Nutrient Cycles: *Part 1*
Nitrogen & Phosphorus

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Slides adapted from Dr. Gurpal Toor

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Plants need 4x more N than K.

Plants need 17x more N than P.

Concentrations in Plant Dry Matter

Element	Concentration (mmol/g)	#atoms	Function	
Molybdenum	0.001	1	N fixation	**Micronutrients**
Copper	0.10	100	Component of enzymes	
Zinc	0.30	300	Activates enzymes	
Manganese	1.0	1000	Activates enzymes	
Iron	2.0	2000	Chlorophyll synthesis	
Boron	2.0	2000	Cell wall component	
Chlorine	3.0	3000	Photosynthesis reactions	
Sulfur	30	30000	Amino acids	
Phosphorus	60	60000	Nucleic acids	
Magnesium	80	80000	Part of chlorophyll	
Calcium	125	125000	Cell wall component	
Potassium	250	250000	Catalyst, ion transport	
Nitrogen	1000	1000000	Proteins, amino acids	

Source: Jones (2012)

Nitrogen

A complicated & fascinating nutrient

- Exists in many forms in soils
- Many reactions are mediated by soil microbes
- Our atmosphere contains:

  78% N gas, 21% O gas, <0.2% CO_2

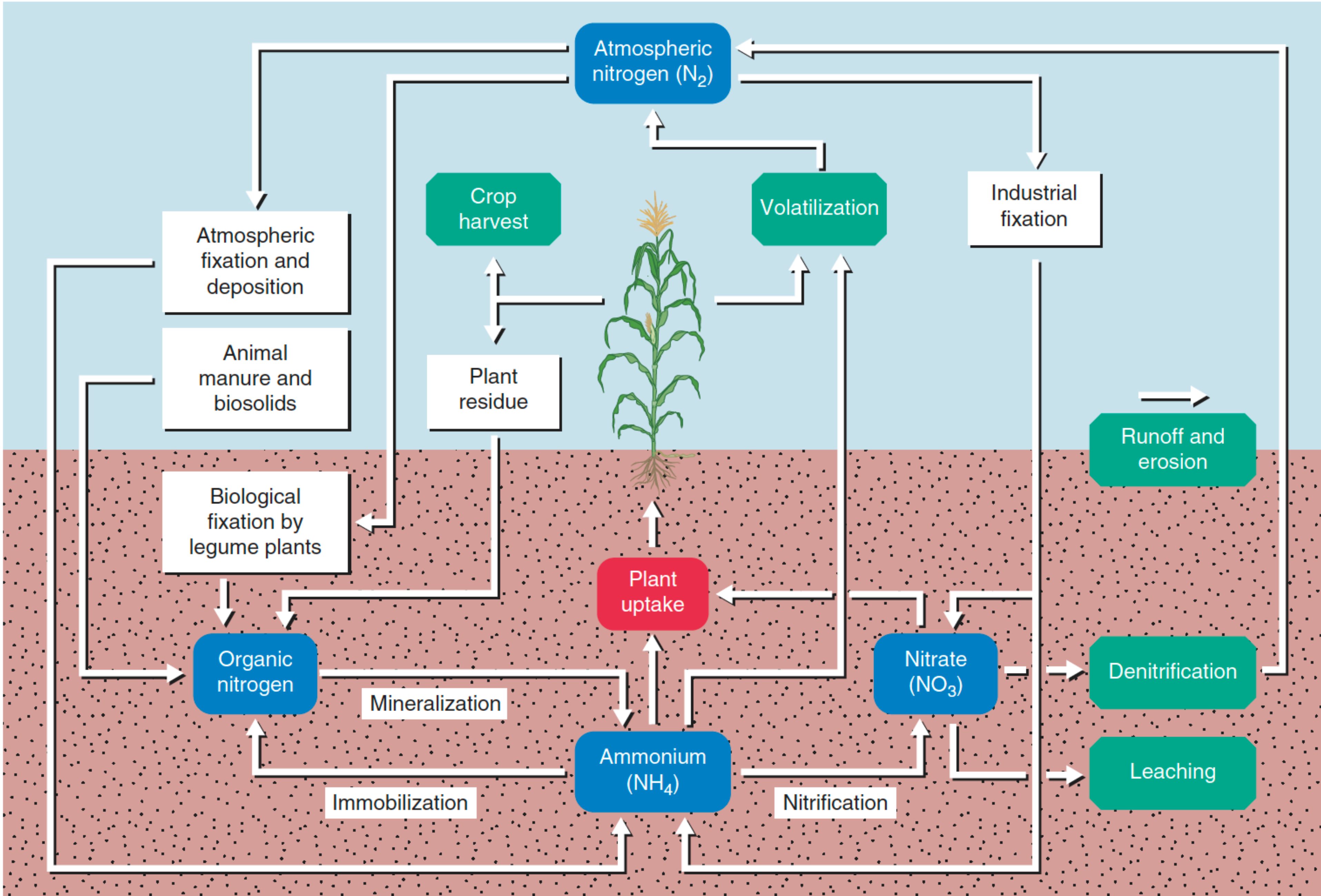
- Compare to Mars:

  3% N gas, <1% O gas, 96% CO_2

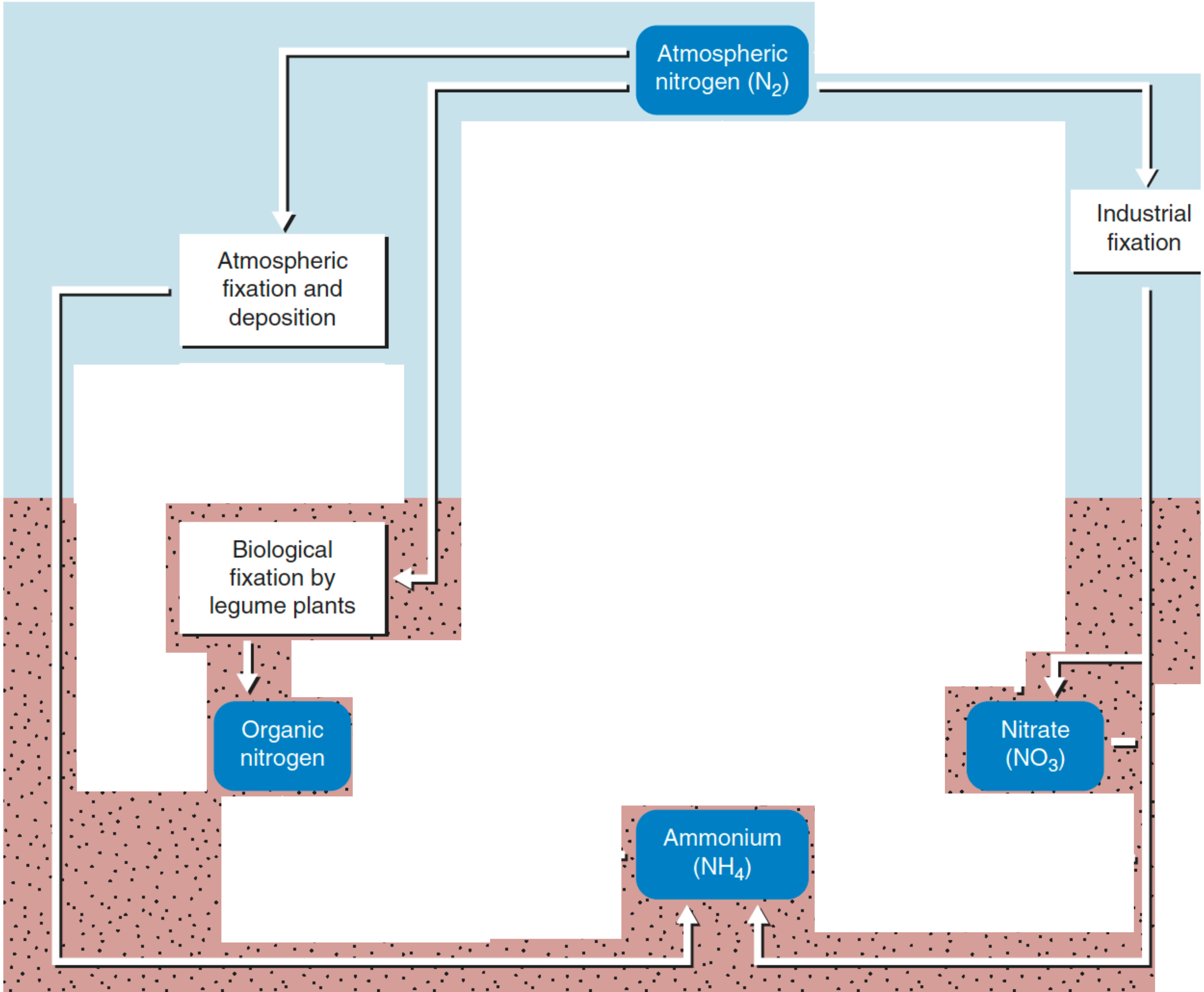
Nitrogen Topics

1. Overview of the N Cycle
2. N Fixation Mechanisms
3. N Transformations
4. Plant N Uptake
5. Role of Carbon
6. Reducing N losses

The Nitrogen Cycle

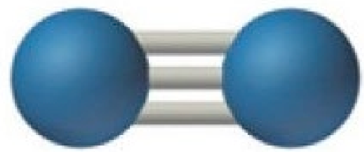


2. N Fixation Pathways



2. N Fixation Pathways

$N \equiv N$



Non-biological

Industrial Haber-Bosch process

Lightning

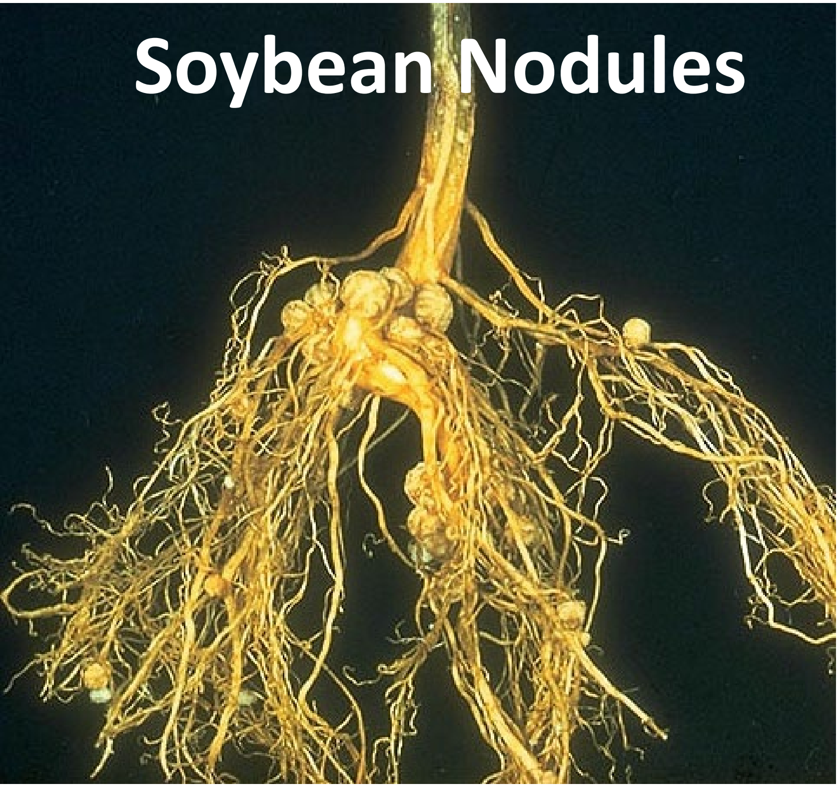
Fossil fuel combustion

Biological

Symbiotic
E.g. nodules in legumes

Non-symbiotic free-living bacteria and blue-green algae

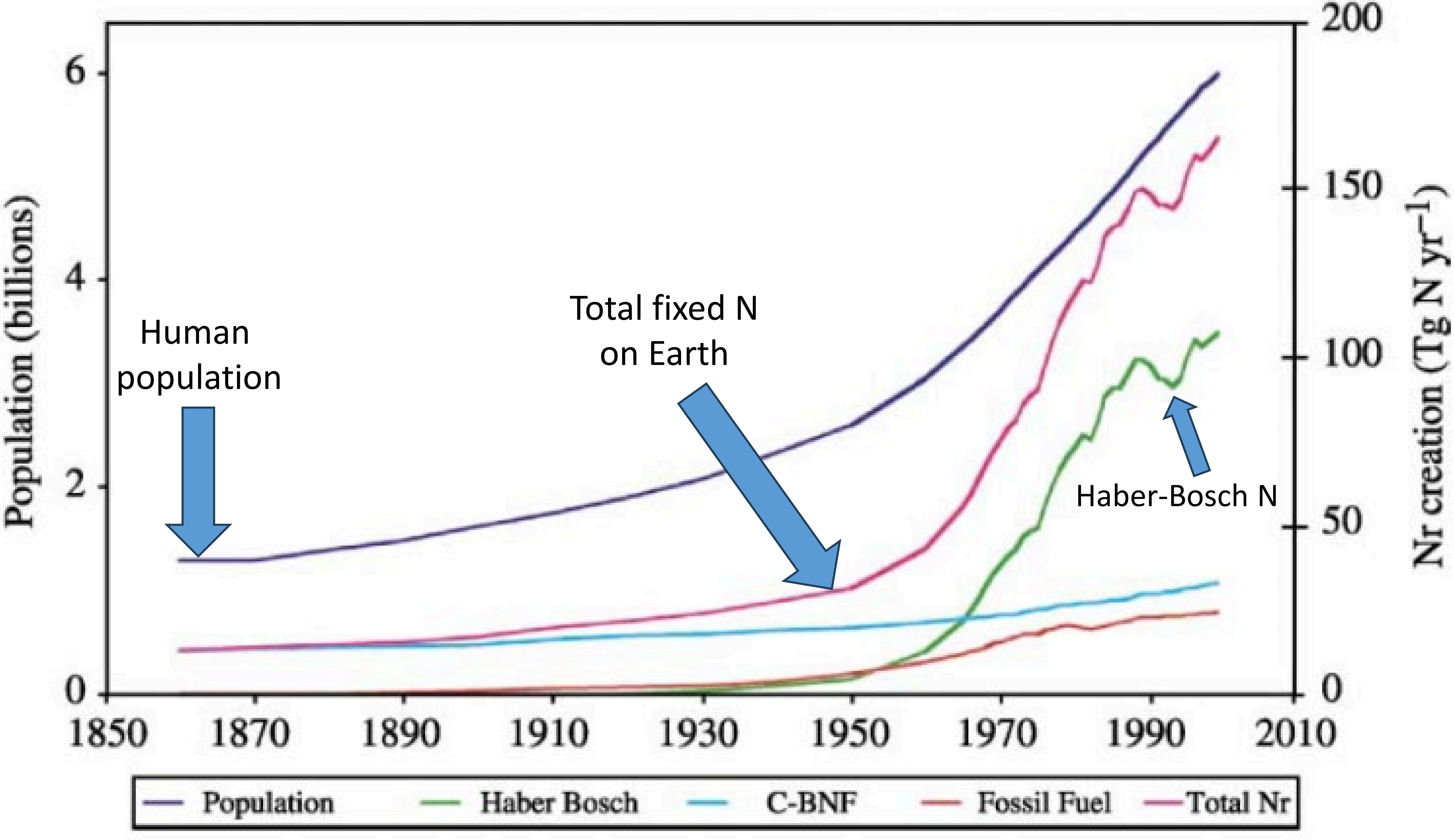
Amount of Biological N Fixation



Species	Typical N Fixation (lb/A)
alfalfa	150-250
soybeans	50-150
beans	30-50
bahai grass (Azotobacter)	5-30
alder (Frankia)	50-150

