Nutrients

Biologically essential nutrients

Table 8.1 Nutrients required by plants and their major functions

Nutrient	Role in plants
Macronutrients	Required by all plants in large quantities
Primary	Usually most limiting because used in largest amounts
Nitrogen (N)	Component of proteins, enzymes, phospholipids, and nucleic acids
Phosphorus (P)	Component of proteins, coenzymes, nucleic acids, oils, phospholipids, sugars, starches
	Critical in energy transfer (ATP)
Potassium (K)	Component of proteins
	Role in disease protection, photosynthesis, ion transport, osmotic regulation, enzyme catalyst
Secondary	Major nutrients but less often limiting
Calcium (Ca)	Component of cell walls
	Regulates structure and permeability of membranes, root growth
	Enzyme catalyst
Magnesium (Mg)	Component of chlorophyll
	Activates enzymes
Sulfur (S)	Component of proteins and most enzymes
	Role in enzyme activation, cold resistance
Micronutrients	Required by all plants in small quantities
Boron (B)	Role in sugar translocation and carbohydrate metabolism
Chloride (Cl)	Role in photosynthetic reactions, osmotic regulation
Copper (Cu)	Component of some enzymes, role as a catalyst
Iron (Fe)	Role in chlorophyll synthesis, enzymes, oxygen transfer
Manganese (Mn)	Activates enzymes, role as a catalyst
Molybdenum (Mo)	Role in N fixation, NO_3 enzymes, Fe absorption, and translocation
Zinc (Zn)	Activates enzymes, regulates sugar consumption
Beneficial nutrients	Required by certain plants or by plants under specific environmental conditions
Aluminum (Al)	
Cobalt (Co)	
Iodine (I)	
Nickel (Ni)	
Selenium (Se)	
Silicon (Si)	
Sodium (Na)	
Vanadium (V)	

Reprinted from Chapin and Eviner (2004)

Nutrients limit productivity (N and P)

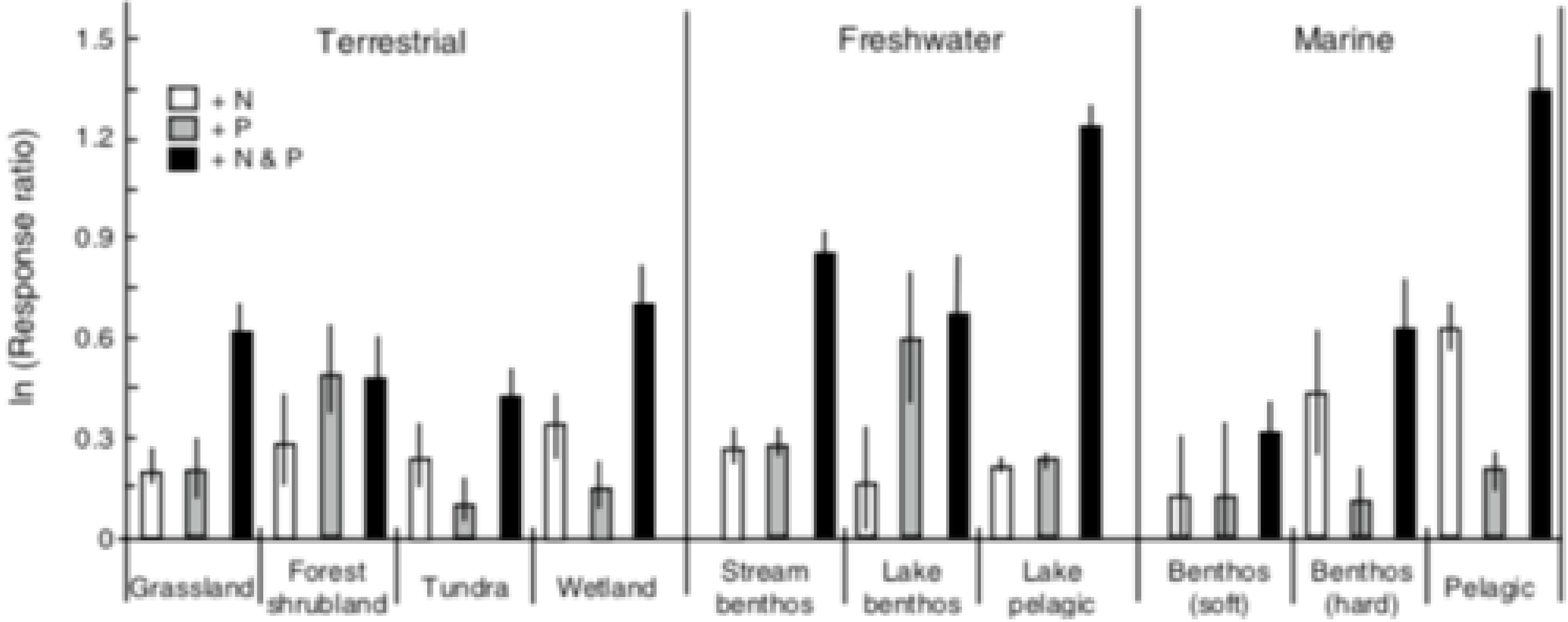
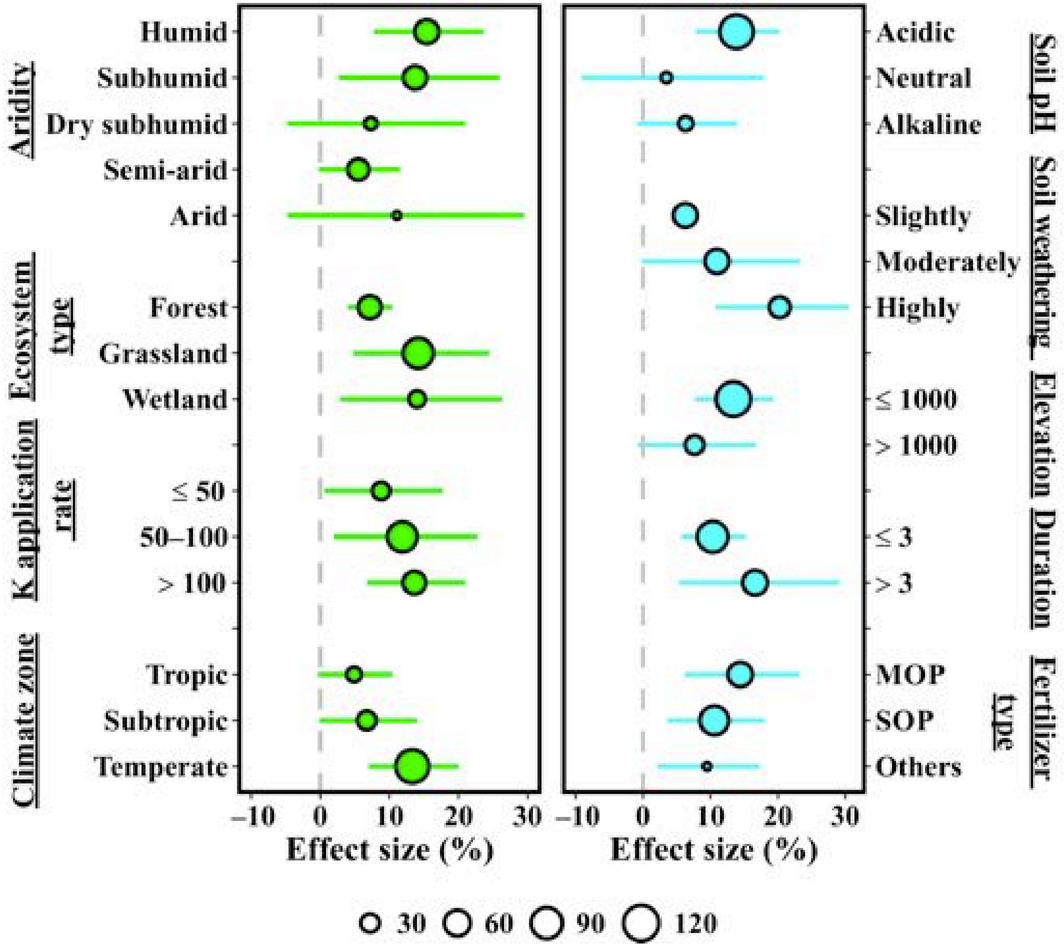


Fig. 8.3 Relative response of plant production to addition of nitrogen or phosphorus or to both nutrients in major habitat types of terrestrial, freshwater, and marine ecosystems. Relative response is calculated as the biomass or production in the enriched treatment divided by its value in the control treatment and then ln-transformed. Redrawn from Elser et al. (2007)

Nutrient limit productivity (also K!)



New Phytologist

Full paper | Full Access

A meta-analysis highlights globally widespread potassium limitation in terrestrial ecosystems

Baozhang Chen, Jingchun Fang, Shilong Piao, Philippe Ciais, Thomas Andrew Black, Fei Wang, Shuli Niu, Zhenzhong Zeng, Yiqi Luo

First published: 07 October 2023 | https://doi.org/10.1111/nph.19294

Nutrient cycling

Nutrients cycle through ecosystems differently

Table 8.2 Major sources of nutrients that are absorbed by terrestrial plants

Nutrient	Source of plant nutrient (% of total)		
	Deposition/ fixation	Weathering	Recycling
Temperate forest (Hubbard Brook)			
Nitrogen	7	0	93
Phosphorus	1	< 10?	> 89
Potassium	2	10	88
Calcium	4	31	65
Tundra (Barrow)			
Nitrogen	4	0	96
Phosphorus	4	< 1	96

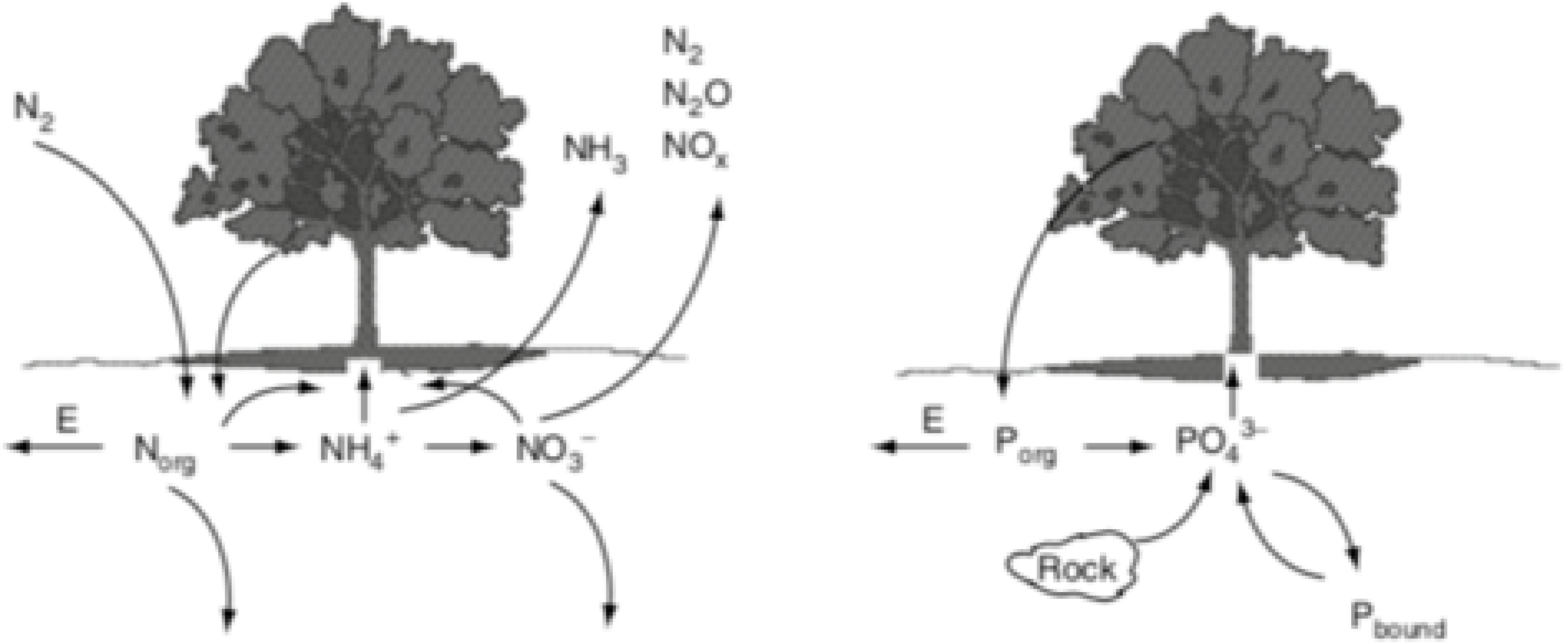
Data from Chapin (1991b)

Nutrients cycle through ecosystems differently

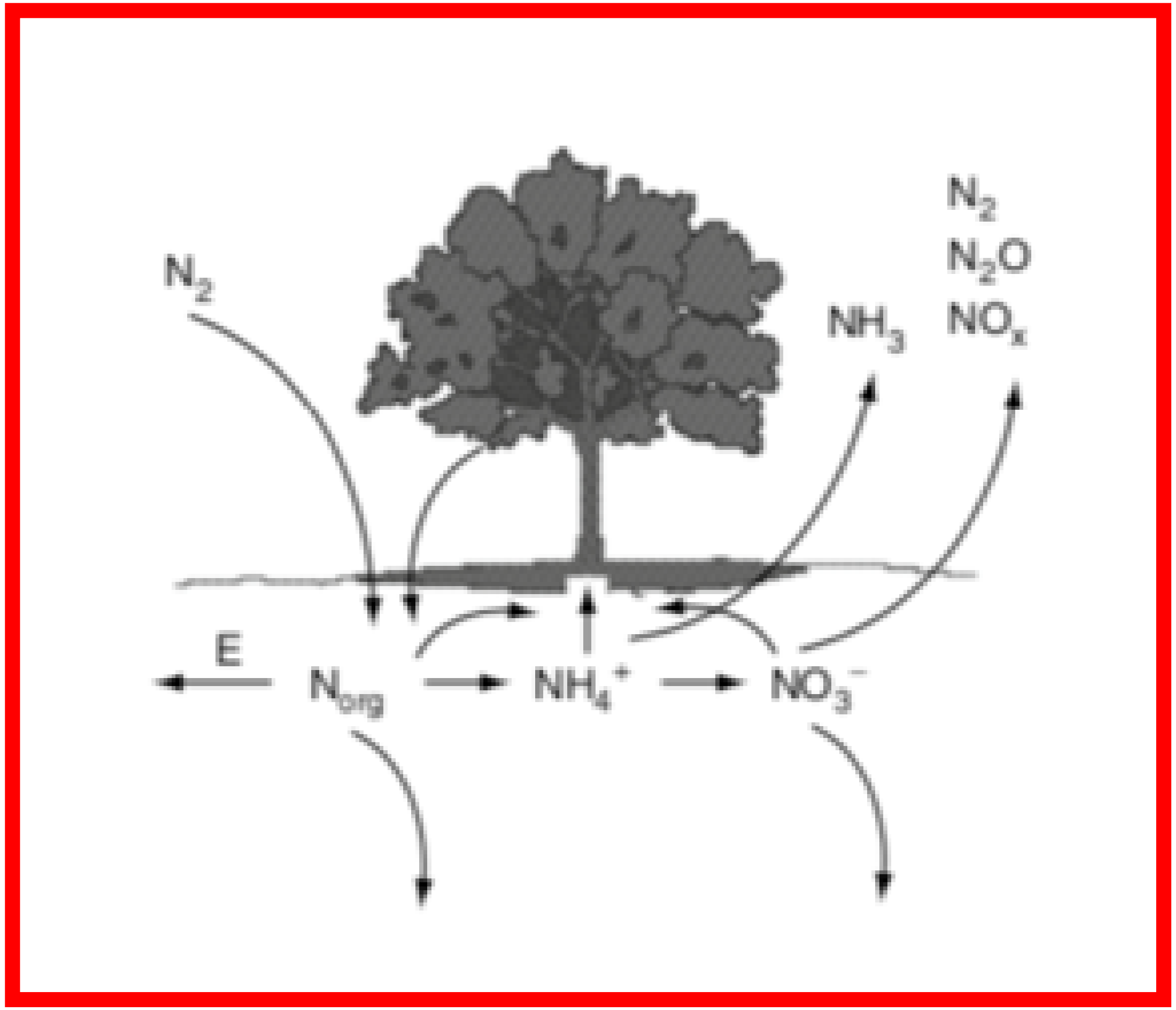
Table 8.2 Major sources of nutrients that are absorbed by terrestrial plants

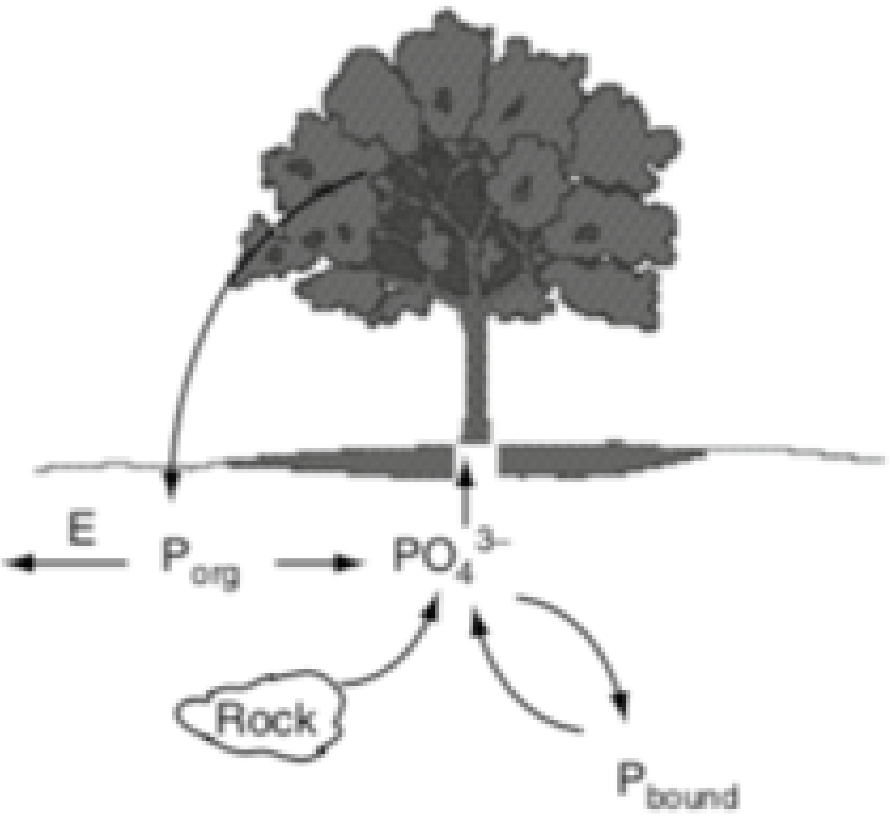
Nutrient	Source of plant nutrient (% of total)		
	Deposition/ fixation	Weathering	Recycling
Temperate forest (Hubbard Brook)			
Nitrogen	7	0	93
Phosphorus	1	< 10?	> 89
Potassium	2	10	88
Calcium	4	31	65
Tundra (Barrow)			
Nitrogen	4	0	96
Phosphorus	4	< 1	96

Data from Chapin (1991b)

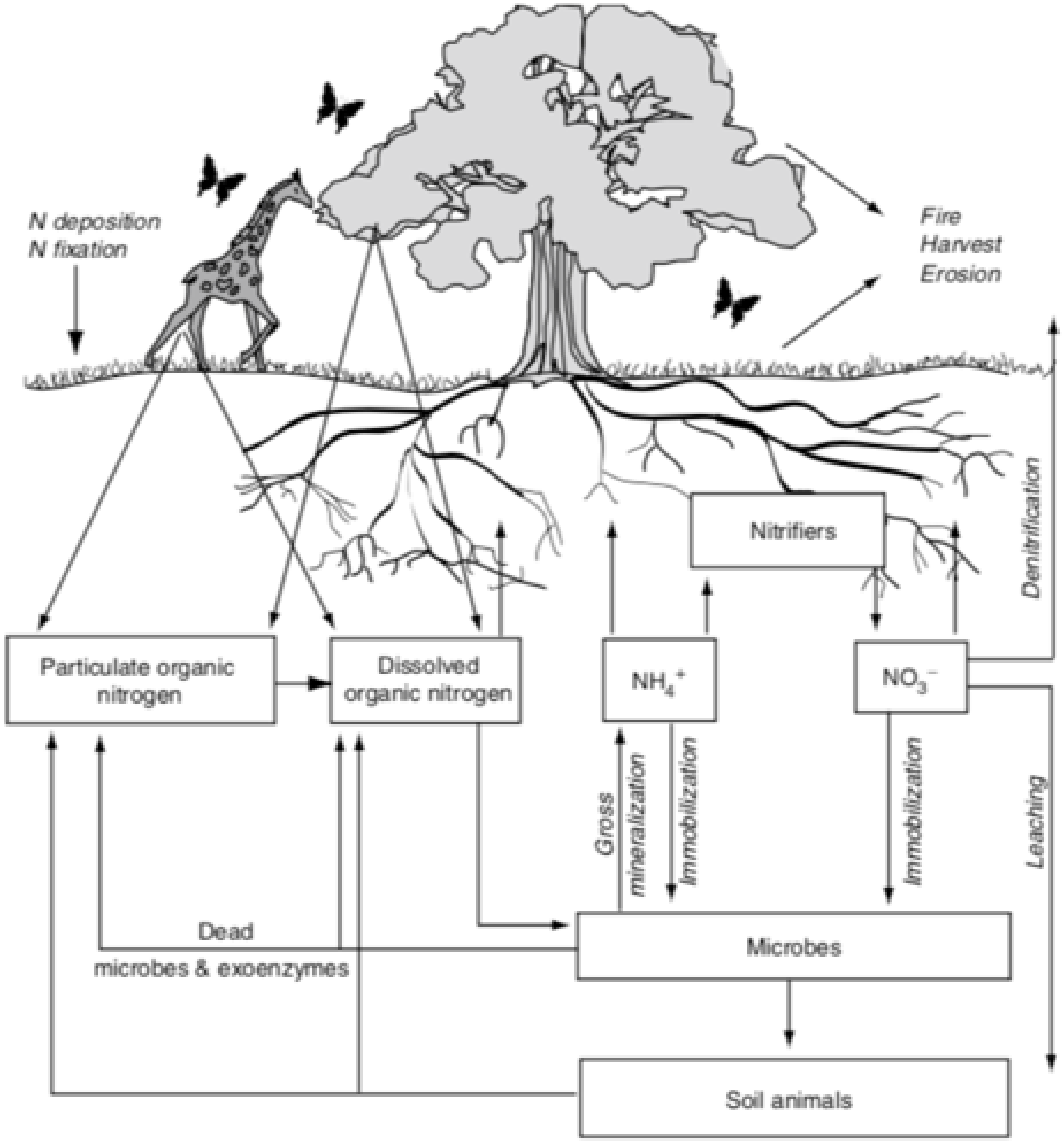


N_2
N_2
N_2O
NO_x
NH_3
E
N_{org}
NH_4^+
NO_3^-
E
P_{org}
PO_4^{3-}
Rock
P_{bound}


