Theoretical concepts and complexity in the soil carbon and nitrogen cycles

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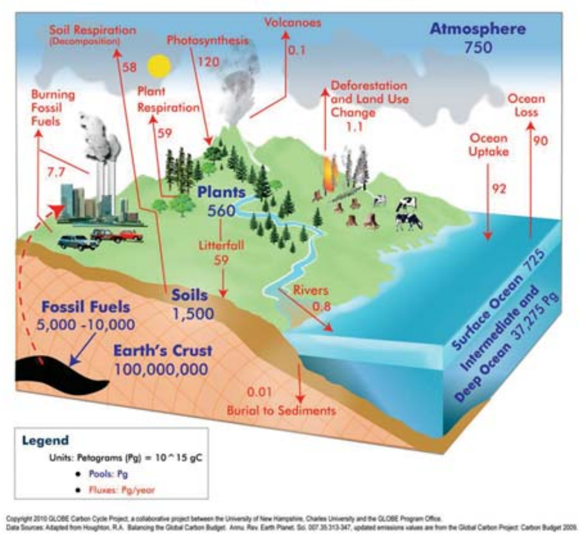
Objective

- Identify the <u>sequence of biological processes</u> that occur when materials containing C and N enter soil
- <u>Biological processes:</u> cascade of biochemical reactions, initiated by chemical signals and responses of genes that encode for enzymes
- We focus on <u>microbially-mediated processes</u>

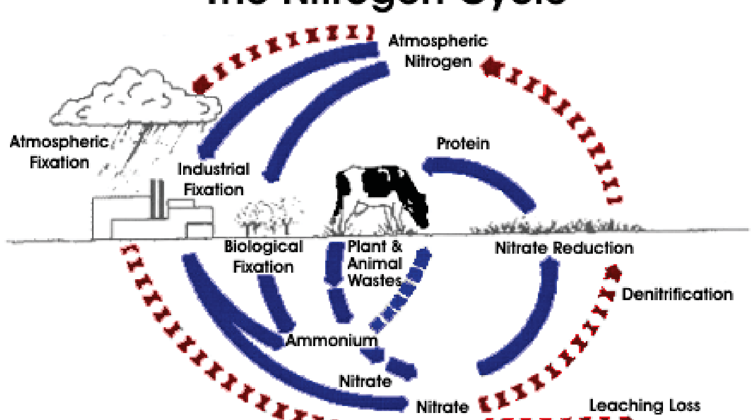
Expected Outcome

- Starting from our fundamental understanding the <u>biological processes</u>, we can then add complexity to the system
  - Change soil conditions (e.g., texture, porosity)
  - Modify environmental conditions (e.g., temperature, moisture)
  - Add other organisms (including plants)
  - Extrapolate to larger spatial and longer temporal scales

Global Carbon Cycle



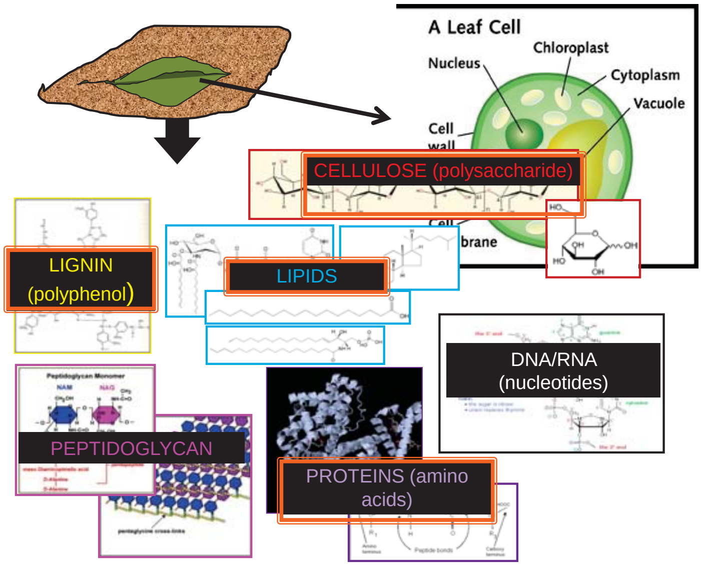
The Nitrogen Cycle

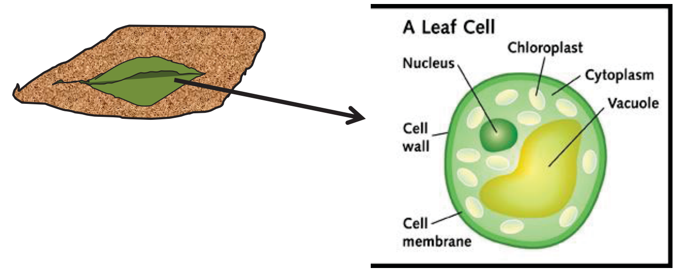


Source: O'Leary et al., 1997.

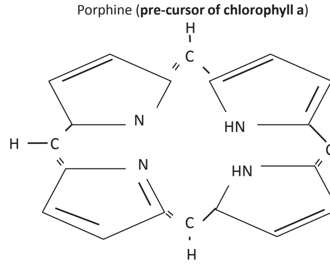
Challenges

- Why are C and N cycles "disconnected"?
- In nature, the C and N cycles are tightly linked… all N compounds are bound to C compounds (C-N bond).
- We will put the cycles together by considering a simple story – how does a leaf decompose?



