Ecological Nutrient Management: The intersection between soil health and improved nutrient management

Practical Soil Health Specialist Training Curriculum
September 25, 2018  Cortland, NY
Laurie Drinkwater (led24@cornell.edu)
Flow of topics

- Define ecological nutrient management and contrast with 4R approach
- The three major elemental cycles: C, N and P
- Why are agricultural systems leaky?
- Using C management to reduce N losses, improve N use efficiency
- The role of the rhizosphere in ecological nutrient management
- Conclusions
The 4Rs fertilizer management

- Strategy developed when fertilizers were first introduced
- Focus is on fertilizer management:
  - Right source/chemical composition
  - Right rate
  - Right time
  - Right placement
- Aim is to maximize delivery to the crop
- Eliminate all other limiting factors to maximize fertilizer uptake

Soluble inorganic N, P
Ammonium $\rightarrow$ nitrite $\rightarrow$ nitrate

N,P fertilizer
Ecological nutrient management

- Goals extend beyond optimizing crop uptake of N fertilizer
- Derived from ecosystem ecology: N saturation conceptual framework
- Aims to re-couple C, N and P cycles
- Promotes accrual of soil organic matter reserves
- Fosters microbially-mediated processes that favor N-P retention
- These enhanced reserves supply N and P to plants
Ecological nutrient management includes practices that build soil health

- Diversification of cash crops
- Cover cropping
- Increased use of perennials
- Use of organic amendments
- Balanced nutrient budgets
Elemental cycles: C, N and P

- The three major cycles occurring in soil are interconnected
- Changes in C, N or P impact cycling of the other two elements
- Carbon: How does the role of C differ from N and P?
- Plants supply carbon to soil food web, decomposers and other soil organisms supply N and P to plants
Carbon Cycling

Labile: OM <1-2 years
- Free particulate and soluble OM
  - Plant & manure litter
  - Plant derived sugars, amino acids
  - Microbial sugars amino acids
  - Other soluble compounds

Slow OM: 10-20 years
- Chemically recalcitrant
  - Lignin
  - Microbial products--PFLAs
- Physically protected OM
  - Pieces of plant litter
  - OM protected by associated minerals or large size
  - Rhizodeposited OM

Stabilized OM: ≥100 years
- Chemically recalcitrant OM
  - Charred plant residues
- Physically protected OM
  - OM inside microaggregates
  - Surface stabilized OM
Decomposition is viewed as a microbial process, separate from plant uptake.

Nitrogen uptake by plants

http://www.sciencelearn.org.nz
Decomposers do not have mouths: The role of exoenzymes in decomposition

Exoenzymes digest strands of lignin, cellulose, and proteins into small chunks that can be taken up through cell membranes.
Carbon Cycling

Crop harvest

CO₂

Photosynthesis

CO₂

Manures, organic amendments

Plant residues

Microbes

Death/grazing

Biosynthesis

Labile: OM <1-2 years

Free particulate and soluble OM
- Plant & manure litter
- Plant derived sugars, amino acids
- Microbial sugars amino acids
- Other soluble compounds

Slow OM: 10-20 years

Chemically recalcitrant
- Lignin
- Microbial products--PFLAs

Physically protected OM
- Pieces of plant litter
- OM protected by associated minerals or large size
- Rhizodeposited OM

Stabilized OM: ≥100 years

- Chemically recalcitrant OM
  - Charred plant residues
- Physically protected OM
  - OM inside microaggregates
  - Surface stabilized OM

Root exudation, fine root turnover

Leaching

Runoff and erosion

Decomposition
Key features of C cycling

• SOM is a continuum
• Newer C is labile and energy rich
• Older C is lower in energy, less easily decomposed, nutrient rich
• The majority of stabilized SOM is of microbial origin
• C cycling is strongly connected to N and P cycles
• Fate of C: respired to CO$_2$, assimilated into biomass, SOM
Nitrogen Cycling

**Decomposition**

- **Manures, organic amendments** → **Soil organic matter**
- **Soil organic matter** → **Plant residues**
- **Plant residues** → **Biological N fixation**
- **Biological N fixation** → **Inorganic fertilizers**
- **Inorganic fertilizers** → **Crop harvest**
- **Crop harvest** → **Residue return**
- **Residue return** → **Soil organic matter**
- **Soil organic matter** → **Microbes**
- **Microbes** → **Death & grazing**
- **Death & grazing** → **Monomers**
- **Monomers** → **Exoenzyme depolymerization**
- **Exoenzyme depolymerization** → **Inorganic N**
- **Inorganic N** → **Nitrification**
- **Nitrification** → **NH₄⁺** → **Microbial assimilation**
- **Microbial assimilation** → **Mineralization**
- **Mineralization** → **DNRA**
- **DNRA** → **NO₃⁻**
- **NO₃⁻** → **Leaching**
- **Leaching** → **Runoff and erosion**
- **Runoff and erosion** → **Nitrogen losses**
- **Nitrogen losses** → **N₂O, NO**
- **N₂O, NO** → **Denitrification**
- **Denitrification** → **N₂"
Key features of N cycle

- N is easily lost from agricultural fields
- Many different types of microbes control the fate of N
- Conservation and loss pathways
- Coupled with C and P cycling
- Greater C abundance generally favors N conservation
- C shortage pushes losses
Phosphorus Cycling

Biological subcycle

- Manures, organic amendments
- Plant residues
- Soil organic matter
- Microbes
  - Death & grazing
  - Microbial assimilation
  - Exoenzyme depolymerization & mineralization
- Plant assimilation
- Crop harvest
- Soluble fertilizers
- Rock P fertilizers
- Runoff and erosion