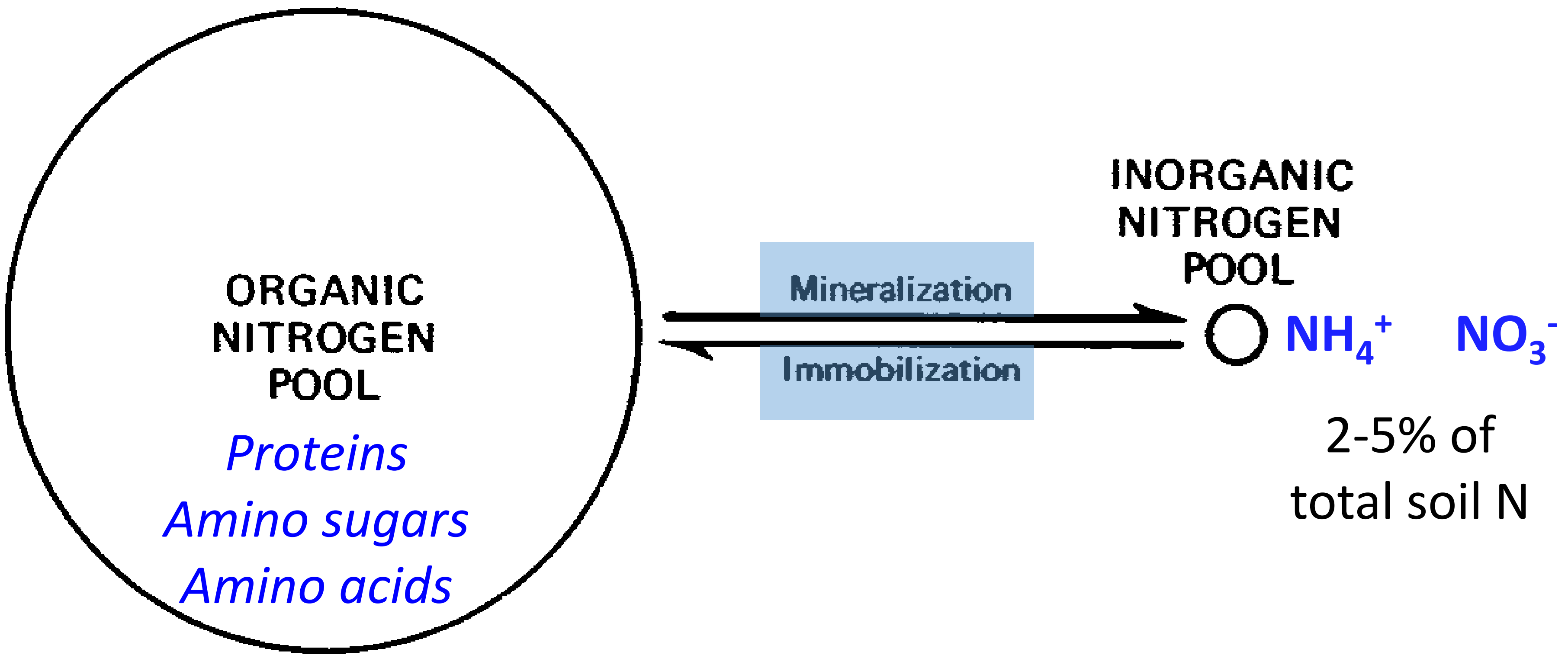
Photo credits: Harold Evans, OSU

N fixation & human population



1 Teragram = 1 billion kg or 2.54 billion pounds

3. N Transformations in Soil



A) Mineralization

- Conversion of organic N to inorganic N, ammonium (NH_4^+)
- Mediated by bacteria and fungi

B) Immobilization (opposite of mineralization)

- Conversion of inorganic N (NH_4^+ & NO_3^-) into organic N
  - Soil organisms assimilate nutrients into biomass

- Soil microbes are numerous and can outcompete plants for available nutrients

C) Nitrification

- Biological transformation of ammonium (NH_4^+) to nitrate (NO_3^-)
- Requires aerobic conditions and moderate pH
  - suppressed below pH 5.5
- Soil bacteria carry out nitrification

Nitrification: A Two-Step Process

Acidifying effect

Nitrosomonas

$$2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 2\ H_2O + 4\ H^+ + e$$

Ammonium *Nitrite* *Hydrogen*

Nitrobacter

$$2\ NO_2^- + O_2 \rightarrow 2\ NO_3^- + e$$

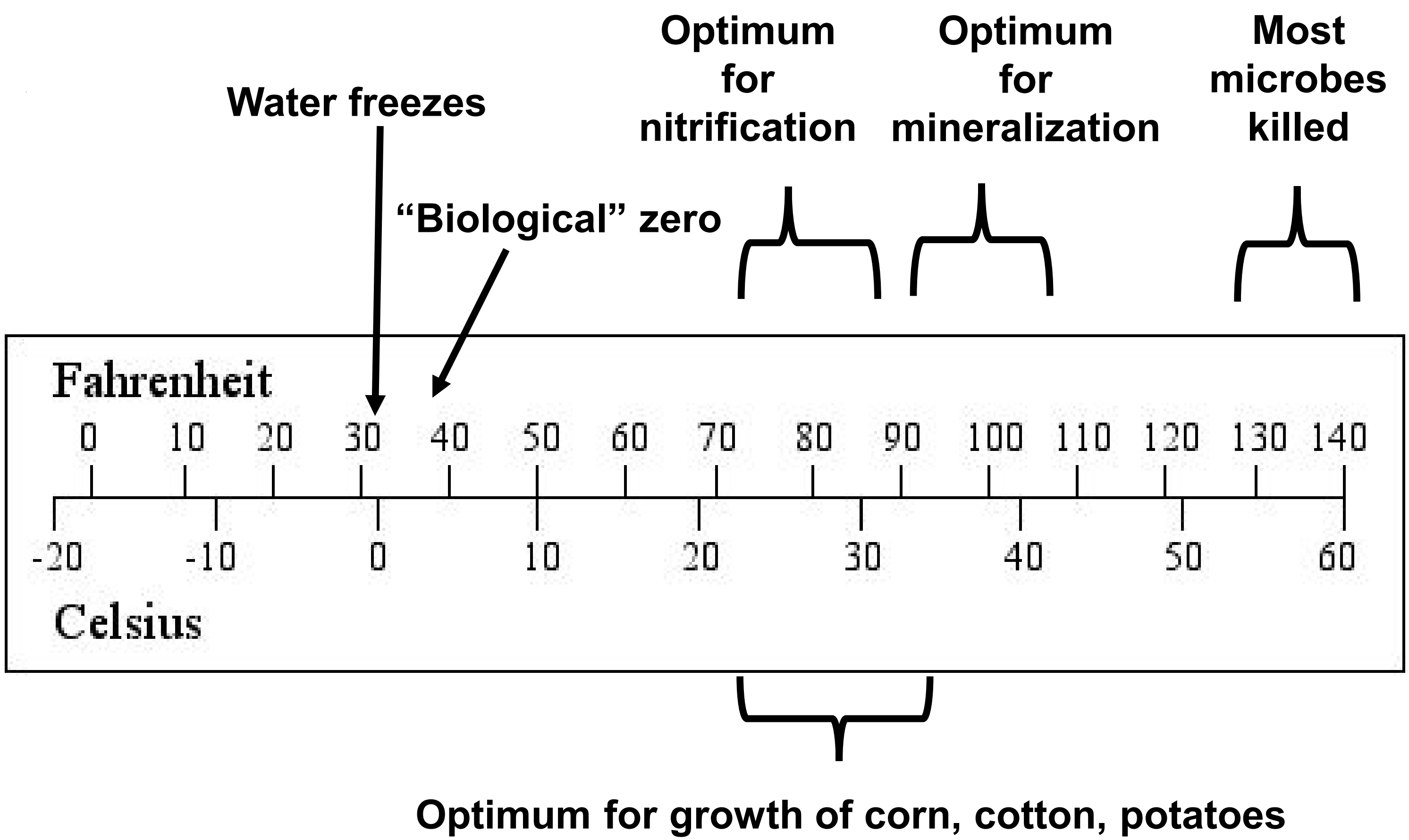
Nitrite *Nitrate*

The Soil N Cycle:
A Biological Phenomenon

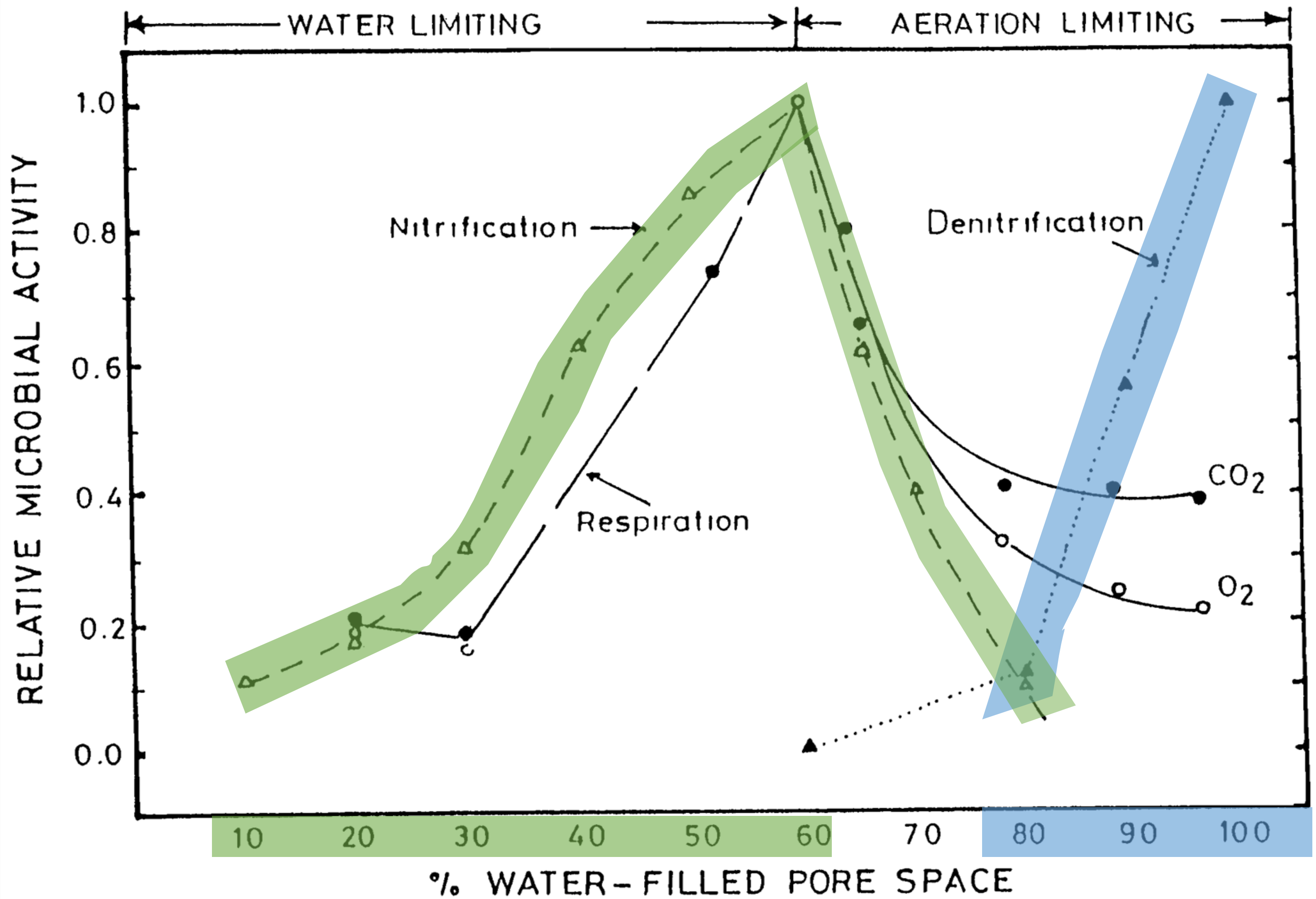
Influenced by:

- pH: most bacteria suppressed at low pH (Nitrification inhibited below pH 5.5)
- Temperature: is the key
- Moisture: affects aeration (oxygen) and transformations

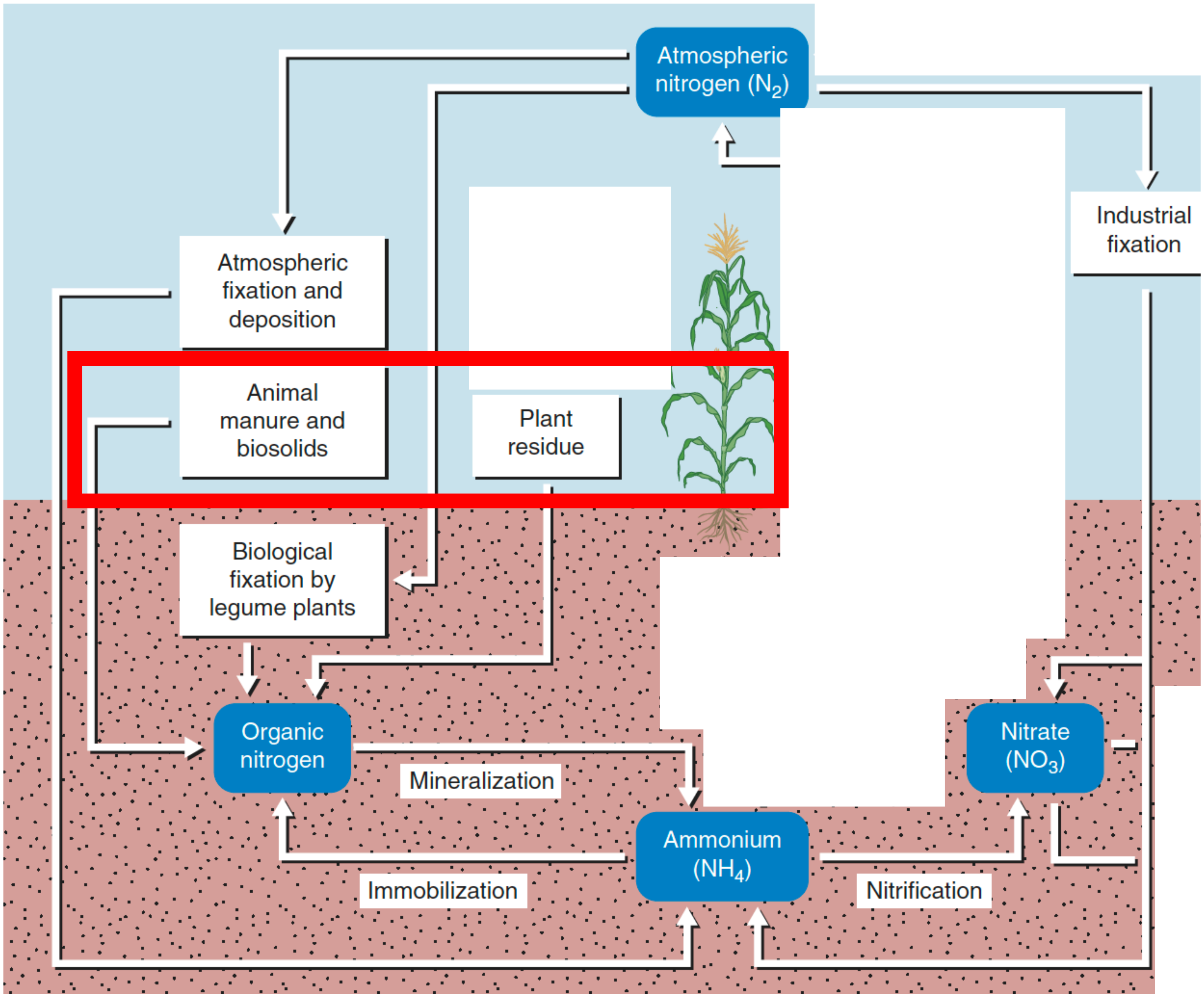
Effect of Temperature on N Cycling:



