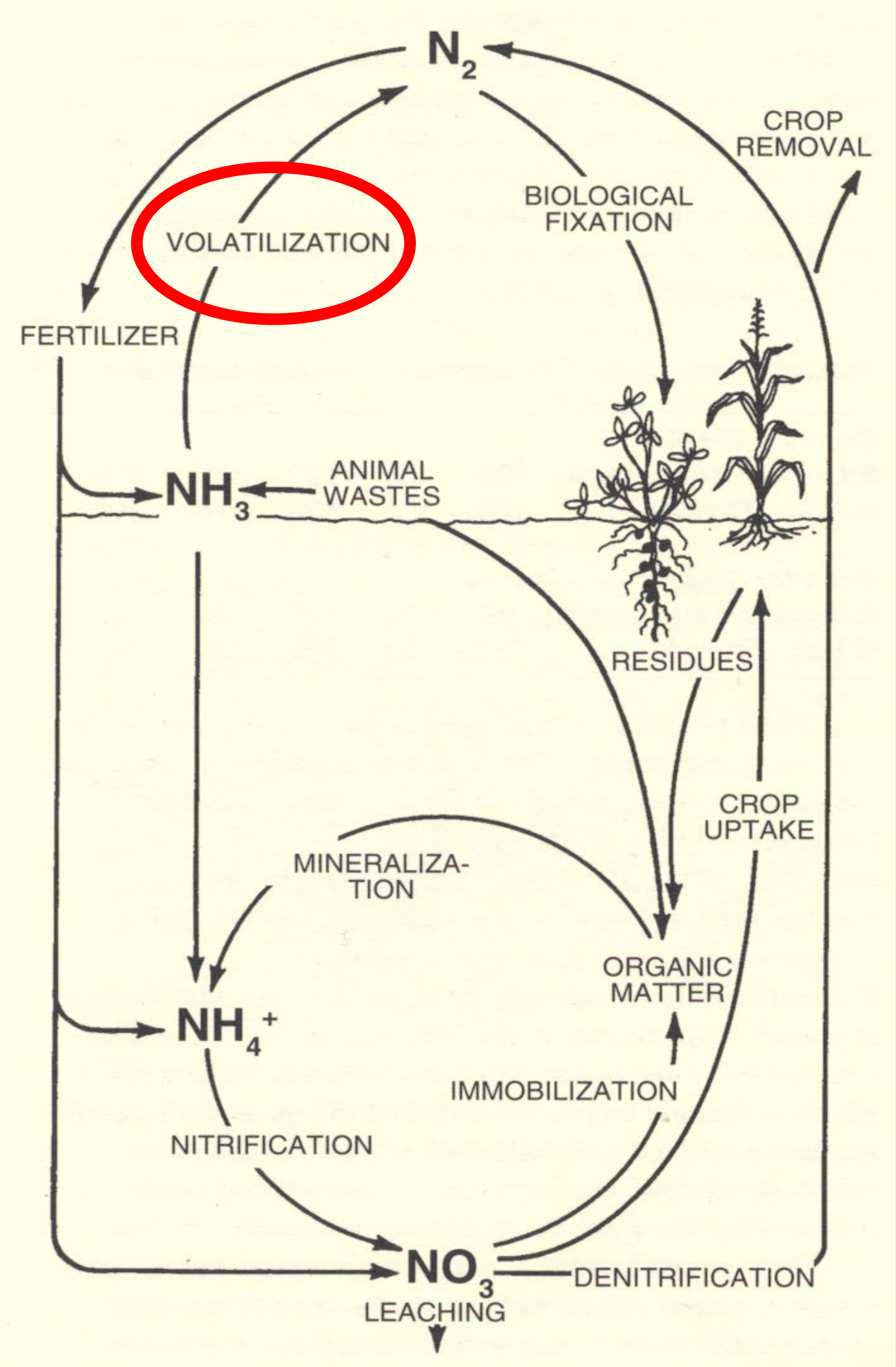
Denitrification

- NO_3^- is converted into gaseous forms of N.
- Common in poorly drained soils, even when tile drained (just less so).
- Common in warm and wet conditions.