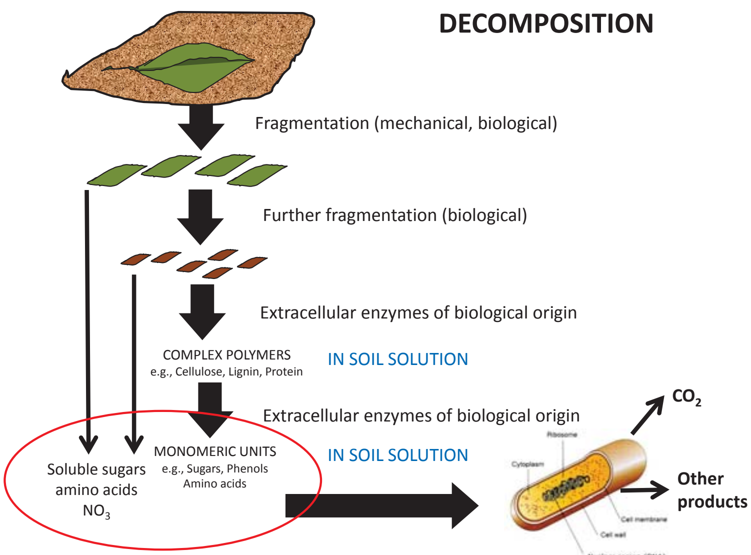


Porphine (**pre-cursor of chlorophyll a**)

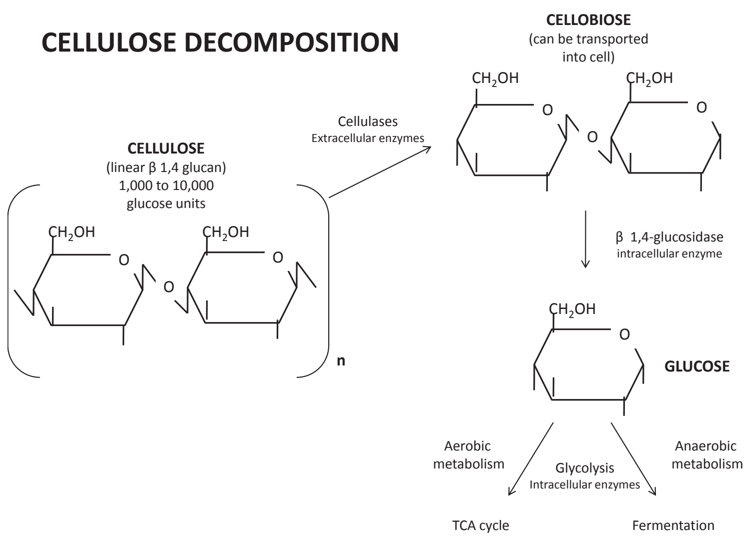


<u>Vaculole</u> contains soluble sugars (C) and NO_3
<u>Chloroplast</u> contains chlorophyll
<u>Nucleus</u> contains DNA, nucleic acids, proteins
<u>Cytoplasm</u> contains mix of C and N compounds
<u>Cell membrane</u> contains C-rich phospholipids, also [illegible]in channels
<u>Primary cell wall</u> contains cellulose, hemicellulose and pectin (C-rich compounds)
<u>Secondary cell wall</u> contains cellulose and lignin (C-rich compounds)

