

Carbon Sequestration and Ecological Research

Jeff Gaffney

UALR



DOE Consortium for Research on *Enhancing*



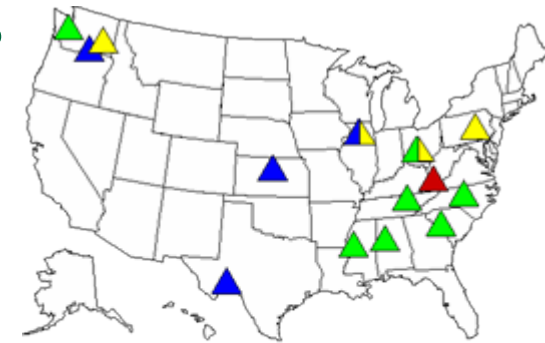
Carbon Sequestration in Terrestrial Ecosystems





Introduction

Gary Jacobs

Oak Ridge National Laboratory

March 19, 2003



-  Forest
-  Agriculture
-  Grassland/Shrubland
-  Degraded Mine

National Laboratories

- Argonne National Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

DOE

- National Energy Technology Laboratory

Universities

- Colorado State University
- University of California - Davis
- Cornell University
- North Carolina State University
- Ohio State University
- Rice University
- Texas A&M University
- University of Washington

Research Institutions

- Joanneum Inst for Energy Res, Austria
- USDA Center for Forested Wetlands Res, SC
- USDA Land Mgmt & Water Cons Unit, WA
- USDA Coshocton Watershed



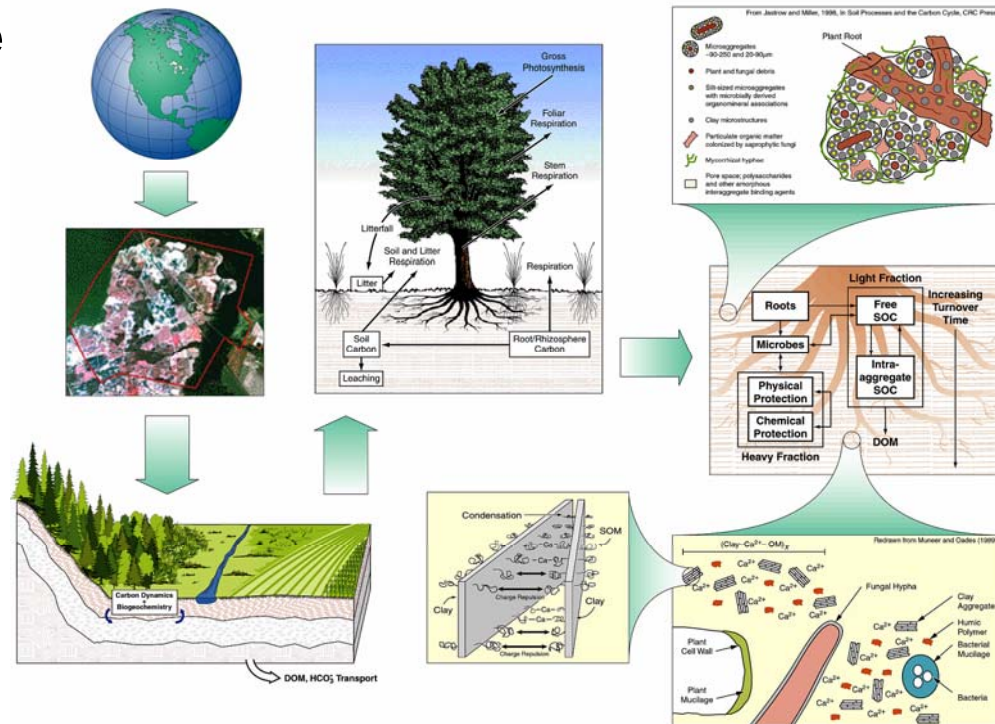
CSiTE Mission

Fundamental science supporting approaches for enhanced sequestration

Soil carbon focus within context of whole ecosystems

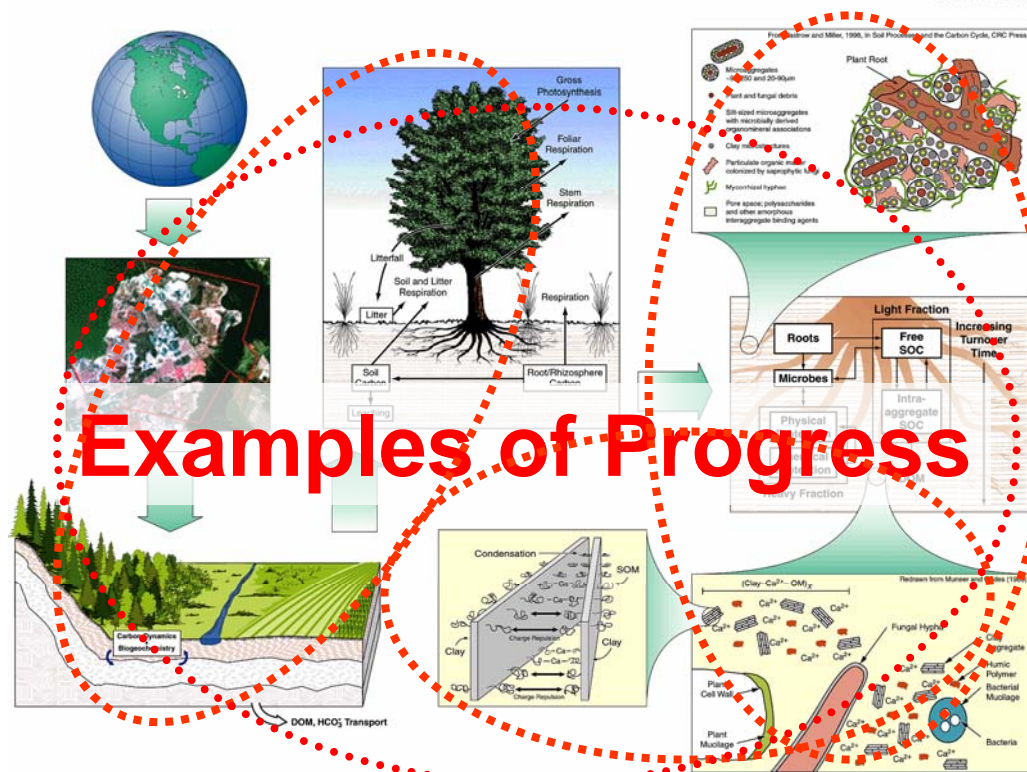
- 1 Discover how to alter carbon capture and sequestration mechanisms from molecular to landscape scales
- 2 Develop conceptual and simulation models for extrapolation across spatial and temporal scales
- 3 Advance science of assessing environmental and economic consequences of sequestration

Multi-scale & multi-disciplinary ORNL 99-0526/abh



What's are some possible options to enhance carbon sequestration?

- ⇒ **Alter inputs (litter), root density, depth, chemistry**
 - Manage vegetation, alter cultivars
 - Fertilization, moisture, etc.
- ⇒ **Shift decomposition rates and products**
 - Shift structure and function of microbial communities
 - Modify chemistry
- ⇒ **Optimize physicochemical conditions**
 - Physical/chemical protection
 - Humification redox reactions
 - Promote deeper transport of C



ORNL 99-0526/abh

Selected Accomplishments

- ① Elucidation of controls on rates and limits of accumulation of soil organic C
- ① Fractionation methods leading to new insights on soil organic carbon capture and longevity
- ① Emerging manipulation concepts
- ① Microbial microarray technology for exploring soil carbon processes
- ② Advances in modeling tools
- ③ Model analysis of full CO₂ and greenhouse gas accounting
- ③ Analyzing economic implications

