Stabilization of Soil Organic Carbon

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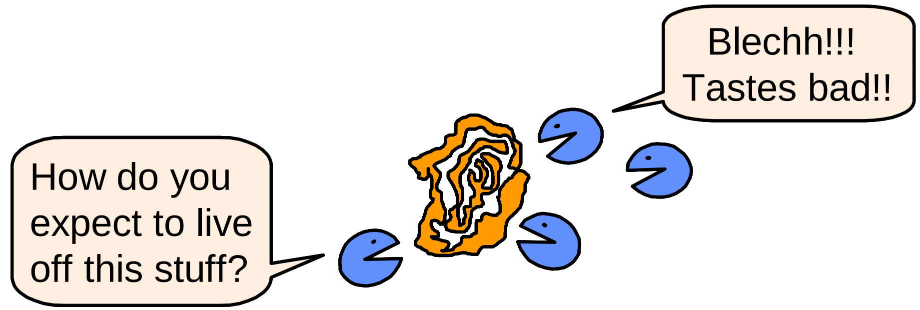
Rationale

- Soil organic C stocks depend on the balance between C inputs and outputs
- A soil's capacity to accumulate and store C is greatly affected by its ability to protect and stabilize organic matter against decomposition
- A mechanistic understanding of factors controlling SOC transformations and stabilization is needed to:
  - Optimize management strategies for increasing soil C sequestration
  - Improve our ability to predict soil C sequestration potentials

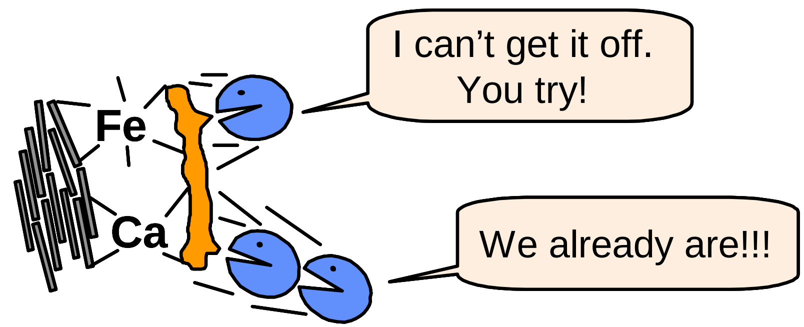
MECHANISMS OF SOIL ORGANIC MATTER STABILIZATION

From Jastrow and Miller, 1998, *In* Soil Processes and the Carbon Cycle, CRC Press.

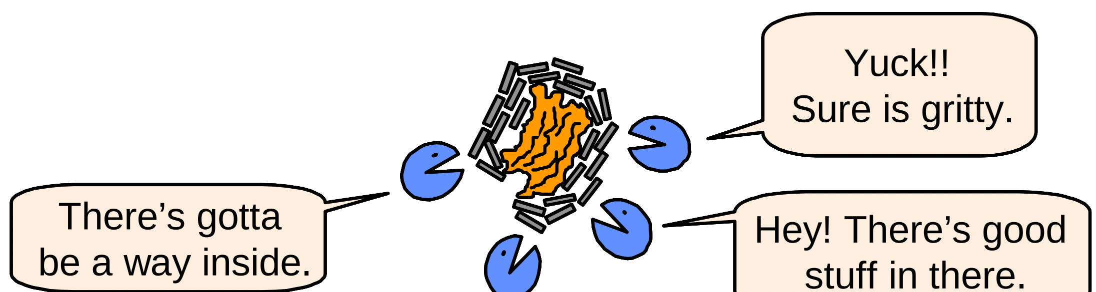
Biochemical Recalcitrance



Chemical Stabilization



Physical Protection

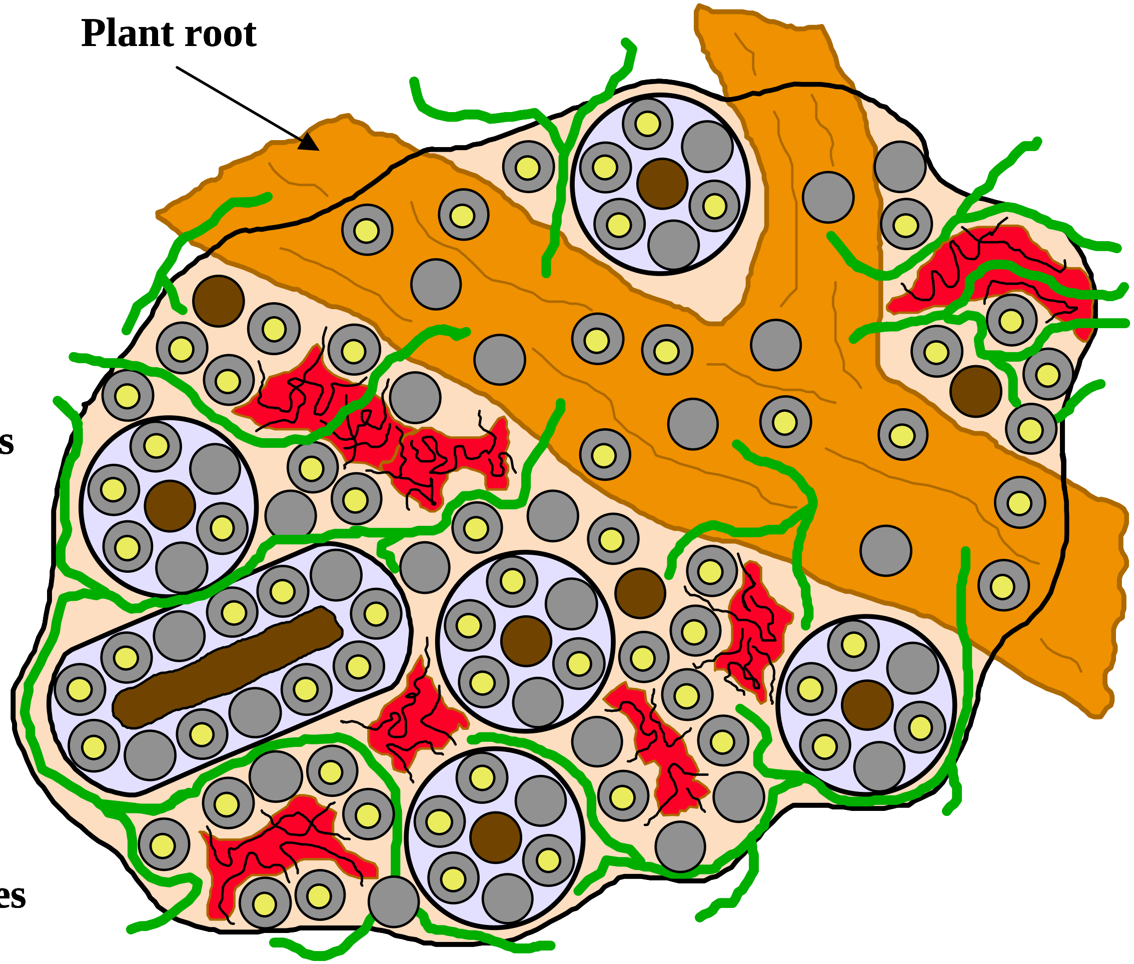


Objectives

- Quantify amounts and dynamics of C and N in soil fractions representing physically and chemically protected SOM pools
- Estimate residence times of C in isolated pools
- Determine chemical functional composition and structural morphology of selected fractions
- Determine extent to which edaphic characteristics, vegetation type, management strategies, and time influence C accumulation in protected pools

CONCEPTUAL DIAGRAM OF AGGREGATE HIERARCHY

From Jastrow and Miller, 1998, *In* Soil Processes and the Carbon Cycle, CRC Press.