Effect of Moisture & Oxygen Status on N Cycling:

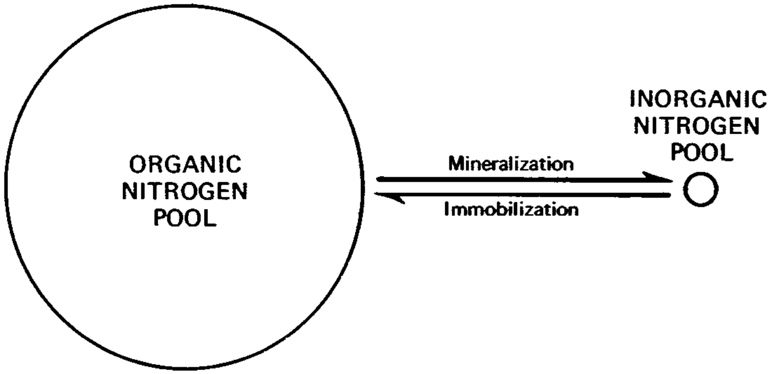


4. The Role of Carbon

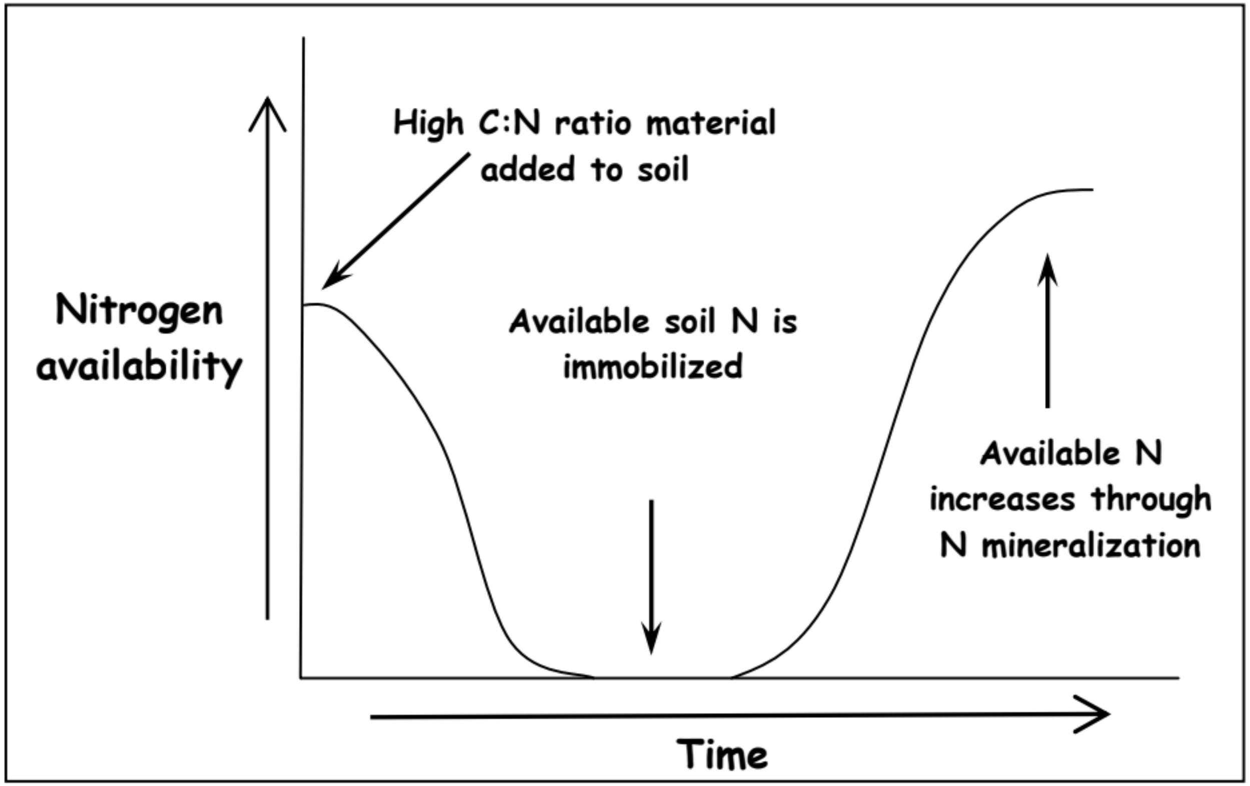


4. The Role of Carbon

- C:N ratio is the amount of C relative to the amount of N in a given material
- A high C:N ratio (>25:1) → N immobilized
- A low C:N ratio (<20:1) → N mineralized



Importance of C:N ratio



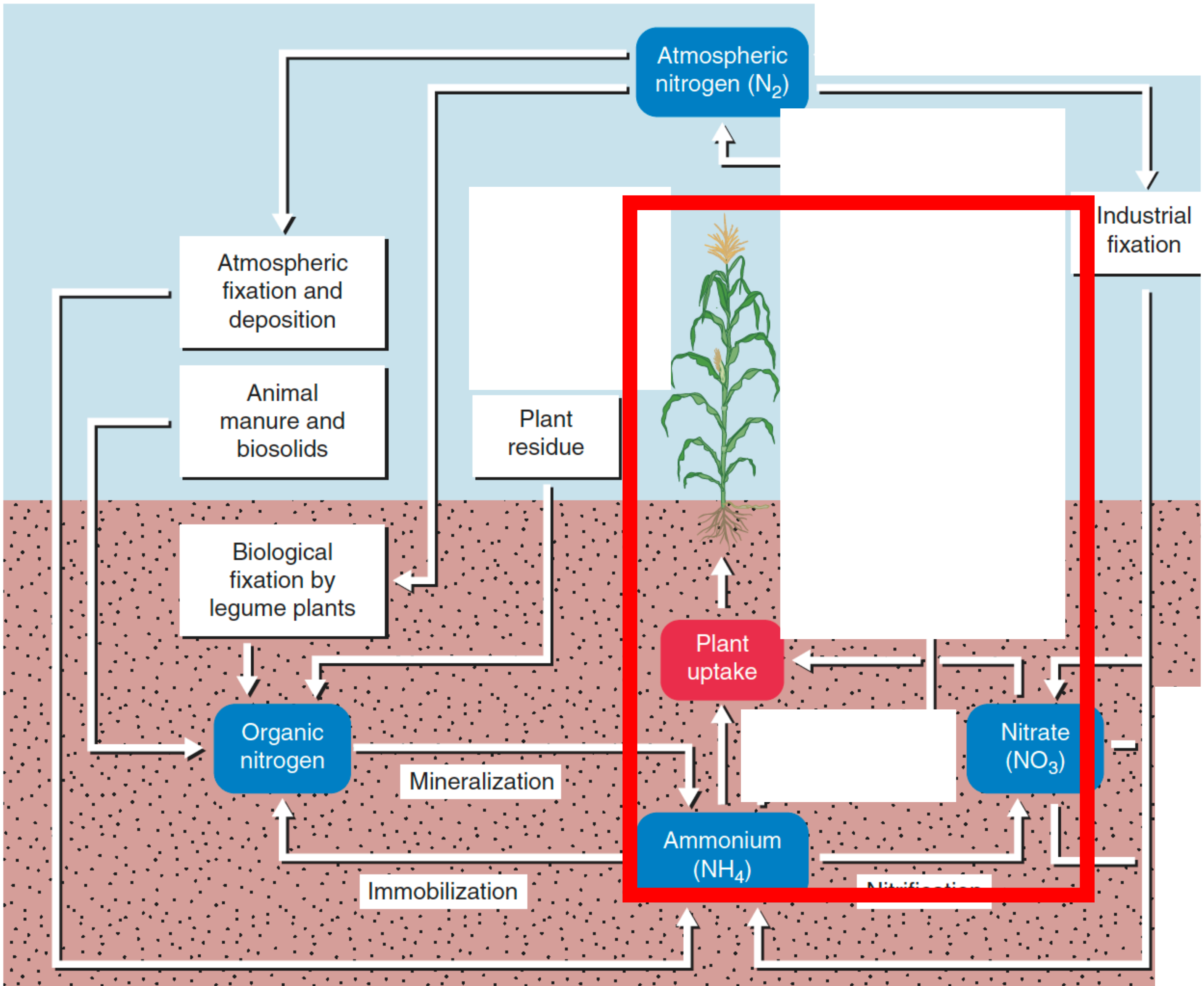
Material	C:N Ratio Range/Typical	
broiler litter	12-15:1[a]	
cattle	11-30:1[a]	
horse	22-50:1[a]	
sewage sludge	5-16:1[a]	Mineralization
straw	48-150:1[a]	
sawdust	200-750:1[a]	Immobilization
leaves	40-80:1[a]	
rye cover crop, vegetative stage	26:1[b]	
rye cover crop, anthesis	37:1[b]	
corn stalks	60-73:1[a]	

a Cornell On-Farm Composting Handbook, Rynk et al, 1992
b The Nature and Properties of Soils, Brady and Weil, 1999

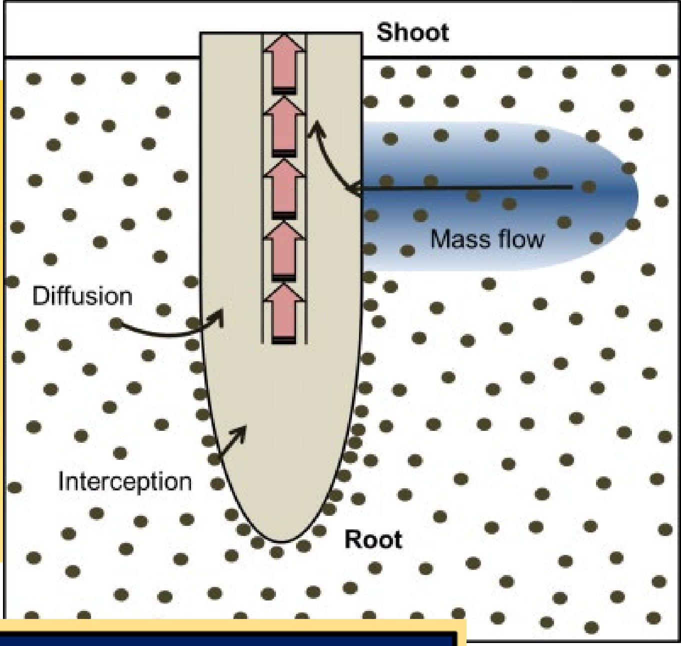
Managing C:N Ratio of Inputs

- Manage cover crops
  - Incorporate cover crops while in vegetative state
  - Leave mature cover crops on surface
- Monitor soil N and plant growth when incorporating straw, sawdust, and other high C:N materials

4. Plant Uptake



Nutrient Movement in Soils

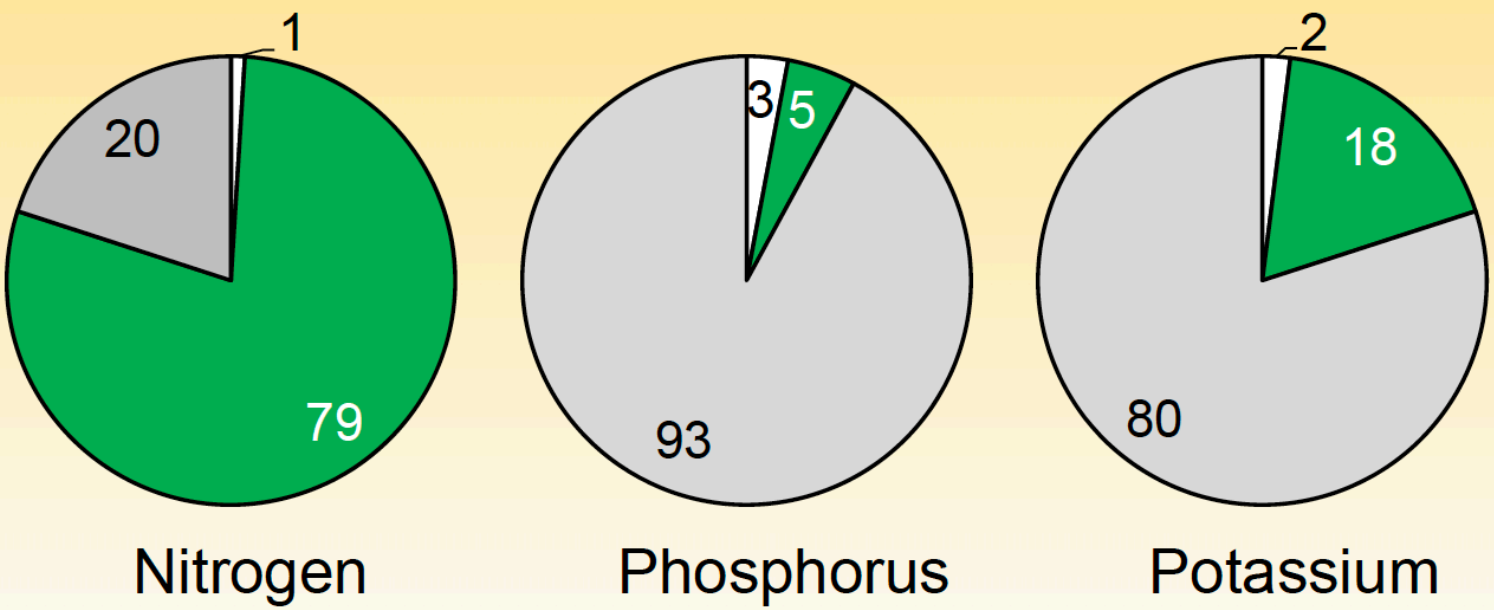


Root interception
(root grows into a nutrient location)

Mass flow
(nutrient moves with the water absorbed by a plant)

Diffusion
(nutrient moves from higher to lower concentration)

Relative contribution of each pathway for corn (%)

