Soil organic matter accrual and protection by aggregates in a restored tallgrass prairie chronosequence

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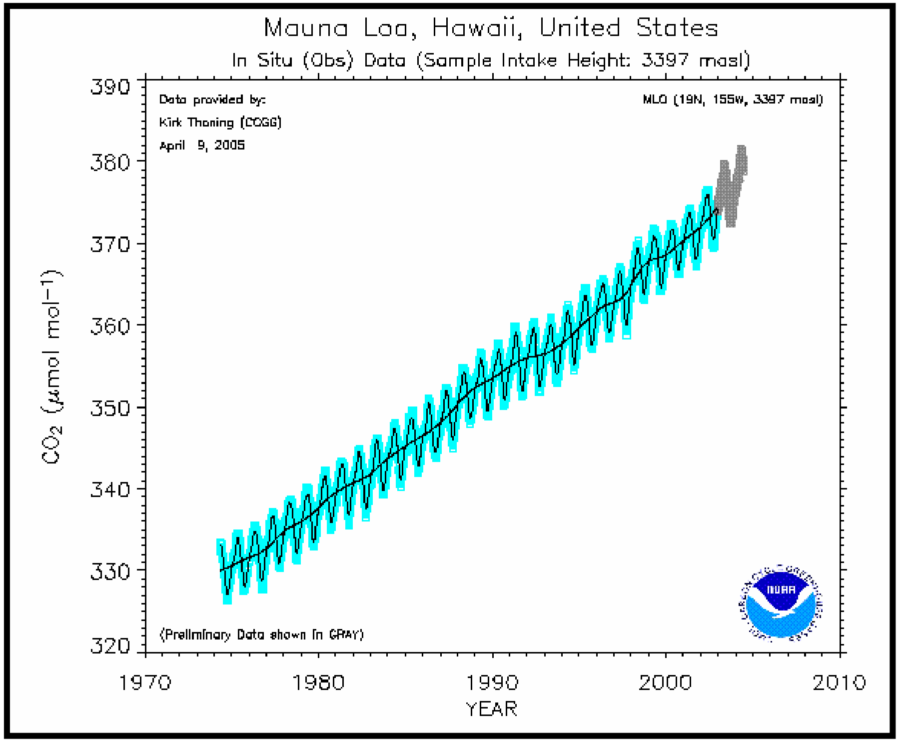
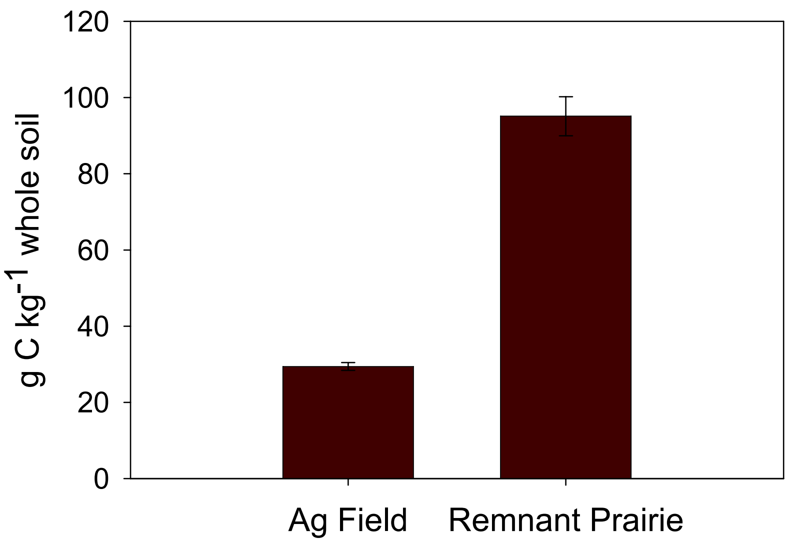
Terrestrial carbon sequestration

- Atmospheric CO_2 is rising
- Cutting emissions is difficult
- Ecosystems may help

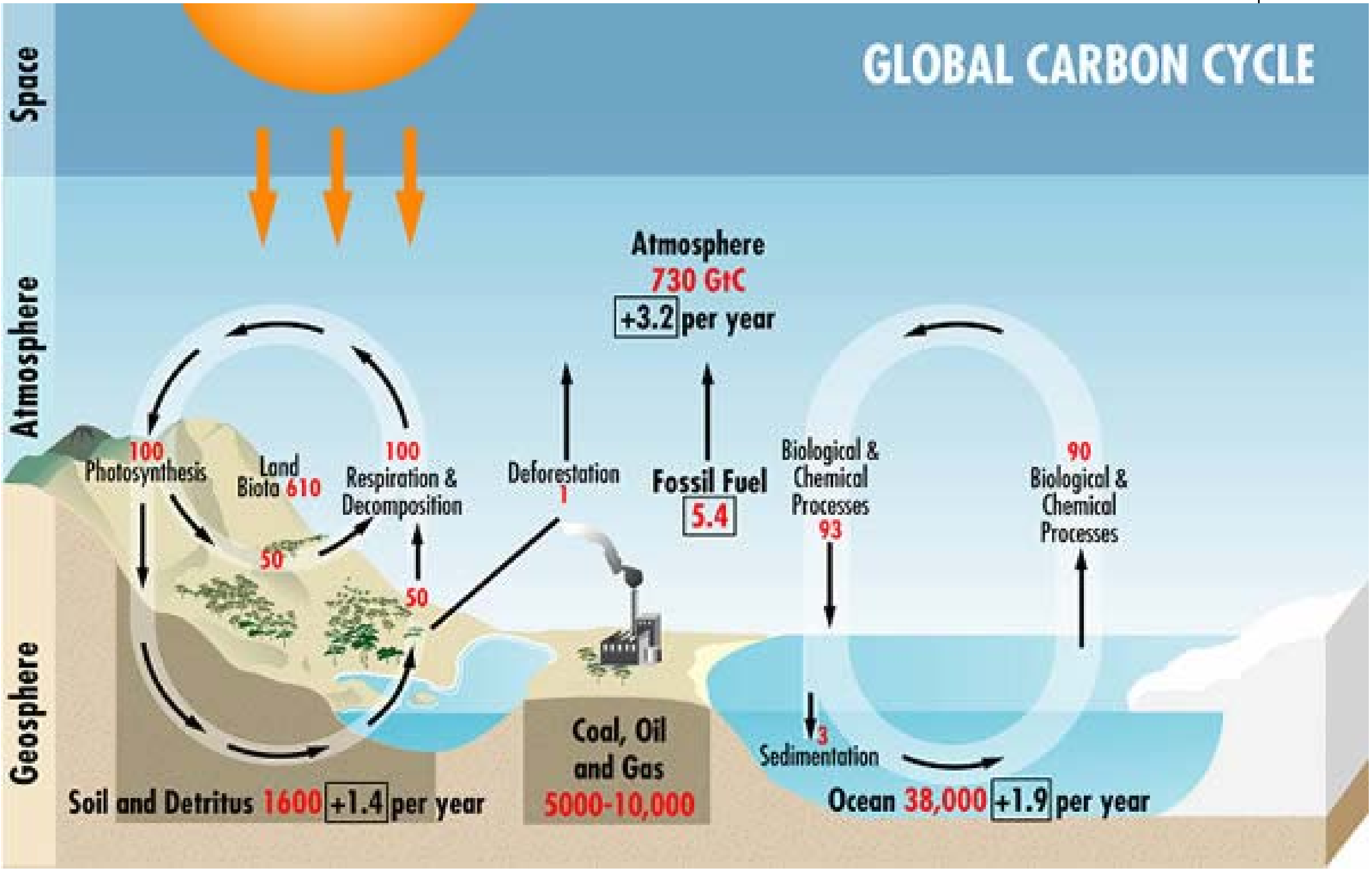


Soil can be a C sink

- Soil C stocks have been depleted
- Potential for soils, especially in temperate perennial grassland, so provide C sink
- Need better understanding of controls on soil C dynamics



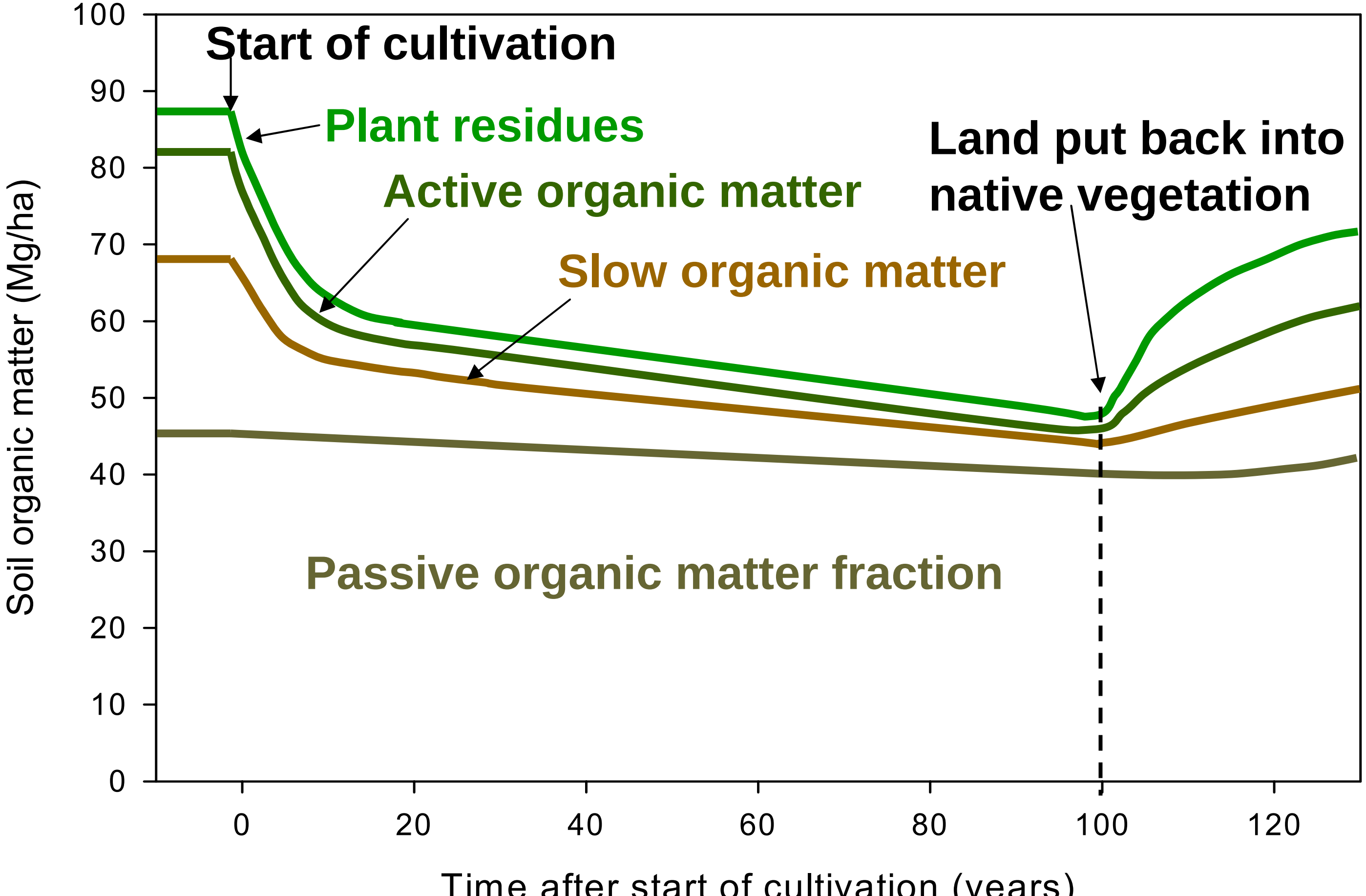
Soil: large, stable C pool



Soil – Our single most valuable ecosystem

- Extremely diverse *living* ecosystem
- Ecosystem services
  - soil (OM cycling)
  - clean water
  - food etc.
  - genetic resources