Geochemical subcycle

- Soil solution Phosphorus
  - \( \text{HPO}_4^{2-} \)
  - \( \text{H}_2\text{PO}_4^{-1} \)
- Mineral surfaces
  - (clays, Fe and Al oxides)
- Secondary compounds
  - (Fe, Al, Mn & Ca phosphates)
- Mineralization
- Assimilation
- Leaching (usually minor)
- Adsorption
- Biochemical weathering
- Biological weathering
- Chemical weathering
- Dissolution
- Precipitation
- Aggregate formation & destruction
- Decomposition
Remember this about P cycling

- No gaseous phase!
- Two distinct interacting sub-cycles: biological and geochemical
- Biological cycling is coupled to C and N, and can influence geochemical cycling
- Abundant C favors assimilation of soluble P into biomass, can reduce soil P “fixation”
Why are agricultural systems leaky? What can be done to reduce nutrient losses?
Applying ecological knowledge to improve Nutrient Use Efficiency (NUE)

N saturation conceptual framework

- Developed to explain differences in N loss & retention across forest ecosystems (late 1980’s)
- Provides an organizing framework for understanding how N cycling interacts with other elemental cycles
- Highlights the tight coupling between N and C cycling

Aber et al. 1989, 1998; Fenn et al. 1998; Perakis and Hedin 2002
What are the symptoms of N saturation?

1. Increased N mineralization
2. Increased rates of nitrification
3. Increased leaching losses of NO$_3^-$
4. Increased N$_2$O production from denitrification
Possible fates of nitrogen

- Organic residue
- Retained on cation exchange sites
- Volatilization
- Lost
  - Denitrification
  - Leaching
Possible fates of nitrogen

- Volatilization
- Leaching
- Converted to $N_2O$ or $N_2$
- Retained on cation exchange sites
Possible fates of nitrogen

N fertilizer → NH$_4^+$ → NO$_3^-$

Lost
- Volatilization
- Converted to N$_2$O or N$_2$
- Leaching

Retained on cation exchange sites

Plant uptake
Agriculture: N leakiness is a systemic problem: C and N cycles have been uncoupled

- Inorganic N is highly mobile, many loss pathways
- Simplification of rotations has led to longer and more frequent bare fallows and reduced N sinks
- Simplified rotations, bare fallows and intensive tillage have all led to depleted SOM
- Surplus N must be added to meet yield goals
- Increased abundance of N relative to energy (C) reduces microbial assimilation—loss pathways predominate
Strategies that re-couple C and N have the greatest impact on N recovery.

Based on 217 field-scale 15N studies, Gardner and Drinkwater 2009, Ecol. Applications

- Organic N source: 42.4%
- Crop rotation: 29.8%
- Timing, fall versus spring: 20.9%
- Proximity to roots: 19.4%
- Management history: 12.8%
- Reduced N rate: 7.0%
- Nitrification inhibitor: 6.9%
- Inorganic N form: 2.6%
Cover cropping reduces $\text{NO}_3^-$ leaching

Tonitto et al. 2006
Two mechanisms lead to reduced N losses

- BNF, Plant & animal residues
- Supply
- N fertilizer
- Cover crops
- Scavenged N: $\bar{X} = 33$ lb/ac

Diagram:

- Microbial biomass
- Particulate organic matter
- Stabilized organic matter
- Labile C
- Assimilation
- Soluble inorganic N and P
- Ammonium $\rightarrow$ nitrate
- Gaseous losses
- Leaching & run-off

\[ \text{Stabilized organic matter} \]
Applying ecological knowledge to improve Nutrient Use Efficiency (NUE)

Rhizosphere ecology: The role of plant-microbial collaborations in driving nutrient cycling

- Transformed our understanding of how nutrients cycle in terrestrial systems
- Small soil habitat plays a dominant role in nutrient cycling: HOT SPOT!
- In agroecosystems plant-microbial linkages improve nutrient conservation
Plant-microbial collaboration and N mineralization

Sterile soil

Sterile soil + bacteria

Sterile soil + bacteria + grazers

Clarholm et al. 1986
Plant-microbial collaboration: Plants exchange C for nutrients

Rhizosphere C and N cycling processes: interactions between new and old organic C
Even with N fertilizer additions, SOM reserves supply the majority of crop N.

Based on 217 field-scale 15N studies, Gardner and Drinkwater 2009, Ecol. Applications
Exchange of C for nutrients re-couples nutrient cycles

- Highly efficient: N is converted to inorganic forms in the proximity of roots
- Rapid cycling, inorganic N does not accumulate
- Plants control the release of C based on their need for nutrients
Practices that contribute to ENM?

Reduced fallow periods, diversified crop rotations, cover cropping, relay cropping, increased reliance on biological N fixation, additions of C containing N/P inputs such as animal and green manures, intercropping, landscape level vegetation management such as grass strips/field boarders, riparian buffers, hedgerows
Ecological nutrient management

- Highly compatible with management strategies that aim to build soil health
- Aims to re-couple C, N & P cycles
- Promotes accrual of soil organic matter reserves
- Fosters microbially-mediated processes that favor N-P retention
- These enhanced reserves supply N and P to plants, additions of soluble fertilizers can be reduced
Thank-you!

Questions?
Three factors that determine if C additions will increase microbial N assimilation (immobilization)

Cheng et al. 2017

[Diagram showing the factors and their effects on microbial communities (MBN) and nitrate (NO₃⁻) levels]
Aggregate Formation and Stabilization

Particulate organic matter (free POM)

Incorporation of plant residues & roots (POM)

Colonization & microbial growth

Aggregate formation:
Clay traps POM

Loss of aggregate stability

Biodegradation:
decline of microbial activity

Occluded POM (oPOM)

Modified after P. Puget-1997