N_2
N_2
N_2O
NH_3
NO_x
E
N_{org}
NH_4^+
NO_3^-

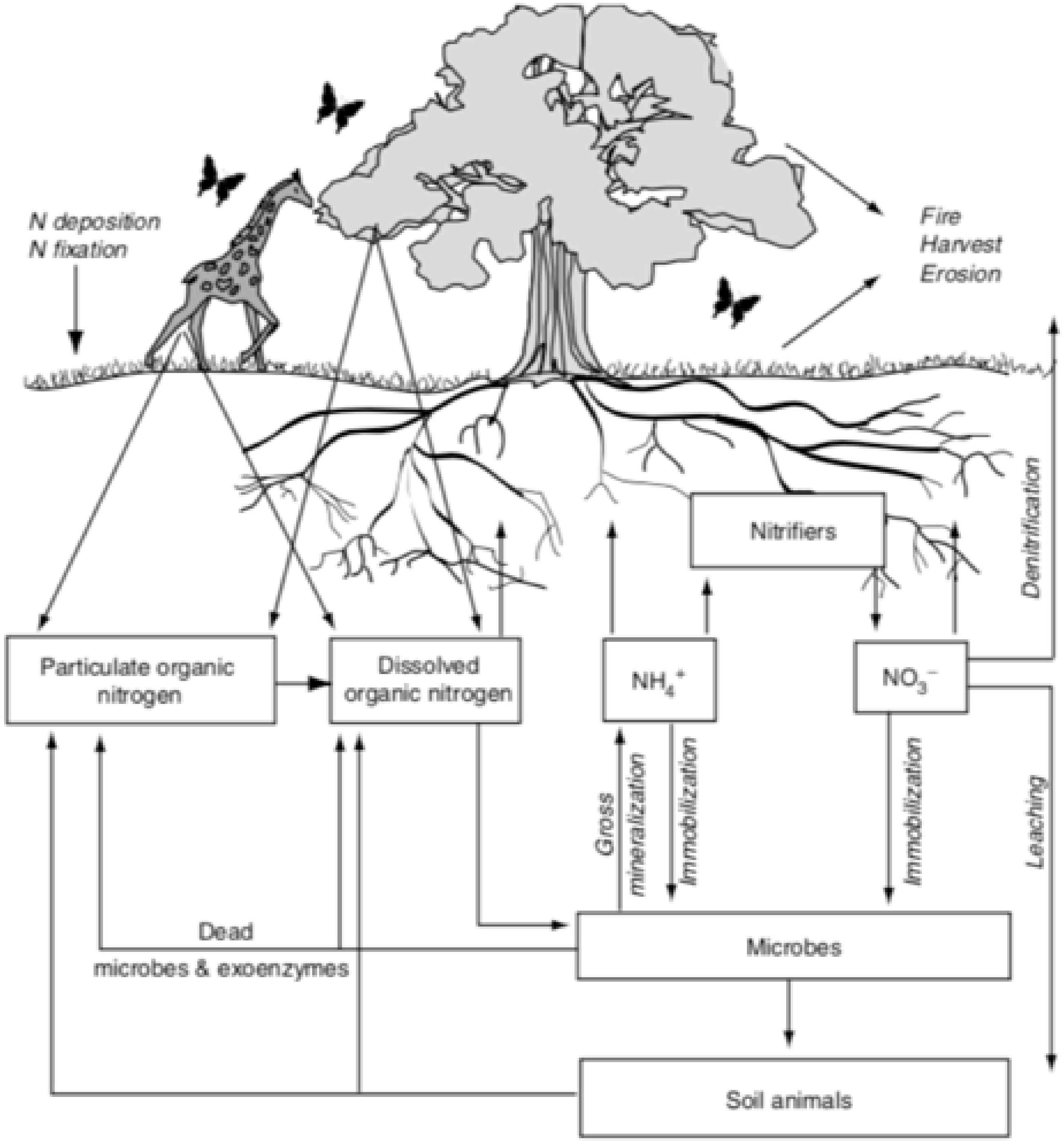

E
P_{org}
PO_4^{3-}
Rock
P_{bound}

The terrestrial N cycle

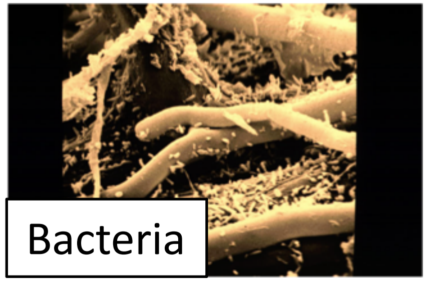


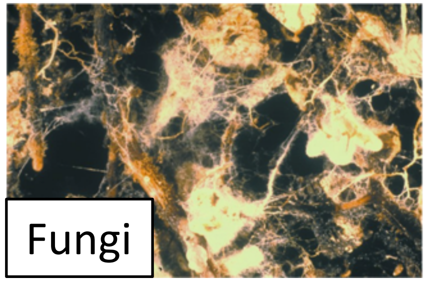
The terrestrial N cycle

Nitrogen is constantly changing forms due to biological organisms

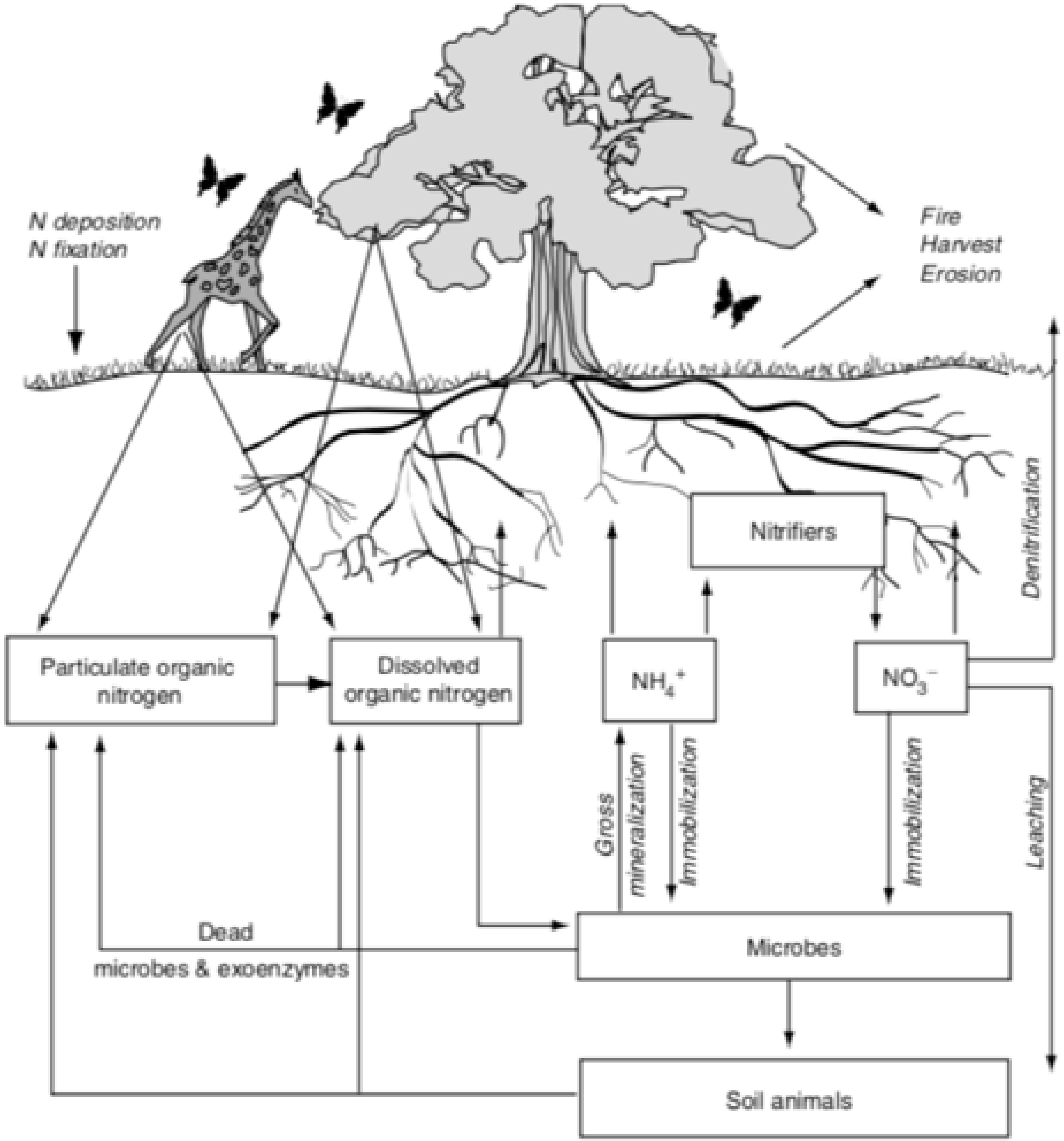


The terrestrial N cycle





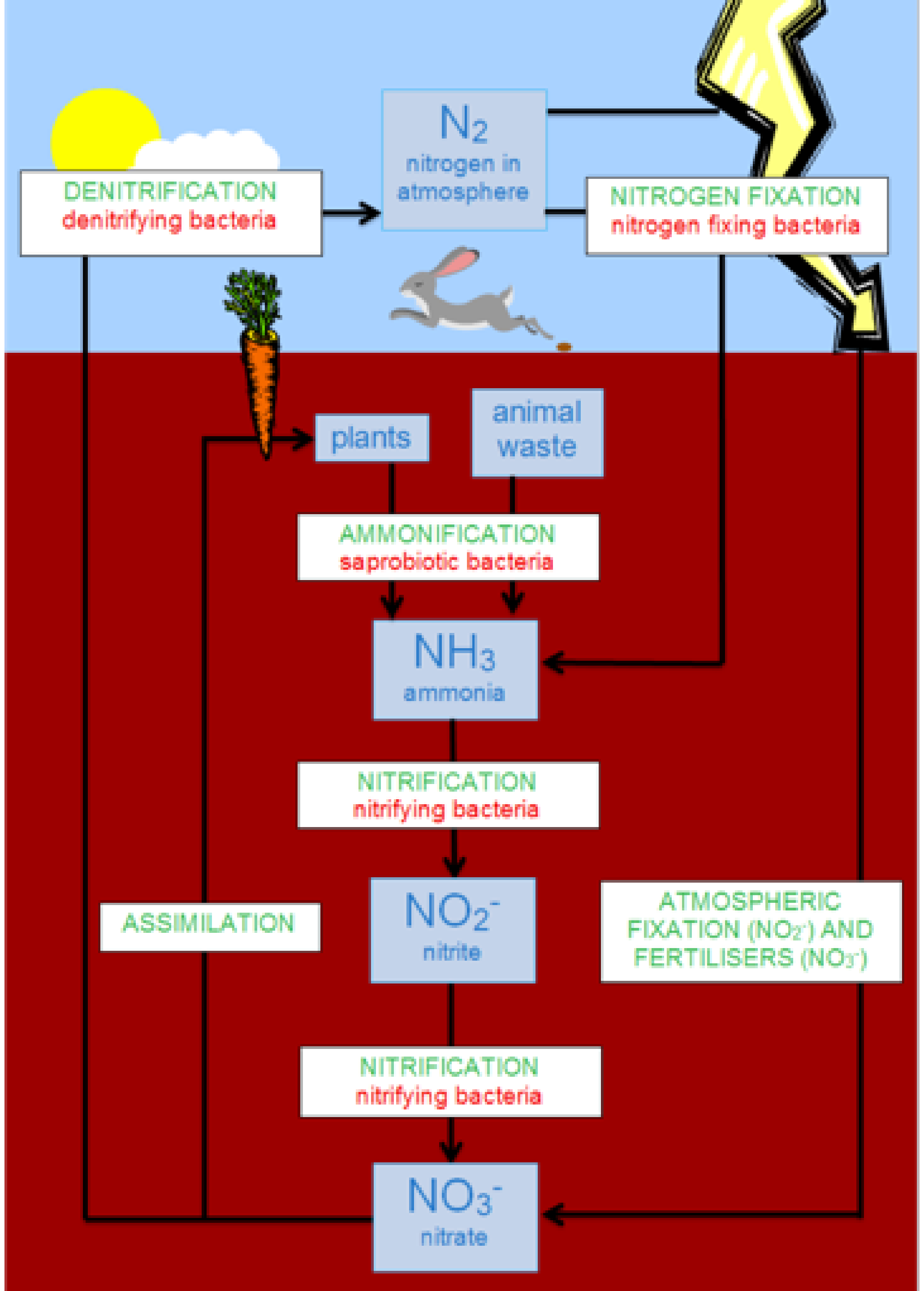
Nitrogen is constantly changing forms due to biological organisms (mostly microbes)



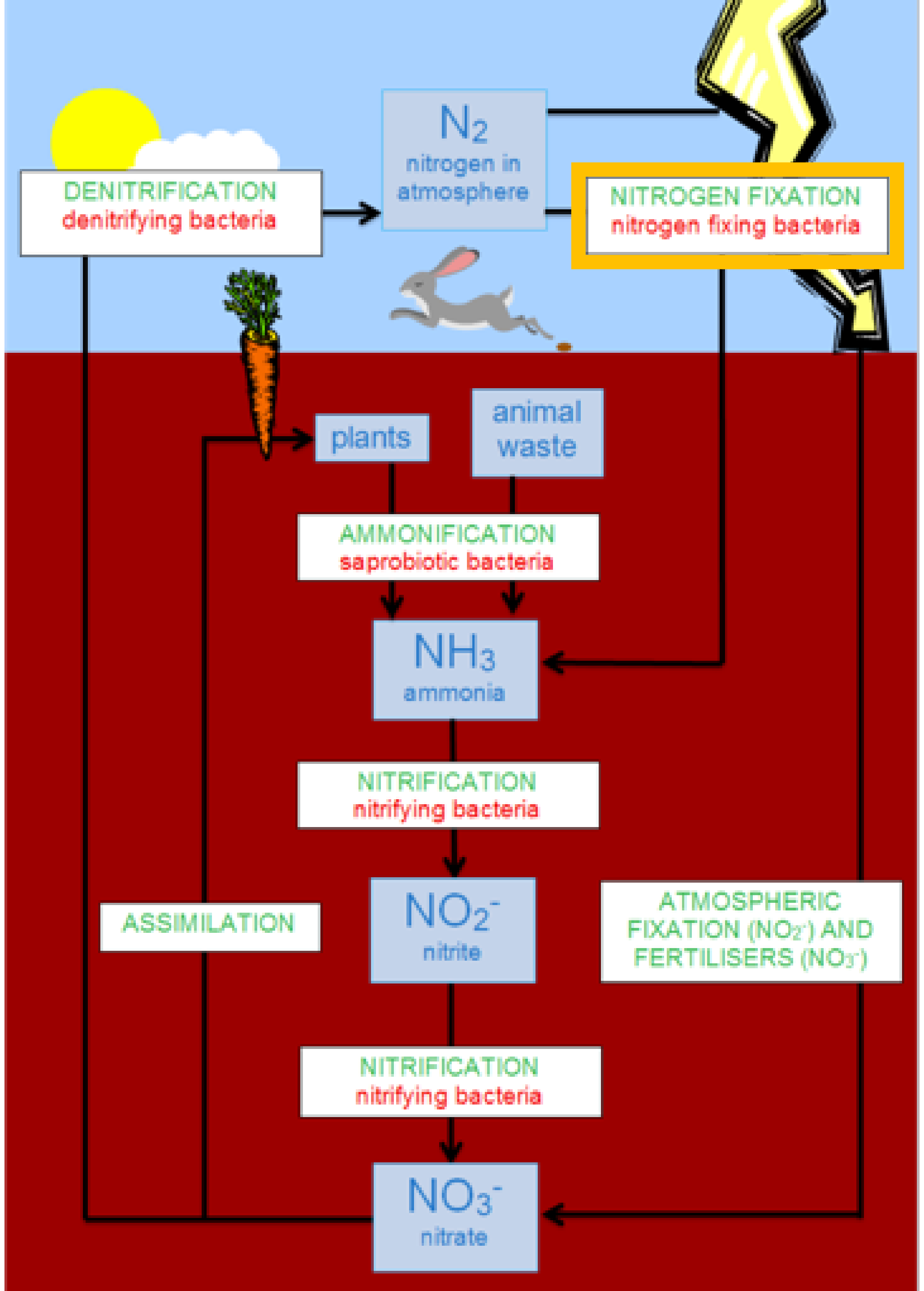
USDA

Important N forms

- N_2
  - Nitrogen gas
  - Lots in the atmosphere
  - Cannot be taken up by plants or most microbes (just N fixers)
- NO_3^-
  - Nitrate
  - Highly mobile
  - Can be easily taken up by plants and most microbes
- NH_4^+
  - Ammonium
  - Mobile
  - Can be easily taken up by plants and most microbes
- Dissolved organic N (DON)
  - Organic (contains C)
  - Produced by dead organisms
  - Cannot be taken up by plants
  - Can be broken down by microbes



N_2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH_3
ammonia
NITRIFICATION
nitrifying bacteria
NO_2^-
nitrite
ASSIMILATION
ATMOSPHERIC FIXATION (NO_2^-) AND FERTILISERS (NO_3^-)
NITRIFICATION
nitrifying bacteria
NO_3^-
nitrate


N2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH3
ammonia
NITRIFICATION
nitrifying bacteria
NO2-
nitrite
ASSIMILATION
ATMOSPHERIC FIXATION (NO2-) AND FERTILISERS (NO3-)
NITRIFICATION
nitrifying bacteria
NO3-
nitrate

Biological N fixation: $N_2 \rightarrow NH_3$

Table 9.1 Organisms and associations involved in di-nitrogen fixation

Type of association[a]	Key characteristics	Representative genera
Heterotrophic N fixers		Bacteria
Associative		
Nodulated (symbiotic)	Legume	*Rhizobium*
	Nonlegume woody plants	*Frankia*
Non-nodulated	Rhizosphere	*Azotobacter, Bacillus*
	Phyllosphere	*Klebsiella*
Free-living	Aerobic	*Azotobacter, Rhizobium*
	Facultative aerobic	*Bacillus*
	Anaerobic	*Clostridium*
Phototrophic N fixers		Cyanobacteria
Associative	Lichens	*Nostoc, Calothrix*
	Liverworts (*Marchantia*)	*Nostoc*
	Mosses	*Holosiphon*
	Gymnosperms (*Cycas*)	*Nostoc*
	Water fern (*Azolla*)	*Nostoc*
Free-living	Cyanobacteria	*Nostoc, Anabaena*
	Purple non-sulfur bacteria	*Rhodospirillium*
	Sulfur bacteria	*Chromarium*

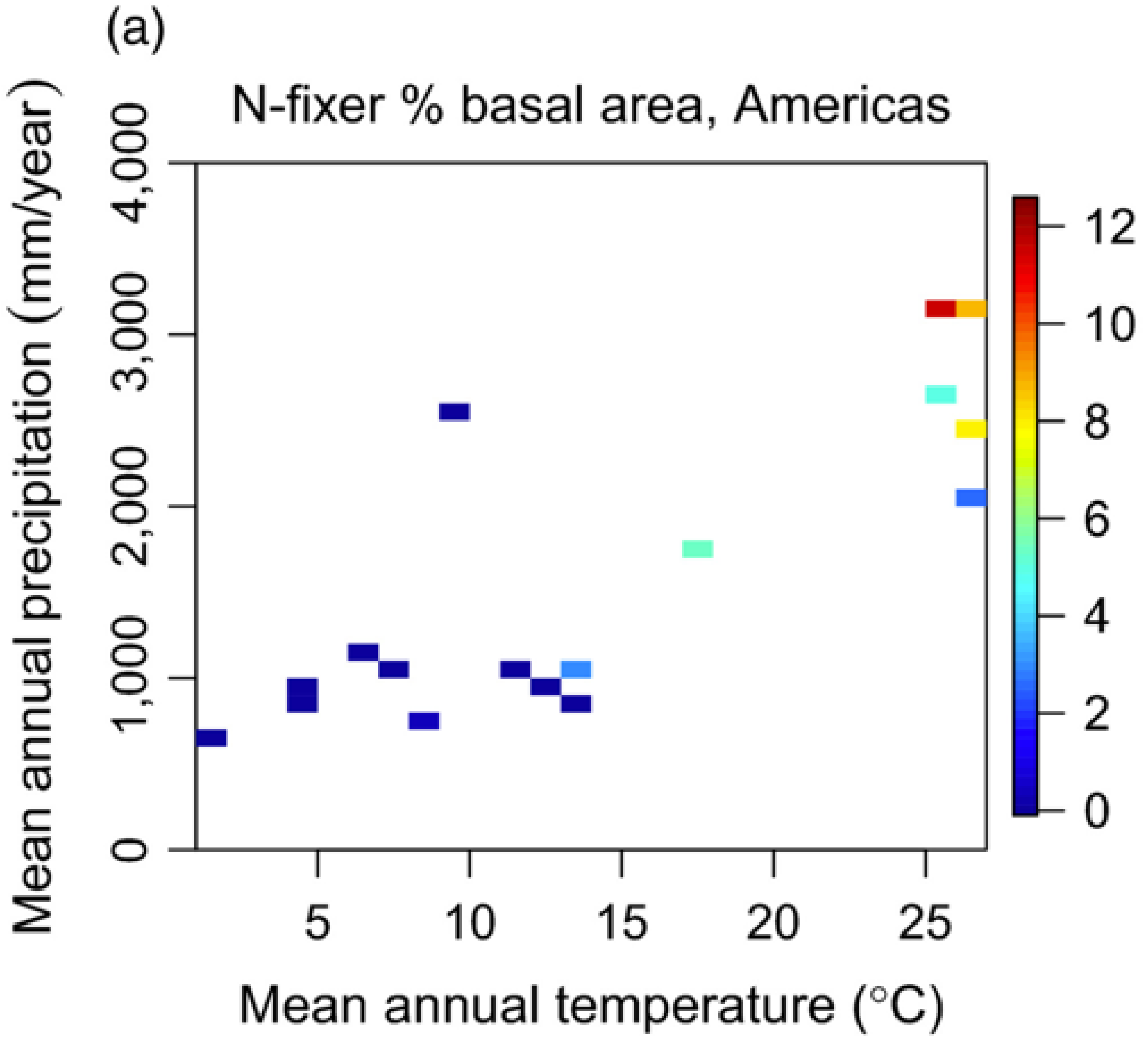
Nodules

Soil Aggregates

Heterocysts

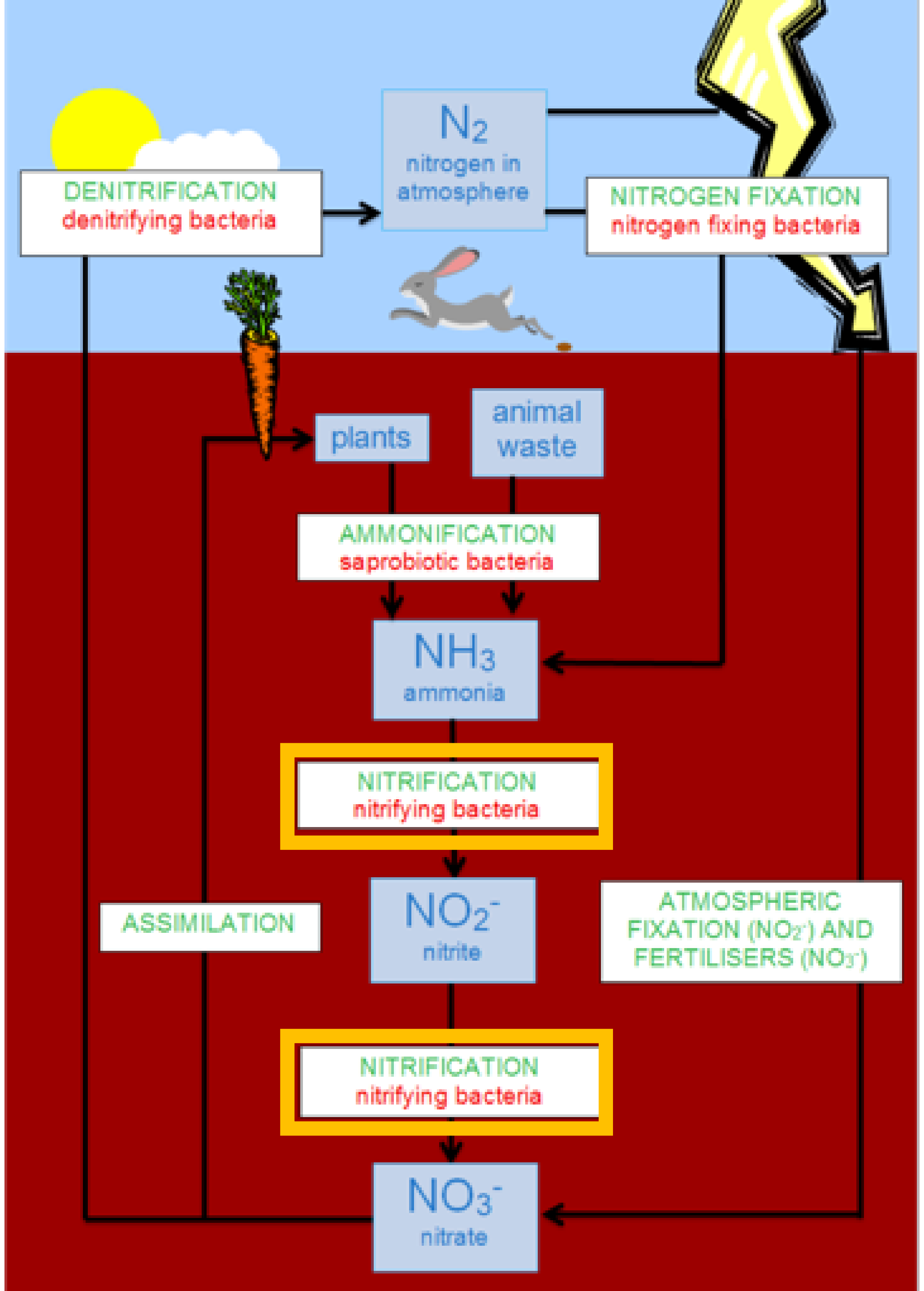
Questions to ponder

- Why wouldn’t all plants associate with N fixing bacteria?
- Where would you expect to find plants that associate with N fixing bacteria?



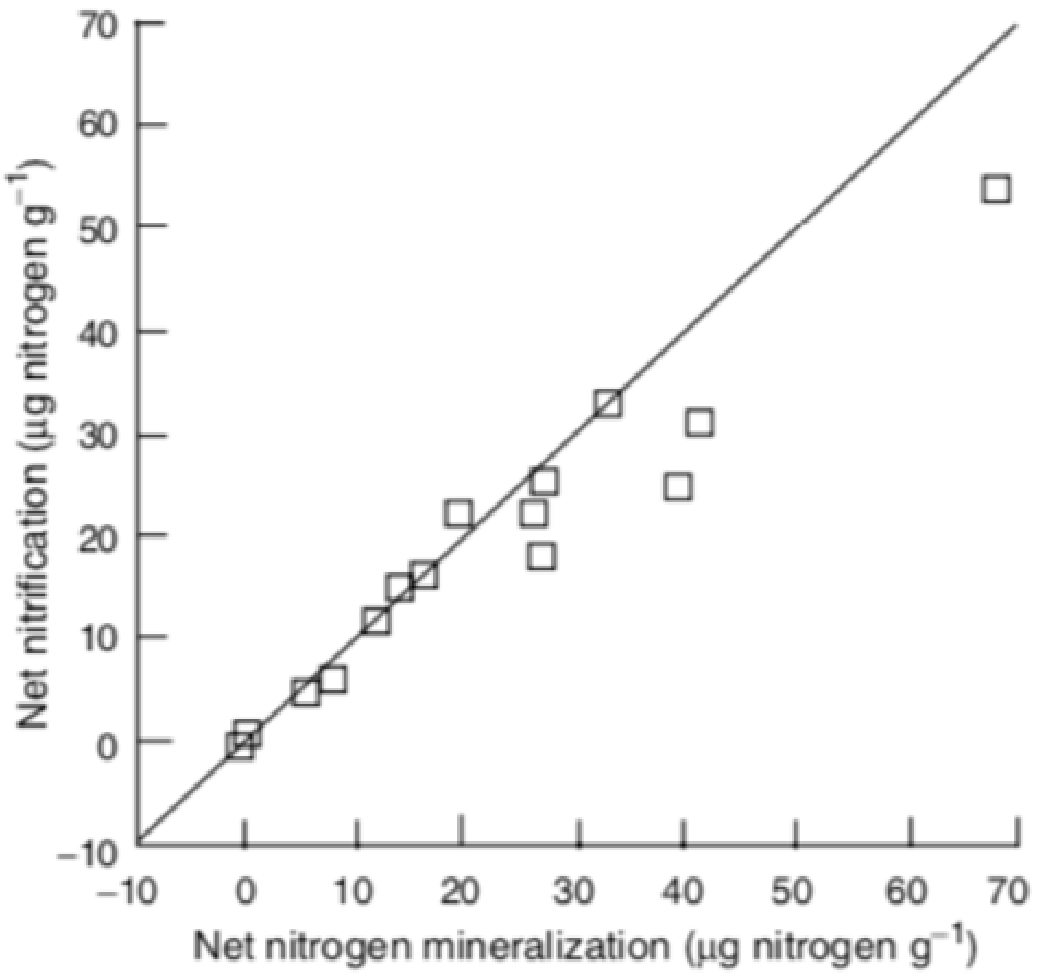
Why this pattern??