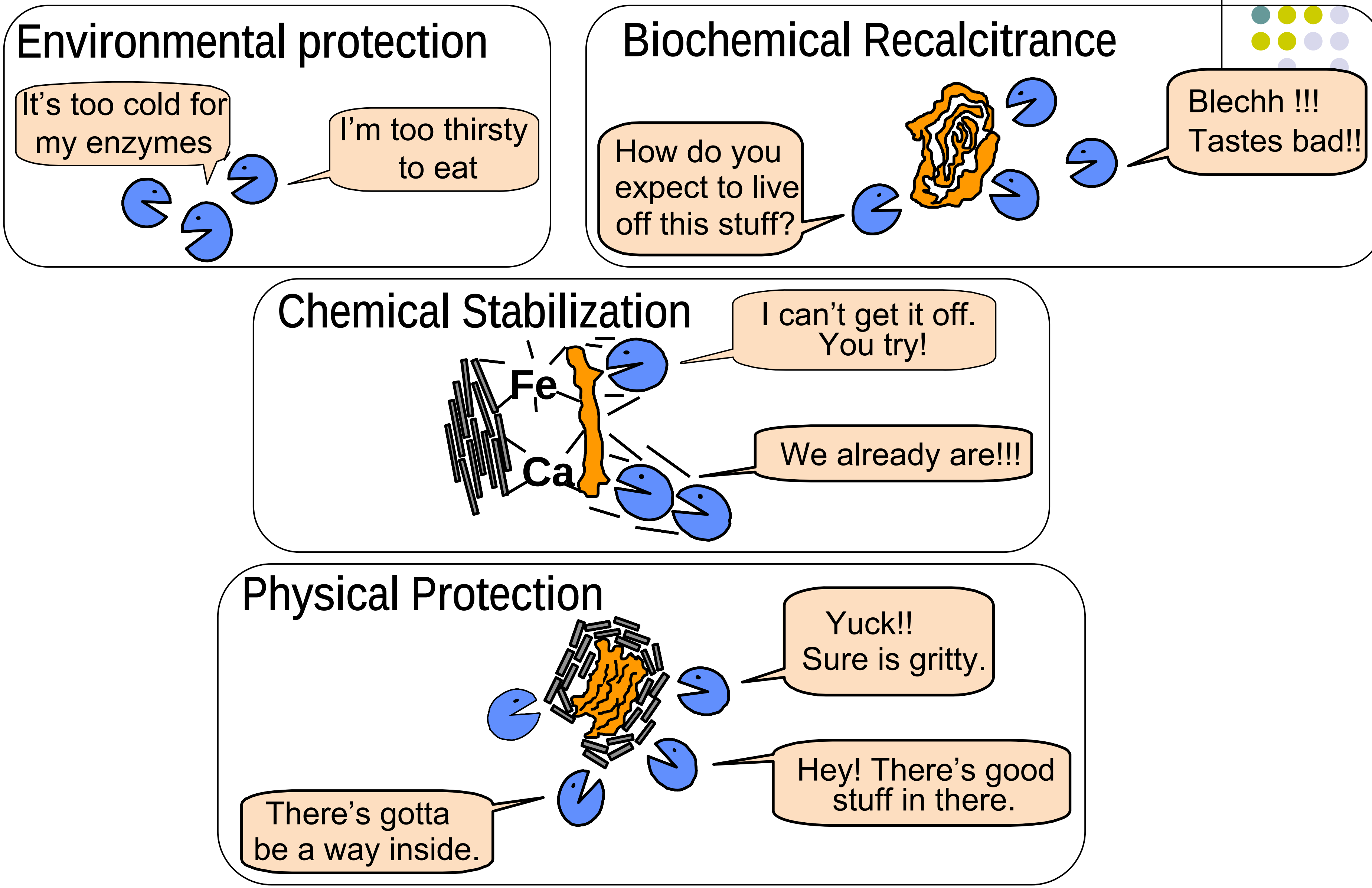
SOM pools: loss after cultivation, gain after restoration



From Brady and Weil 1999

Mechanisms of soil organic matter stabilization

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



Soil structure

- Exists in three dimensions
- Dynamic and heterogeneous in space and time
- Habitat of all soil biota
- Framework in which and through ALL soil processes occur

Soil structure – an integrator of many soil processes

Root growth & turnover
Food web dynamics
Decomposition
Physicochemical protection
of organic matter
Humification

Erosion
Runoff
Infiltration
Hydraulic conductance
Gaseous diffusion
Aeration

Mineral weathering
Ion exchange
Leaching
Solute transport
Nutrient cycling
Carbon cycling

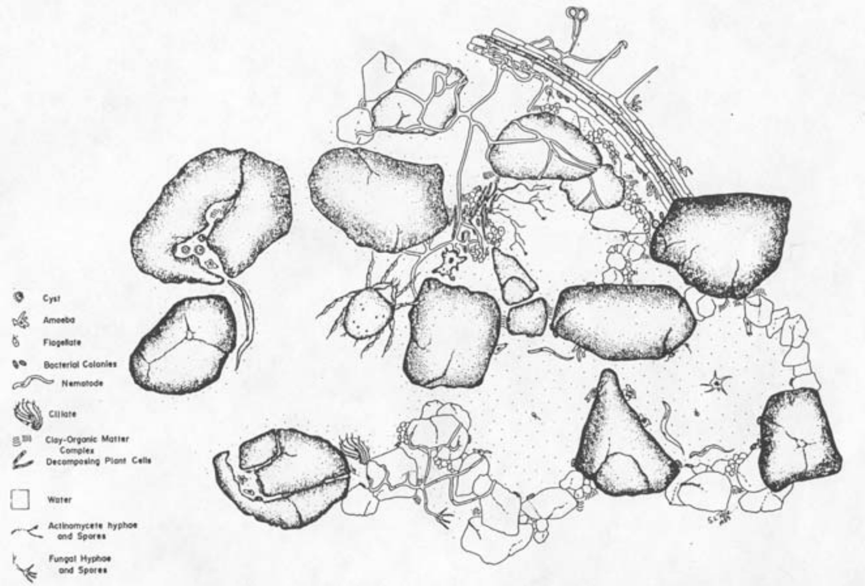
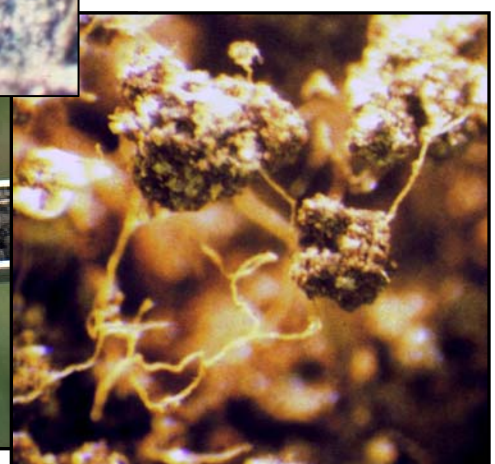


Fig. 4. Horizontal cross section (1 cm^2) of a highly structured and biologically active microsite in the short grass prairie. It depicts how the different classes of pore space and the distribution of water within pores influence the feeding and habitat relationships among the different groups of soil organisms. Illustration by S. L. Rose.

Soil aggregation

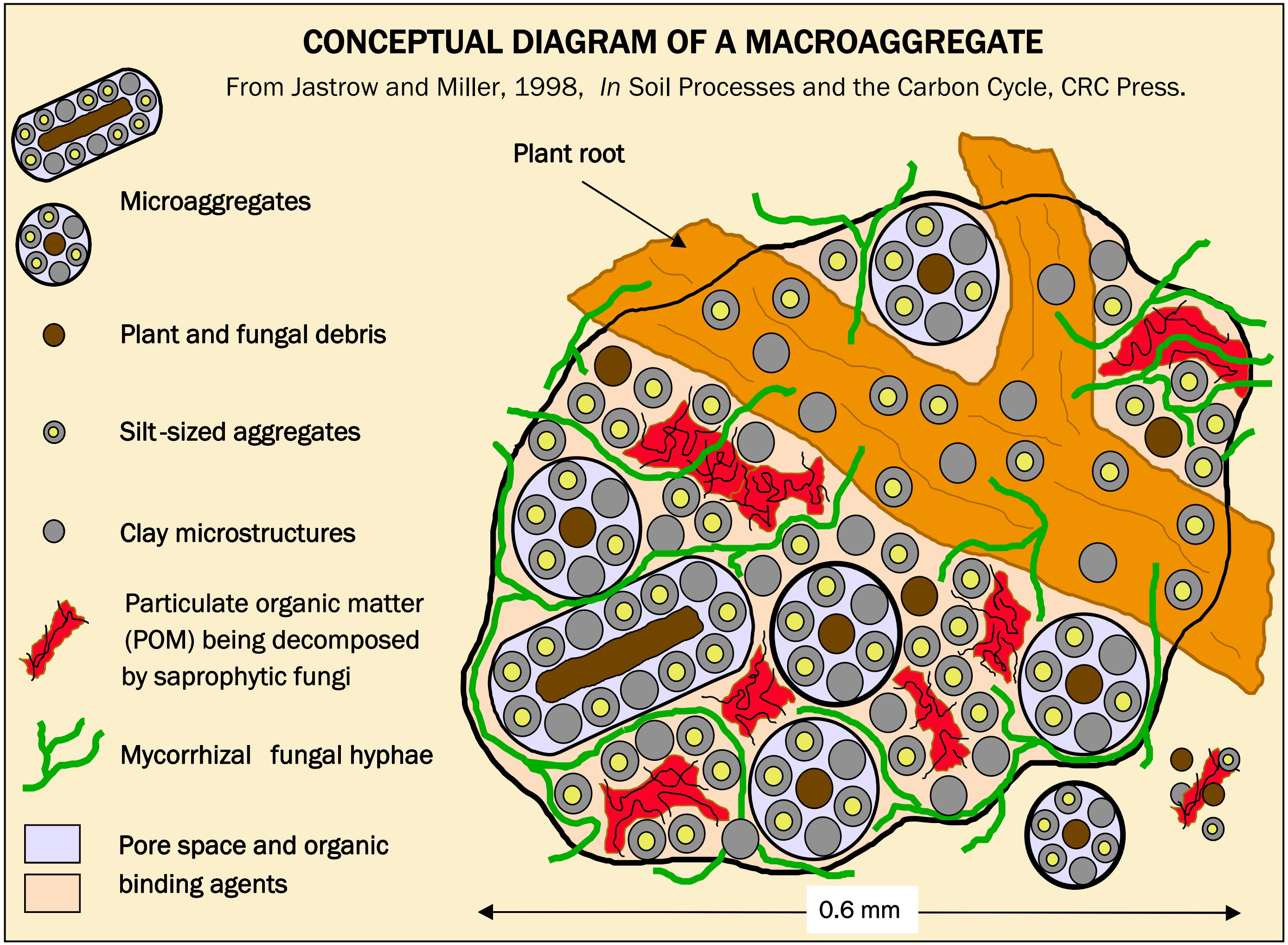
"... the naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates."

J. P. Martin et al. 1955. Soil aggregation. Advan. in Agronomy 7:1-37.



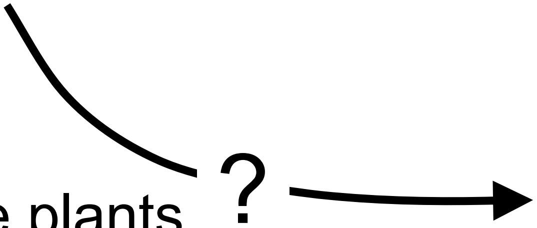
Highly structured soils have a diversity of pore sizes created by the hierarchical organization of soil aggregates

Aggregate hierarchy



Can soil be restored?
Can soil sequester CO_2?

Bellmuseum.org



- After planting native prairie plants, does the soil return to precultivation conditions?
- Will the ecosystem function as though it had never been disturbed?
- Will SOM return?