Microaggregates
~ 90-250 and 20-90 μm

Plant and fungal debris

Silt-sized microaggregates with microbially derived organomineral associations

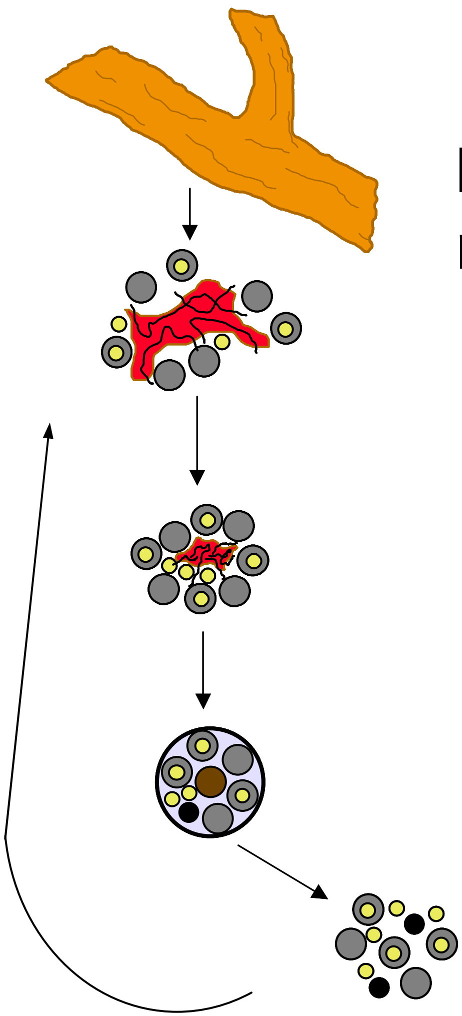
Clay microstructures

Particulate organic matter colonized by saprophytic fungi

Mycorrhizal hyphae

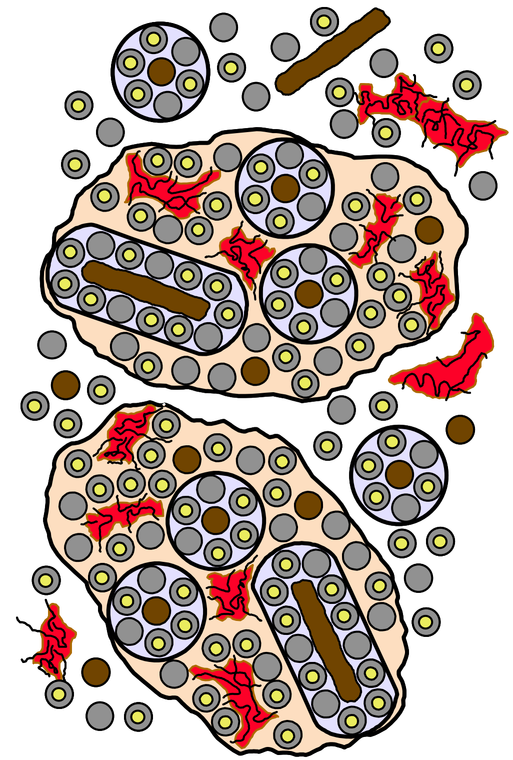
Pore space; polysaccharides and other amorphous interaggregate binding agents

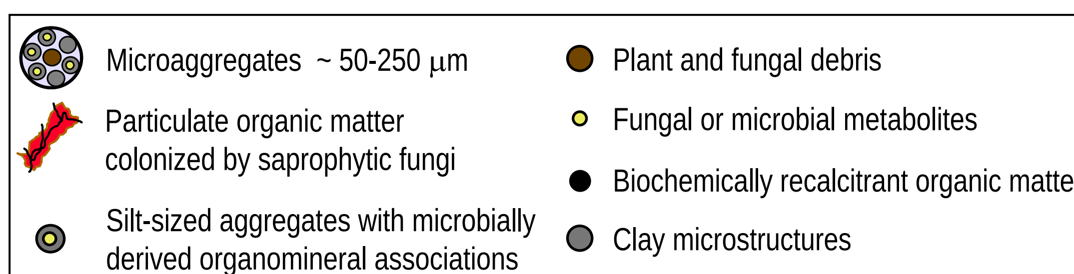
Conceptual models of soil C cycling and protection mechanisms used to develop new soil fractionations



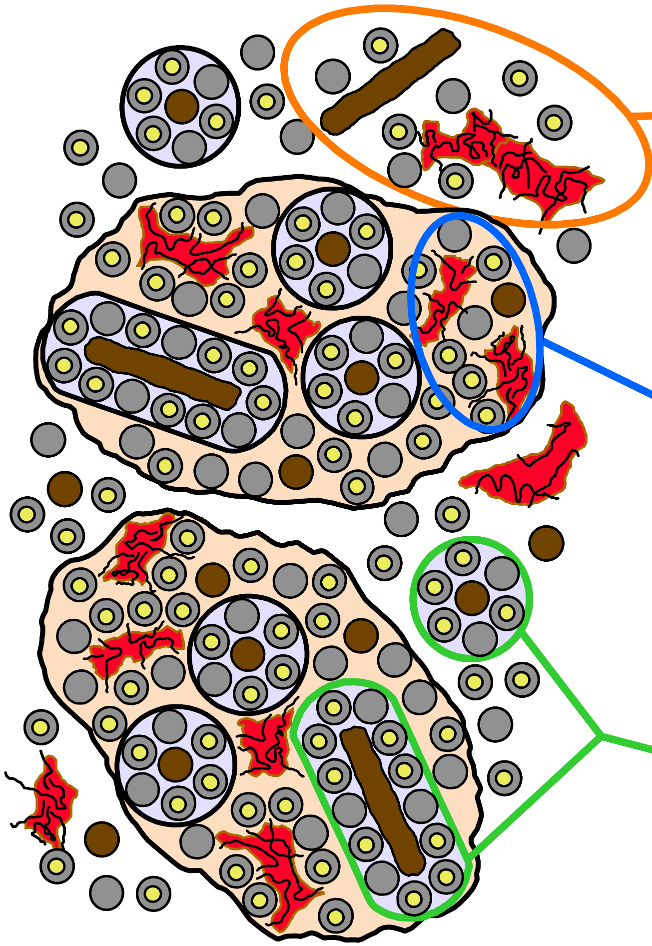
Incorporation into microaggregates:

- Physically protects organic inputs from decomposition
- Enables organic matter to be humified or chemically protected by association with the mineral fraction





