# Nutrient Cycling 1: The nitrogen cycle

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Powerpoint modified from Harte & Hungate (http://www2.for.nau.edu/courses/hart/for479/notes.htm)
and Chapin (http://www.faculty.uaf.edu/fffsc/)

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I. Intro to the Nitrogen Cycle

Productivity of many ecosystems (managed & unmanaged) is limited by nitrogen availability:

terrestrial – temperate, boreal, arctic
aquatic – open oceans

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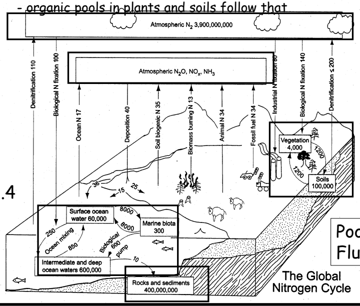
A. Global Pools:

- most in the atmosphere, but not biologically available
- reactive N in atmosphere: trace gases
- lots in sediments and rocks, but not available
- inorganic N in ocean is next largest
- organic pools in plants and soils follow that



15.4

Pools in Tg = $10^{12}$ g
Fluxes in Tg $yr^{-1}$

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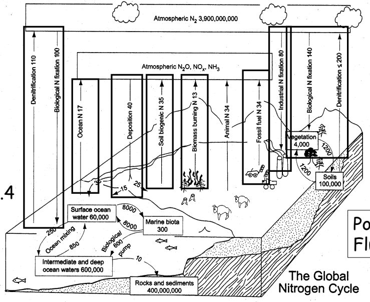
Fluxes: several important biosphere-atmosphere N exchanges

- biological: fixation, denitrification, nitrification
- abiotic: industrial fixation, lightning fixation, fossil fuel and biomass burning, deposition



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Pools in Tg
Fluxes in Tg $yr^{-1}$

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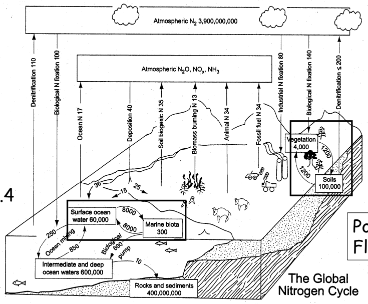
Biological cycling within systems greatly outweighs inputs/outputs (i.e., N cycle is much more "closed" than the C cycle)



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Pools in Tg
Fluxes in Tg $yr^{-1}$

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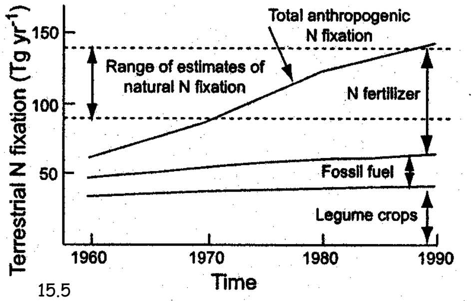
B. Human-mediated fluxes in the global N cycle now exceed 'natural' (pre-industrial) fluxes



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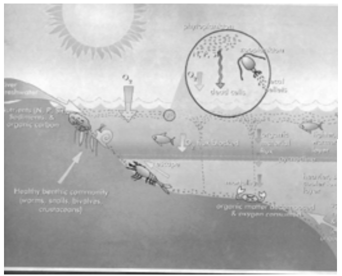
How much N is added in agriculture?

Cotton 56-78 Kg/ha

- Iowa corn 170-225 Kg/ha
- Taiwan rice: 270 Kg/ha

# C. Consequences

- Eutrophication
- Species changes/losses
- Atmospherically active trace gases

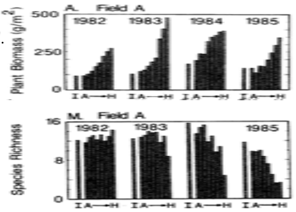


# Consequences

- Eutrophication
- Species changes/losses
- Atmospherically active trace gases

N fert → increasing prod.

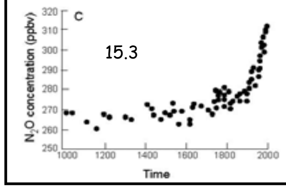
N fert → increasing dominance, decreasing diversity



Tilman 1987

# Consequences

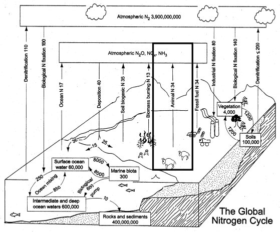
- Eutrophication
- Species changes/losses
- Atmospherically active trace gases
  - NO + $NO_2$ ($NO_x$): fossil fuel combustion
    - NO (highly reactive) → smog, tropospheric $O_3$ formation
    - Acid rain ($NO_2 + OH^- \rightarrow HNO_3$)
  - $N_2O$: increased fertilizer application → denitrification
    - Potent greenhouse gas (200x more effective than $CO_2$, 6% of total forcing)
    - Chemically inert in troposphere, but catalyzes destruction of $O_3$ in stratosphere
  - $NH_3$