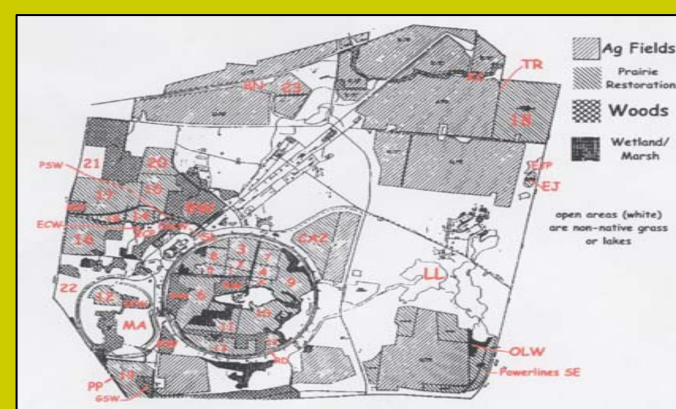
What controls soil C dynamics in restored prairie?

- C sequestration
  - How much C will restored prairies accumulate?
  - How fast will it build up?
  - How long will it remain in the system?

- Moisture
- Plant community
- Protection from mineralization, especially physical protection

Study site:
Fermilab restored prairies

- Restoration of native tallgrass prairie began 1975
- Annual plantings create a chronosequence of restorations encompassing over 400 hectares.



Fermilab prairies

- Prairies initially established to recreate, on a large scale, the assemblage of prairie plants observed in nearby remnants.
- Terrestrial Ecology Group at Argonne began researching Fermilab prairies in 1985.
- Also onsite
  - Never-cultivated remnant prairie
  - Agricultural fields
  - Pasture of *Bromus inermis*, a cool-season grass

Fermilab restored prairies : aboveground

First year

Second year

Eleventh year

- Initial years are dominated by species typical of old-field succession (annuals → biennials → weedy perennials).
- Once litter buildup is sufficient to carry a fire, prairie grasses and forbs begin to take over.

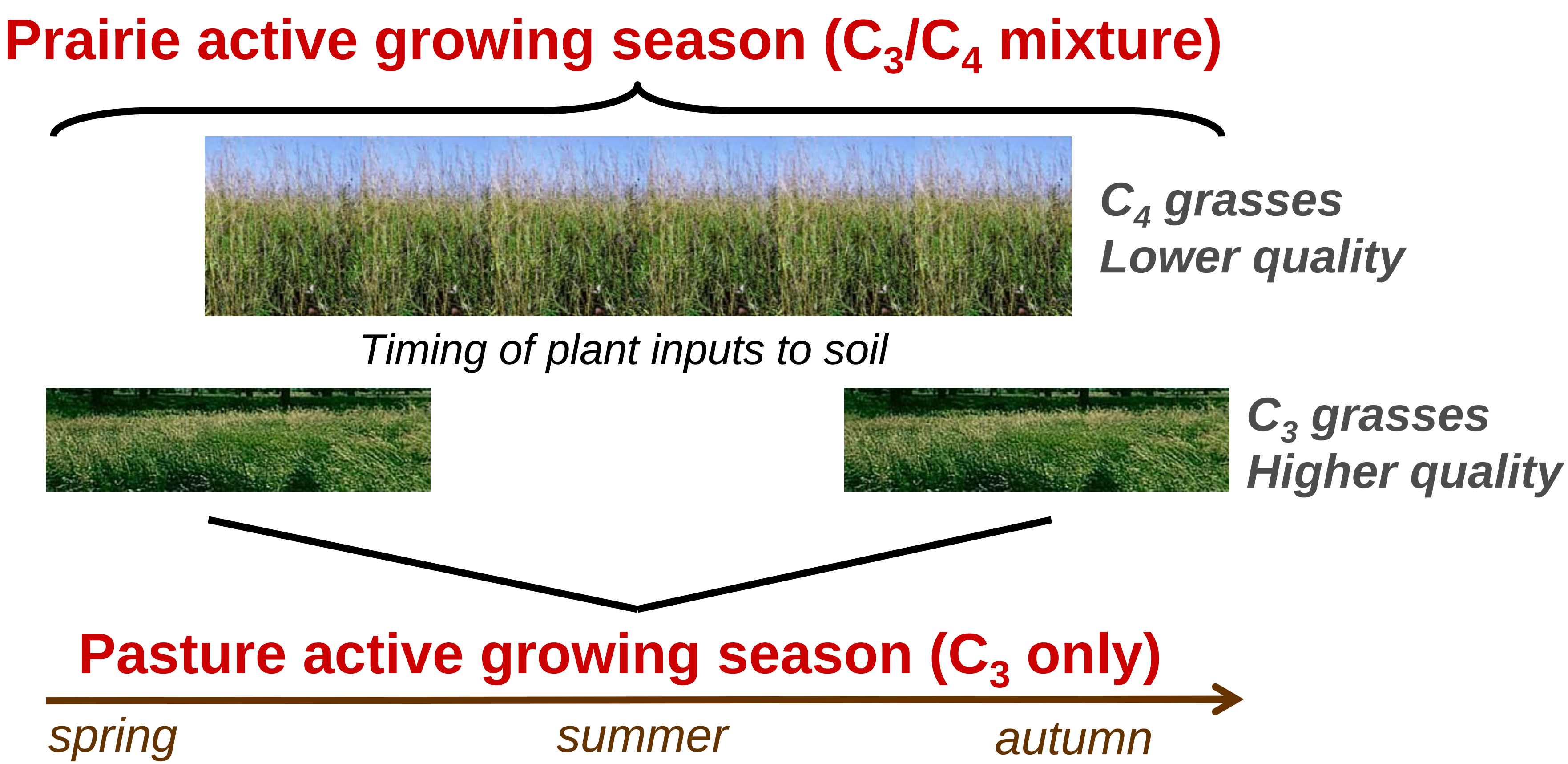
Carbon inputs to prairie soil

- C_3/ cool season
  - Eurasian pasture grasses, including brome
  - Prairie forbs, although some are warm season
  - Relatively narrow C:N → more decomposable

- C_4 / warm season
  - Prairie grasses, including big bluestem, Indiangrass, switch grass
  - Relatively broad C:N → less decomposable
  - More water and N use efficient

Plant inputs influence SOM dynamics

- Longer duration of inputs to prairie soil
- Lower quality of inputs from C_4 plants
- Timing of inputs favors decomposition/mineralization in pasture

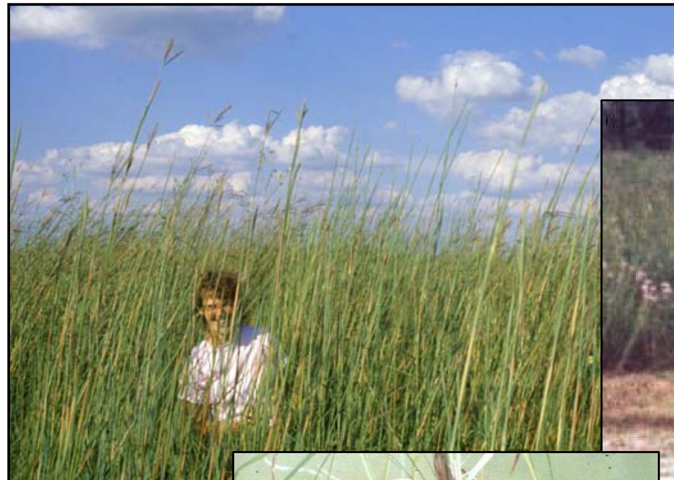


Fermilab restored prairies: belowground

- Highly structured silt loams degraded by a century of agriculture.

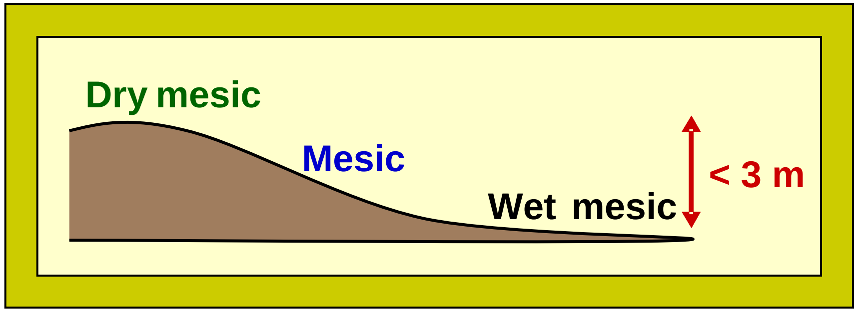
- Peak standing crops can be over 1 kg dry wt m^{-2} aboveground and 2 kg dry m^{-2} belowground.

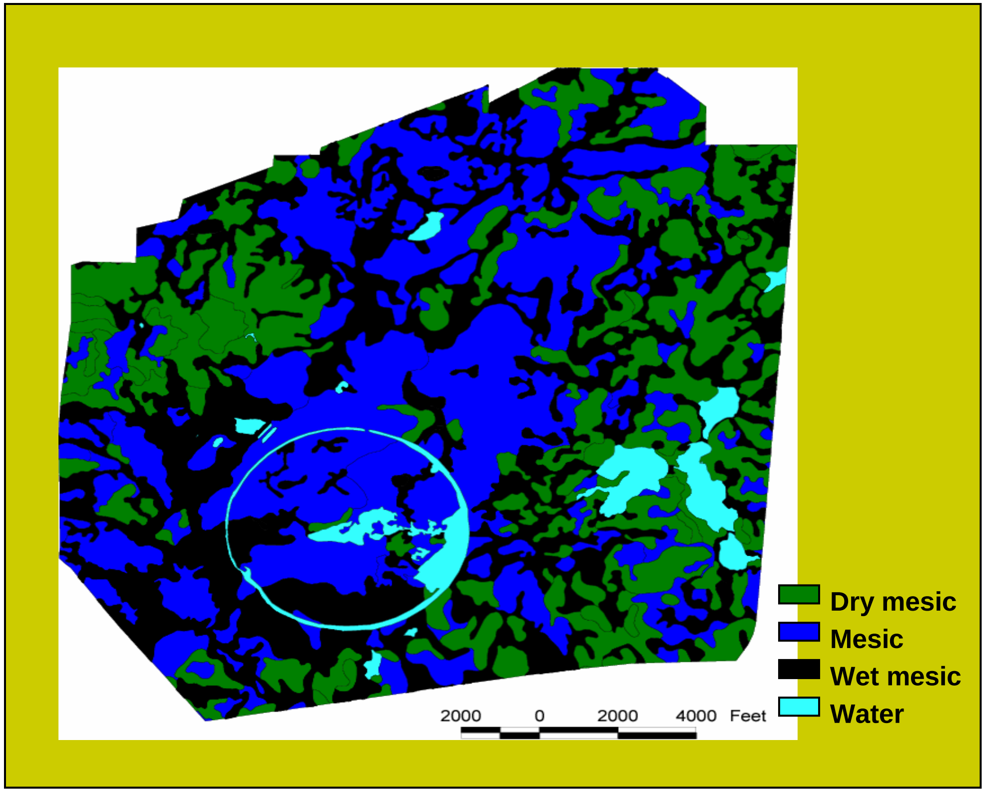
- Surface litter is burned regularly → belowground inputs drive soil system