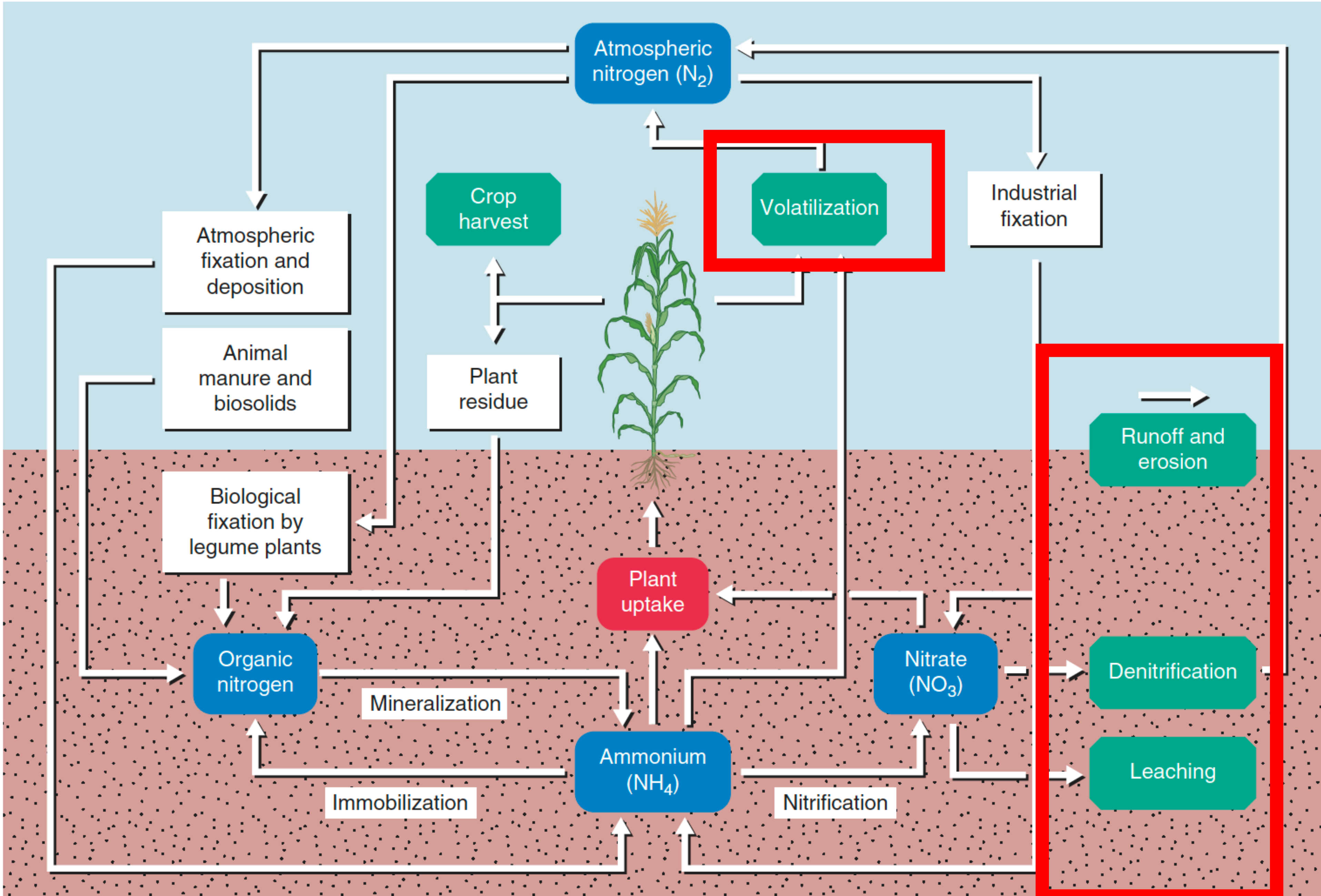


Barber, S.A. 1995. Soil nutrient bioavailability: A mechanistic approach. 2nd ed. John Wiley and Sons, New York, NY.

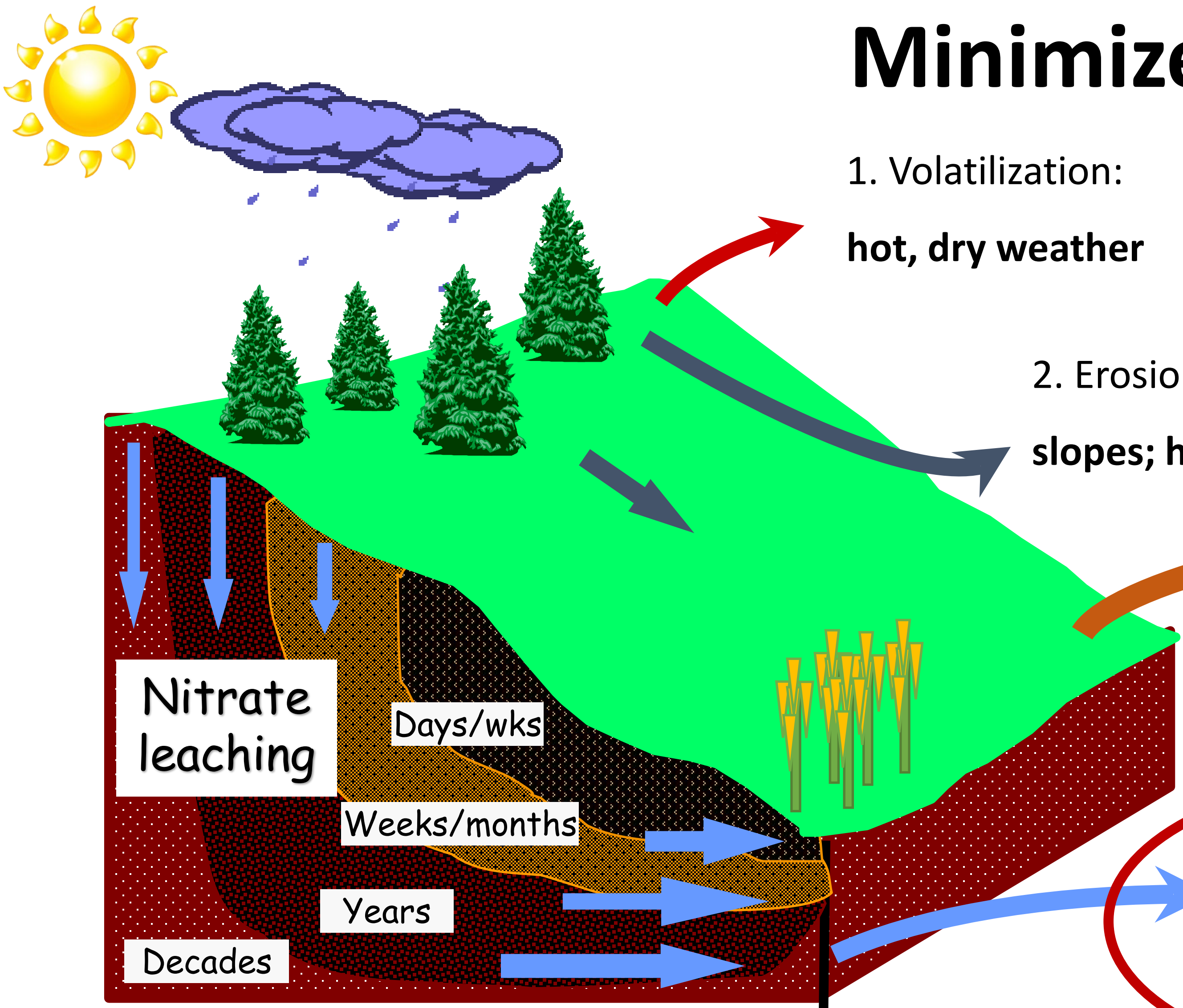
4. Plant Uptake

- Plants use N (mainly) in the form of NH_4^+ or NO_3^-
- **Recovery of N fertilizer varies from 25% to 78%.** Depends on soil type, rainfall and irrigation distribution, rate and timing of N fertilizer applications.
- **Other ag factors:** tillage systems, cropping systems

5. Reducing N Losses



5. Reducing N Losses



Minimize Losses:

1. Volatilization:

hot, dry weather

2. Erosion/runoff:

slopes; heavy rain

3. Denitrification:

waterlogged soils

4. Leaching:

soil texture; rain amount

(J.J. Meisinger, USDA)

1. **Ammonia Volatilization** (a gaseous loss)

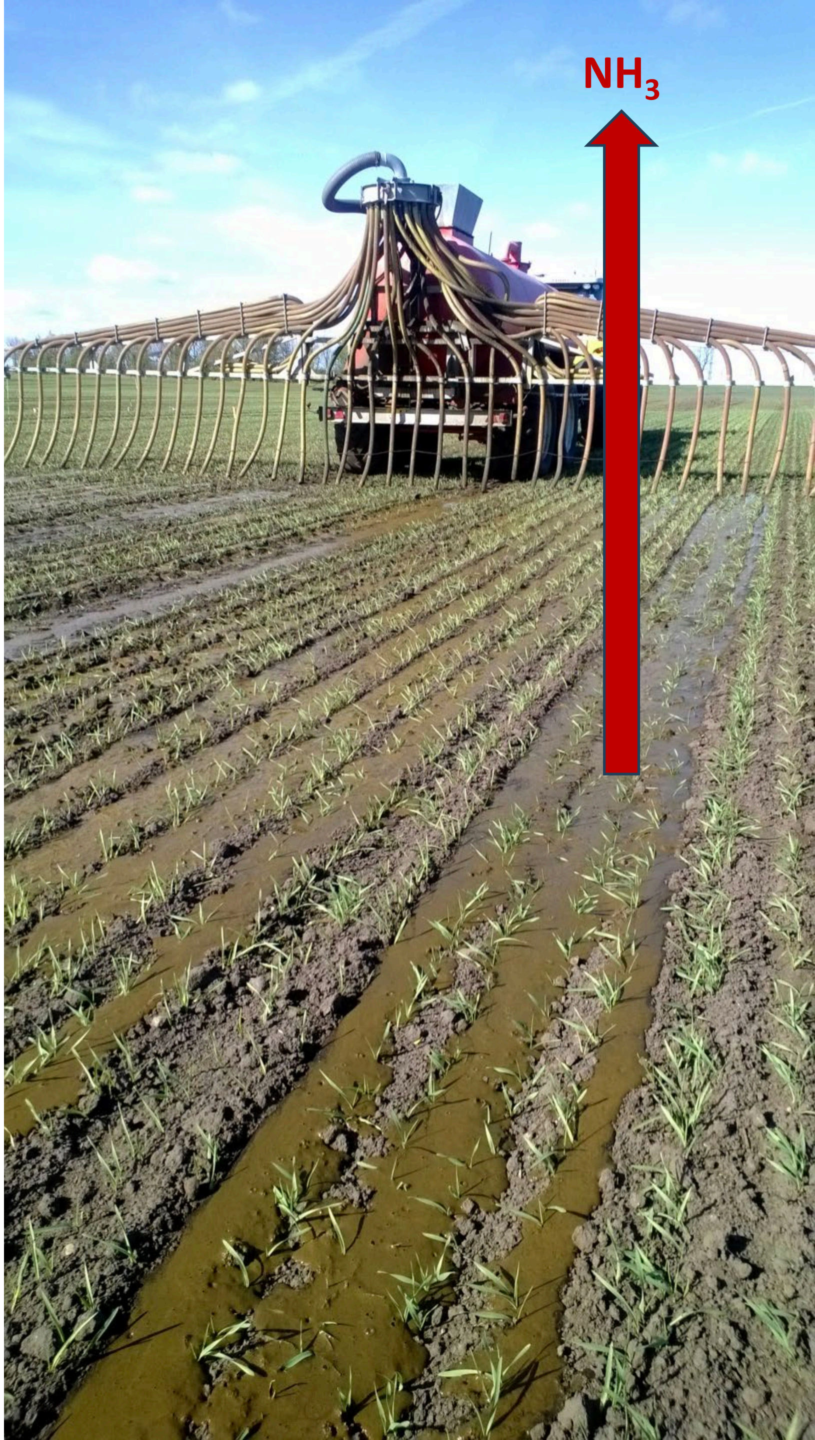
- Loss of ammonia-N (NH_3) to the atmosphere
- Ammonium in the presence of hydroxyl (OH^-) can produce ammonia gas

$$NH_4^+ + OH^- \rightarrow H_2O + NH_3$$

- Can occur in any surface-applied N source containing NH_3 / NH_4^+
  - Urea, ammonium nitrate, manure
- Enhanced by warm, dry atmospheric conditions

Problems caused by ammonia volatilization

- Economic loss to the farm
- Lowers N:P ratio of manure
  - Accelerates P buildup in soils using N-based manure management
  - Accelerates shift to P-based manure management



Factor that affect ammonia volatilization

Increase NH_3 loss

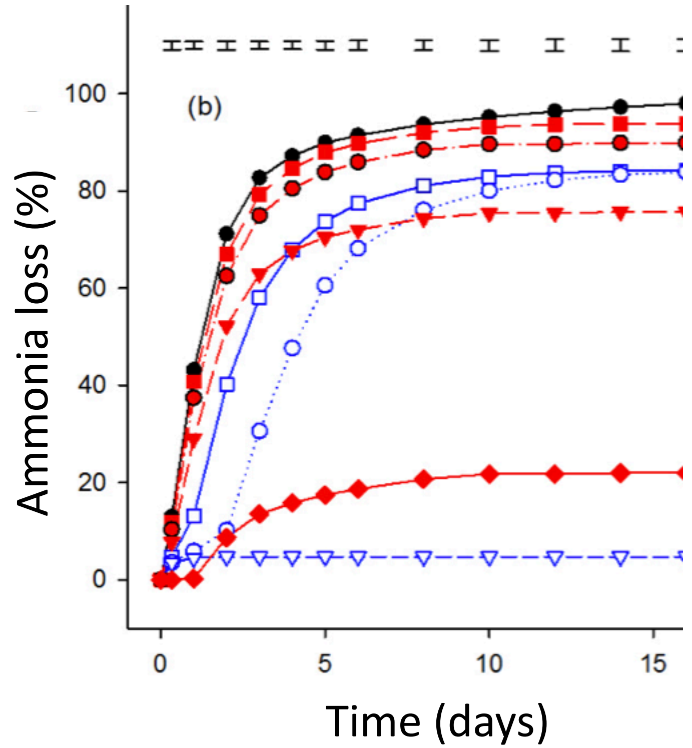
- Temperature
- Wind
- Solar radiation

Decrease NH_3 loss

- Rainfall
- Humidity
- Acidity (low pH)

→ *Generally, the same factors that increase water evaporation also increase NH_3 loss*

Managing Ammonia Losses:



- Know where and when ammonia loss occurs
  - First day of application
  - Sunny, warm, low humidity, breezy conditions
- Incorporation is required under many circumstances in Maryland
- Spread and incorporate manures in the early morning or evening (when dew is still present)

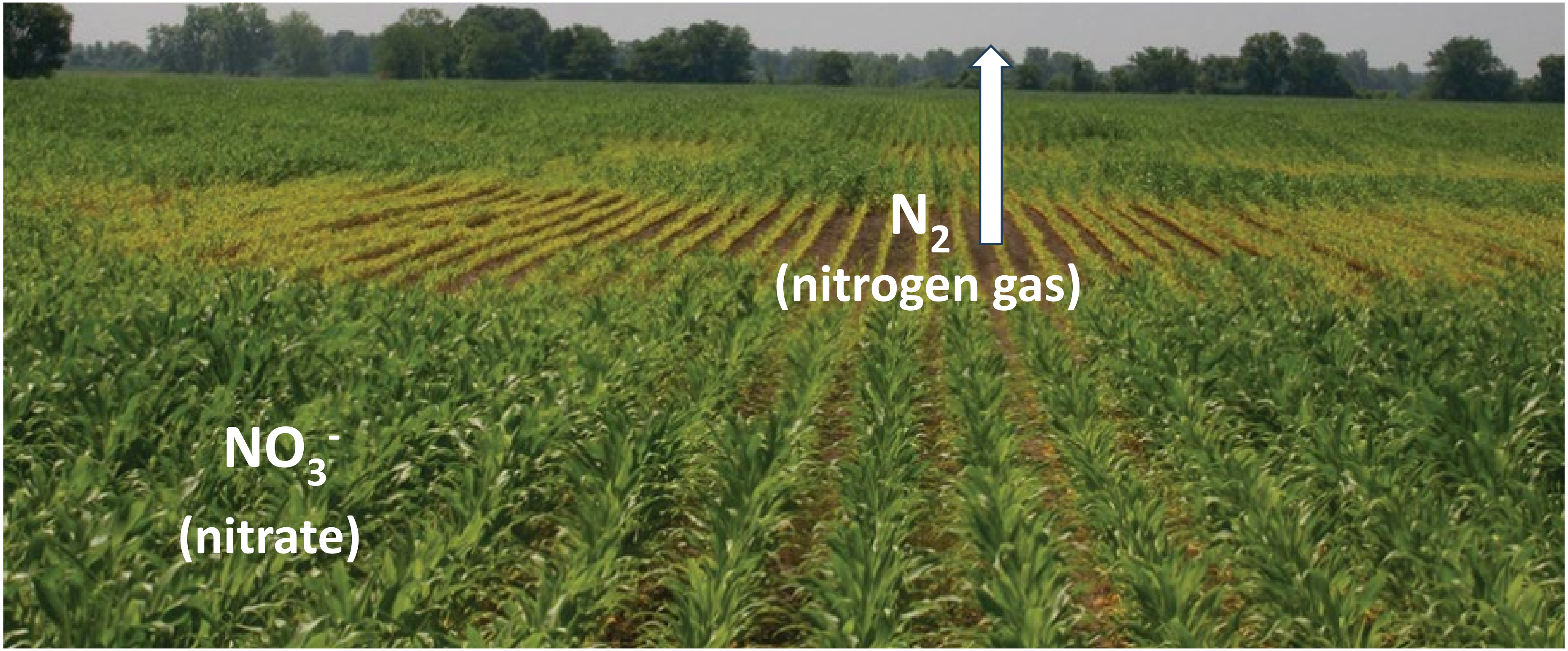
2. Denitrification (a gaseous loss)

$$NO_3^- \longrightarrow N_2O\uparrow \longrightarrow N_2\uparrow$$

nitrate — **nitrous oxide gas** — **dinitrogen gas**

- Biological reduction of nitrate to N_2 gas
- NO_3^- transformed to gaseous compounds
- Favored when soil is saturated (anaerobic conditions)

A Visual on Denitrification (Wet Spot) in Field



How to avoid denitrification?