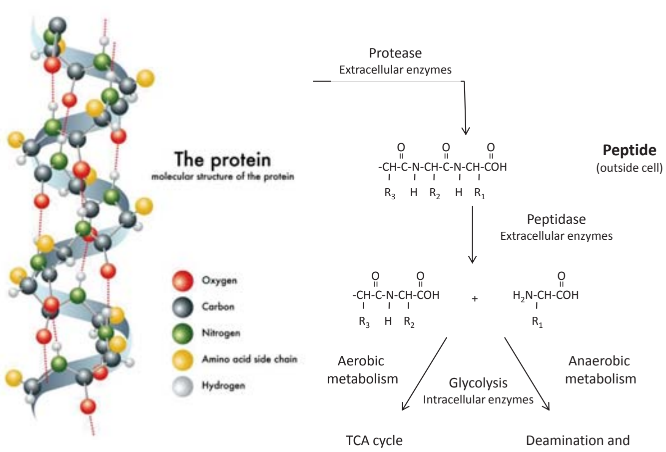
DECOMPOSITION



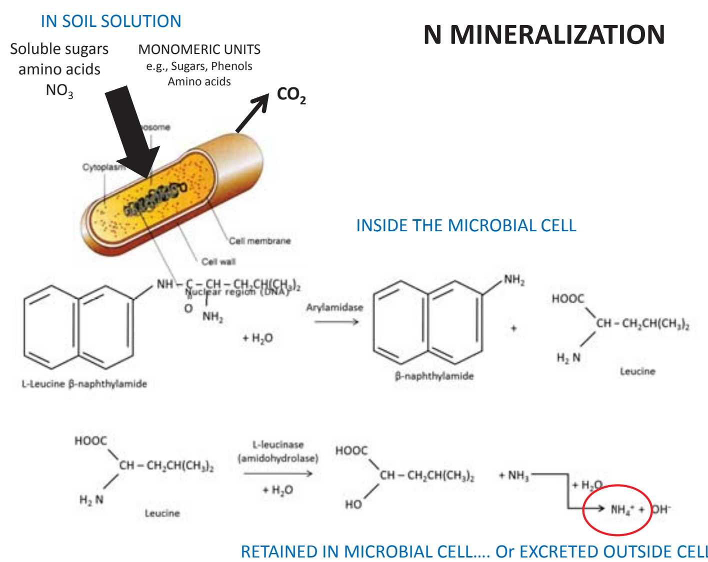
CELLULOSE DECOMPOSITION



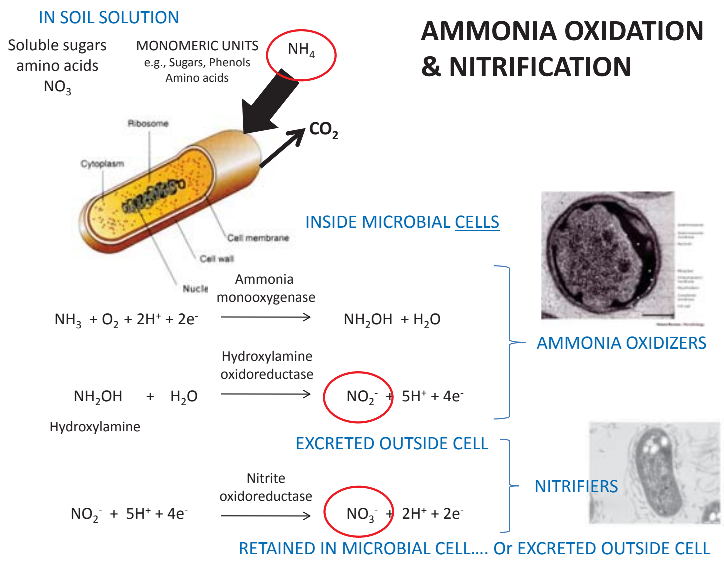
PROTEIN DECOMPOSITION



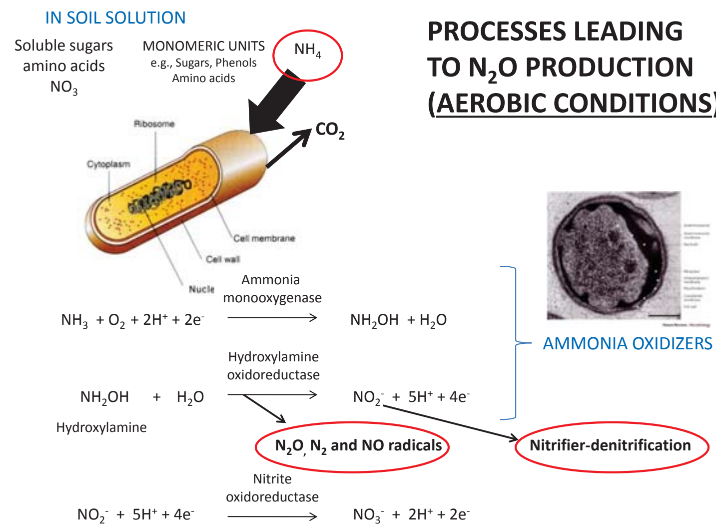
N MINERALIZATION

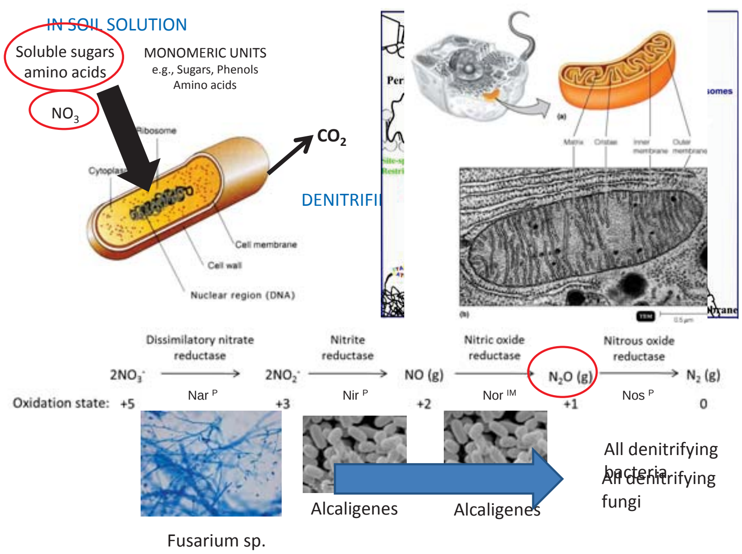


AMMONIA OXIDATION & NITRIFICATION



PROCESSES LEADING TO N_2O PRODUCTION (AEROBIC CONDITIONS)