Fractionation of Soil Organic Matter Based on Aggregate Hierarchy



Physical fractionation

Non-aggregated (NA)
Slaking
⇒ POM, silt & clay

Macroaggregated (MA)
Microaggregate isolator
⇒ POM, silt & clay

Microaggregated (mA)
Dispersion
⇒ POM, silt & clay

Based on increasing disruptive energies

Chemical fractionation

Acid hydrolysis
silt & clay

Acid hydrolysis
silt & clay

Acid hydrolysis
silt & clay

Yields resistant and more labile fractions

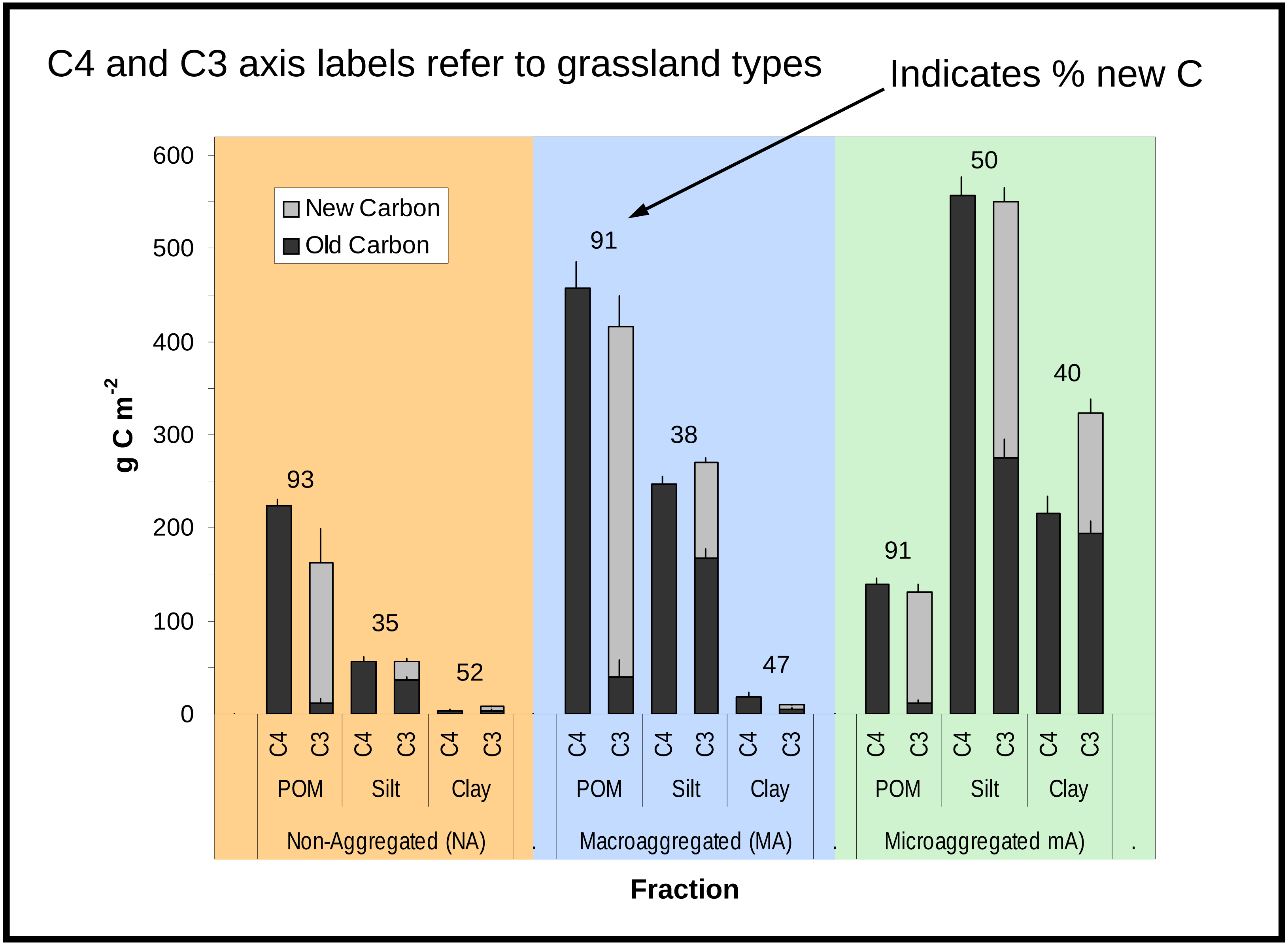
Evaluating the role that aggregate hierarchy plays in the storage and turnover of soil C

- **Tracers:**
  Native Kansas tallgrass prairie dominated by C4 grasses converted to C3 brome grass 62 yr before sampling (fertilized with 112 kg N ha^{-1} y^{-1})

- **Steady state conditions:**
  Whole soil C stocks reasonably close to equilibrium

  C4 = 2028 ± 25 g C m^{-2}

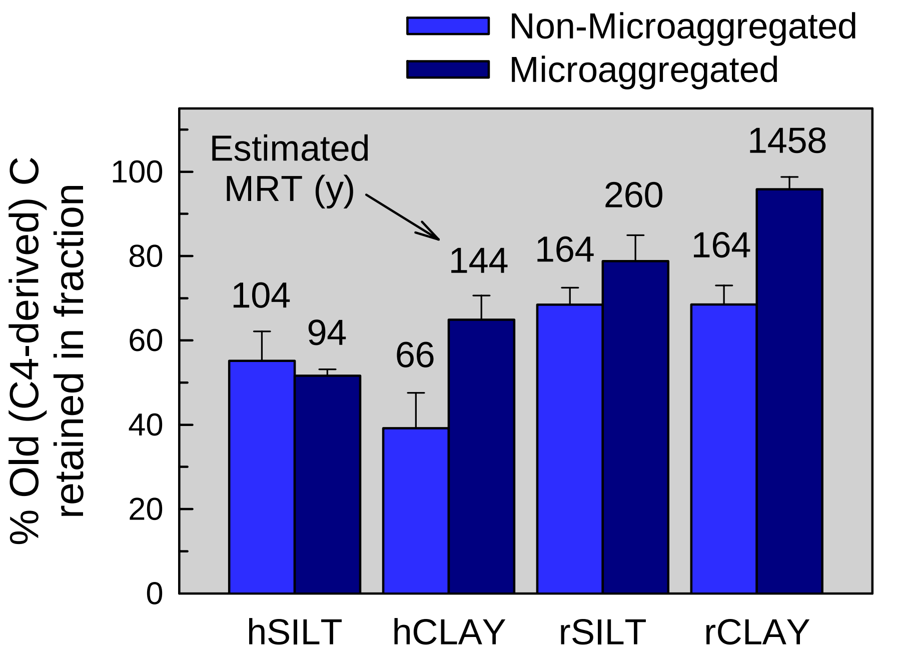
  C3 = 2130 ± 43 g C m^{-2} (surface 5 cm)



- Near equilibrium in most fractions
- >55% of POM C in MA (all replaced)
- Most silt and clay C in mA
- No difference in % new C for NA & MA
- mA has more new silt C
- mA also has greatest retention of old clay C