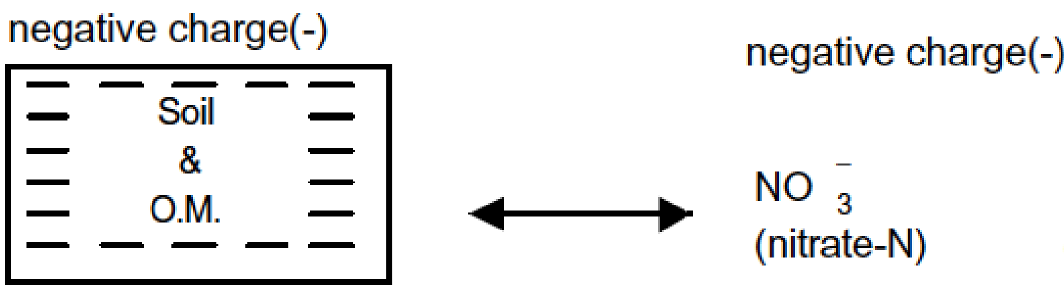
- Improve soil drainage
- Delay N application on wet soils
- Split N application in targeted areas

Photo credit: www.agleader.com

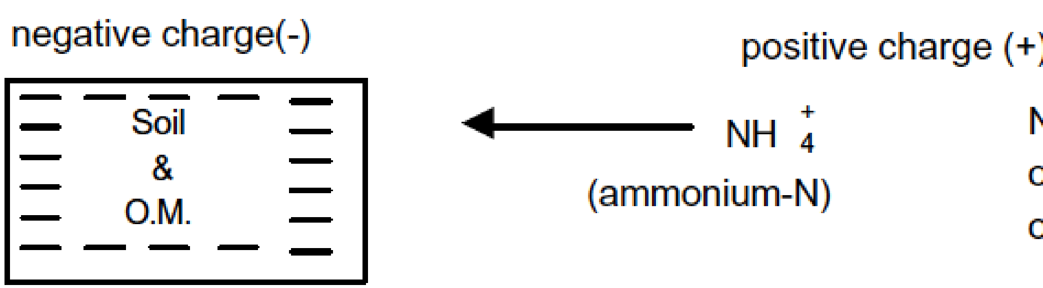
3. Leaching (loss with water through soil)

- Primarily lost as nitrate (NO_3^-)
  - Moves freely in soil profile
    - Transported by drainage water
    - Especially important in sandy soils
  - Can lead to pollution of groundwater
- Greater under modern row-crop production systems
- An economic loss with environmental consequences

Why does nitrate leach, but not ammonium?



NO_3^- is repelled by soil and organic matter particles because each has a negative charge. NO_3^- is then subject to movement with soil water.



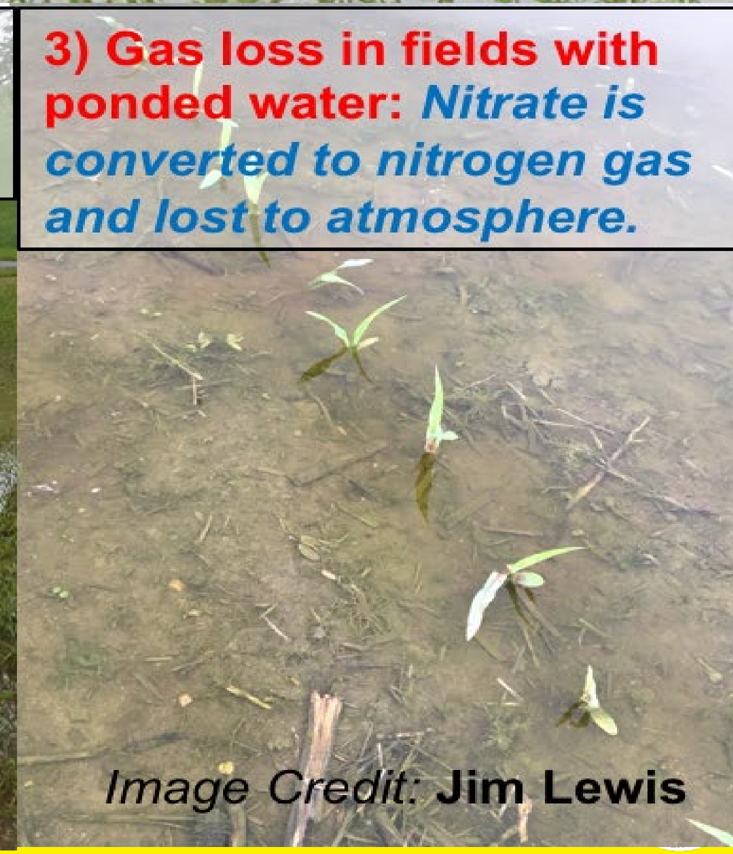
NH_4^+ is attracted onto soil and organic matter particles because of opposite charge attraction.

Reasons for excessive nitrate leaching

- **Inefficient N management**
  - Heavy one-time applications (**RATE**)
  - Improper timing (**TIME**)
  - Over-application of manure/sludge
- **Enhanced by periods of heavy rainfall or irrigation**


1) Leaching in fields with standing water: Nitrate is mobile in soil and will leach to groundwater.
Image Credit: Jim Lewis


2) Runoff from fields: Nitrogen is lost in runoff waters and will escape into drainage ditches and streams.
Image Credit: Matt Morris


3) Gas loss in fields with ponded water: Nitrate is converted to nitrogen gas and lost to atmosphere.
Image Credit: Jim Lewis

Principles of N Management

- Maintain soil pH appropriate for crop
- Reduce losses (leaching, gaseous, runoff/erosion)
- Apply N fertilizers and manure when plants need it, where they need it
- Timely incorporation of manure and sewage sludge when practical
- Using 4Rs principles is a good start. Look for other opportunities to improve N use

Concluding Thoughts

- **Challenges:**
  - No direct soil tests. Variability in fields
  - **Complexity:** N mineralization (microbes control N cycling), cover crops N contribution, manure N contribution
- **Opportunities:**
  - **<u>Room to improve:</u>**
  - Split applications w/PSNT
  - Accounting for N from legumes, cover crops, and manure

N deficiency in Corn

Phosphorus (P)

15
P
Phosphorus
30.974

- Simpler cycle than N
  - No gaseous forms
- Available P can be "fixed" to less available forms

P deficiency in corn

Phosphorus Topics

1. **P in soils:** origin, cycling
2. **P in plants:** uptake, distribution
3. **P in fertilizers:** reactions, availability, fixation
4. **P in manures:** animal diets, P forms
5. **Legacy P in soils:** cause, leaching, drawdown

1. P in soils: origin, cycling

What is the source/origin of P in soils?

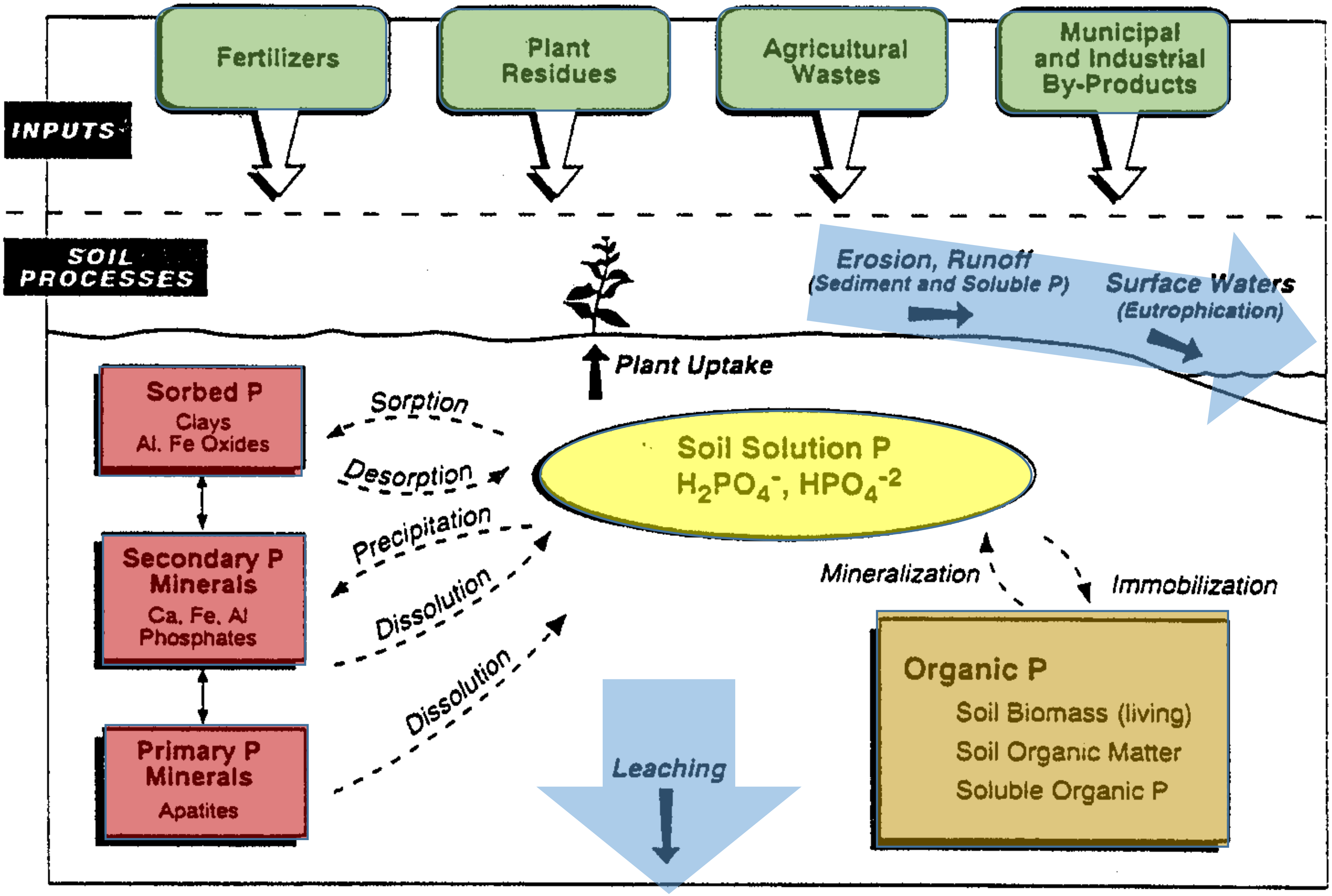
- **NATURAL SOILS:** P in most soils originated from weathering of rocks that contains apatite (calcium phosphate mineral) and other minerals

- **MANAGED SOILS:** Today, 20 to 80% of P is present in organic forms. Phytic acid is a major form

- The remainder P is found in in inorganic forms, in combination with Fe, Al, Ca

- Soil microbes release and immobilize P to/from the soil solution

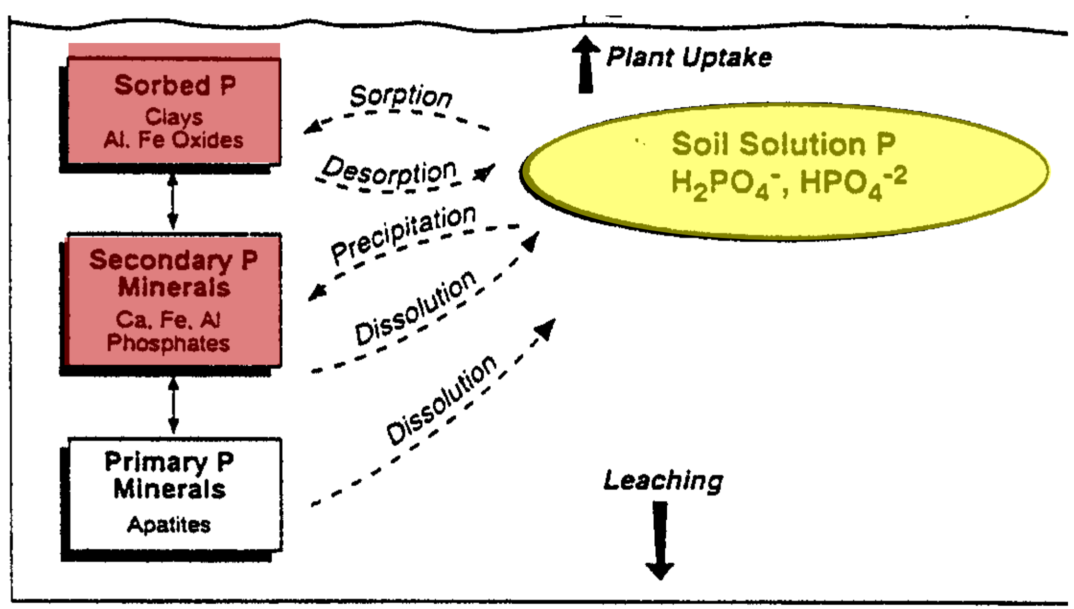
Cycling of P



Source: Pierzynski et al. (2000)