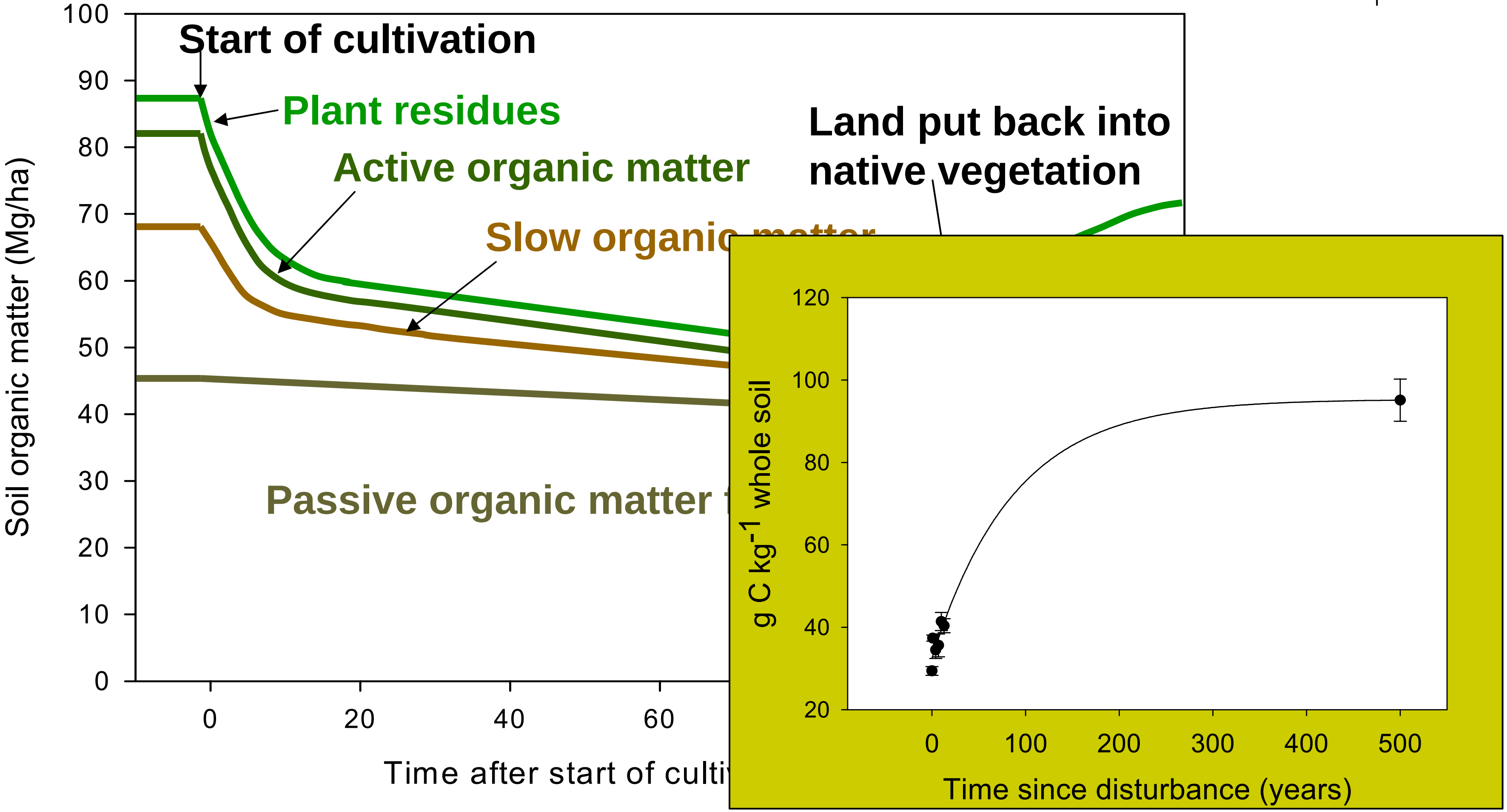
Fermilab restored prairies: belowground

- Artificial drainage
  - Tiled during cultivation
  - Most tiles inside accelerator ring nonfunctional after construction
  - Cooling moat for ring restricts drainage





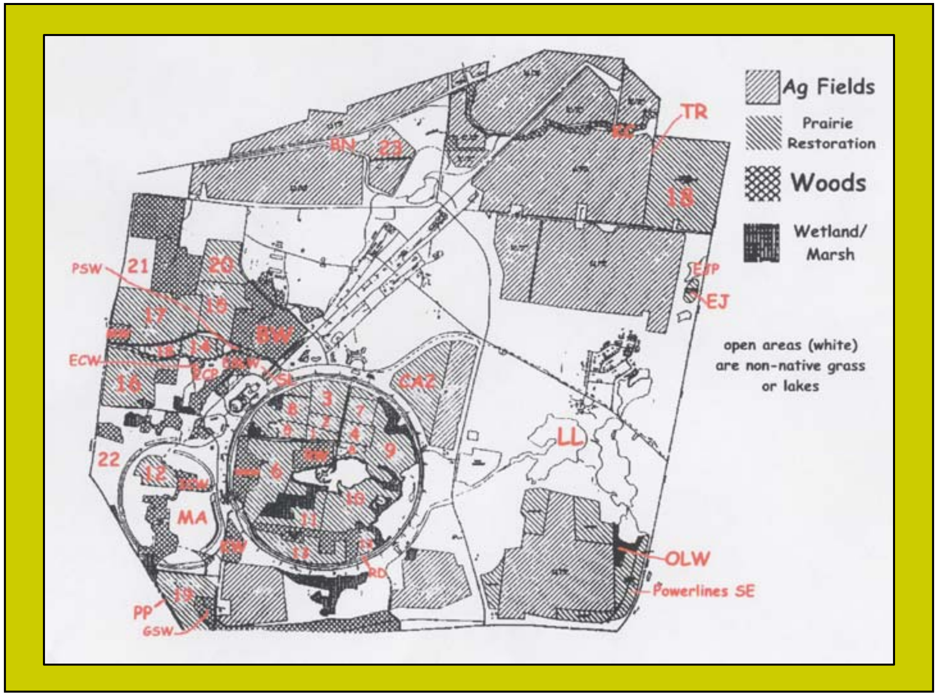
Fermilab prairies have accumulated SOM



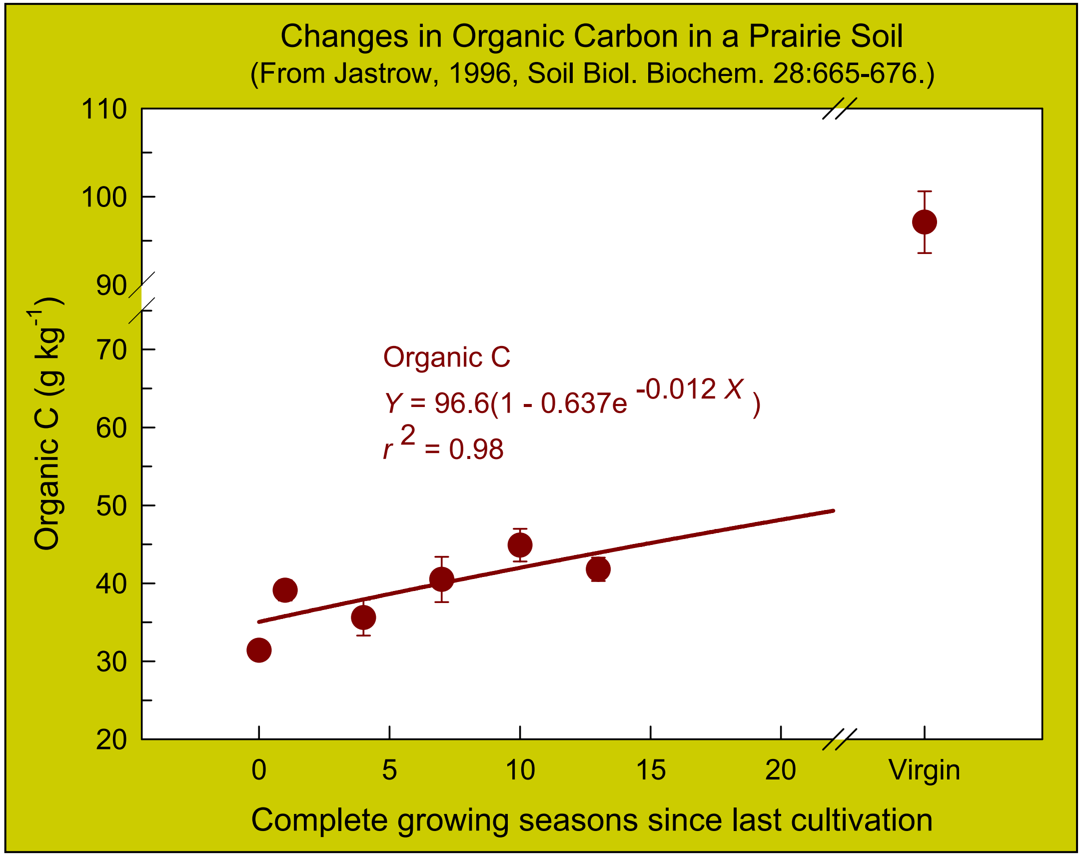
Jastrow 1996

Chronosequence approach

- Space-for-time substitution
- Assumes all plots identical except for age
- Interpretation on site level, not plot level



SOC takes much longer to recover



- Soil organic C takes ~ 380 years to return to precultivation levels.

By 2004, measured SOC was marginally significantly lower ($p=0.06$) and N was not different ($p=.4$) than what was predicted from the 1985 model based on a paired t-test.

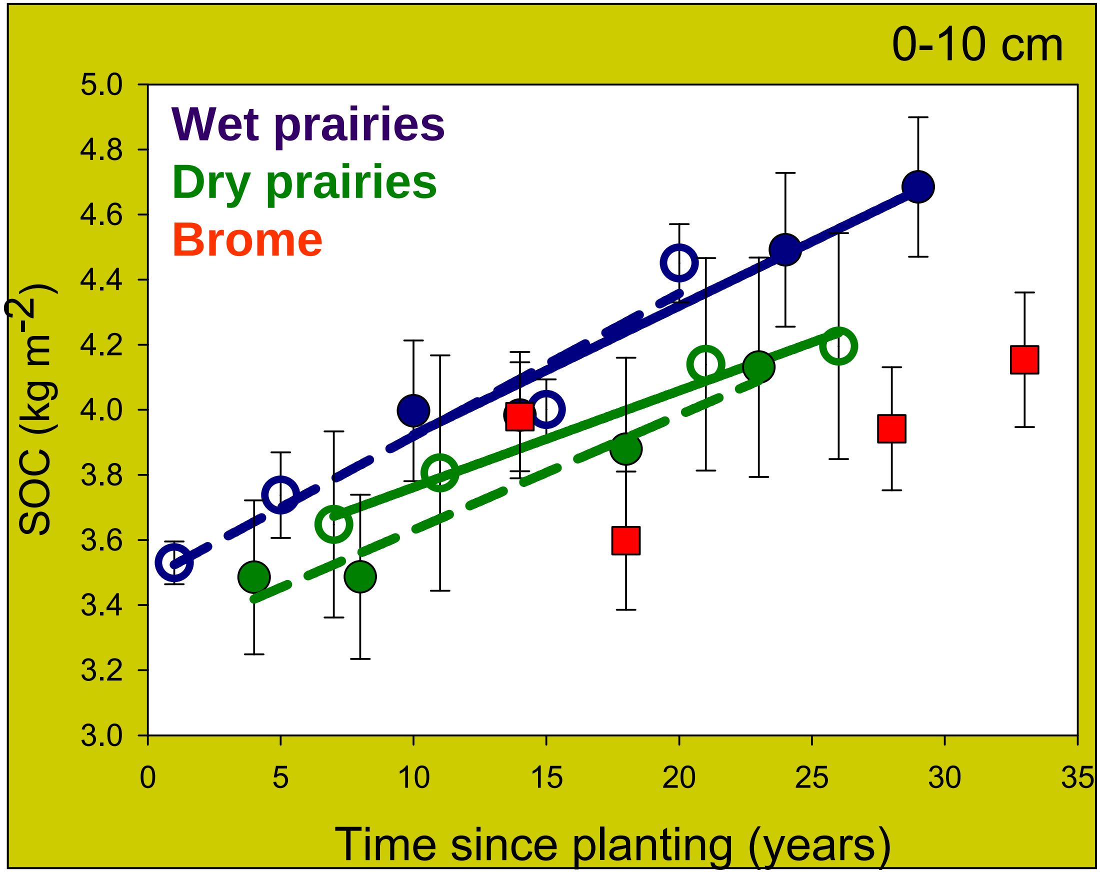
Experiment 1
The resampling approach

- Permanent markers in each plot
  - 1985, 1989, 1999, 2004
  - 0-10 cm 10-20 cm
- Plot revisited over time, thus
  - No space-for-time substitution
  - C accrual rate can be estimated for individual plots
  - Differences among plots can be assessed