nitrate — nitric oxide gas — dinitrogen gas

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

nitrite ions — nitrous oxide gas



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From Penn State Agronomy Facts 12

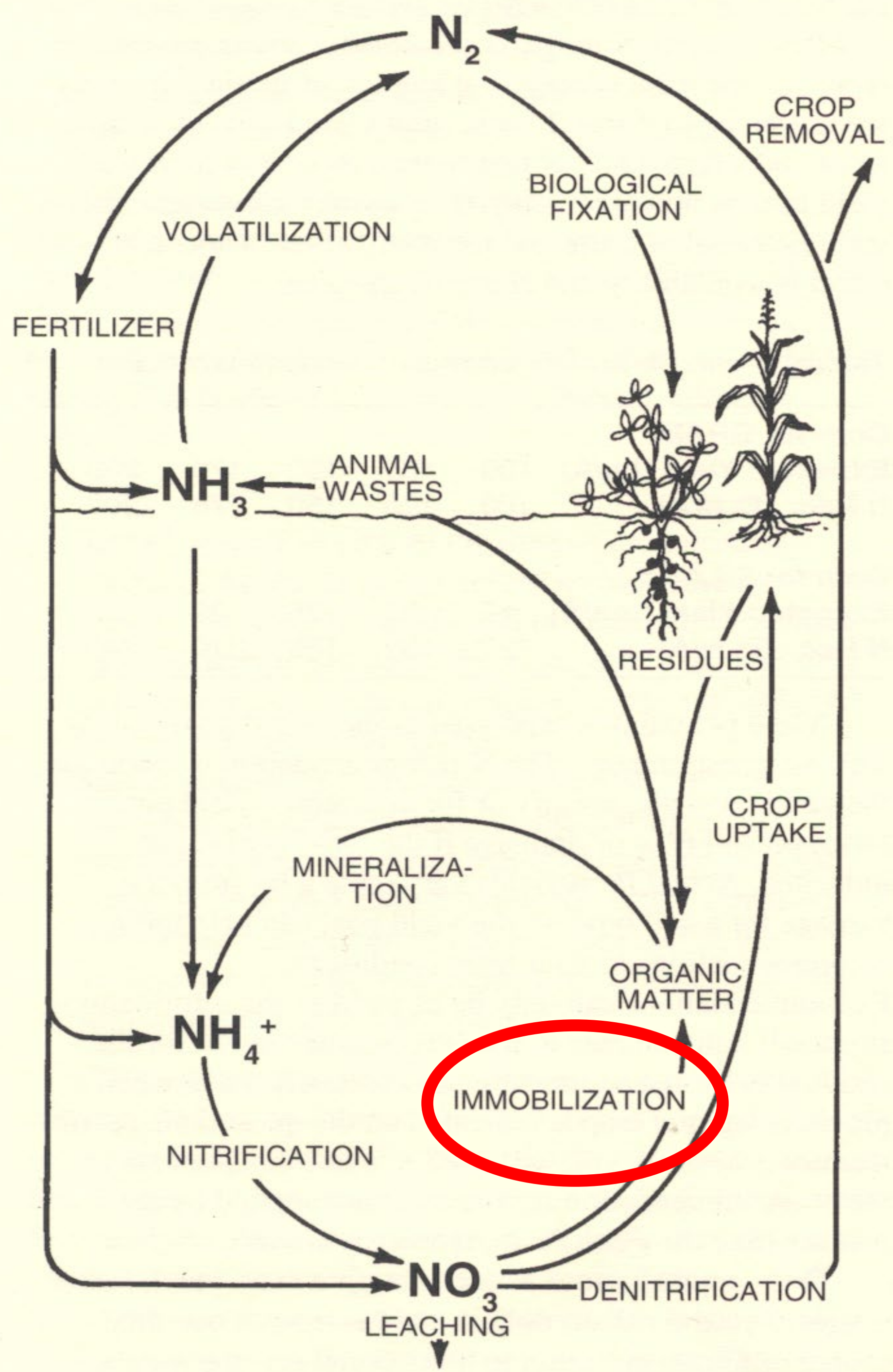
Ammonia Volatilization

- Production + loss of ammonia gas from ammonium.
- Ammonia volatilization increases with pH.