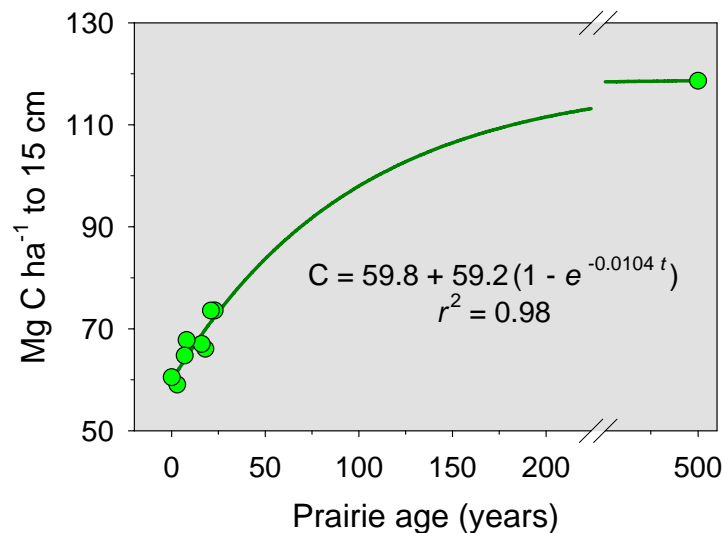
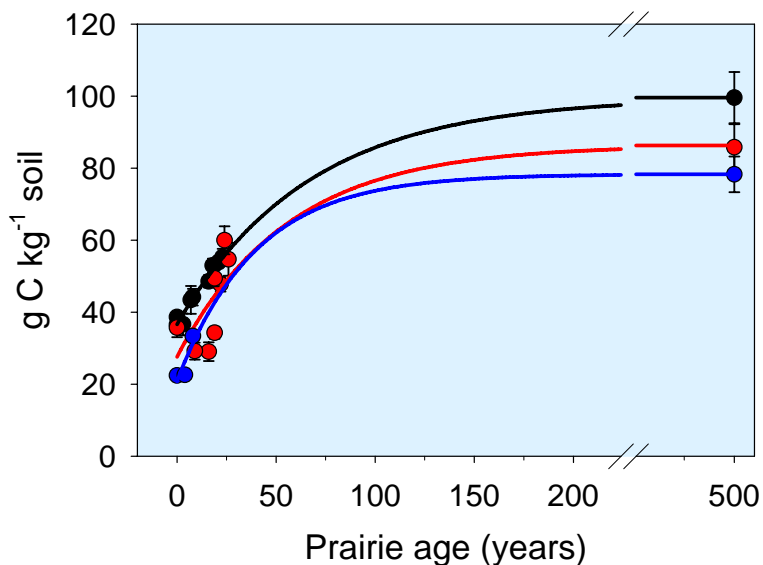
DOE National Environmental Research Park at Fermilab: Research site of opportunity

- ⇒ Row-crop agriculture for ~150 y
- ⇒ Chronosequence of prairie restorations initiated in 1975
- ⇒ Prairie remnants
- ⇒ Fields converted to Eurasian pasture grasses c.1971
- ⇒ Woodlands
- ⇒ Wetlands

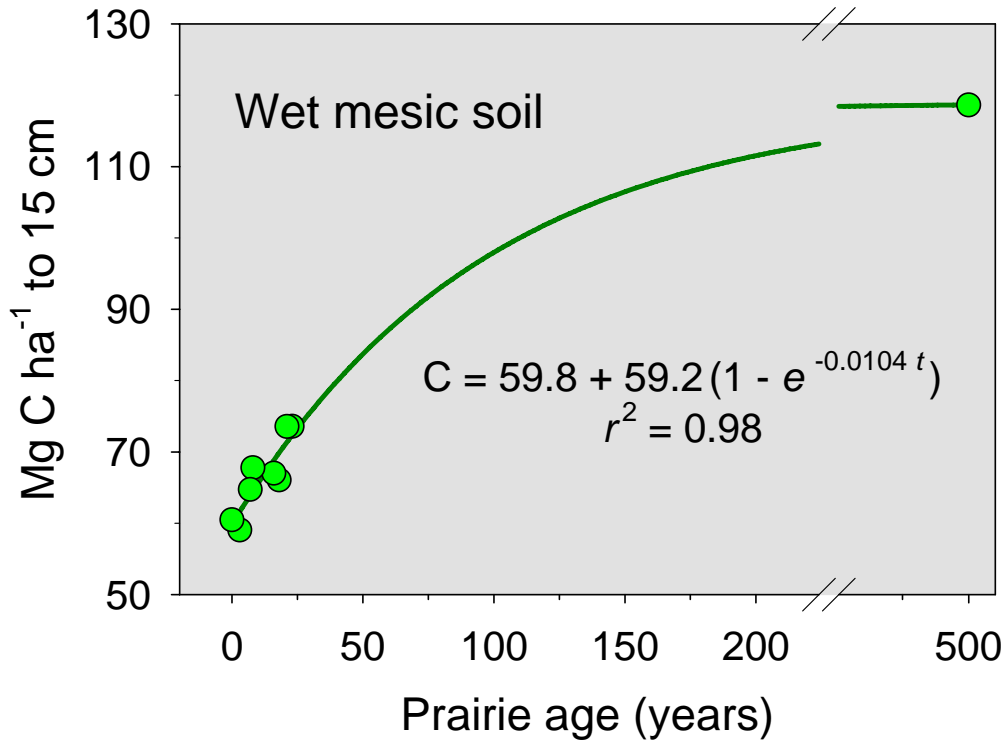


Elucidation of controls on rates & limits of accumulation of soil organic carbon

- ⇒ Inputs
- ⇒ Rates & Limits
- ⇒ Moisture
- ⇒ Nitrogen
- ⇒ Microbial processes



Accrual of soil organic C sustained over 25 years



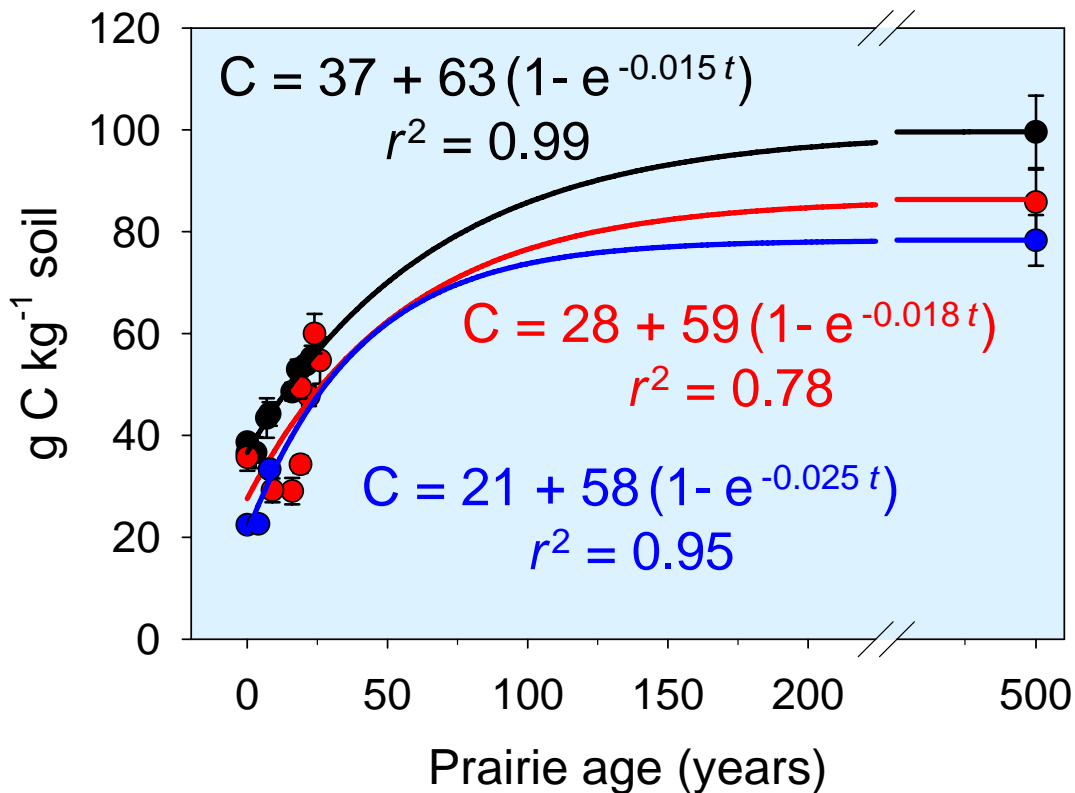
Exponential model predicts accrual of **0.54 Mg C ha⁻¹ y⁻¹** for 25 years in the surface 15 cm

C_e	118.6 Mg ha ⁻¹
MRT	96 y
t_{50}	66 y

Based on equivalent soil mass for 0-15 cm depth at time zero

Effect of soil moisture/drainage conditions

- ⇒ Moisture affects equilibrium C for both disturbed and native
- ⇒ Initial rates of C accrual are similar
- ⇒ Time to equilibrium may vary



