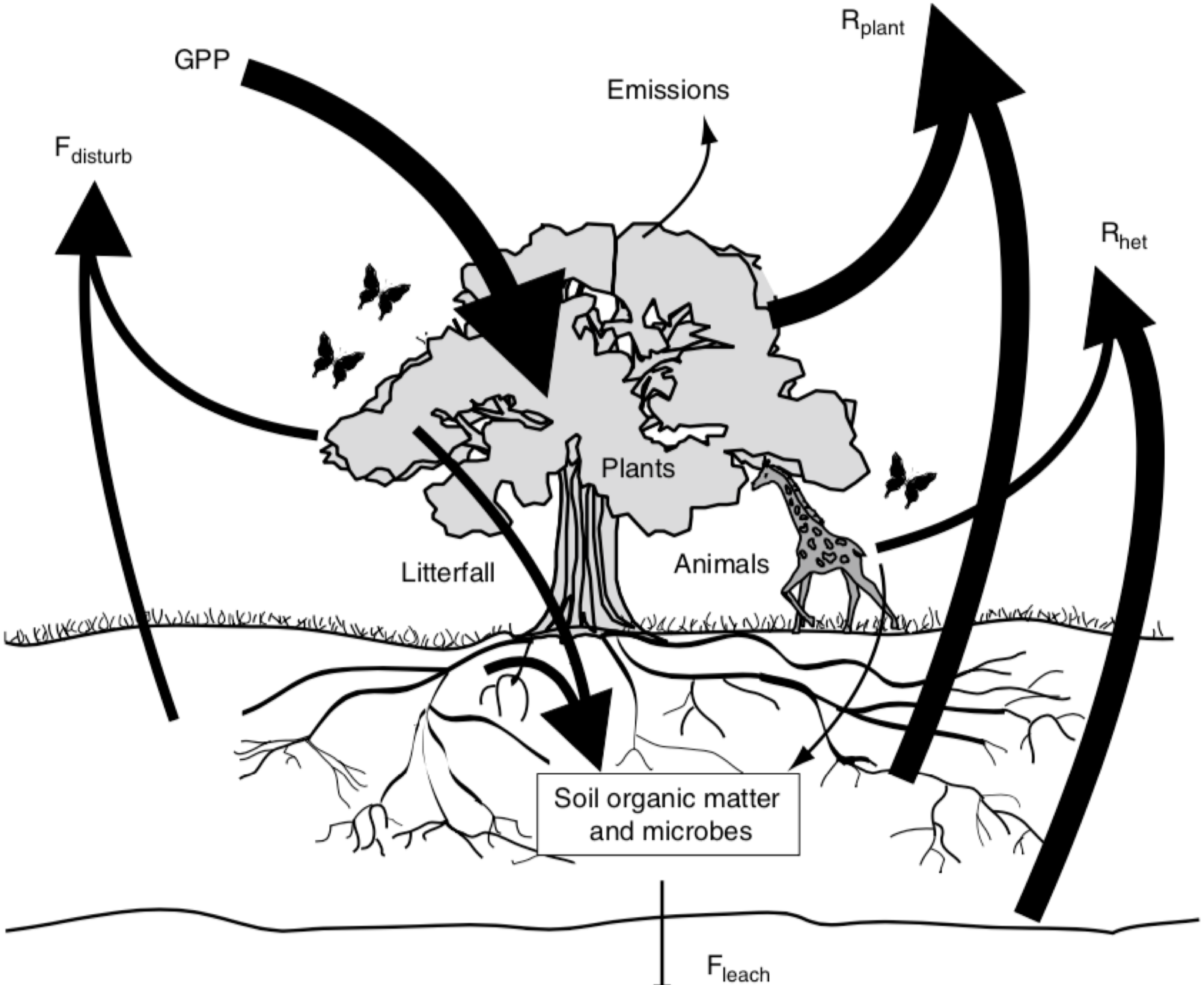
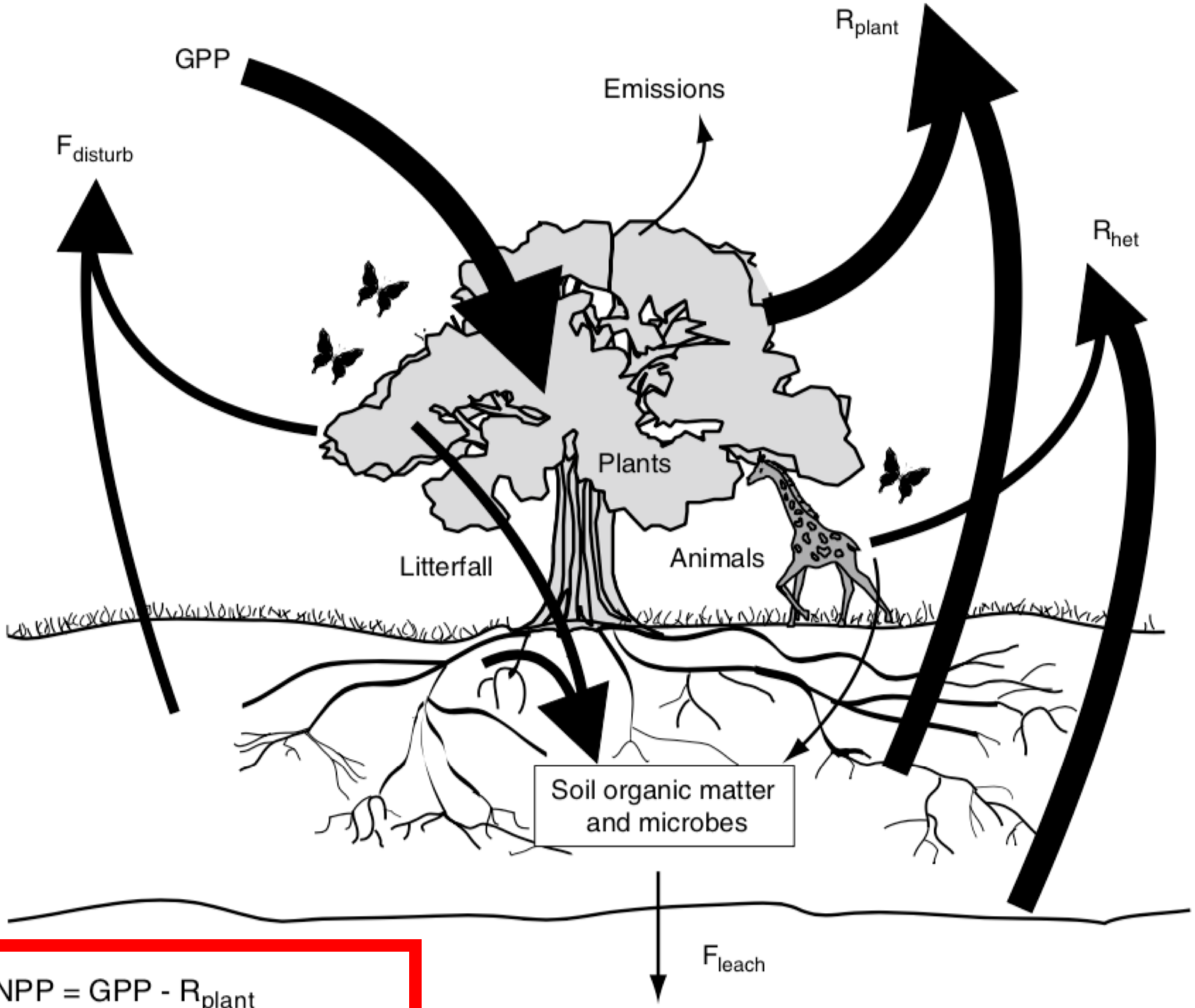
Terrestrial ecosystem C and N cycling

Terrestrial Ecosystem Carbon Cycle



$$NPP = GPP - R_{plant}$$

$$NEP = GPP - (R_{plant} + R_{het})$$



Terrestrial Ecosystem Carbon Cycle

$NPP = GPP - R_{plant}$

$NEP = GPP - (R_{plant} + R_{het})$

$$NPP = GPP - R_{plant}$$

Net Primary Productivity (C into plants – C out of plants; per ground area)

$$\boxed{NPP} = GPP - R_{plant}$$

Gross Primary Productivity (total flux of C into plants; per ground area)

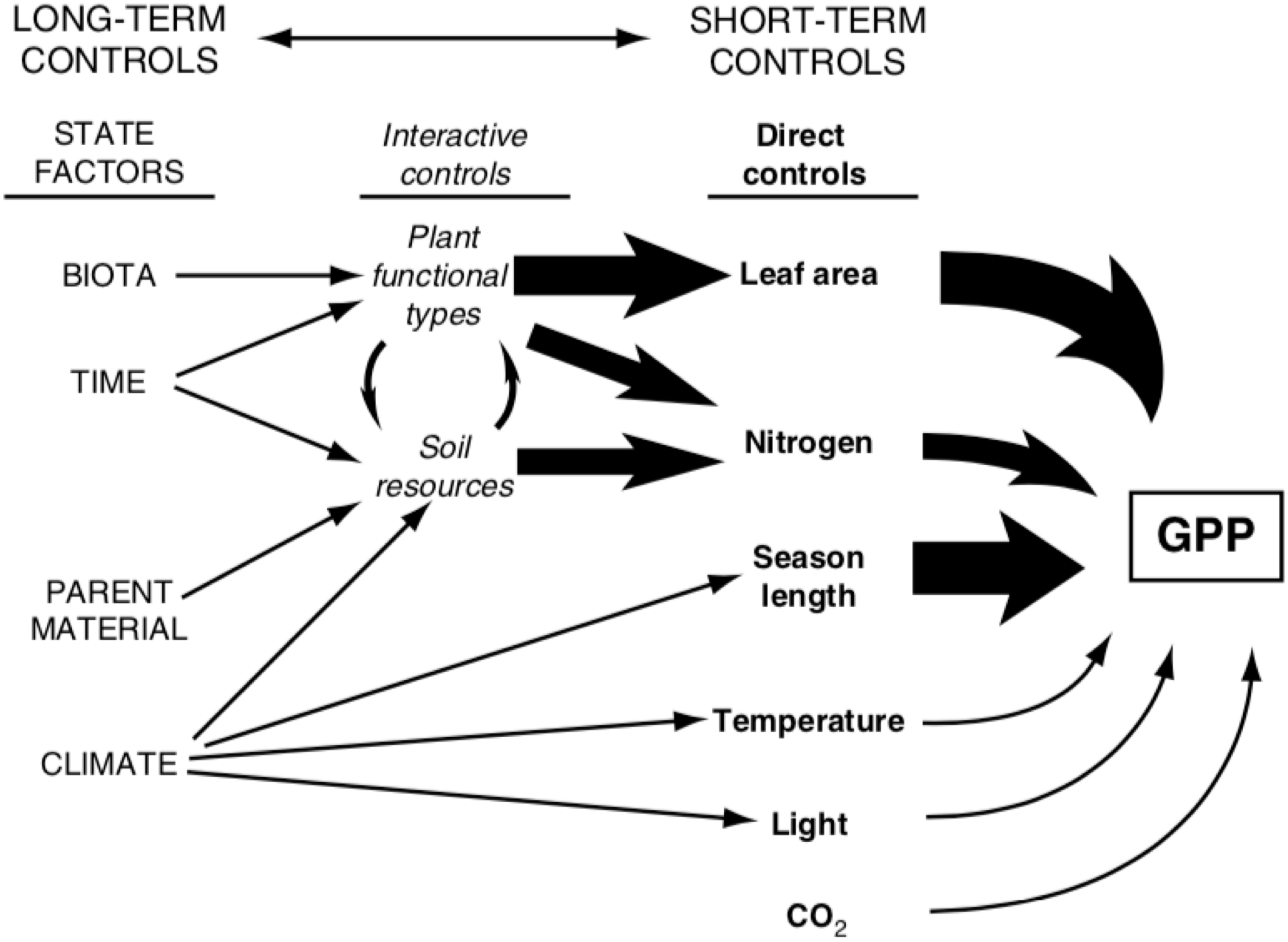
$$NPP = \boxed{GPP} - R_{plant}$$

Plant Respiration (total flux of C out of plants ; per ground area)

$$NPP = GPP - \boxed{R_{plant}}$$

Gross Primary Productivity (total flux of C into plants; per ground area)

$$NPP = \boxed{GPP} - R_{plant}$$



LONG-TERM CONTROLS
SHORT-TERM CONTROLS
STATE FACTORS
Interactive controls
Direct controls
BIOTA
TIME
PARENT MATERIAL
CLIMATE
Plant functional types
Soil resources
Leaf area
Nitrogen
Season length
Temperature
Light
CO_2
GPP

GPP = photosynthesis * LAI

Carbon in to leaves (per leaf area)

$$GPP = \boxed{\text{photosynthesis}} * LAI$$

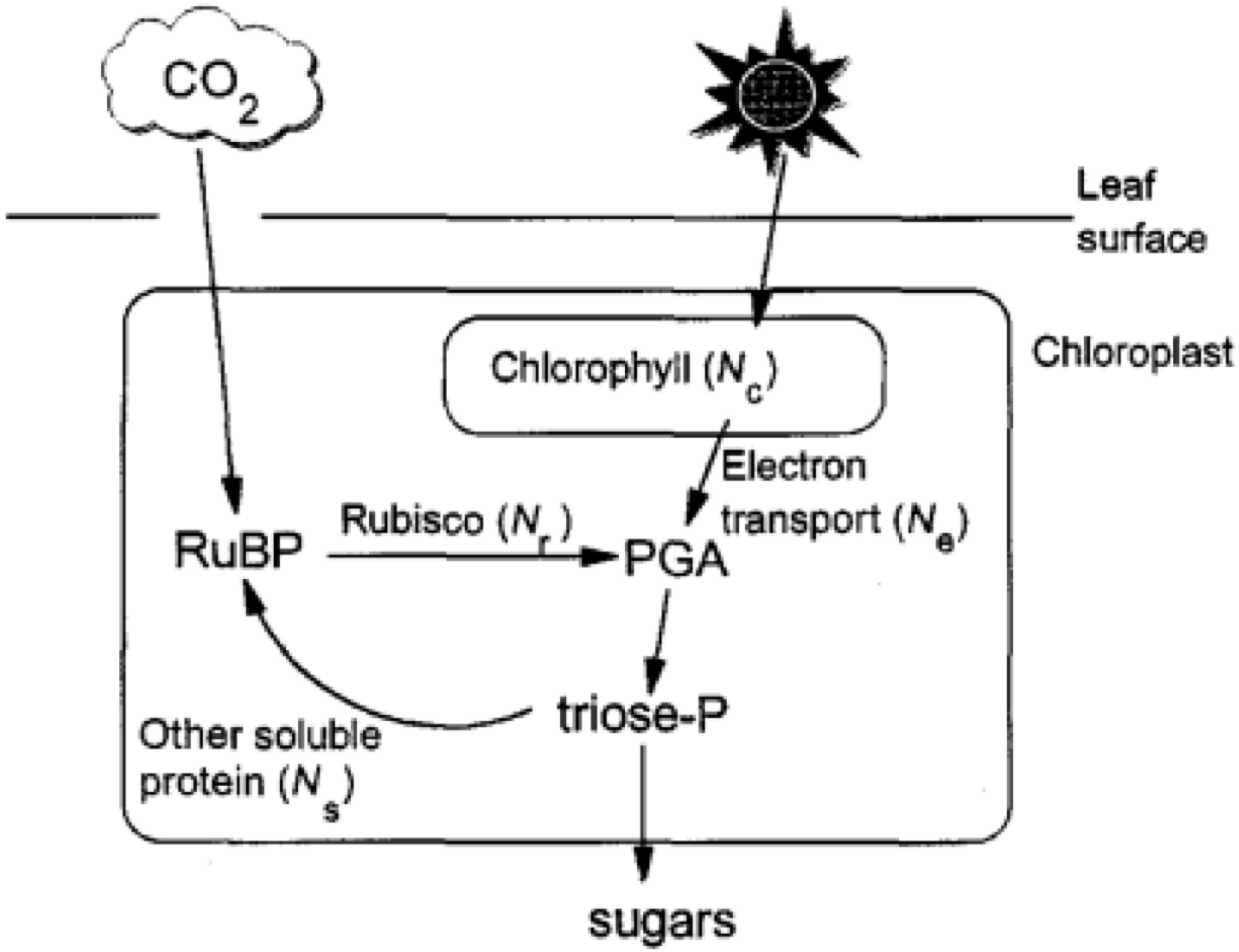
Leaf area index (leaf area per ground area)

$$GPP = photosynthesis * \boxed{LAI}$$

Carbon in to leaves (per leaf area)

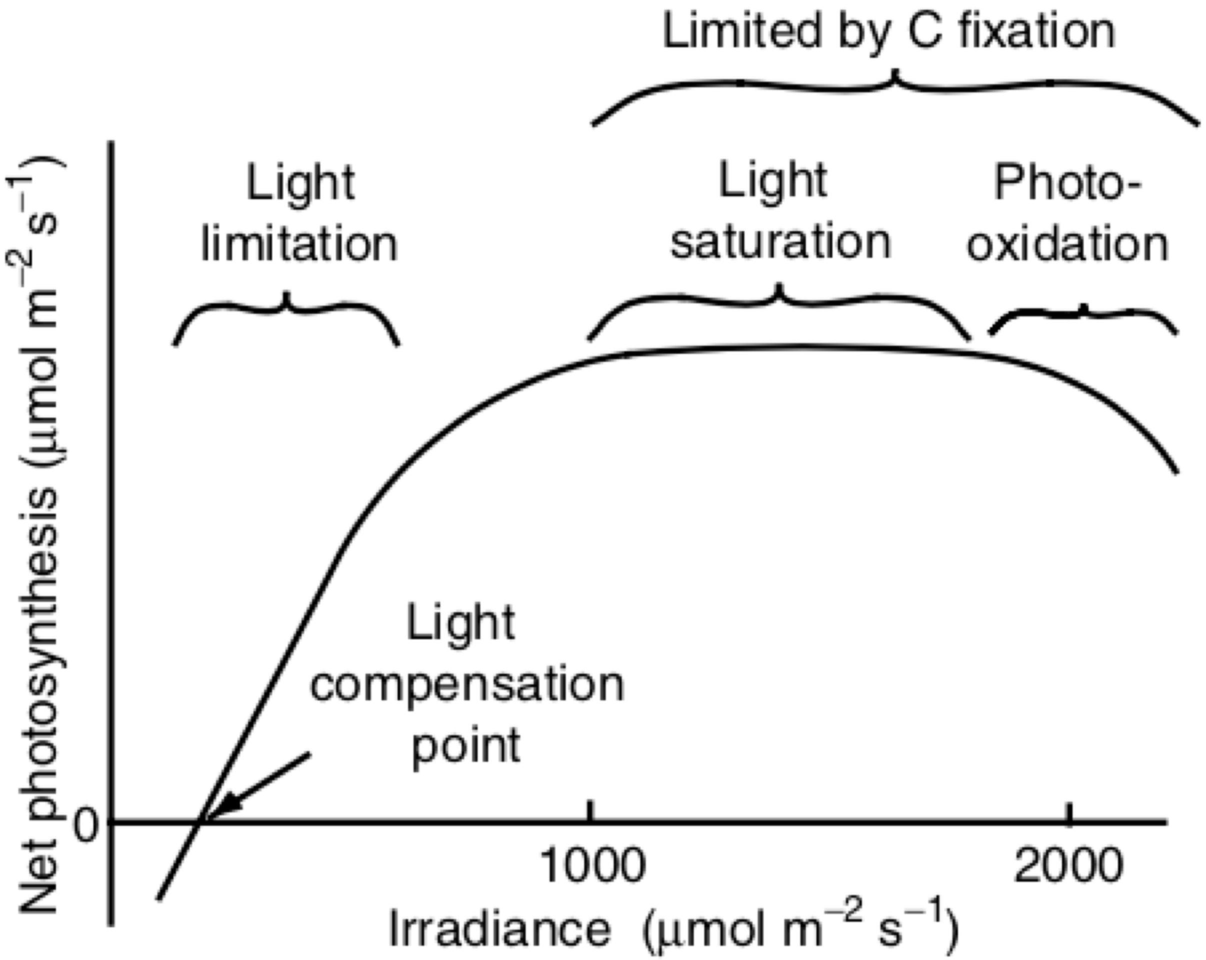
$$GPP = \boxed{\text{photosynthesis}} * LAI$$

Simple recap of photosynthesis

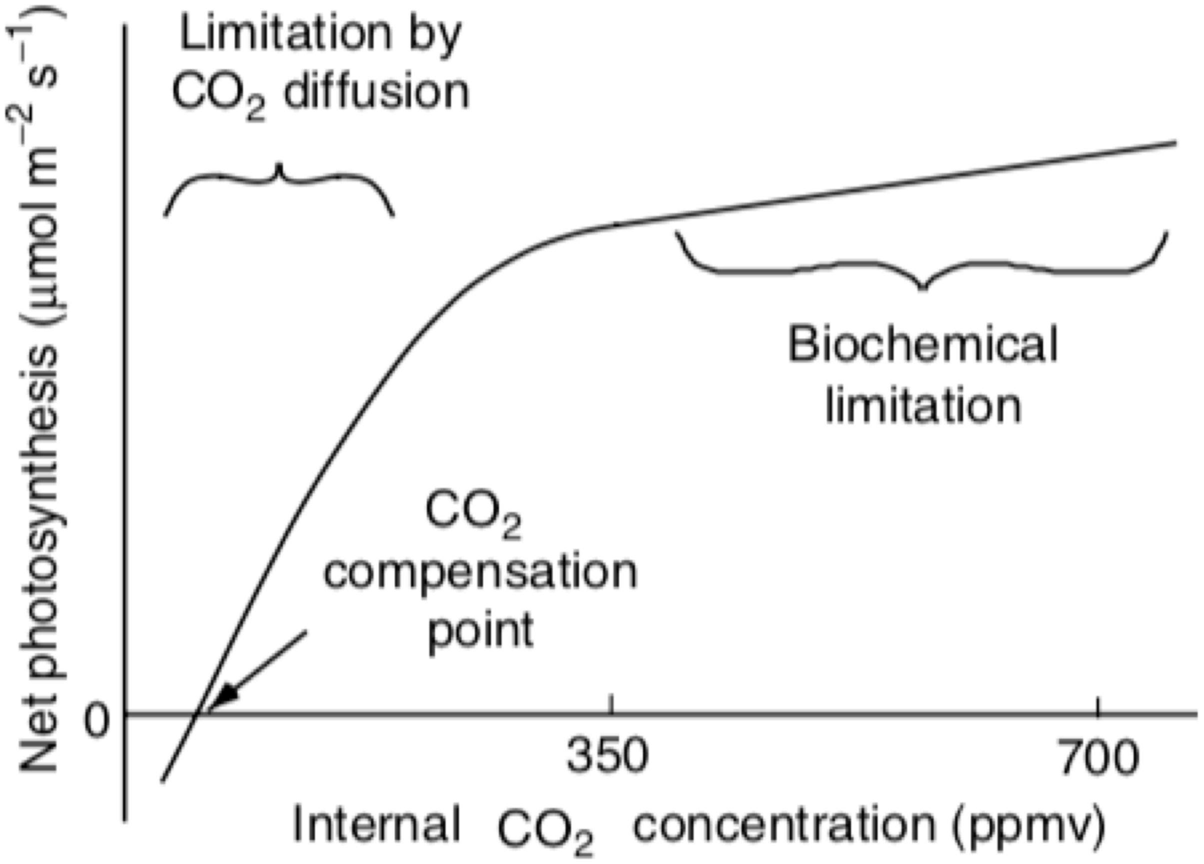


Medlyn 1996

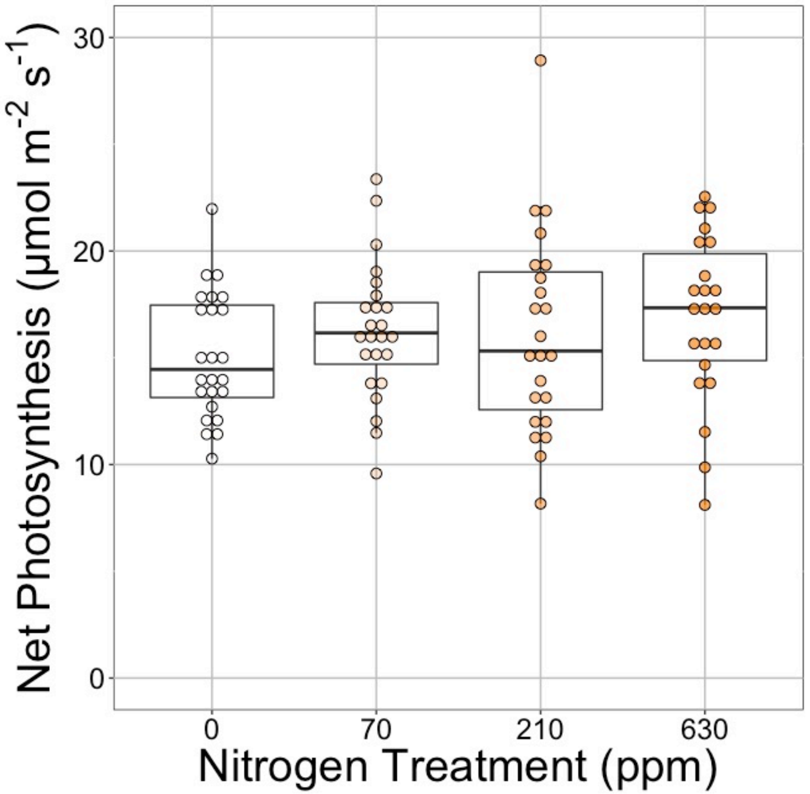
Environmental responses - light



Environmental responses – CO_2

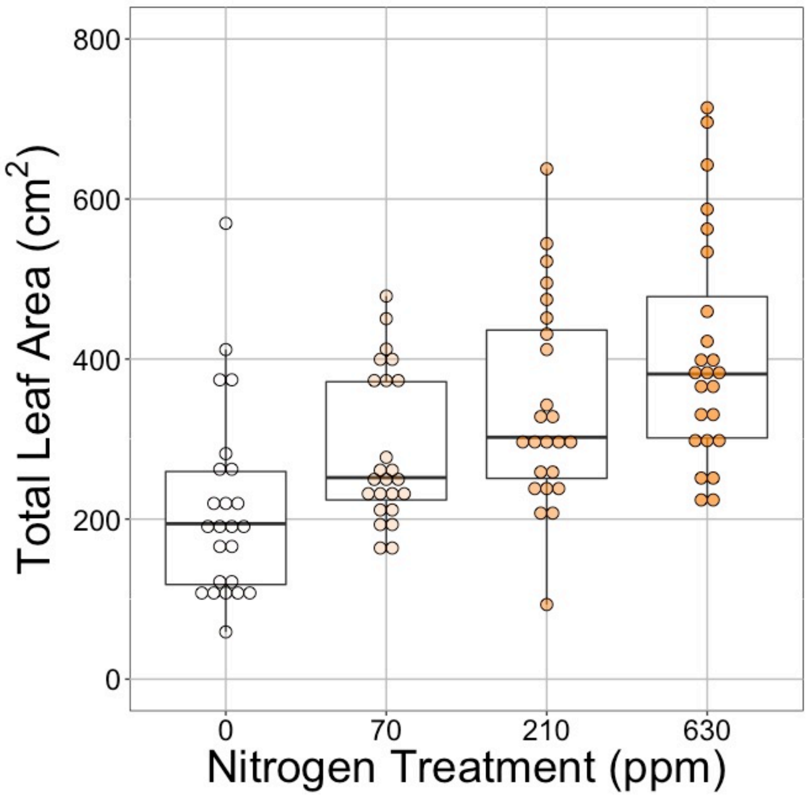


Photosynthesis is less responsive to soil resources (water and nutrients). Why?