- High evaporation = high volatilization.
- Volatilization losses may be high for unincorporated urea fertilizer or manure (urine).
- Incorporation of manure and fertilizers can reduce ammonia losses by 25-75%.

ammonia gas

$$NH_4^+ \rightarrow NH_3 \uparrow$$

ammonium ions



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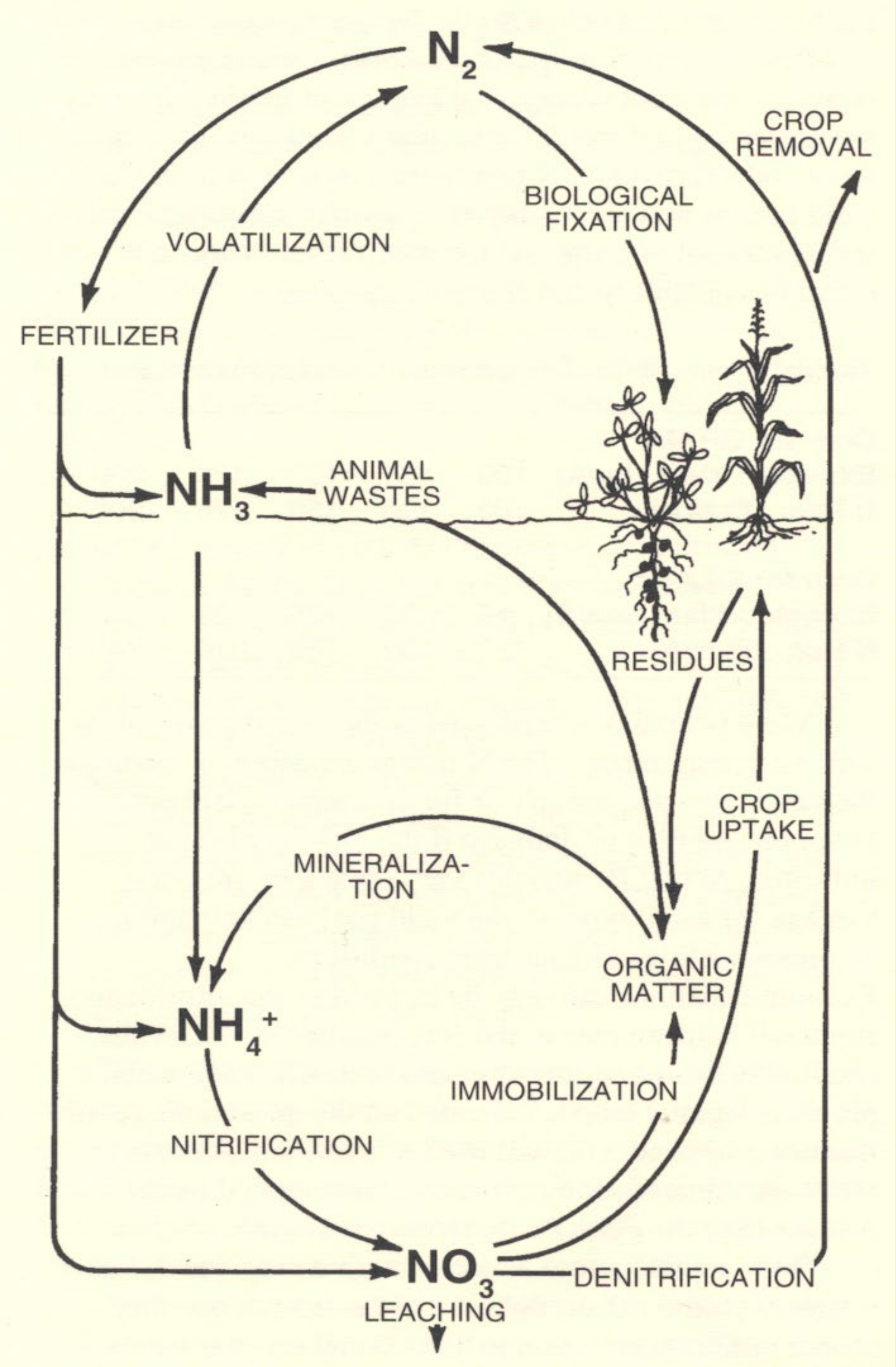
From Penn State Agronomy Facts 12