Menge et al. (2019)



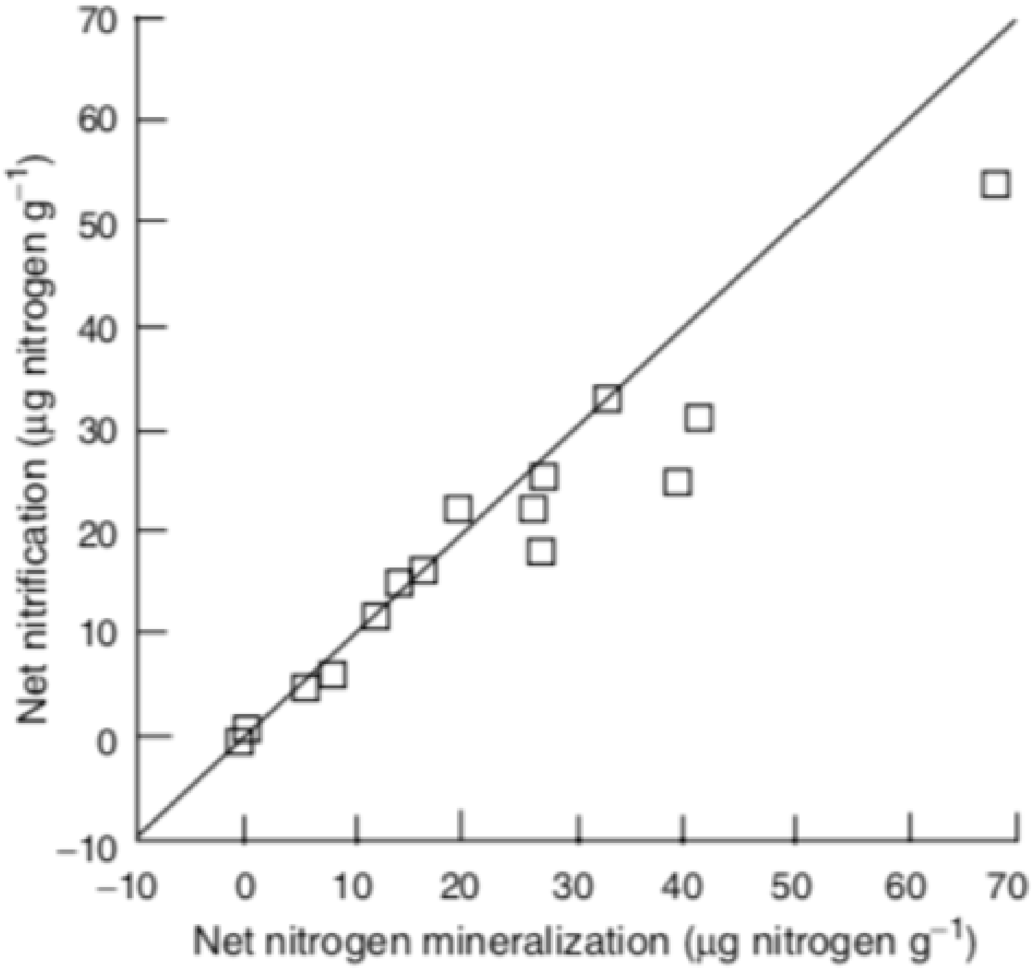
DENITRIFICATION
denitrifying bacteria
N2
nitrogen in atmosphere
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH3
ammonia
NITRIFICATION
nitrifying bacteria
NO2-
nitrite
ASSIMILATION
ATMOSPHERIC FIXATION (NO2-) AND FERTILISERS (NO3-)
NITRIFICATION
nitrifying bacteria
NO3-
nitrate

Nitrification: $NH_3 \rightarrow NO_2 \rightarrow NO_3$



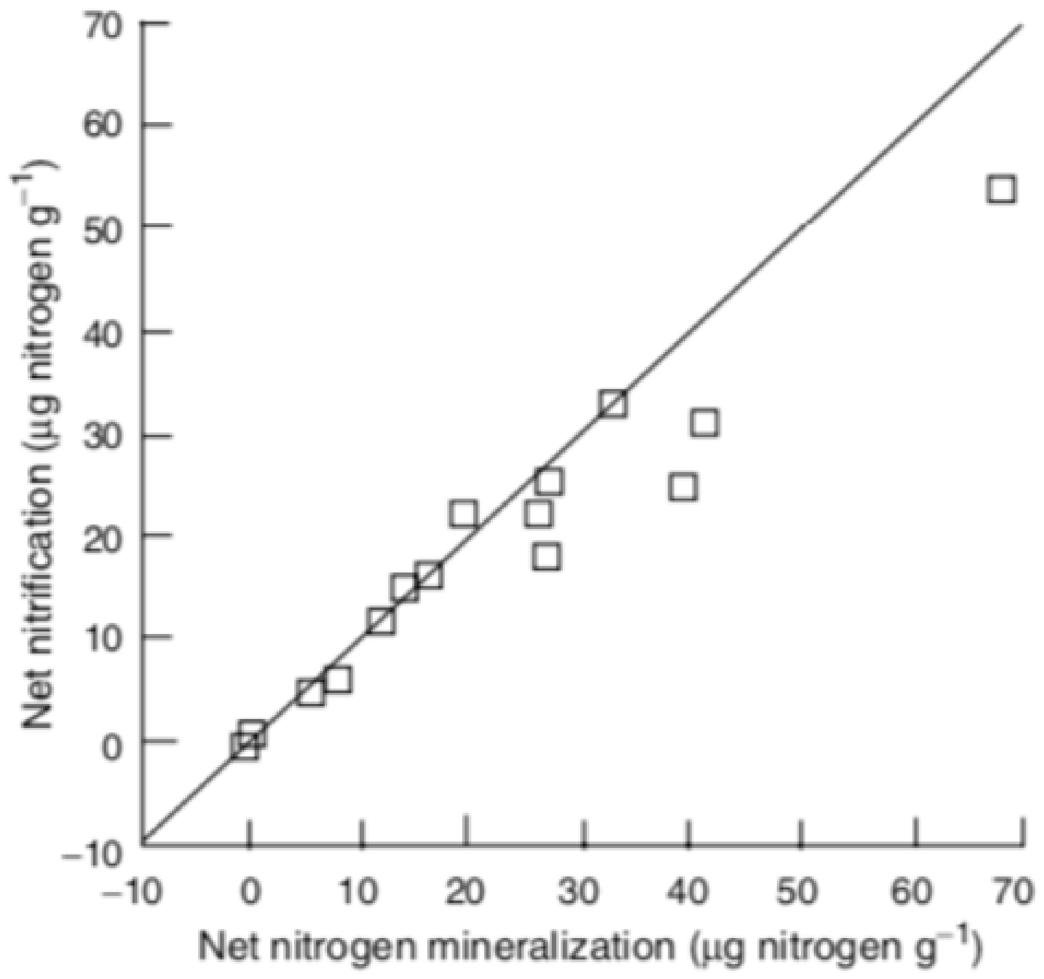
Constantly happening in soil and determined by the amount of NH_3 produced by mineralization

Nitrification: $NH_3 \rightarrow NO_2 \rightarrow NO_3$

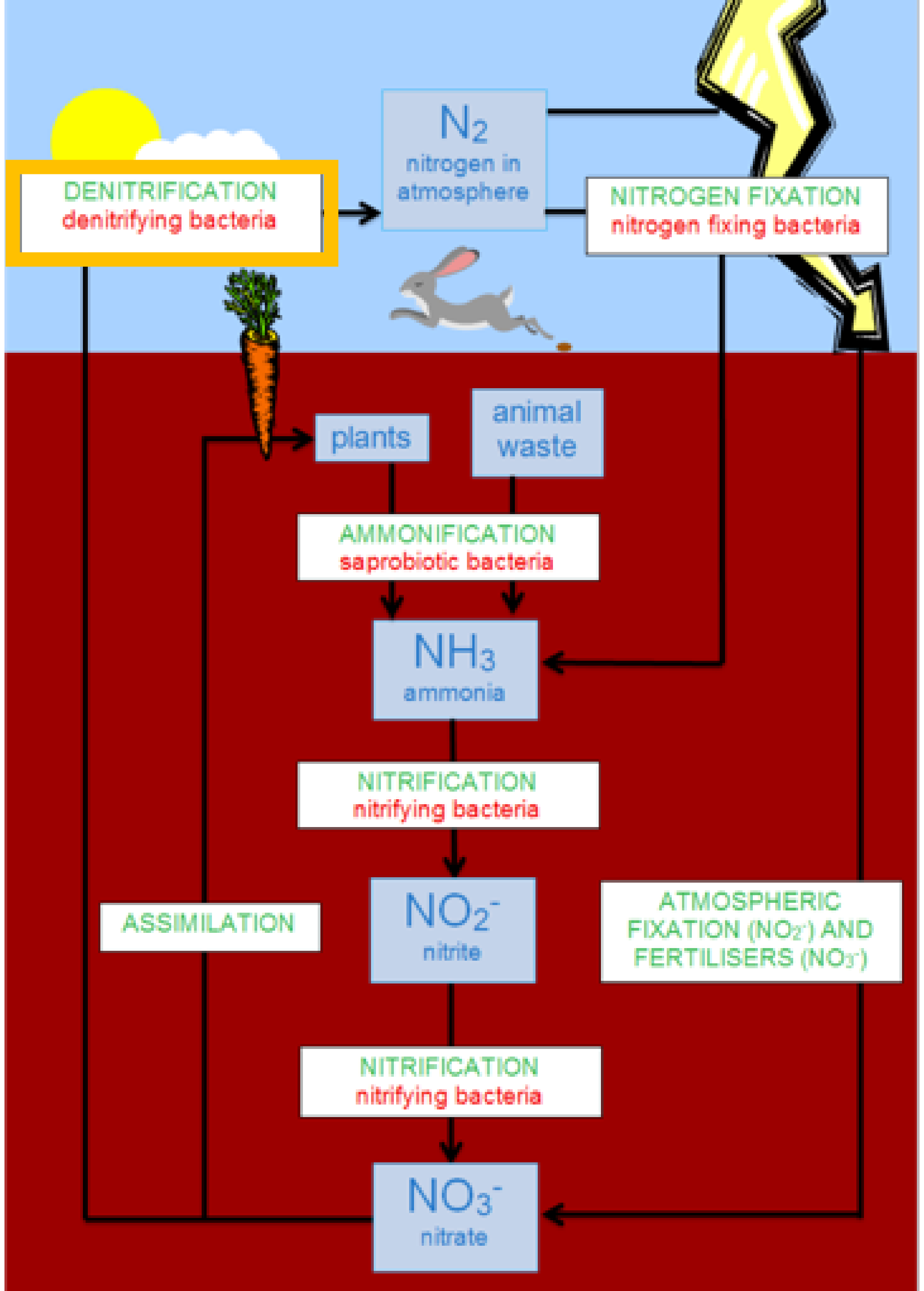


NH_3 amount explains spatial and temporal variability in nitrification

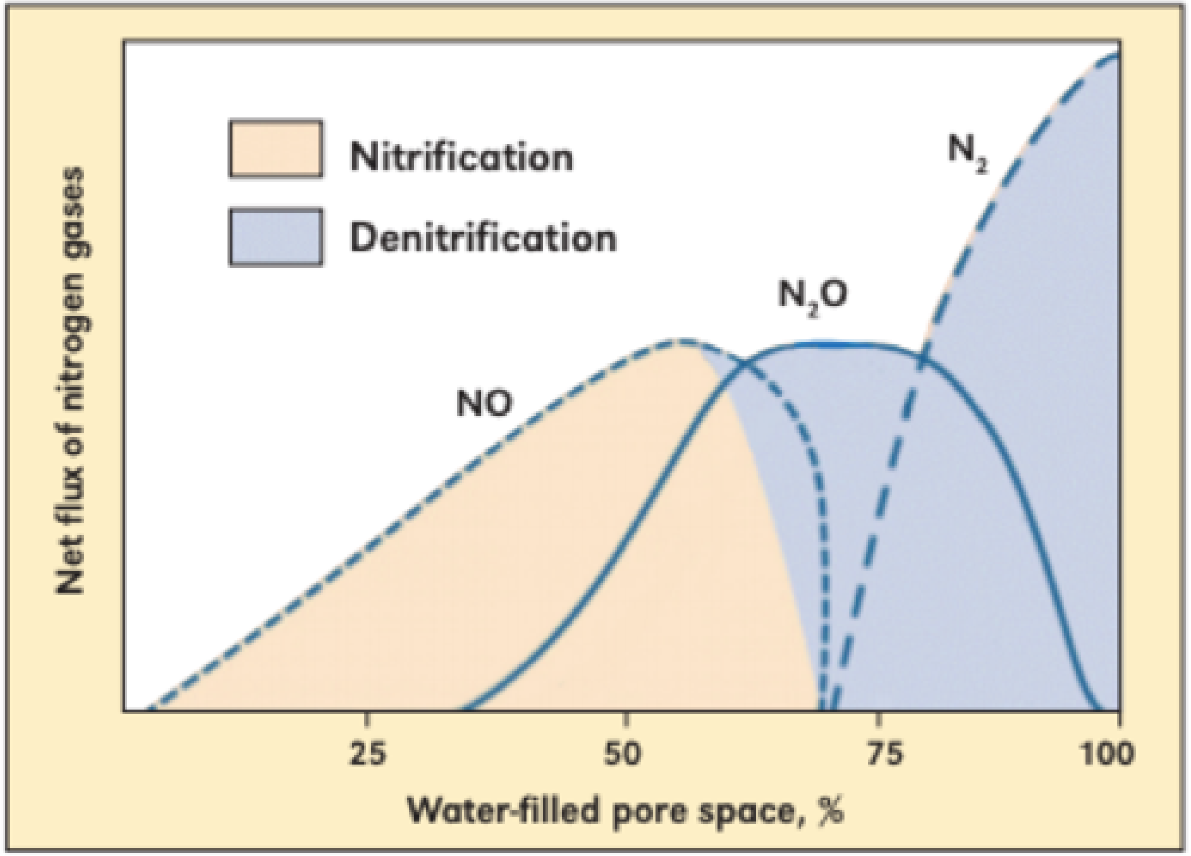
Nitrification: $NH_3 \rightarrow NO_2 \rightarrow NO_3$



Consequences
- N gas production
- N more mobile

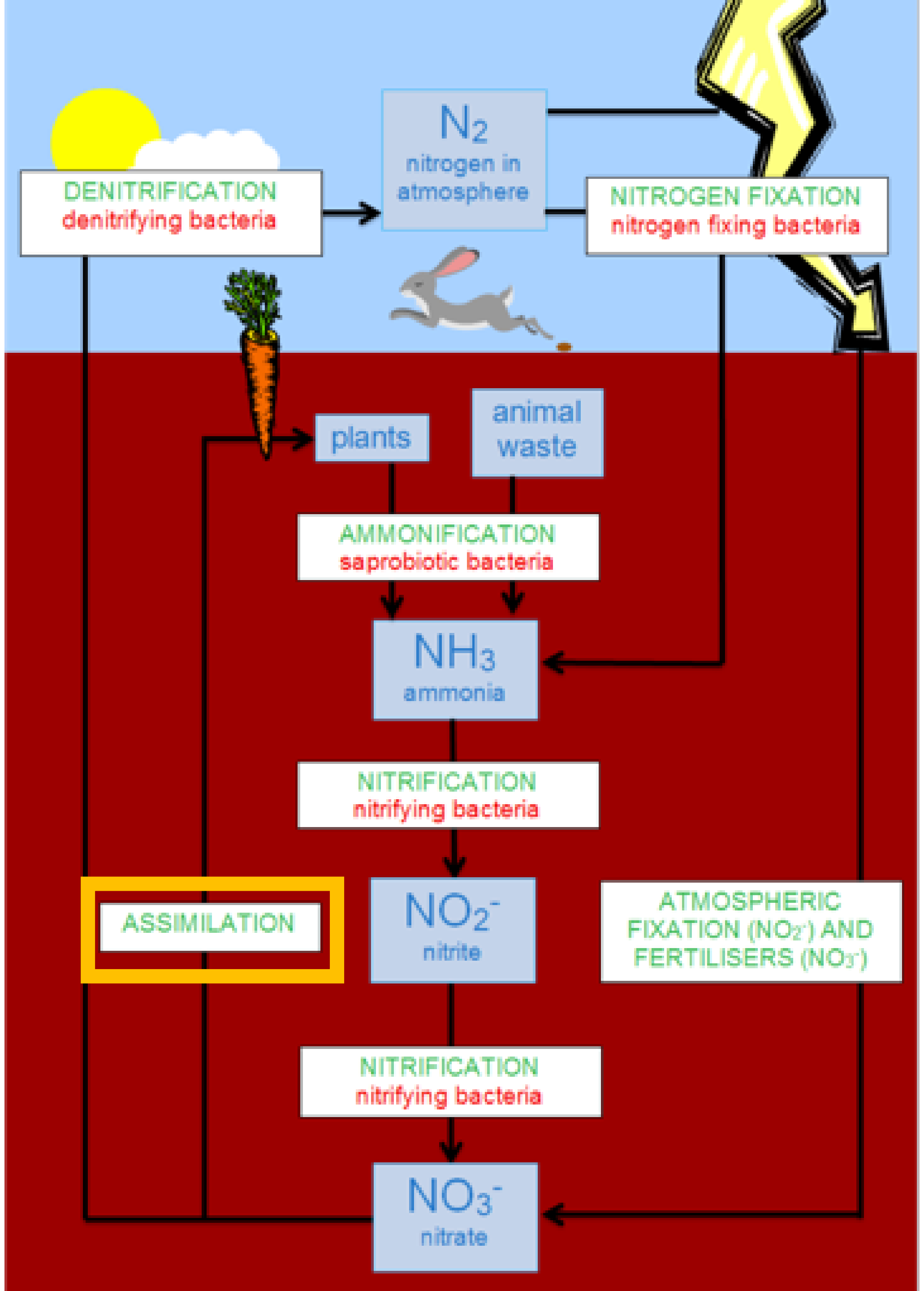

N2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH3
ammonia
NITRIFICATION
nitrifying bacteria
ASSIMILATION
NO2-
nitrite
ATMOSPHERIC FIXATION (NO2-) AND FERTILISERS (NO3-)
NITRIFICATION
nitrifying bacteria
NO3-
nitrate

Denitrification: $NO_3 \rightarrow NO, N_2O \rightarrow N_2$



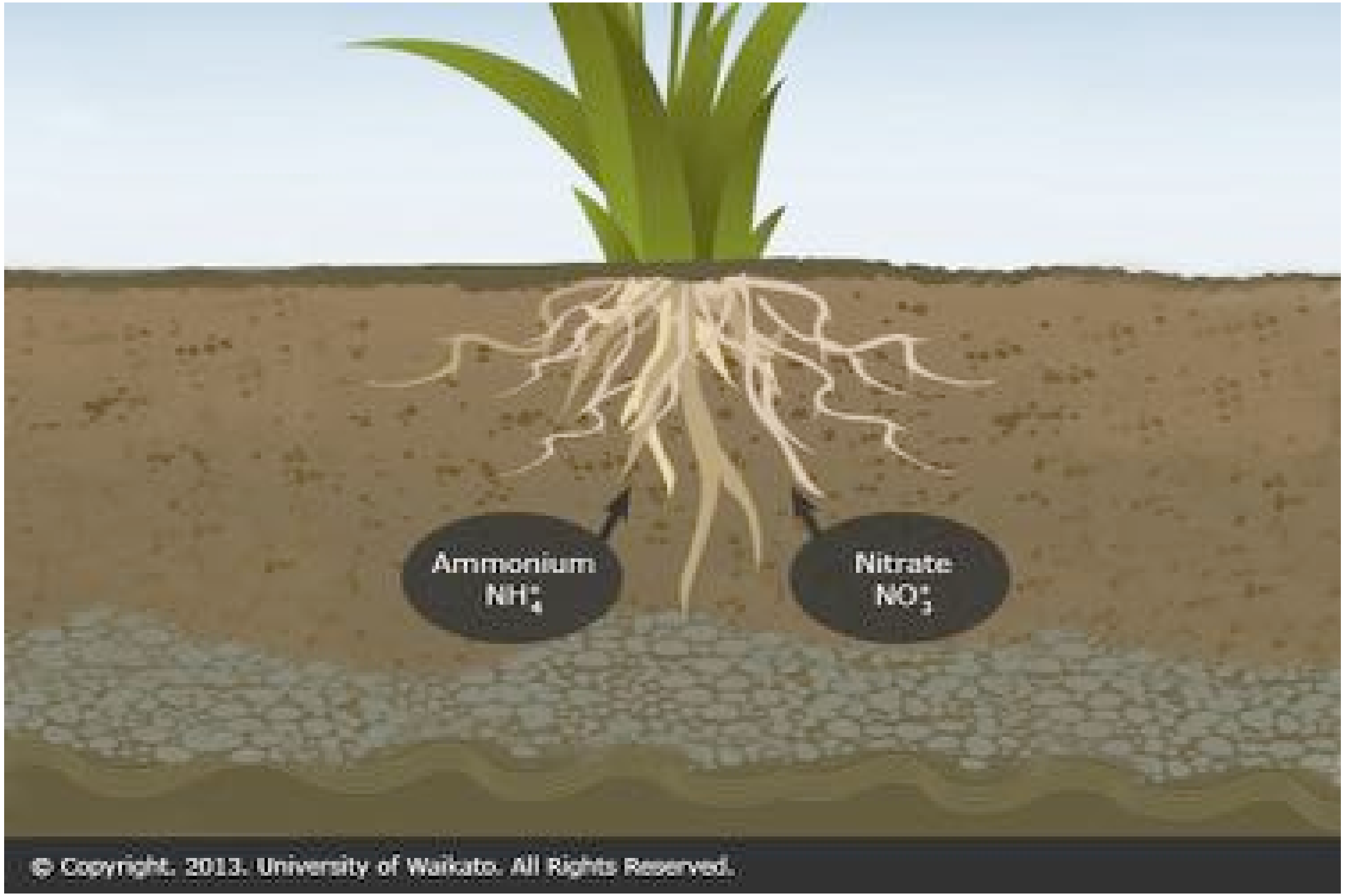
Occurs under high NO_3 and low O_2 conditions (e.g., high soil moisture)

Bouwman (1998)

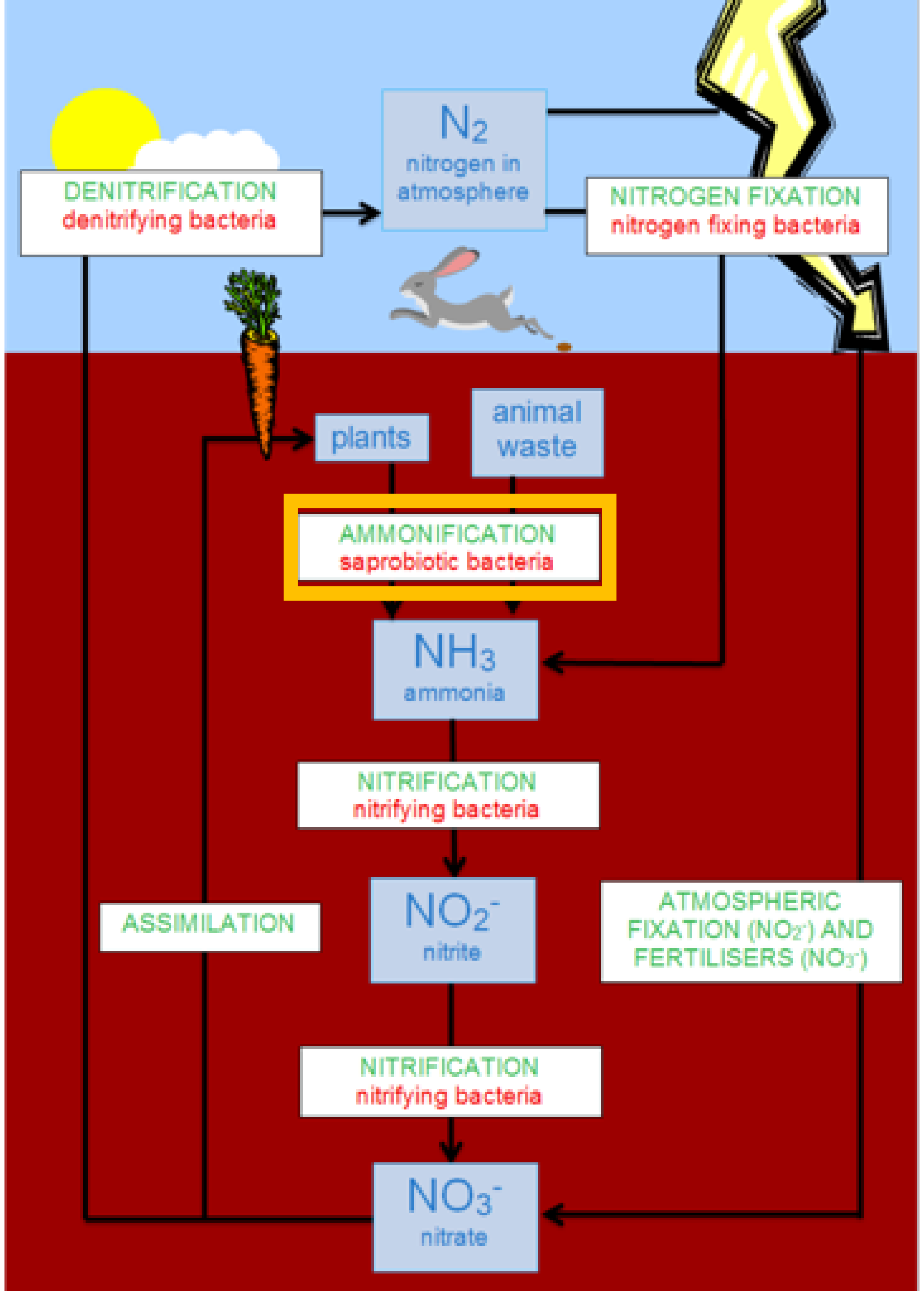


N_2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH_3
ammonia
NITRIFICATION
nitrifying bacteria
ASSIMILATION
NO_2^-
nitrite
ATMOSPHERIC FIXATION (NO_2^-) AND FERTILISERS (NO_3^-)
NITRIFICATION
nitrifying bacteria
NO_3^-
nitrate