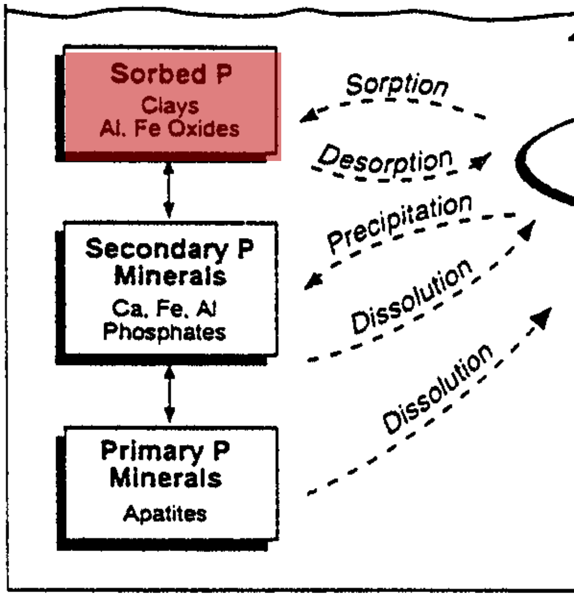
P Fixation (a transformation)

- A set of processes through which P is converted to less available forms
  - Adsorption/sorption
  - Precipitation



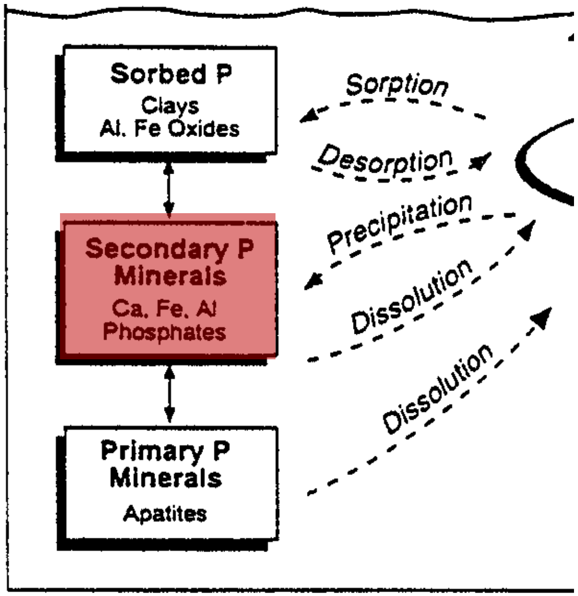
P fixation

- *Adsorption or Sorption*
  - In acid soils, P is adsorbed to surfaces of Al/Fe oxides and clay minerals
  - In neutral and calcareous soils, P is adsorbed to surfaces of $CaCO_3$ and clay minerals

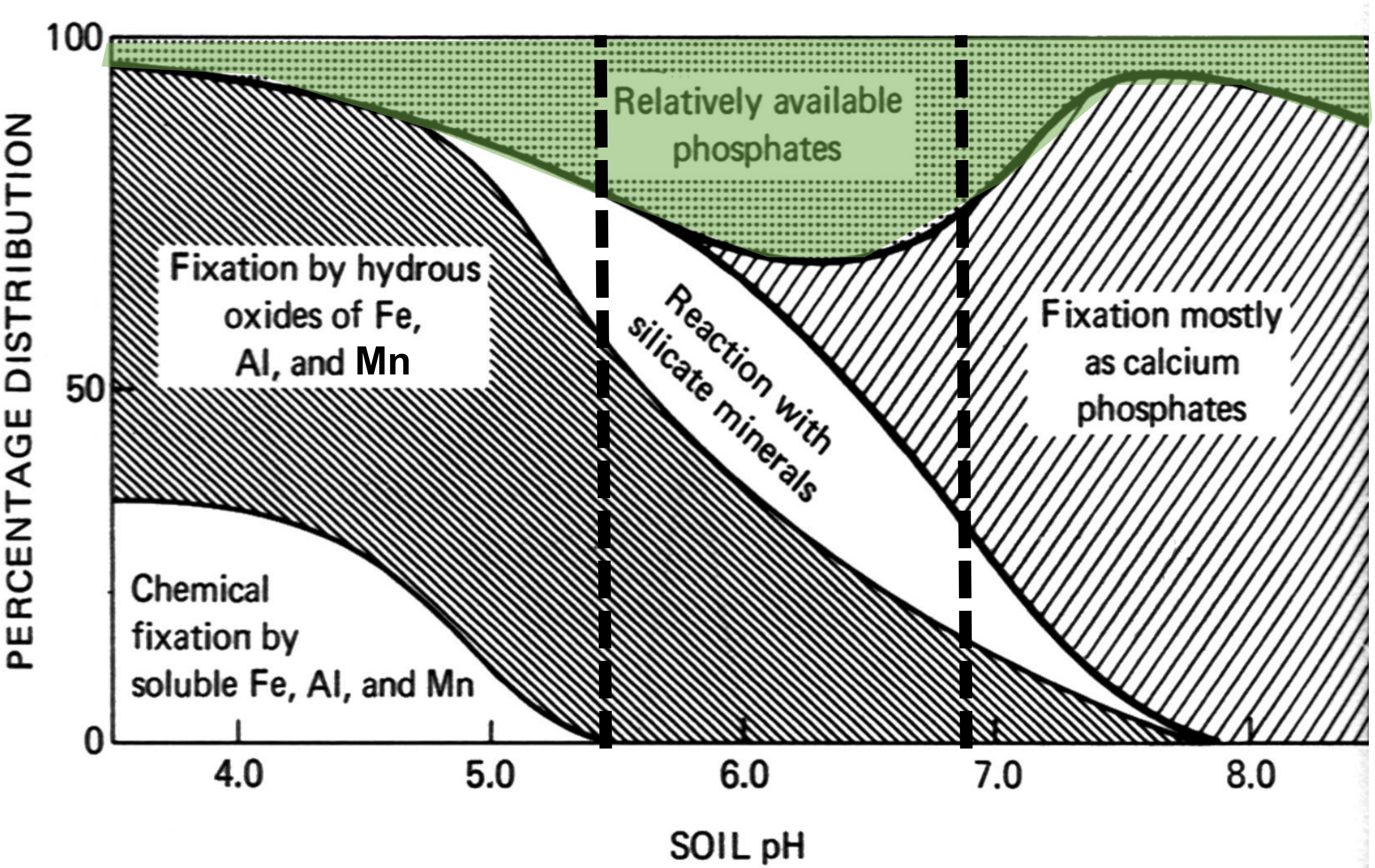


P Fixation

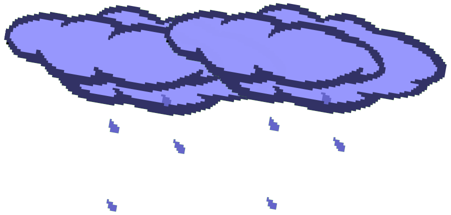
- Precipitation as secondary P compounds
  - In acid soils, P combines with iron (Fe) and aluminum (Al) to form insoluble compounds
  - In neutral and calcareous soils, P combines with (Ca) to form insoluble compounds



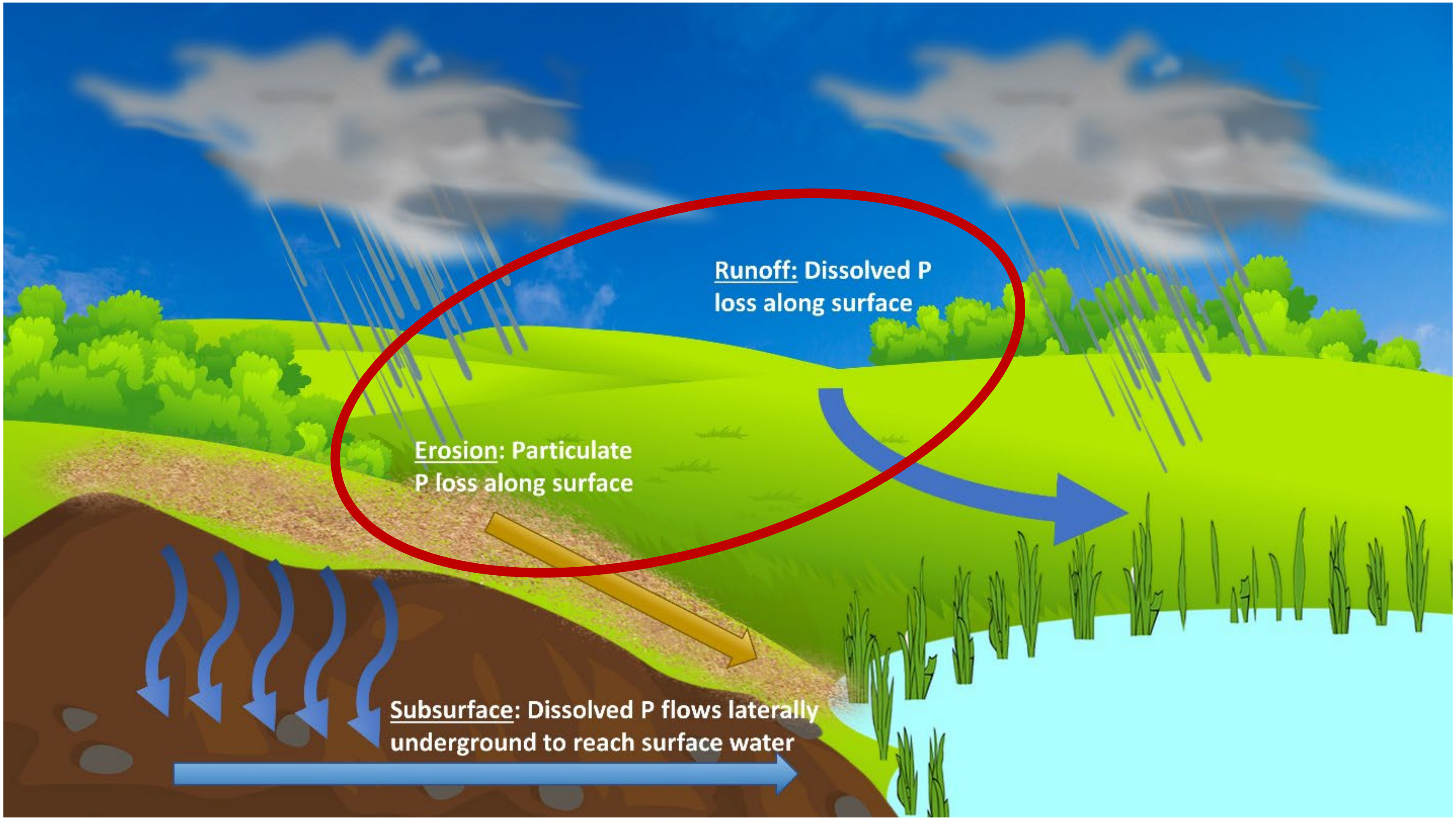
Plant Available P: *Soil pH affects P availability*



N.C. Brady, 1974



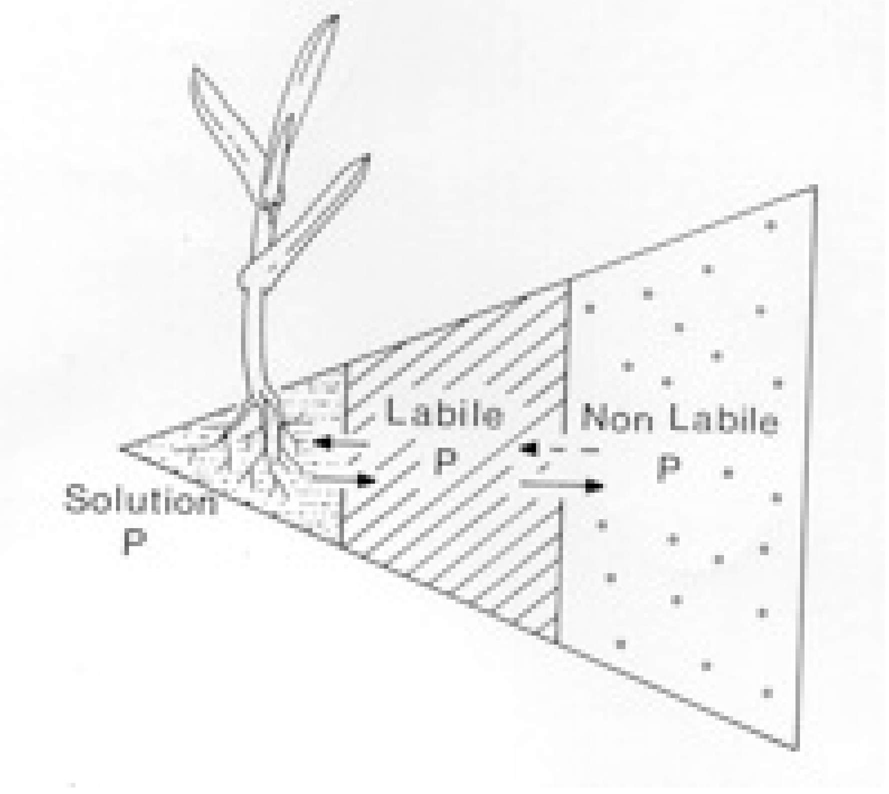
P Loss Pathways



Source: Lucas et al. (2023)