Waring et al. (2023)

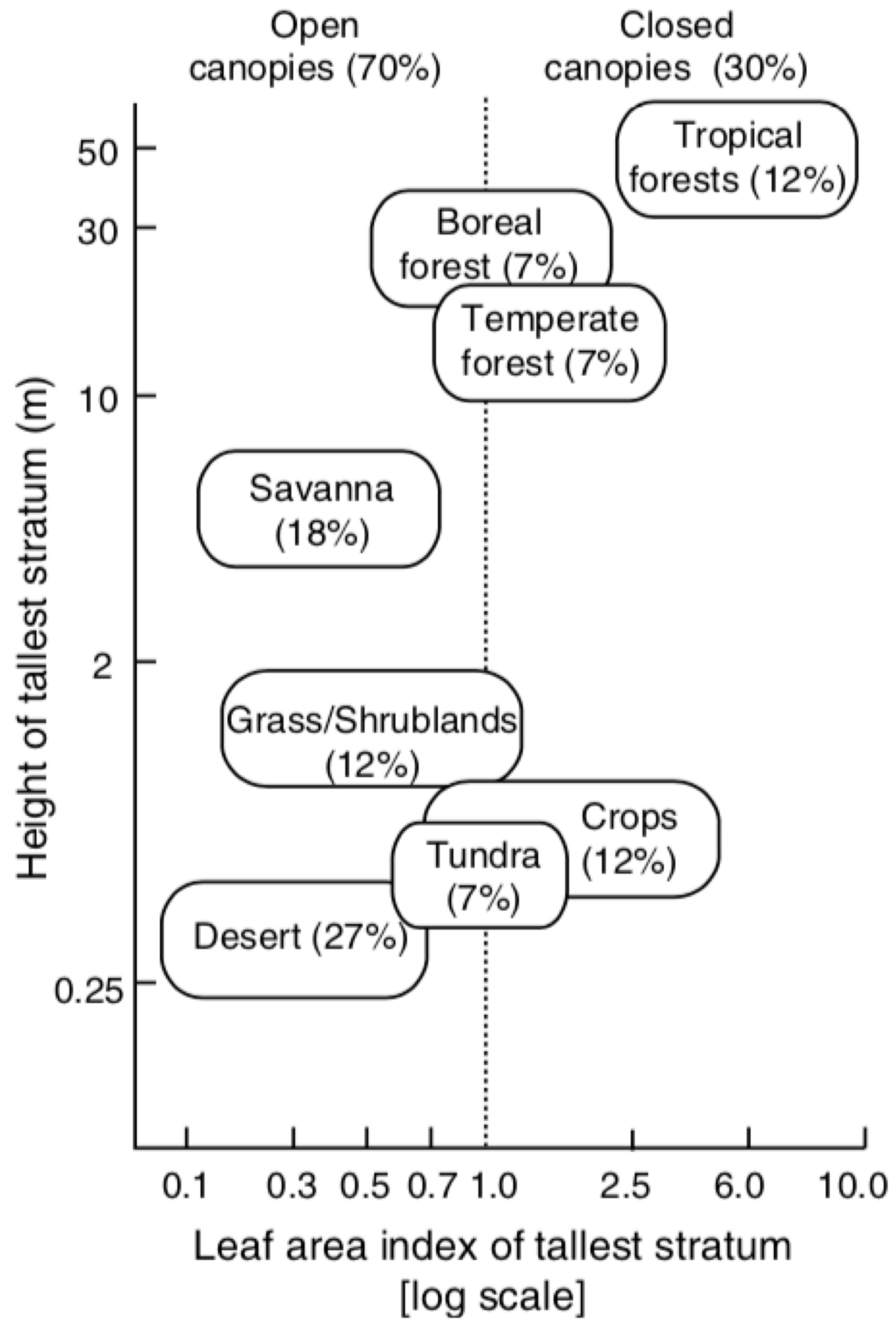
Photosynthesis is less responsive to soil resources (water and nutrients). Why?



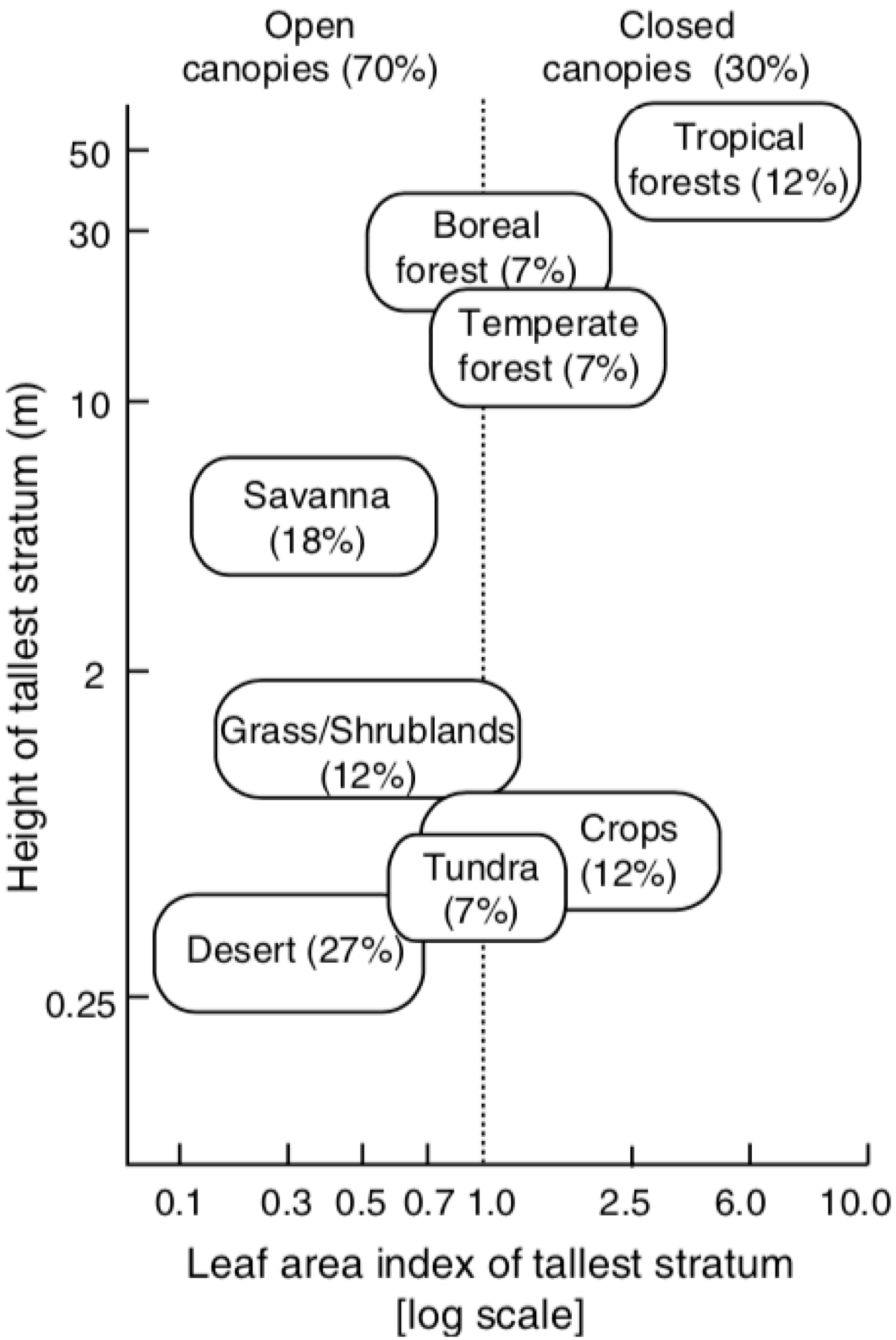
Waring et al. (2023)

Leaf area index (leaf area per ground area)

$$GPP = photosynthesis * \boxed{LAI}$$

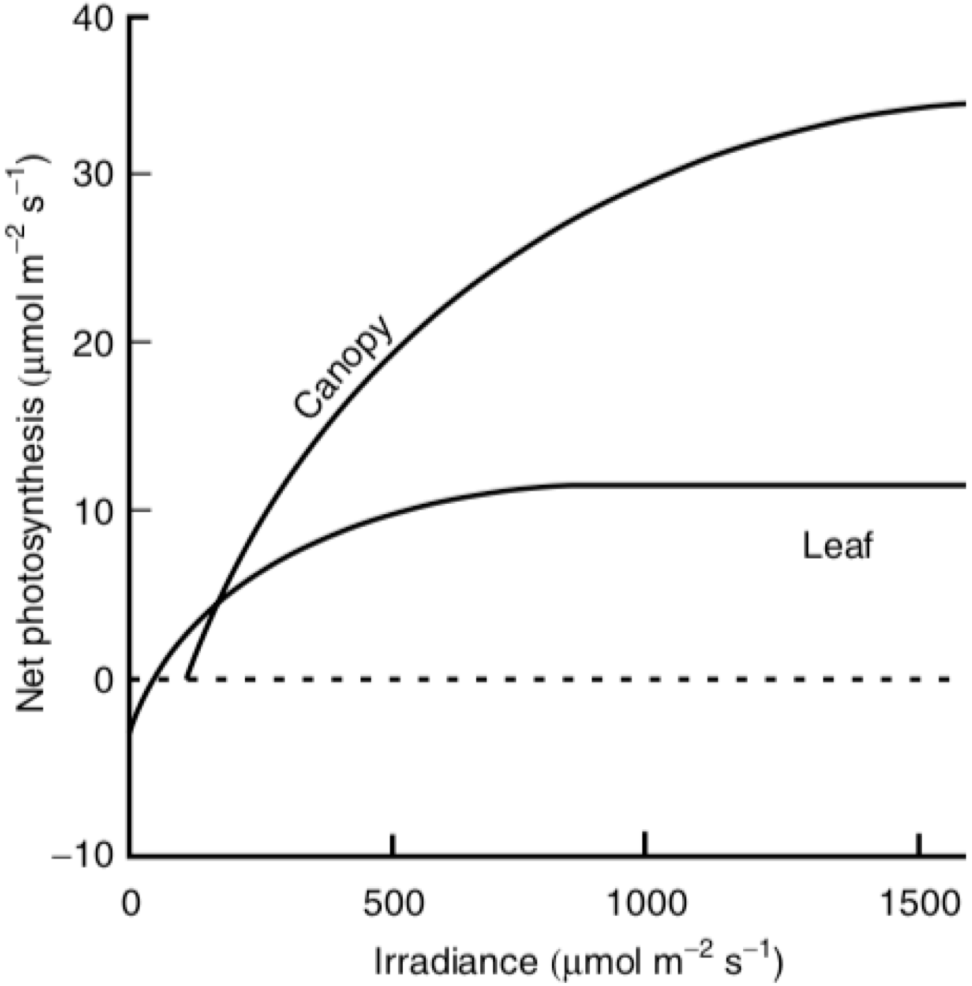


What's driving the x-axis distribution?



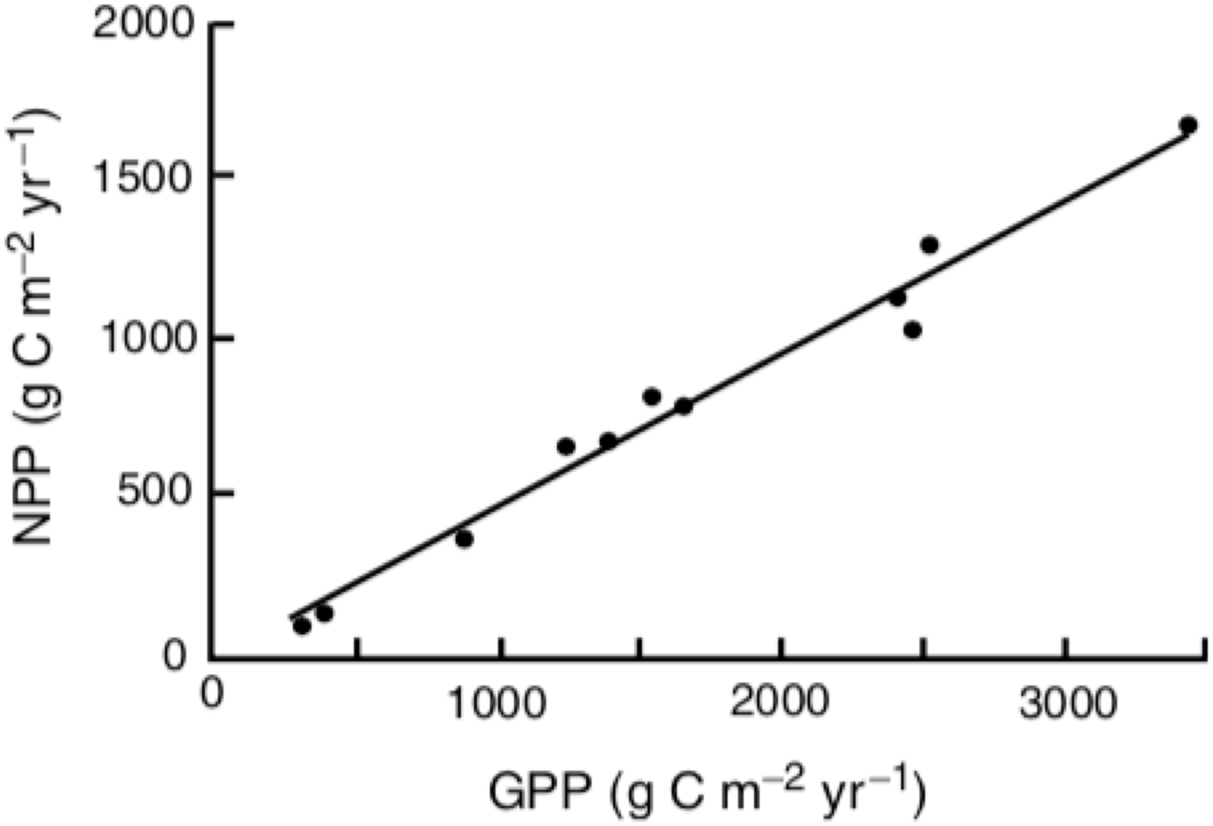
What's driving the y-axis distribution?

Canopies tend to have higher light use efficiency than leaves



Plant Respiration (total flux of C out of plants ; per ground area)

$$NPP = GPP - \boxed{R_{plant}}$$



NPP = GPP – 0.47*GPP

Originally proposed by Waring (1998)

JOURNAL ARTICLE

Is NPP proportional to GPP? Waring's hypothesis 20 years on

A Collalti, I C Prentice

Tree Physiology, Volume 39, Issue 8, August 2019, Pages 1473–1483,
https://doi.org/10.1093/treephys/tpz034

Published: 17 May 2019 **Article history** ▾

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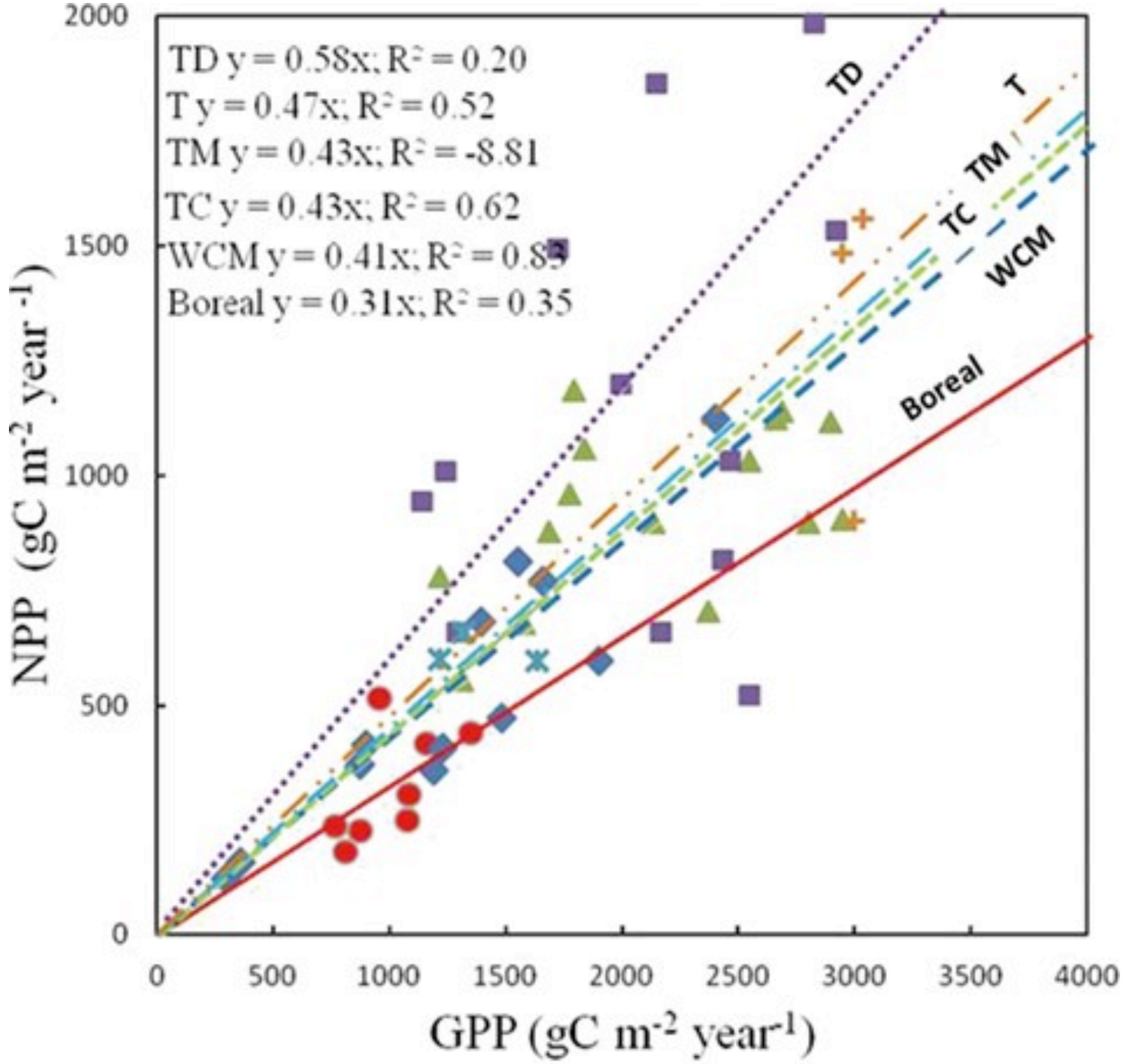
Abstract

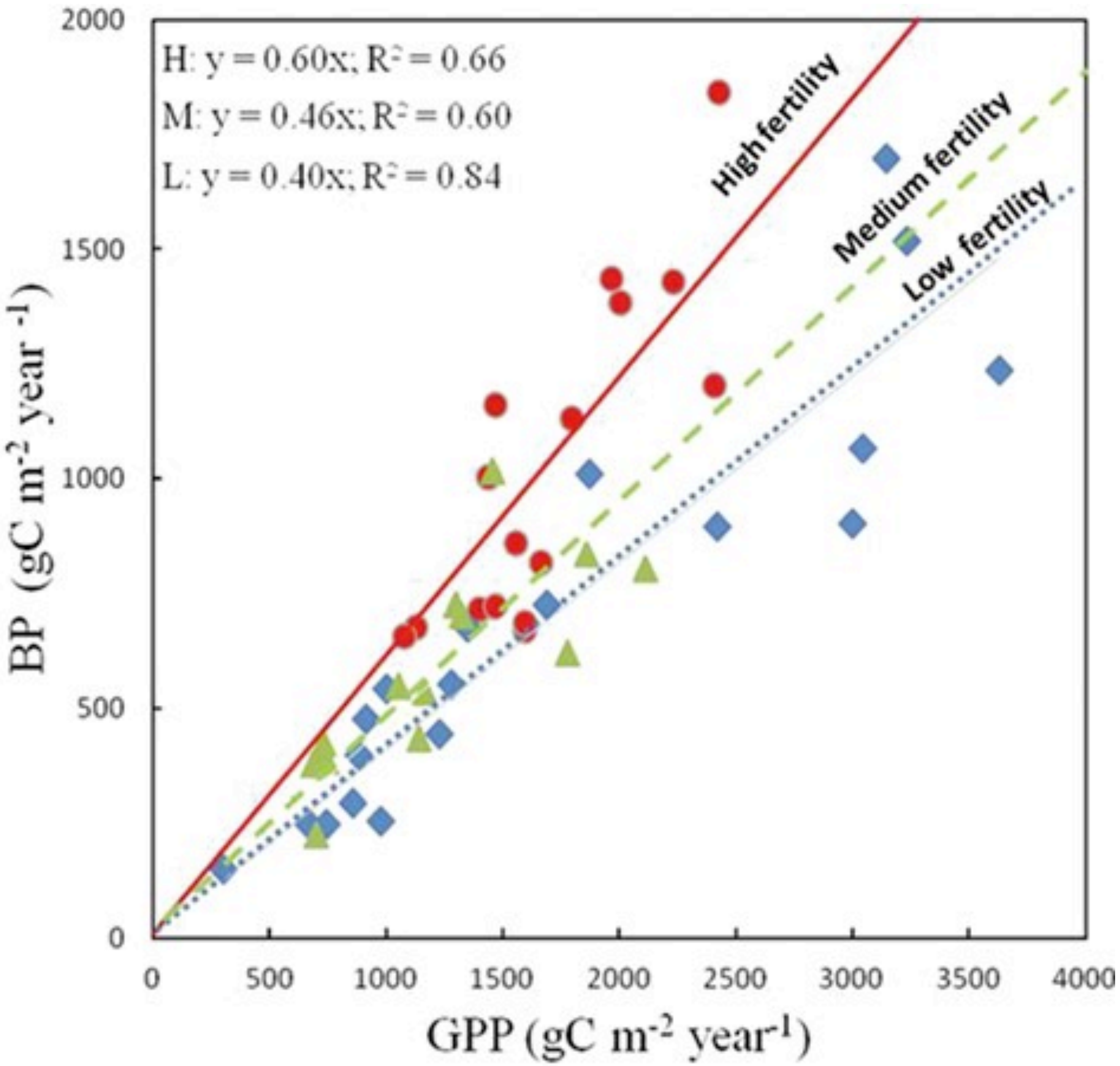
Gross primary production (GPP) is partitioned to autotrophic respiration (R_a) and net primary production (NPP), the latter being used to build plant tissues and synthesize non-structural and secondary compounds. Waring et al. (1998; Net primary production of forests: a constant fraction of gross primary production? *Tree Physiol* 18:129–134) suggested that a NPP:GPP ratio of 0.47 ± 0.04 (SD) is universal across biomes, tree species and stand ages. Representing NPP in models as a fixed fraction of GPP, they argued, would be both simpler and more accurate than trying to simulate R_a mechanistically. This paper reviews progress in understanding the NPP:GPP ratio in forests during the 20 years since the Waring et al. paper. Research has confirmed the existence of pervasive acclimation mechanisms that tend to stabilize the NPP:GPP ratio and indicates that R_a should not be modelled independently of GPP. Nonetheless, studies indicate that the value of this ratio is influenced by environmental factors, stand age and management. The average NPP:GPP ratio in over 200 studies, representing different biomes, species and forest stand ages, was found to be 0.46, consistent with the central value that Waring et al. proposed but with a much larger standard deviation (±0.12) and a total range (0.22–0.79) that is too large to be disregarded.