Assimilation: Inorganic N → Organic N

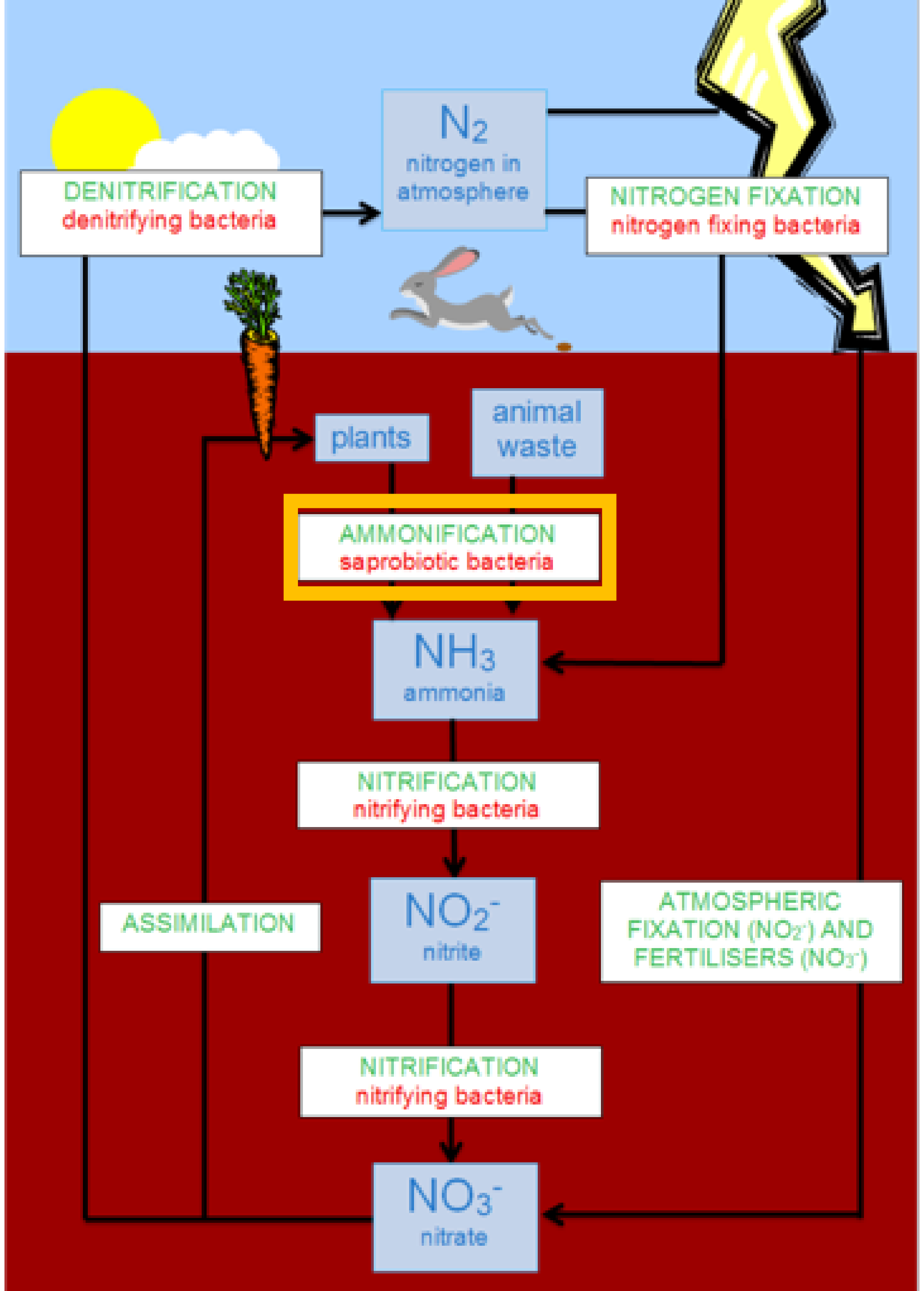


Via microbes or plants

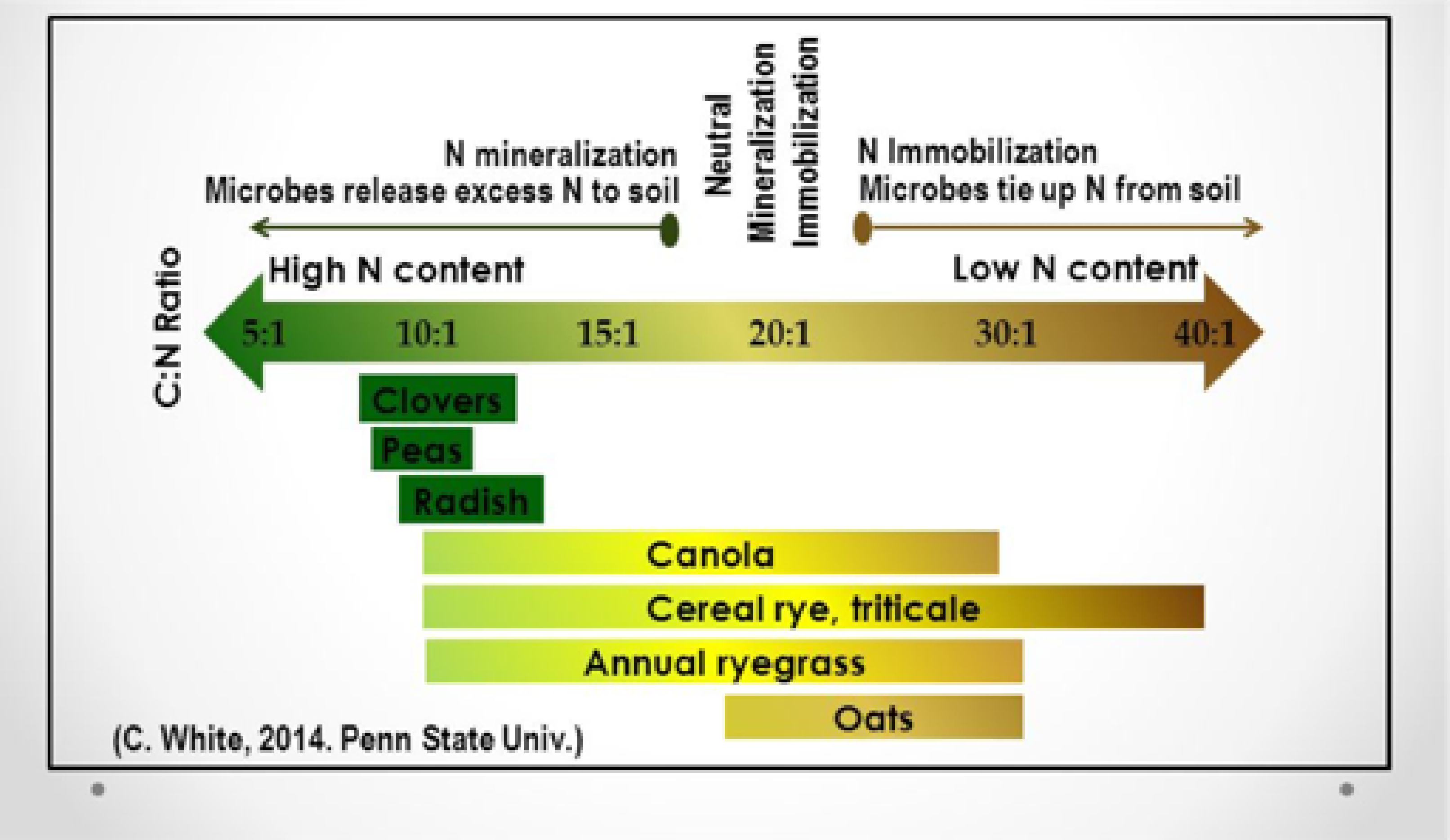


N2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH3
ammonia
NITRIFICATION
nitrifying bacteria
NO2-
nitrite
ASSIMILATION
ATMOSPHERIC FIXATION (NO2-) AND FERTILISERS (NO3-)
NITRIFICATION
nitrifying bacteria
NO3-
nitrate

Ammonification + Nitrification = Mineralization



Assimilation: Inorganic N → Organic N
Mineralization: Organic N → Inorganic N



Whether you have net mineralization or assimilation depends on the environment

High N = mineralization
Low N = assimilation

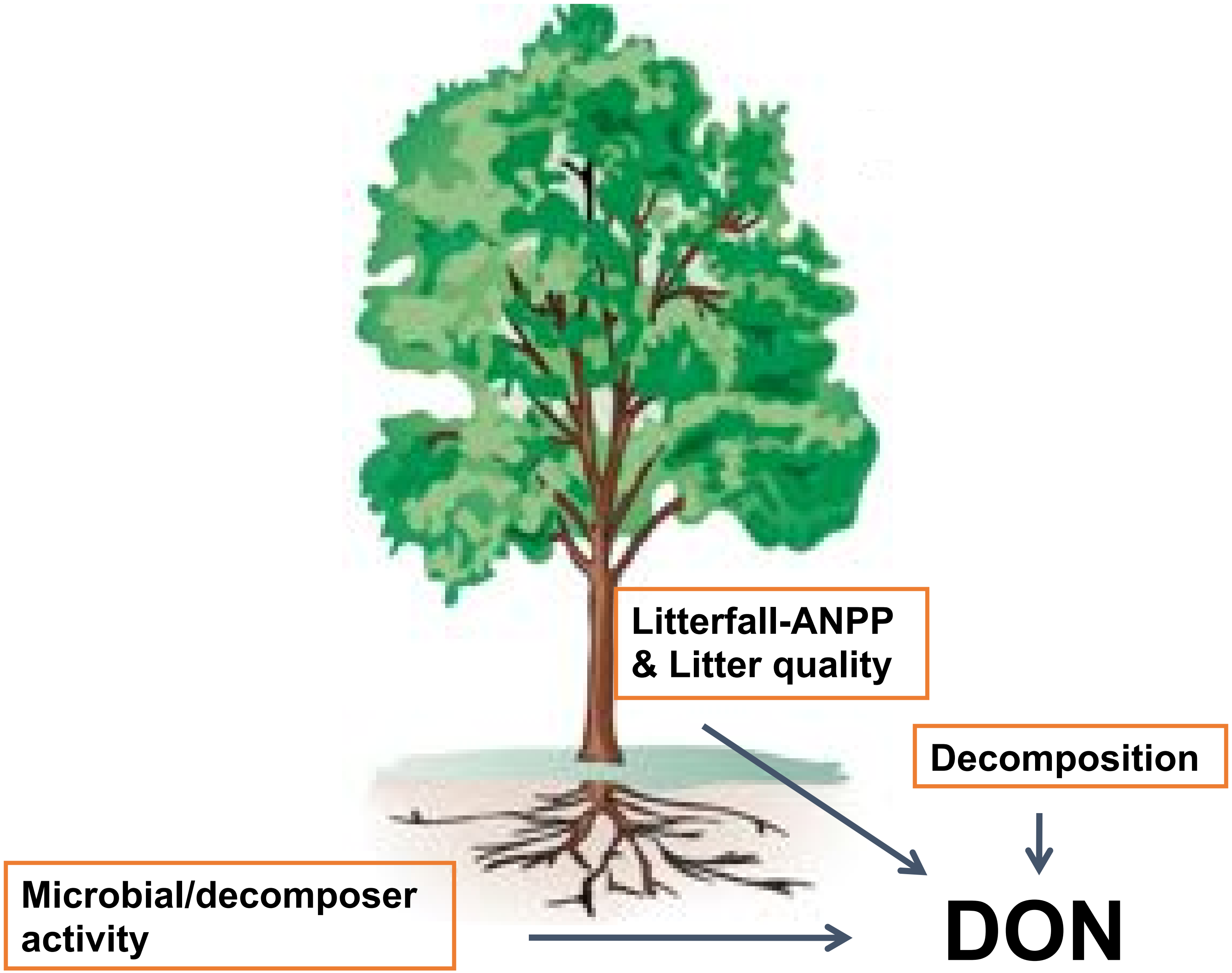
Gross Mineralization = Total amount of N released by mineralization (NH_4^+ and NO_3^-)

Net mineralization = Gross – immobilization – losses (NH_4^+ and NO_3^-)

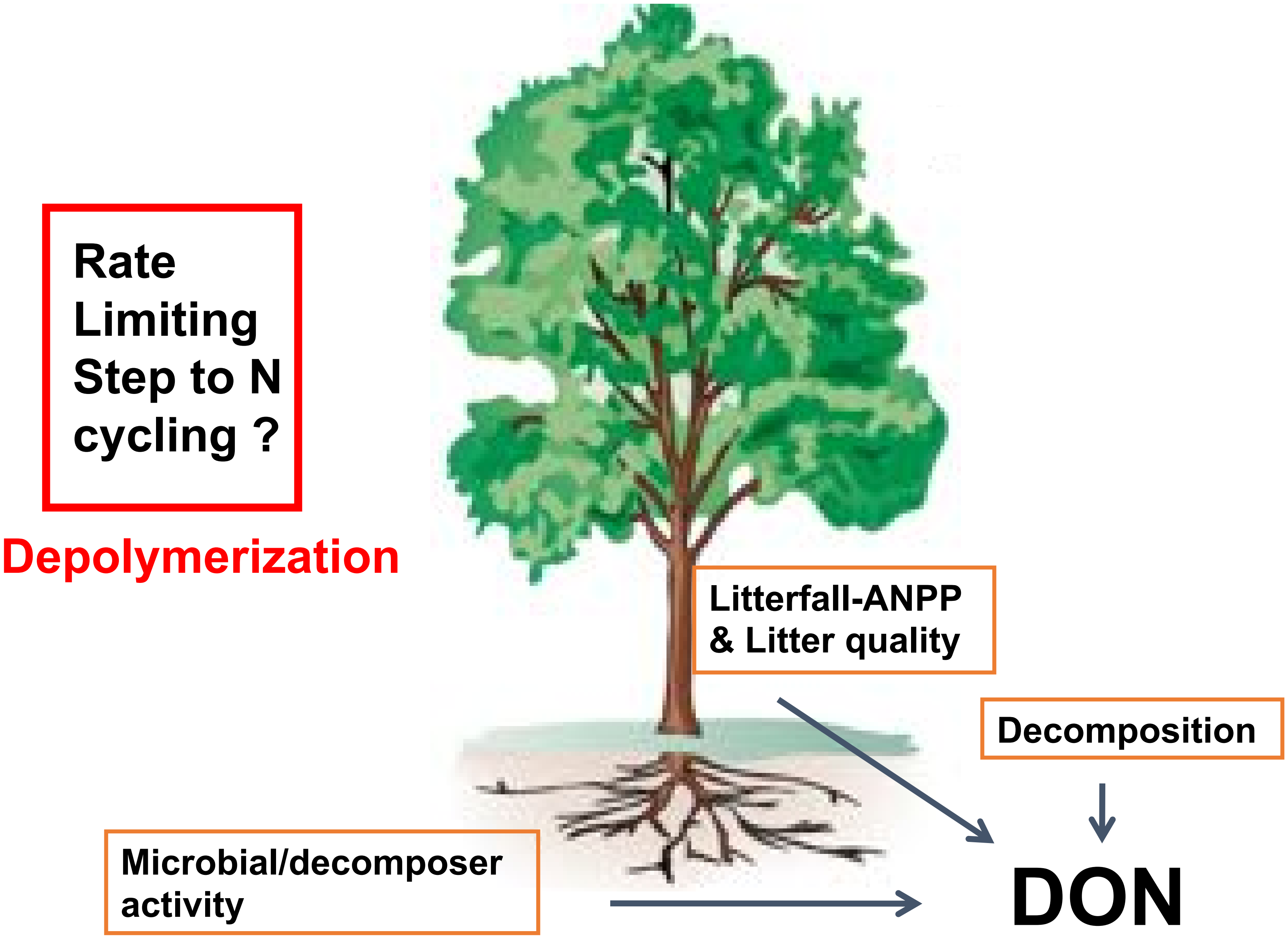
Net mineralization = available for plant uptake

Linking above- and belowground processes

Linkages between above- and belowground processes



Linkages between above- and belowground processes

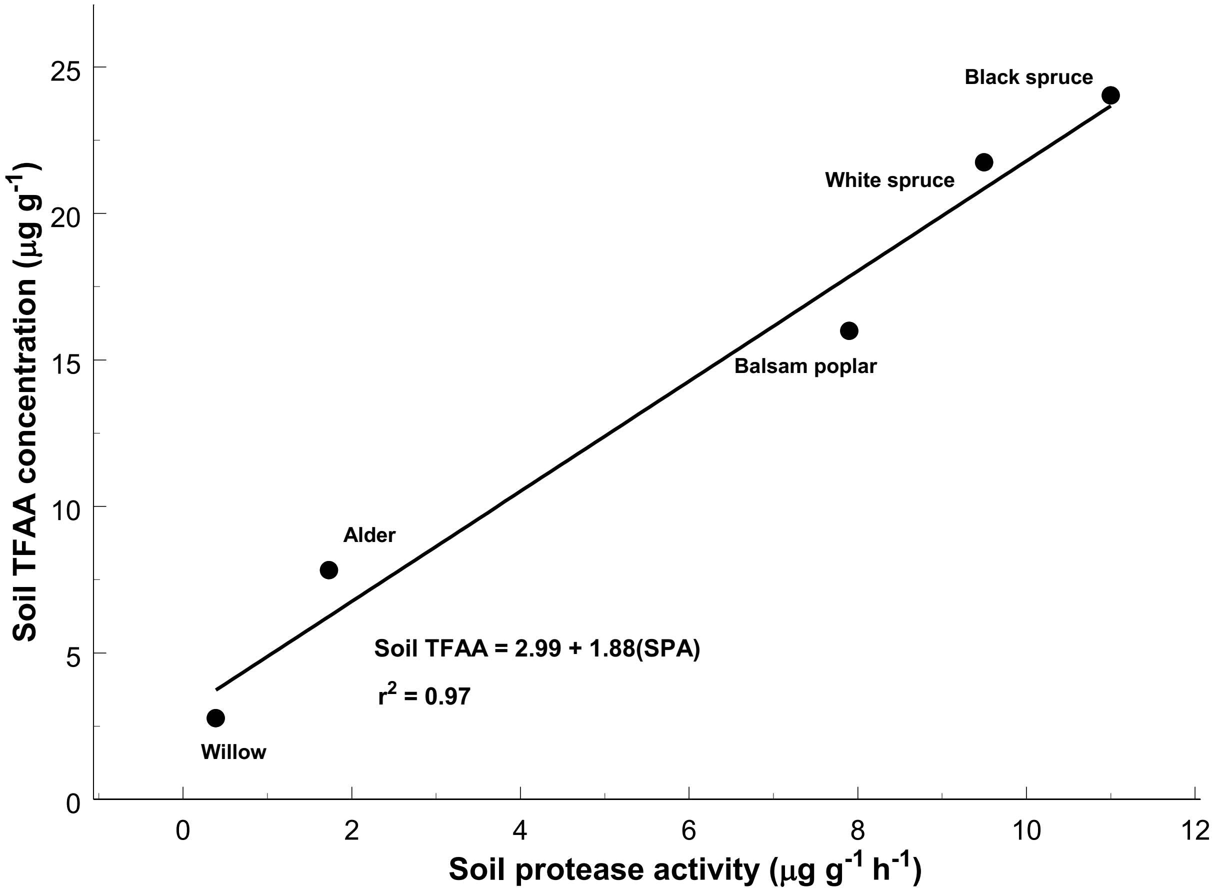


DON

Bacteria and fungi secrete extracellular enzymes to break complex polymers down into water soluble units that can pass through cell membranes

Proteases	Proteins	Amino acids
Ribonucleases	Nucleic acids	Nucleotides
Chitinases	Chitins	
Cellulase	N polymers	

High protease activity yields more amino acids



Kielland 2006

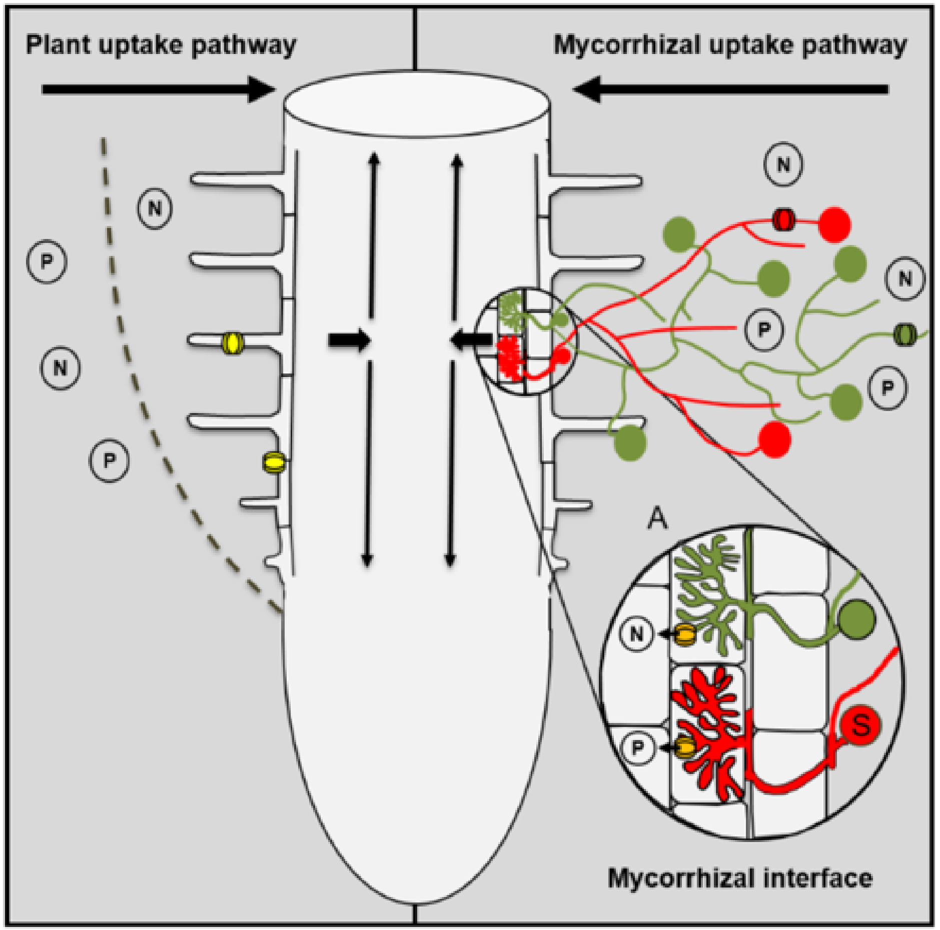
Fate of DON???

Fate of DON

1. Taken up by mycorrhizae

Linkages between above- and belowground processes

DON



Uptake by ECM & plants

Fate of DON

1. Taken up by mycorrhizae
2. Mineralized by microbes

Nitrogen Mineralization

•N Mineralization results from microbial break-down of DON

•Microbes release NH_4^+ to soil solution as they use carbon

Linkages between above- and belowground processes

CO_2

DON

NH_4^+

Ammonification

Fate of DON

1. Taken up by mycorrhizae
2. Mineralized by microbes
3. Leached (not too common)

Fate of NH_4^+???

Fate of NH_4^+

1. Nitrified by microbes

Linkages between above- and belowground processes

DON

NO_2^- ← NH_4^+

NO_3^- ←

Nitrification | Ammonification

Mineralization

Fate of NH_4^+

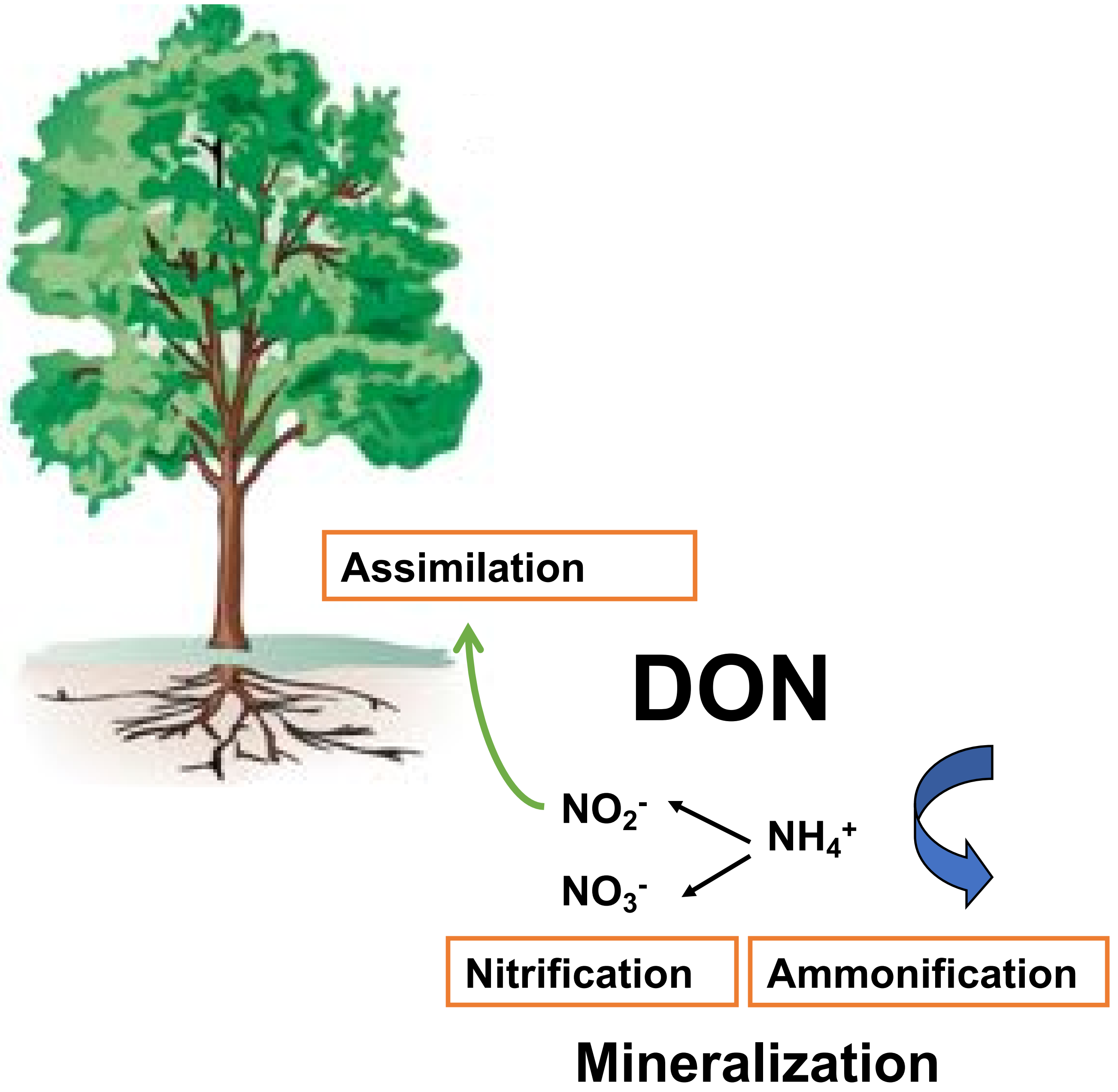
1. Nitrified by microbes
2. Assimilated up by microbes (not too common)
3. Assimilated up by plants (not too common)
4. Leached (not too common)

Fate of NO_3^-???