15.3

# Consequences

- Eutrophication
- Species changes/losses
- Atmospherically active trace gases
  - $NH_3$: domestic animals, ag fields (fert), biomass burning
    - Atmospherically active → aerosols, air pollution
    - Deposition, N availability downwind



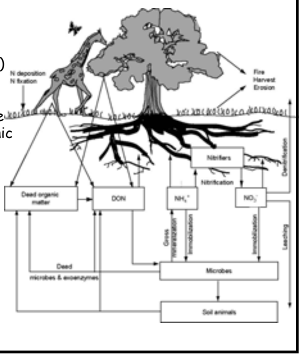
15.4

# Consequences

- N deposition → increased growth (C sequestration)…to a point.
- N saturation: availability exceeds demand
  - Associated with decreases in forest productivity, potentially due to indirect effects such as acidification, altered plant cold tolerance
- N saturation → N losses → “opening” of the N cycle

## B. Overview of Ecosystem N cycle (Ch. 9)

1. Major pools & fluxes
2. Main Points
   1. Inputs~outputs
   2. Open (C) vs. closed (N)
   3. Plant needs met by internal recycling
   4. Available soil pools are small relative to organic pools.
   5. Microbes rule bg



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## II. Controls on N cycle fluxes in soil
## A. N Inputs

1. Biological N fixation
2. Atmospheric N deposition
3. Mineral weathering?

## 1. Biological N Fixation

a. What is it?

- Conversion of atmospheric $N_2$ to $NH_4^+$ (actually, amino acids)
- Under natural conditions, nitrogen fixation is the main pathway by which new, available nitrogen enters terrestrial ecosystems

## Nitrogen fixation

b. Who does it?

- Carried out by bacteria
  - Symbiotic N fixation (e.g., legumes, alder)
  - Heterotrophic N fixation (rhizosphere and other carbon-rich environments)
  - Phototrophs (bluegreen algae)
- The characteristics of **nitrogenase**, the enzyme that catalyzes the reduction of $N_2$ to $NH_4^+$, dictate much of the biology of nitrogen fixation
  - High-energy requirement (N triple bond)
    - Requires abundant energy and P for ATP
  - Inhibited by $O_2$
  - Requires cofactors (e.g., Mo, Fe, S)

## Types of N-fixers

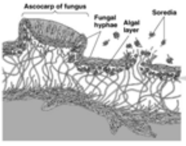
- There's no such thing as a N-fixing plant
- Symbiotic N-fixers
  - High rates of fixation (5-20+ g-N $m^{-2}$ $y^{-1}$) with plants supplying the C (and the plant receiving N)
  - Protection from $O_2$ via leghemoglobin (legumes)
  - Microbial symbiont resides in root nodules
    - Bacteria (*Rhizobia*) – Legumes (*Lupinus*, *Robinia*)
    - Actinomycetes (*Frankia*) - *Alnus*, *Ceanothus* (woody non-legumes)
  - N-fixation rates reduced in presence of high N availability in the soil

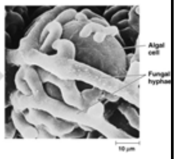
## Types of N fixers

- Associative N fixers
  - Occur in **rhizosphere** of plants (non-nodulated); moderate rates with C supply from plant root turnover and exudates (1-5 g-N $m^{-2}$ $y^{-1}$)
  - Reduced $[O_2]$ by rapid respiration from plant roots
  - *Azotobacter*, *Bacillus*

## Types of N fixers

- Free-living N fixers
  - Heterotrophic bacteria that get organic C from environment and where N is limiting (e.g., decaying logs)
  - Rates low due to low C supply and lack of $O_2$ protection (0.1-0.5 g-N $m^{-2}$ $y^{-1}$)
- Also, **cyanobacteria** (free-living photo-autotrophs); symbiotic **lichens** (cyanobacteria with fungi offering physical protection)





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C. When/where does it happen? N-fixing species are common in early succession

- Lichens early in primary succession following deglaciation in Alaska.
- Alder at later stages.