The Plots

	Vegetation	Year Planted	Management
Plot 1	Prairie (C_4/C_3 mixture)	1975	•Burned every 1-3 years • Inside accelerator ring (poorly drained, sometimes flooded due to engineering for the ring)
Plot 4		1978	
Plot 7		1981	
Plot 11		1984	
Brome	C_3 Pasture (*Bromus inermis* & *Poa pratensis*)	1972	• Mowed biannually • Outside accelerator ring (well drained)

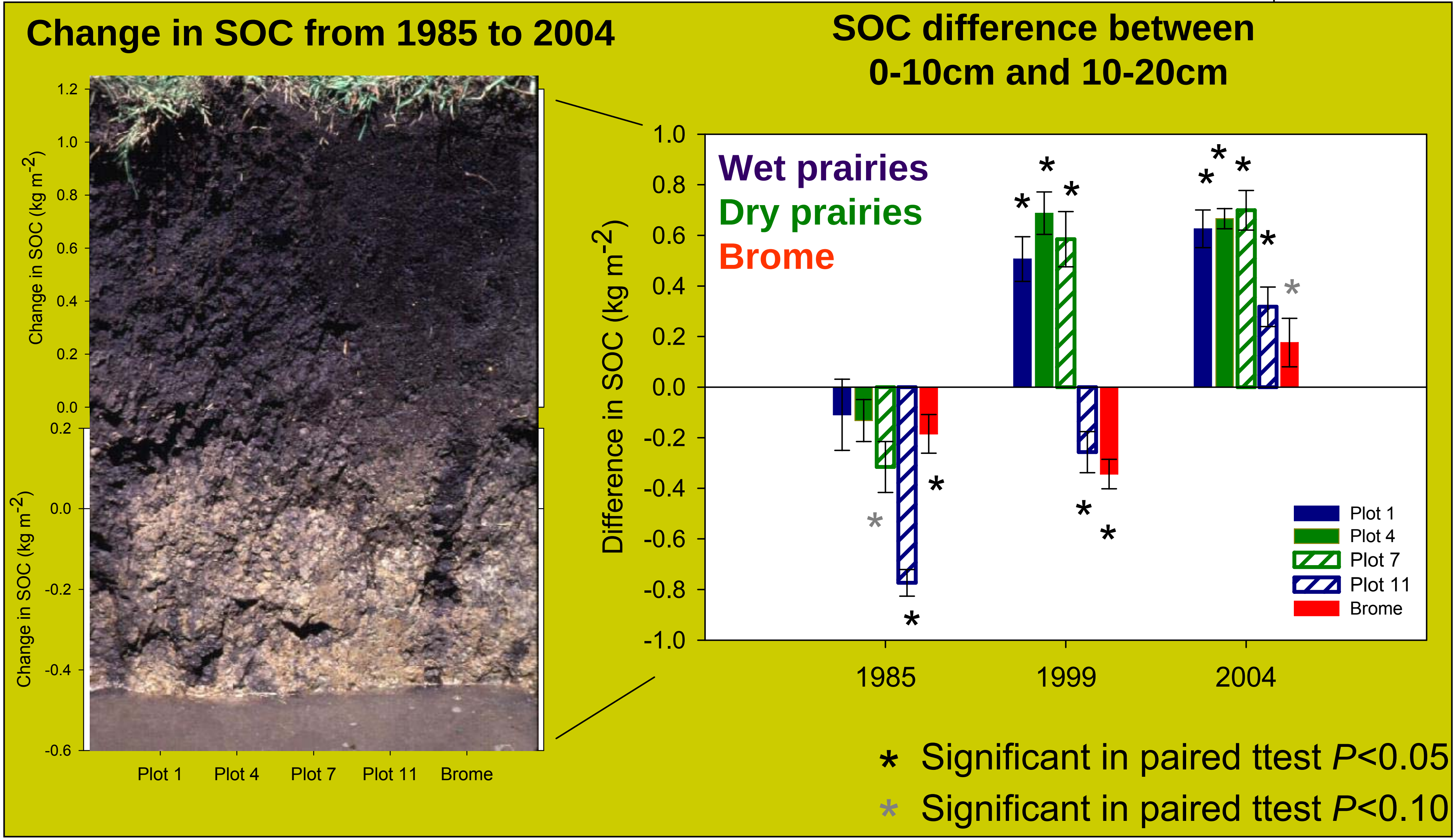
Soil accrues C in prairies but not in brome field



- All prairies have significant, positive linear change in SOC.
- No significant regression for Brome.

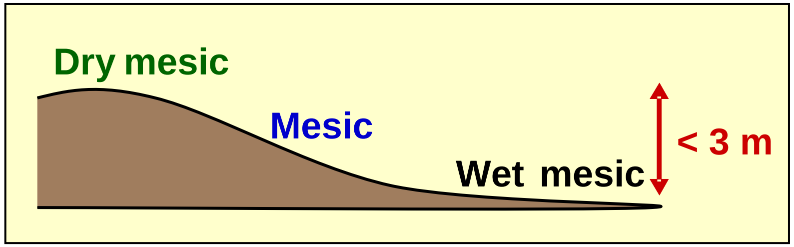
Average slope: 0.355
Range: 0.29 – 0.43

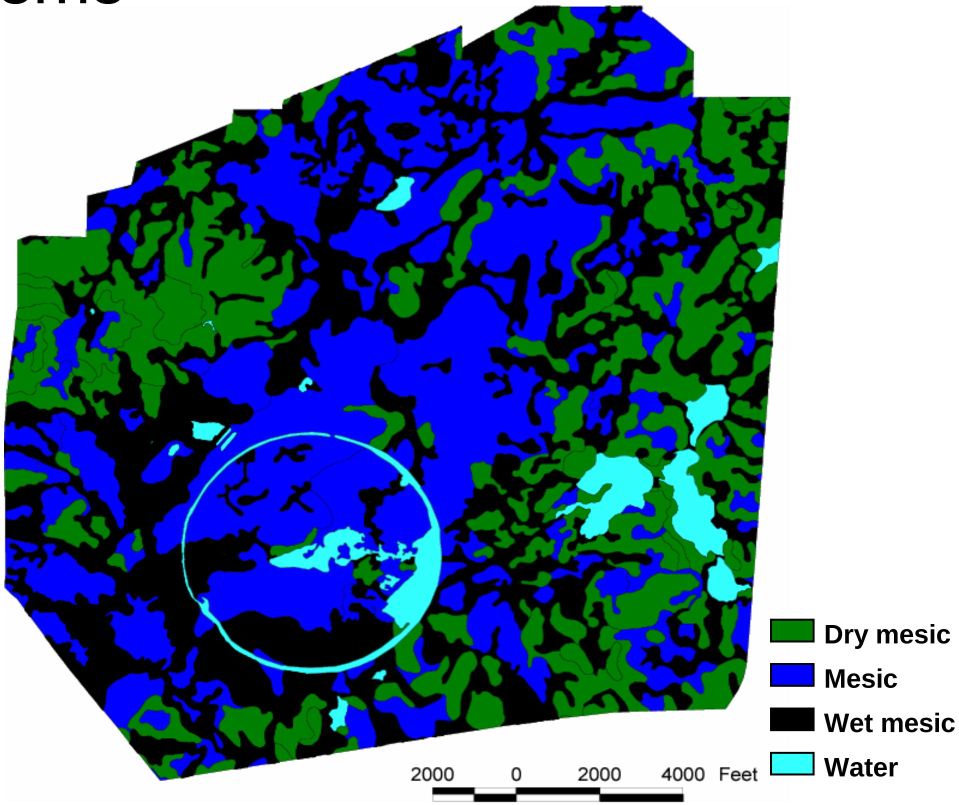
Depth distribution of C changes over time



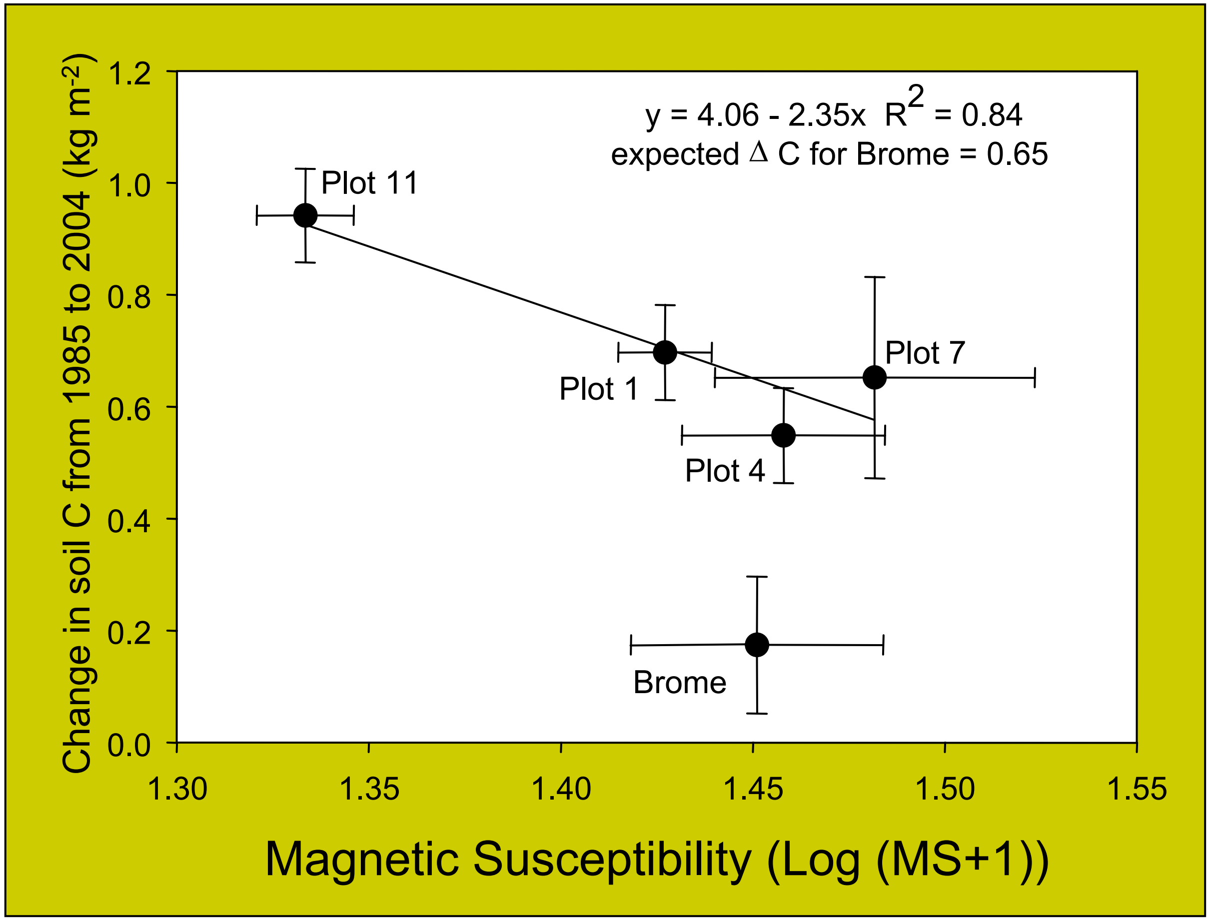
Hydrology may influence soil C dynamics

- Control plant growth → inputs to soil
- Control decomposition → anaerobic conditions in soil or desiccation of organisms





Moisture control on SOM accrual

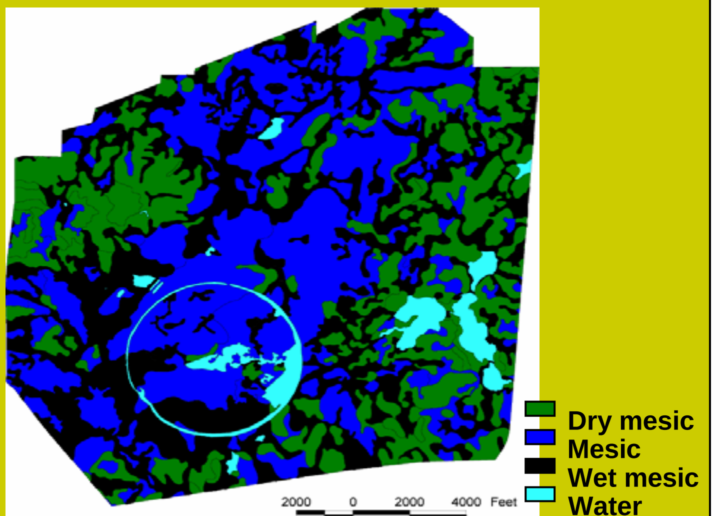


Low magnetic susceptibility indicates poor drainage / high soil water content.