NPP – GPP relationship varies slightly by biome



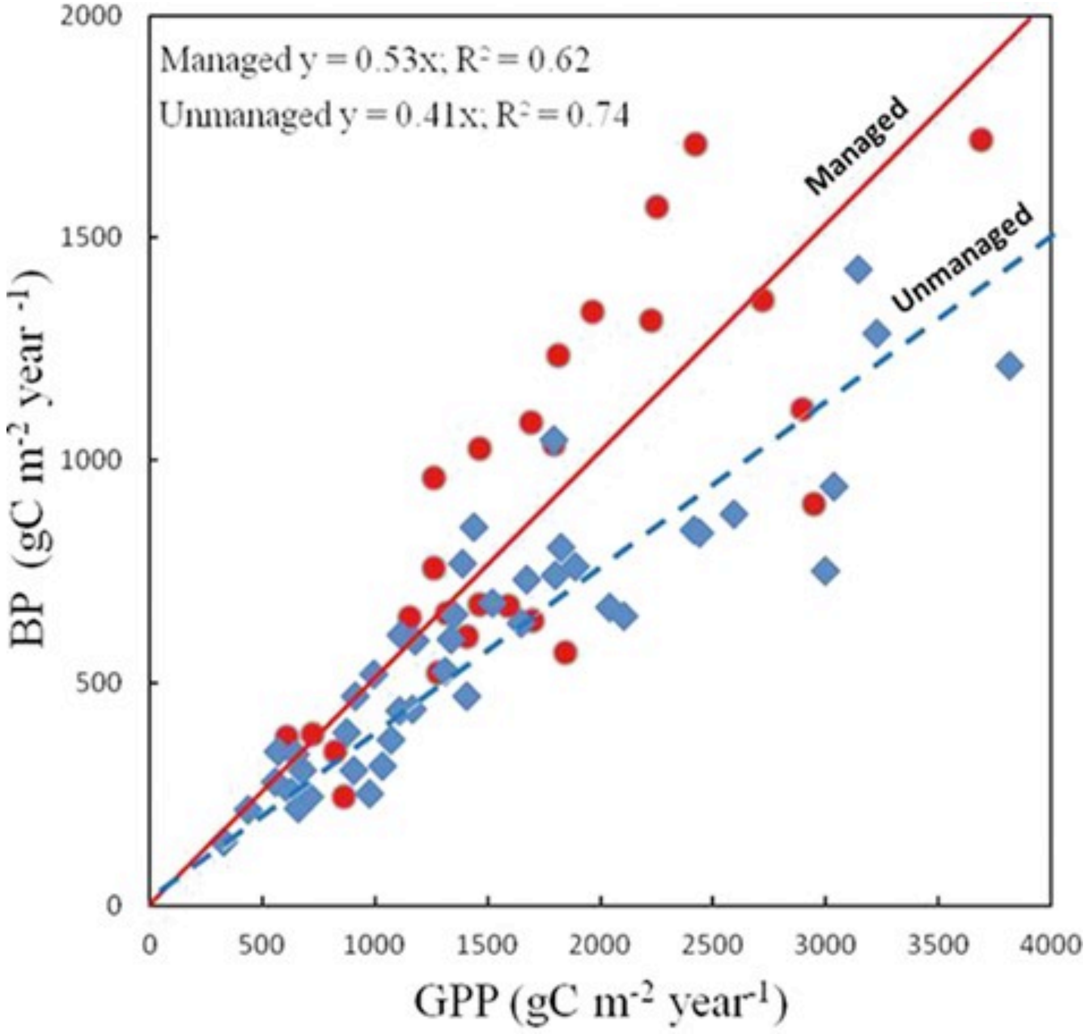
Collalti and Prentice (2019)

NPP – GPP relationship varies slightly by soil resources



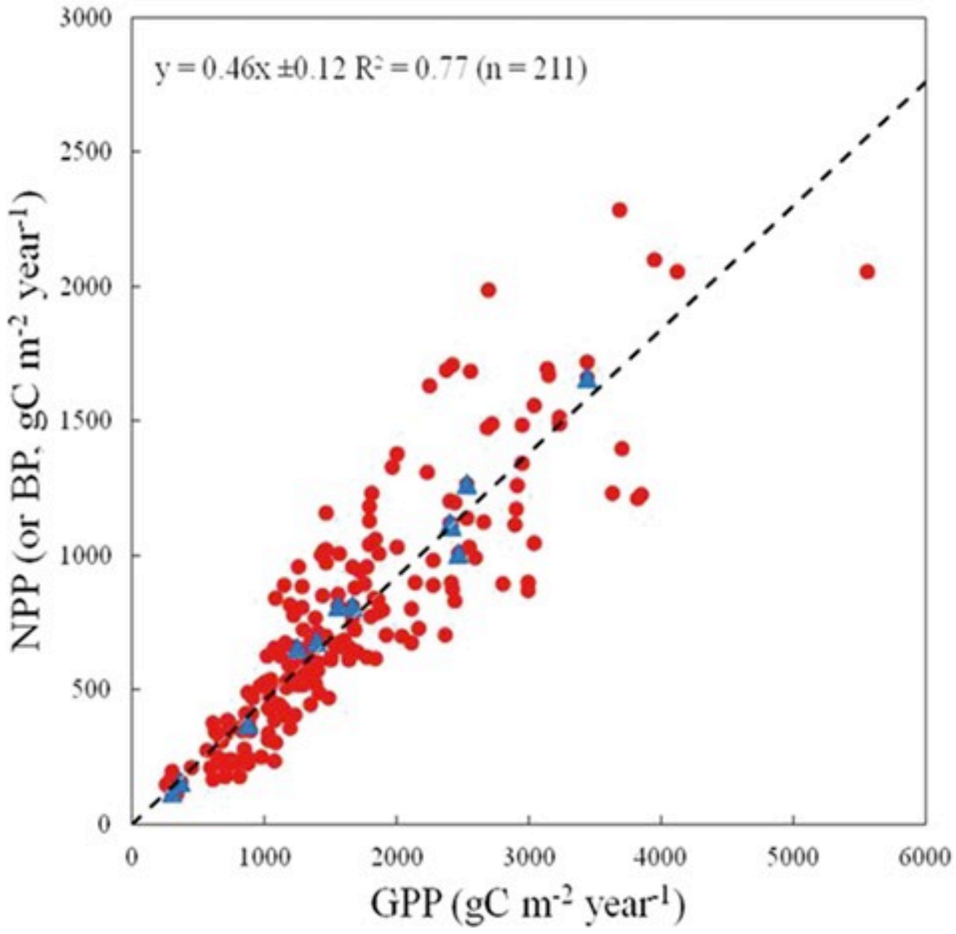
Collalti and Prentice (2019)

NPP – GPP relationship varies slightly by management



Collalti and Prentice (2019)

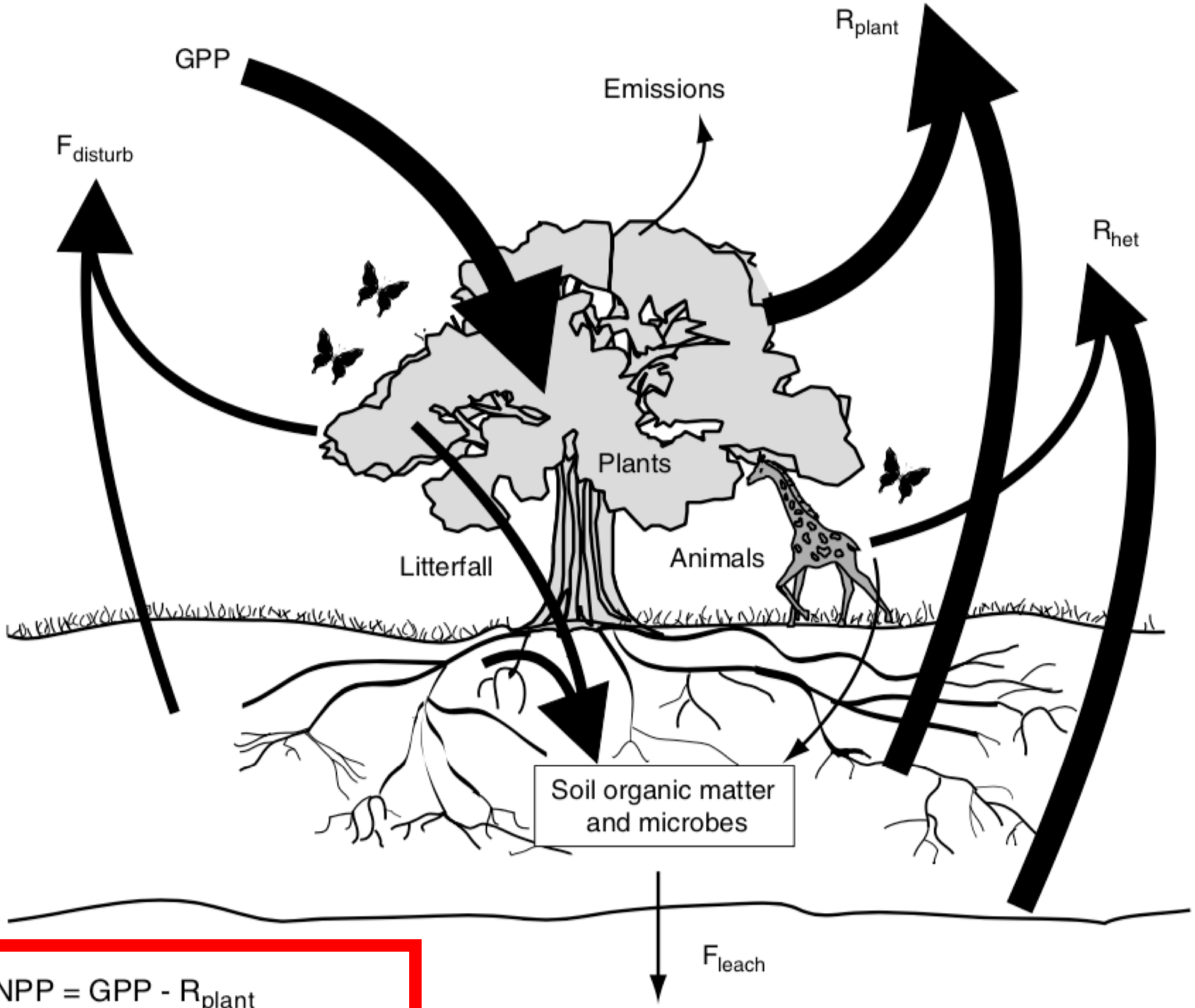
With more data, the relationship on average is still close to Waring’s



Collalti and Prentice (2019)

What drives NPP?

- Over short time scales (seconds to days)
  - Photosynthesis
  - Light, temperature, atmospheric conditions
- Over long time scales (weeks to months)
  - LAI
  - Growth demand
  - Management
  - Soil resources



Terrestrial Ecosystem Carbon Cycle

$$NPP = GPP - R_{plant}$$

$$NEP = GPP - (R_{plant} + R_{het})$$

$$NEP = GPP - (R_{plant} + R_{heterotroph})$$

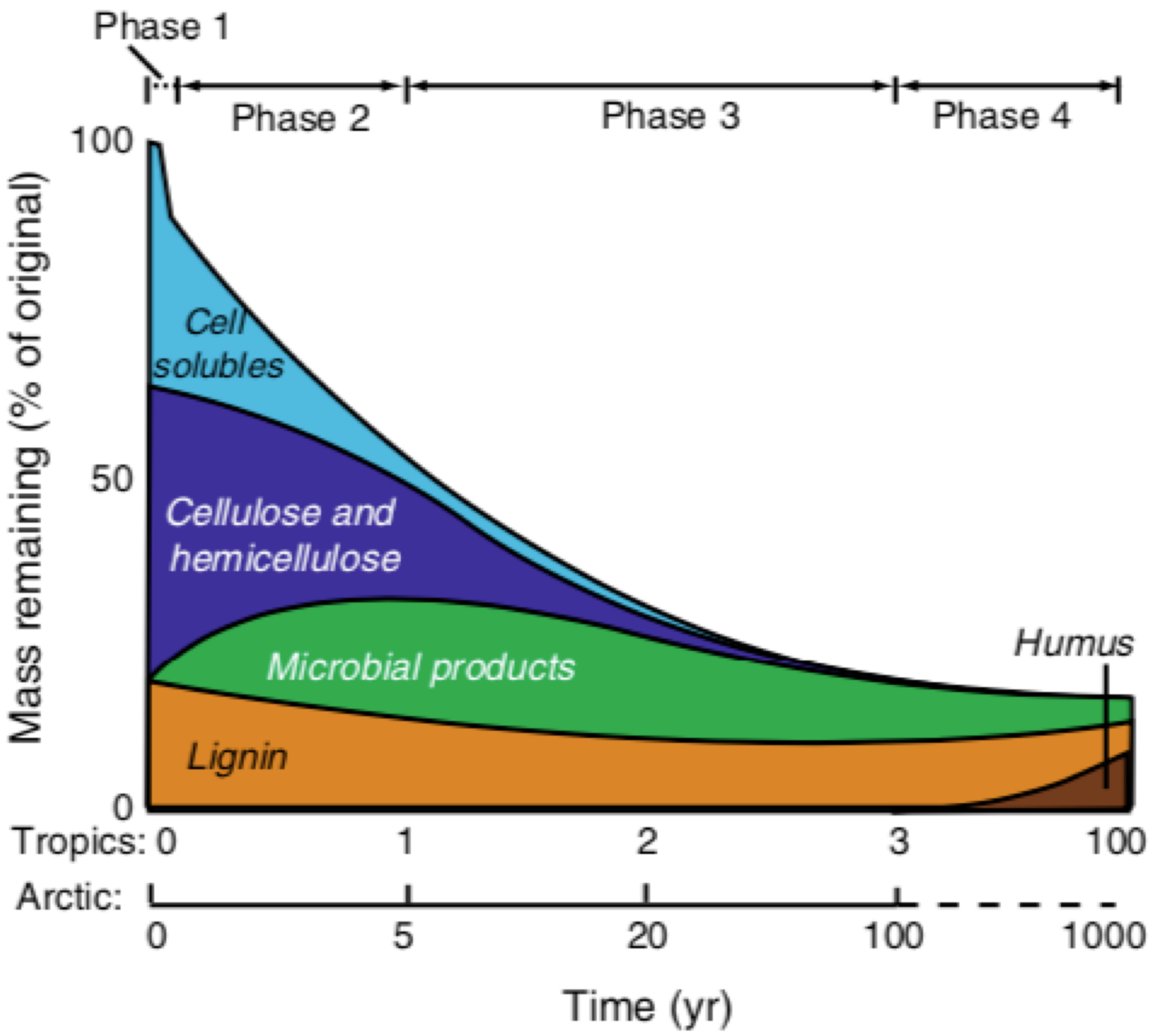
Net ecosystem production (total flux of C into ecosystem; per ground area)

$$\boxed{NEP} = GPP - (R_{plant} + R_{heterotroph})$$

Heterotrophic respiration (C flux out from heterotrophs; per ground area)

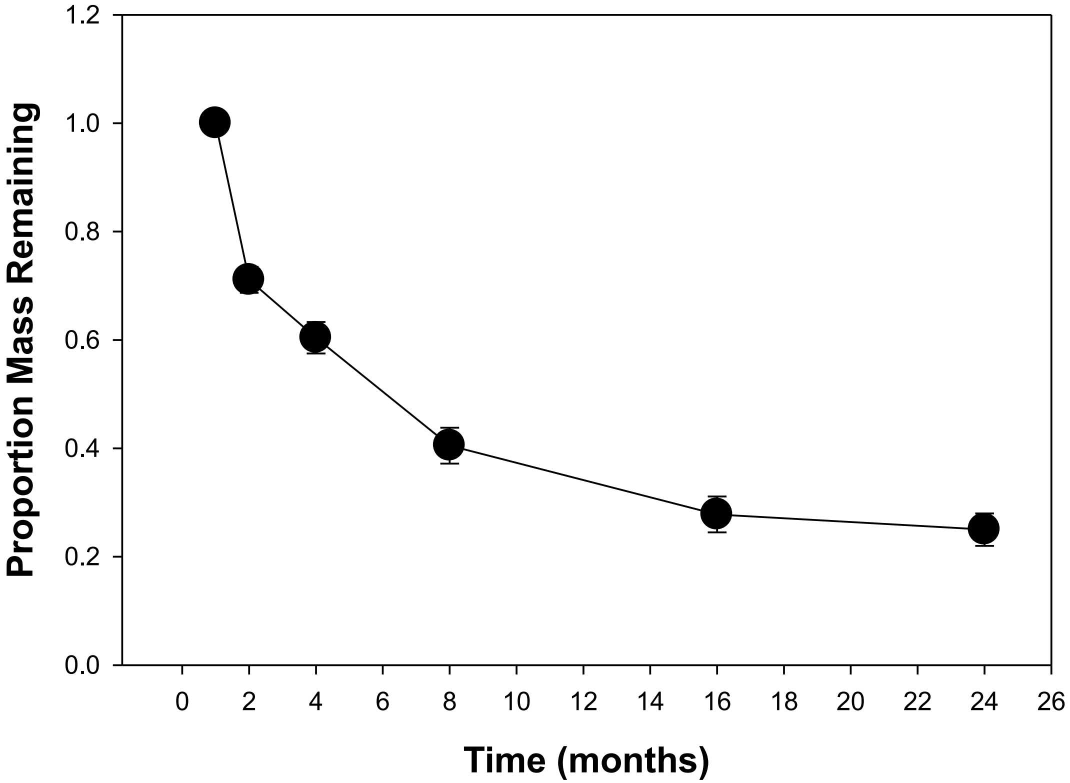
$$NEP = GPP - (R_{plant} + \boxed{R_{heterotroph}})$$