Fate of NO_3

1. Assimilated by plants

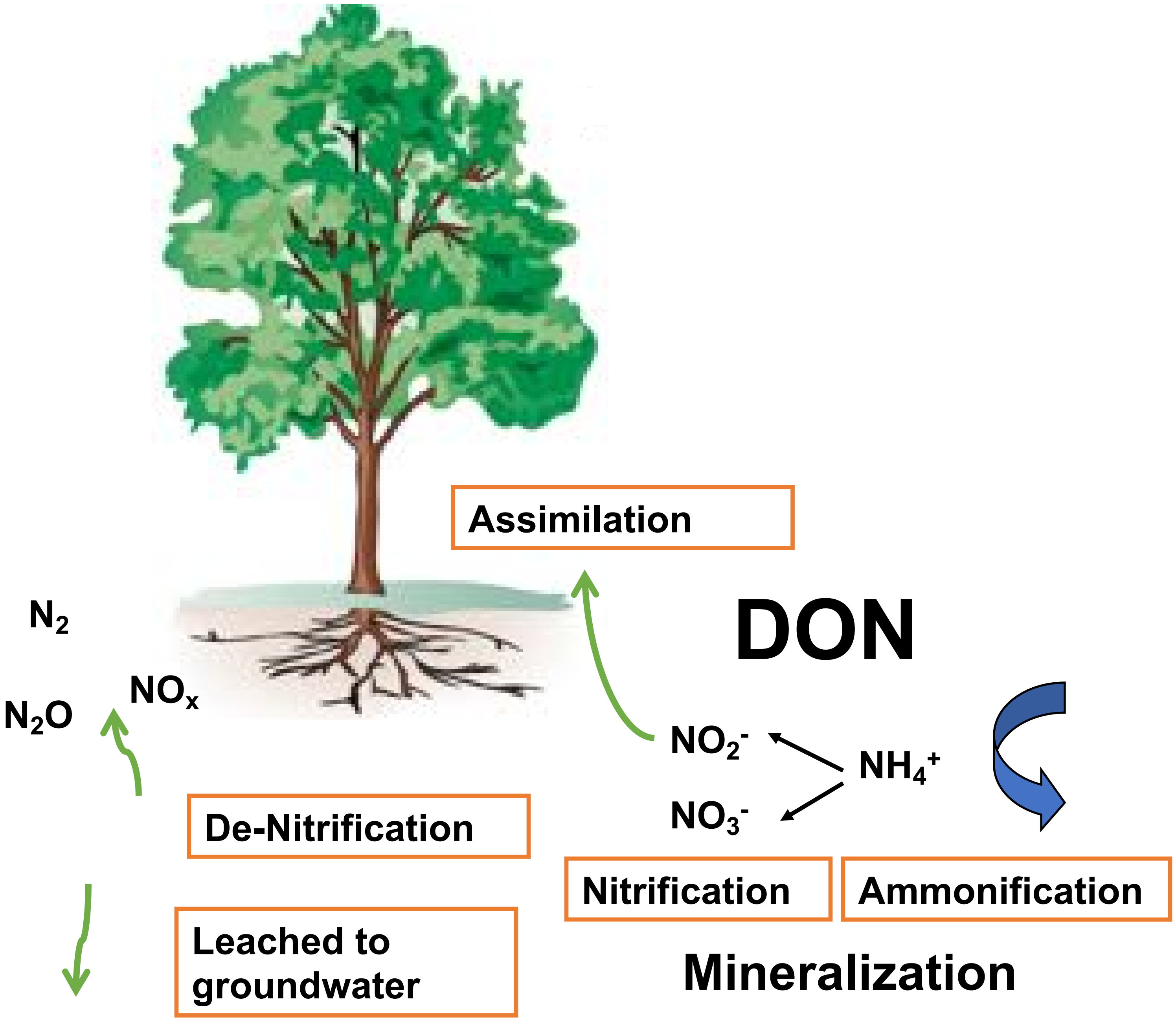
Linkages between above- and belowground processes



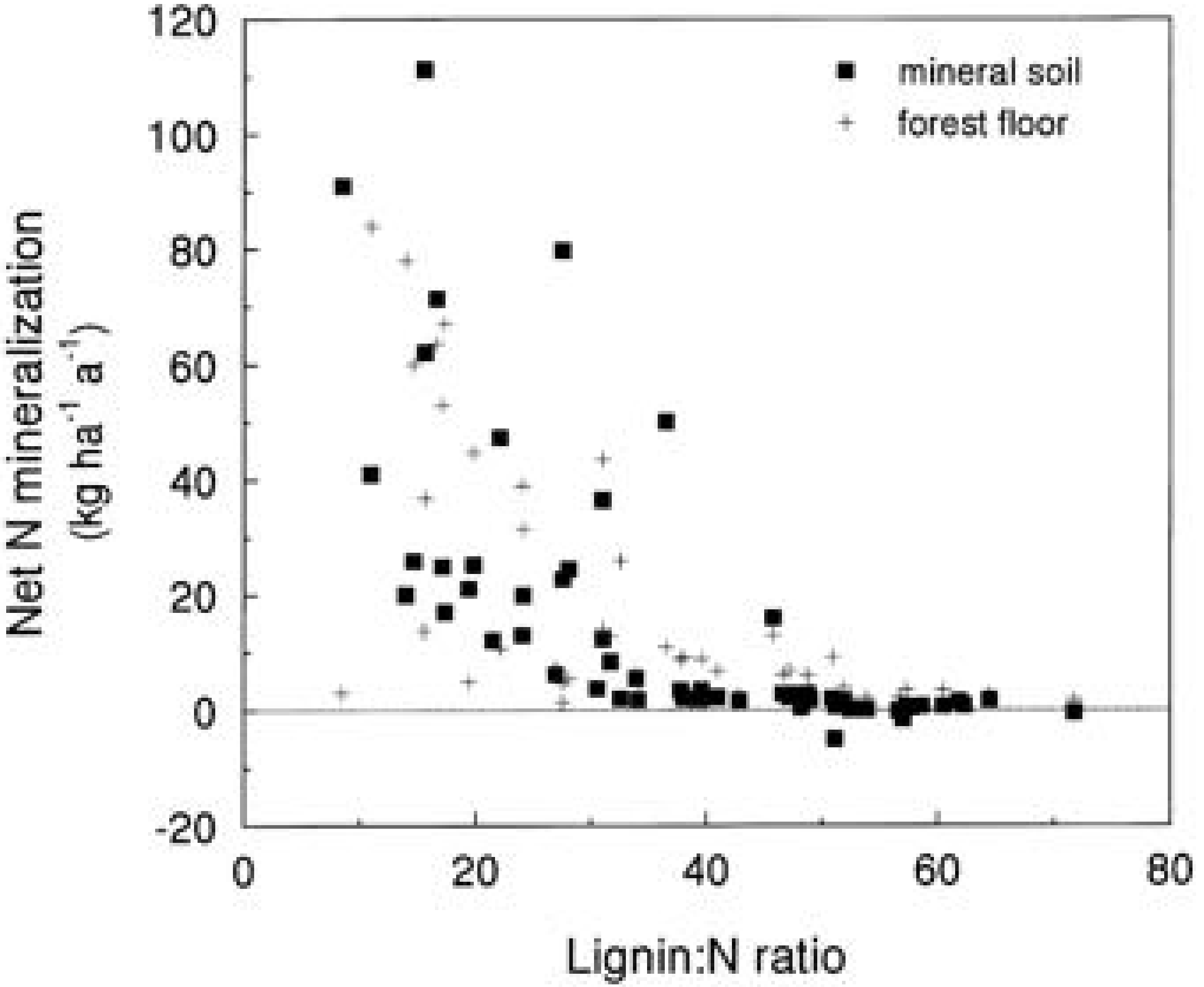
Fate of NO_3

1. Assimilated by plants
2. Denitrified by microbes
3. Leached

Linkages between above- and belowground processes



Speed of N cycling



Litter quality increases N cycling

Scott & Binkley 1997

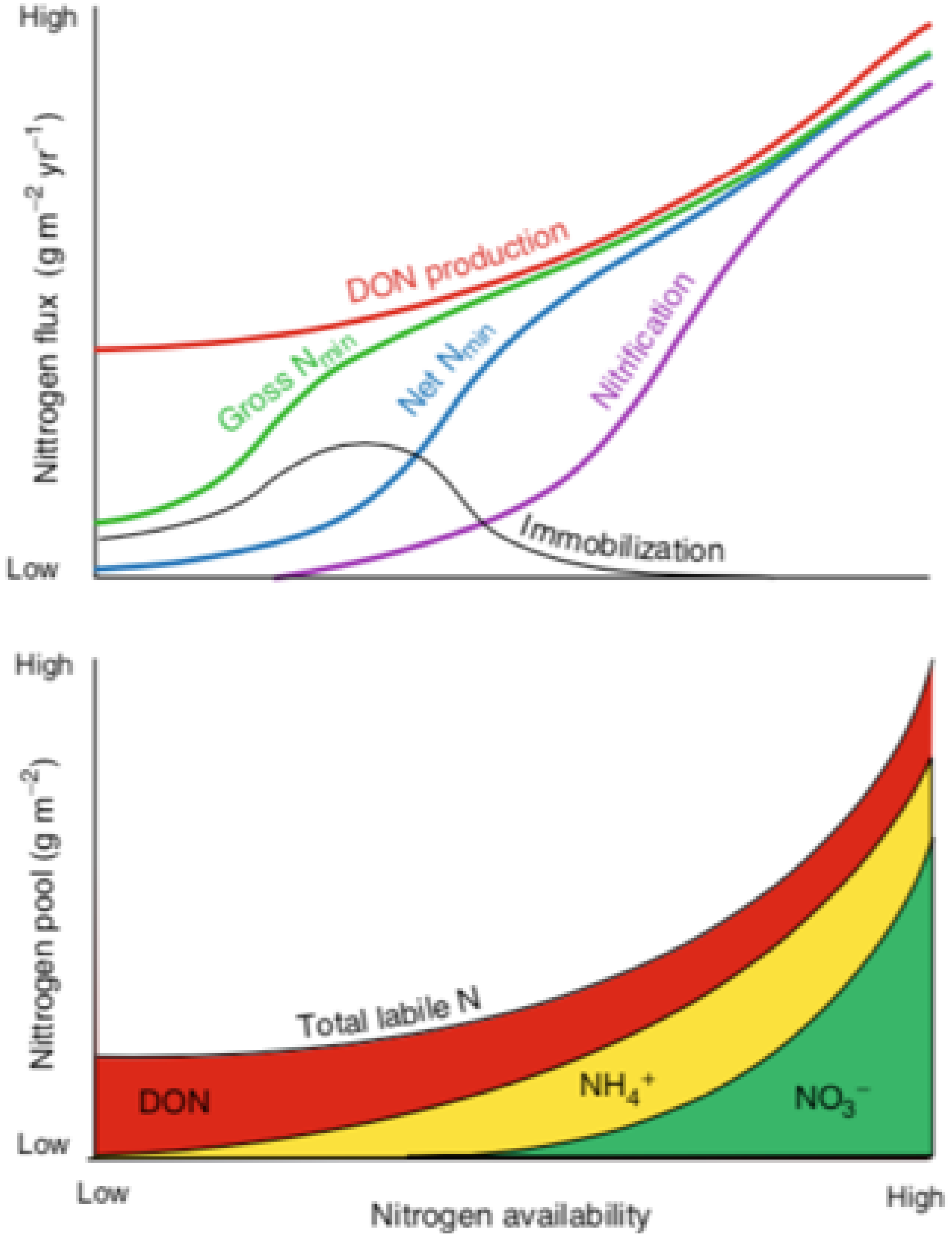
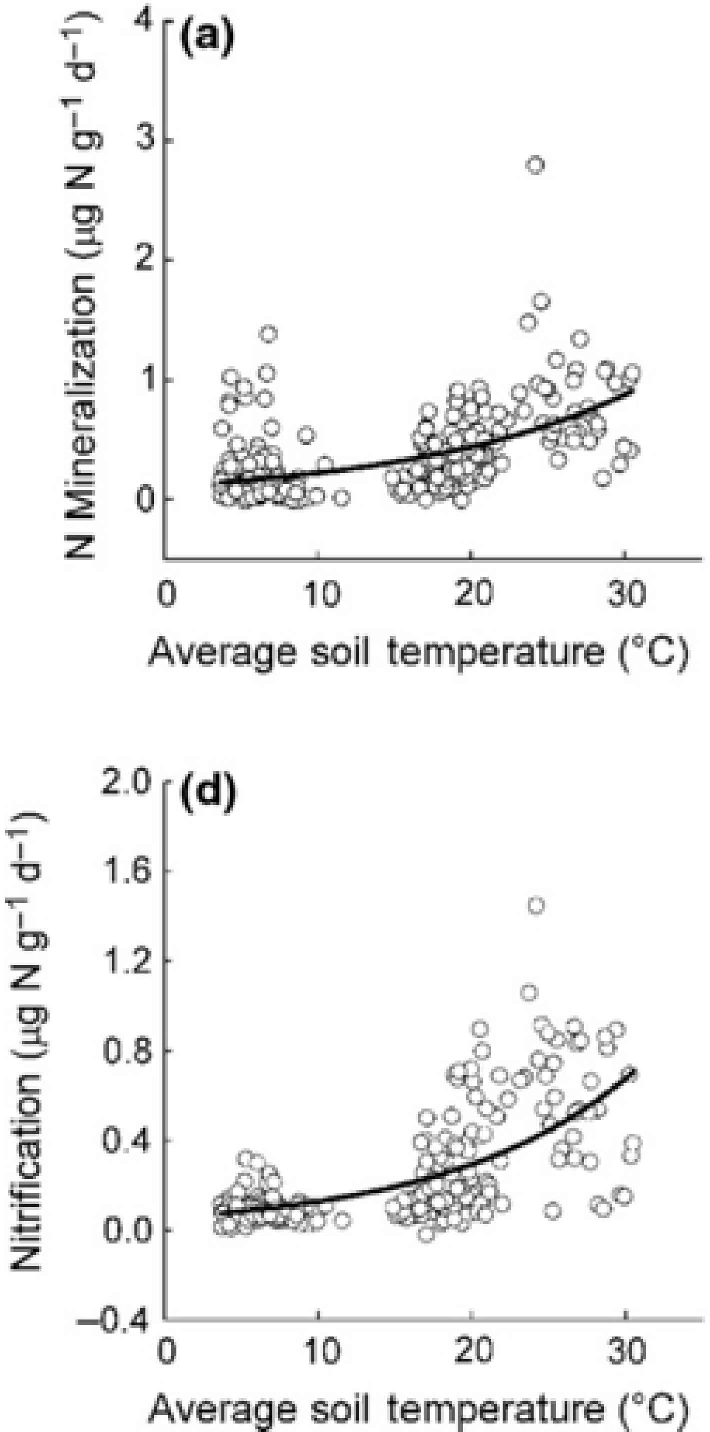
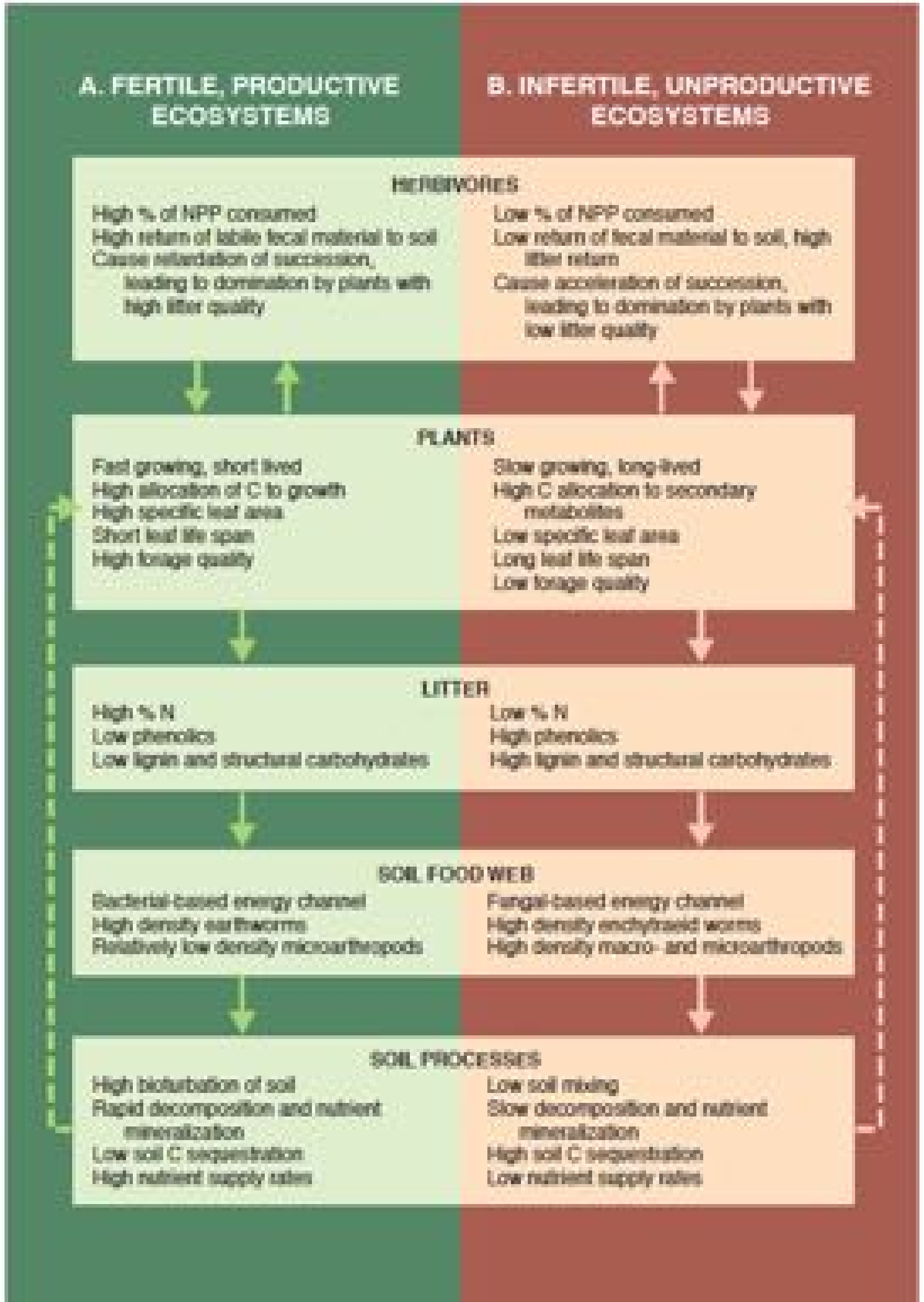


Fig. 9.7 Effect of nitrogen availability on the pools and fluxes of major forms of available nitrogen (dissolved organic nitrogen [DON], ammonium, and nitrate)



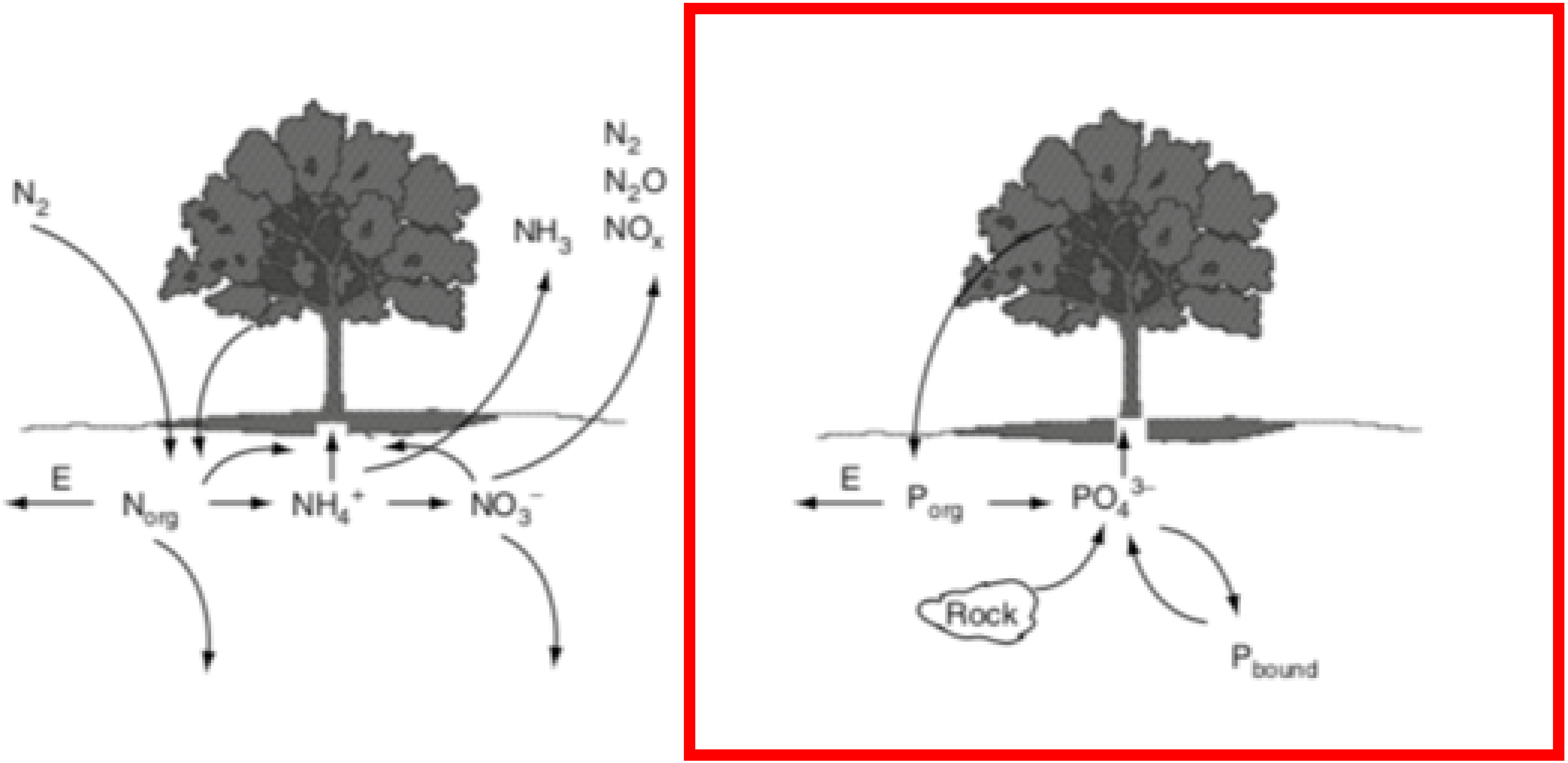
Temperature increases N cycling

Fast Cycling Systems

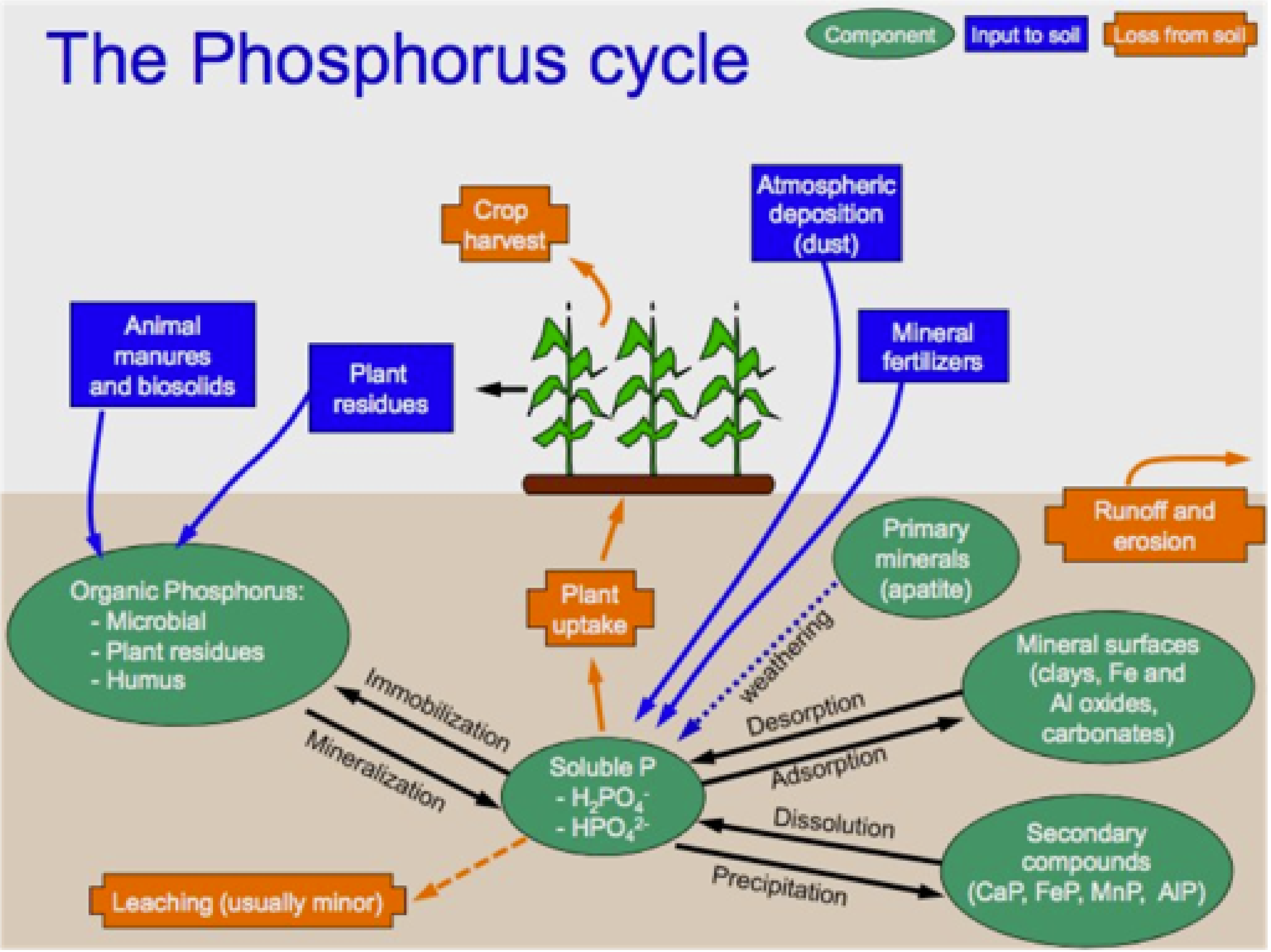


Slow Cycling Systems

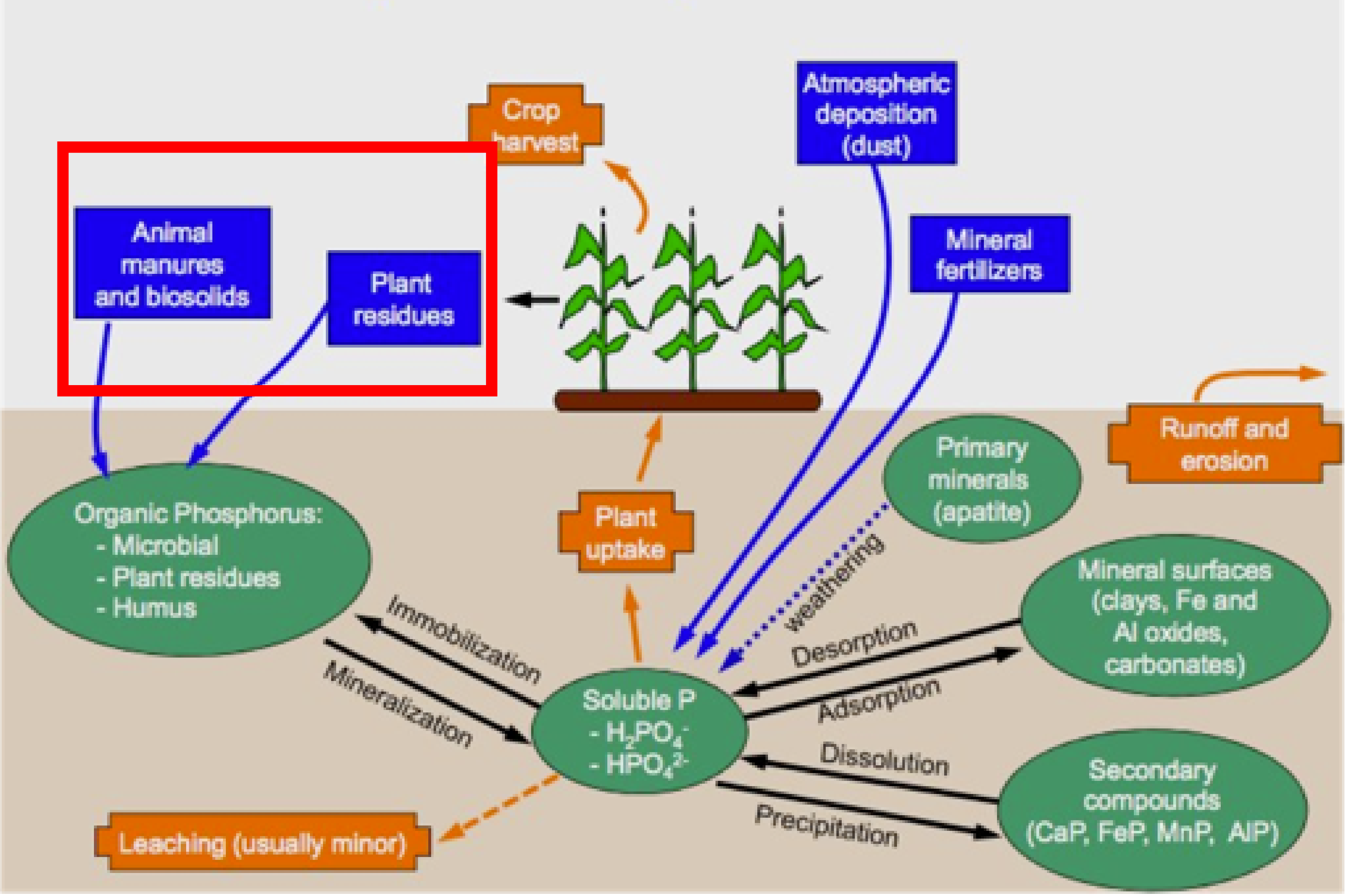
Why might organisms manipulate the speed of N cycling?