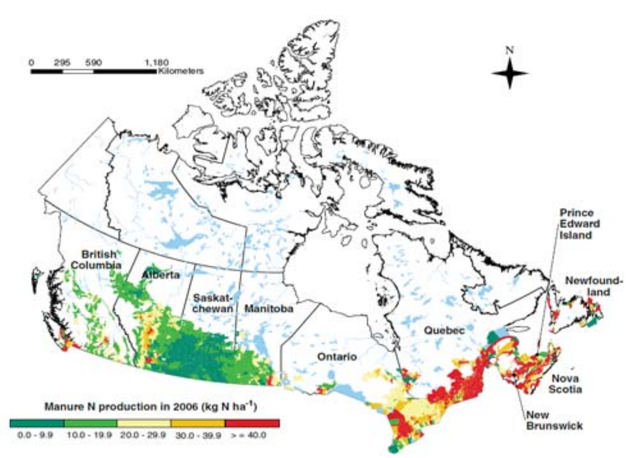




Student presenters

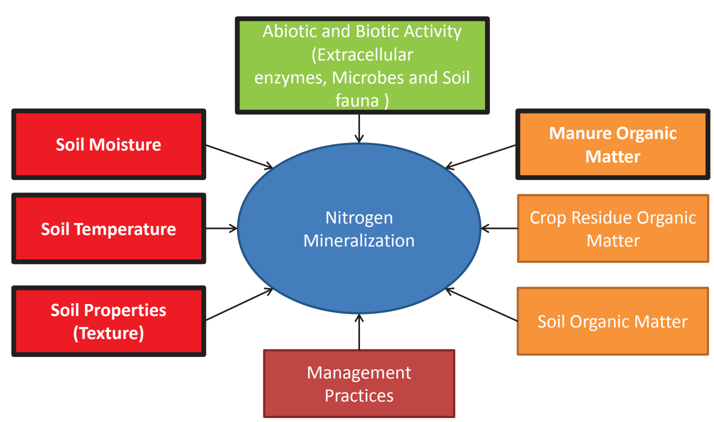
- Starting from our fundamental understanding the biological processes, we can then add complexity to the system
  - Change soil conditions (e.g., texture, porosity)
  - Modify environmental conditions (e.g., temperature, moisture)
  - Extrapolate to larger spatial and longer temporal scales

Manure Nitrogen Production



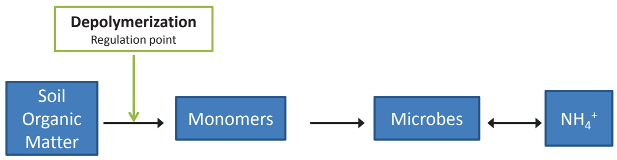
Yang et al. (2011)

Factors Influencing N Mineralization



Extracellular Enzyme Activity

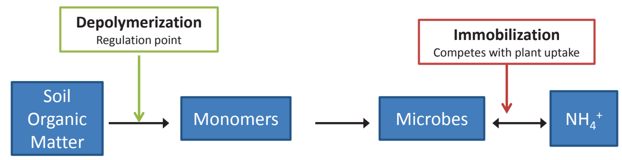
- Extracellular enzyme activity can be used to predict soil N mineralization
  - N-acetylglucosaminidase (NAGase) (Tabatabai 2010; Dyck 2012)
    - Cleaves peptidoglycan into amino sugar monomers



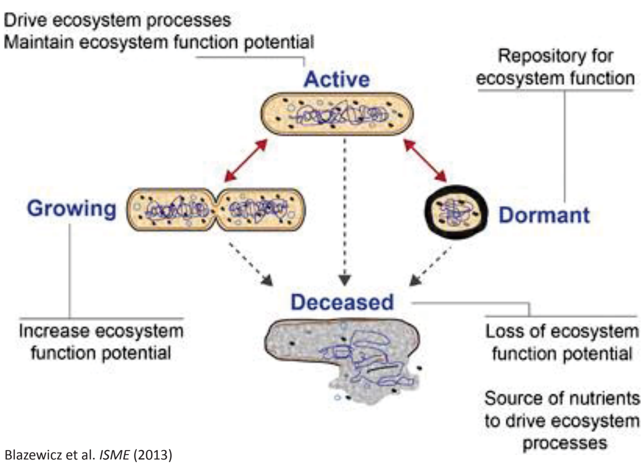
Schimel and Bennet *Ecology* (2004)

Two Microbial-Mediated Routes

- Direct Route
  - Microbes directly assimilate small monomeric compounds e.g. amino acids and amino sugars
- Mineralization – Immobilization – Turnover
  - Organic N must mineralize, then be immobilized and turnover to release N into the soil solution



Microbial turnover releases NH4 into soil solution



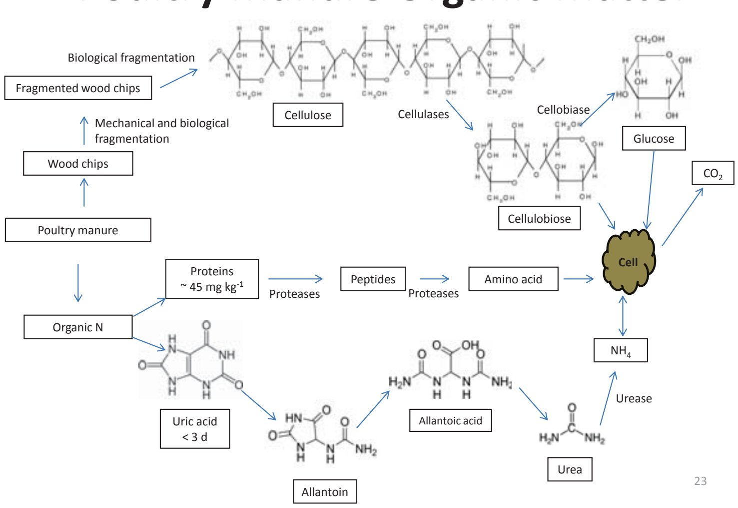
Blazewicz et al. *ISME* (2013)

Enzymes are produced by soil microbial communities

- Functional genes encode for the extracellular enzymes that hydrolyse organic N to NH4
- Present (DNA based) vs Potential microbial activity (RNA based)
- Functional capacity = presence of genes that encode for the enzymes
  - E.g. copiotropic vs oligotropic