Acid hydrolysis used to evaluate the nature of protected C

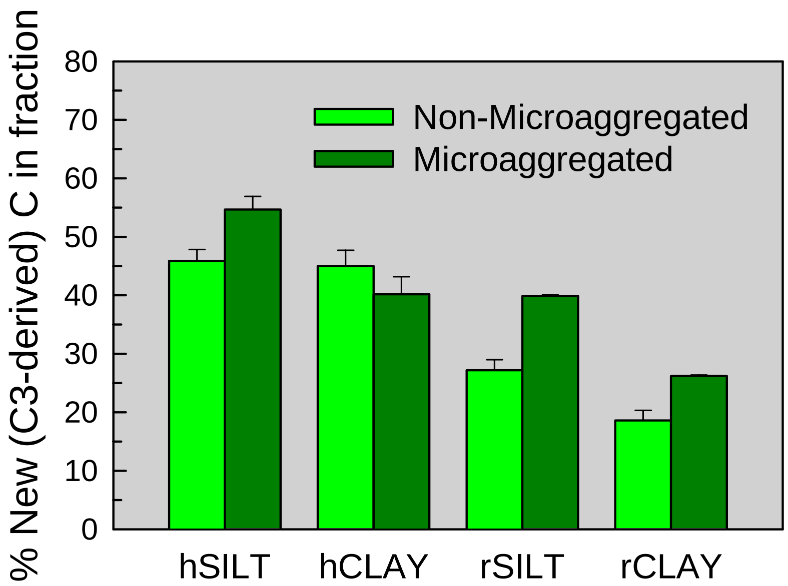
- Greater retention of old chemically resistant silt & clay C in microaggregates
- Microaggregate protection also increased retention of hydrolyzable clay C



h = Hydrolyzable C
r = Chemically resistant C

MRT (mean residence time) = 1/*k*;
where *k* is estimated as -ln(% old C/100)/62 y

Acid hydrolysis used to evaluate the nature of protected C

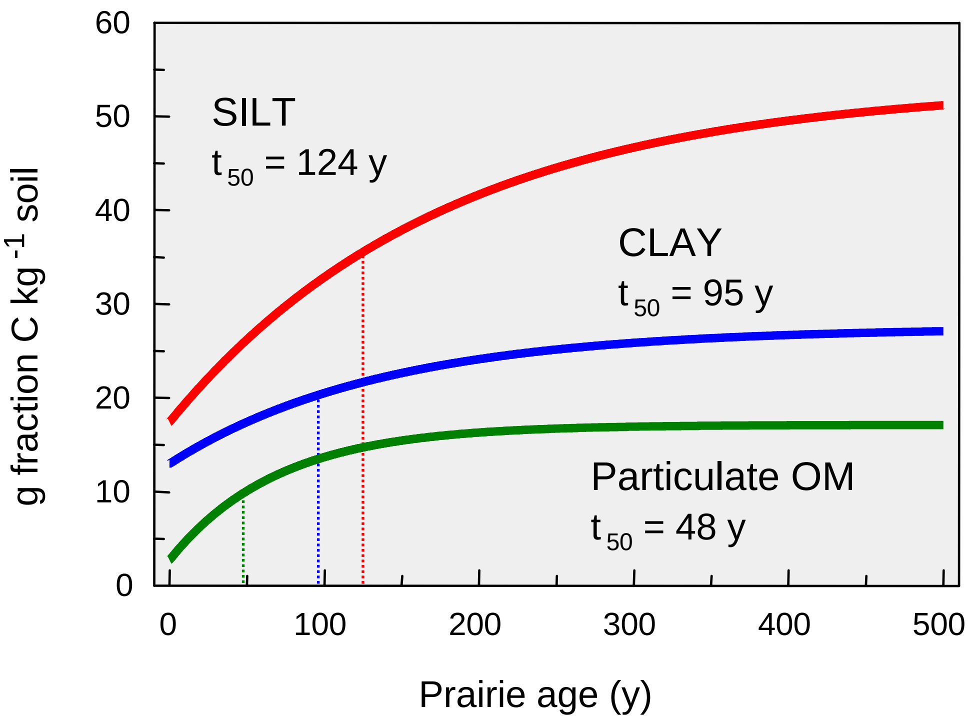


h = Hydrolyzable C
r = Chemically resistant C

- More new chemically resistant C in microaggregated silt & clay
- Increased hydrolyzable C in microaggregated silt may be physically protected
- Suggests microaggregates can facilitate creation of new organomineral associations

Accumulation of new C in microaggregates suggests these fractions may not be saturated and could increase, even in some high C soils

Rates of C accrual in soil fractions and their potential saturation limits



Fermilab Prairie

- POM reaches equilibrium first
- Clay equilibrates next
- Largest increases in silt-sized fraction
- ~50% of silt-associated C is chemically resistant across the chronosequence

- Aggrading system facilitates investigation of saturation limits
- What is the nature and source of accrued C?
  - C4 vs. C3; grass vs. forb; plant vs. microbial; extent of rendering

Organic matter preservation in microaggregates

Objectives

- Quantify internal pore structure *(nm to μm)*
- Determine location of OM within those pores
- Evaluate the role of pore-OM relationships under management practices that increase SOM storage

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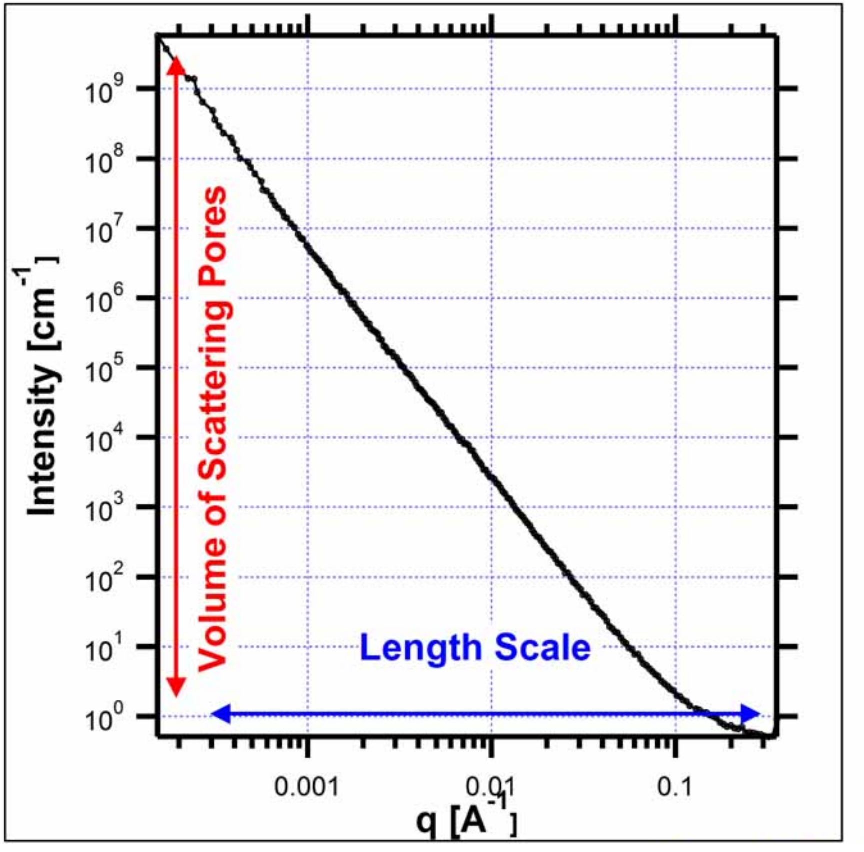
Ultra-Small Angle X-Ray Scattering

USAXS Scattering Curve



- Size distribution of pore volume
- Quantifies pore sizes ranging from 4 nm to 5 µm
- Based on change in x-ray contrast
  - Air: *very weak x-ray scatterer*
  - Minerals or OM: *strong scatterers*