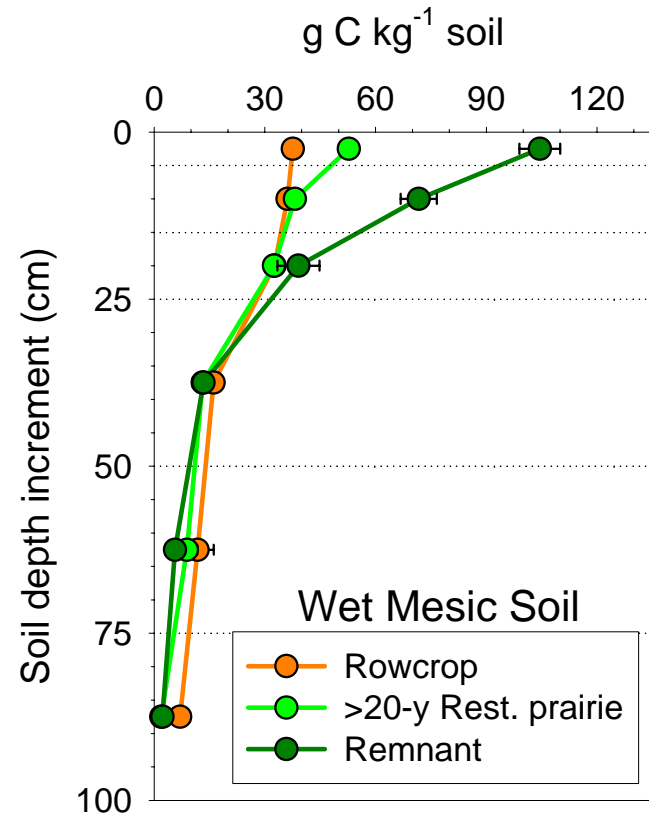
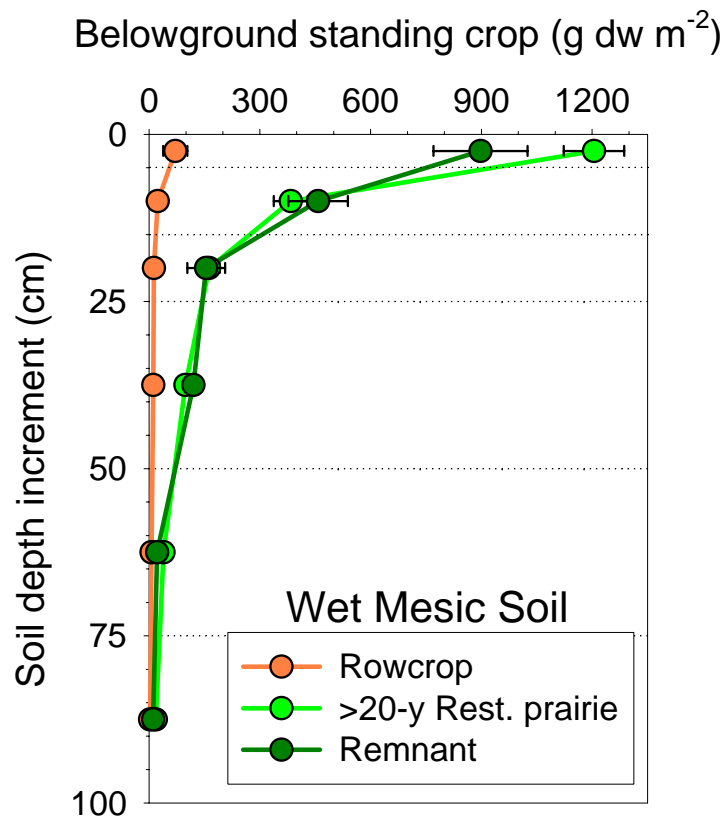
Protective capacity
of these soils
overcomes any
differences in inputs

% of C_e
accrued in 50 y

Wet mesic	53
Mesic	59
Dry mesic	71

Depth distribution of inputs and soil C

- ⇒ Belowground biomass in older restored prairies equals or exceeds remnants
- ⇒ Root and rhizome inputs drive changes in soil C
- ⇒ Greatest soil C increases in surface 5-10 cm
- ⇒ Potential for long-term soil C accrual to 25-30 cm

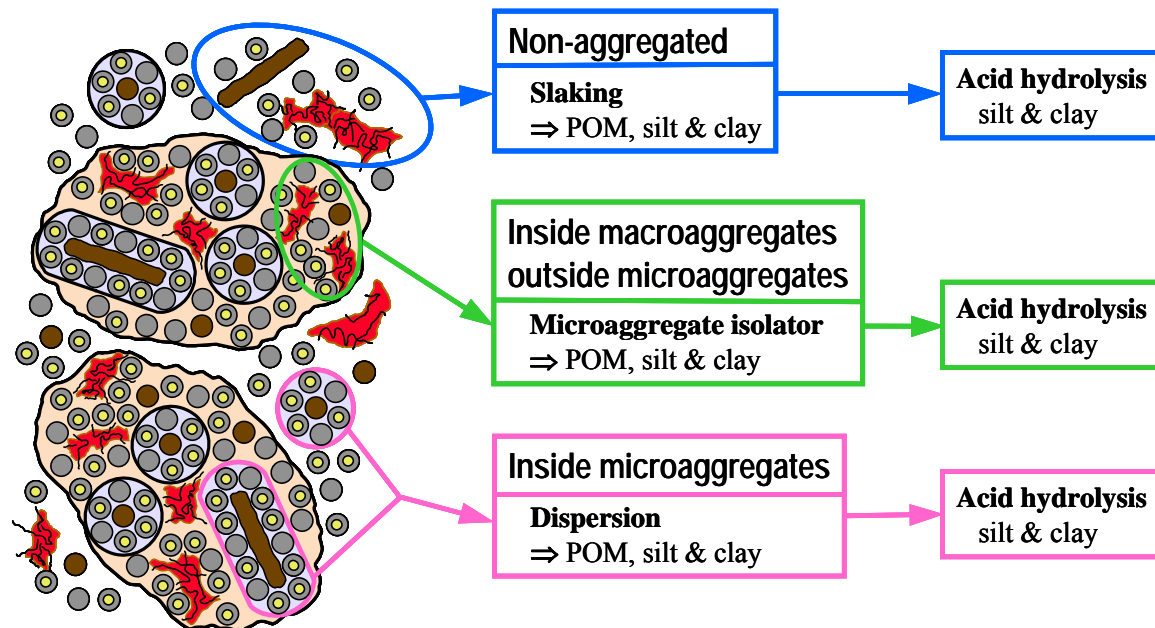


Fractionation methods leading to new insights on soil organic carbon capture and longevity

⇒ Soil organic matter is heterogeneous

- Various physically protected forms
- Stages of chemical transformation
- Microsites with varying environmental conditions

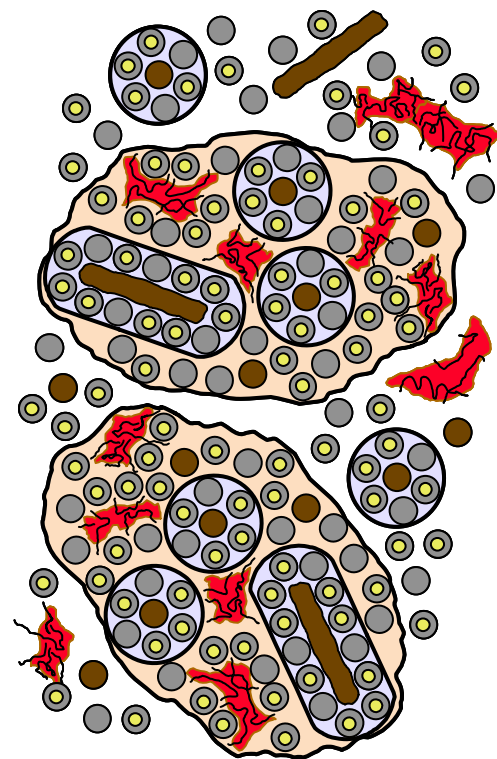
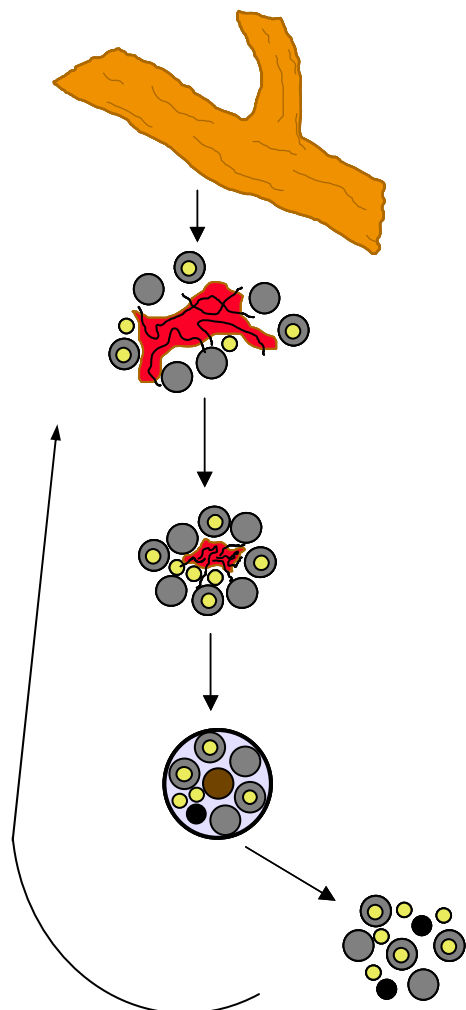
⇒ Understanding processes that control C capture and longevity