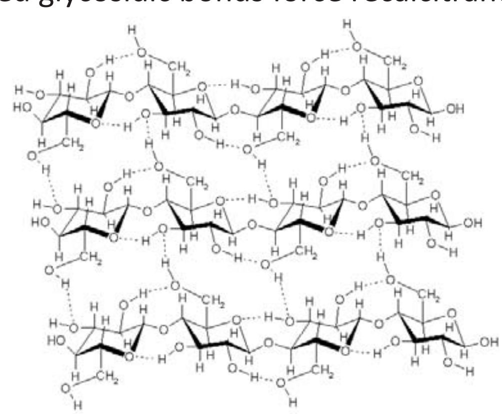
Blazewicz et al. *ISME* (2013)

Poultry Manure Organic Matter

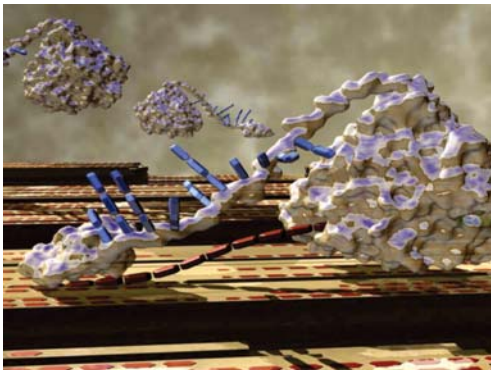


Crystalline Cellulose

- Buried glycosidic bonds force recalcitrance



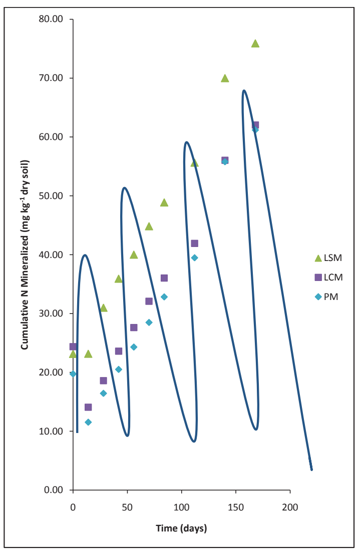
Process of Cellulose Depolymerization



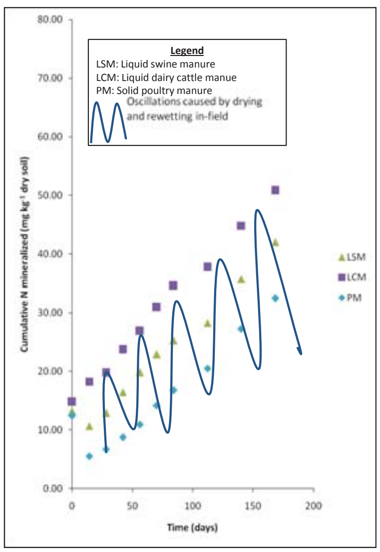
Himmel et al. *Science* (2007)

Environmental Conditions

- -Numerous studies indicate an effect of texture on N mineralization
- Drying and rewetting act as a dominant controls over N mineralization but do not seem to alter potential function Barnard et al. *ISME* (2013)
  - Fast response of the bacterial community
  - Fungal community - not so fast



Sandy soil



Clayey soil

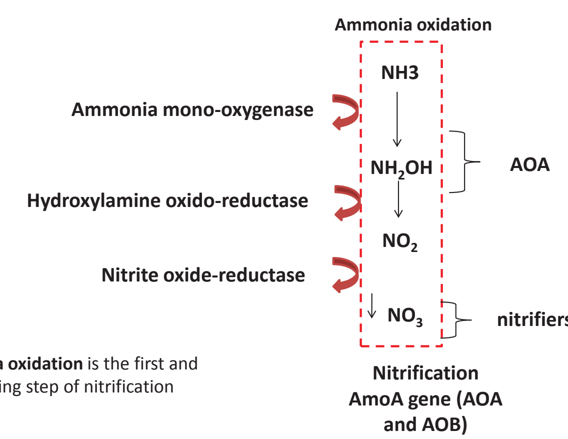
Nitrification

Nitrification

- Nitrification, the oxidation of ammonia (NH_3) to nitrate
- Drive soil nitrification
  - Ammonia-oxidizing archaea (AOA)
  - Ammonia-oxidizing bacteia (AOB)
- The *amoA* is a biomarker used to quantify A-oxidizers
- Archaeal *amoA* genes
- Bacterial amoA genes

Substrate affinity

Nitrification Pathway



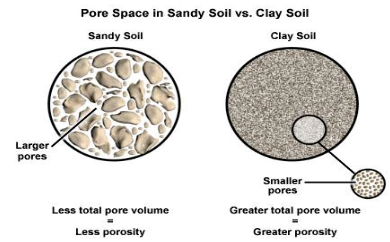
Ammonia oxidation is the first and rate-limiting step of nitrification

Microbial community interaction

- Soil pH
- Oxygen
- Climate factors
- Ammonia concentration in soil solution
- Soil texture

Soil texture

- Particle size
  - Clay <2mm in diameter
  - Sandy 0.02 - 2000mm
- Fine particles reduces hydraulic conductivity
  - http://wegc203116.uni-graz.at/meted/hydro/basic/Runoff/media/graphics/soil_textures.swf
- Fertility : finer textured soils tend to have greater ability to store soil nutrients.