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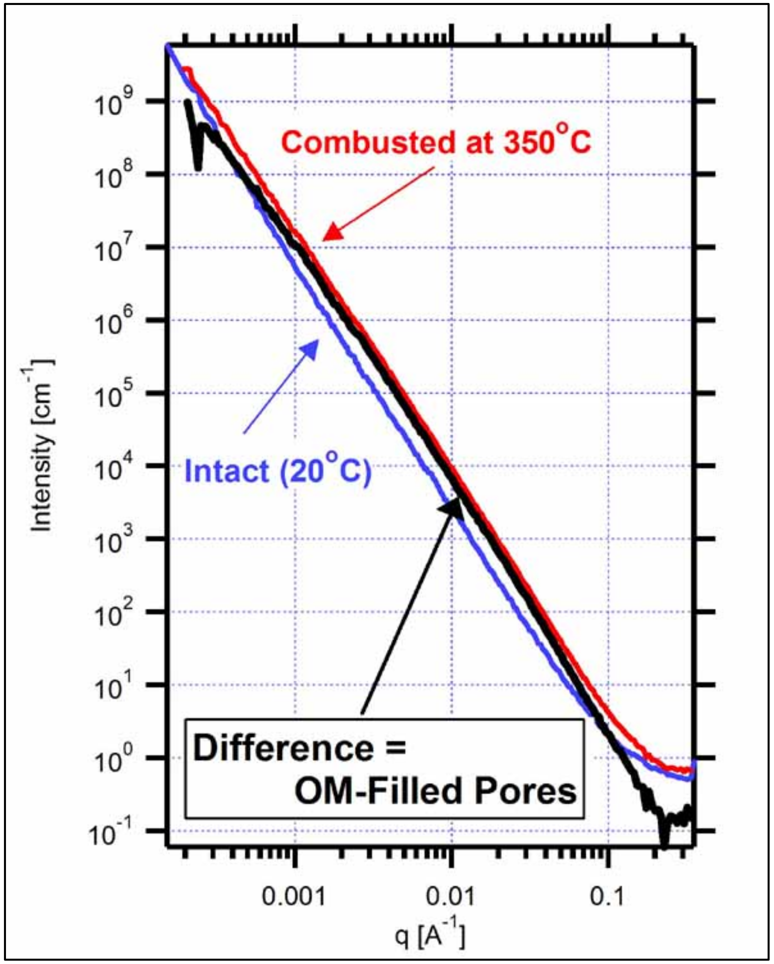
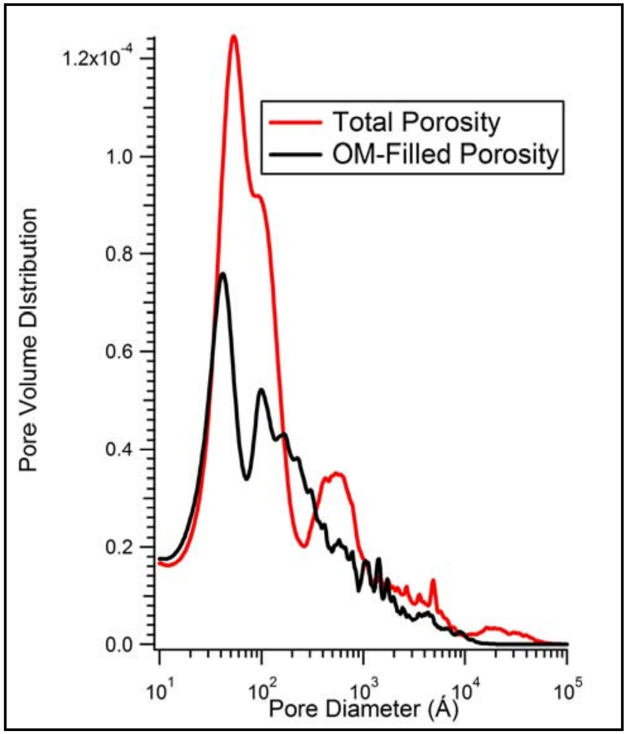
Total and OM-filled porosity by USAXS

- Total Porosity
  - Remove OM by combustion
- OM-Filled Porosity
  - By difference between combusted soil and intact (non-combusted) soil



Pore Volume Size Distribution *(fit from scattering curve)*



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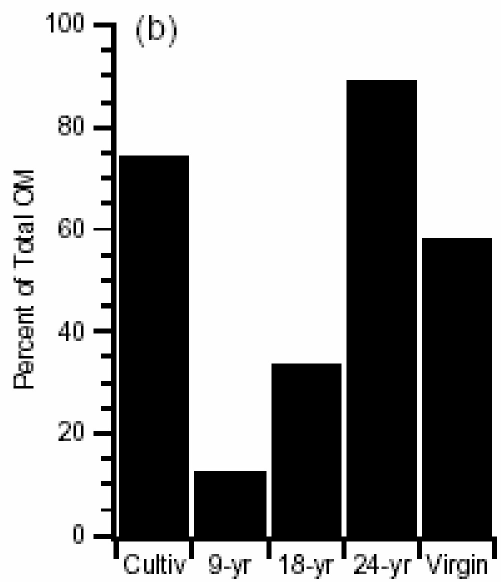
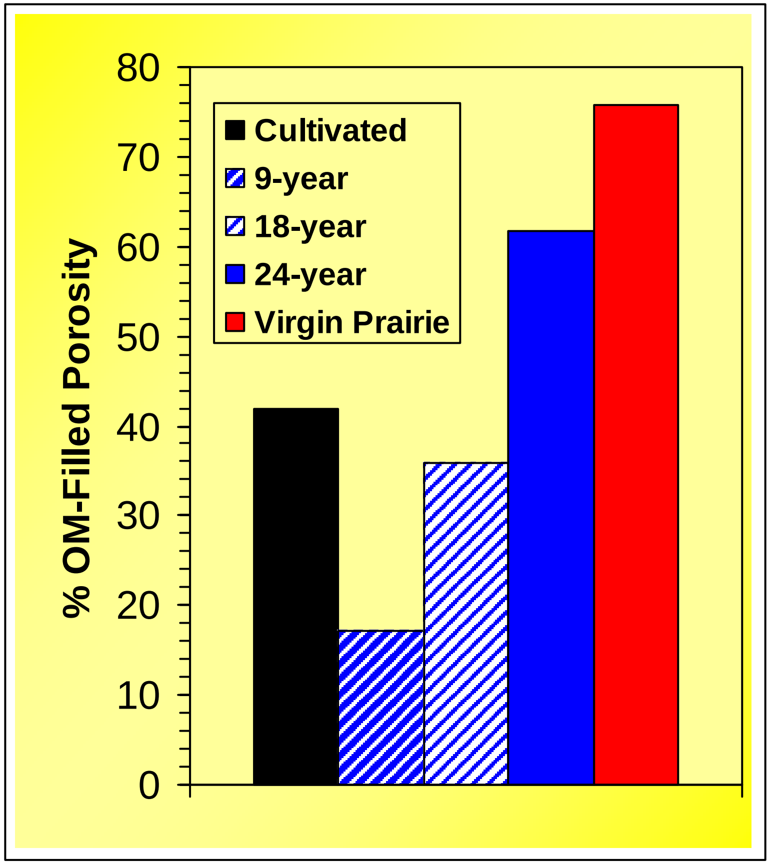
OM-filled porosity of microaggregates increases with prairie restoration

Restructuring of OM distribution within pores (<5µm)

- Initial loss of OM-filled porosity
  - But cultivated soil has less total pore volume
- OM-filled porosity then increases
  - Up to 80% of pores filled with OM
- Distribution of total OM within microaggregates also changes, suggesting differences in nature and/or mechanisms protecting OM