Immobilization

- Reverse of mineralization.
- Microbes compete with crops for NH_4^+ and NO_3^- for their own survival.
- Immobilization ties up available N in microbial tissue.
- This must be “re-mineralized” to become plant available.

NH_4^+ (ammonium) $\longrightarrow$ $R\text{-}NH_2$ (organic N)

NO_3^- (nitrate) $\nearrow$



Conversion processes:

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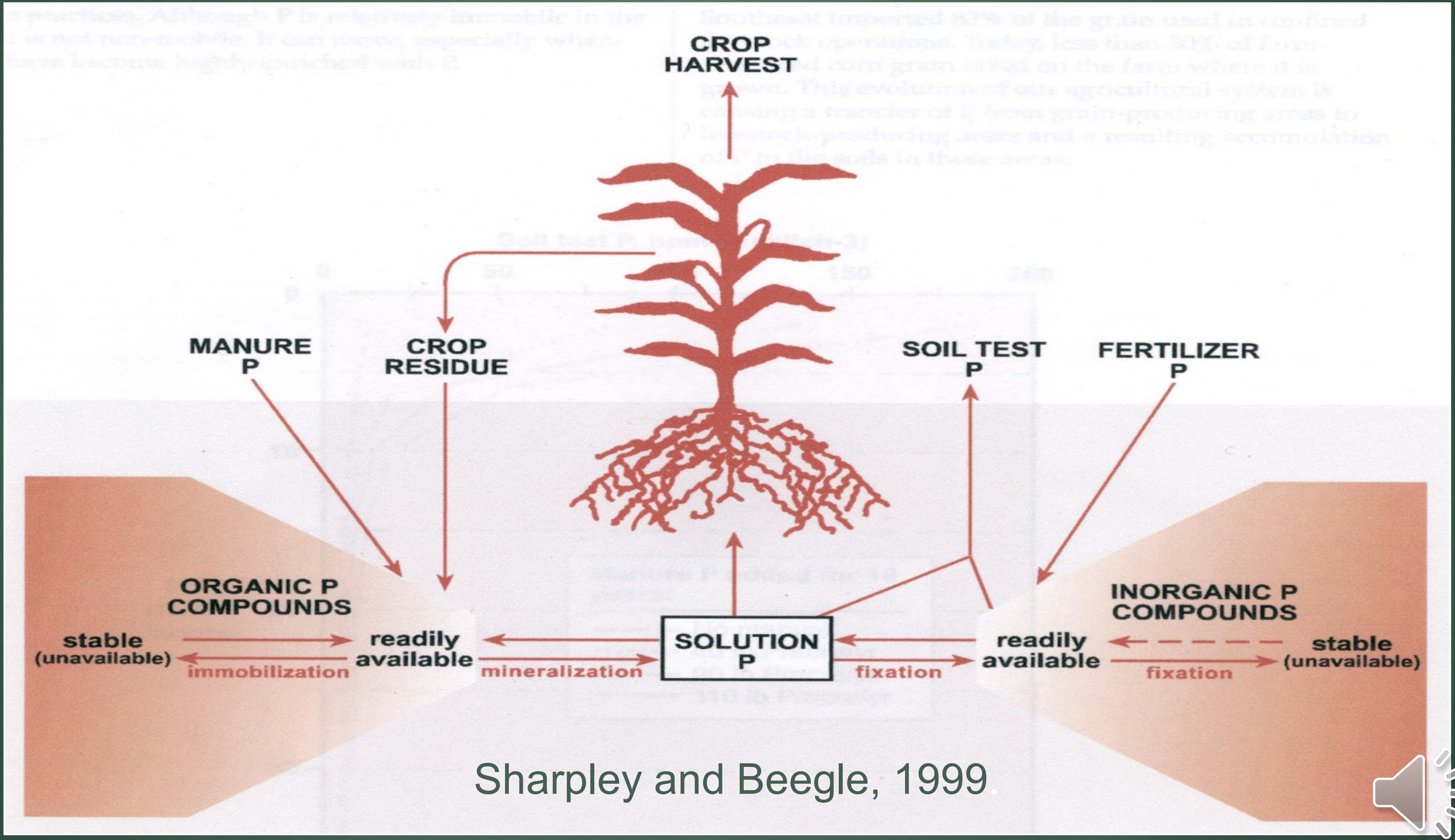
\+ Nitrate leaching