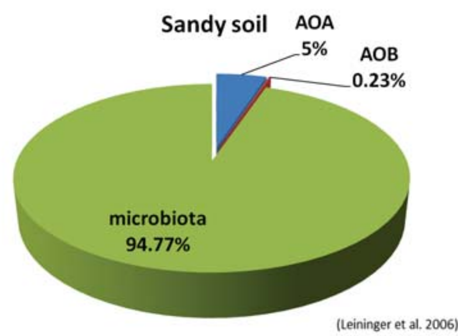
Clay soil

- Adsorption of (NH_3)
- Location in the soil matrix
  - AOA does not decreases with the soil depth(Sher et al. 2012)
  - AOB and AOA are more present in the top (0.5m) of the soil profile (e.g *Nitrosomonas* and *Nitrosospira)* (Sher et al. 2012)
- Distribution pattern of AOA and AOB (Erguder et al. 2009)

Sandy soils

- Have the light power of retaining (NH_3)
- archaeal amoA gene
- bacterial amoA gene

↔ Little variations



Nitrification rate in coastal surface water

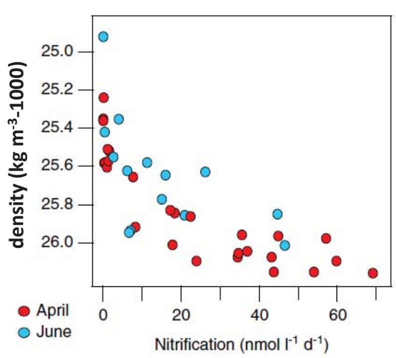
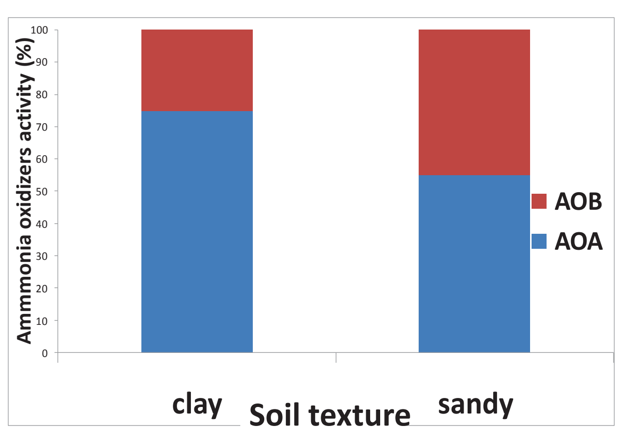


Figure 2 Nitrification rates in Monterey Bay surface waters in April ($N=27$) and June ($N=15$) of 2011. Data are plotted against density rather than with depth.

Smith et al. 2014

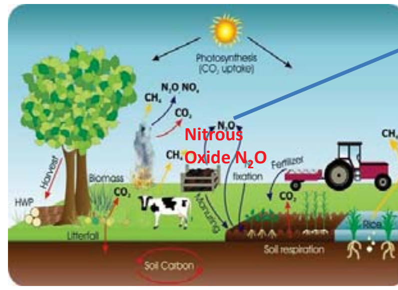
Summary

Other factors that influence abundance
°T, O_2, pH, NH_3 conc.



Soil Moisture influences Nitrous oxide (N_2O) Emission from Agricultural Soils

Facts about Nitrous Oxide (N_2O)



- 5% GWP
- 300 times > potent than CO_2
- Threat to ozone layer

- Agr. Leading generator of N20 (86%)

Factors Controlling N_2O production

- Nitrogen availability/type
- Soil Moisture
- Soil texture
- Soil temperature
- Carbon availability
- pH

Soil Moisture: Proxy for oxygen availability

- Oxygen concentration is rarely measured and soil moisture is used as a measurable proxy for oxygen availability.
- Soil oxygen concentration controls the redox potential which governs microbially - mediated reactions (aerobic vs anaerobic).

<u>Soll Moisture Content also affects:</u>

- Metabolic activity of microorganisms
- Substrate availability and redistribution

Challenge: Distinguishing the effect of O2 and substrate availability on N_2O production in soils.

Influence of oxygen availability on the different N_2O production

Nitrifier Nitrification

Aerobic
High oxygen

NH_3 ↓ NH_2OH → N_2O/NO

NH_2OH ↓ NO_2^- → N_2O/NO

NO_2^- ↓ NO_3^-

Influence of oxygen availability on the different N_2O production

Nitrifier - Denitrification

Aerobic/Anaerobic

NH_3 ↓ NH_2OH ↓ NO_2^- → NO → N_2O → N_2

Denitrification

Anaerobic/Low oxygen

NO_3^- → NO_2^- → NO → N_2O → N_2

Contributions of different pathways to N_2O production (Zhu 2013)

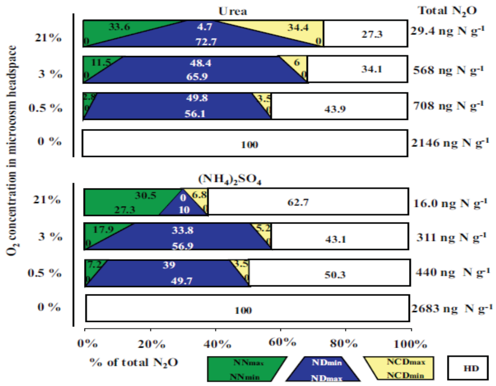


Fig. 2. Relative contributions of nitrifier denitrification (ND), nitrifier nitrification (NN), nitrification-coupled denitrification (NCD), heterotrophic denitrification (HD) to N_2O production in clay loam soil.