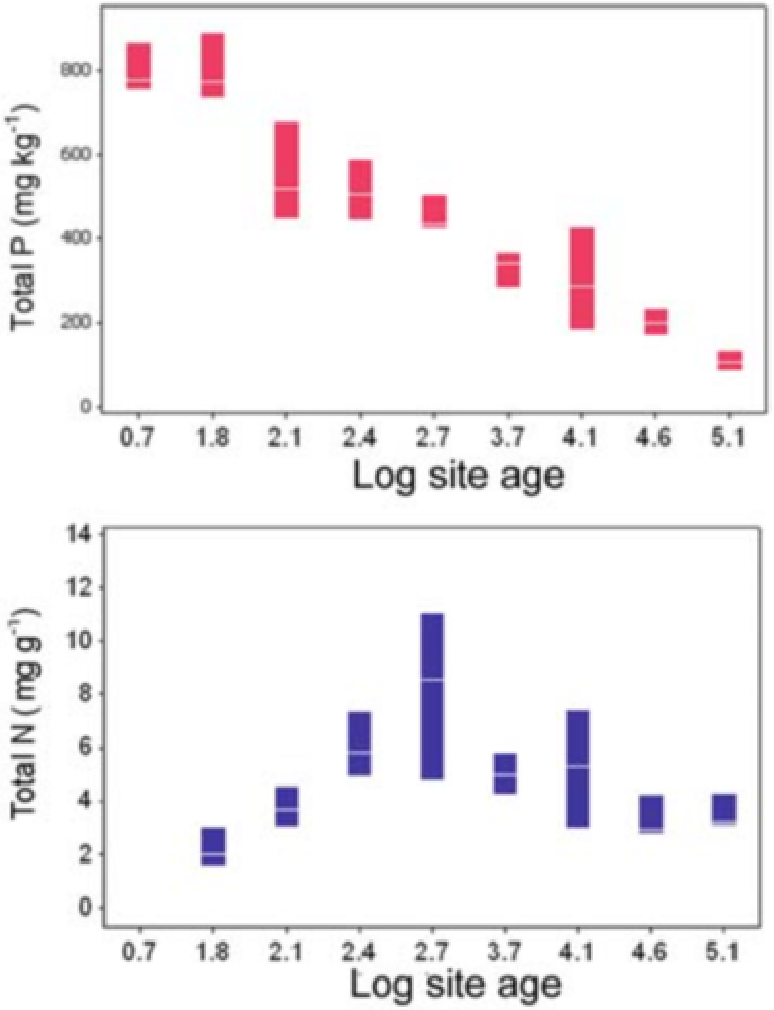
N2
N2
N2O
NOx
NH3
E
Norg
NH4+
NO3-
E
Porg
PO4 3-
Rock
Pbound

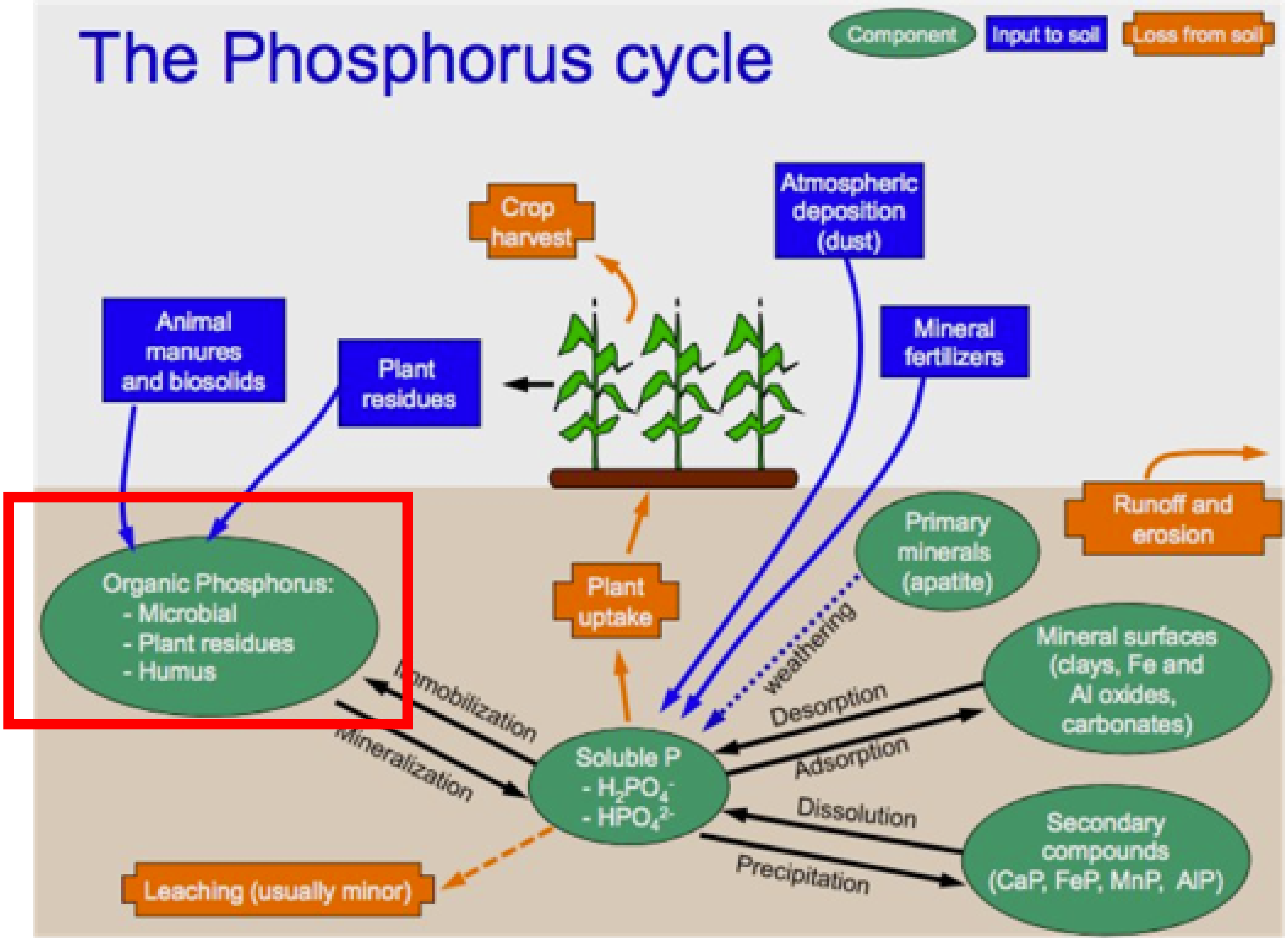

The Phosphorus cycle
Component
Input to soil
Loss from soil
Crop harvest
Atmospheric deposition (dust)
Animal manures and biosolids
Plant residues
Mineral fertilizers
Runoff and erosion
Primary minerals (apatite)
Plant uptake
Organic Phosphorus:
- Microbial
- Plant residues
- Humus
weathering
Mineral surfaces (clays, Fe and Al oxides, carbonates)
Desorption
Adsorption
Immobilization
Mineralization
Soluble P
- $H_2PO_4^-$
- HPO_4^{2-}
Dissolution
Precipitation
Secondary compounds (CaP, FeP, MnP, AlP)
Leaching (usually minor)

The Phosphorus cycle



Most P enters systems through recycling




The Phosphorus cycle
Component
Input to soil
Loss from soil
Crop harvest
Atmospheric deposition (dust)
Animal manures and biosolids
Plant residues
Mineral fertilizers
Runoff and erosion
Primary minerals (apatite)
Plant uptake
Organic Phosphorus:
- Microbial
- Plant residues
- Humus
weathering
Mineral surfaces (clays, Fe and Al oxides, carbonates)
Desorption
Immobilization
Adsorption
Mineralization
Soluble P
- $H_2PO_4^-$
- HPO_4^{2-}
Dissolution
Secondary compounds (CaP, FeP, MnP, AlP)
Precipitation
Leaching (usually minor)

Microbes have a ton of P!

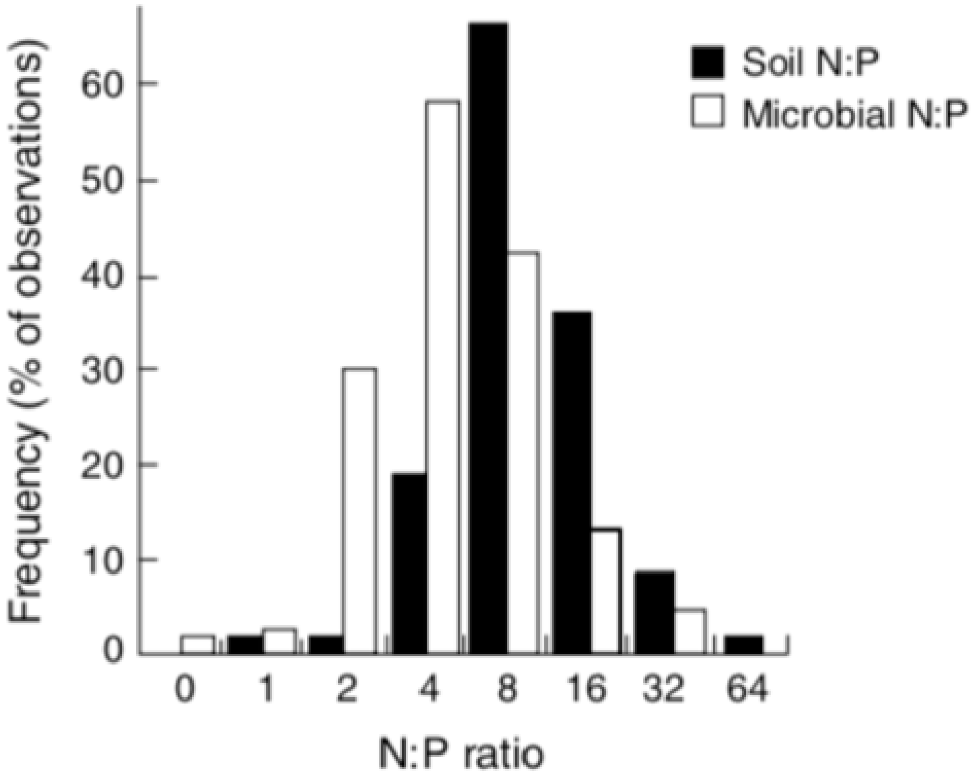
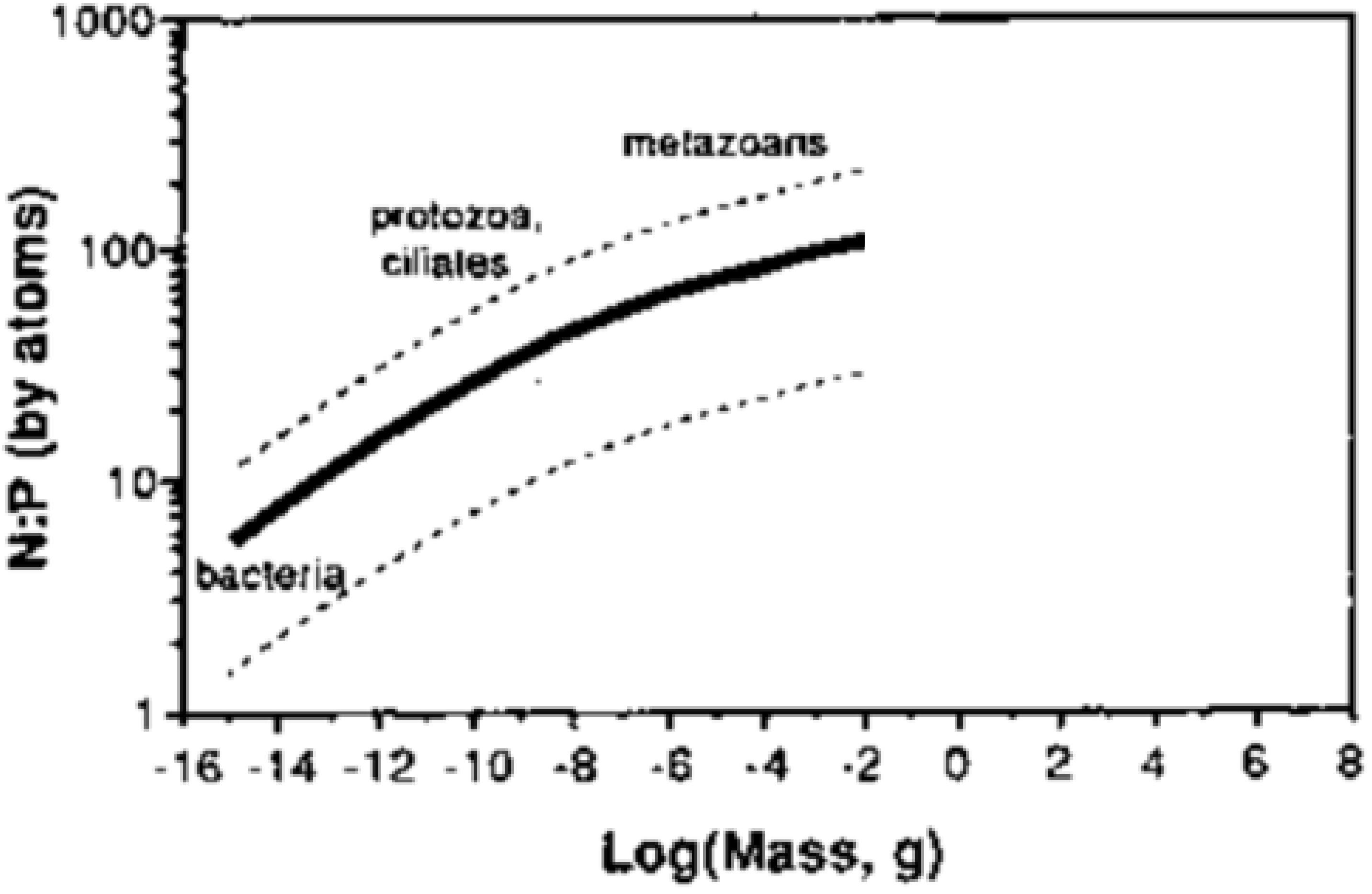


Fig. 9.15 Frequency distribution of N:P ratios in soils and microbial biomass on a $\log_2$ scale. Redrawn from Cleveland and Liptzin (2007)

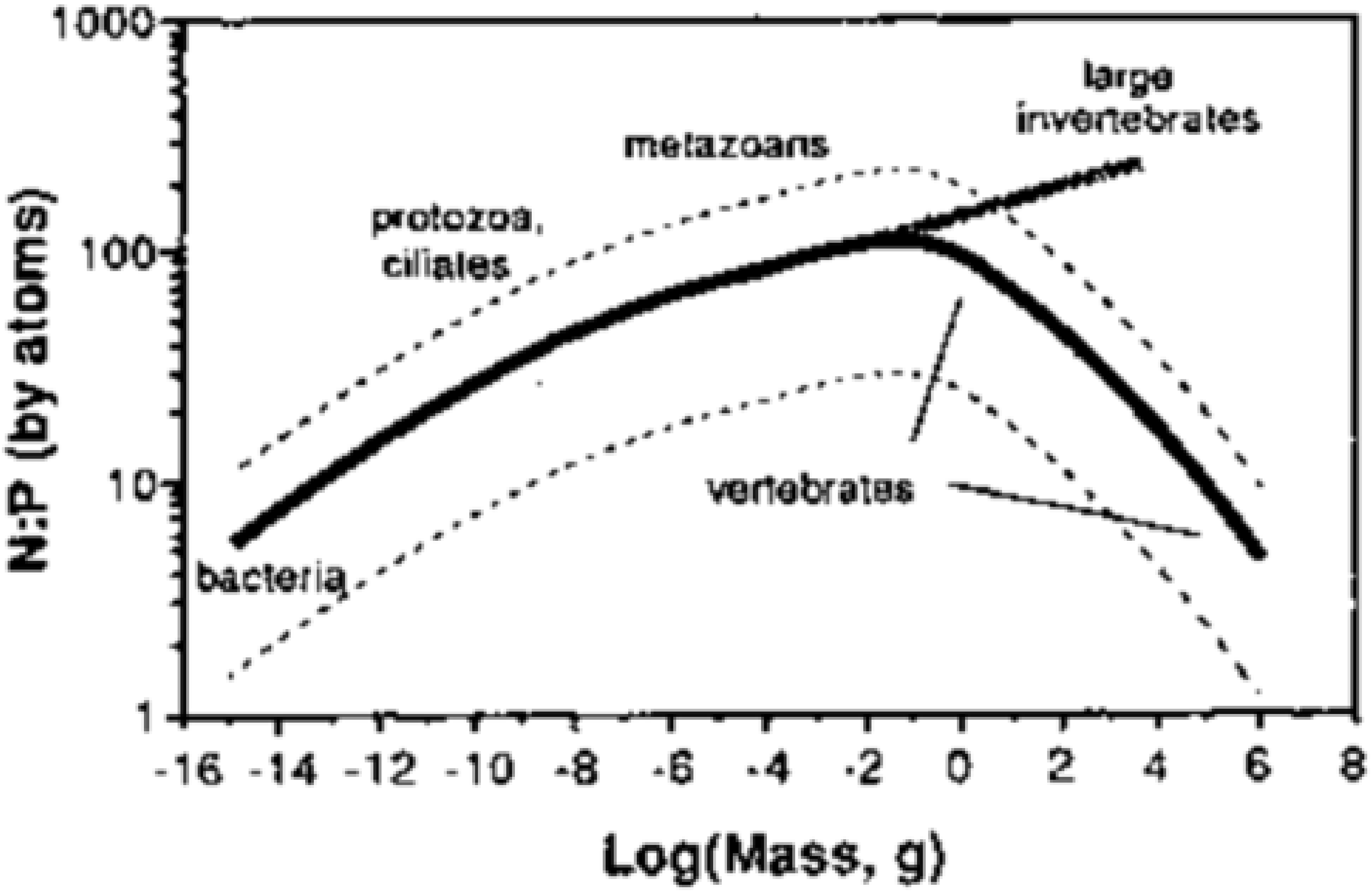
Microbial P = 20-30% total ecosystem P
Microbial N = 4% total ecosystem N
Microbial C = 2% total ecosystem C

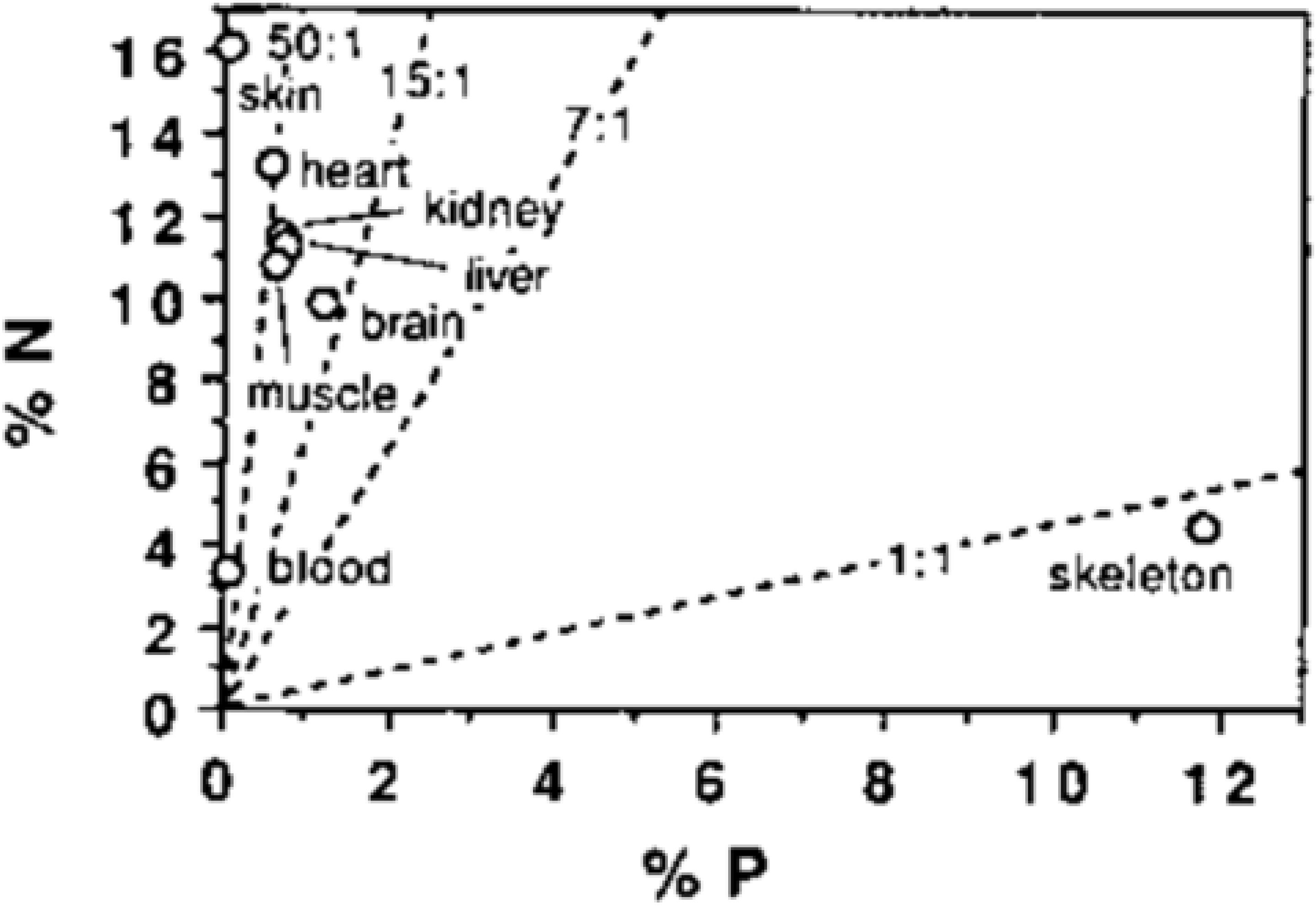
Microbial N:P = 7:1
Plant N:P = 28:1

N:P tends to increase with organism size…



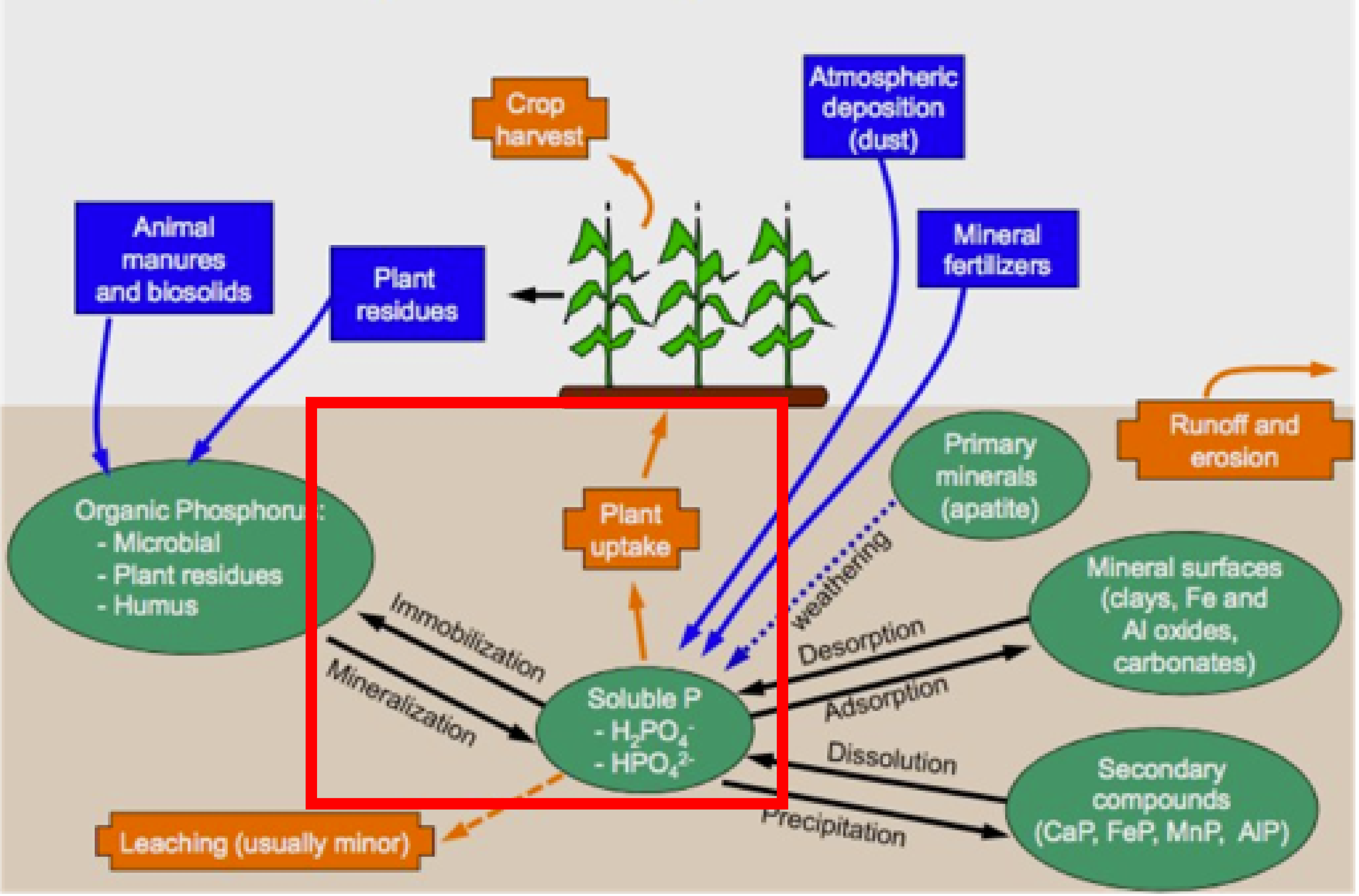
…but vertebrates are weird!