From Penn State Agronomy Facts 12

Nitrate Leaching

- NO_3^- does not attach to soil particles and thus easily leaches from the soil.
- Leaching losses are determined by water movement and nitrate contents of the soil.

Basics of P Cycling



Sharpley and Beegle, 1999

Basics of P Cycling

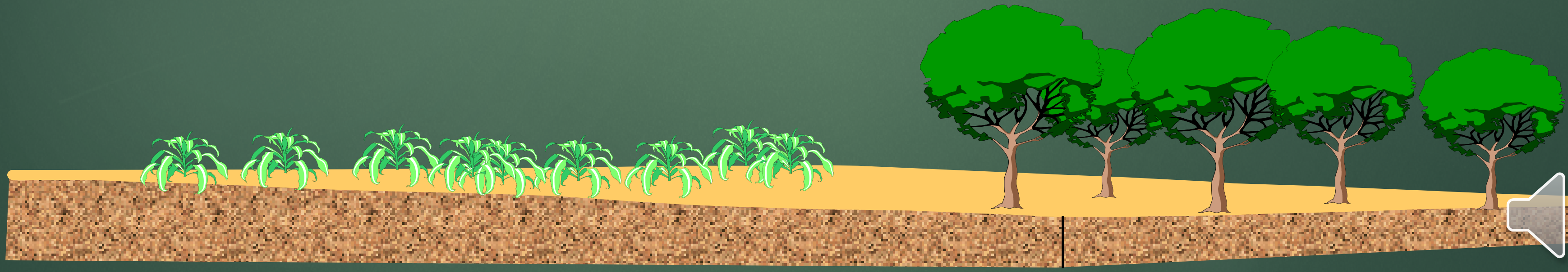
P can appear in different forms:

Dissolved P

- Organic and inorganic P dissolved in the soil solution.
- $R\text{-}PO_4^{2-}$, HPO_4^{2-}, $H_2PO_4^{-}$