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



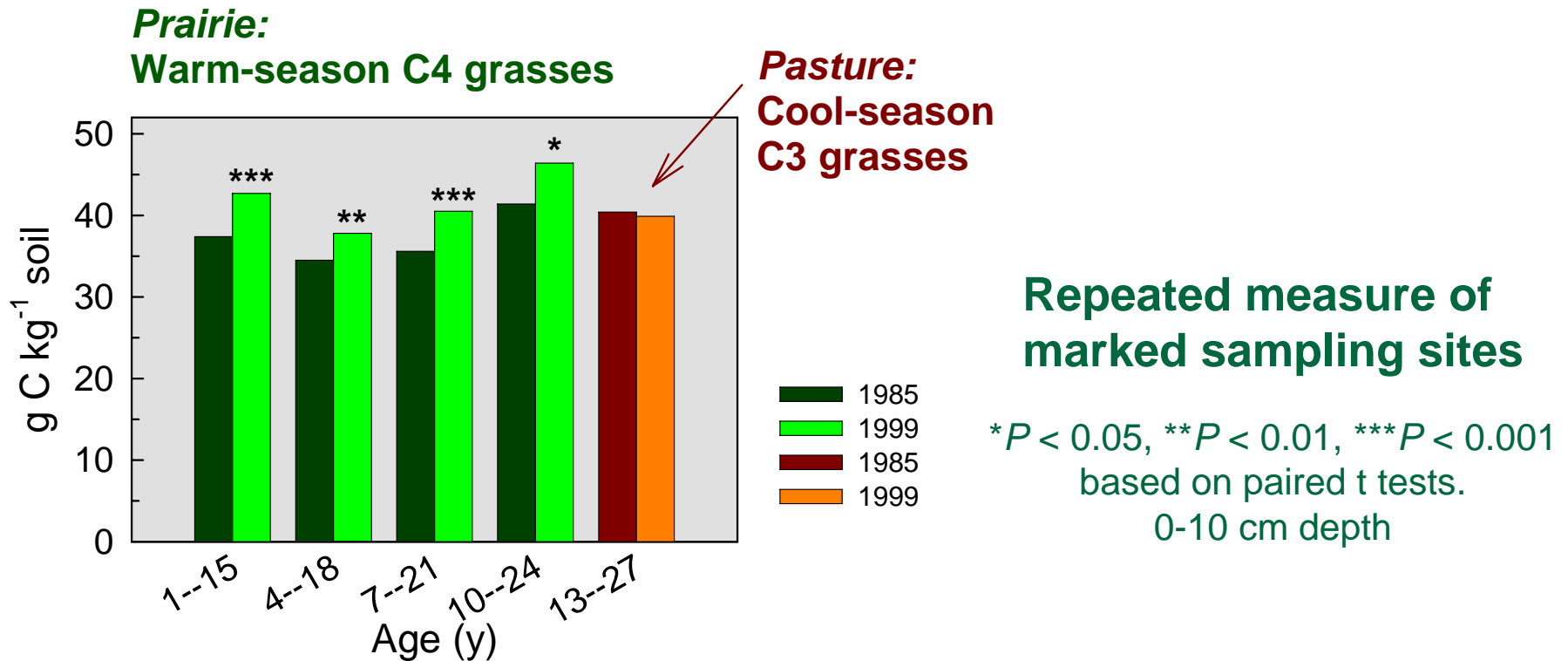
	Microaggregates ~ 50-250 μm		Plant and fungal debris
	Particulate organic matter colonized by saprophytic fungi		Fungal or microbial metabolites
	Silt-sized aggregates with microbially derived organomineral associations		Biochemically recalcitrant organic matter
			Clay microstructures

Changes in soil N cycling under restored prairie lead to accumulation of soil N

Site	Estimates based on ^{15}N pool dilution		
	Mineralization	NH_4 Consumption	Nitrification
	$\mu\text{g N g}^{-1} \text{ soil d}^{-1}$		
Row crop	22.2	17.5	14.7
8-y Prairie	11.6	9.5	0.1
22-y Prairie	4.3	9.7	0.3

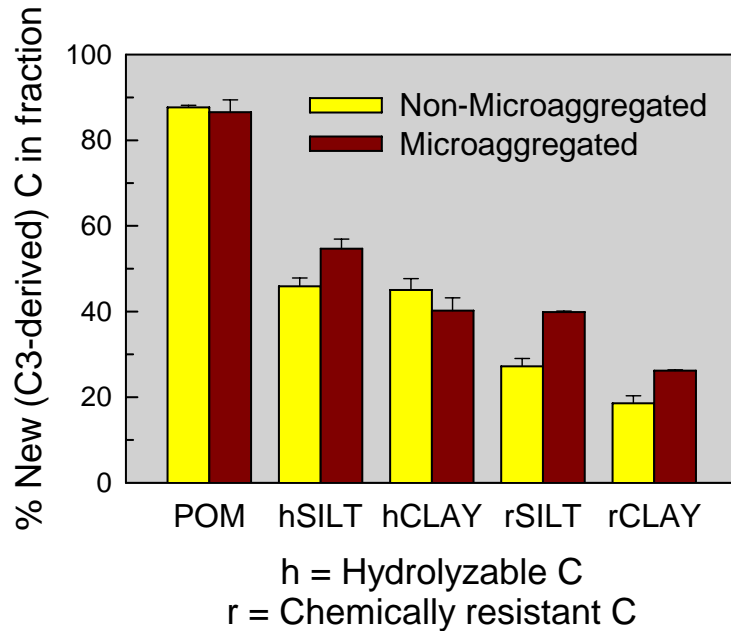
- ⇒ N cycling most rapid in the agricultural soil
- ⇒ Net N mineralization decreases with time in prairie
- ⇒ Increased N retention and tighter N cycling
- ⇒ N accrual sustains plant productivity and thus increases C storage

Grassland type influences soil C accrual



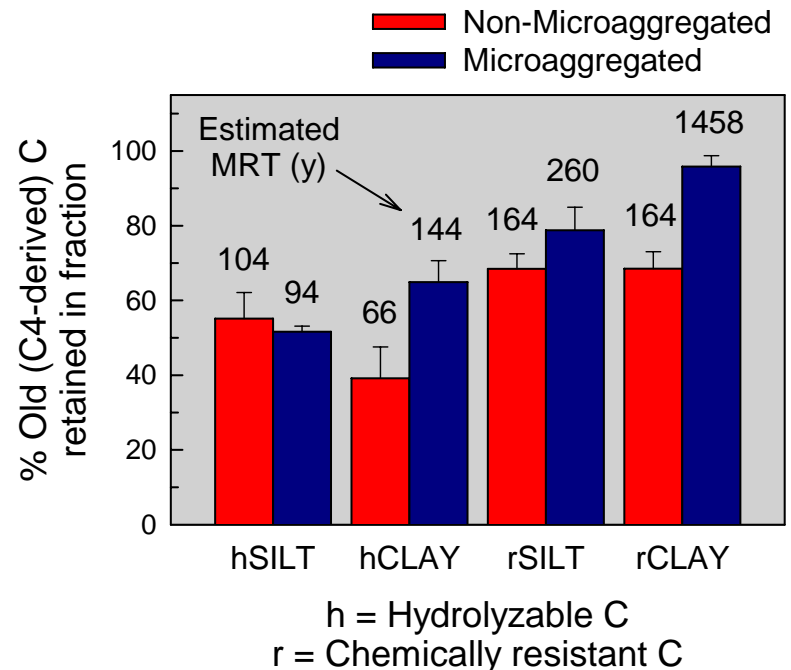
- ⇒ Prairie increments verify modeled rates
- ⇒ Pasture grasses at equilibrium by 13 years
 - Lower productivity (fertilizing might raise equilibrium)
 - Timing and quality of inputs affect decomposition

Mechanistic-based soil fractionations and stable isotopic tracers provide new insights to understanding C capture and storage

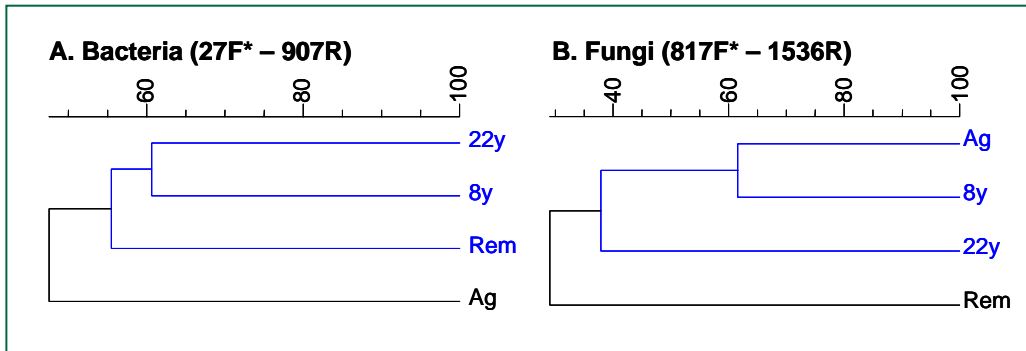


Microaggregates facilitate creation of organomineral associations (more new C in microaggregate-associated silt and clay)