Detritus

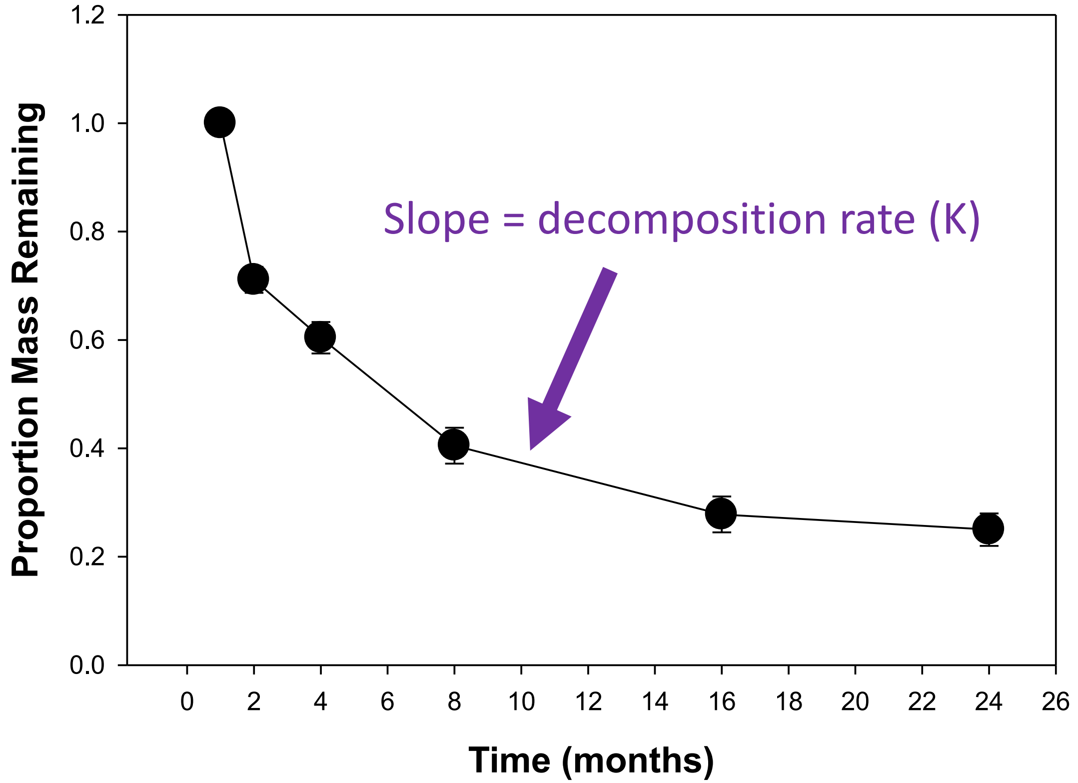


Microbes break down easy stuff before moving to more recalcitrant material

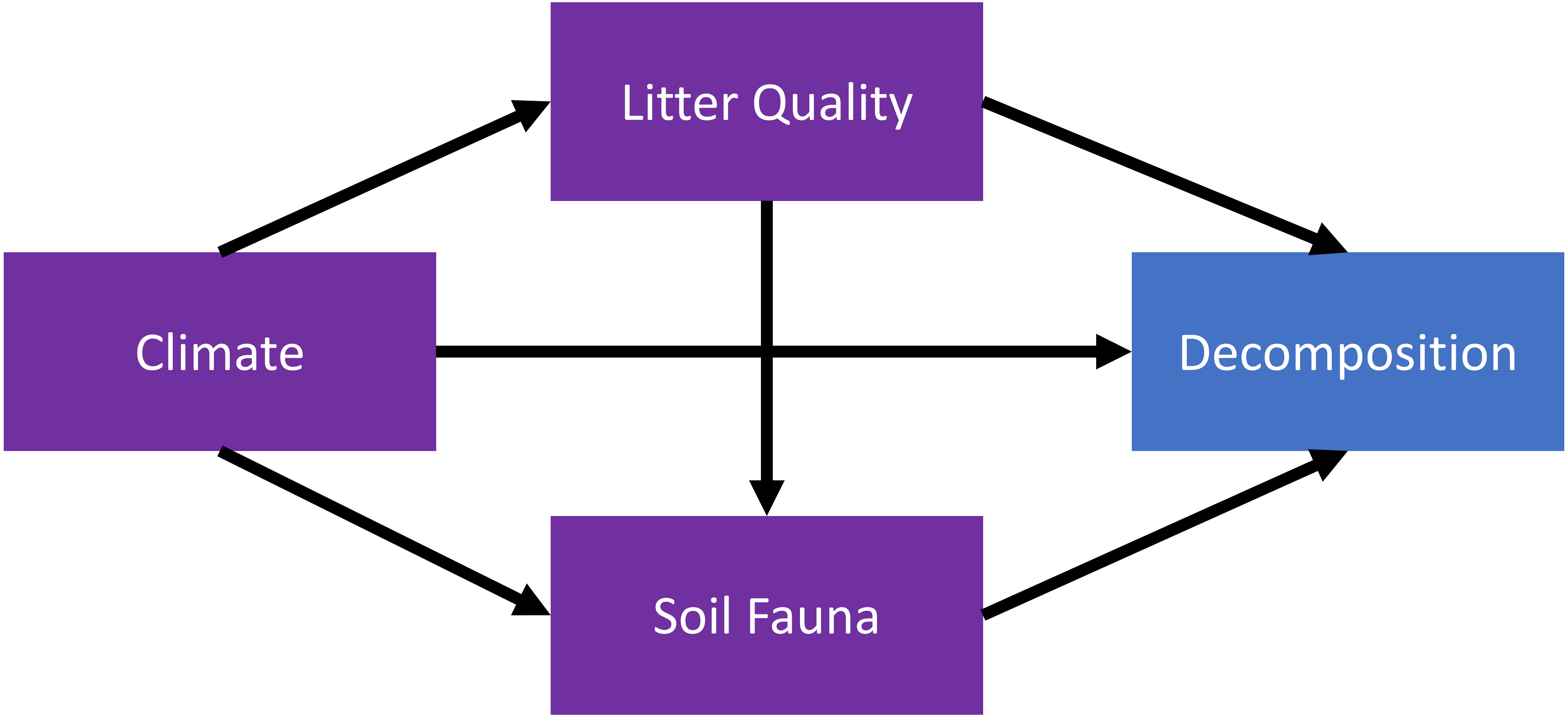
The rate of decomposition



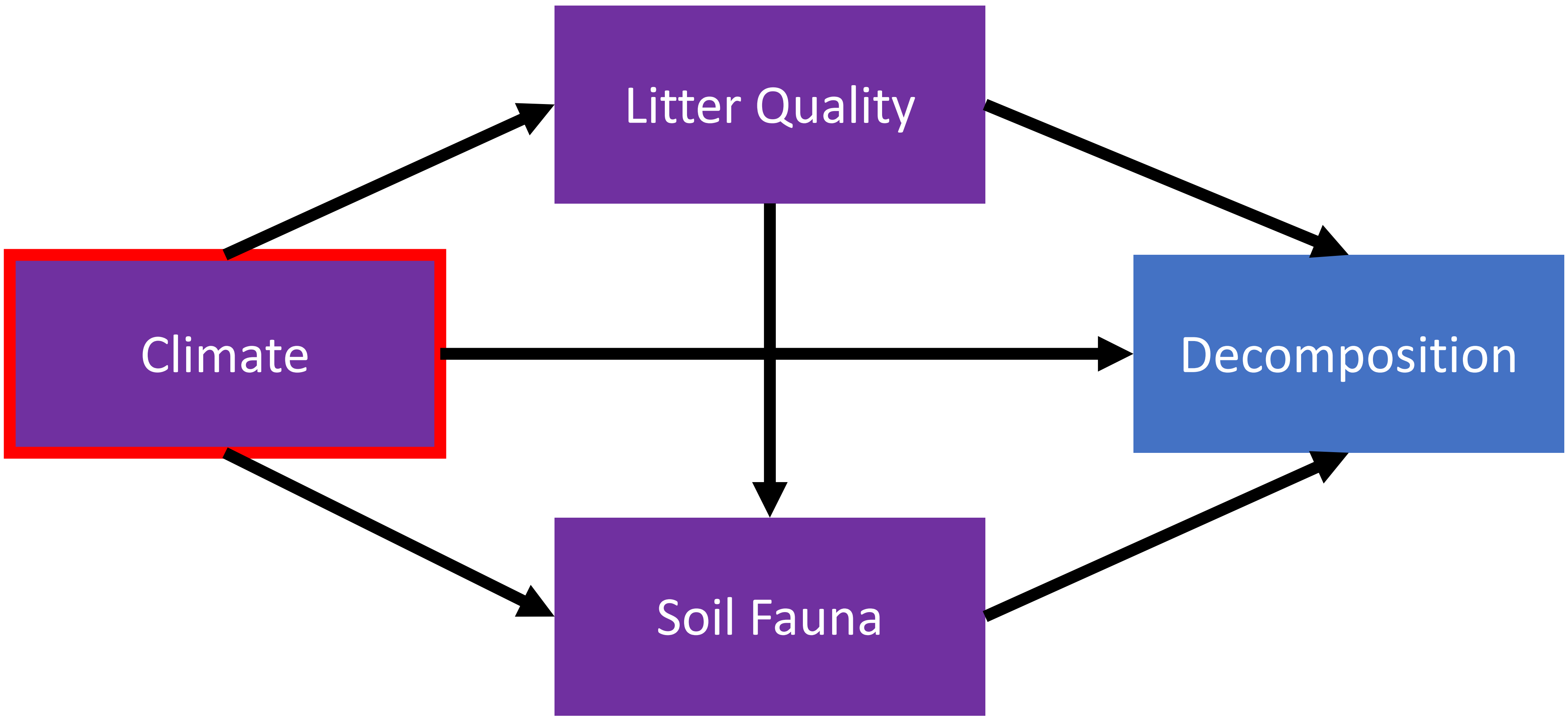
The rate of decomposition



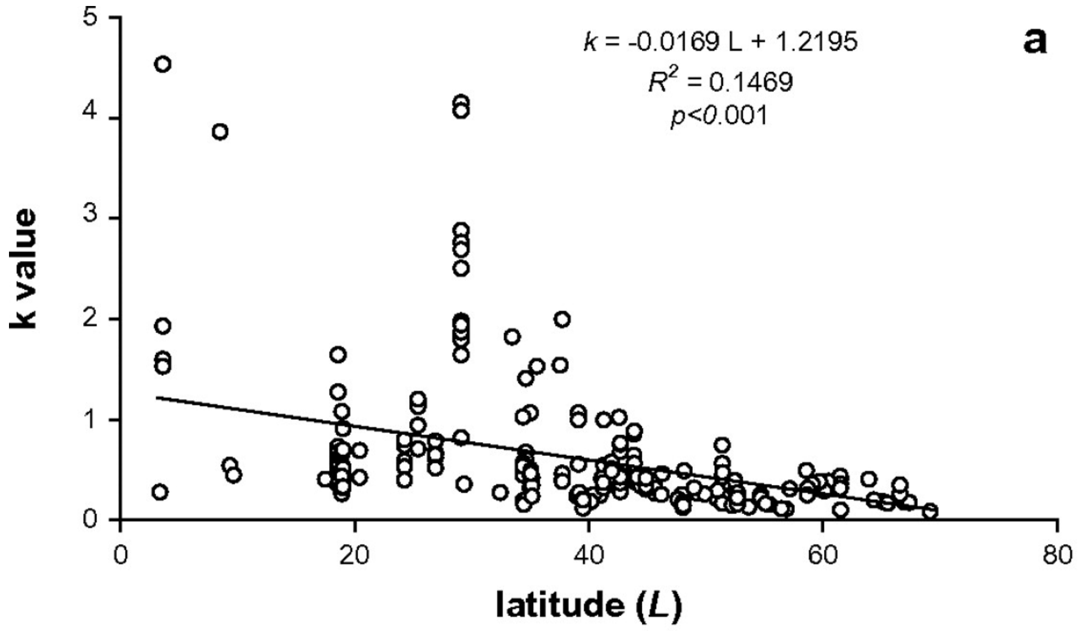
Major controls of decomposition



Major controls of decomposition

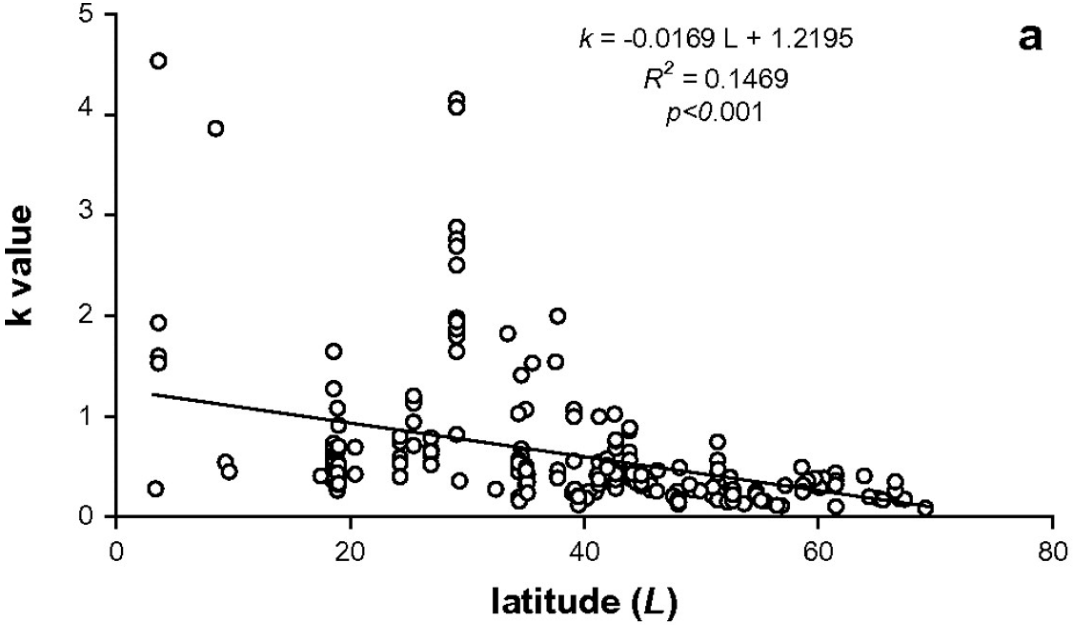


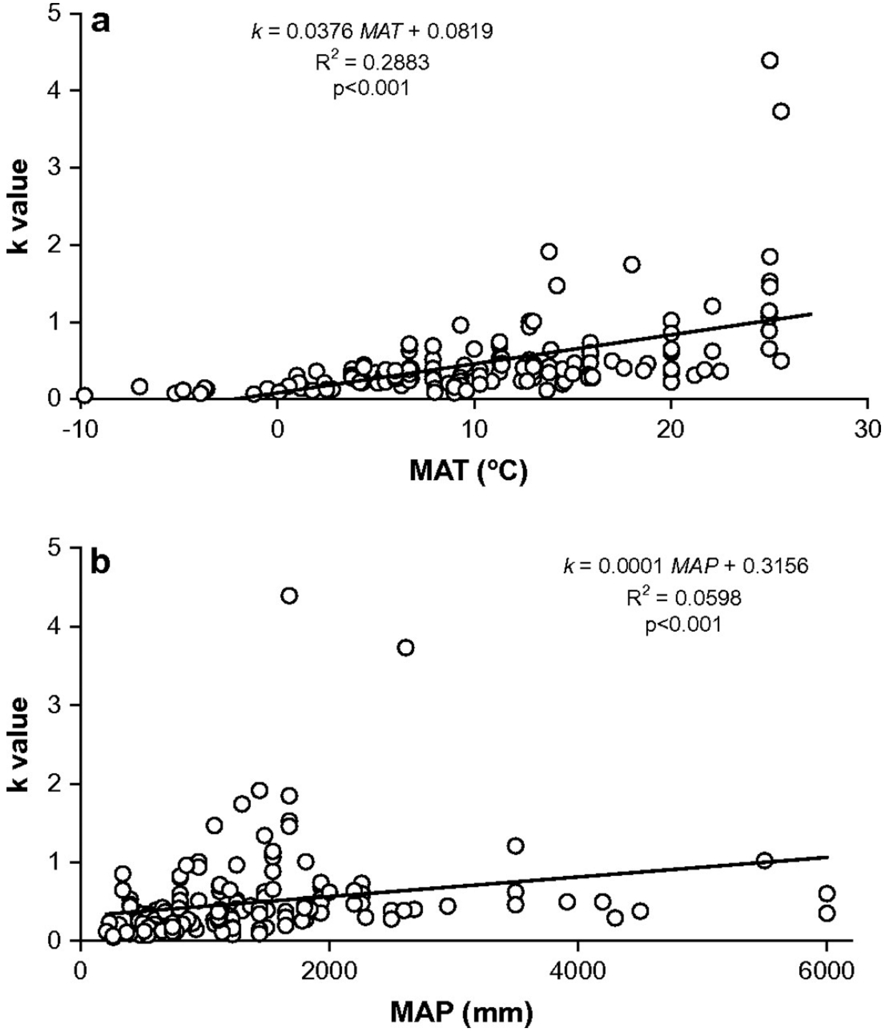
Climate and decomposition



Zhang et al. 2008

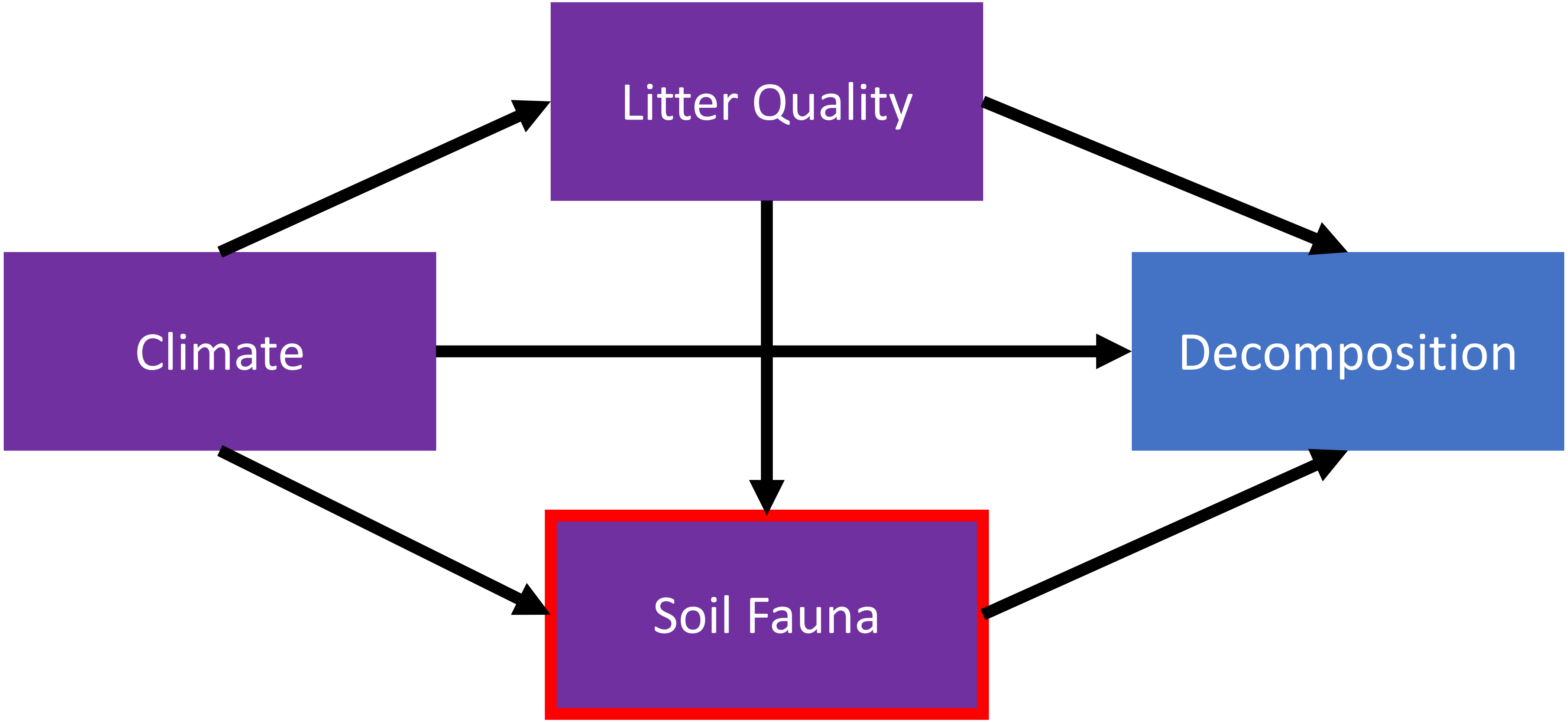
Climate and decomposition





Zhang et al. 2008

Major controls of decomposition

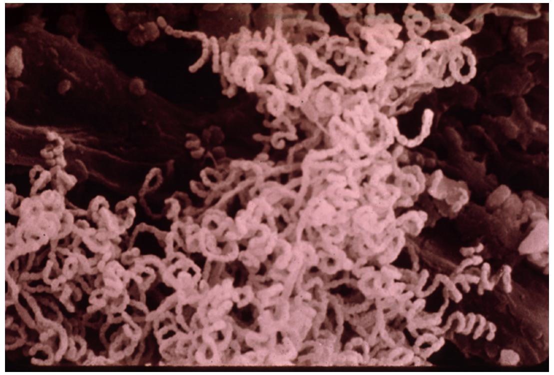


Soil organisms

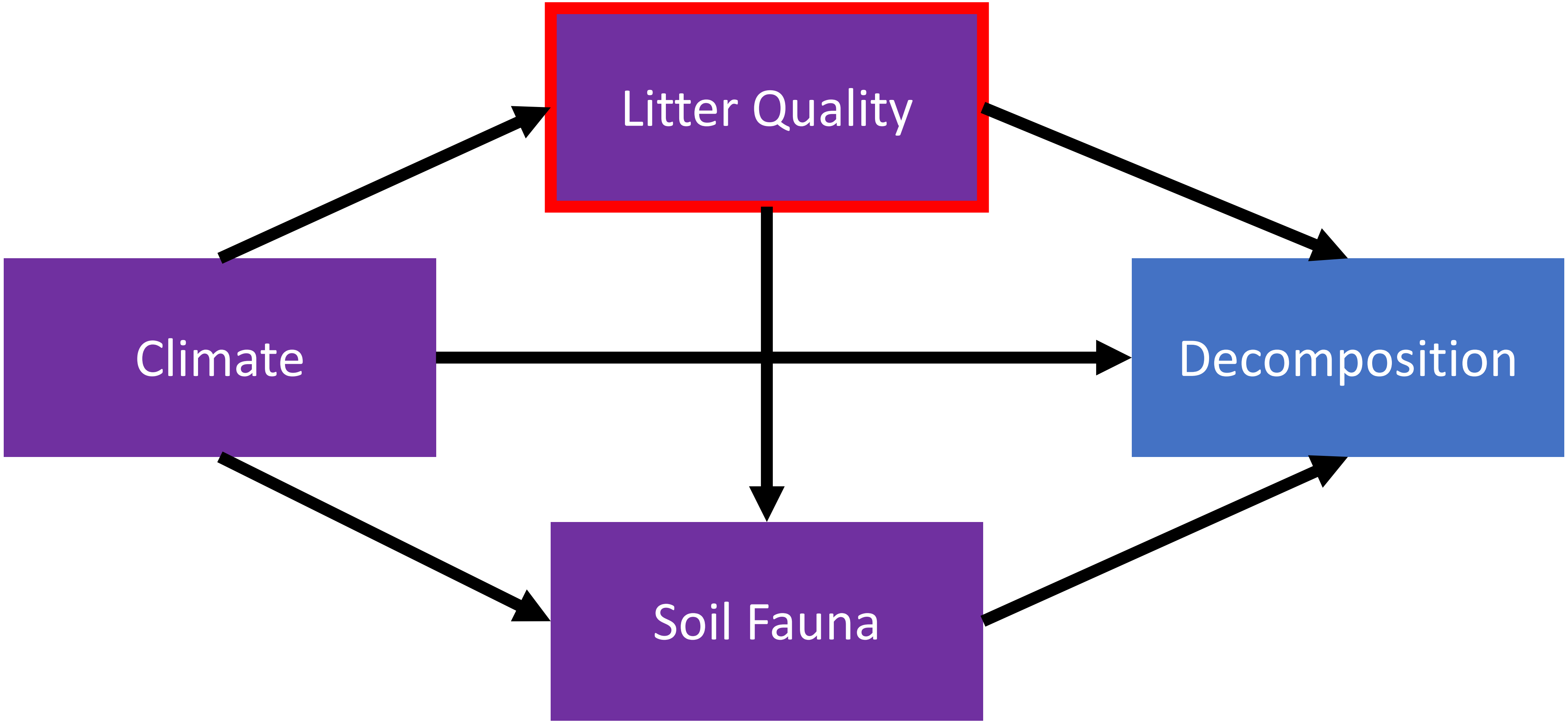
- Breakdown organic material
  - Releases mineral nutrients
  - Stabilizes soil structure
  - Forms humus
- Inorganic transformations
  - Transforms N, P, S into plant available forms
- Nitrogen fixation
  - Fix N_2 from atmosphere

Microbial community characteristics determine litter decomposition

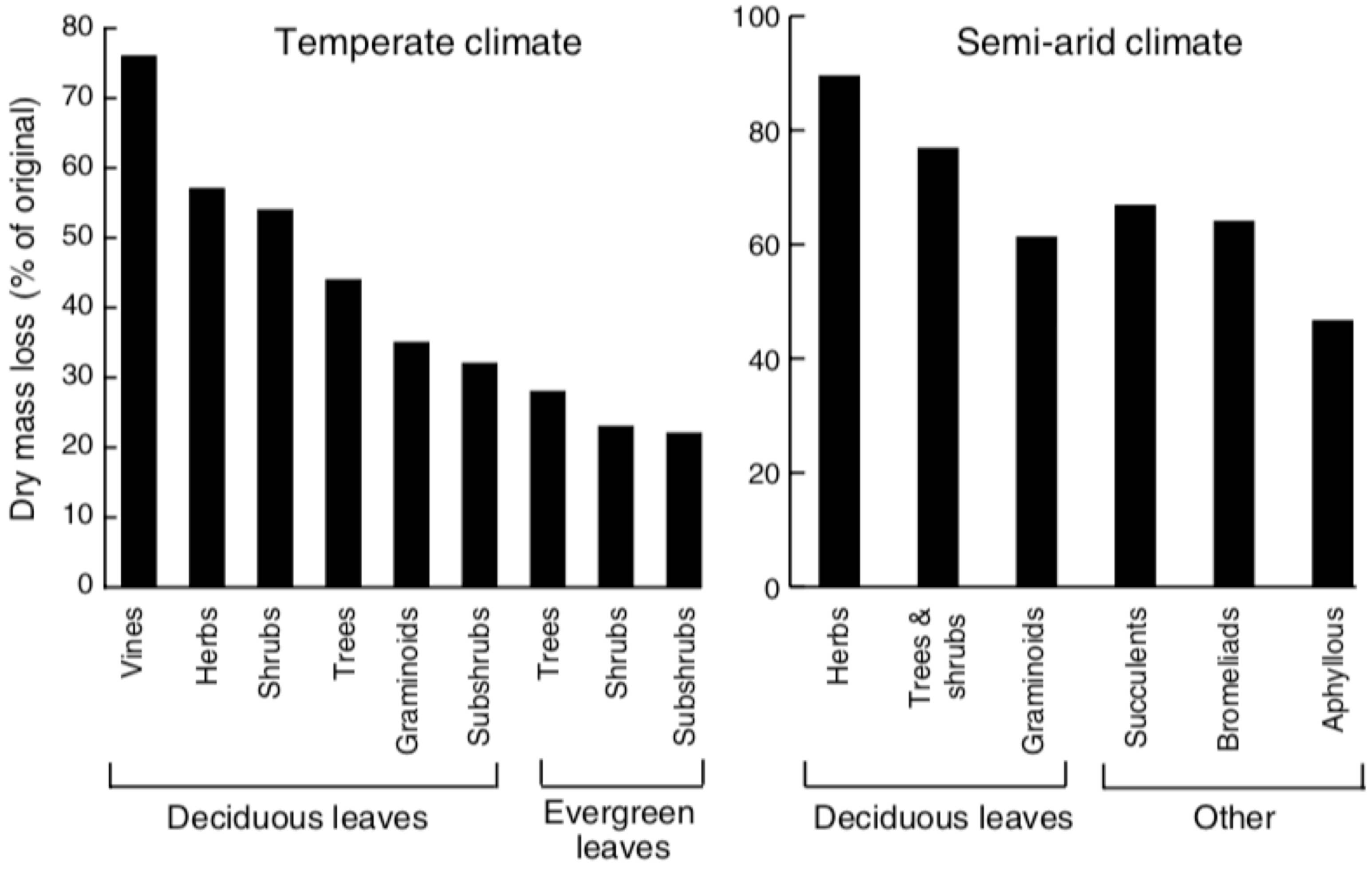
- Community composition
  - Who’s there
- Enzyme activity – speed breakdown
- Most processes are mediated by enzymes secreted



Major controls of decomposition



Litter quality varies with plant type



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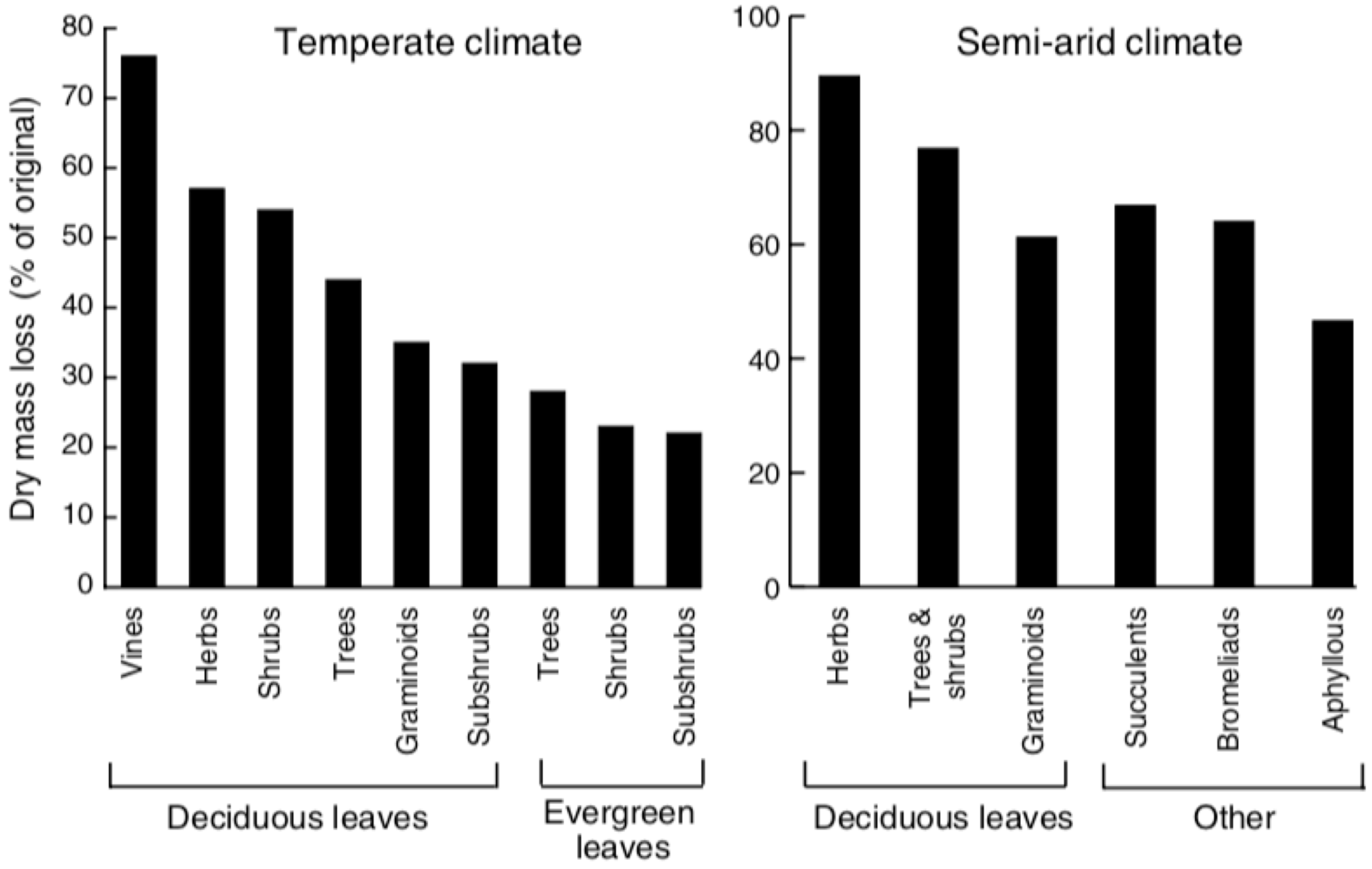
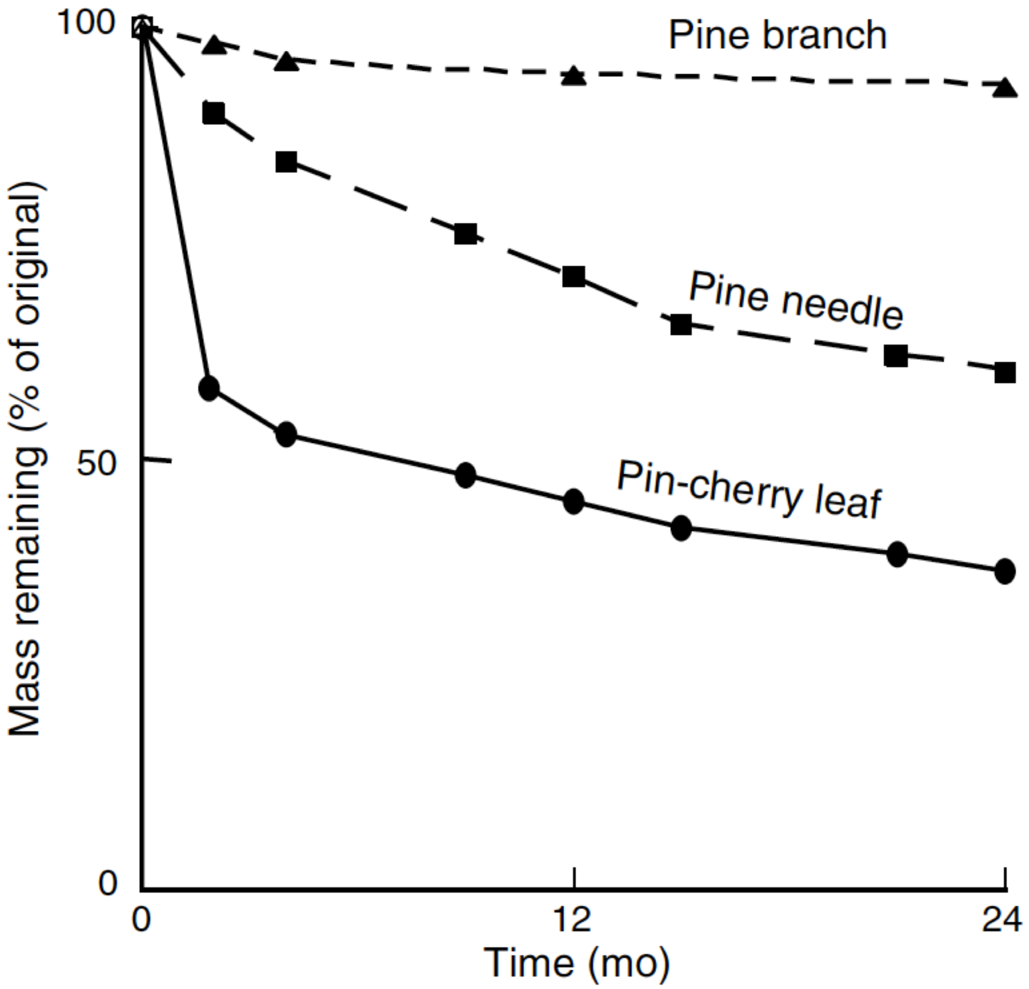
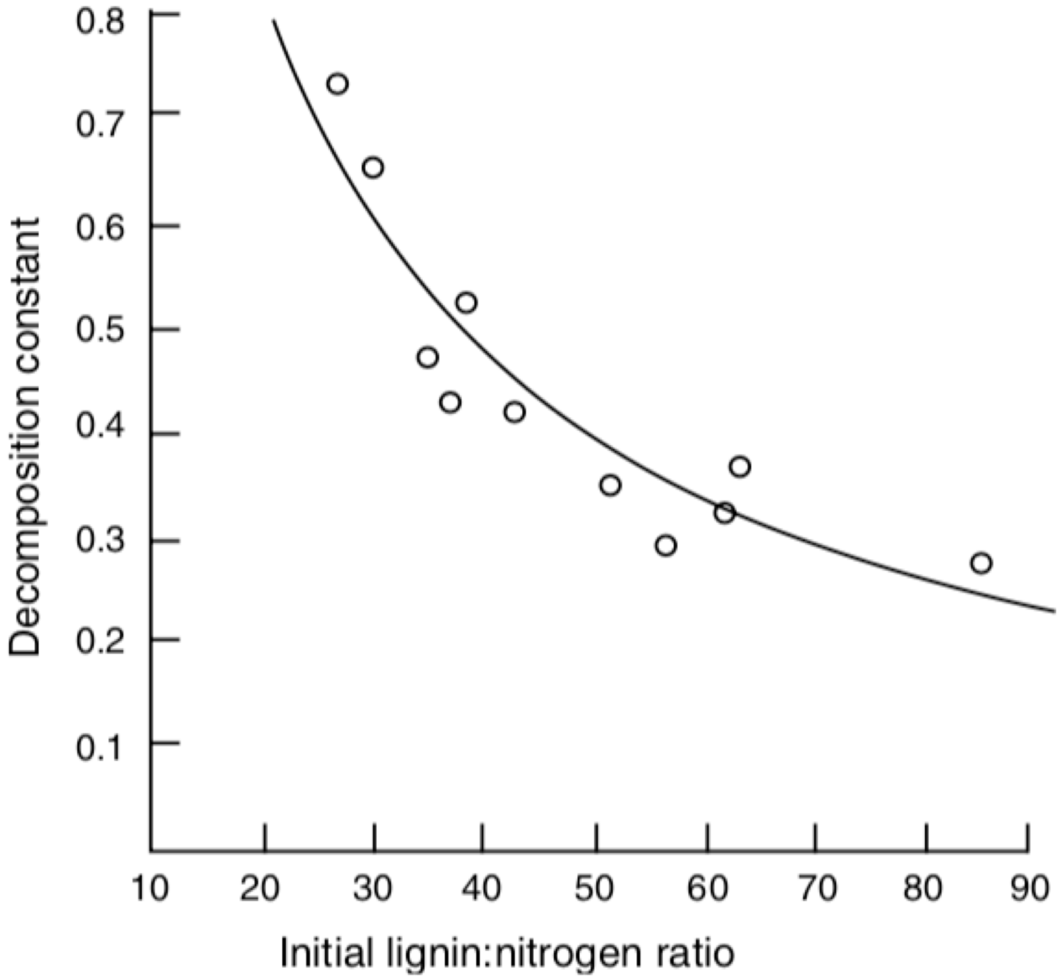


Why don’t all decompose fast?