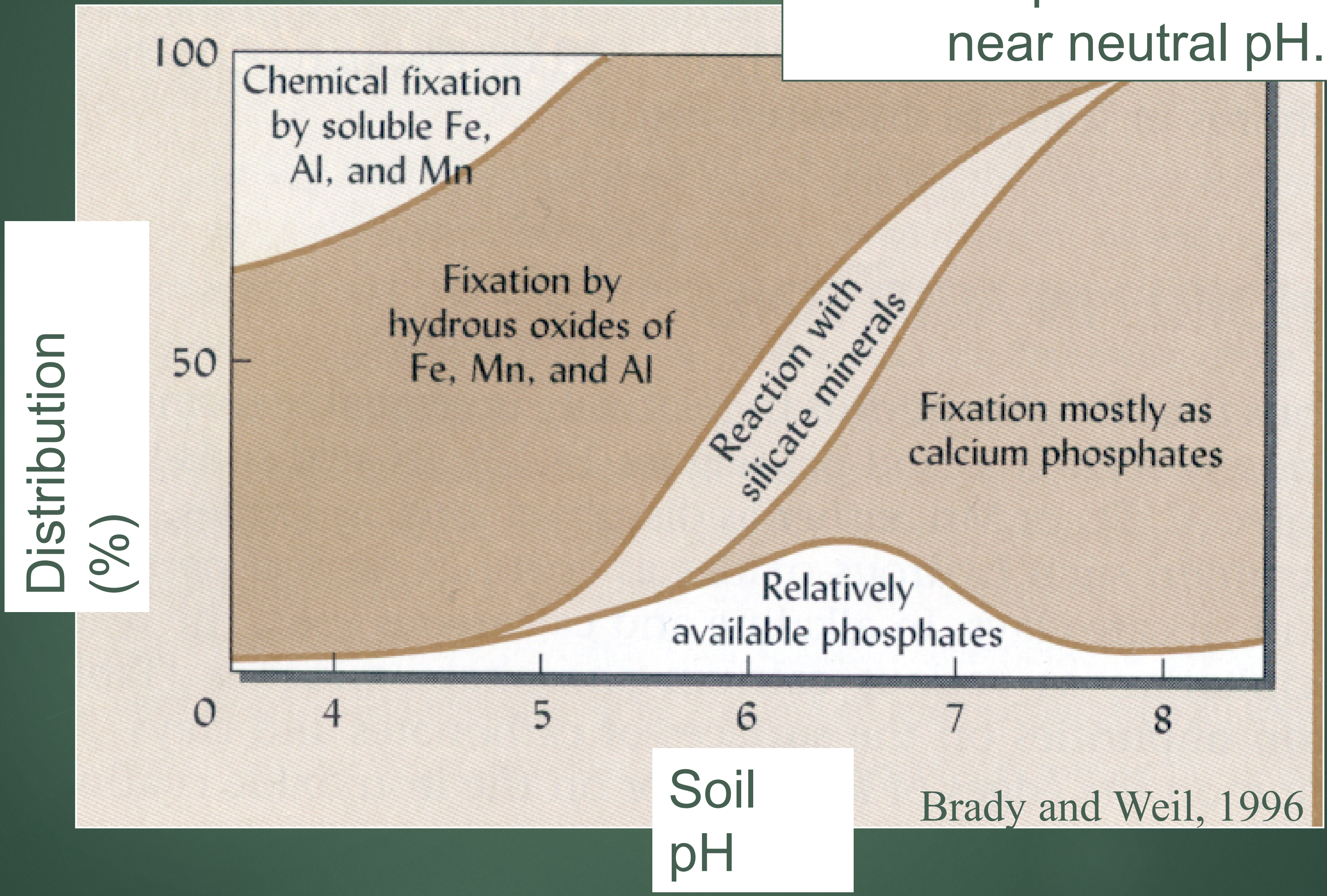
Particulate P

- Calcium phosphate minerals.
- P attached to clay minerals, iron and aluminum oxides.
- P incorporated into iron and aluminum minerals.
- P in soil organisms, active and stable organic matter.