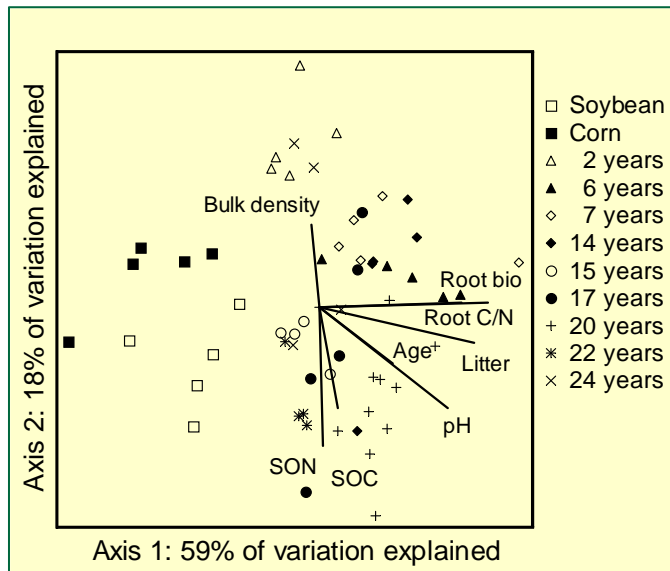
Microaggregate protection increases the longevity of silt- and clay-associated C



Plant inputs, quality, and manipulations associated with microbial changes



DNA fingerprinting shows bacterial community structures recover faster than fungal communities

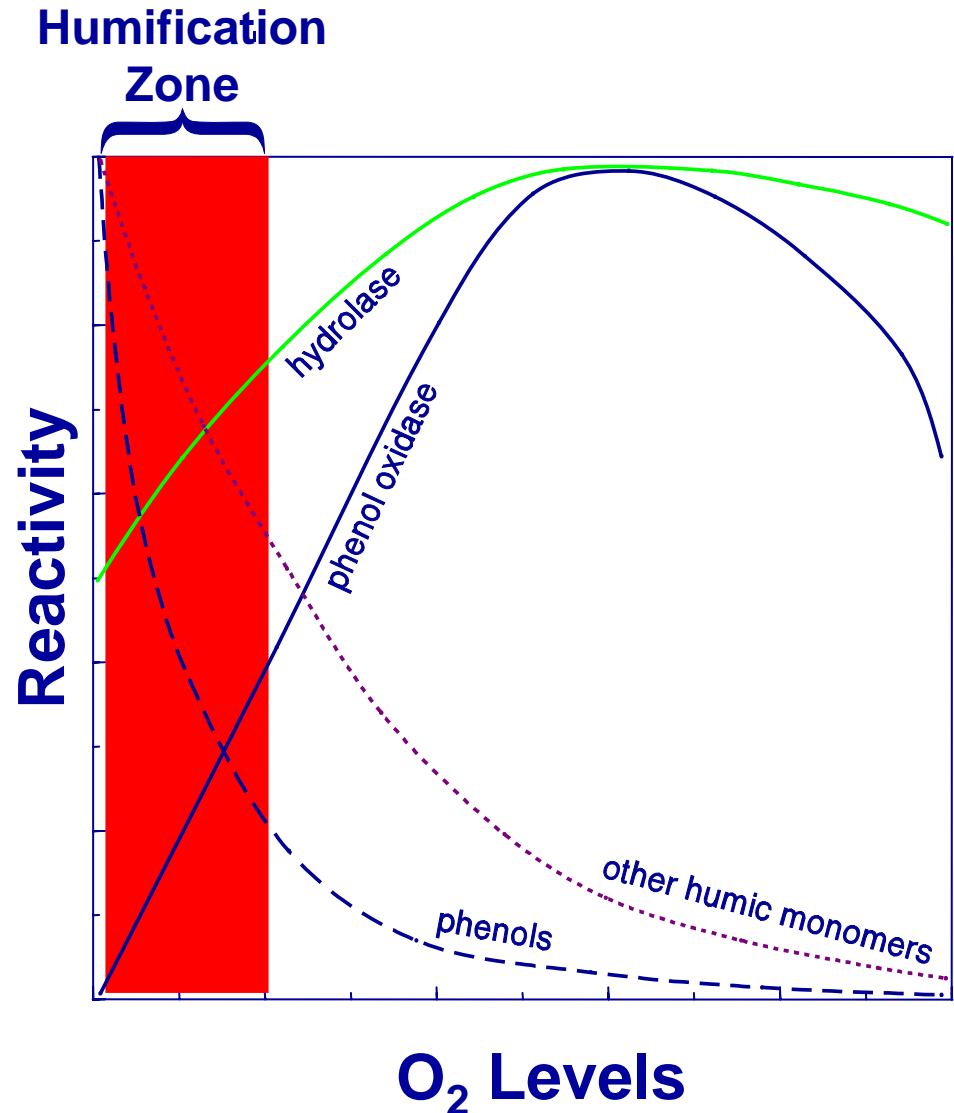


PLFA analyses indicate:

- ⇒ Changes in relative abundance of microbial functional groups are driven by plant inputs (amounts and quality) and related to changes in SOM and bulk density
- ⇒ Fungal:bacterial ratios directly related to plant inputs
- ⇒ Mycorrhizal fungi account for most of the increased fungal abundance

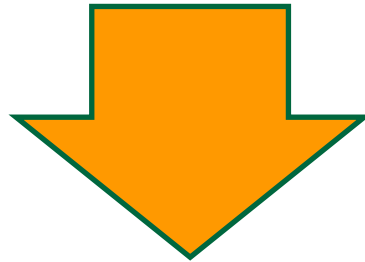
Emerging manipulation concepts: Controls on humification

- ⇒ **Redox conditions**
 - Wetting/drying cycles
- ⇒ **Fe/Mn oxide content**
 - Fertilization
- ⇒ **Enzyme activities**
 - High-phenolic cropping, green manures, fungal/bacterial ratios



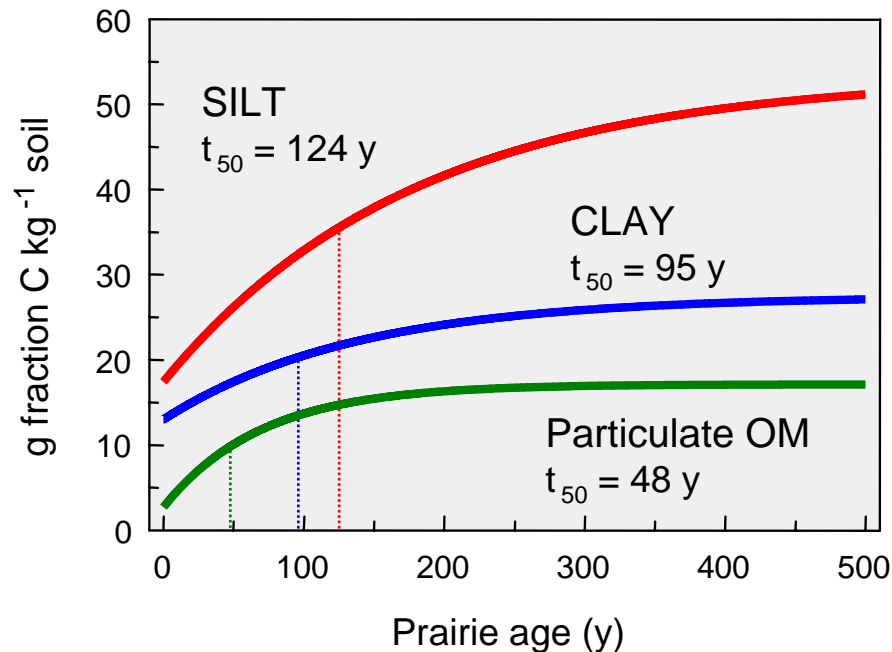
Increases in soil fungal:bacterial ratios and microbial diversity could increase the longevity of stored C

- ⇒ Fungi use carbon more efficiently than bacteria (more C goes to biomass and less to respiration)
- ⇒ Fungal cell walls are more difficult to decompose (e.g., chitin, melanin)



Managing plant communities or cultivars could effect micro-scale changes that may enhance sequestration