Leaves decompose faster than branches



Higher nutrient litter decomposes faster



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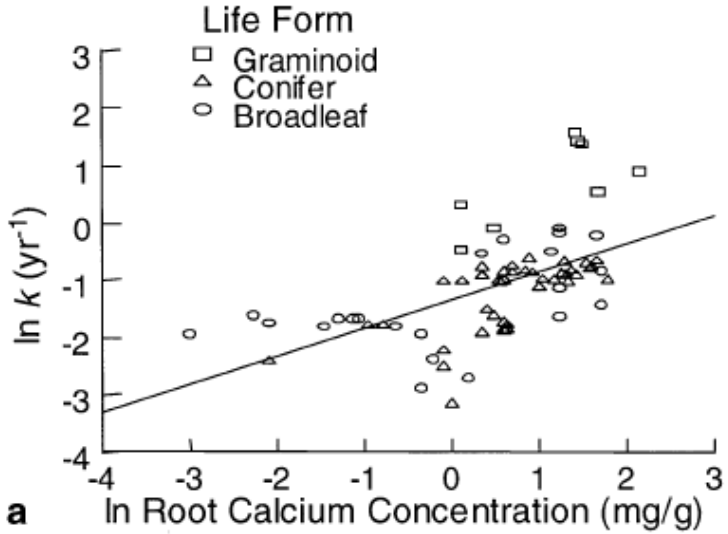
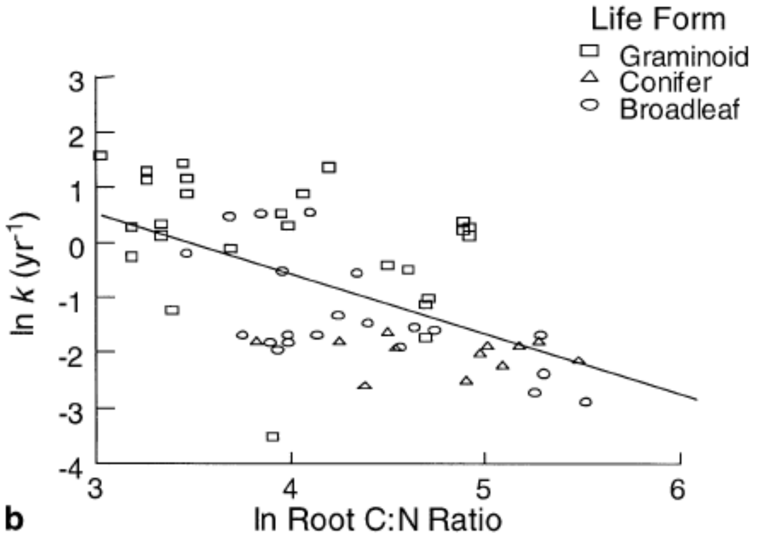
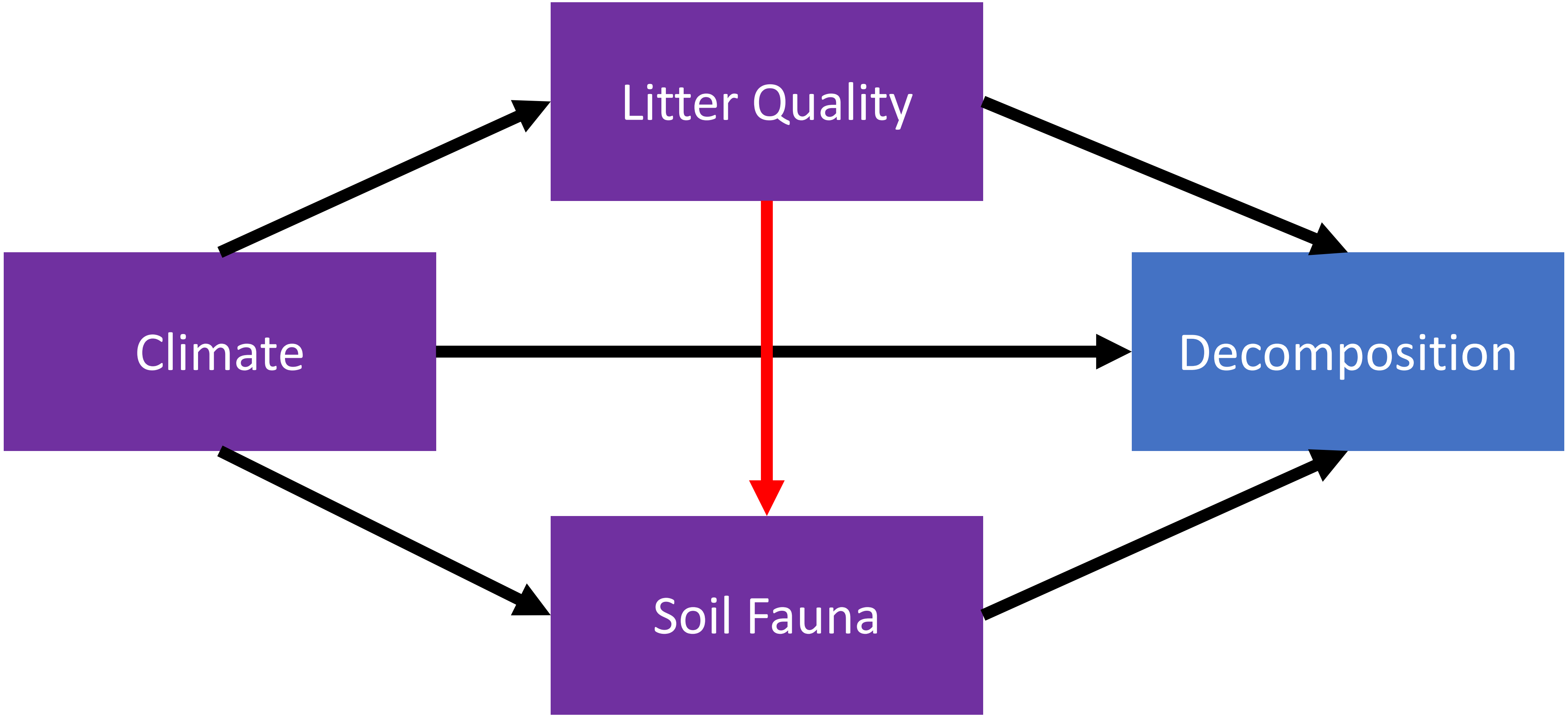




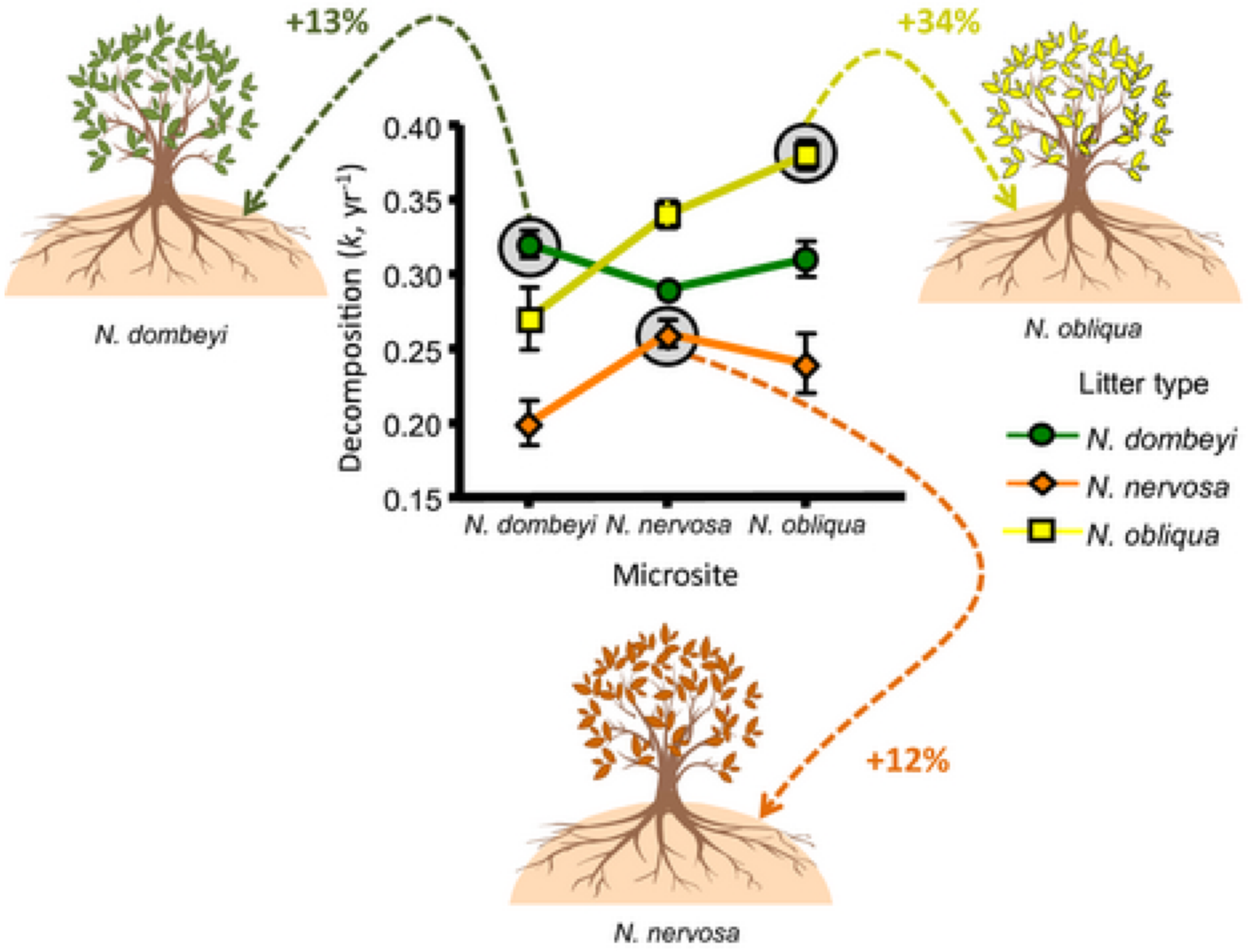
Silver & Miya 2001

Major controls of decomposition



Home Field Advantage

Do microbes decompose substrates that they've "seen" before better than naïve substrates?



Austin et al. 2014

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

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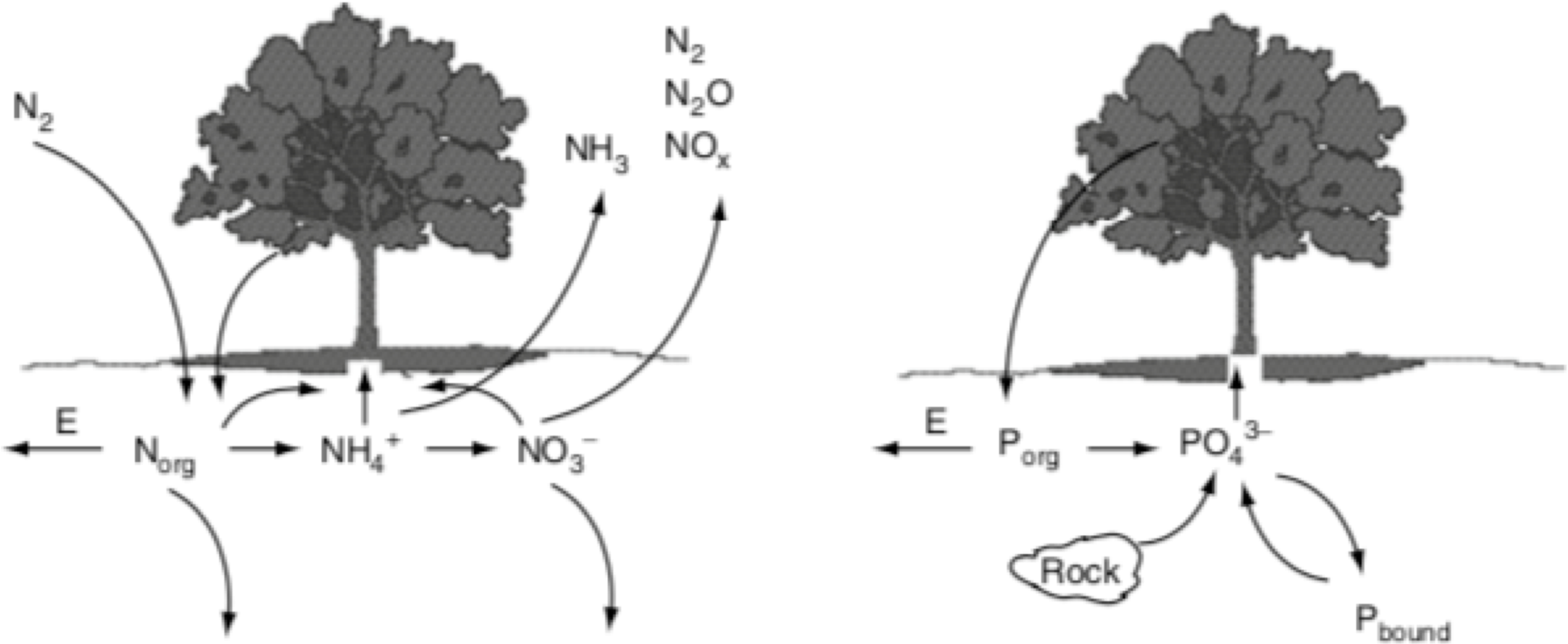
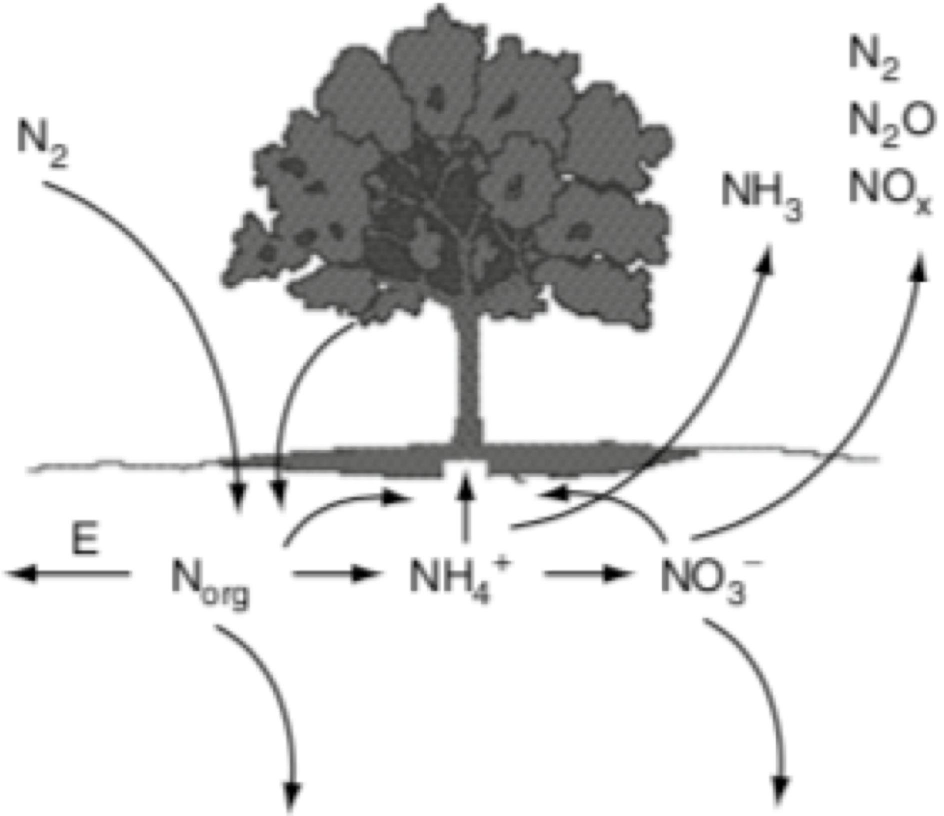
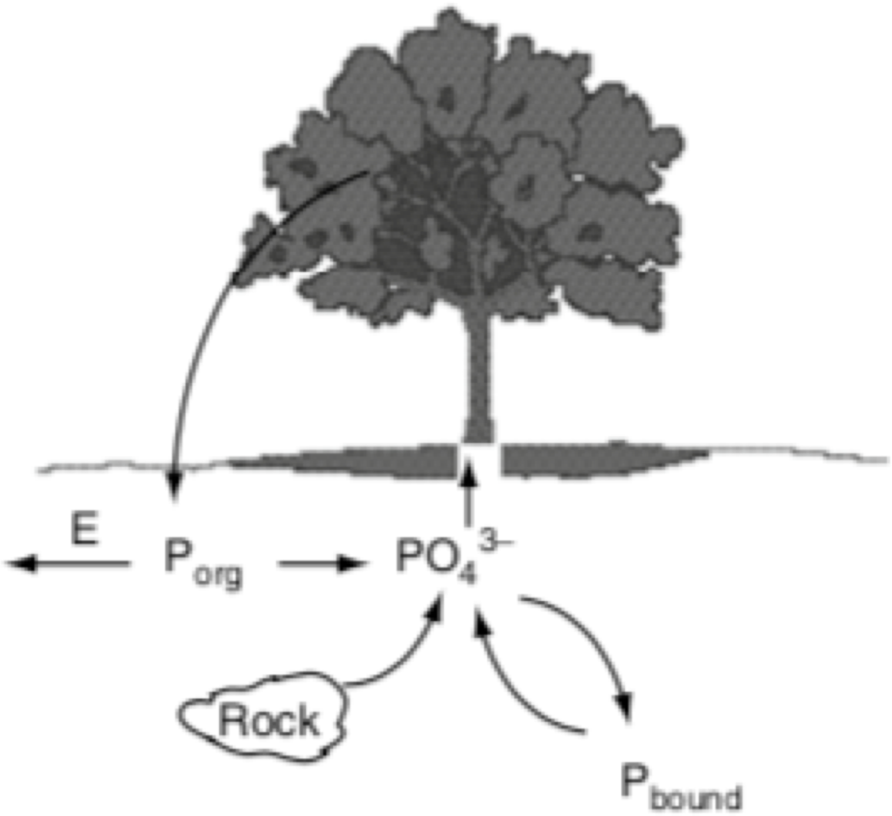

N$_2$
N$_2$
N$_2$O
NO$_x$
NH$_3$
E
N$_{org}$
NH$_4^+$
NO$_3^-$
E
P$_{org}$
PO$_4^{3-}$
Rock
P$_{bound}$

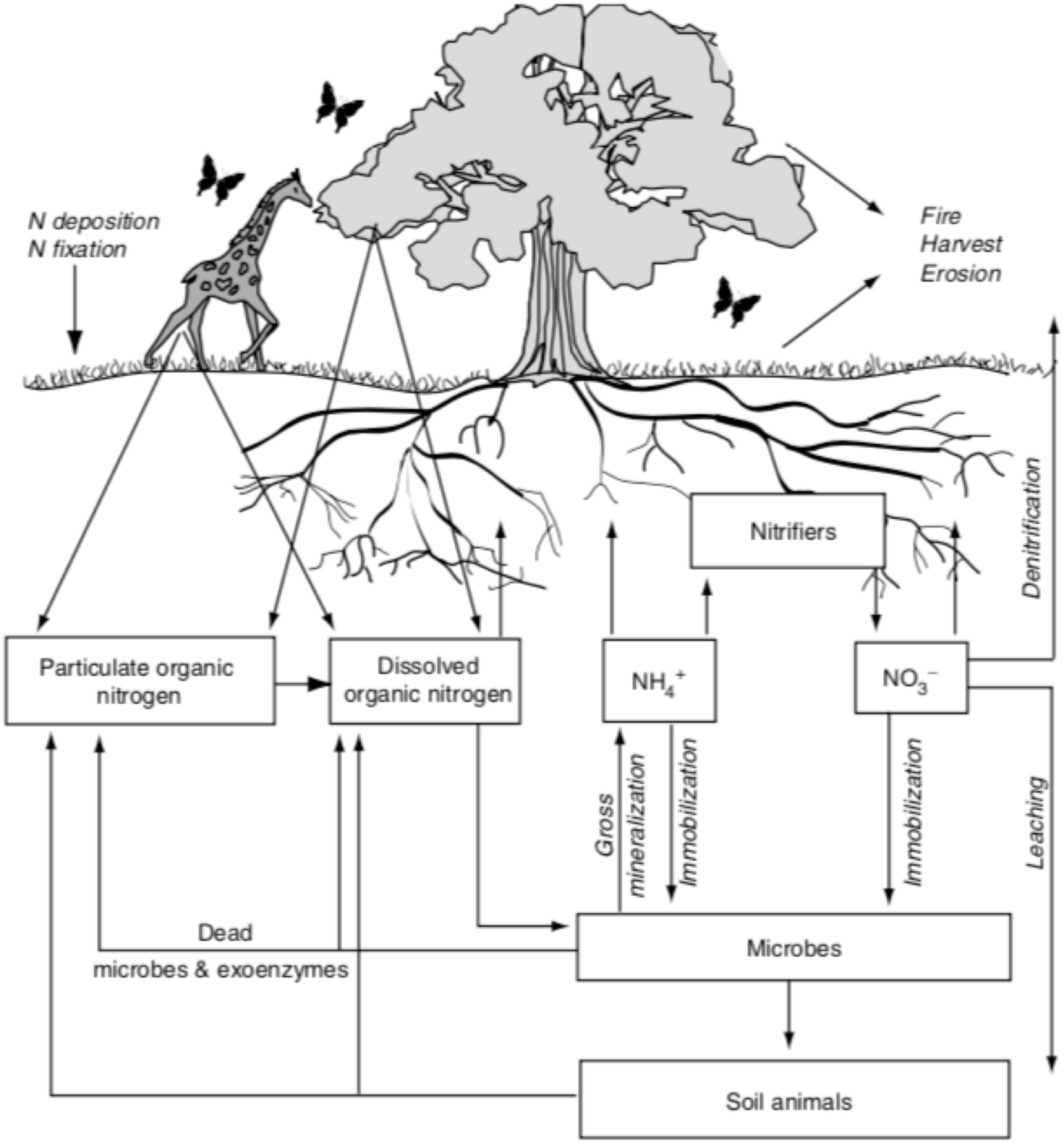


N_2
N_2
N_2O
NO_x
NH_3
E
N_{org}
NH_4^+
NO_3^-

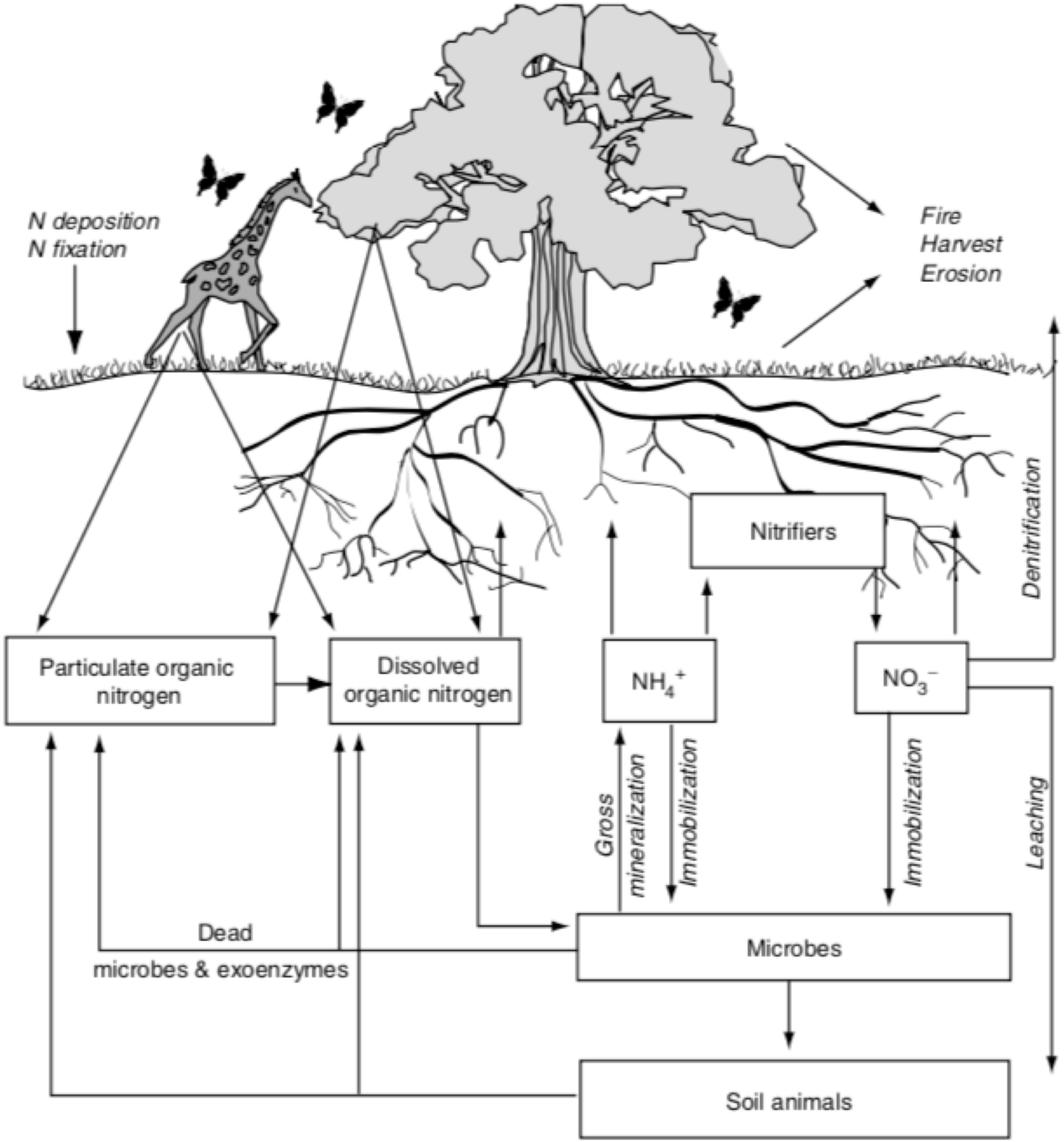


E
P_{org}
PO_4^{3-}
Rock
P_{bound}

The terrestrial N cycle

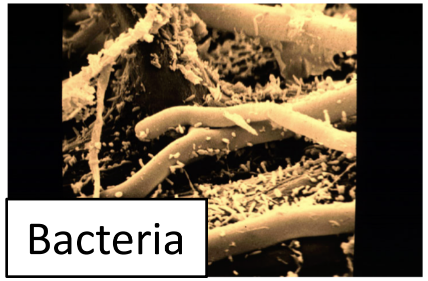


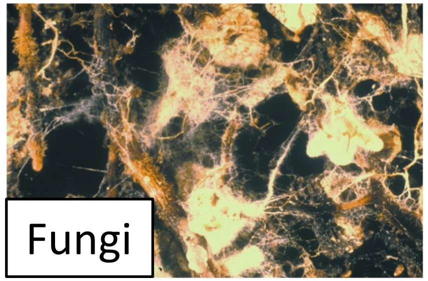
The terrestrial N cycle



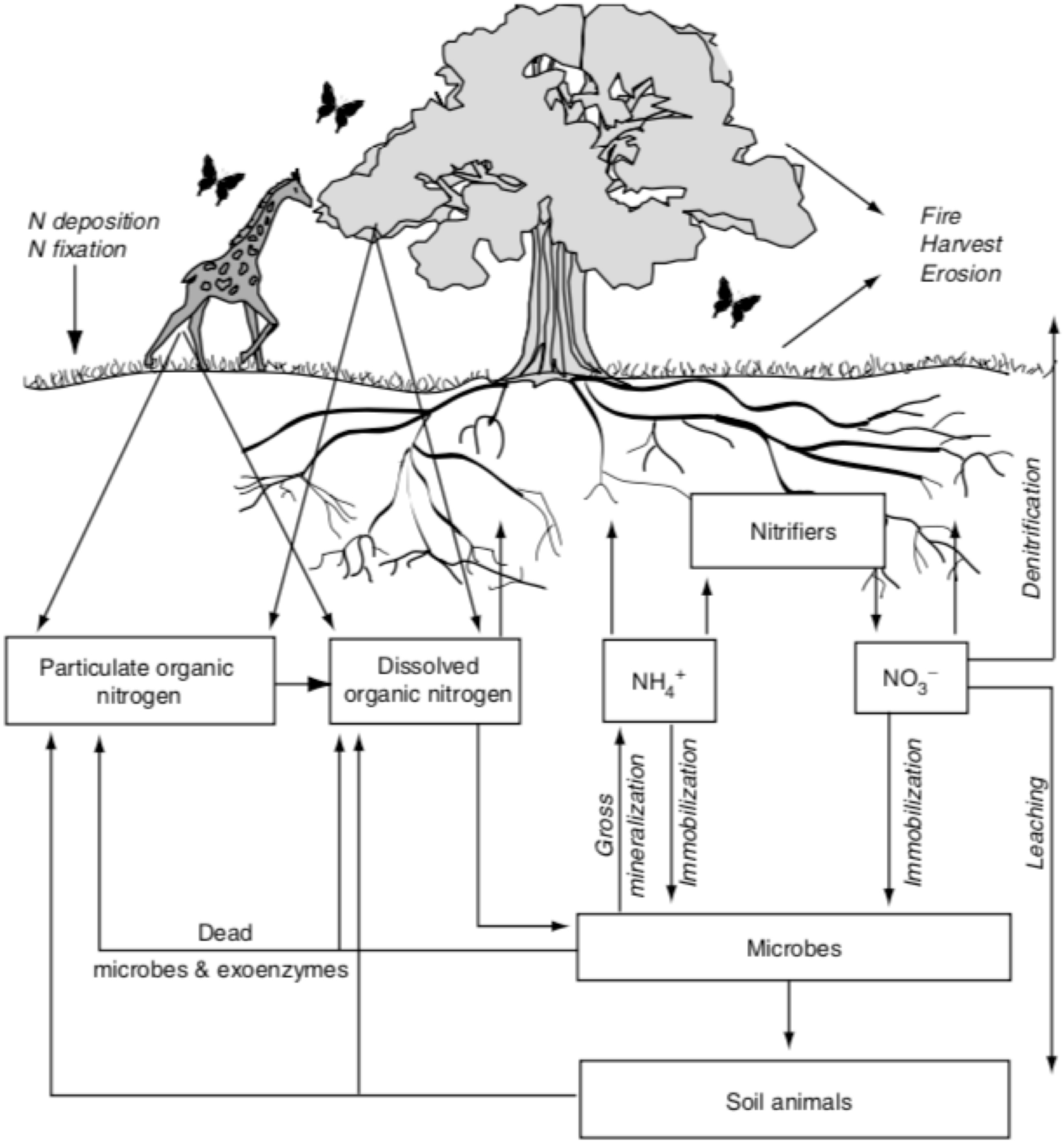
Nitrogen is constantly changing forms due to biological organisms