3. P in plants: uptake, distribution

Plants contain ~0.2% P or 2 g/kg

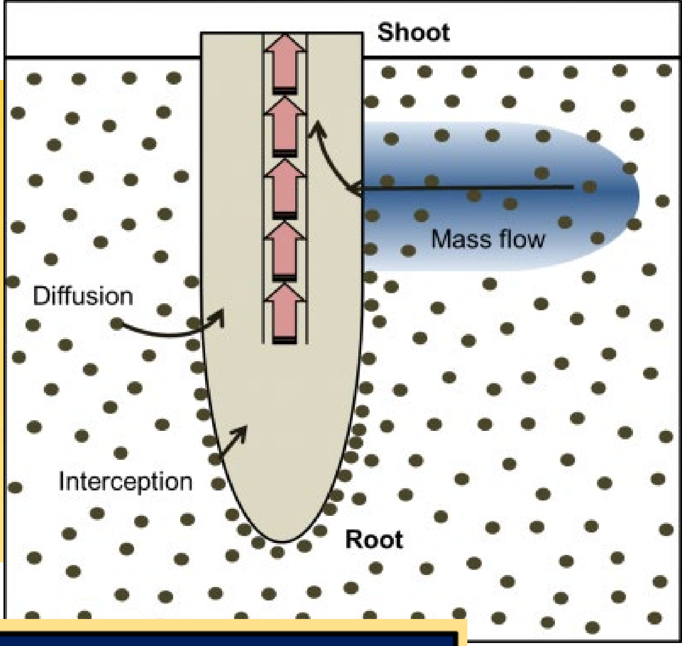


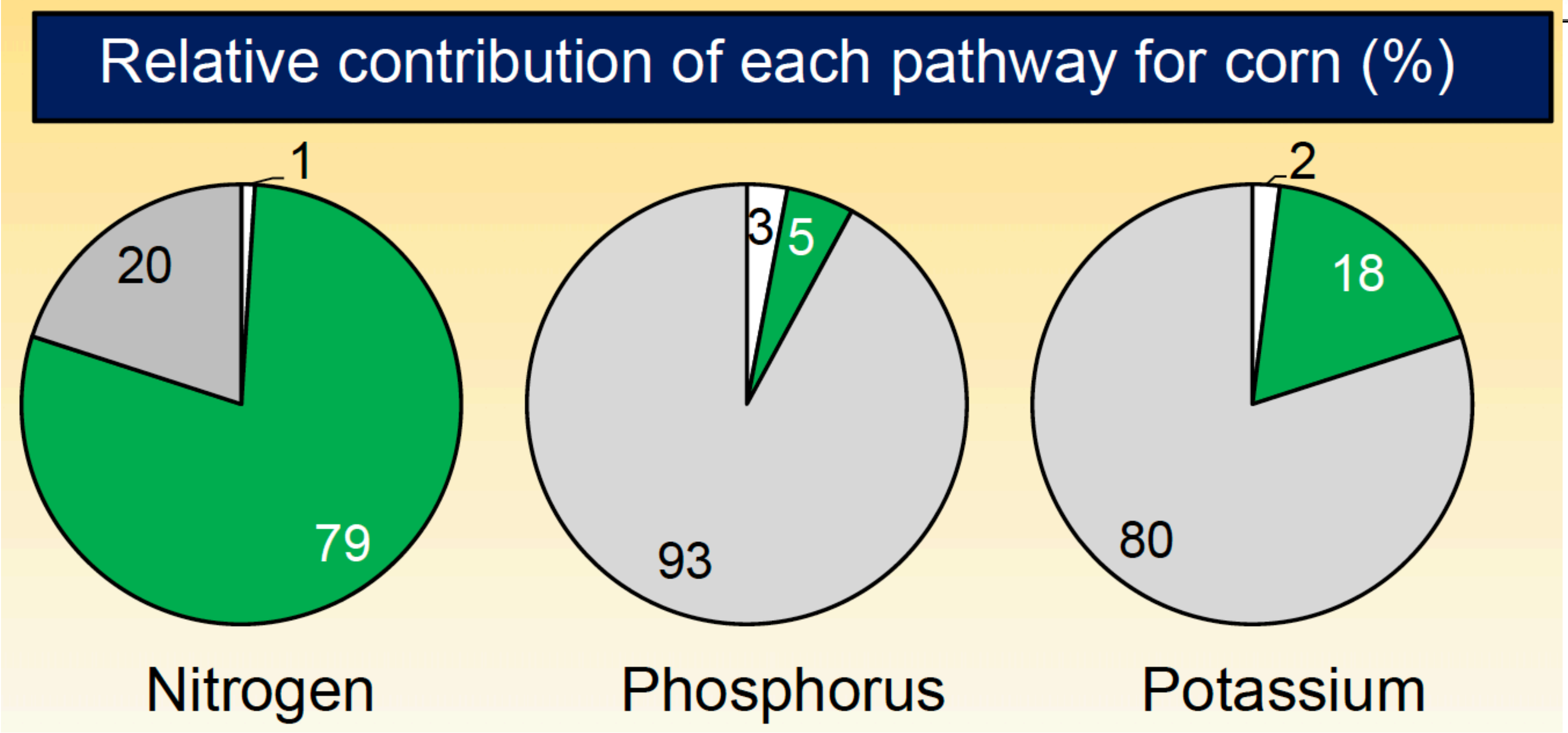
Nutrient Movement in Soils

Root interception
(root grows into a nutrient location)

Mass flow
(nutrient moves with the water absorbed by a plant)

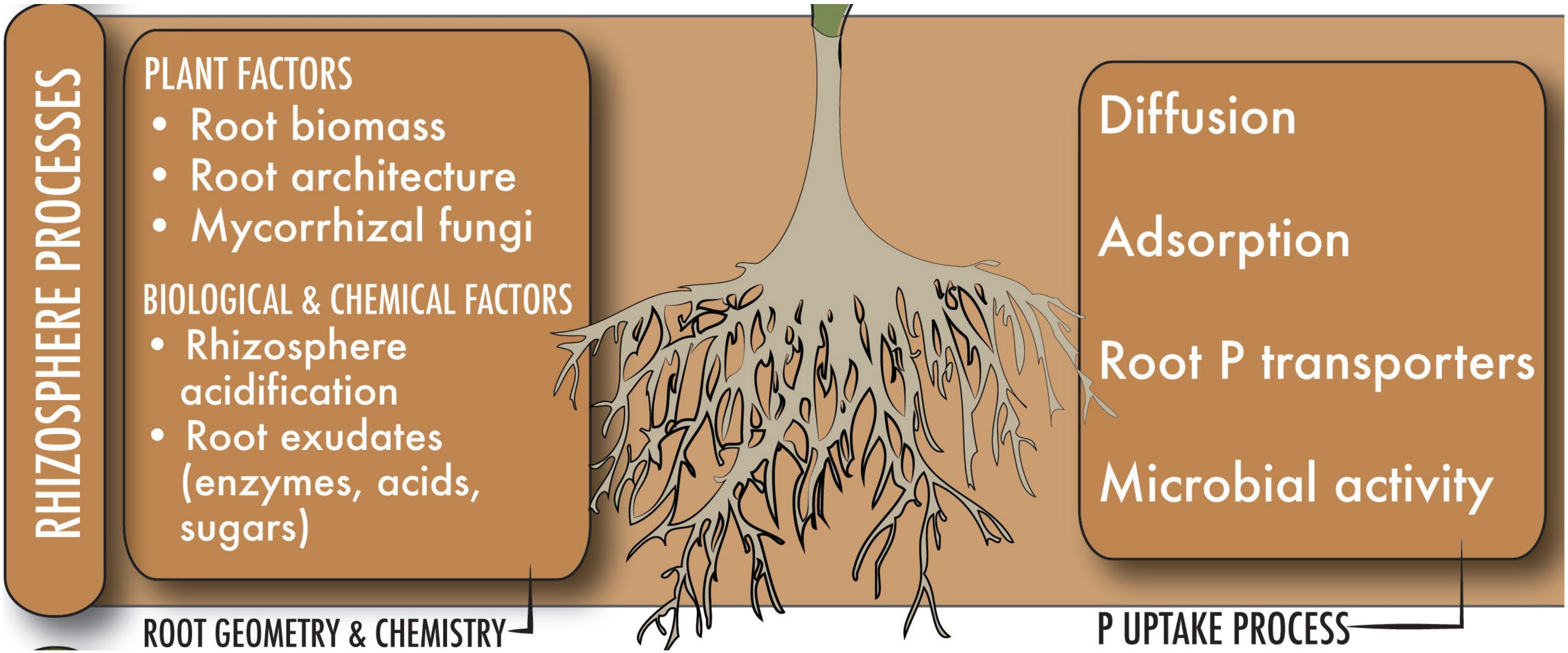
Diffusion
(nutrient moves from higher to lower concentration)





Barber, S.A. 1995. Soil nutrient bioavailability: A mechanistic approach. 2nd ed. John Wiley and Sons, New York, NY.

Factors affecting P availability:



Plants are Smart

Case 1: Limited P supply in soils (Low to Medium FIV):

- Plants grow more roots
- Increase the root uptake of P from the soil
- Move P from older leaves to new leaves
- Use/deplete the vacuolar stores of P
- Mycorrhizal fungi may more extensively colonize the roots

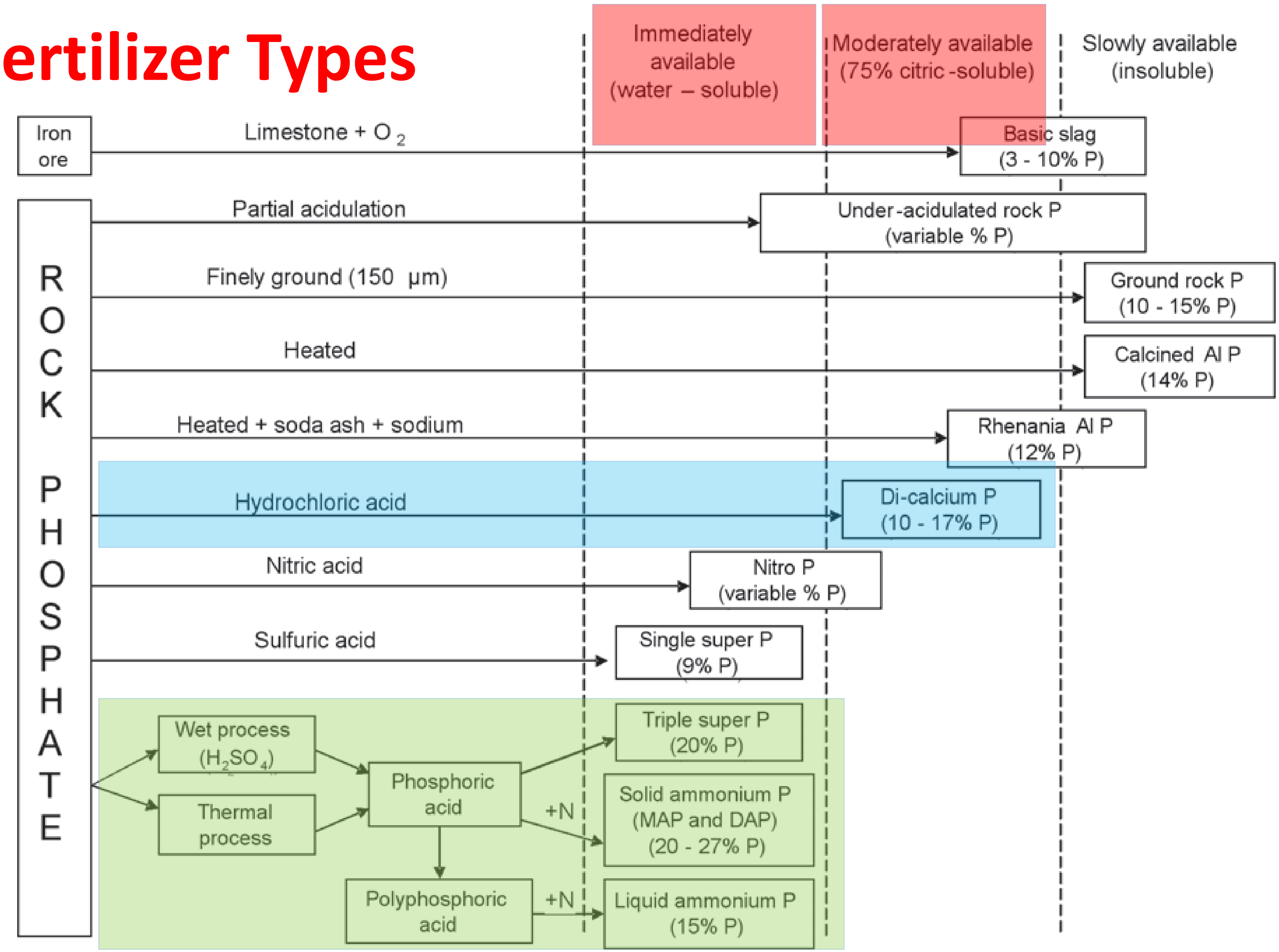
Case 2: Adequate P supply in soils (High/Very High FIV):

- Goal is to prevent the accumulation of toxic P concentrations
- Plants convert inorganic P into organic P (e.g. phytic acid)
- Reduce inorganic P uptake rate from soil
- Lose extra inorganic P by efflux (~8 to 70% of the influx)

The plant's goal is to maintain constant levels of intracellular inorganic P

4. P in fertilizers: reactions, availability, fixation

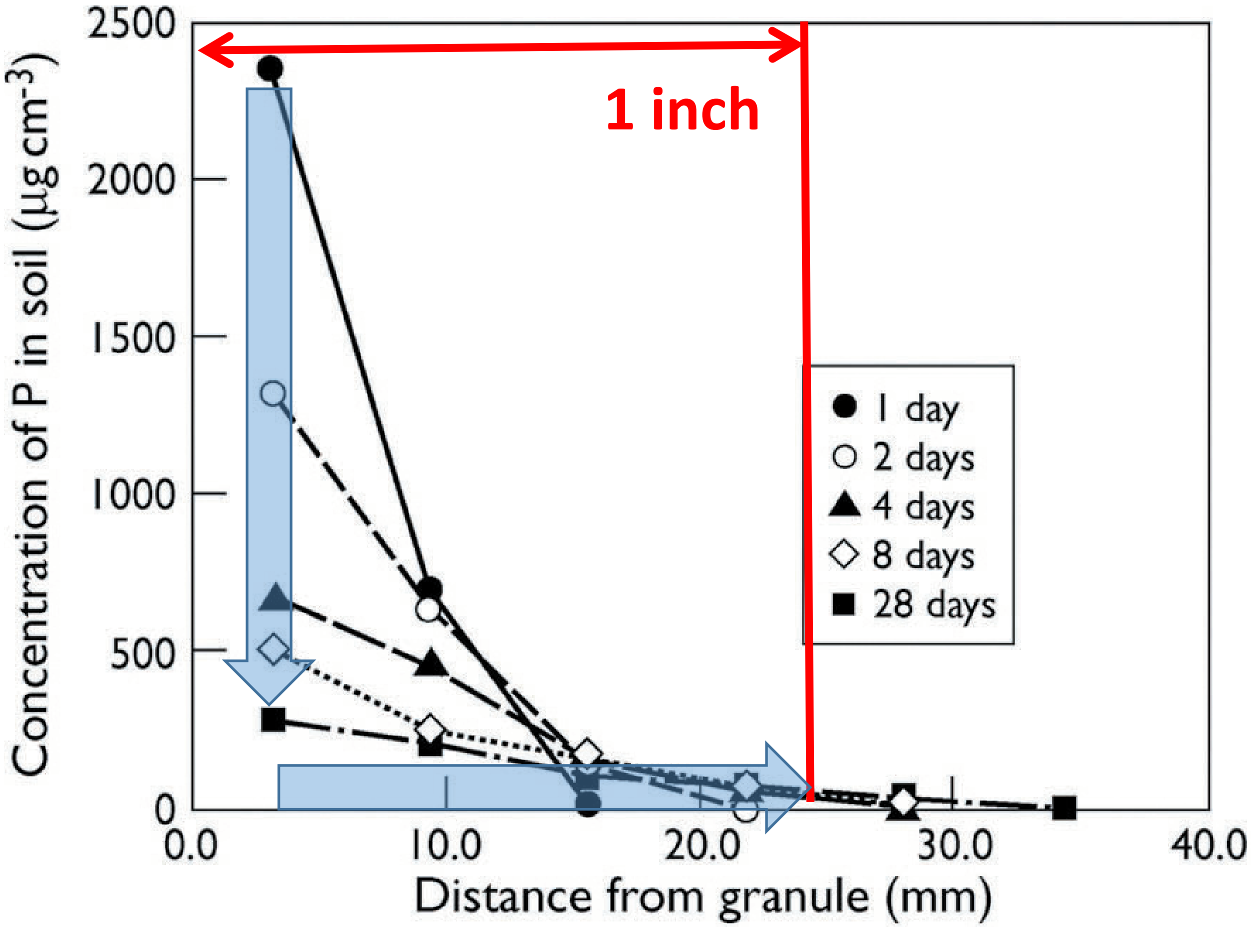
Fertilizer Types



P fertilizers, their manufacture, and relative plant availabilities

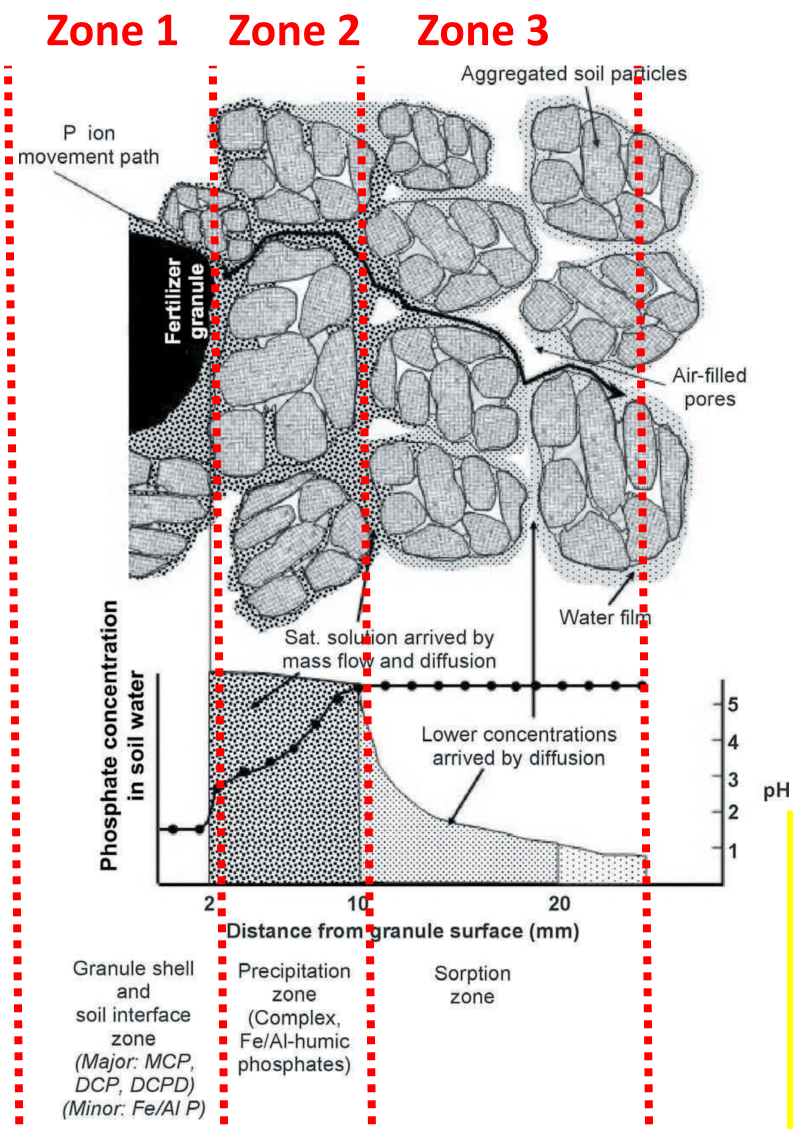
P availability decreases over time & away from application site