Rates of C accrual vary with particle size

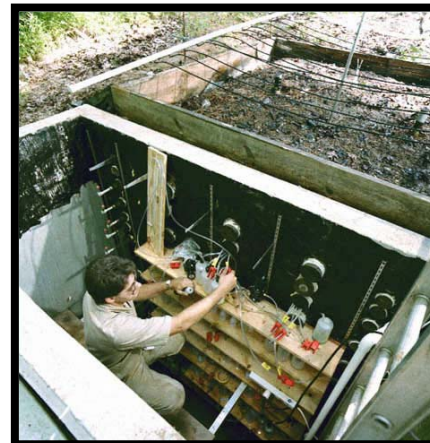
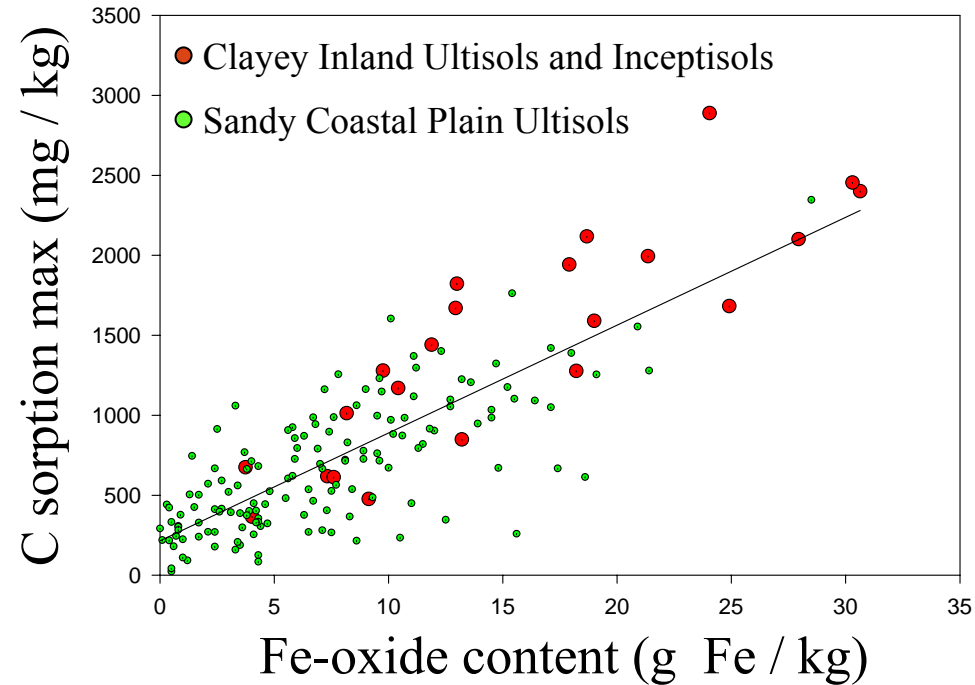


- ⇒ Particulate OM reaches equilibrium first
- ⇒ Largest increases in silt-sized fraction

- ⇒ ~50% of silt-associated C is chemically resistant across the chronosequence
- ⇒ Mineral-associated C has potential for entering longer lived pools

Emerging manipulation concepts: Mobilization to deeper horizons

- ⇒ **Enhance hydrolysis of active organic C pools**
- ⇒ **Conversion to passive organic C pools**
- ⇒ **Amendments that promote deeper transport of C**
- ⇒ **Approach**
 - **Regional soils**
 - **Lab-scale studies**
 - **Field-scale manipulation**



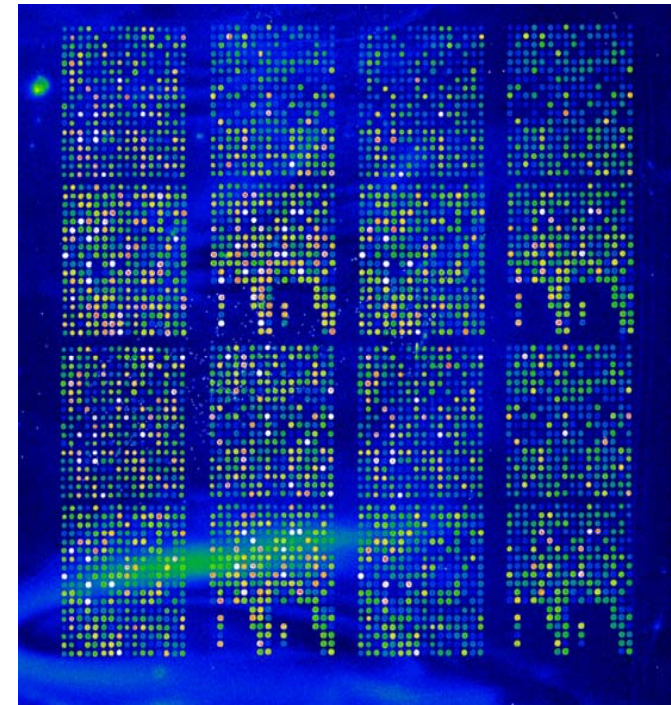
Microbial microarray technology for exploring soil carbon processes

Functional Gene Arrays allow insights into microbial processes, community structure, and activities

6,698 gene probes from 30 organisms

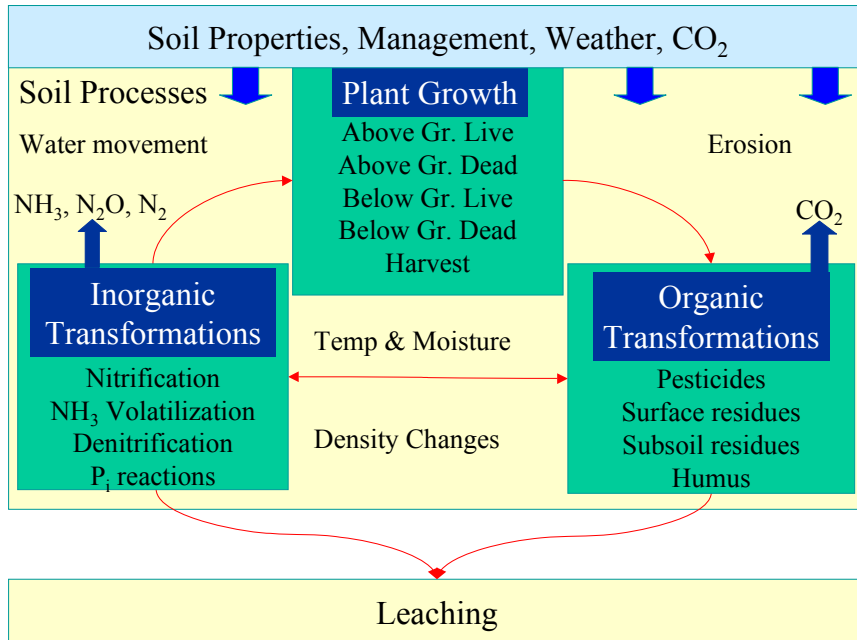
- Nitrogen cycling: 1,882
- Sulfate reduction: 1,050
- Carbon cycling: 1,810
- Phosphorus utilization: 156
- Organic degradation: 1607
- Metal resistance and oxidation: 193

**Preliminary results: Sample from reclaimed mined lands
(NETL Project, Palumbo & Amonette)**



Advances in Modeling Tools: Improving process models and extrapolations

EPIC Model



- ⇒ Data are used to improve applicability of the model for spatial and temporal extrapolation
- ⇒ Combined with regional databases model can extend observations over conditions not directly measured
- ⇒ EPIC model also handles management and erosion

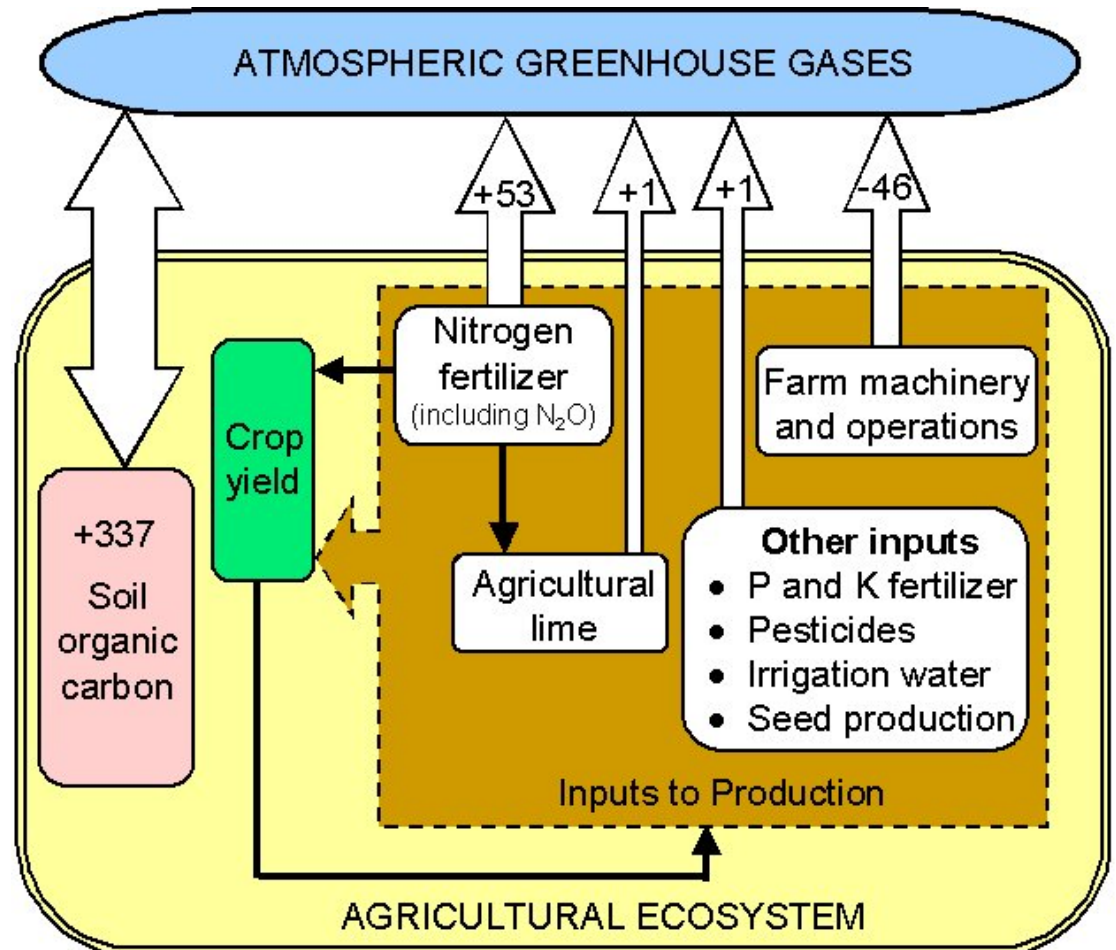
Model analysis of full CO₂ and greenhouse gas accounting