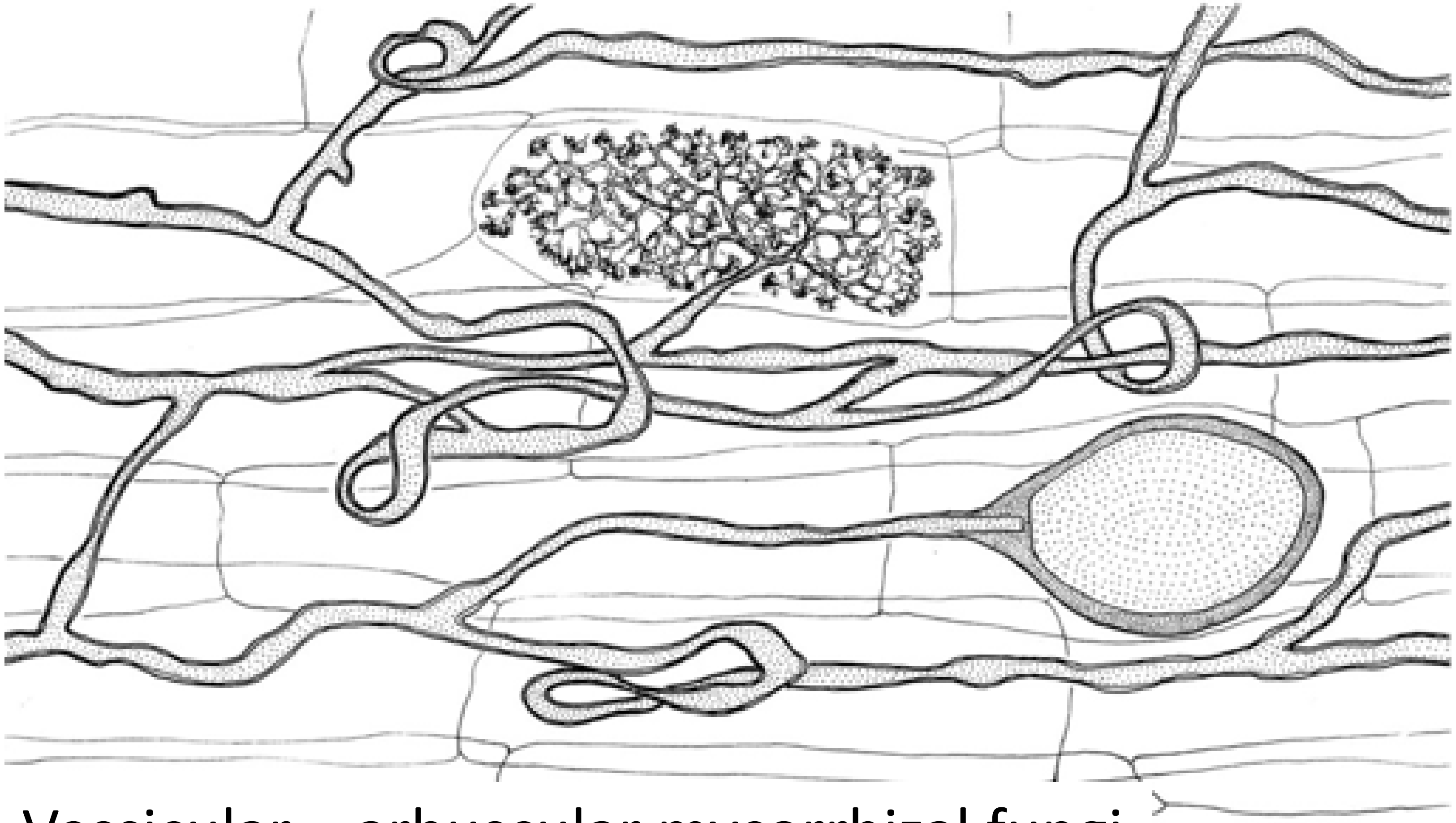


50:1
skin
15:1
7:1
heart
kidney
liver
brain
muscle
blood
1:1
skeleton
% N
% P
0
2
4
6
8
10
12
14
16
0
2
4
6
8
10
12

The Phosphorus cycle



Mycorrhizae are very important for plant P uptake

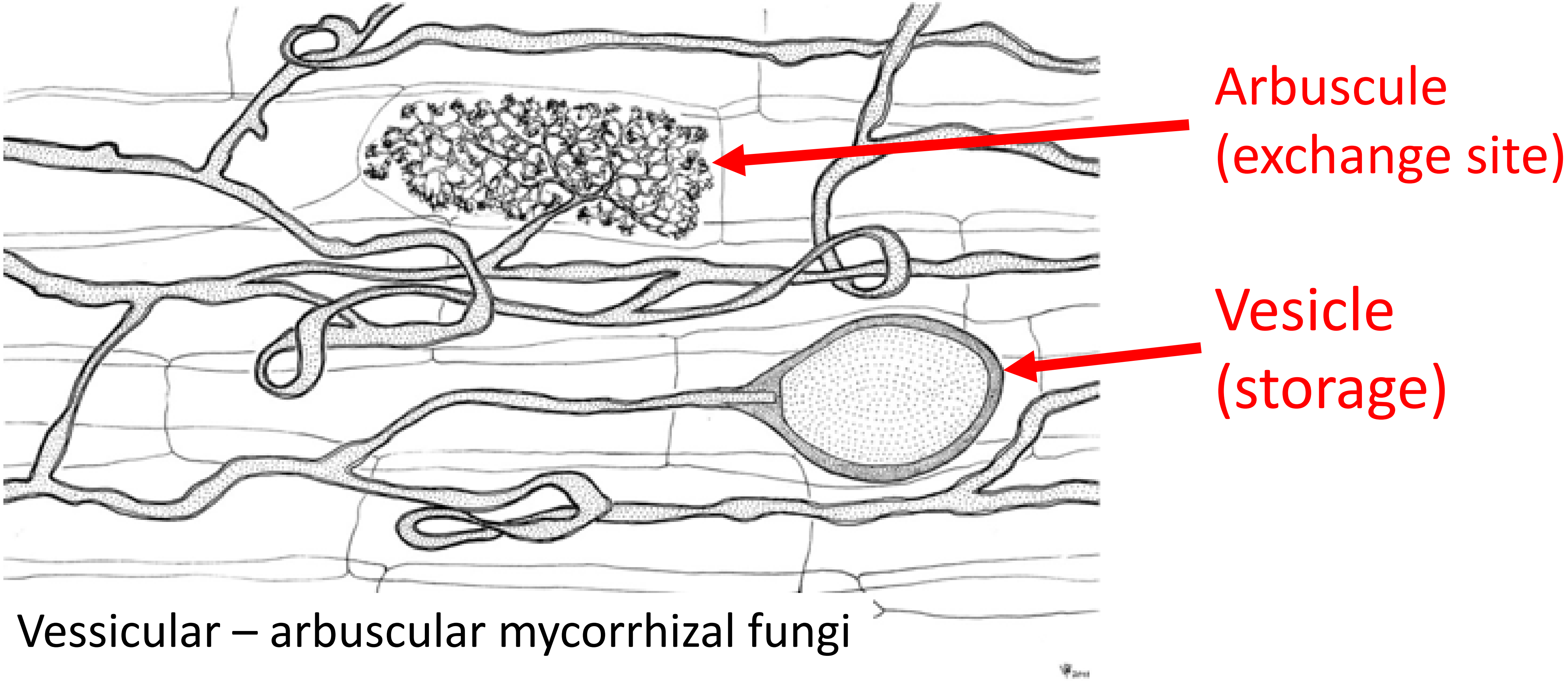


Vessicular – arbuscular mycorrhizal fungi

Exchange P for C

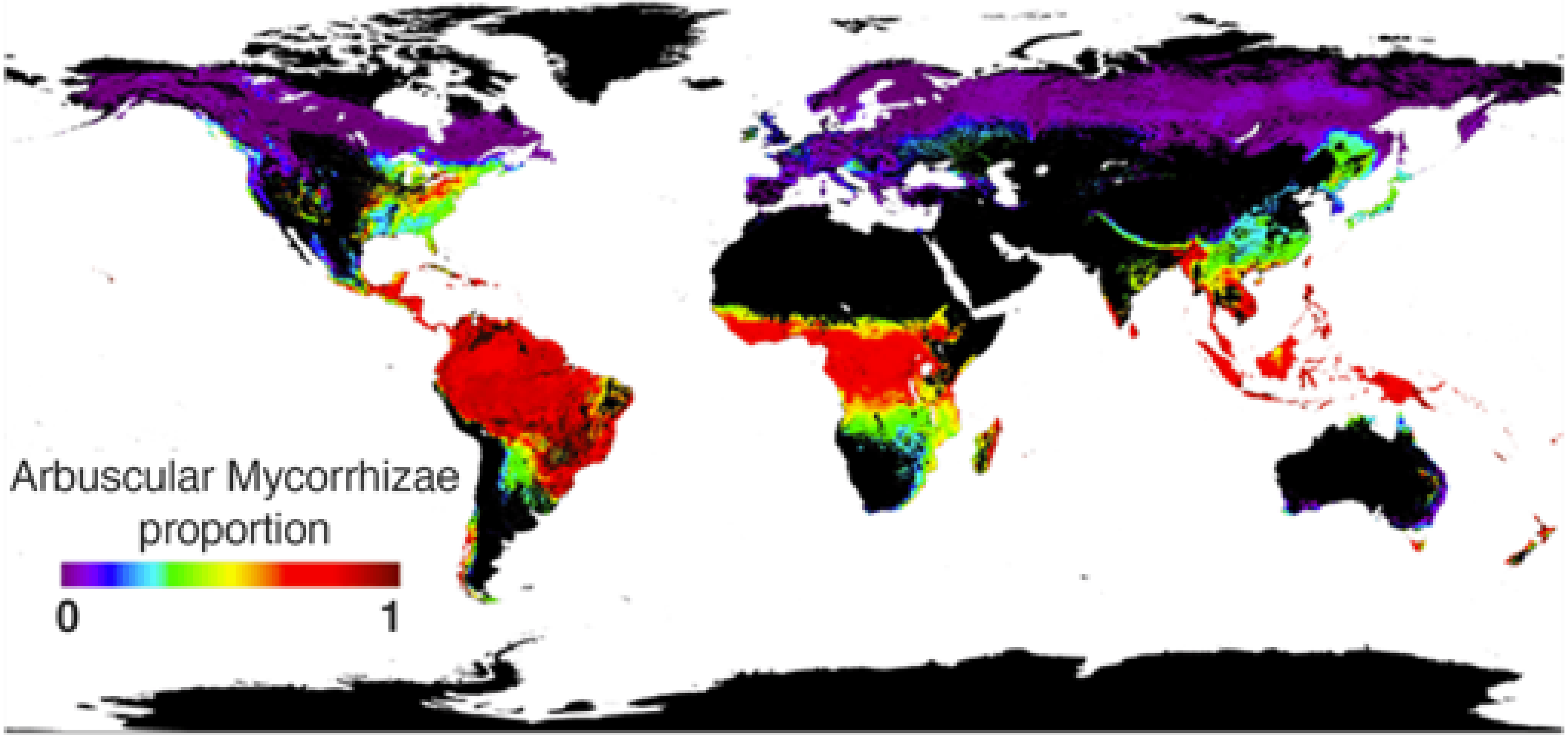
Define the plant-soil P interface

Mycorrhizae are very important for plant P uptake

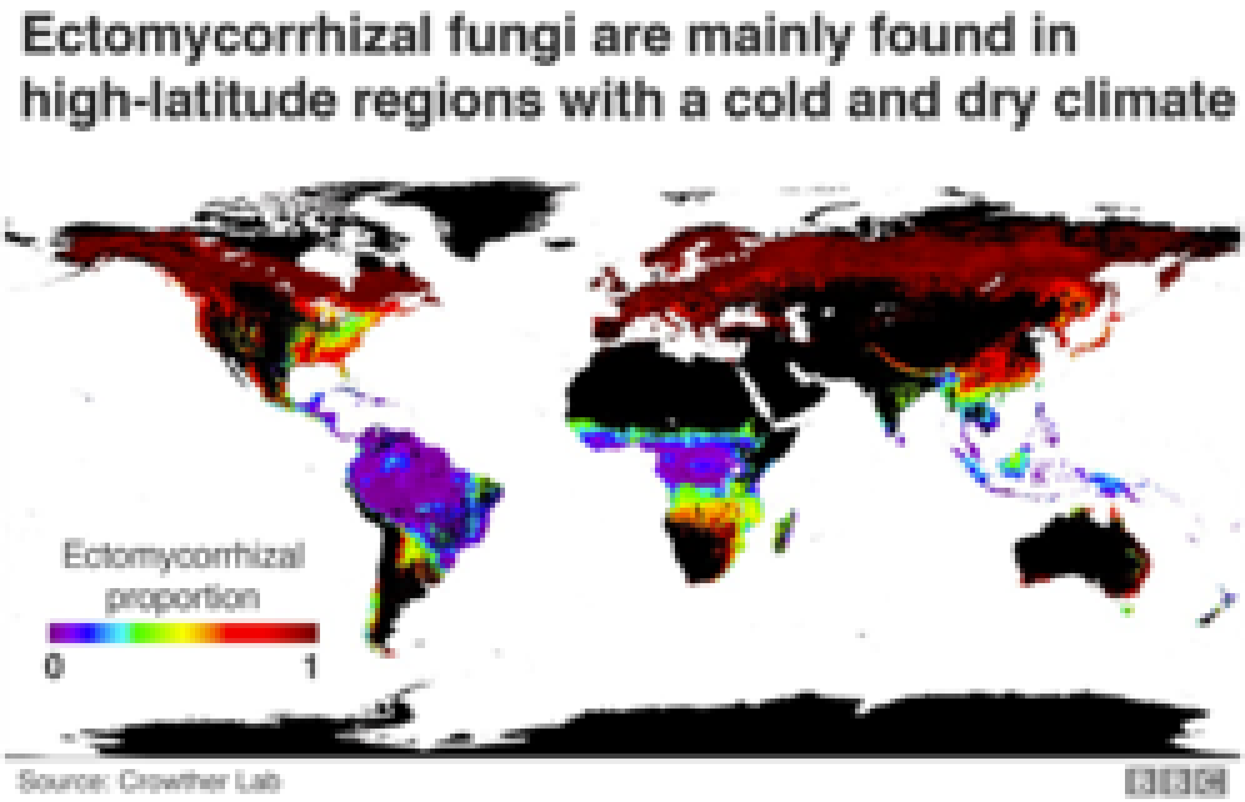


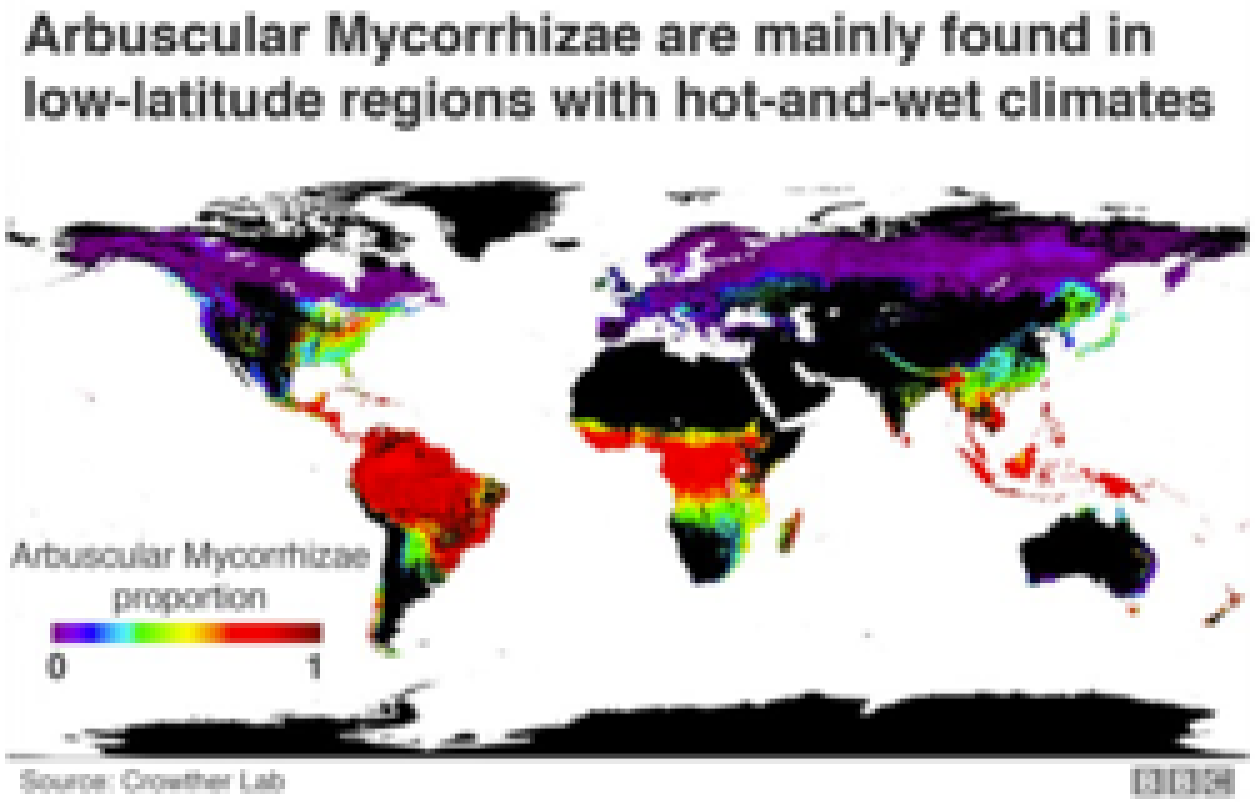
Vessicular – arbuscular mycorrhizal fungi

Arbuscular Mycorrhizae are mainly found in low-latitude regions with hot-and-wet climates



Source: Crowther Lab

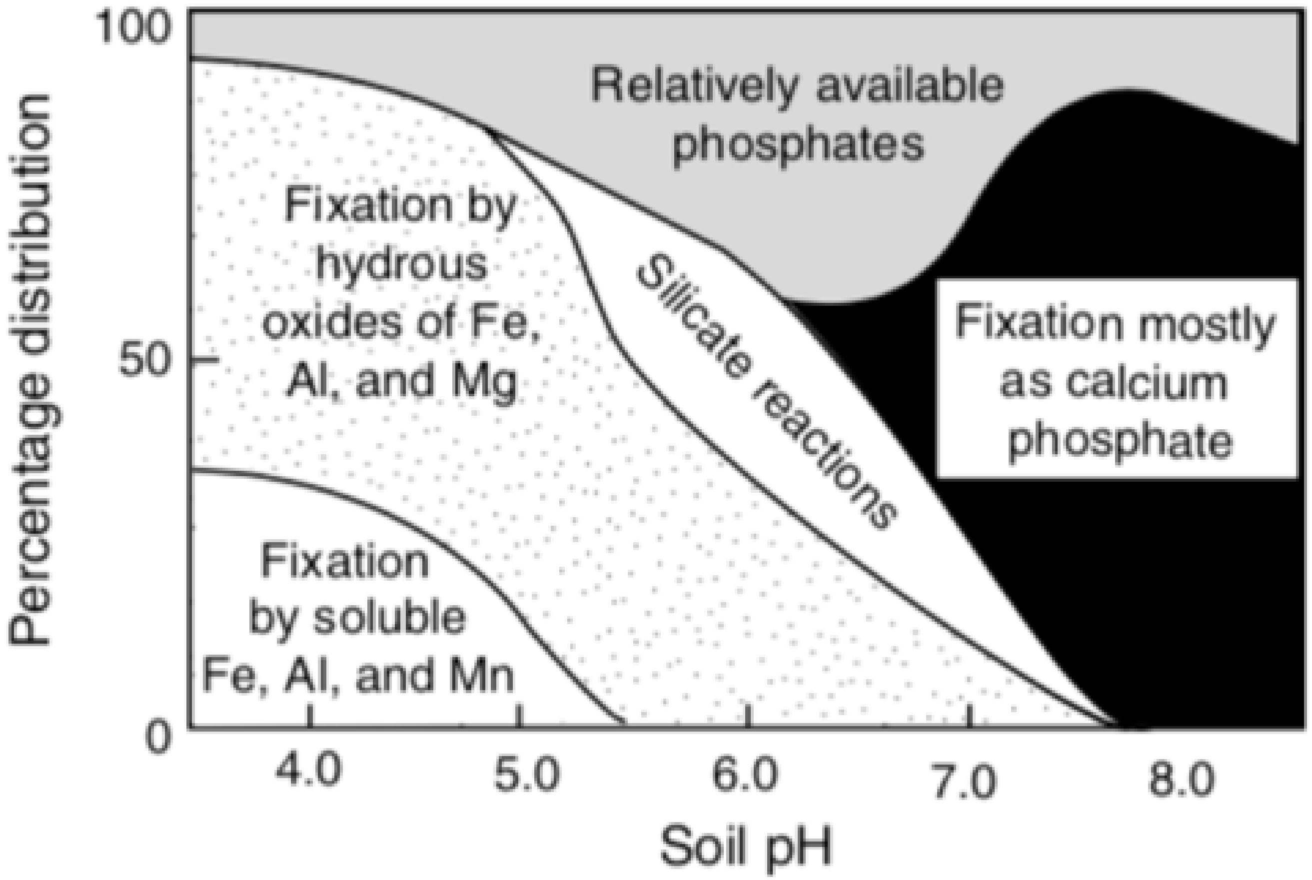




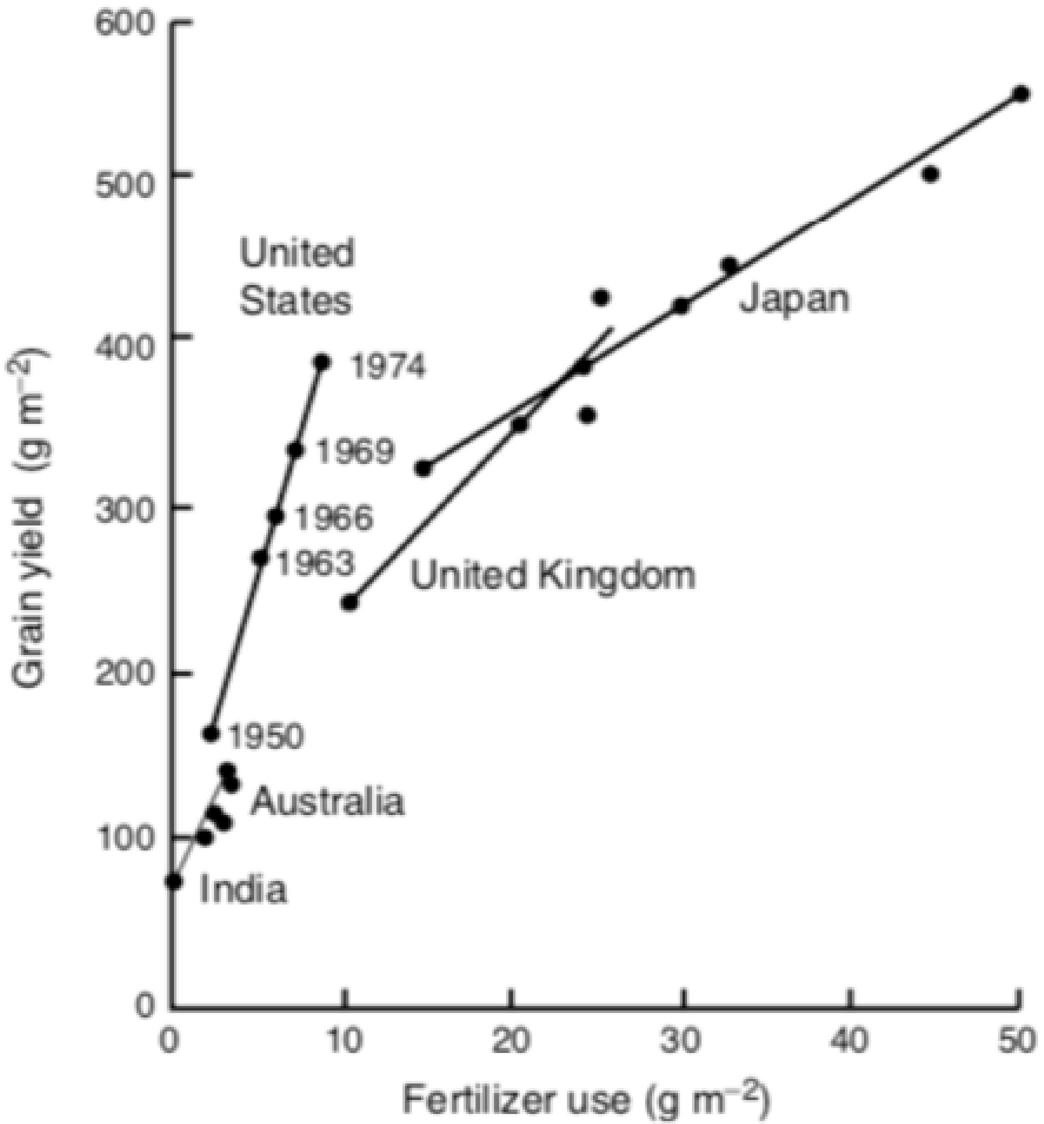
Ectomycorrhizae get relatively more N than P