Percent of total pores filled with OM



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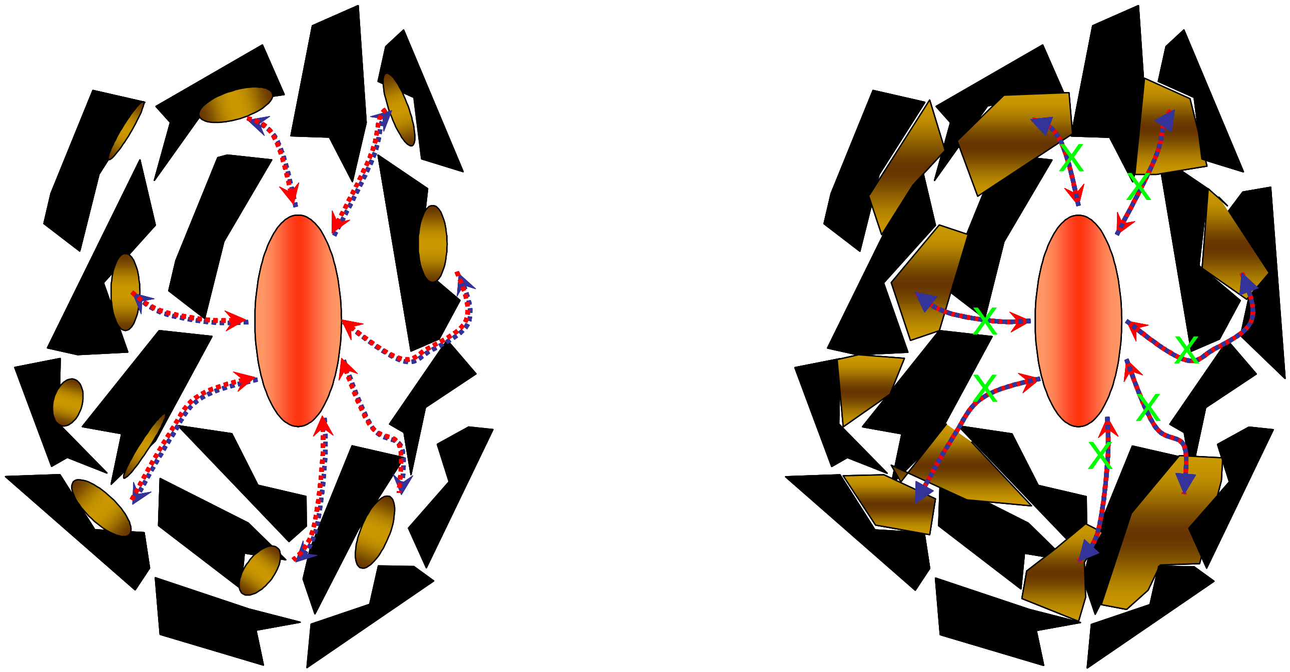
Conceptual model of OM protection by OM-filled pores



- ⇨ Slow diffusion of exoenzymes and hydrolysate
- ⇨ Limit access to OM
  - ➢ Only the small surface area at pore necks are accessible
  - ➢ OM in pore body is protected
- ⇨ Microbial growth and activity becomes limited

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Microbial enzyme activity and carbon cycling in grassland soil fractions

- How do enzymes change across restoration chronosequence?
- How do enzymes interact with soil structure to control C balance?
  - Does soil aggregation prevent microbes and enzymes from accessing substrates within aggregates (2° organomineral complexes)?
  - Does enzyme activity reflect the level of degradation and turnover of substrates in 1° organomineral complexes (particle size fractions)?

Methods

- Row crop, 11-yr & 25-yr restored prairie, prairie remnant, and 32-yr C3 grassland
- Soil fractions (field-moist bulk soil sieved to 8 mm)
  - Macroaggregates(>250µm): wet-sieving; removed nonaggregated LF with Ludox (1.3 g cm^{-3})
  - Microaggregates: microaggregate isolator (modified from Six et al., 2000)
  - "Primary" particles: coarse (>250µm) & fine (53-250µm) POM, silt- and clay-sized fractions (dispersion in water 60 min on wrist-action shaker with glass beads)
- Potential enzyme activity of fractions and bulk soil assayed (modified from Sinsabaugh et al., 1993)
  - Enzyme recovery from POM, silt & clay fractions was 84-112% of bulk soil

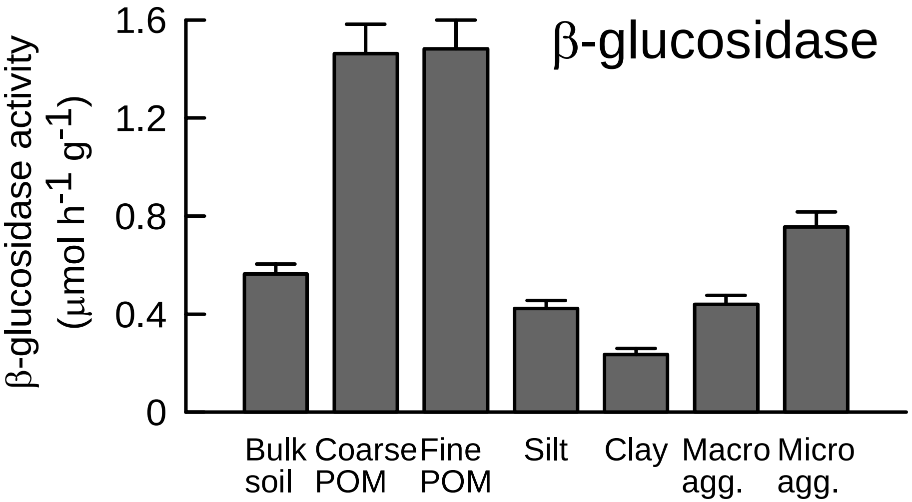
Assayed enzymes and their functions

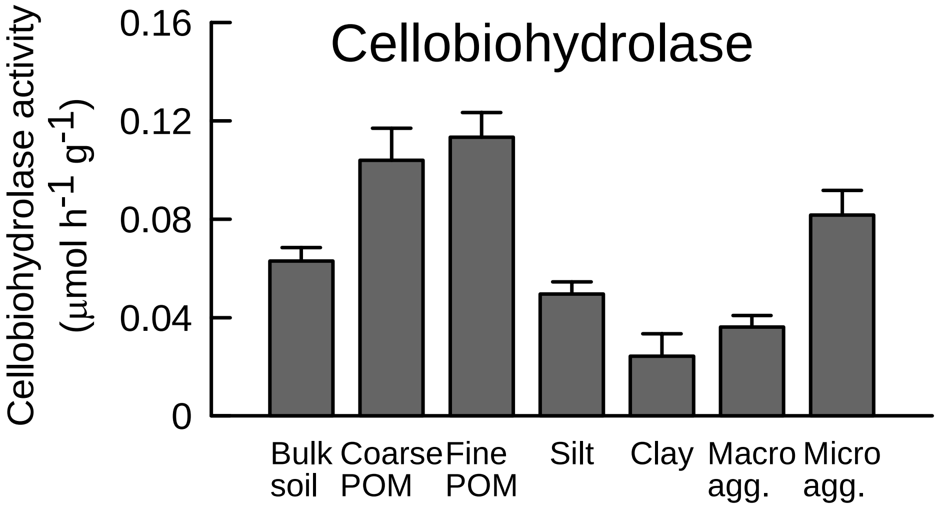
Enzyme	Function
Phosphatase	Releases PO_4^{3-}
Protease	Releases amino acids
Chitinase	Releases chitin monomers
Beta-glucosidase	Degrades cellulose
Cellobiohydrolase	Degrades cellulose
Polyphenol oxidase	Degrades lignin