⇒ Agriculture

- Tillage
- Fuel
- Fertilizer/pesticides
- Lime, seeds
- N₂O, CH₄

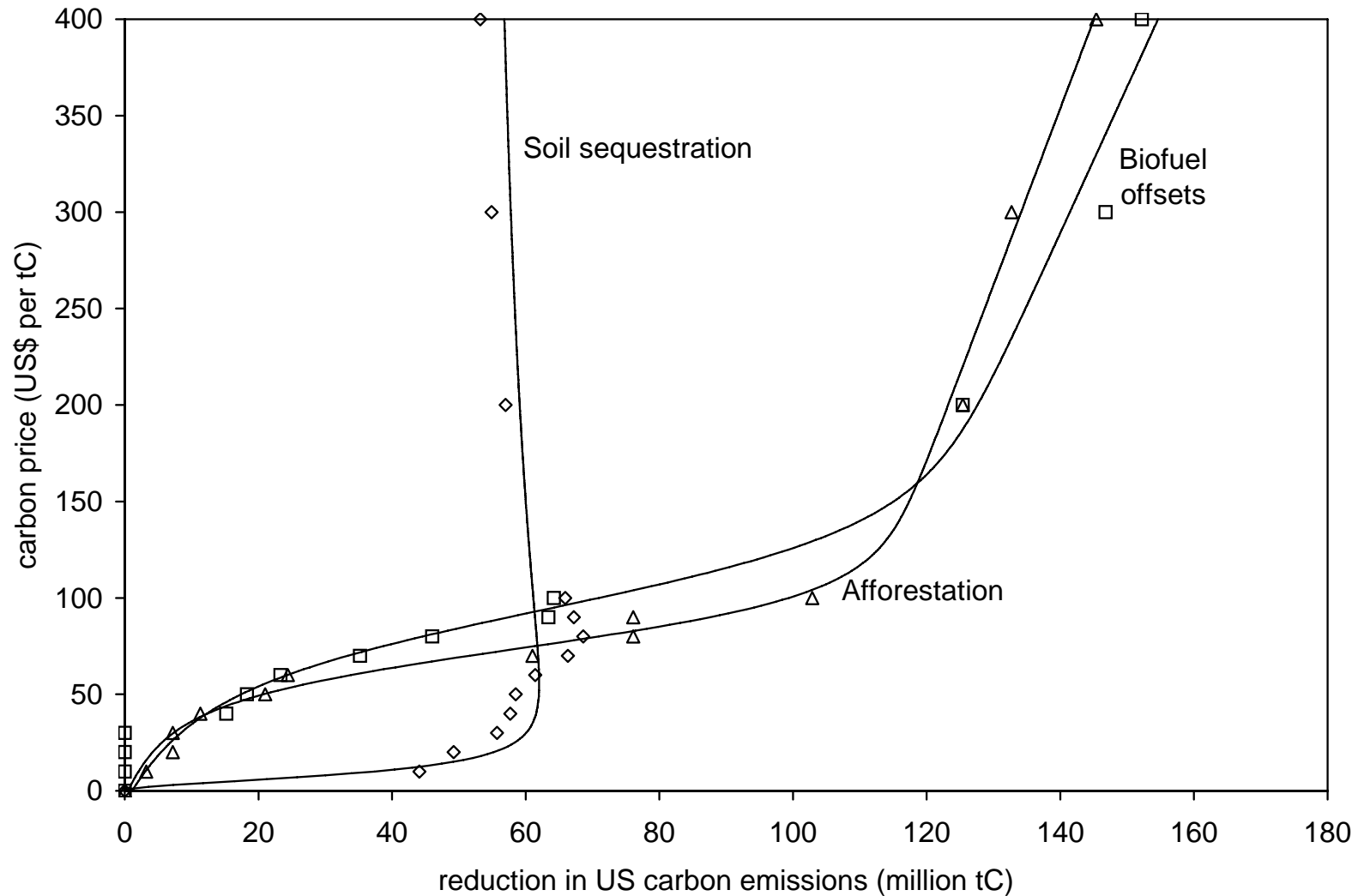
⇒ Forest harvest

- Forest growth, age
- Harvest operations
- Fate of wood products



West, T.O. and G. Marland. 2002. Environ. Pollution 116:437-442.

Analyzing economic implications (Agricultural Sector Model)



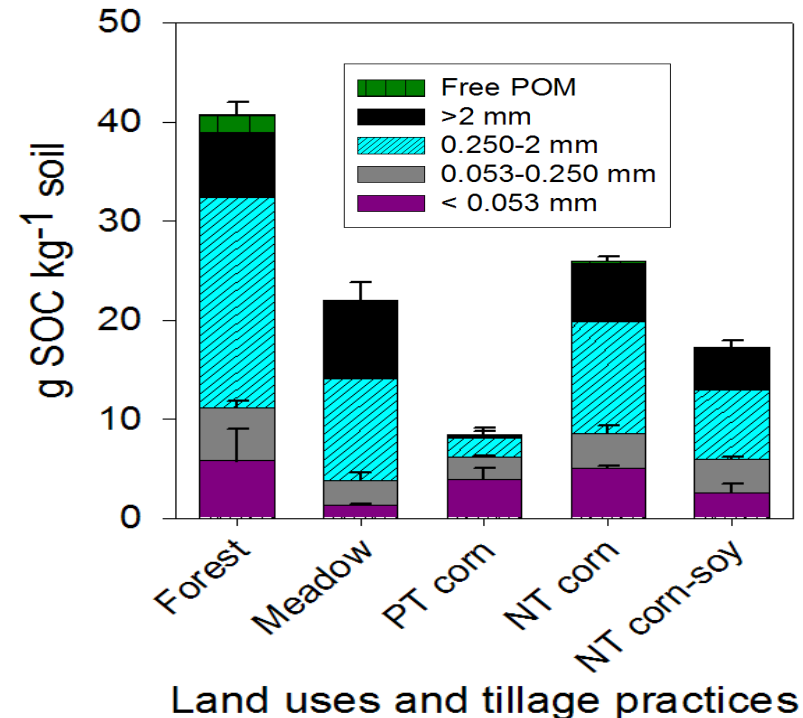
McCarl, B.A. and Schneider, U.A. (2001). *Science* **294**, 2481-2482.

Management effects on C and N stocks

Puget et al.

	Soil C (Mg ha ⁻¹)	Soil N (Mg ha ⁻¹)
Old growth forest	65	5.8
Meadow (Hayed field)	49	4.8
Plow till corn	41	3.5
No till corn	52	5.6
No till corn-soybean	47	5.3

- ⇒ Plow till corn soil contained 63% of C in forest soil
- ⇒ No till corn had highest soil C content of all managed systems
- ⇒ Soil N content in no till soils was very similar to that found in forest soils



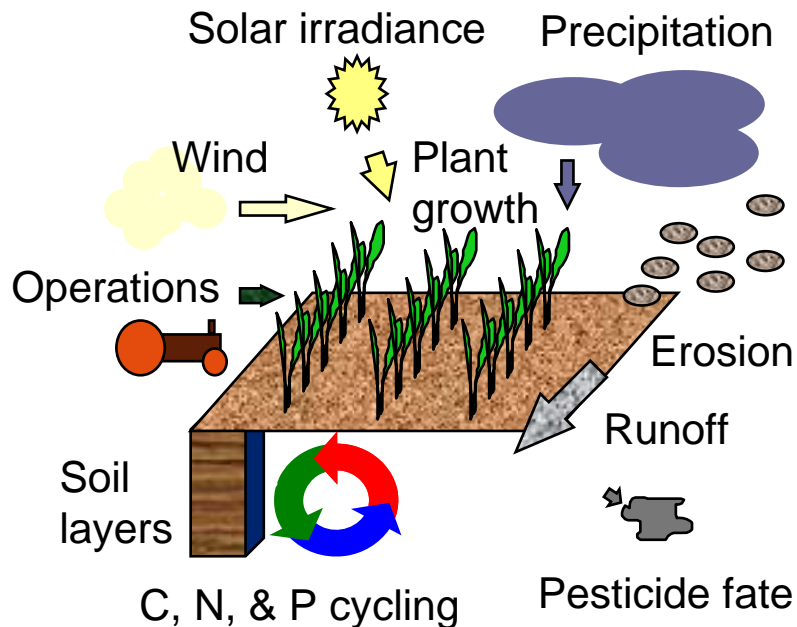
Carbon and soil aggregates

Puget et al.