The terrestrial N cycle


Bacteria


Fungi

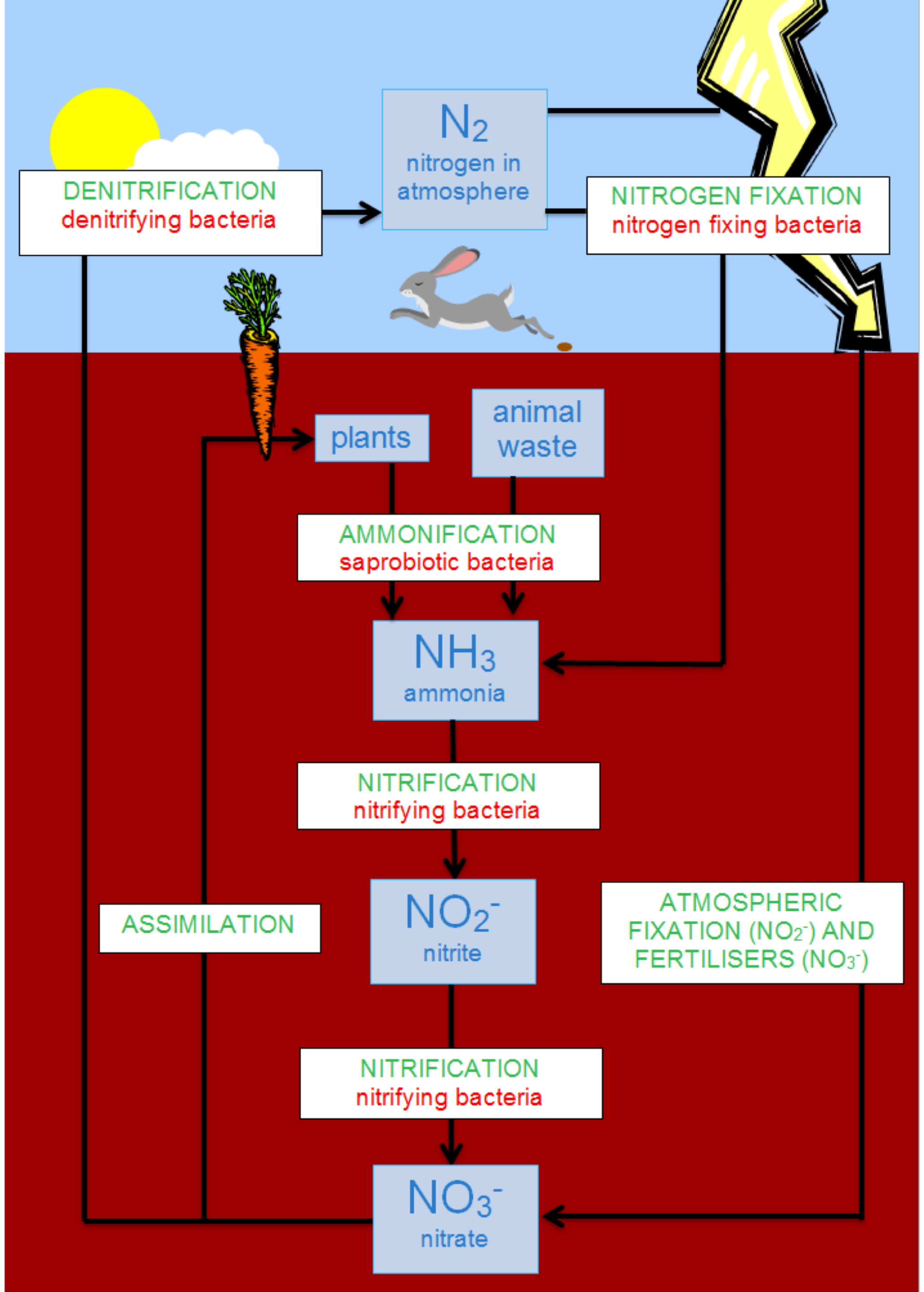
Nitrogen is constantly changing forms due to biological organisms (mostly microbes)



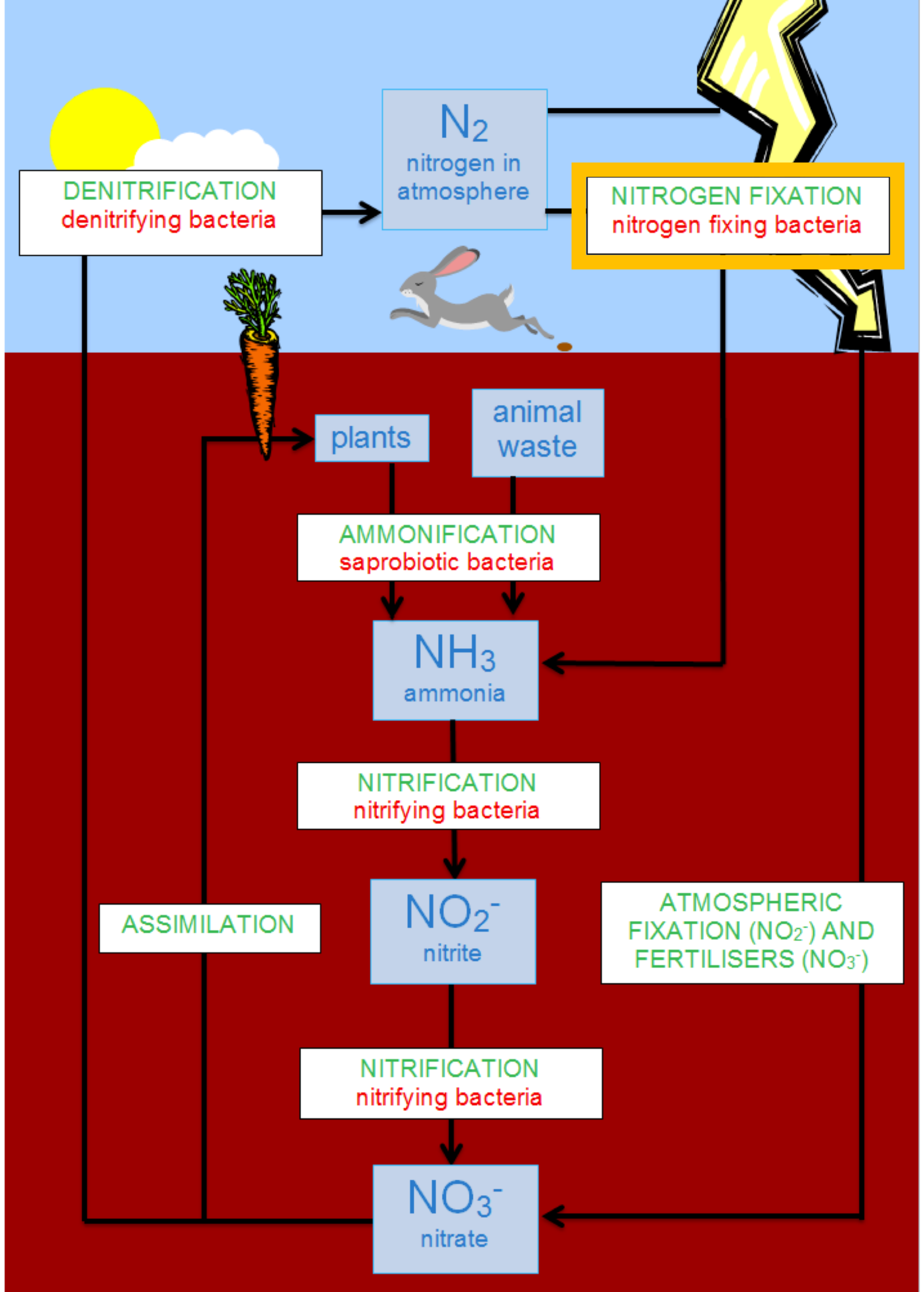
USDA

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
ASSIMILATION
NO_2^-
nitrite
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
ASSIMILATION
NO2-
nitrite
ATMOSPHERIC FIXATION (NO2-) AND FERTILISERS (NO3-)
NITRIFICATION
nitrifying bacteria
NO3-
nitrate

Biological N fixation: $N_2 \rightarrow NH_3$

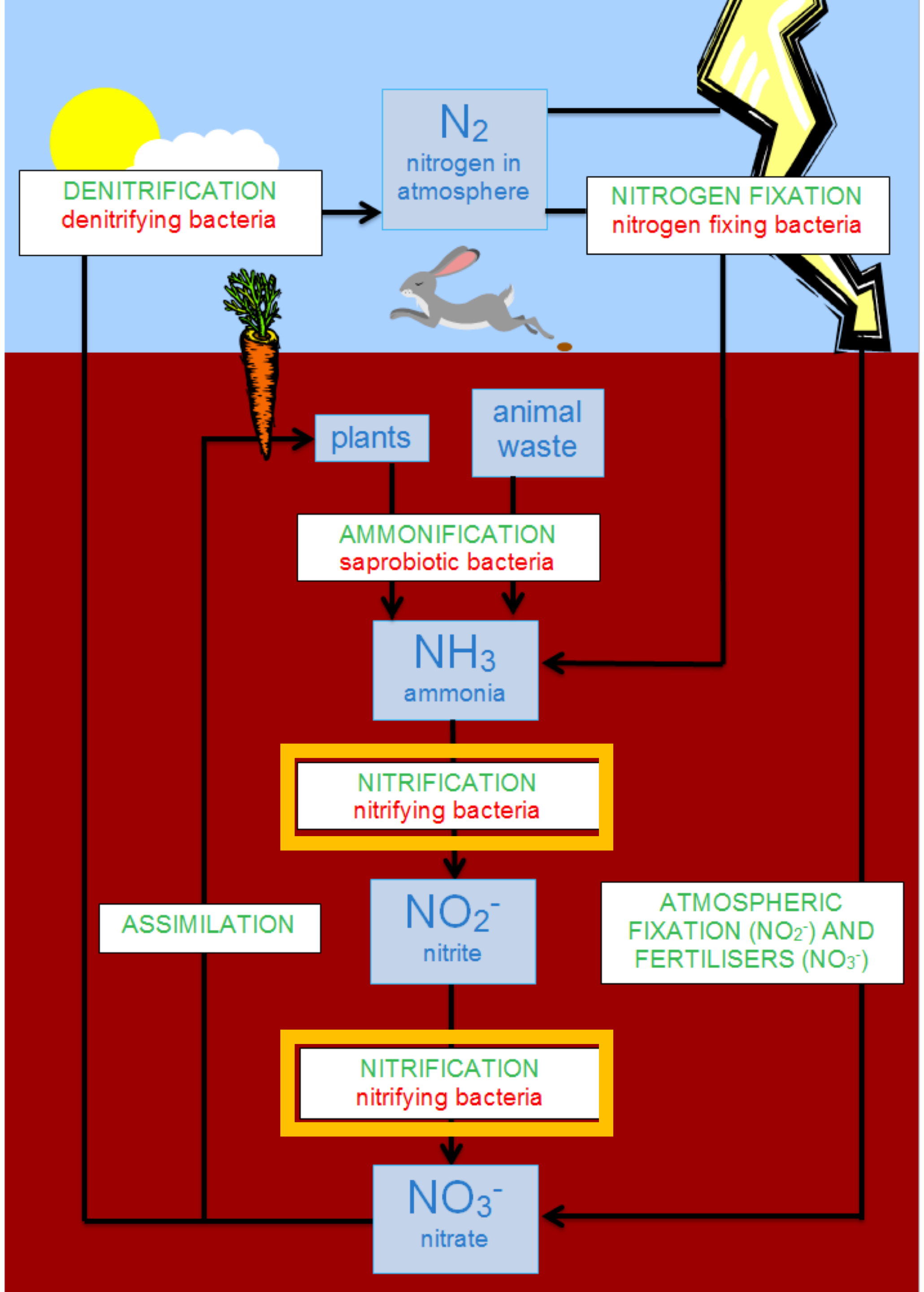
Table 9.1 Organisms and associations involved in di-nitrogen fixation

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

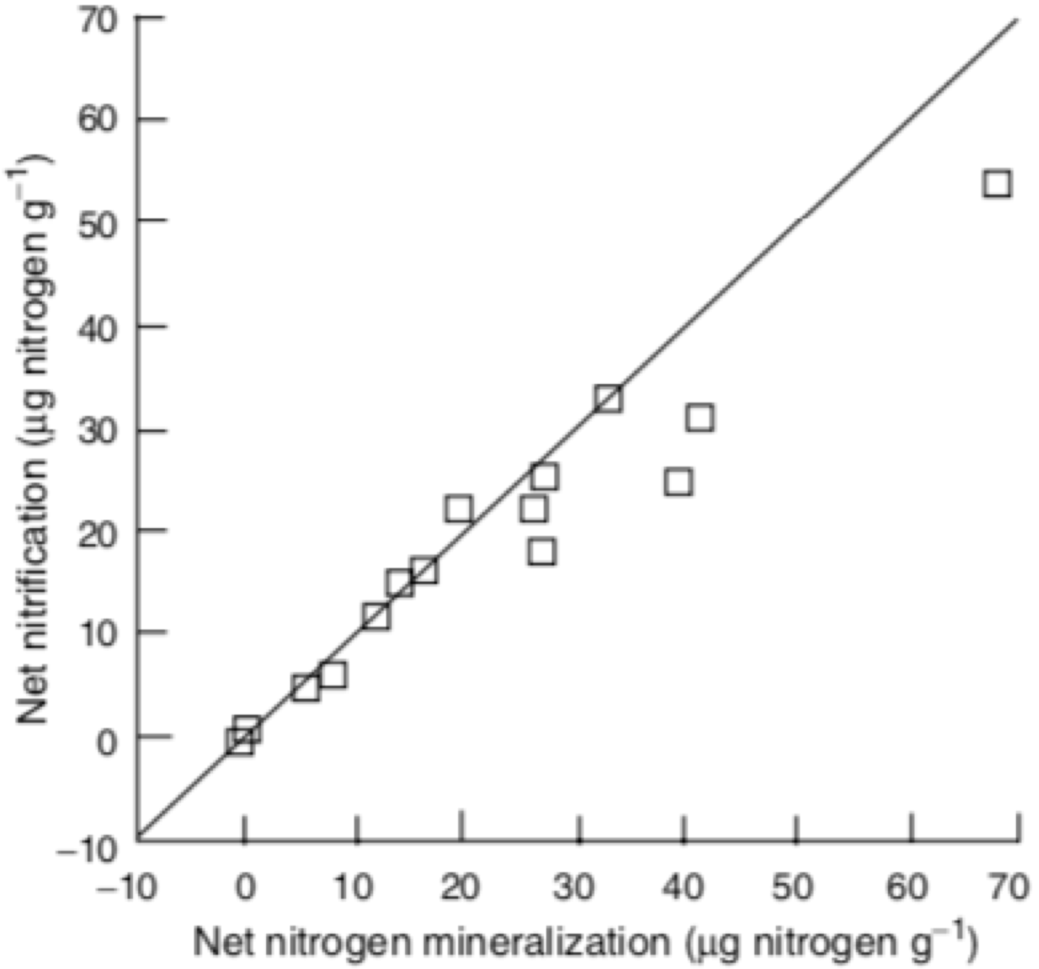
Heterocysts

Soil Aggregates



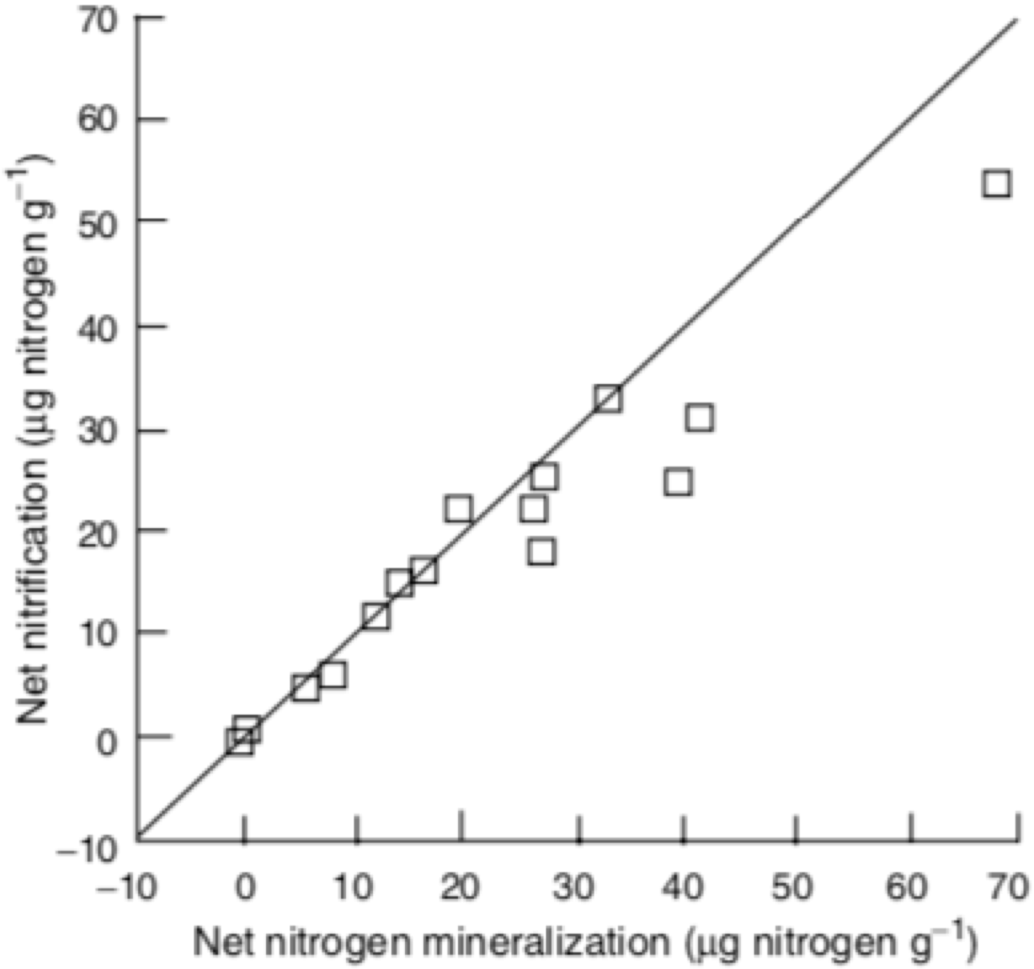
N_2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH_3
ammonia
NITRIFICATION
nitrifying bacteria
ASSIMILATION
NO_2^-
nitrite
ATMOSPHERIC FIXATION (NO_2^-) AND FERTILISERS (NO_3^-)
NITRIFICATION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

Nitrification: $NH_3 \rightarrow NO_2 \rightarrow NO_3$



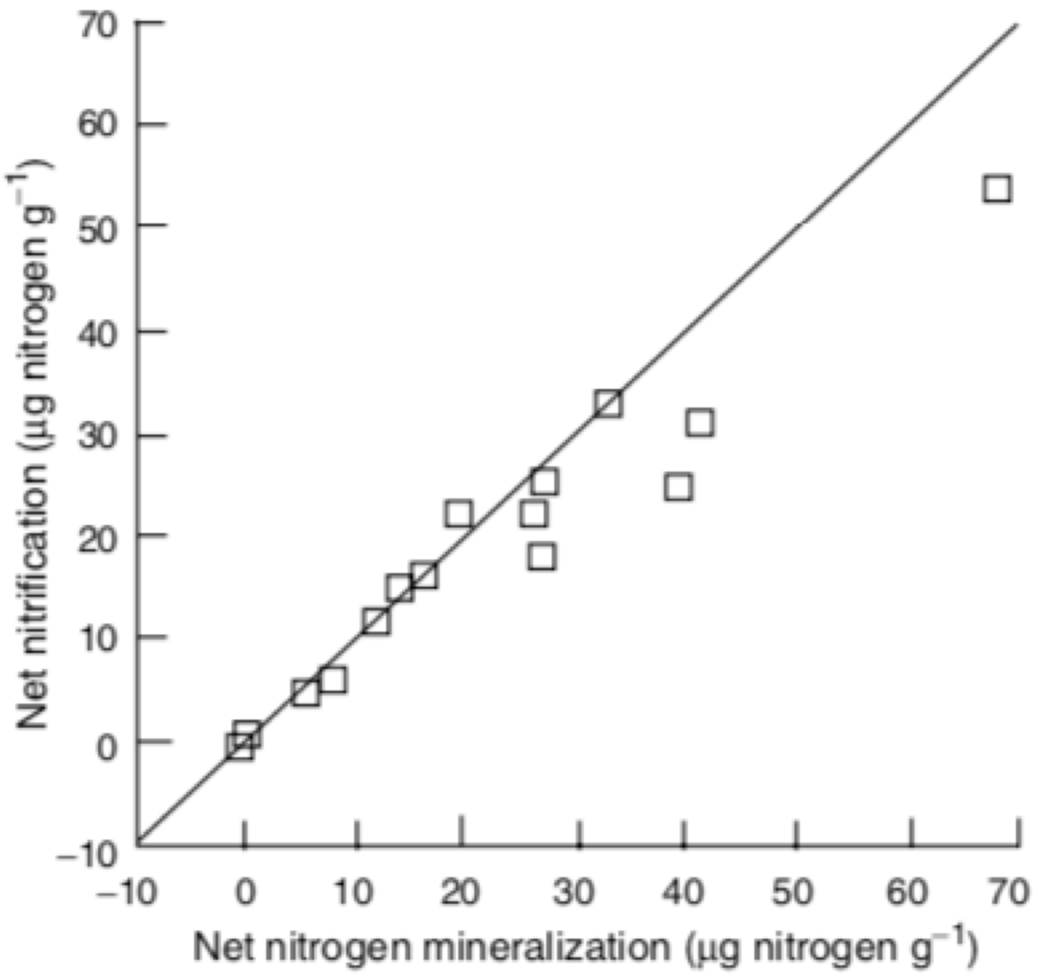
Constantly happening in soil and determined by the amount of NH_3 produced by mineralization

Nitrification: $NH_3 \rightarrow NO_2 \rightarrow NO_3$



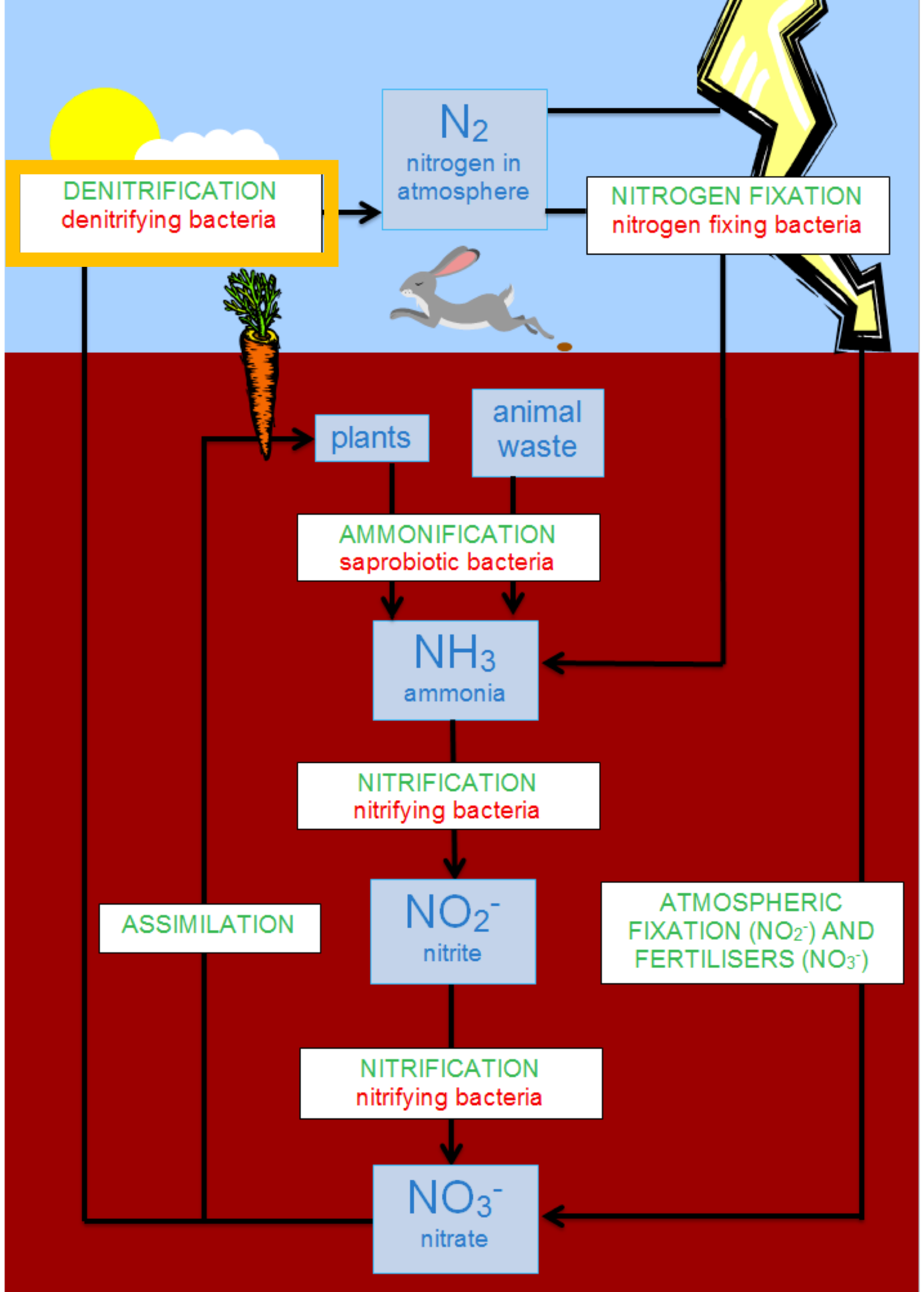
NH_3 amount explains spatial and temporal variability in nitrification