Photo: D. Hooper

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## Red alder in secondary succession following clearcutting near Lake Whatcom

Photo: D. Hooper

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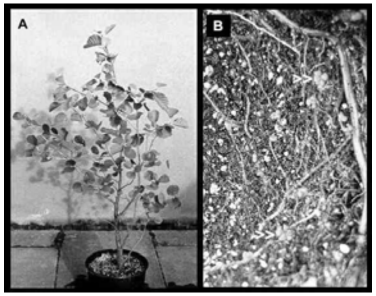
Alder and the other woody hosts of *Frankia* are typical pioneer species that invade nutrient-poor soils. These plants probably benefit from the nitrogen-fixing association, while supplying the bacterial symbiont with photosynthetic products.



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## d. Paradox of N limitation

- Nitrogen is the element that most frequently limits terrestrial NPP
- $N_2$ is the most abundant component of the atmosphere
- Why doesn't nitrogen fixation occur almost everywhere?
- Why don't N fixers have competitive advantage until N becomes non-limiting?

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## Environmental limitations to N fixation

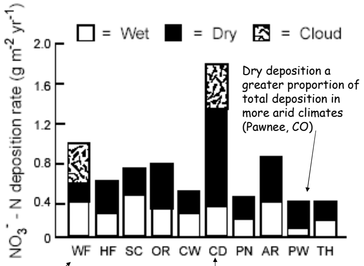
- Energy availability in closed-canopy ecosystems
  - N-fixers seldom light-limited in well-mixed aquatic ecosystems (e.g., lakes)
- Nutrient limitation (e.g., P, Mo, Fe, S)
  - These elements may be the ultimate controls over N supply and NPP
- Grazing
  - N fixers often preferred forage

## A. Inputs
## 2. Nitrogen Deposition

- **Wet deposition**: dissolved in precipitation
- **Dry deposition**: dust or aerosols by sedimentation (vertical) or impaction (horizontal)
- **Cloud water**: water droplets to plant surfaces immersed in fog; only important in coastal and mountainous areas

Wet deposition typically scales with precipitation.

Dry deposition can be significant even in humid climates.

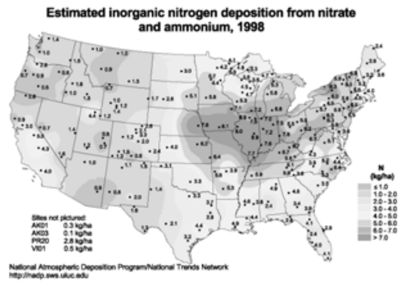


Dry deposition a greater proportion of total deposition in more arid climates (Pawnee, *CO*)

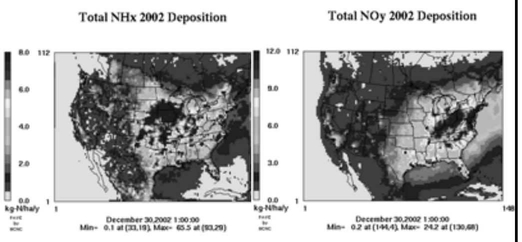
Adirondacks

Appalachians

## Deposition depends on upwind sources



## N species in deposition depends on type of source



http://pah.cert.ucr.edu/aqm/ndep/results.shtml

## 3. Rock weathering as a source of N?

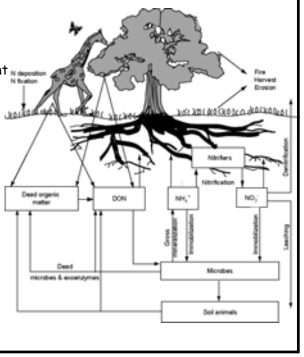
- Some sedimentary rocks contain substantial amounts of N with high rates of N release (up to 2 g-N $m^{-2}$ $y^{-1}$); however, most rocks contain little N.

## B. Internal Cycling of Nitrogen

- In natural ecosystems, most N taken up by plants becomes available through decomposition of organic matter
  - Over 90% of soil nitrogen is organically bound in **detritus** in a form unavailable to organisms
  - The soil microflora secrete **extracellular enzymes** (**exoenzymes**) such as proteases, ribonucleases, and chitinases to break down large polymers into water-soluble units such as amino acids and nucleotides that can be absorbed

## Internal Cycling of Nitrogen

- **The pools**
  - Plant biomass
  - SOM (solid; including litter)
  - Microbial biomass
  - DON (a variable portion "plant available")
  - $NH_4^+$ (plant available)
  - $NO_3^-$ (plant available)
- **The processes**:
  - (Gross) N ***mineralization***
  - (Gross) N ***immobilization***
  - (Gross) ***autotrophic nitrification***
  - N ***uptake (and assimilation) by plants***