Predictions

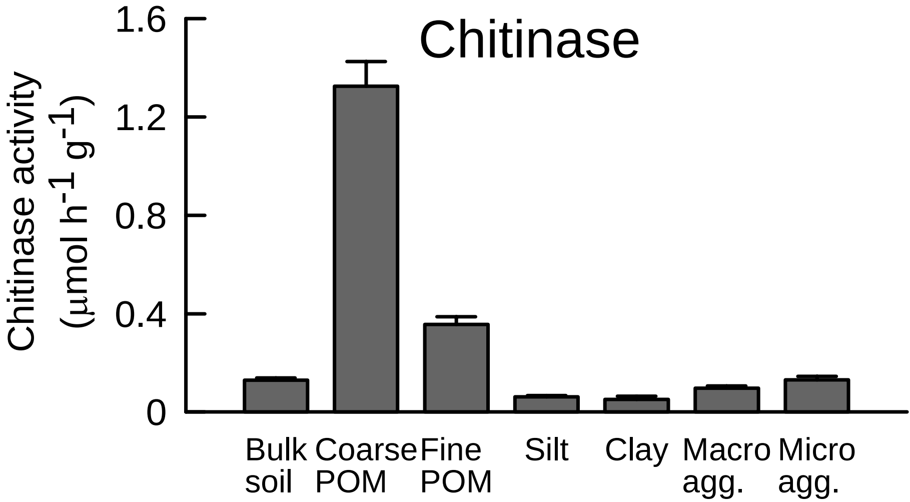
Fraction (Estimated MRT of C)	Prediction
Particulate organic matter (6-30 yr)	Accessible substrates, high microbial activity; high enzyme activity
Macroaggregates (50 yr)	Includes coarse particulate organic matter; above average enzyme activity
Microaggregates (80 yr)	Physically protected; below-average enzyme activity
Silt (75 yr)	Low enzyme activity
Clay (200 yr)	Lowest enzyme activity

Cellulose- and chitin-degrading enzymes localized near their substrates

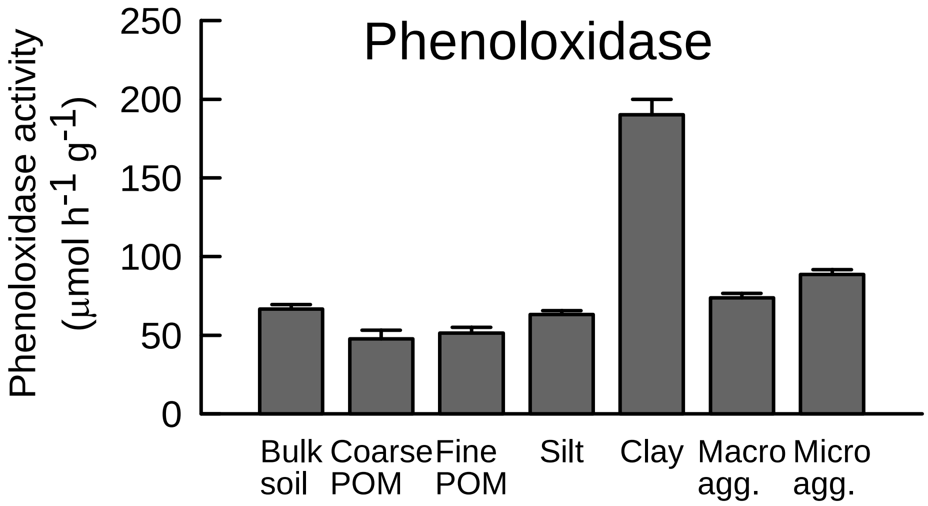


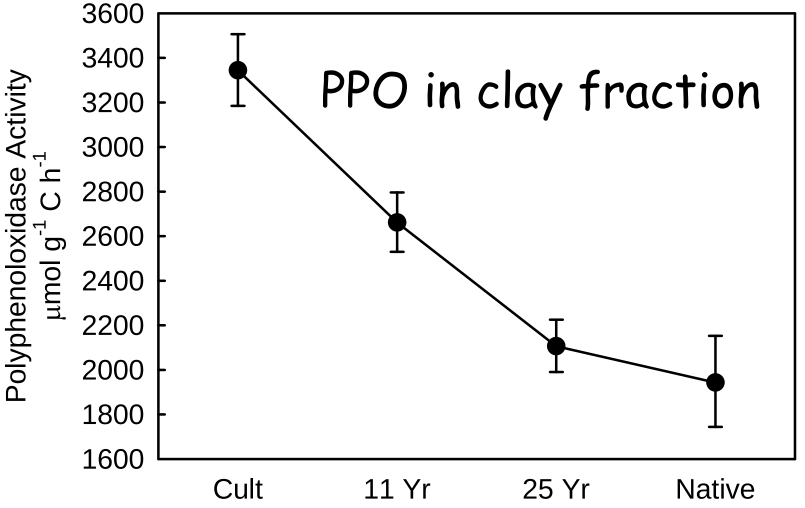


- Changes across the chronosequence were small relative to fraction differences
- General increase in activity was related to increase in C content