Nitrification: $NH_3 \rightarrow NO_2 \rightarrow NO_3$

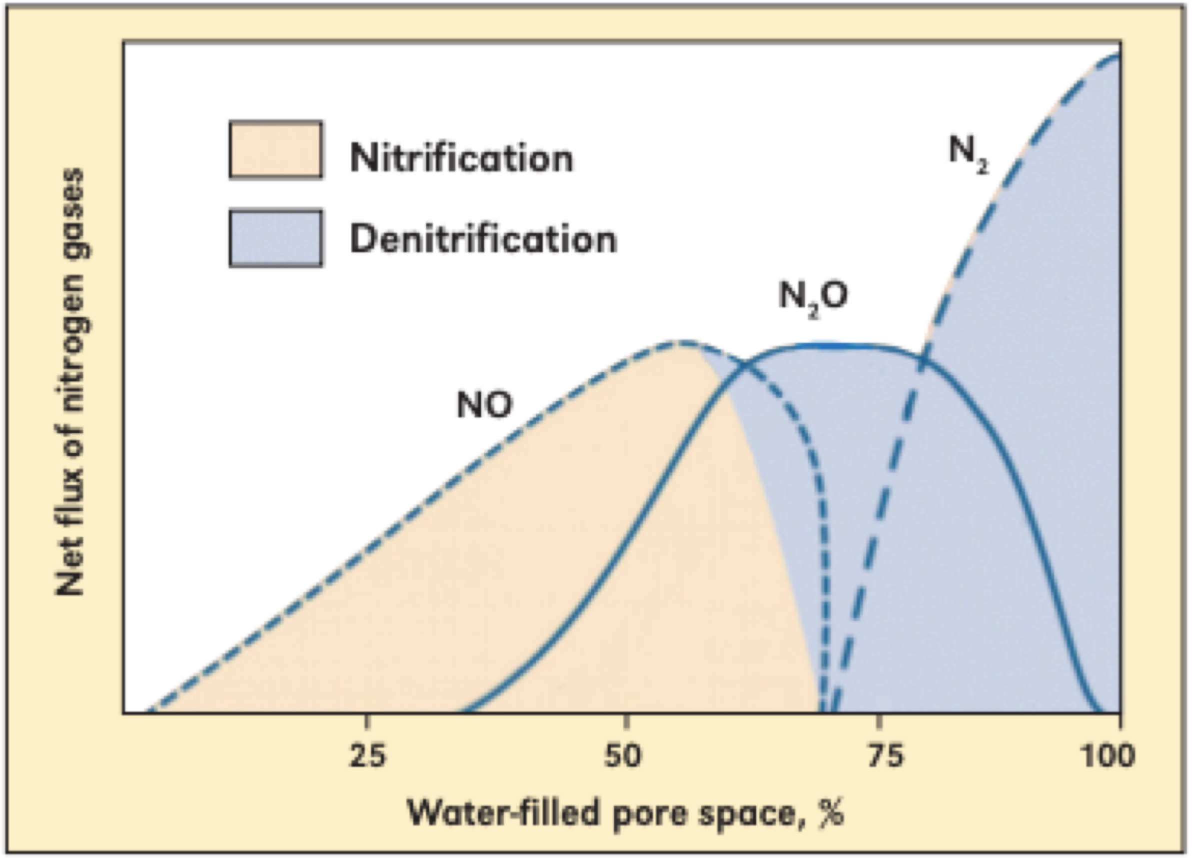


Consequences

- N gas production
- N more mobile

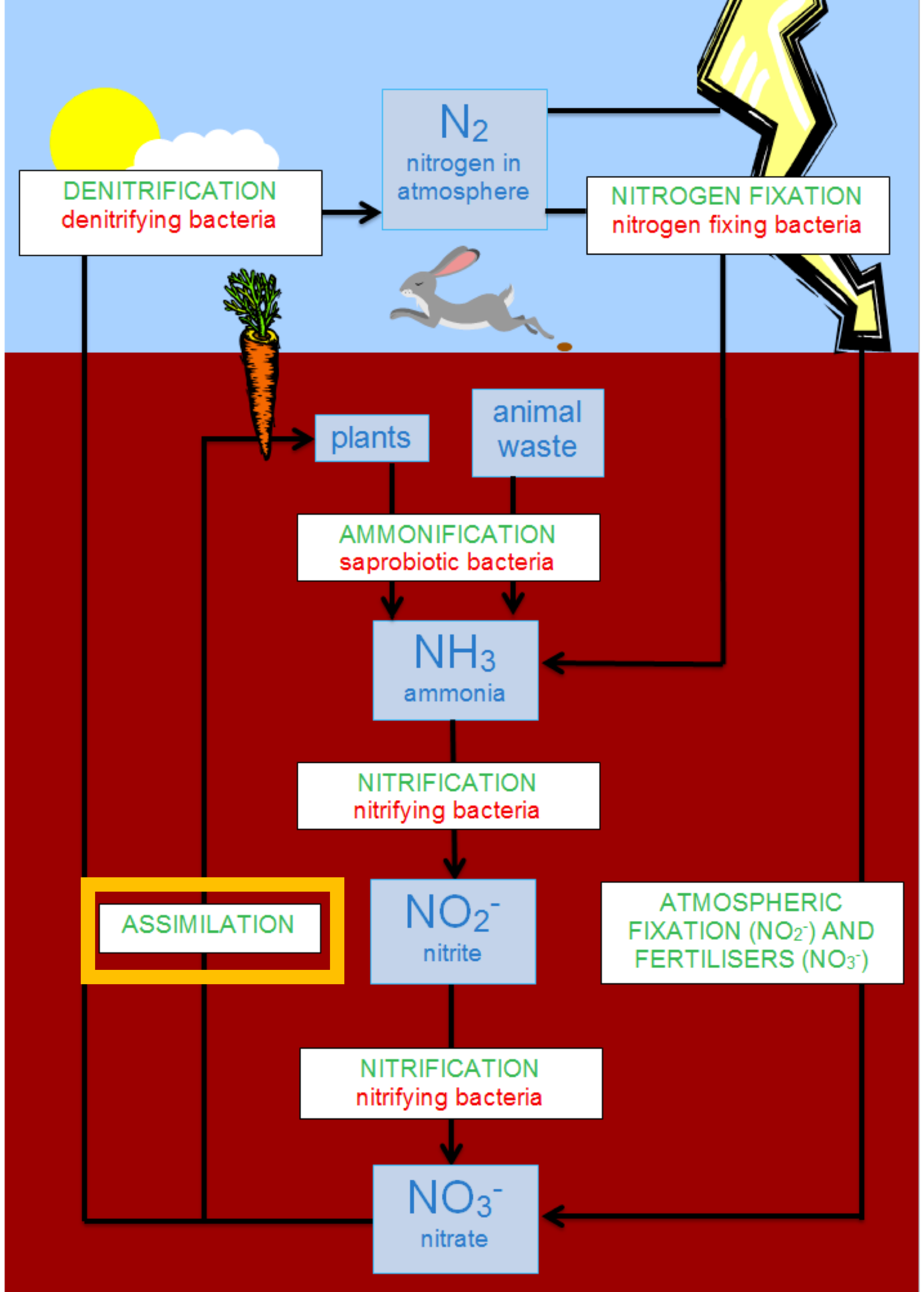

N_2
nitrogen in atmosphere
DENITRIFICATION
denitrifying bacteria
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH_3
ammonia
NITRIFICATION
nitrifying bacteria
ASSIMILATION
NO_2^-
nitrite
ATMOSPHERIC FIXATION (NO_2^-) AND FERTILISERS (NO_3^-)
NITRIFICATION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

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)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nitrogen in atmosphere
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nitrifying bacteria
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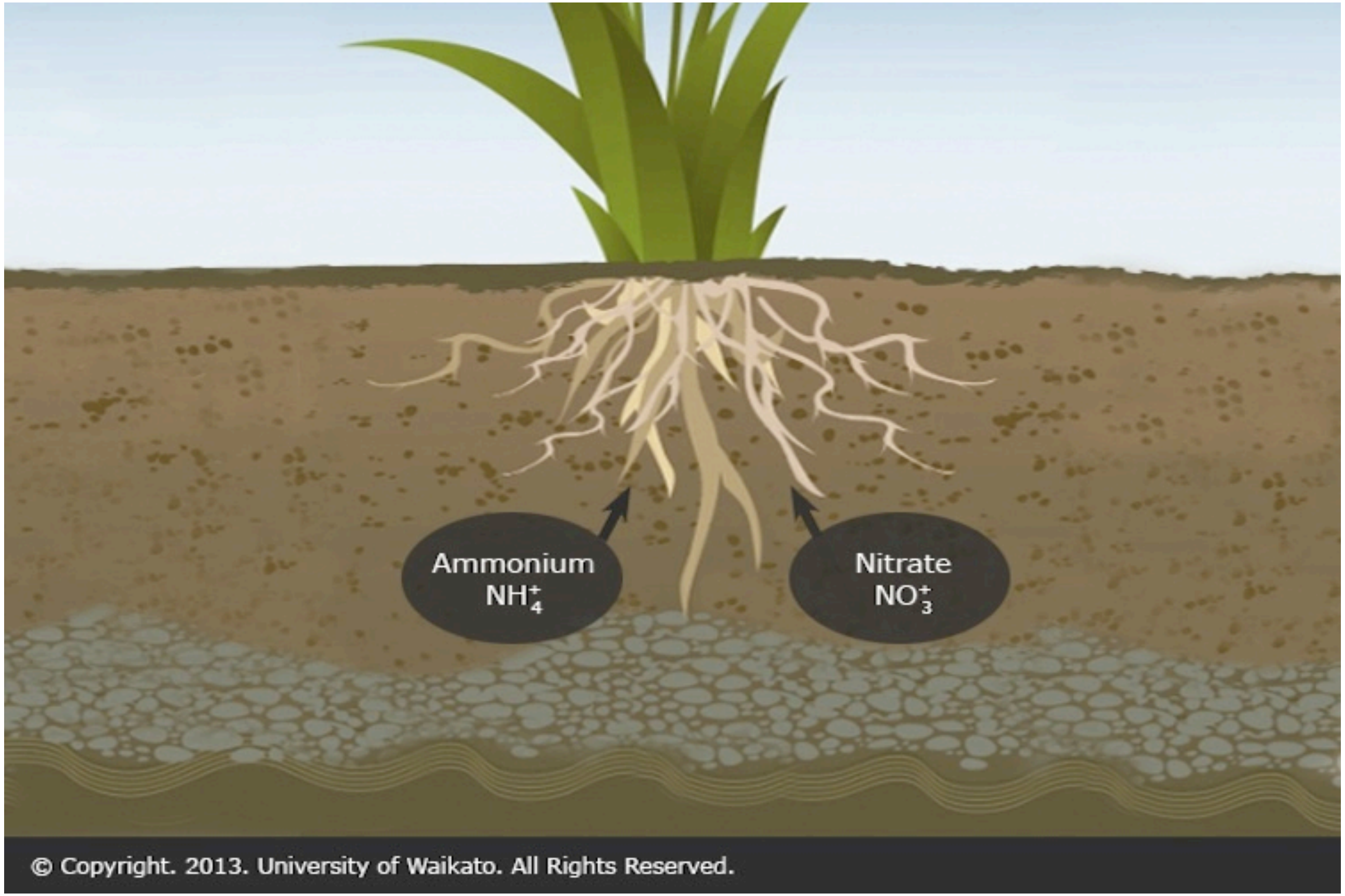
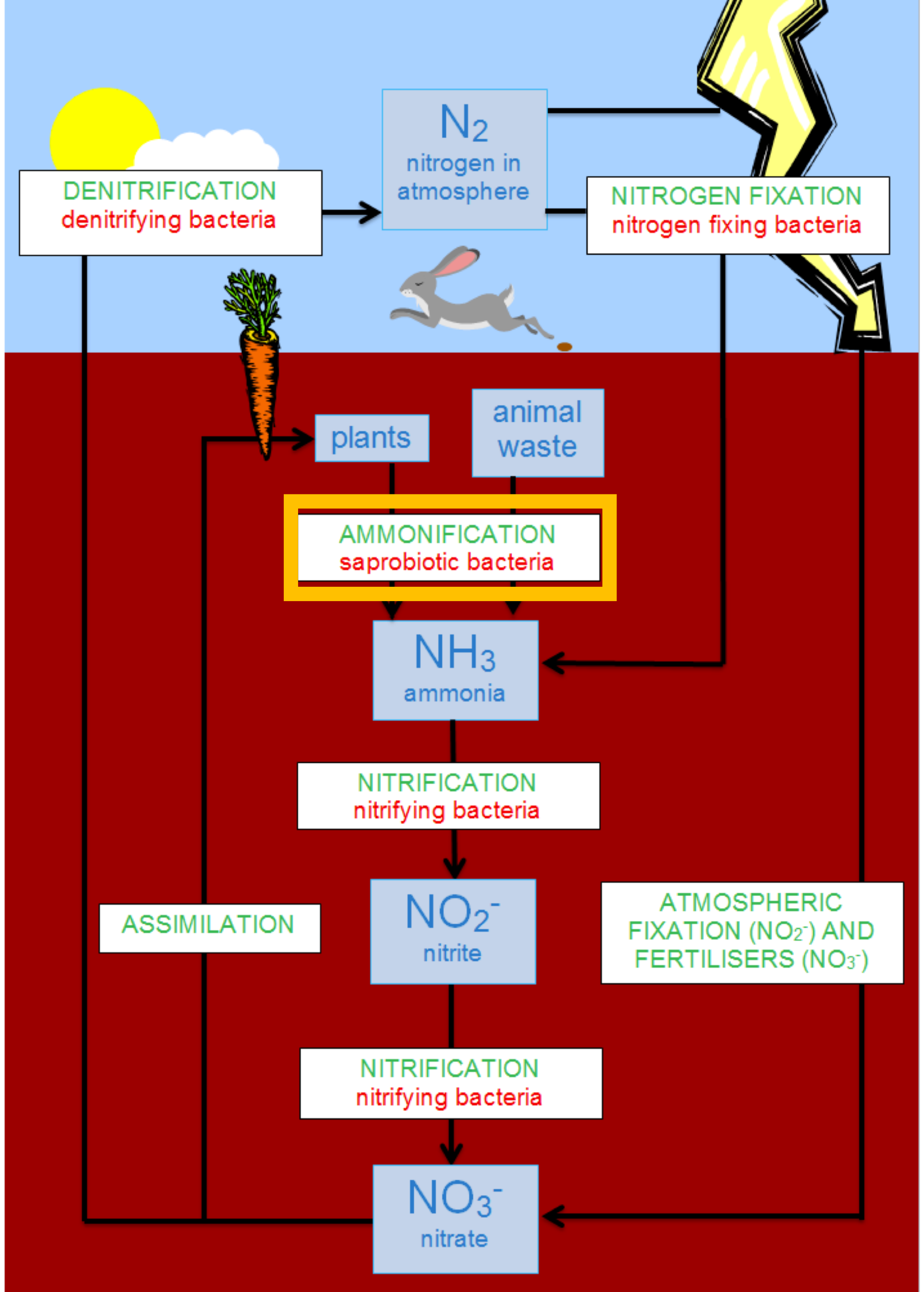
NO_2^-
nitrite
ATMOSPHERIC FIXATION (NO_2^-) AND FERTILISERS (NO_3^-)
NITRIFICATION
nitrifying bacteria
NO_3^-
nitrate

Assimilation: Inorganic N → Organic N

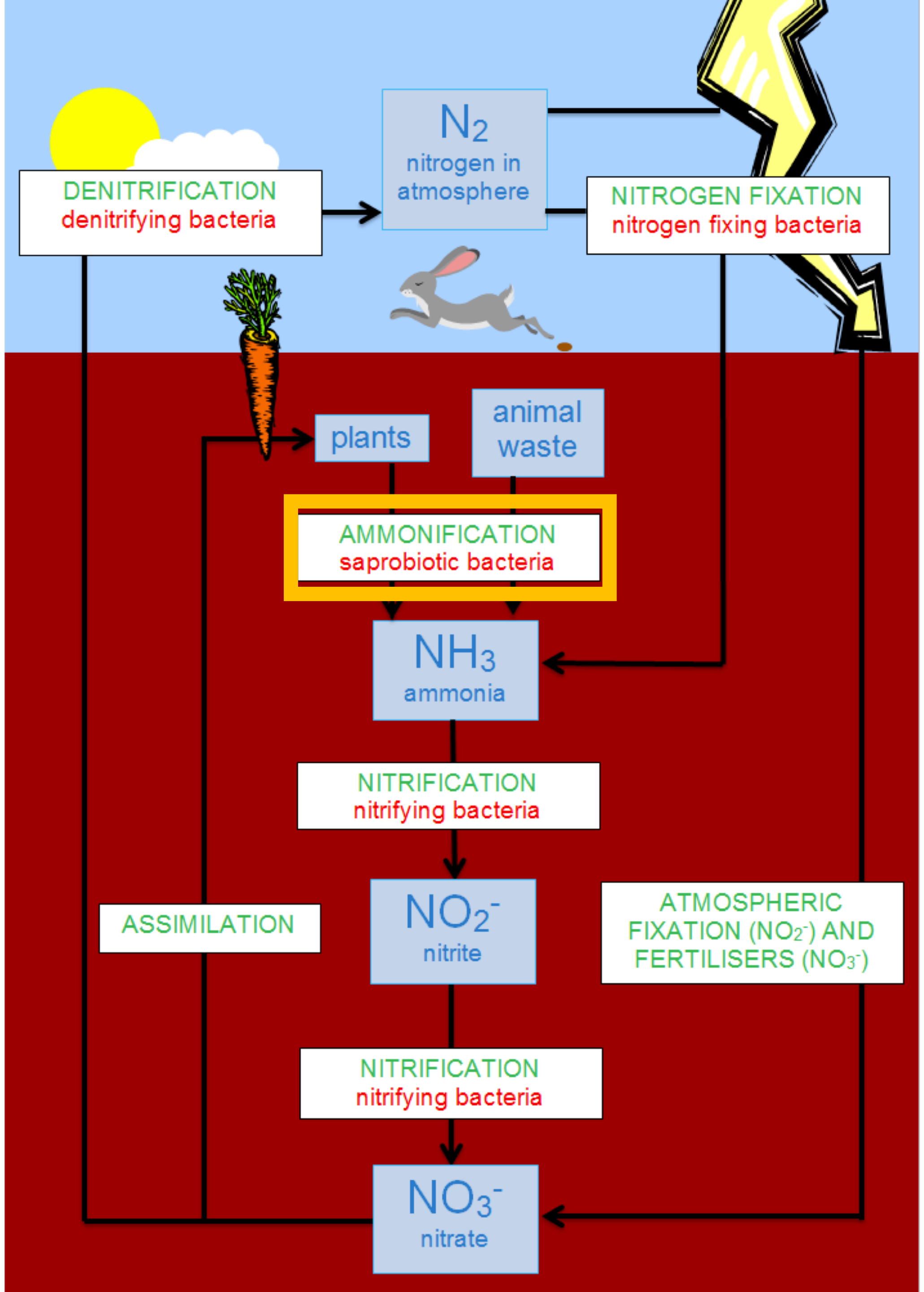


Via microbes or plants

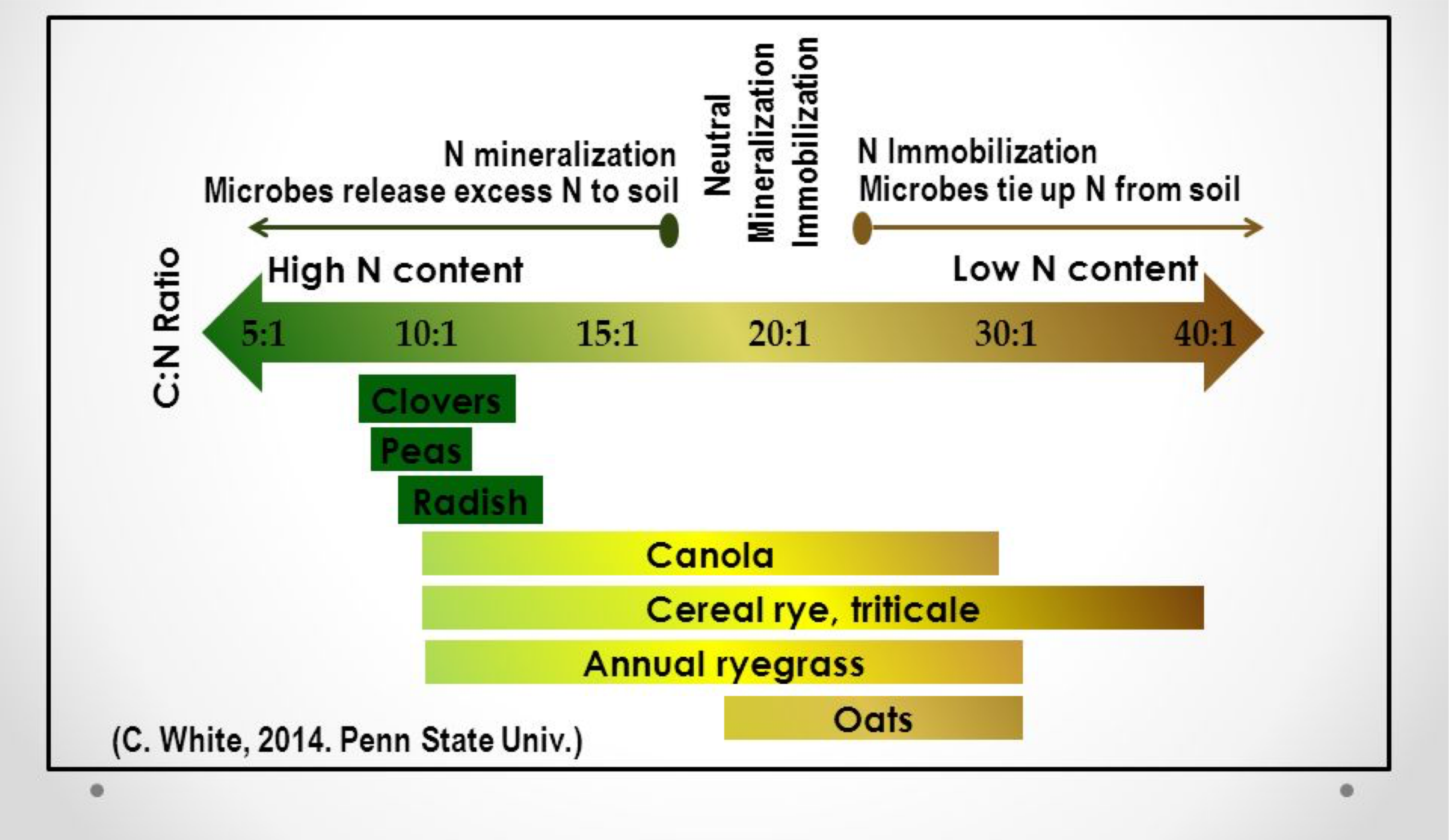


DENITRIFICATION
denitrifying bacteria
N_2
nitrogen in atmosphere
NITROGEN FIXATION
nitrogen fixing bacteria
plants
animal waste
AMMONIFICATION
saprobiotic bacteria
NH_3
ammonia
NITRIFICATION
nitrifying bacteria
ASSIMILATION
NO_2^-
nitrite
ATMOSPHERIC FIXATION (NO_2^-) AND FERTILISERS (NO_3^-)
NITRIFICATION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

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

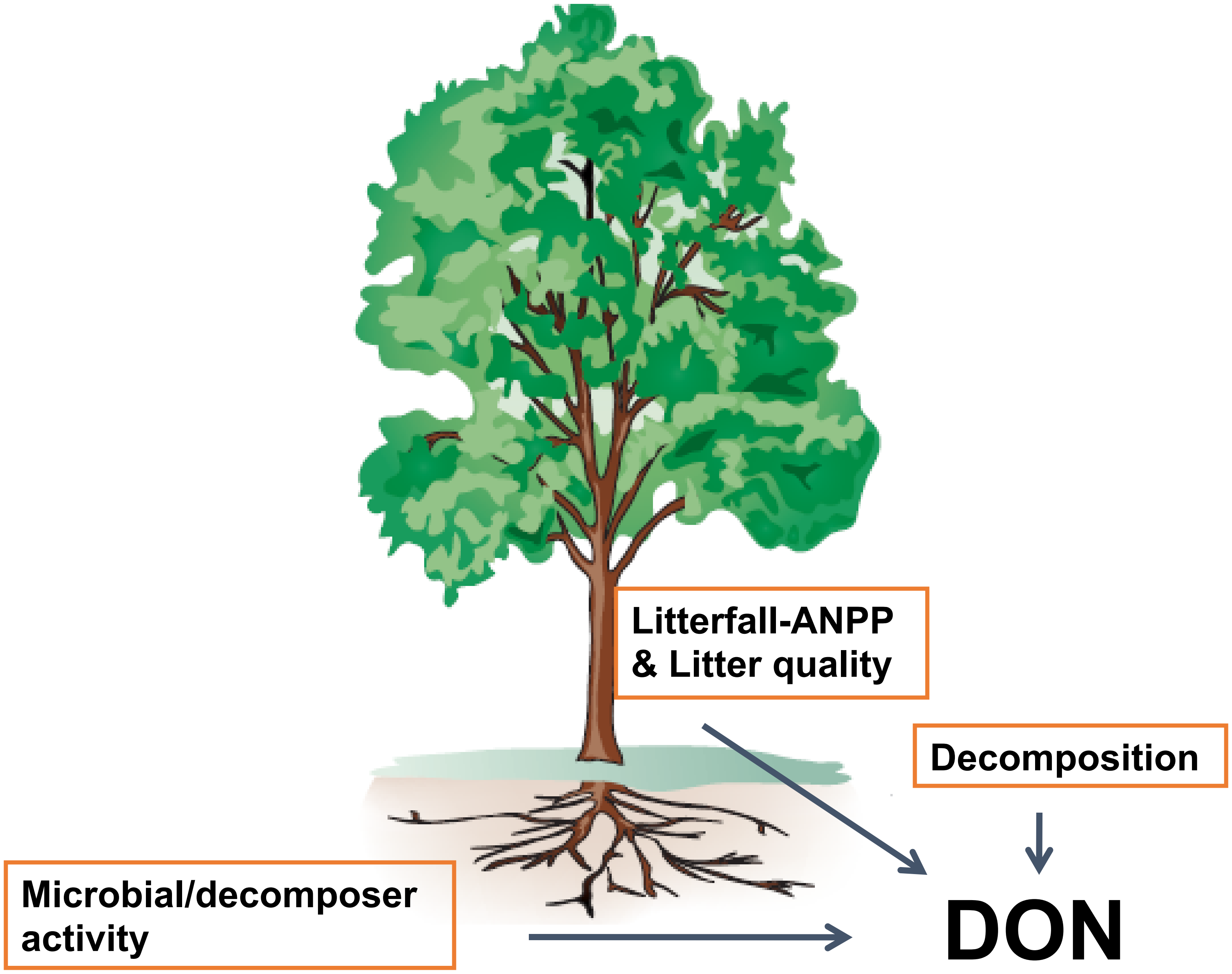
Gross Mineralization = Total amount of N released by mineralization (NH_4^+ and NO_3^-)