Resampling summary

- Prairies accumulated C over past 20 years, brome did not
- Moisture influences rate of C gain in prairies
- Plant community appears to control SOM in Brome field, but
- Relative influence of moisture and species composition unresolved

Experiment 2
Hydrology vs. Species composition



VS.

Prairie active growing season (C_3/C_4 mixture)

C_4 grasses

Timing of plant inputs to soil

C_3 grasses

Pasture active growing season (C_3 only)

spring *summer* *autumn*

A moisture gradient

Replicate Plots	Moisture Regime	C_3 patches	C_4/C_3 mixed patches	Location
3	Seasonally flooded	2	2	Inside ring
3	Down-slope	2	2	Outside ring
3	Poorly drained	2	2	Inside ring
3	Up-slope	2	2	Outside ring
		Total n = 48 patches		

Prairies with differing soil moisture were selected to construct a moisture gradient. Within each prairie, patches with exclusively C_3 grasses and patches with prairie mixtures were located so that effects of soil moisture and species composition could be studied.

Experiment 3
Physical protection and SOM accrual

- Rate of SOM accrual not expected to remain linear
- Controls on longevity of SOM not fully explored
- Capacity of soil to protect SOM may be limited

- Objectives
  - Investigate how hierarchical soil aggregates determine SOM accrual
  - Determine if some pools reach steady state faster than others → protective mechanisms may have saturated

Chronosequence approach

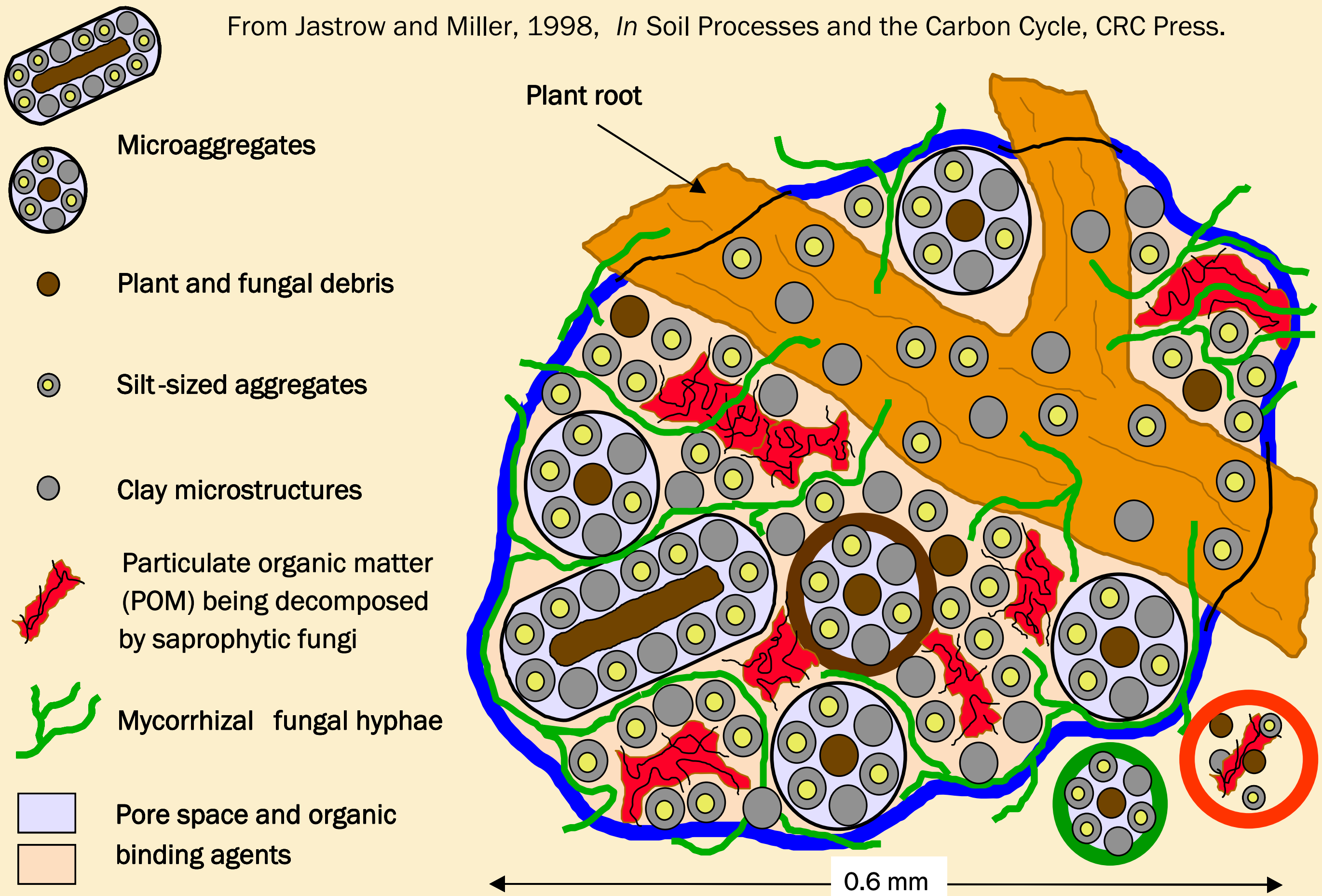
- Agricultural field
  - Soybean phase of corn/soybean rotation
  - Time zero
- Restored prairies
  - 3, 8, 16, 18, 21, 23 completed growing seasons
- Remnant prairie
  - Equilibrium or steady state condition
  - Constrains model

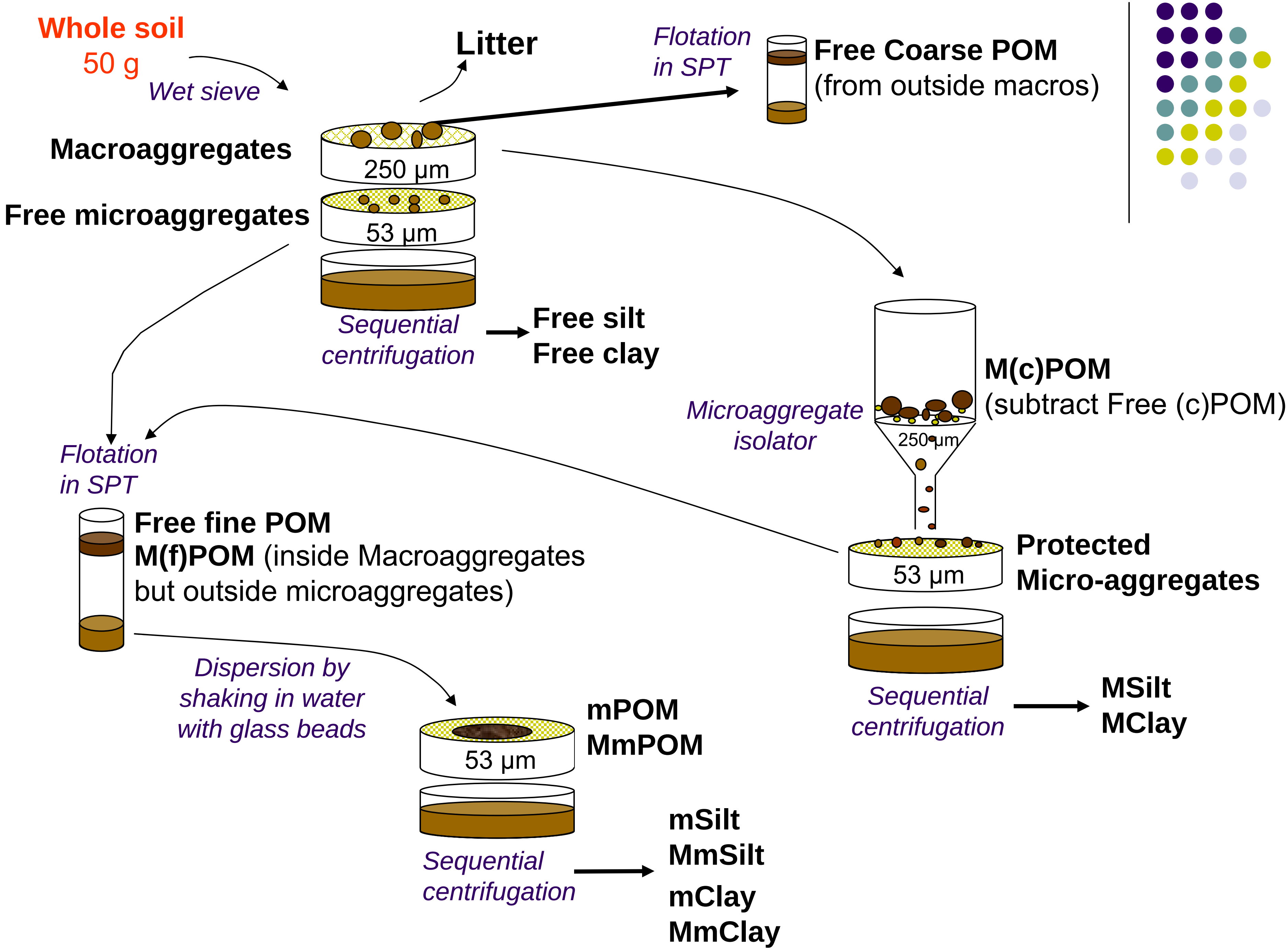
- $C_t = C_o + C_a (1-e^{-k*time})$ where
  - C_o is the initial C content estimated from the agricultural field,
  - C_a is the accrued C,
  - $C_o + C_a$ is the equilibrium C content estimated from remnant prairie,
  - C_t is C content at time *t*,
  - k is the first-order rate constant for loss of C; MRT is -1/k.

  - 500 years was the assumed age for remnant prairie because the time to 99% of equilibrium is accommodated by this age.