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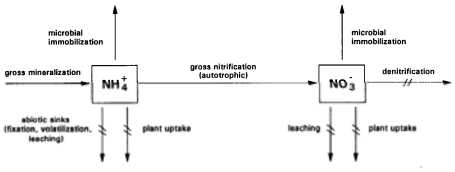
## Net Ain't Gross

- **Net rates of N transformations** (mineralization and nitrification)

Net N mineralization = $\Delta$ ($NH_4^+$ +$NO_3^-$ pools)
= gross N mineralization-gross N immobilization



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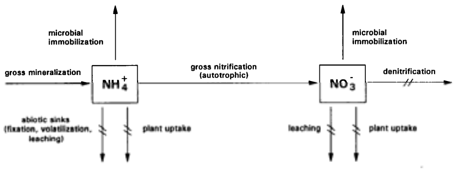
## Net Ain't Gross

- Similarly…

Net nitrification = $\Delta$ $NO_3^-$ pool
= gross nitrification – gross $NO_3^-$ immobilization



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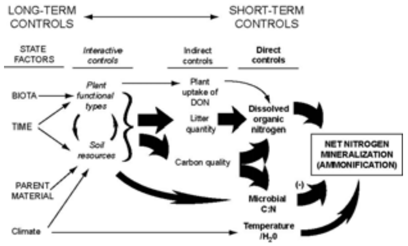
## 1. Mineralization/immobilization

-Mineralization is closely linked to decomposition.
-Plant functional types: effects via litter quality influence on both breakdown of plant material and immob by microbes.
-Climate affects mineralization via decomposition (microbial activity).
-Species effects can be much greater than differences in climate.



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## Critical litter C:N for net N min. (box 9.1)

- Microbial C:N ~10:1
- Microbial growth efficiency ~40%
- So, for 100 units C, 40 units → mic biomass, 60 units respired.
- For mic C:N of 10:1, need 4 units of N per 40 units C.
- So substrate needs C:N of 100:4 (i.e., 25:1) for net N mineralization.

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## 2. Nitrification
## a. Why is Nitrification Important?

- Nitrate is more mobile than ammonium, so more readily leached from soil
- Substrate for denitrification (N loss as a gas)
- Generates acidity if nitrate is lost from soil
- Loss of nitrate results in loss of base cations

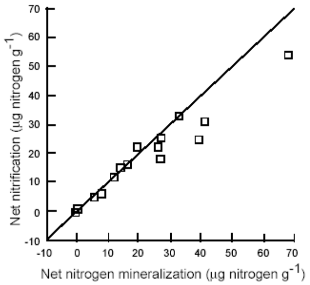
## 2.b. Controls on Nitrification

- $NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$
  - Two-step process conducted by chemoautotrophic bacteria:
    - First step conducted by *Nitrosomonas* (other Nitroso-), $NH_4^+ \rightarrow NO_2^-$ , ammonia mono-oxygenase, need $O_2$
    - Second step conducted by *Nitrobacter*, $NO_2^- \rightarrow NO_3^-$
  - Controls:
    - $NH_4^+$
    - $O_2$
    - Slow growth of nitrifiers

Nearly all nitrogen that is mineralized in these systems is nitrified on a net basis.

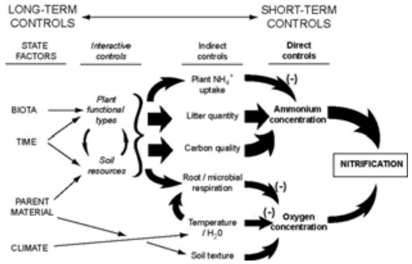
-In contrast, net nitrification is frequently less than 25% of net mineralization in temperate coniferous forests.

- Semi-arid forests tend to show more net nitrification relative to net N mineralization



9.6 - The relationship between net nitrogen mineralization and net nitrification (µg nitrogen g-1 of dry soil for a 10-day incubation) across a range of tropical forest ecosystems (Vitousek and Matson 1984).

- Substrate limitation is common.
- Nitrifiers are obligate aerobes.



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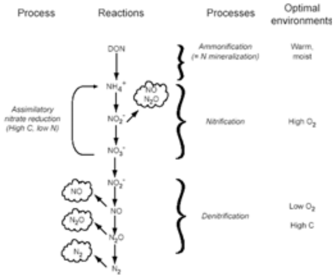
## C. N outputs

1. Gaseous losses
   - Ammonia gas (pK = 8.2, $NH_4^+ \rightarrow NH_3 + H^+$)
   - Fire
   - Oxides of N (NO, $N_2O$, $N_2$)
     - **NO** and $N_2O$ from autotrophic nitrification
     - NO, **$N_2O$, $N_2$** from denitrification
   - Most denitrification conducted by heterotrophic bacteria (many are facultative anaerobes that use $NO_3^-$ as a terminal $e^-$ acceptor in the absence of $O_2$)
     - Controls: $NO_3^-$, *C* availability, $O_2$,

- Nitrification and denitrification occur under different conditions.
- Gaseous losses for both follow the “hole-in-the-pipe” model.
- H-in-the-P depends on rate of flux and percent of losses.