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

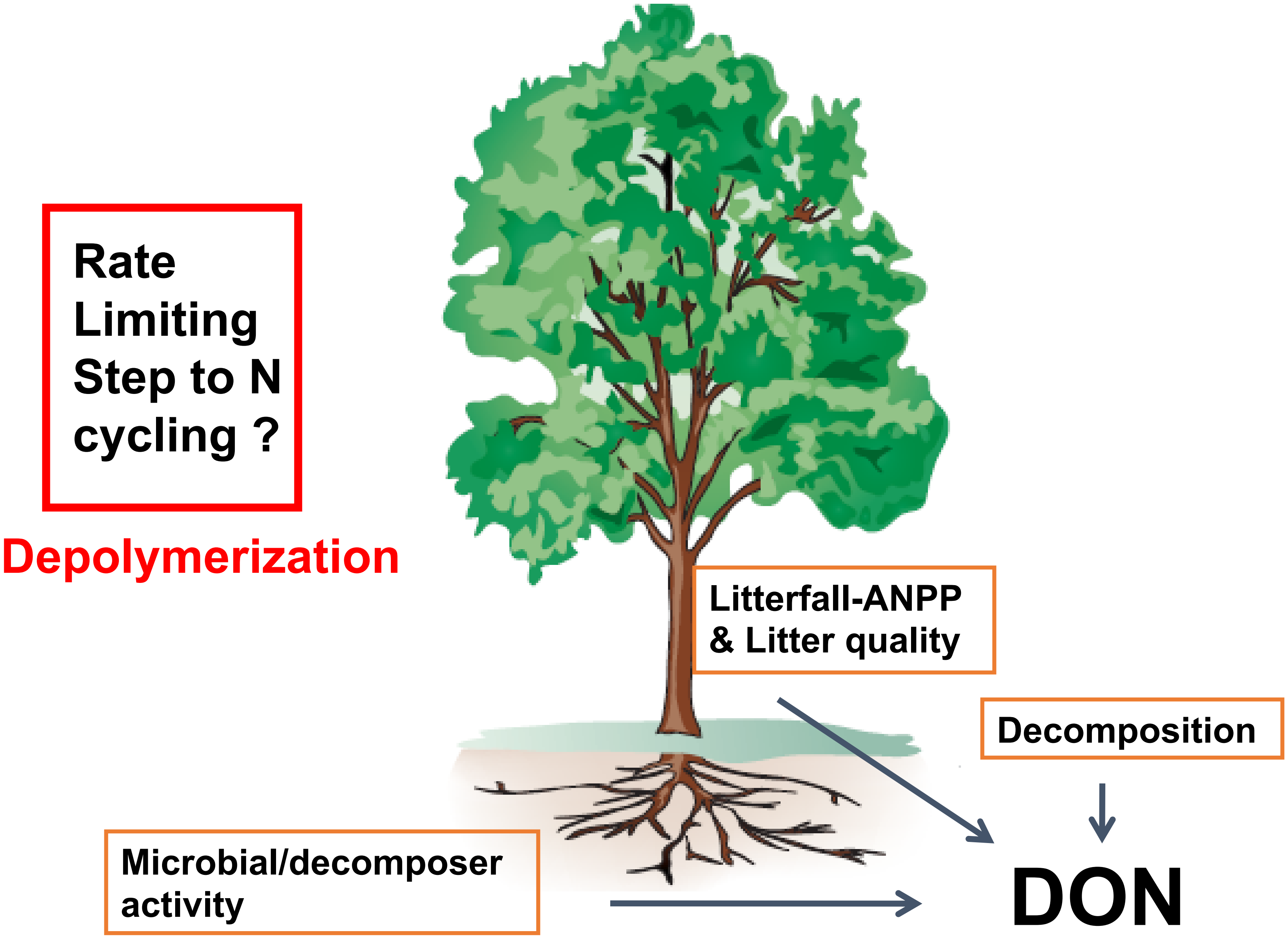
Net mineralization = available for plant uptake

Linking above- and belowground processes

Linkages between above- and belowground processes



Linkages between above- and belowground processes



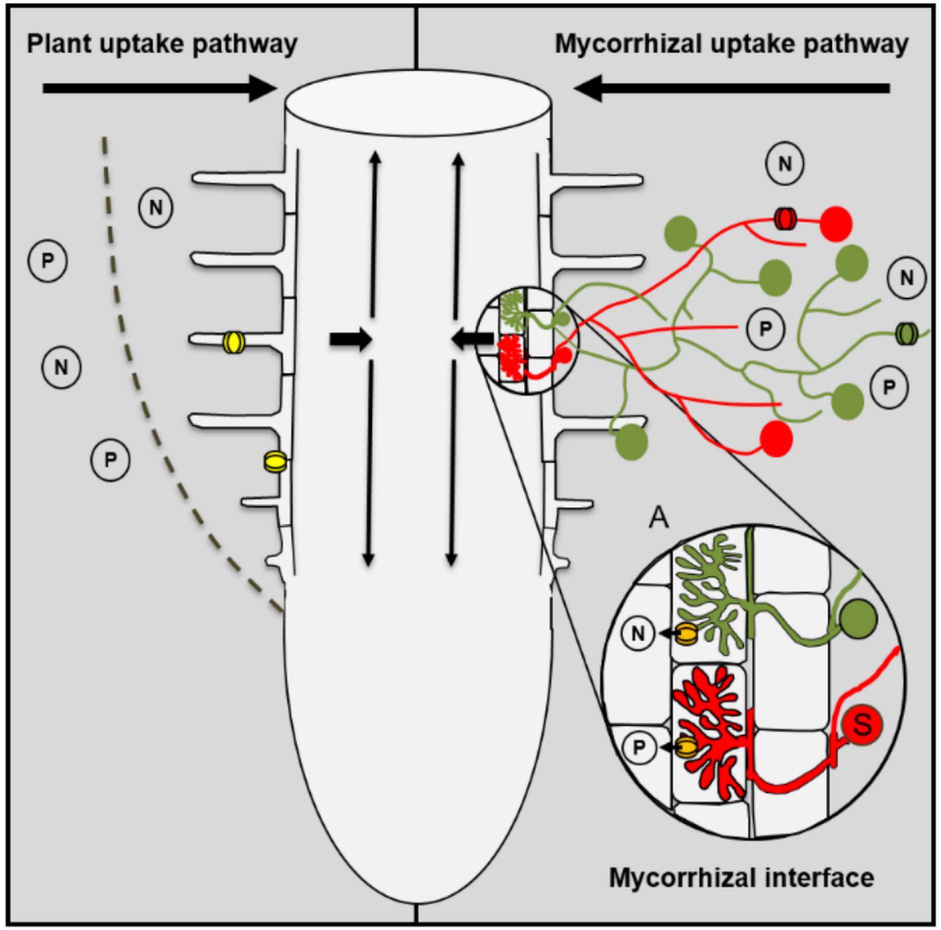
Fate of DON???

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

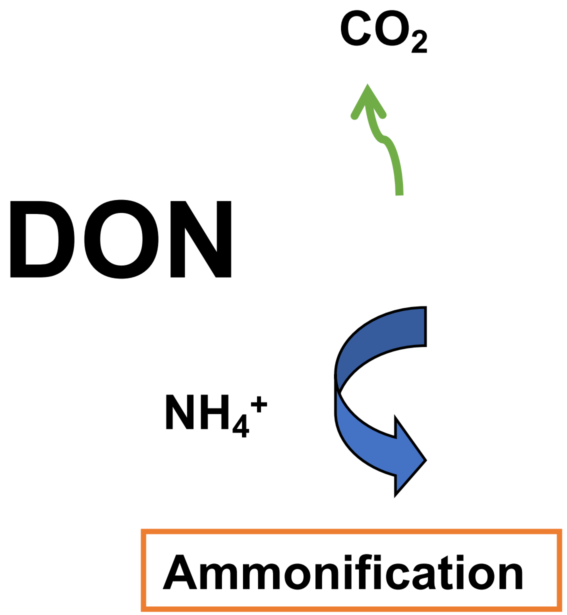
•N Mineralization results from microbial break-down of DON

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

Organic-N ($R\text{-}NH_2$) → **NH_4^+**

Mineralization (ammonification)

Linkages between above- and belowground processes



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^+

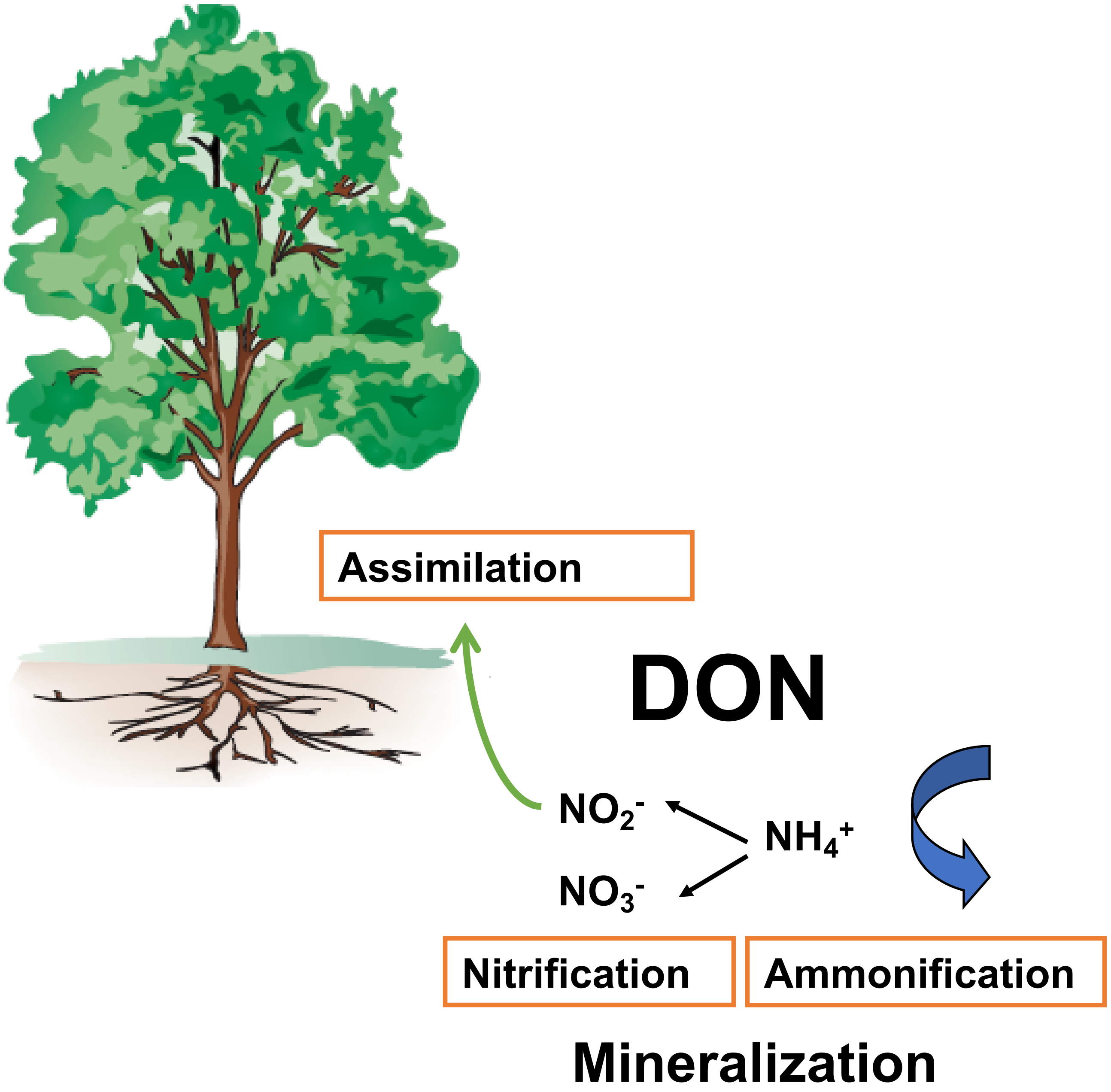
1. Nitrified by microbes
2. Assimilated up by microbes (not too common)
3. Assimilated up by plants (not too common)
4. Leached (not too common)

Fate of NO_3^-???

Fate of NO_3

1. Assimilated by plants

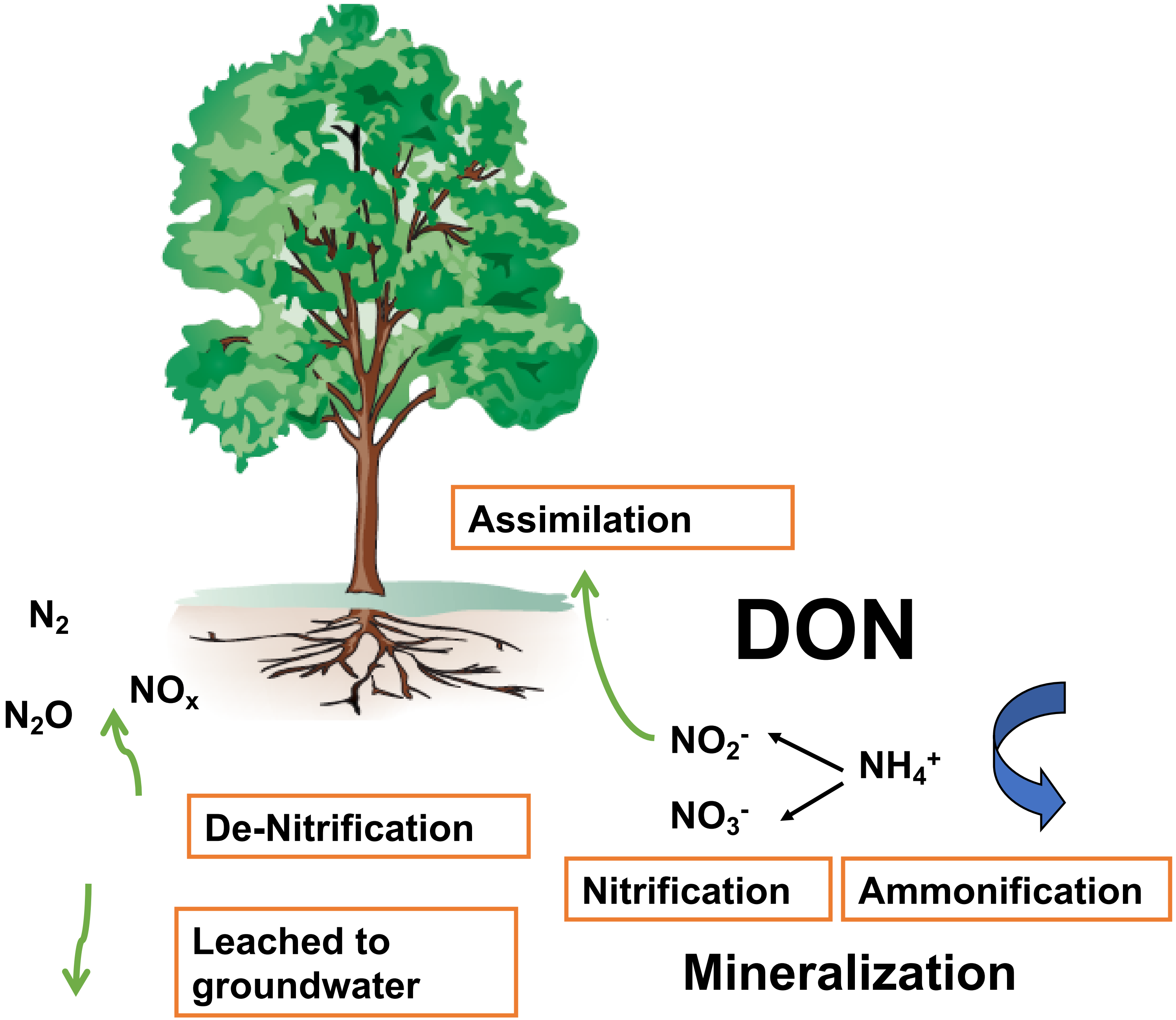
Linkages between above- and belowground processes



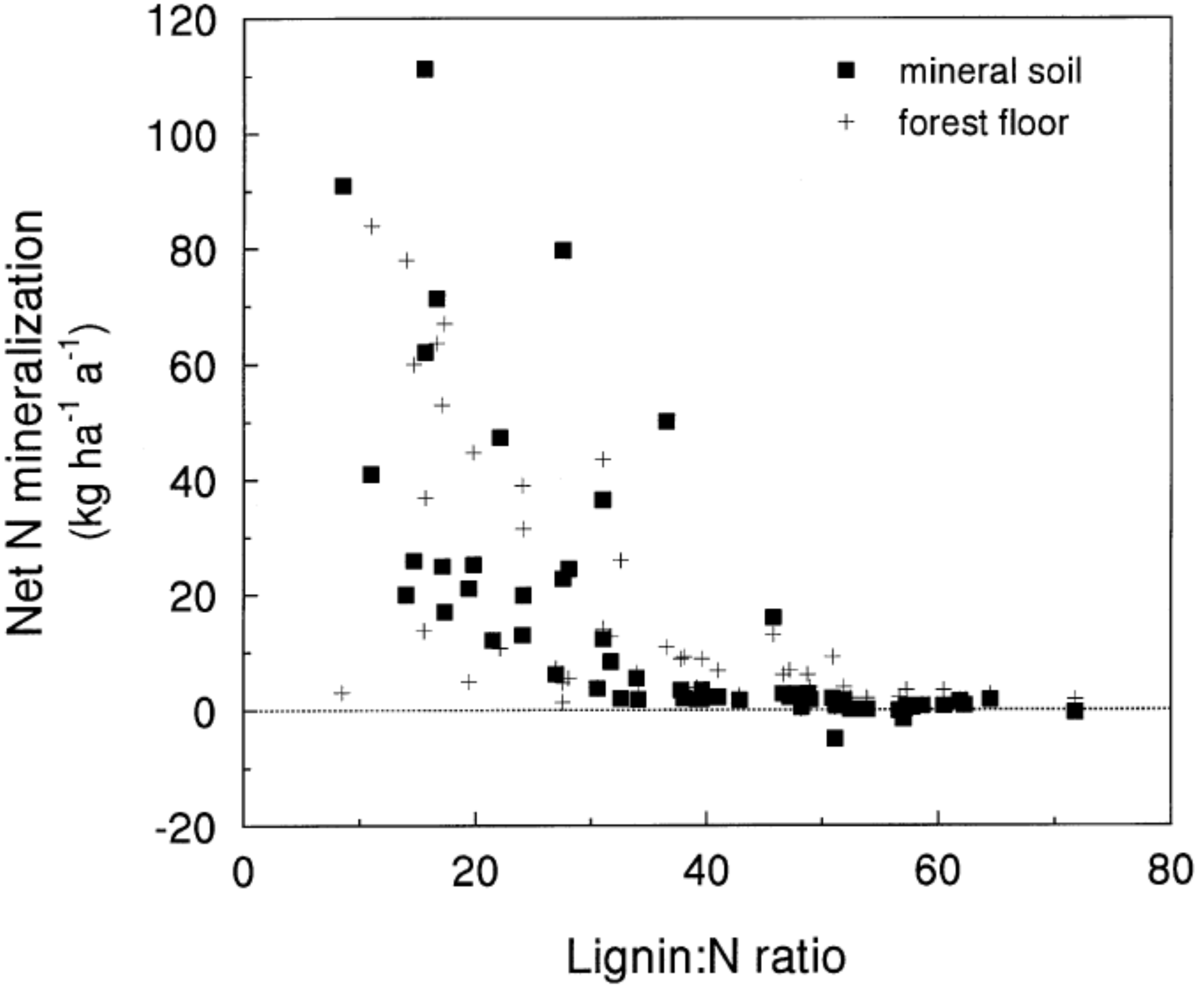
Fate of NO_3

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

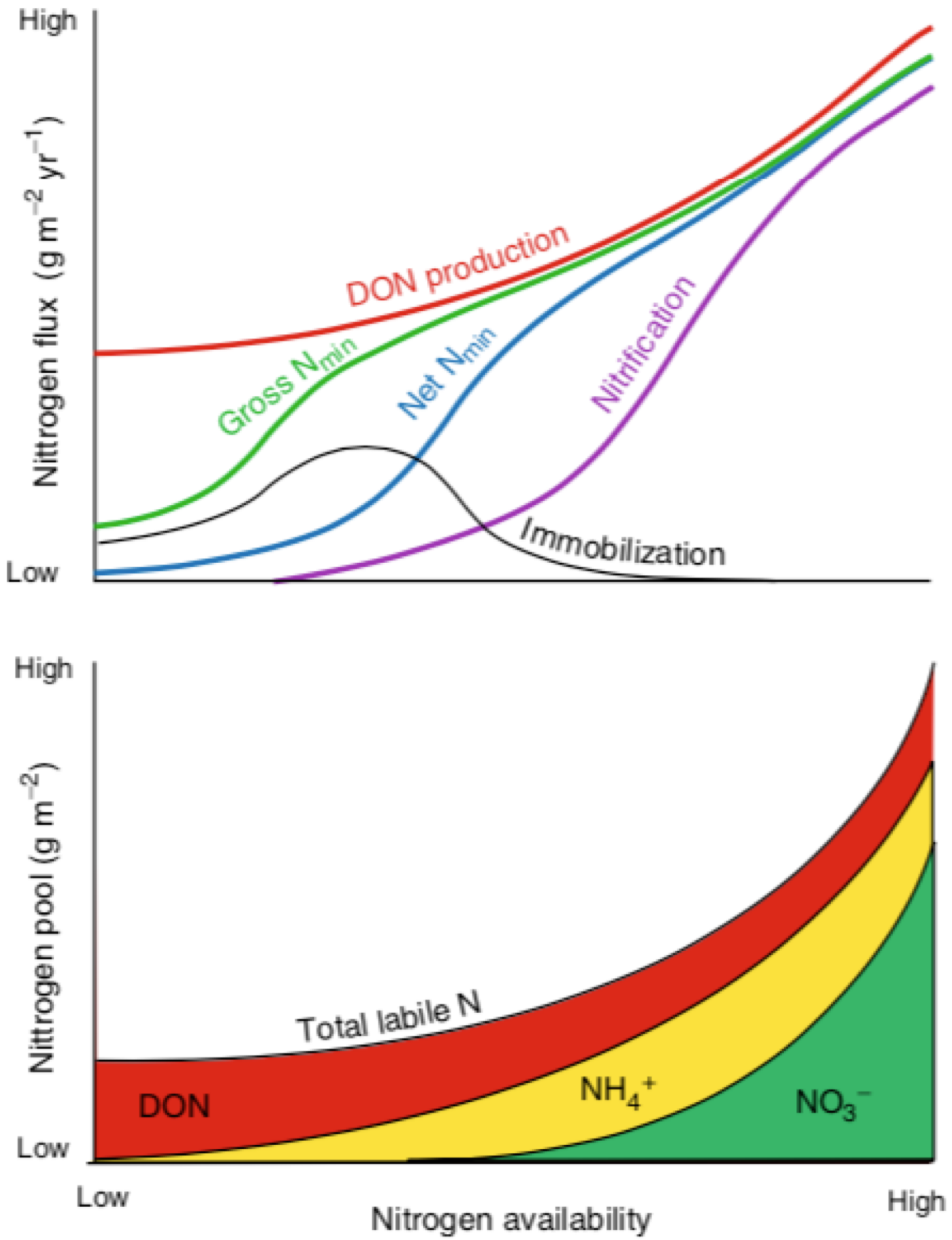
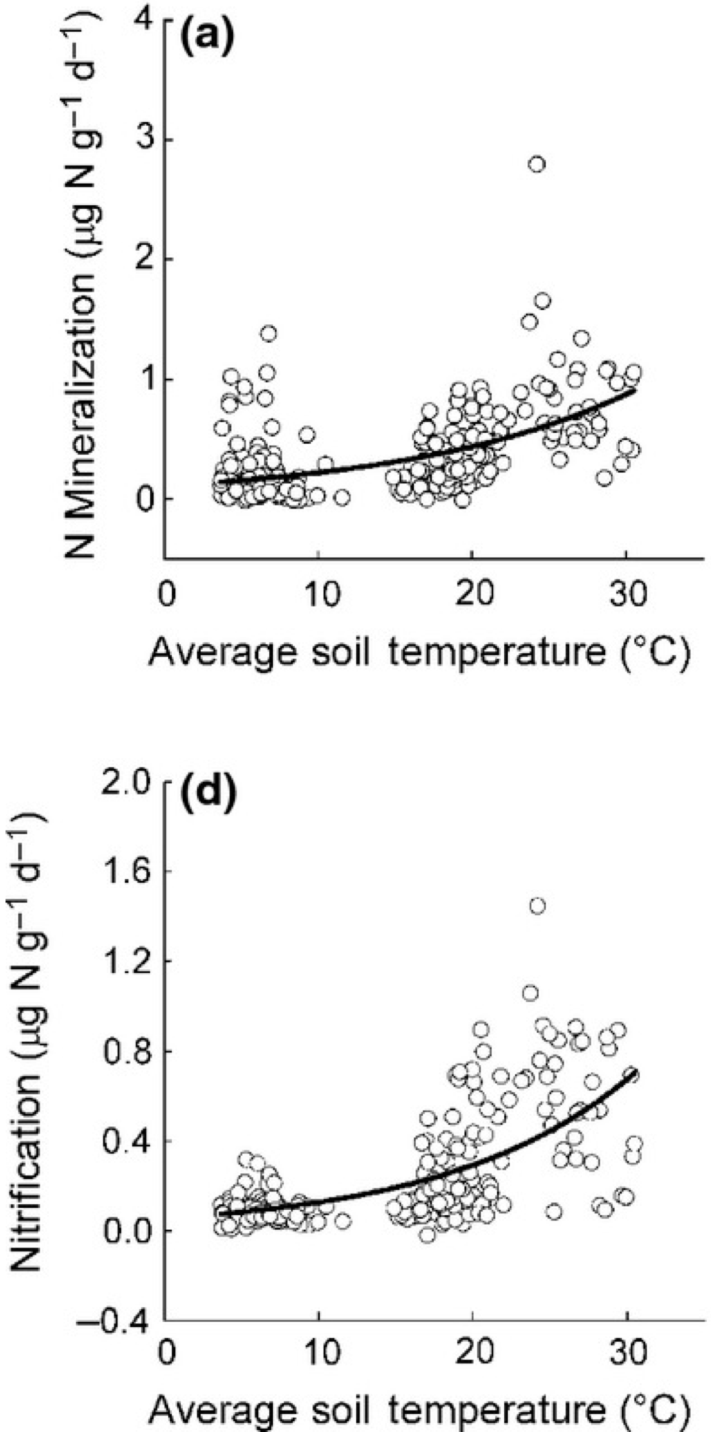


Fig. 9.7 Effect of nitrogen availability on the pools and fluxes of major forms of available nitrogen (dissolved organic nitrogen [DON], ammonium, and nitrate)



Temperature increases N cycling