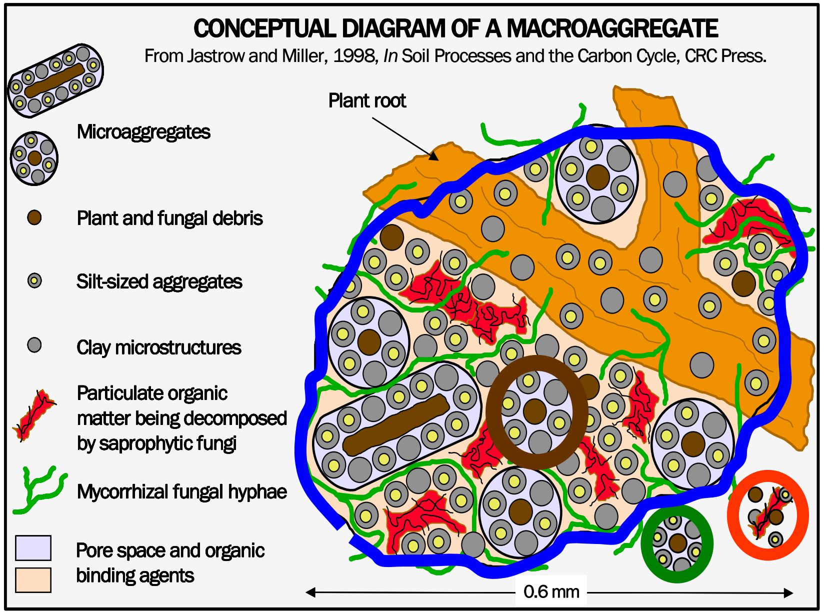
CONCEPTUAL DIAGRAM OF A MACROAGGREGATE

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





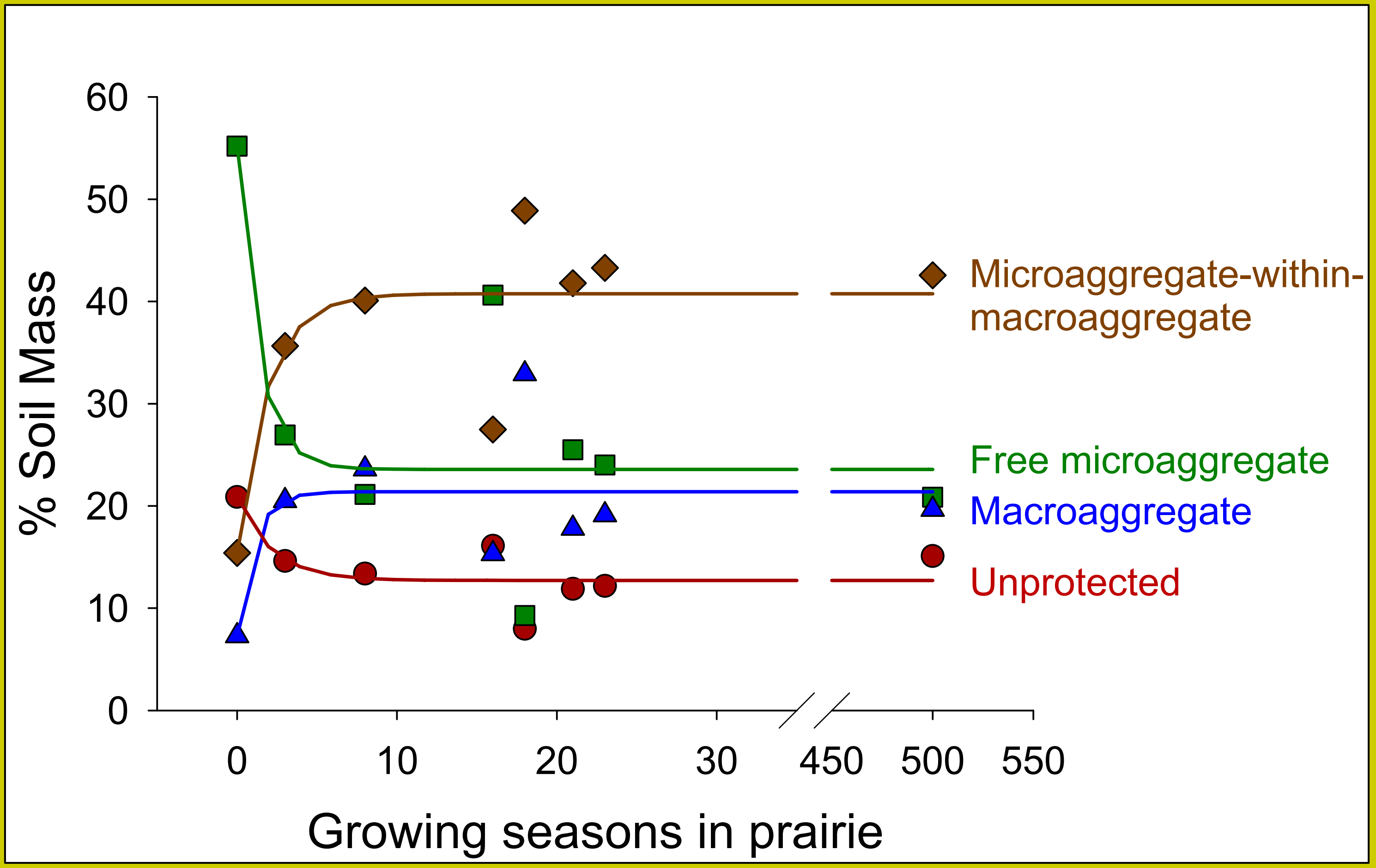
Whole soil
50 g
Wet sieve
Litter
Flotation
in SPT
Free Coarse POM
(from outside macros)
Macroaggregates
250 µm
Free microaggregates
53 µm
Sequential
centrifugation
Free silt
Free clay
M(c)POM
(subtract Free (c)POM)
Microaggregate
isolator
250 µm
Flotation
in SPT
Free fine POM
M(f)POM (inside Macroaggregates
but outside microaggregates)
Protected
Micro-aggregates
53 µm
Sequential
centrifugation
MSilt
MClay
Dispersion by
shaking in water
with glass beads
mPOM
MmPOM
53 µm
Sequential
centrifugation
mSilt
MmSilt
mClay
MmClay



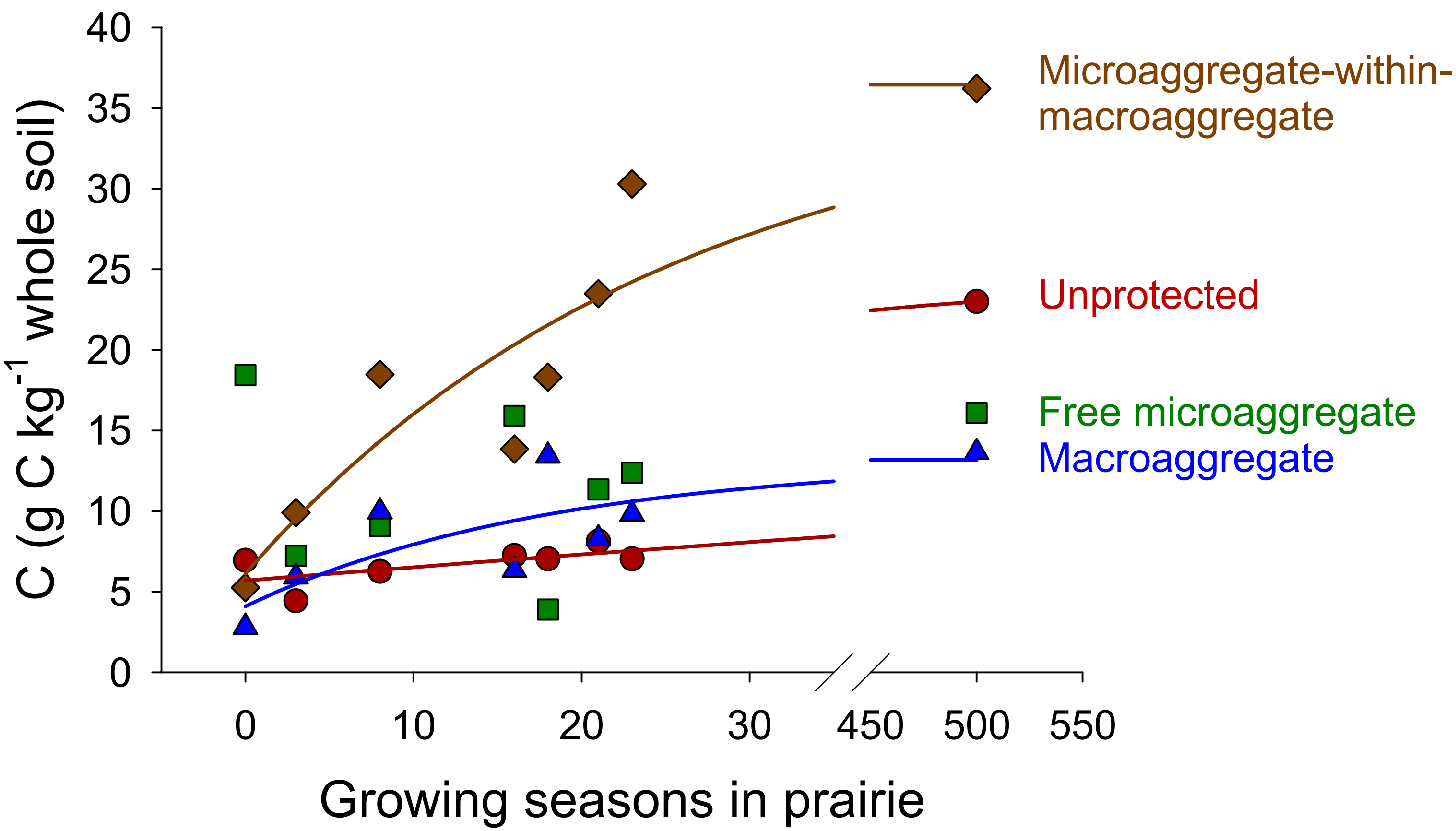
Fractionation yields POM, Silt, and Clay for each of level of aggregate protection.

Unprotected	Macroaggregate	Free microaggregate	Microaggregate-within-macroaggregate
POM *Litter + F cPOM + F fPOM*	**POM** *>250 – F cPOM + M(f)POM*	**POM** *mPOM*	**POM** *MmPOM*
Free Silt	**MSilt**	**mSILT**	**MmSILT**
Free Clay	**MClay**	**mCLAY**	**MmCLAY**

Soil structure recovers quickly



Aggregate-protected SOM takes longer to recover



Time to accrue 95% of steady-state (years)

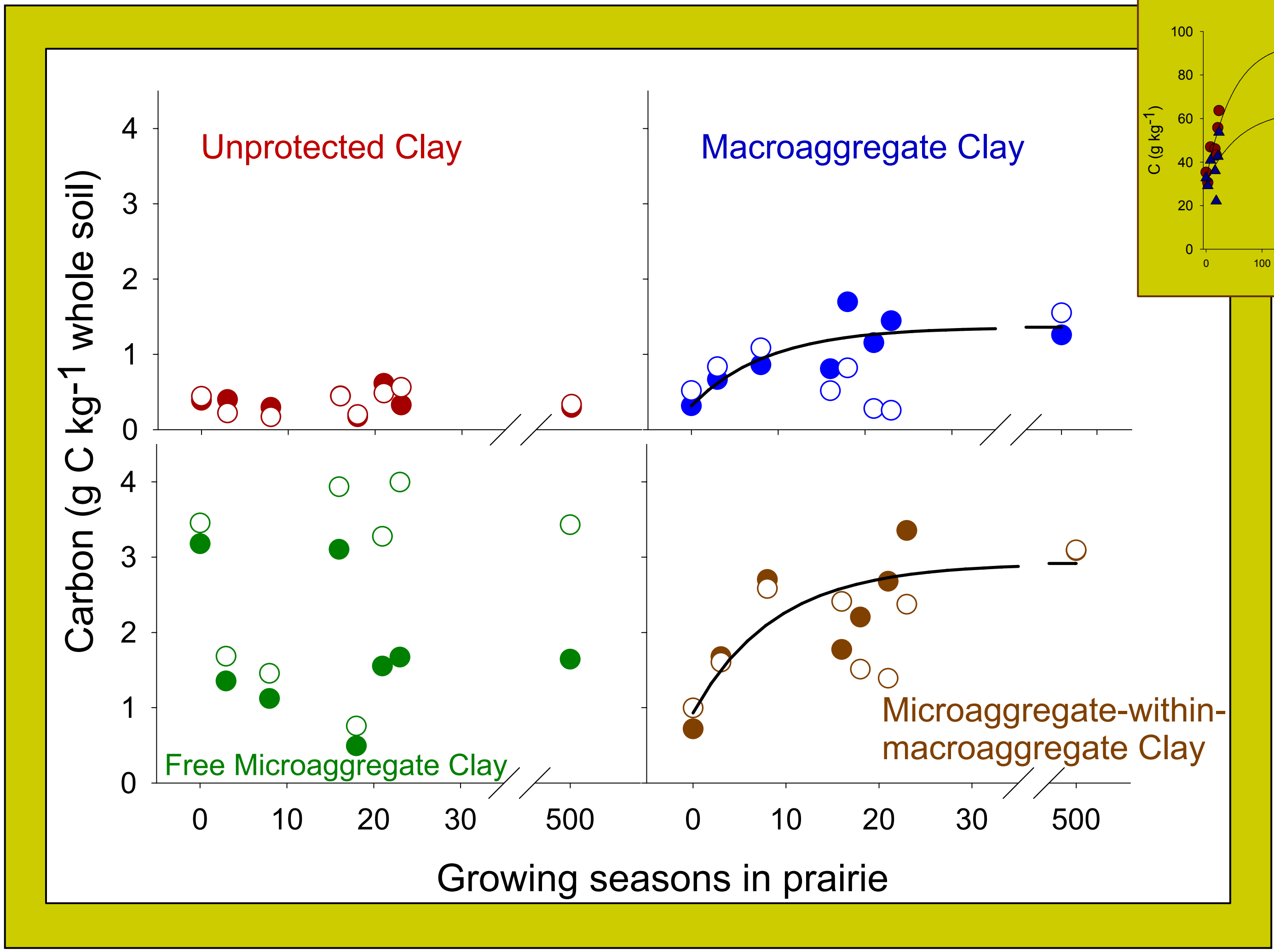
	Unprotected		Macro-aggregates		Free micro-aggregates		Microaggregate-within-macroaggregates	
	0-5	**5-15**	**0-5**	**5-15**	**0-5**	**5-15**	**0-5**	**5-15**
Mass	6.5	4.0	3.2	NA*	3.9	NA	5.6	NA
MRT	2.2	1.3	1.0	NA	1.3	NA	1.9	NA
Carbon	>500	>500	54.5	NA	NA	97.9	75.8	174.2
MRT	~200	~300	18.2	NA	NA	32.7	25.3	58.1