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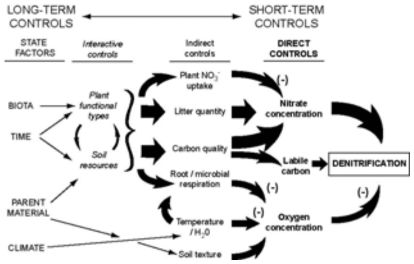
-High nitrate concentration, much labile *C*, and lack of oxygen together lead to high denit. rates.



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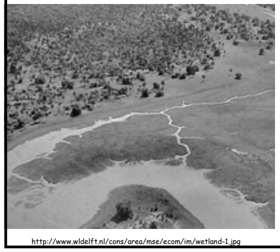
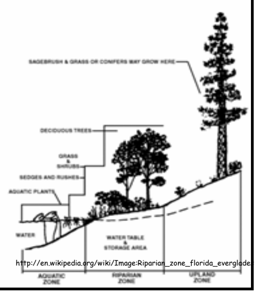
## Denitrification – where?

- Very important in wetlands, riparian areas.
- Spatially very patchy in well-drained soils.



http://www.wldelft.nl/cons/area/mse/ecom/im/wetland-1.jpg



http://en.wikipedia.org/wiki/Image:Riparian_zone_florida_everglade

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## C. N outputs
## 2. Leaching

- Erosional losses
- Solution losses
  - $NO_3^-$ >> DON >$NH_4^+$
  - Greatest when water flux is high and biological demand for N is low (e.g., after snowmelt!)

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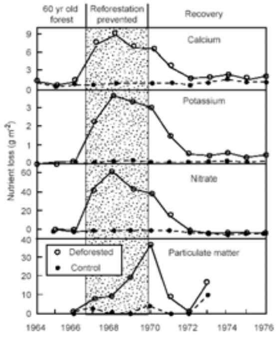
- Leaching losses of nitrate and cations decrease with forest regrowth at Hubbard Brook.
- Plant **and** microbial demand



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-Leaching increases when plant and microbial demand are exceeded (e.g., N saturation).

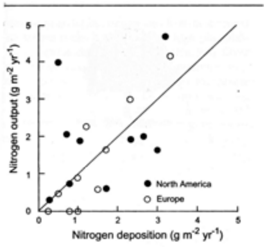

FIGURE 9.9. Comparisons of inputs from nitrogen deposition and nitrogen outputs in solution from forests of North America and Europe. There is a strong relationship between inputs and outputs in nitrogen-saturated ecosystems. (Data from Tietema and Beier 1995, Fenn et al. 1998.)

Fig. 9.9

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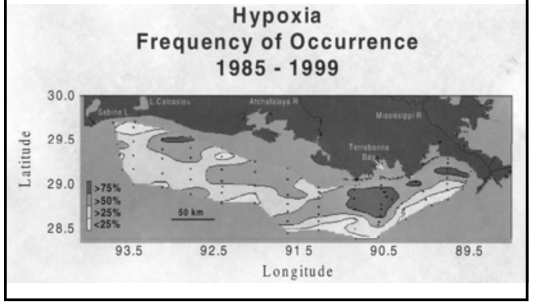
## Consequences of Mississippi River N runoff: The Gulf of Mexico "Dead Zone"



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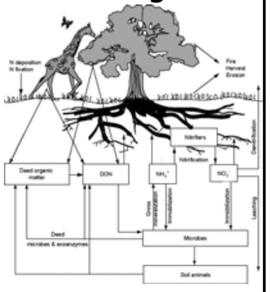
## Summary: small → big

- Controls on mineralization (C quality, AET) are similar to those for decomposition, and this is the major source of plant nutrients for natural ecosystems.
- Humans are influencing N inputs to ecosystems: N fixation, N deposition.
- Higher N availability → greater plant growth, until demand saturates.
- Microbes compete with plants for available N.
- Presence of substrate ($NH_4^+$) is a major controller of nitrification; nitrate is much more susceptible to loss than ammonium.
- Losses of N cause
  - Nitrate and nitrite pollution in groundwater (toxicity)
  - Chemically active N species ($NO_x$) in atmosphere
  - Radiatively active N species ($N_2O$) in atmosphere
  - Increased output to aquatic ecosystems (eutrophication).



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