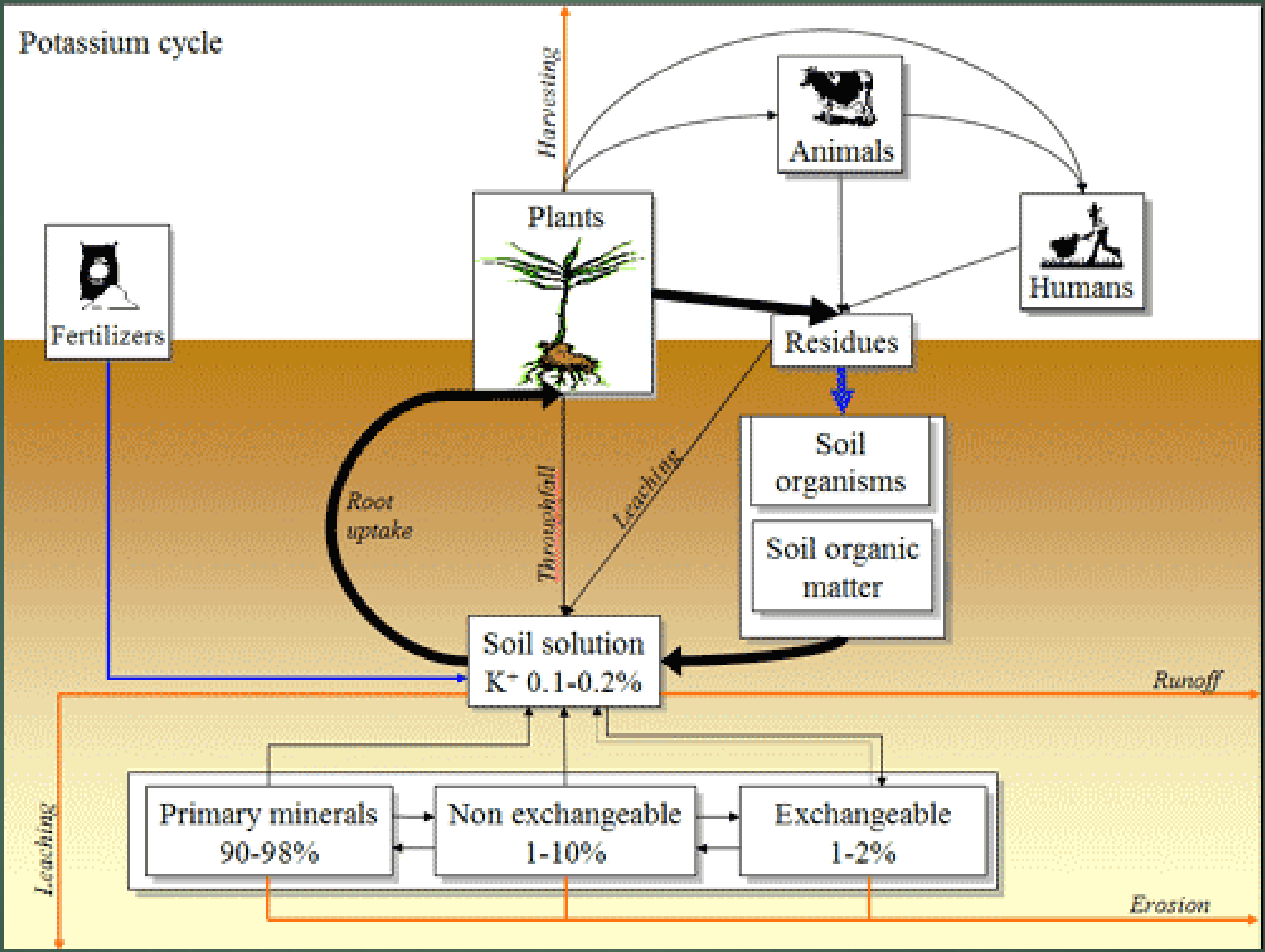
Basics of P Cycling

P is most plant available at a near neutral pH.



Brady and Weil, 1996

Basics of K Cycling



Potassium Forms

- Primary Minerals
  - Feldspar
  - Mica
- Clay minerals
  - Illites
- Non-exchangeable K^+
- Exchangeable K^+
  - 2 to 5% saturation on the CEC
- Solution K^+
  - 1 to 10 mg/L in solution

~ 90-98% (Primary Minerals, Clay minerals)

~ 1-10% (Non-exchangeable K^+)

~ 2% (Exchangeable K^+, Solution K^+)

Exchangeable + non-Exchangeable K