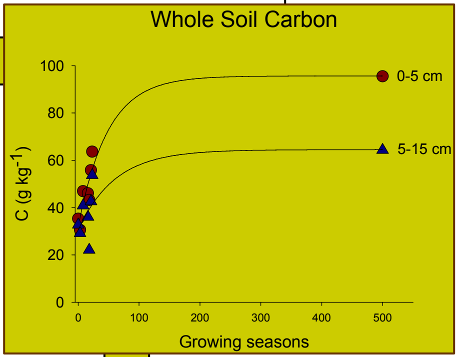
- SOM builds up in aggregates even after the structure is formed
- Pore spaces filling over time

* Data did not fit model

Clay

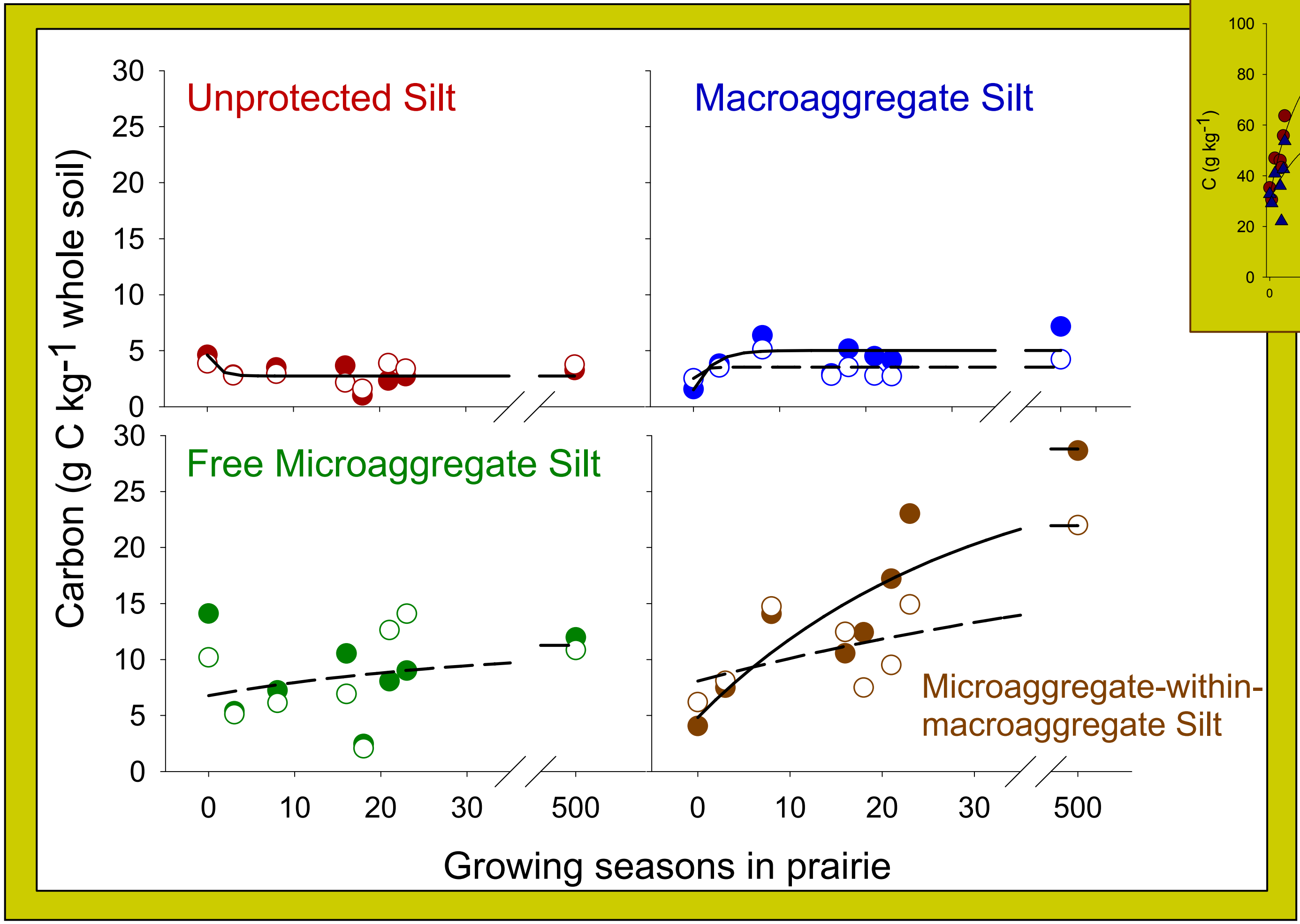
- Small contribution to total SOM accumulation

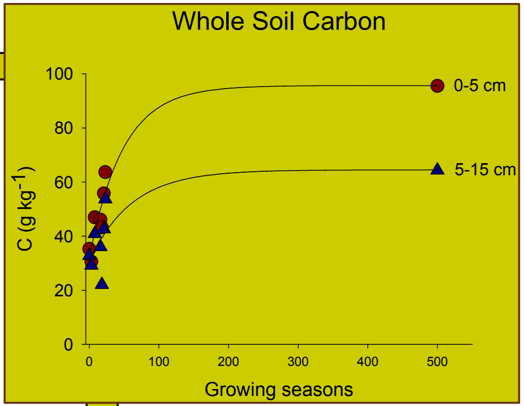




Silt

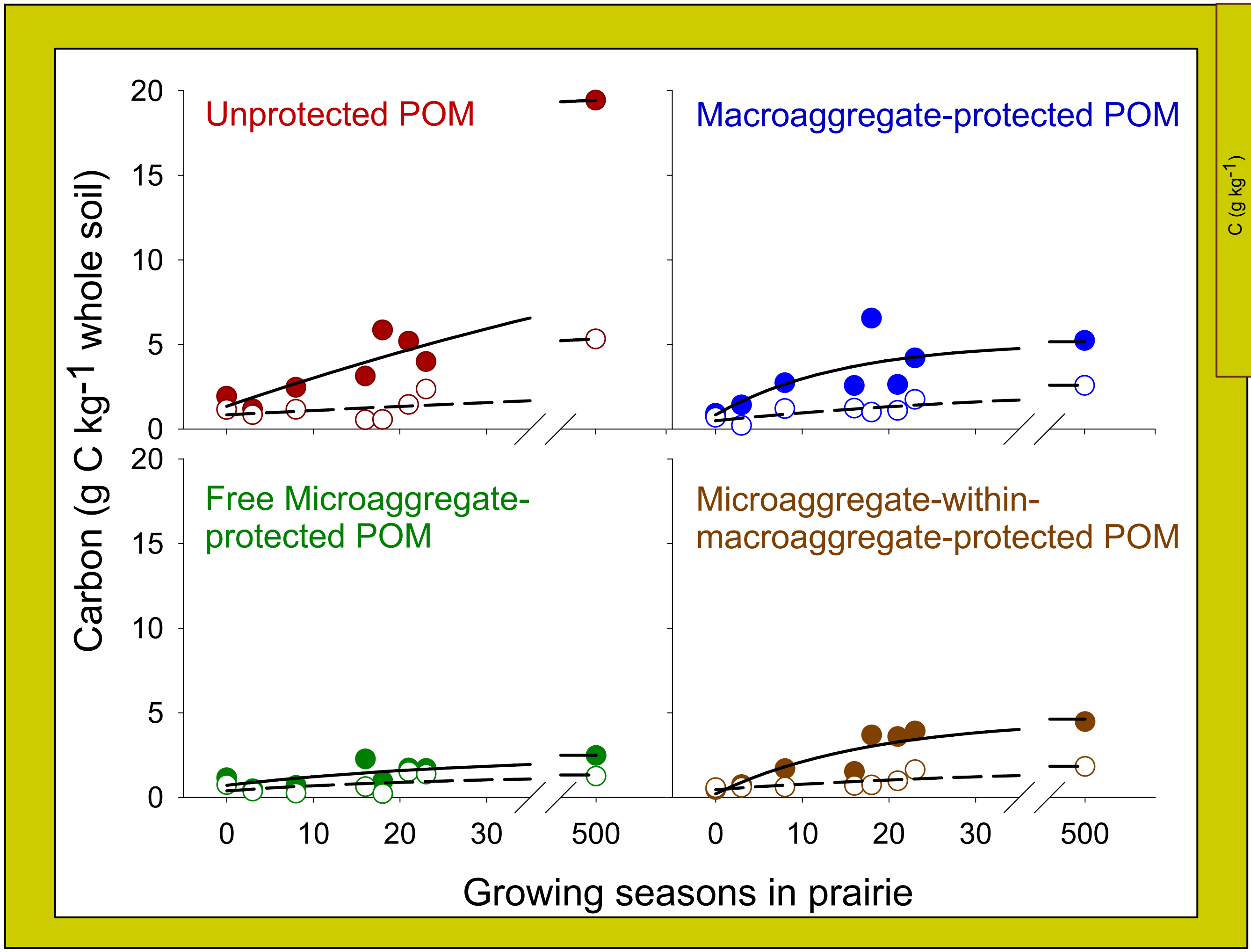
- Silt in micro-within-macro is largest component of total SOM accumulation
- Others contribute little

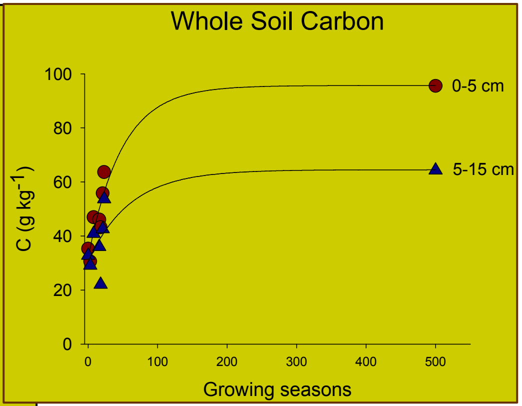




Particulate organic matter

- Most POM gain is in the unprotected pool





Fractionation summary

- Some fractions are too variable to model – replicates may help
- C accumulates in aggregates even after the structures are formed.
- Some pools reach steady state before others → protection is saturated
  - Little or no accumulation in clay
  - Accrual is slowest in unprotected pools and is attributable to the Unprotected POM

Conclusions

- Prairie restoration can build soil C.
- Drainage may influence rate at which soils respond to vegetation change.
- Vegetation type may also influence how the soil recovers and builds SOM.
- Potential for saturation.
  - Mineral pools reach steady state before unprotected pools, especially unprotected POM.
  - Better understanding of why whole soil steady state occurs.

Thanks

- For your attention
- Terrestrial Ecology Group at Argonne National Laboratory
- GCEP