Arbuscular mycorrhizae get relatively more P than N

P binds to things, is more available at moderate pH

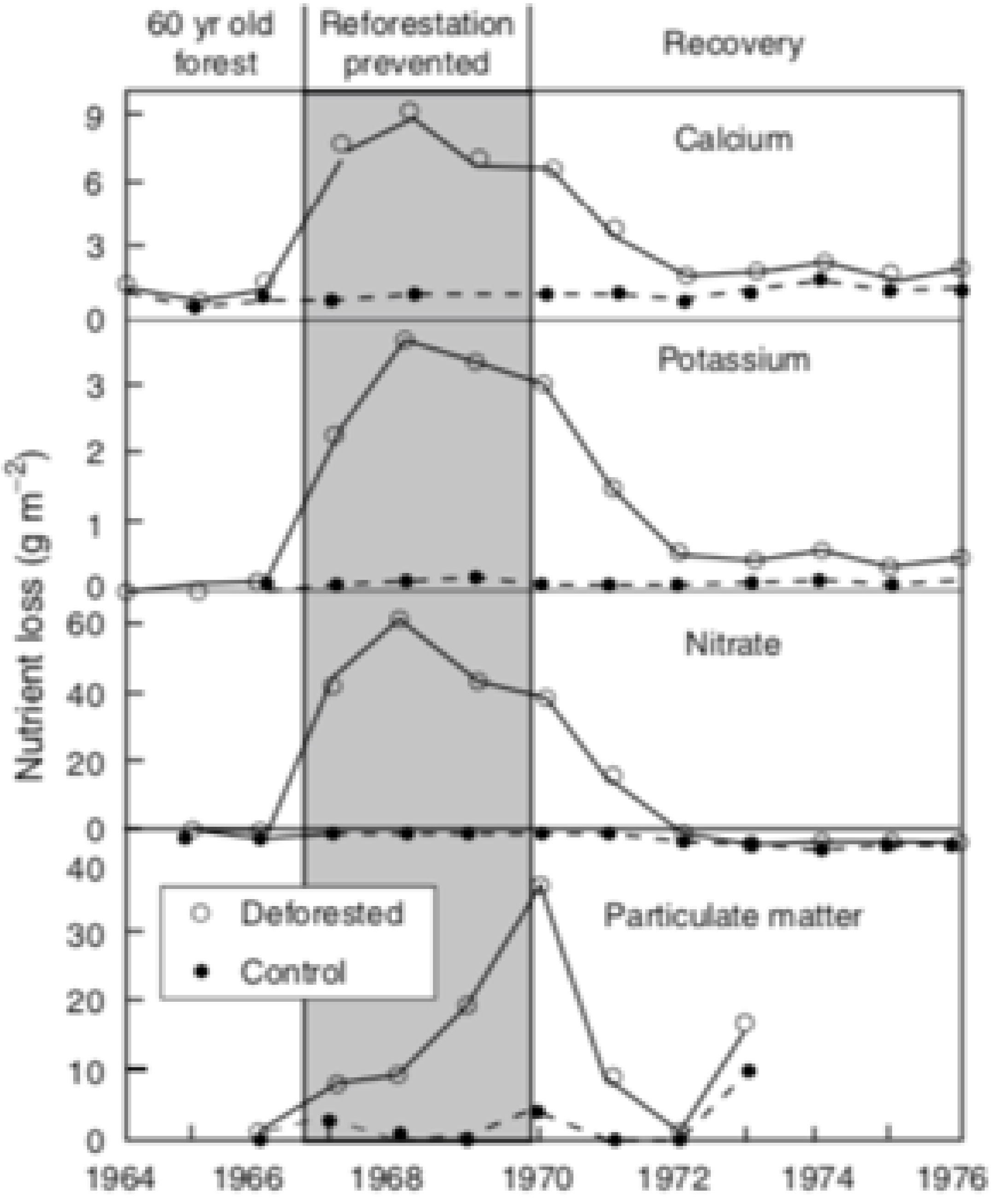


Agriculture



Grain yield (g m^{-2})
Fertilizer use (g m^{-2})
0
100
200
300
400
500
600
0
10
20
30
40
50
United States
1974
1969
1966
1963
1950
Japan
United Kingdom
Australia
India

Fig. 9.14 Losses of calcium, potassium, nitrate, and particulate organic matter in stream water before and after deforestation of an experimental watershed at Hubbard Brook in the northeastern U.S. The shaded area shows the time interval during which vegetation was absent due to cutting of trees and herbicide application. Redrawn from Bormann and Likens (1979)



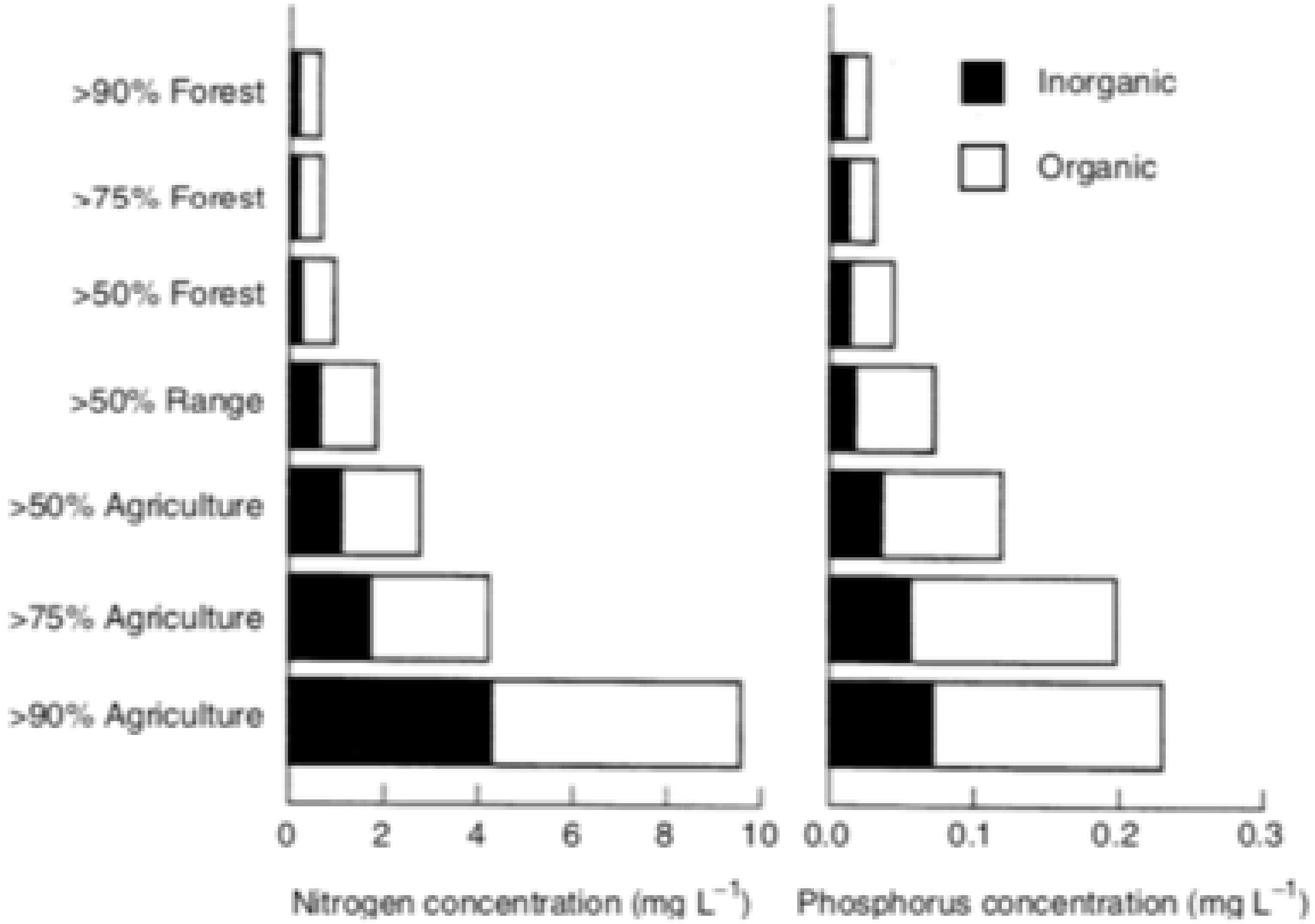
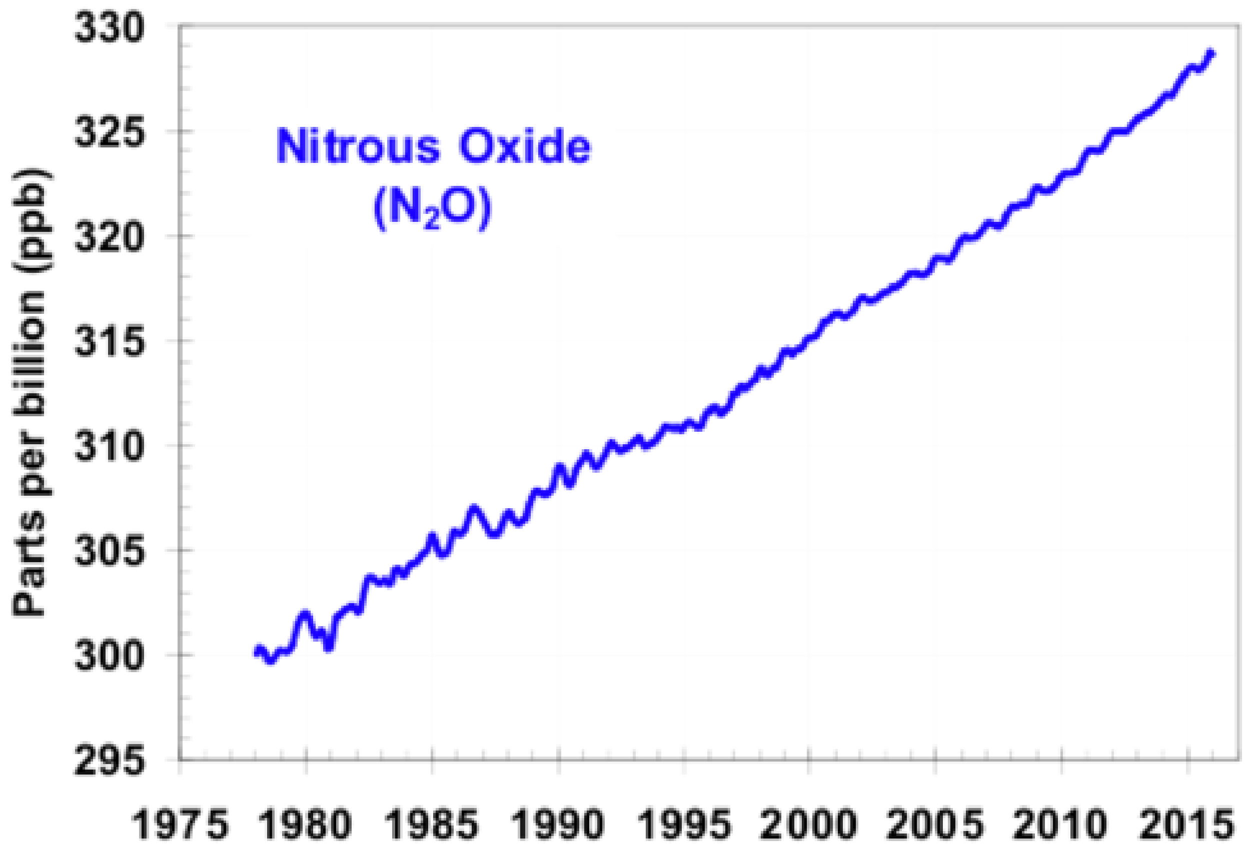
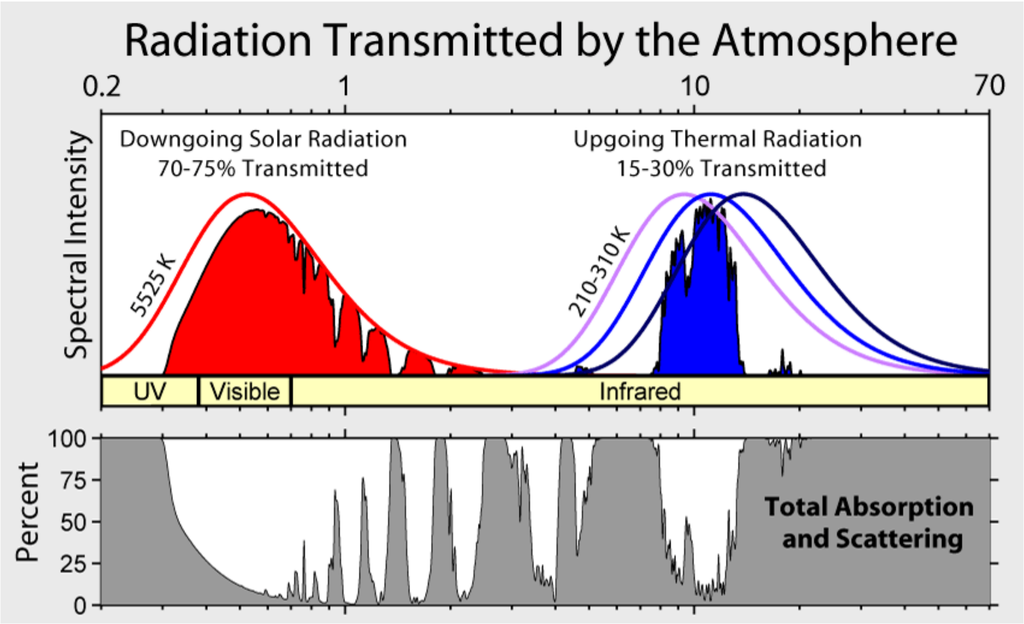


Fig. 9.4 Concentrations of organic and inorganic nitrogen and phosphorus in 928 relatively unpolluted U.S. streams in watersheds with varying degrees of conversion from forest to agriculture. Redrawn from Allan and Castillo (2007)

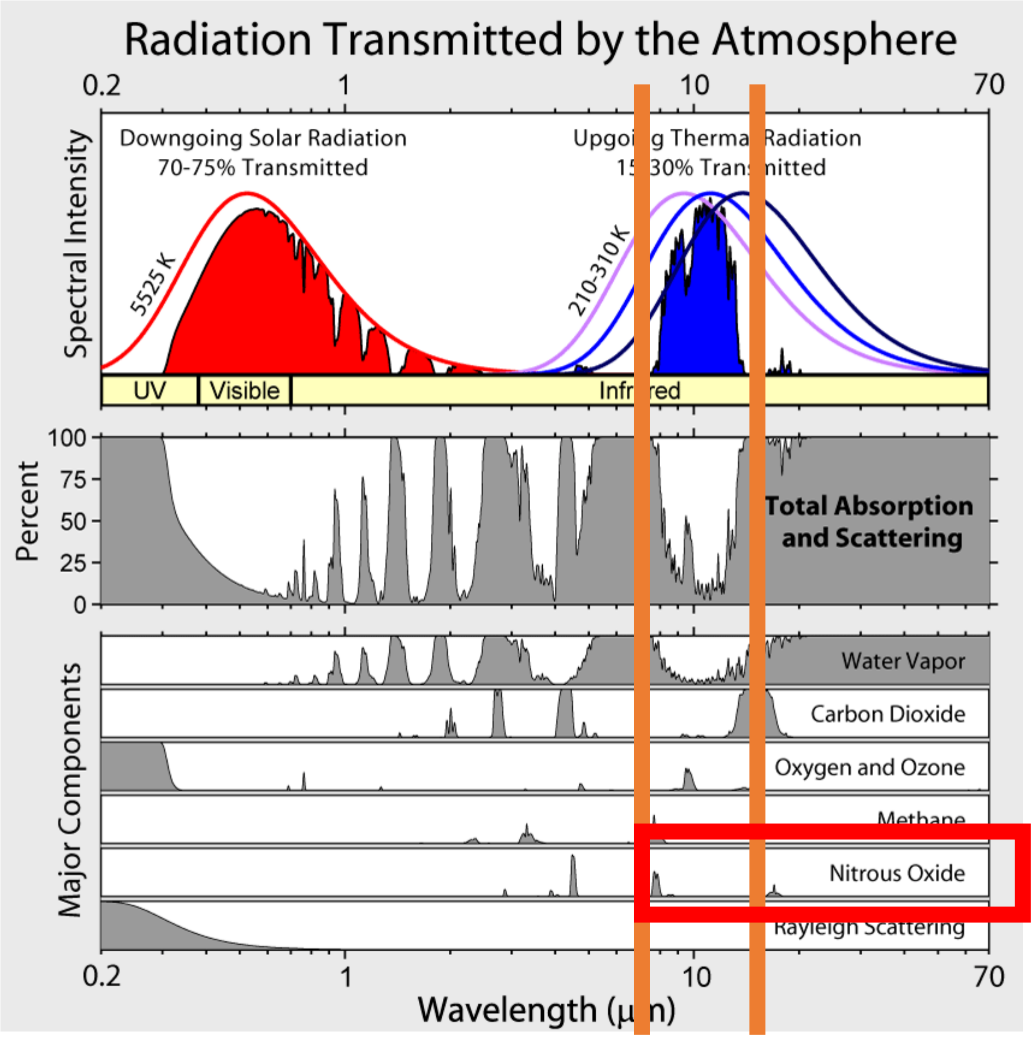


From agriculture and fossil fuel burning

NOAA



Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption
and Scattering



Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (µm)

What might be the ecosystem impacts of fertilizer use?

How do we avoid these?

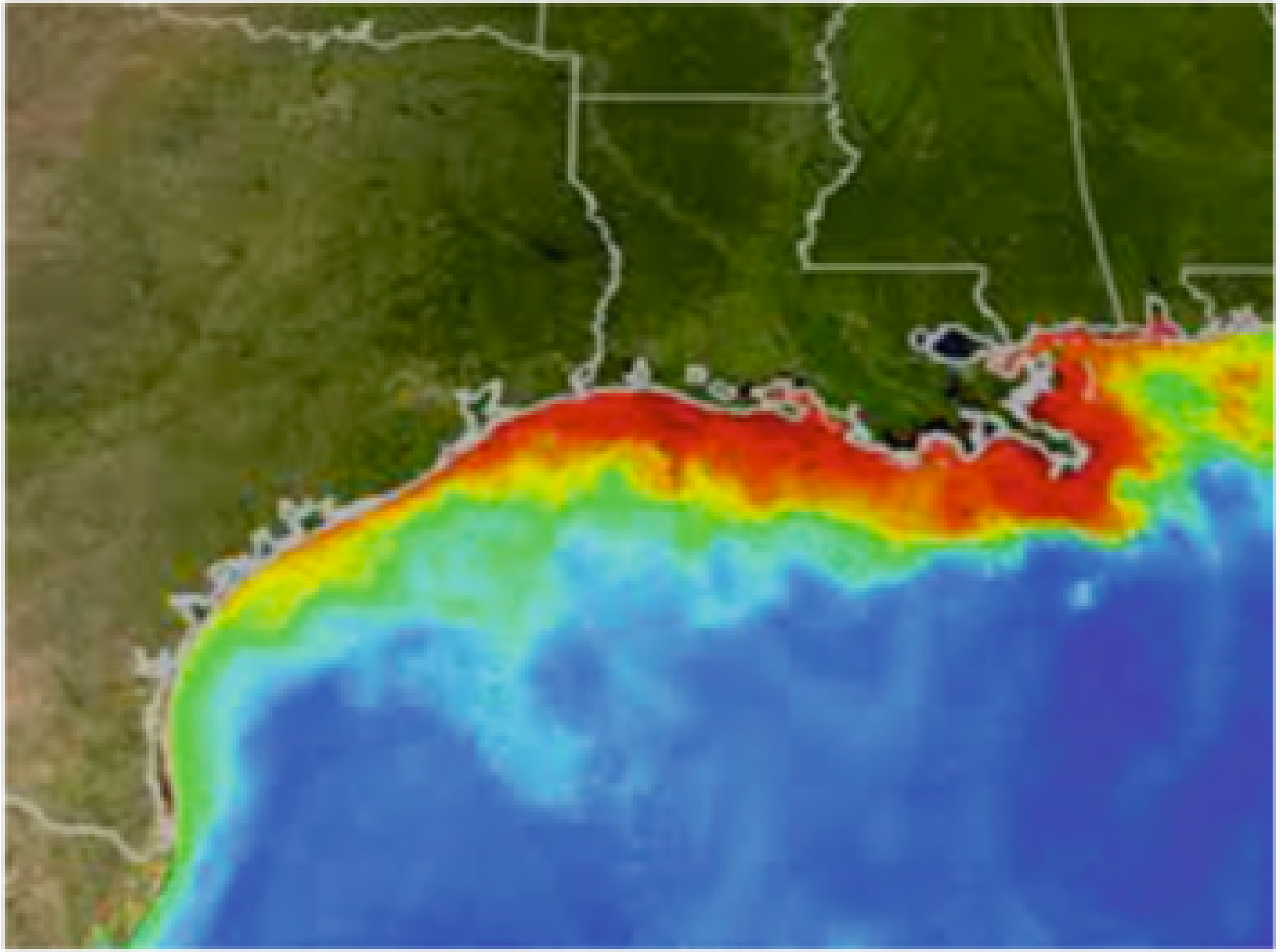
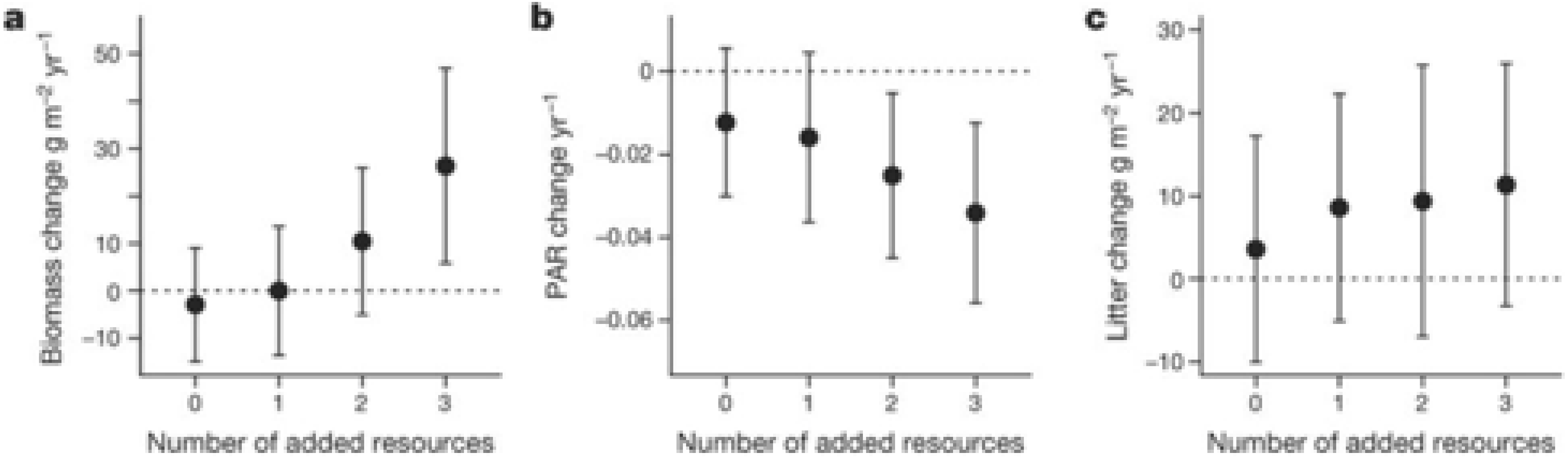
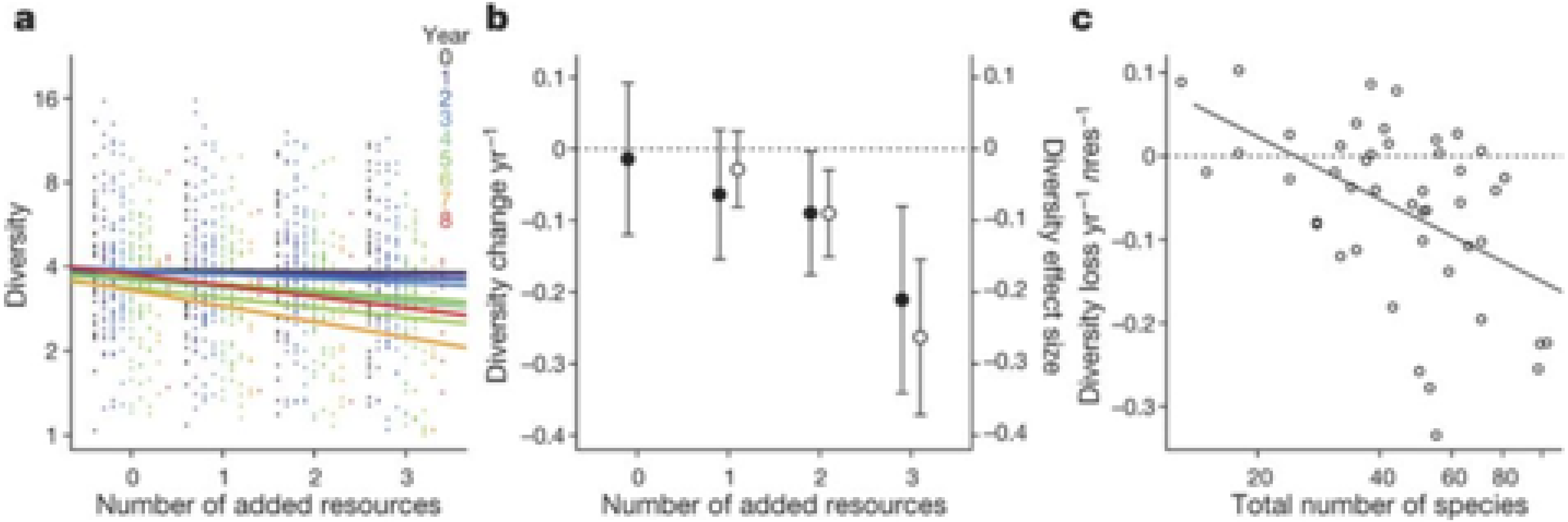


Fig. 9.1 Dead zone in the Gulf of Mexico, magnified by nutrient inputs from agricultural runoff from the Mississippi river drainage. Reds and oranges represent high concentrations of phytoplankton and sediments (http://www.nasa.gov/vision/earth/environment/dead_zone.html)



Harpole et al. (2016)



Harpole et al. (2016)