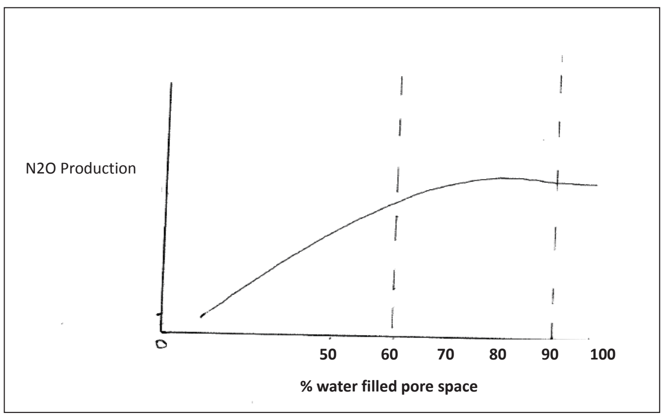
N_2O Study (Laboratory Study)

- Objective:

To measure N_2O emissions from three agriculturally important Trinidadian soil types under varying moisture contents and N-Fertilizer application rates.

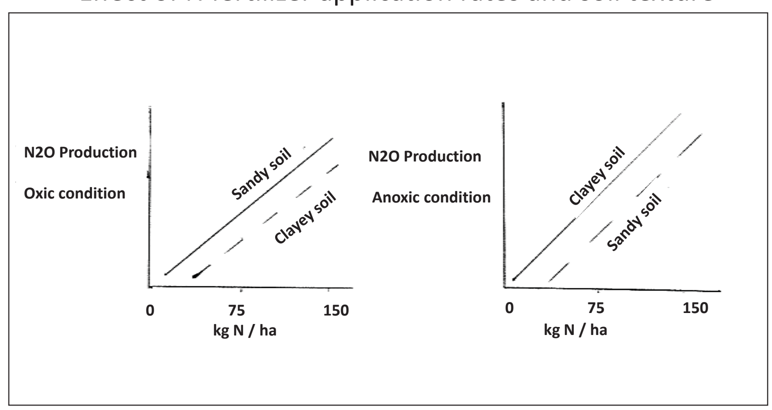
Hypothesis 1

- Effect of soil moisture



Hypothesis 2

- Effect of N fertilizer application rates and soil texture



A Safe Operating Space for Humanity

NATURE|Vol 461|24 September 2009

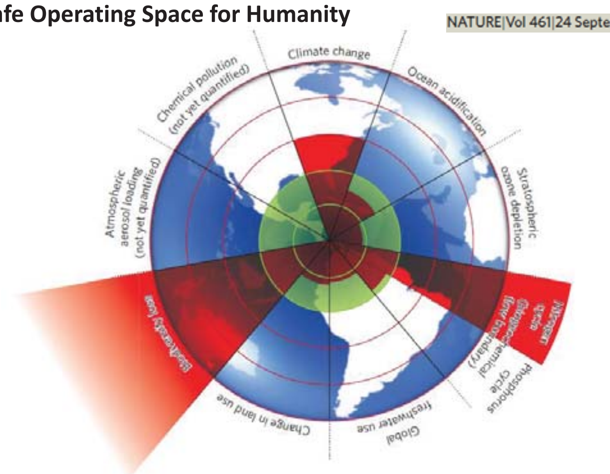
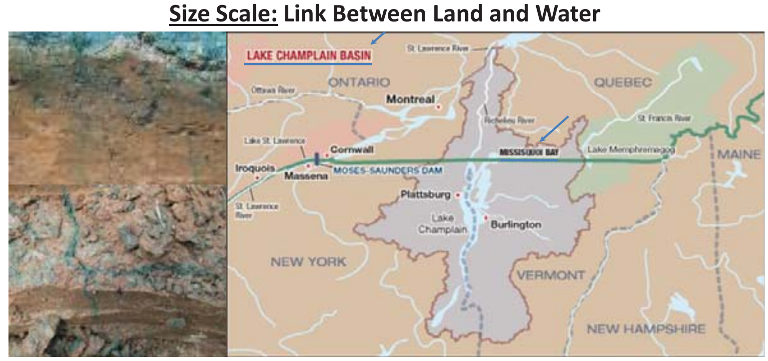


Figure 1 | Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.

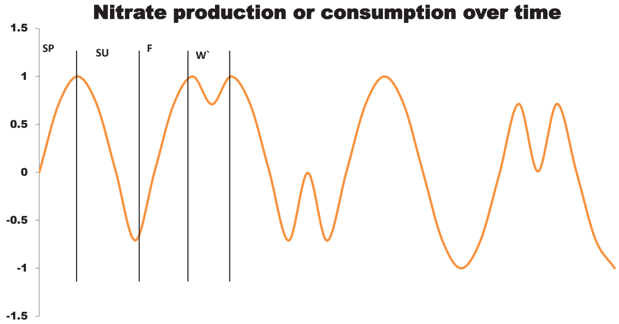
<u>Size Scale:</u> Link Between Land and Water



Soil is central to the system

- Connects the Ag-Aquatic sub-systems
- Physical and biological processes
- Hosts highly specialized organisms