- **Highest P availability in the vicinity of a superphosphate granule**



Influence of increasing contact time on P concentration in soil at different distances away from a superphosphate granule placed on the surface of a soil at 20% gravimetric water content (data from Williams, 1971b).

P movement in soils



P in soils moves by two ways:

- **Diffusion:** major pathway of P movement in soils. High to low concentration [Zone 3]. Low P availability and sorption
- **Mass flow:** wherever water goes [Zone 2]. High P availability and quick precipitation.

- **Highest P availability in the vicinity of a superphosphate granule**
- **Implications? P Fertilizer should be applied closer to roots (banded)**

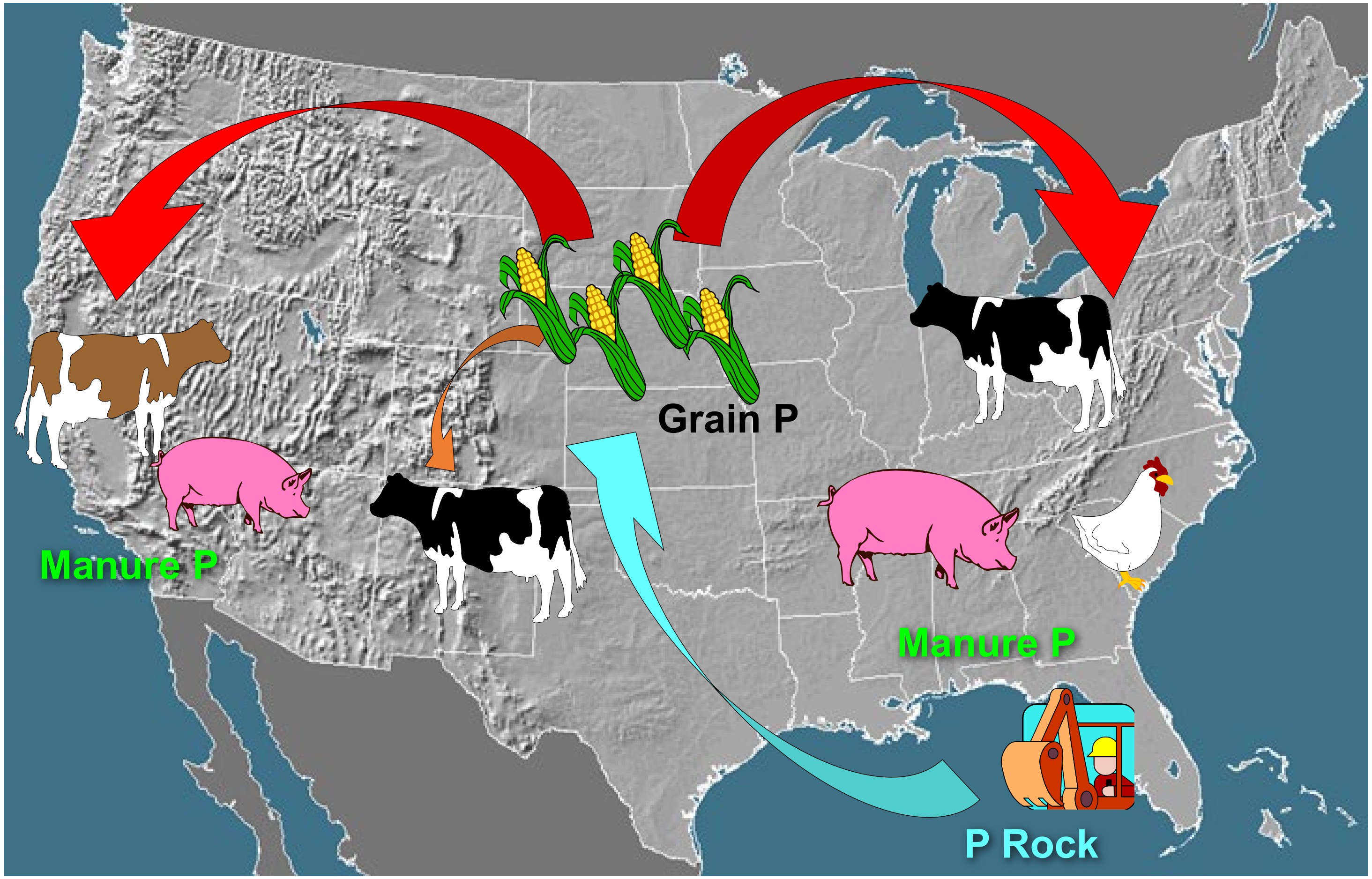
5. P in manures and litters

- Dairy manure/slurry: most of P is available right away
- Poultry litter (with bedding): a majority of P is available in the first year

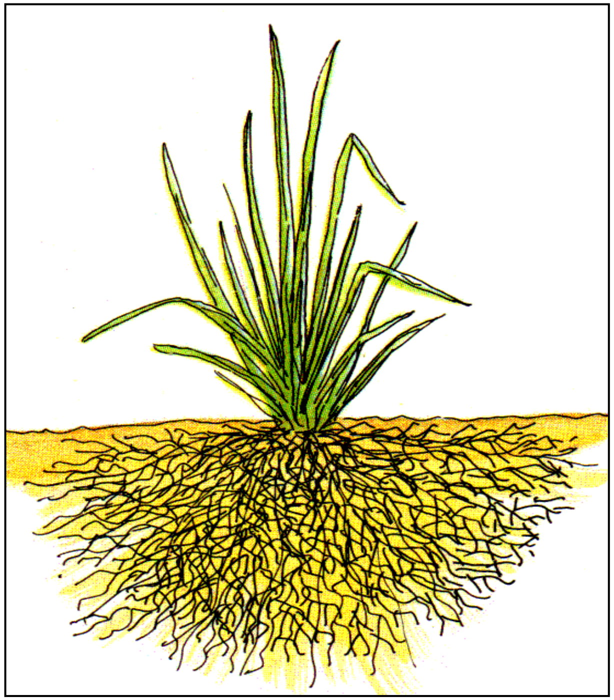
6. Legacy P in soils: cause, leaching, drawdown

Cycling of P: Before World War II

Cycling of P: After World War II

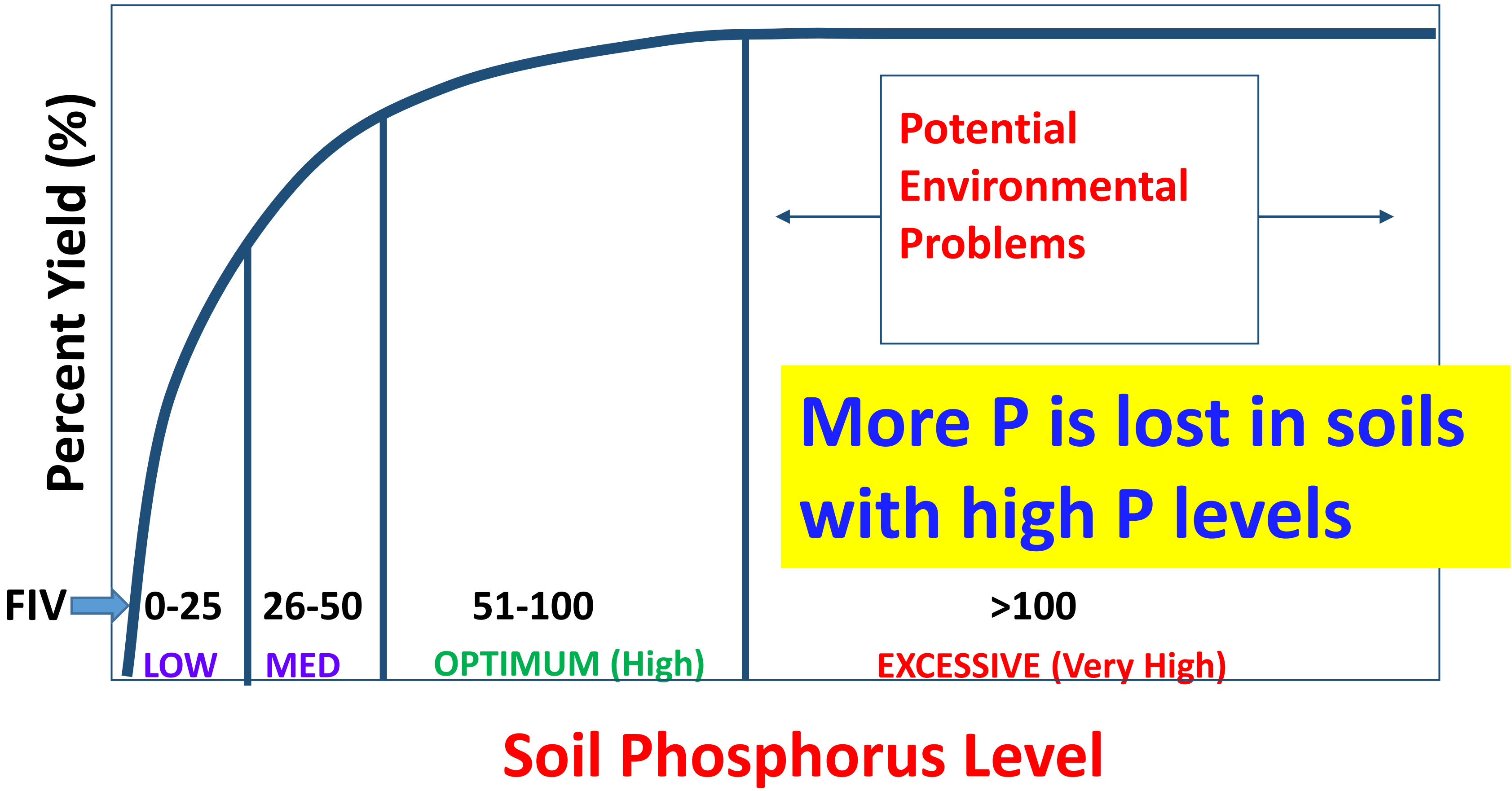


Why are Some Soil P Levels Excessive?



- Using organic nutrient sources (i.e. manures) at N-based rates
- Over-application of commercial fertilizer
- P recommendation for some crops continue into the excessive range (for example, vegetables)

Phosphorus Soil Test Correlation



Principles of P Management

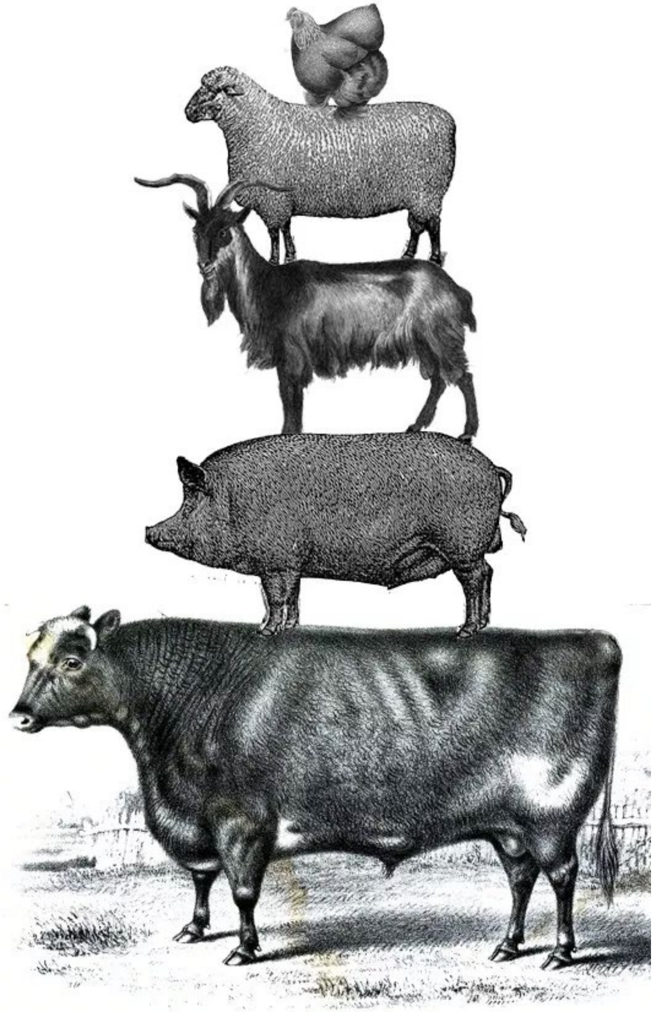
- Maintain soil pH for desired crop
- Apply P fertilizers when needed, where most efficiently utilized
  - *Band starter fertilizer*
- Utilize practices that reduce soil erosion and runoff
- Keep soil P levels in optimum category

Summary

- **P in soils:**
  - pH critical for P availability. Lime as needed
  - Soil solution pool is small, but in dynamic equilibrium with inorganic & organic P pools
- **P in plants:**
  - Plants are clever and devise ways to take up P
- **P in fertilizers:**
  - Rapid reactions in soil, where P is quickly fixed
  - Band starter P fertilizer when soil P is in low to medium FIV
- **P in manures:**
  - Animals produce manures with almost similar P chemistry
  - If **using manure, you will get enough P**. Skip fertilizer
- **Legacy P in soils:**
  - Concerns about P loss in P saturated soils are supported by data
  - Drawdown of P once soils are saturated with P is very slow (decades time scale)

Thank you!

Any questions?



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