Polyphenoloxidase localized in clay fraction

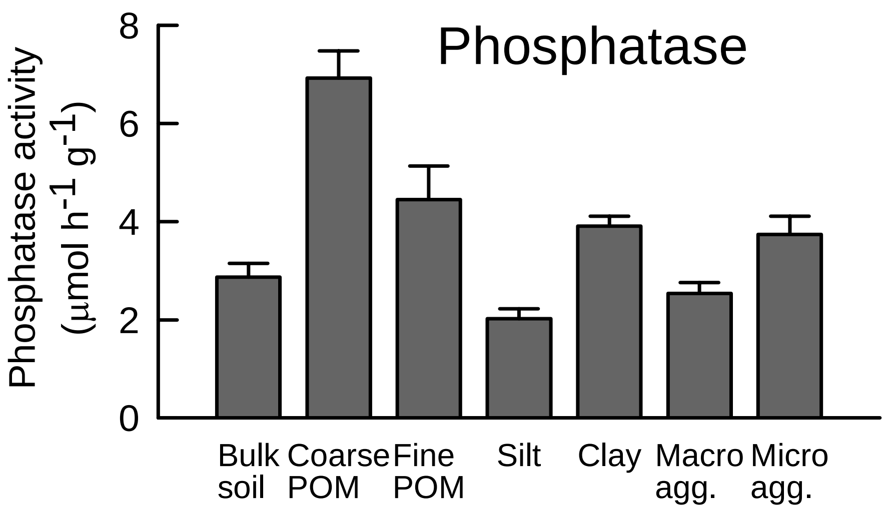


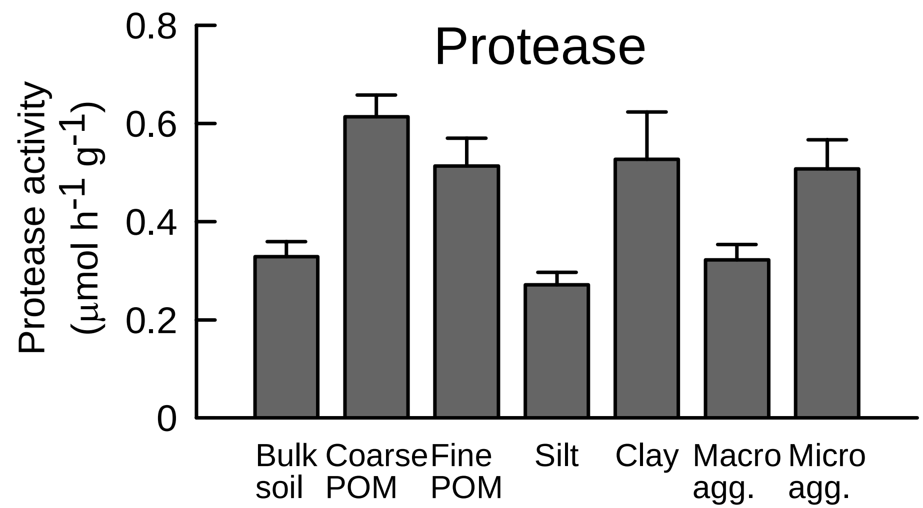


Phenoloxidase relatively constant with soil mass but declines by almost 50% across chronosequence

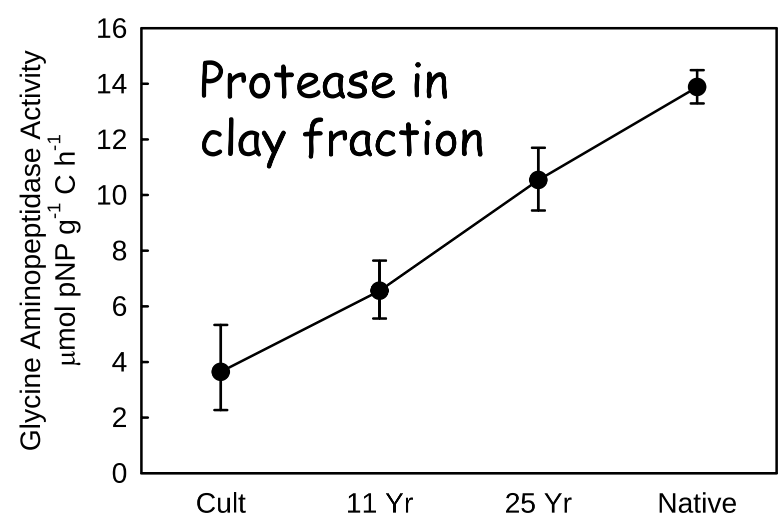
- Suggests enzymes are bound to minerals independent of substrate concentrations
- OR excluded from access to substrates in OM-filled pores

Nutrient enzymes produced across all fractions relative to SOM contents



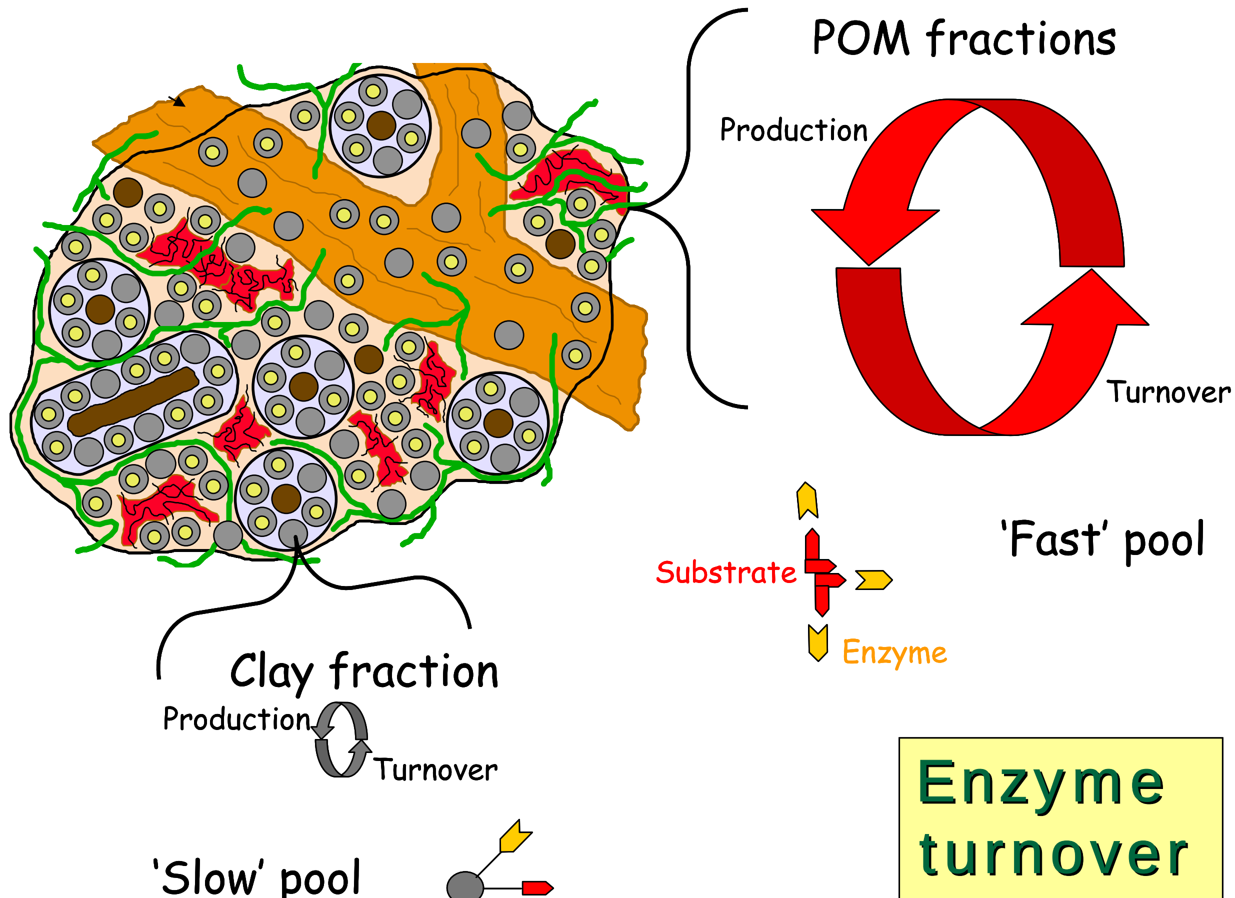


- Protease activity more than triples relative to C content in clay
- Likely tied to organic sources of N in accumulating peptides and amino compounds



Conclusions

- High production of specific enzymes on organic substrates
- Specific locations of enzymes unresolved:
  inside aggregates or on aggregate surfaces?
- Substantial potential activity in C fractions with long mean residence times
- ‘Two pool’ model of enzyme activity?



Enzyme turnover model

Significance and goals

- Gain better mechanistic understanding of factors controlling long-term C stabilization in soils
- Determine how management practices and site factors (e.g., soil type, climate) affect:
  - C inputs to pools with varying residence times
  - Potential for long-term C storage in protected pools
- Contribute to better parameterization or refinement of existing models and/or development of a new generation of SOM models based on measurable pools