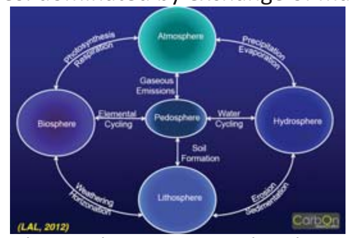
Nitrogen Transformation in the Time Scale



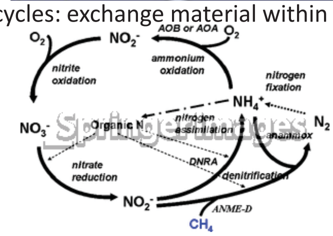
- Soil having N prod ≥ N cons at critical growth stages will have enough supply of N for crop=>no response to additional N inputs
- Soil having N prod < N cons have less plant-avail. N and thus respond N fertilizer inputs
- Plant-avail. N pools at the end of the growing season (harvest) are better indicator of soil N supply than pool sizes at the beginning of the growing season (pre-planting)

Earth systems operate in a cyclic way & time scales and size scales are related

Geochemical cycles: dominated by exchange of material among ecosystems

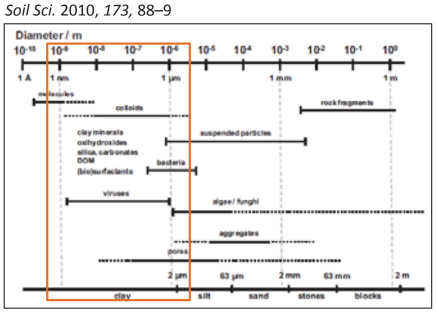


Biogeochemical cycles: exchange material within ecosystems N cycle



Size spectrum of different particles in soil, pores and biota

J. Plant Nutr. Soil Sci. 2010, *173*, 88–9



$NH_3 + O_2 + 2H^+ + 2e^-$ ⟶ $NH_2OH + H_2O$

$NH_2OH + H_2O$ —Hydroxylamine oxidoreductase→ $NO_2^- + 5H^+ + 4e^-$

$NO_2^- + 5H^+ + 4e^-$ —Nitrite oxidoreductase→ $NO_3^- + 2H^+ + 2e^-$

Differential contributions of AOA ecotypes to nitrification

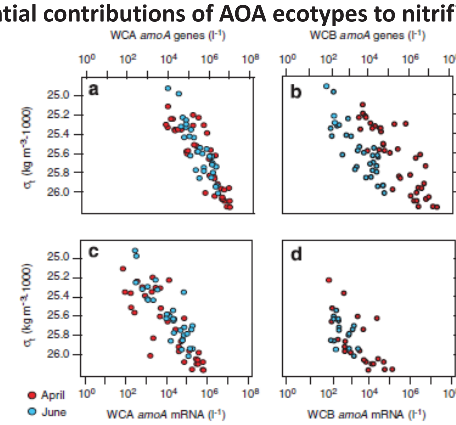
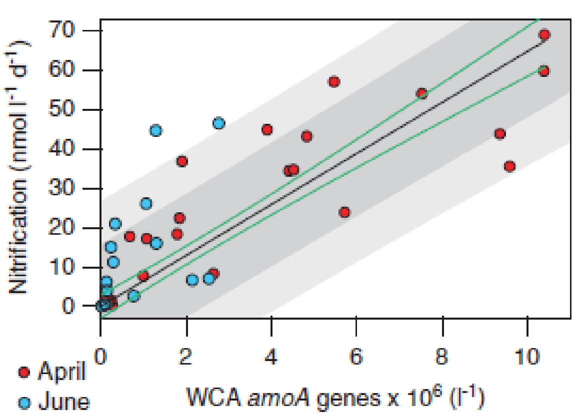


Figure 3 The distribution and abundance of archaeal *amoA* genes and transcripts along density surface in Monterey Bay surface waters. (**a**) WCA and (**b**) WCB *amoA* gene abundances plotted along density surface in April ($N=41$ for both genes) and June ($N=32$ for both genes). Transcript abundances for (**c**) WCA *amoA* ($N=37/31$ for April/June) and (**d**) WCB *amoA* ($N=22/17$). All data are plotted on the same axis for comparison purposes.

Differential contributions of AOA ecotypes to nitrification

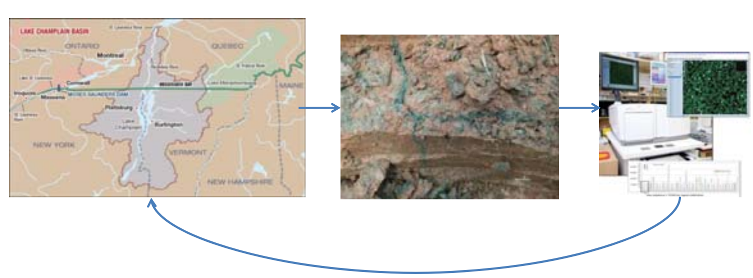


•AOA could potentially yield valuable relationship for prediction of soil nitrification rates from amoA genes

ISME Journal (2014)

Research Tools

- Controlled lab experiment
- DNA based tools
- Mathematical models & geostatistics
- Field-scale validation



Summary

- Require experiments at a minimum of two scales to develop and test models for nitrifiers functioning
    - Selected fields within a watershed scale and lab scale
- Integrate multiple factors influencing N cycle
    - E.g, ammonification nitrification and genes
- Integrate nitrifiers diversity into assessment of ecosystem function

Thank you!

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