- ⇒ Carbon distributed differently among soil aggregate fractions
- ⇒ Larger aggregates contained more C than smaller aggregates, except in PT corn
- ⇒ ¹³C analysis revealed that corn residues represented about 1/2 the C in PT corn while it represented >90% in NT corn

Integrating soil and biological processes at landscape scale through simulation modeling

EPIC Model



Representative EPIC modules

Williams (1995)

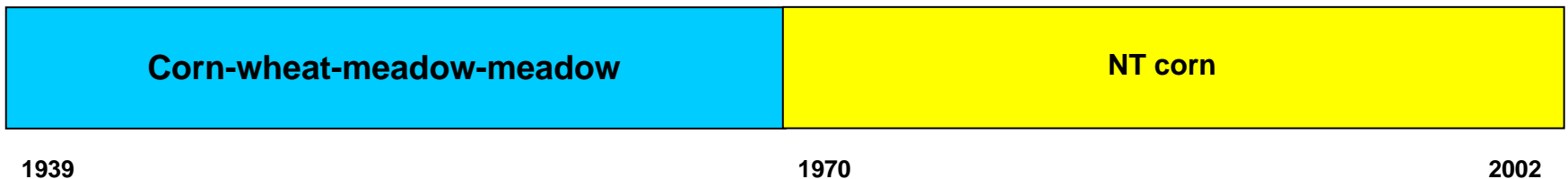
- ⇒ EPIC is a comprehensive model to describe climate-soil-management interactions at point or small watershed scales
- ⇒ EPIC estimates the impacts of management on wind and water erosion
- ⇒ CSiTE investigators recently updated C & N modules in EPIC (Izaurre et al., 2001)
- ⇒ CSiTE data could be used to improve applicability of the model for spatial and temporal extrapolation
- ⇒ Combined with regional databases, this and other models (e.g., Century) can extend observations over conditions not directly measured

Land-use History for Conventionally Tilled (CT or PT) and No Tilled (NT) Watersheds (Puget et al.)

Watershed 128 (W128)



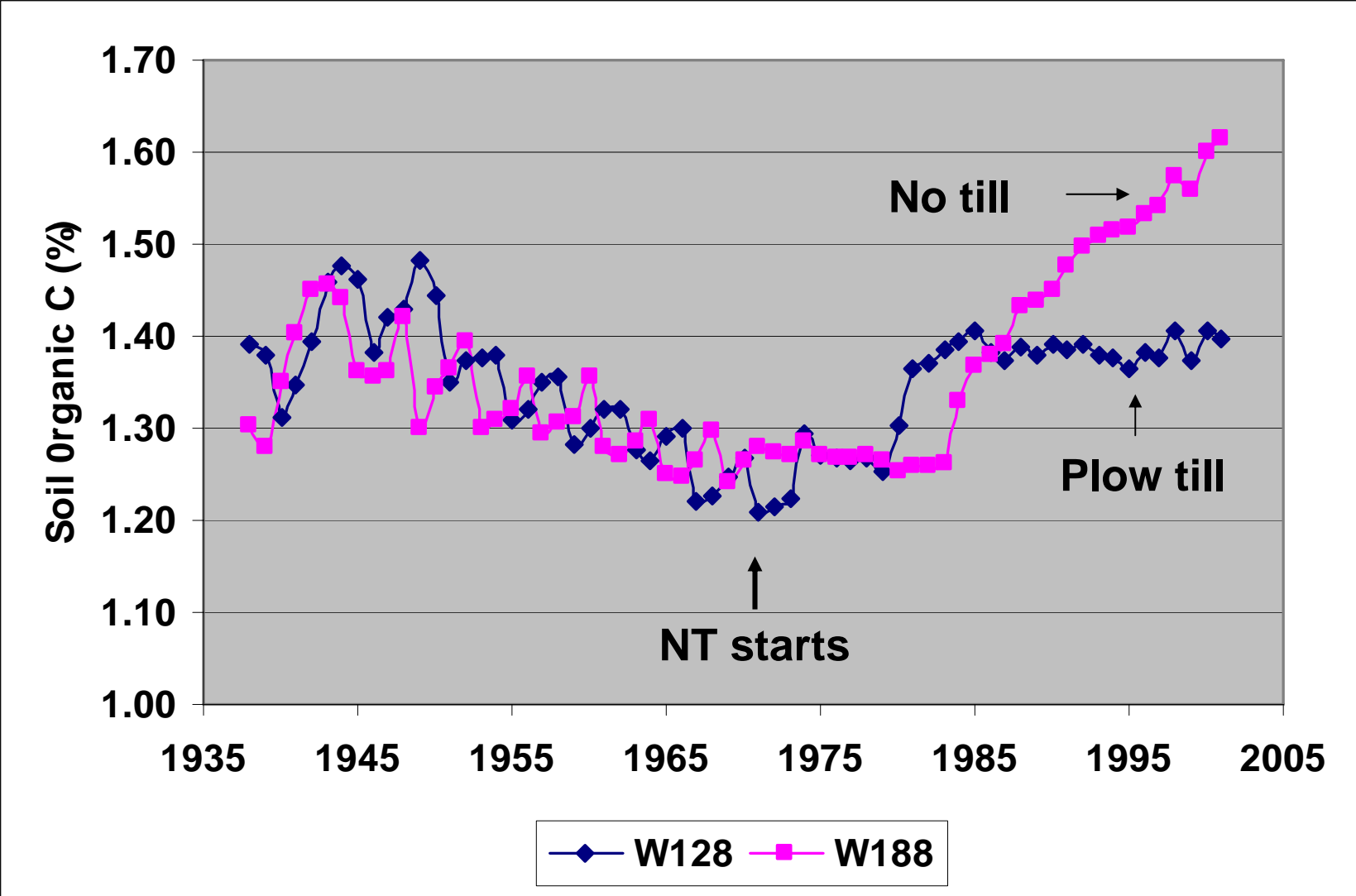
Watershed 188 (W188)



- ⇒ The EPIC model prepared to study management and erosion effects on soil C of W128 and W188
- ⇒ A 63-y weather record was assembled using data from New Providence, OH
- ⇒ Crop modeled included: corn, wheat, timothy, fescue, and alfalfa
- ⇒ Soil layer properties were obtained from Kelley et al. (1975) and L. Owens (pers. comm.)
- ⇒ Two 63-y runs (1939 – 2001) were made with management described above
- ⇒ CO₂ concentration increased from 296 to 370 ppm (25% increase)

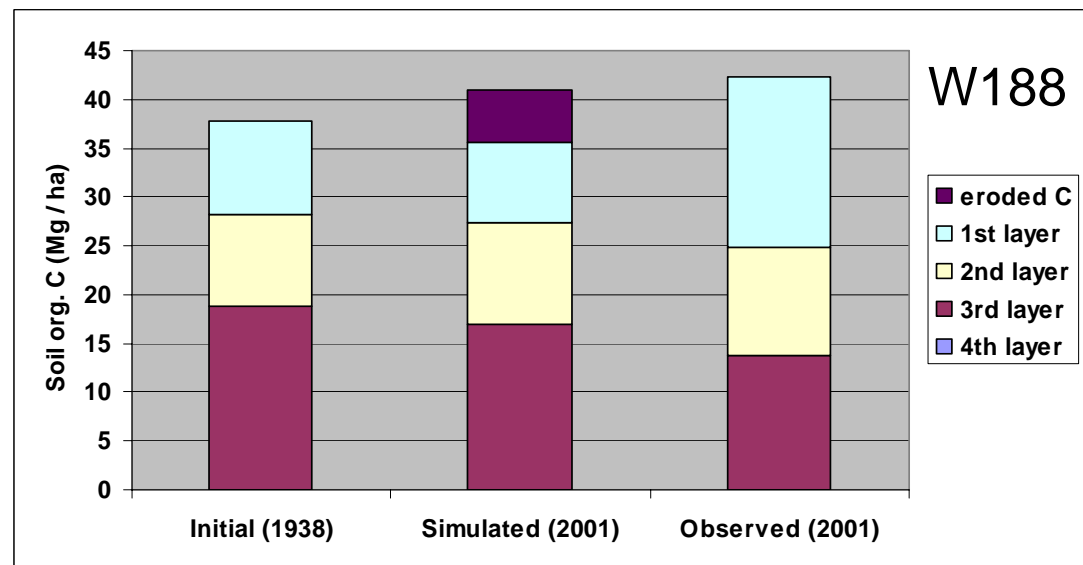
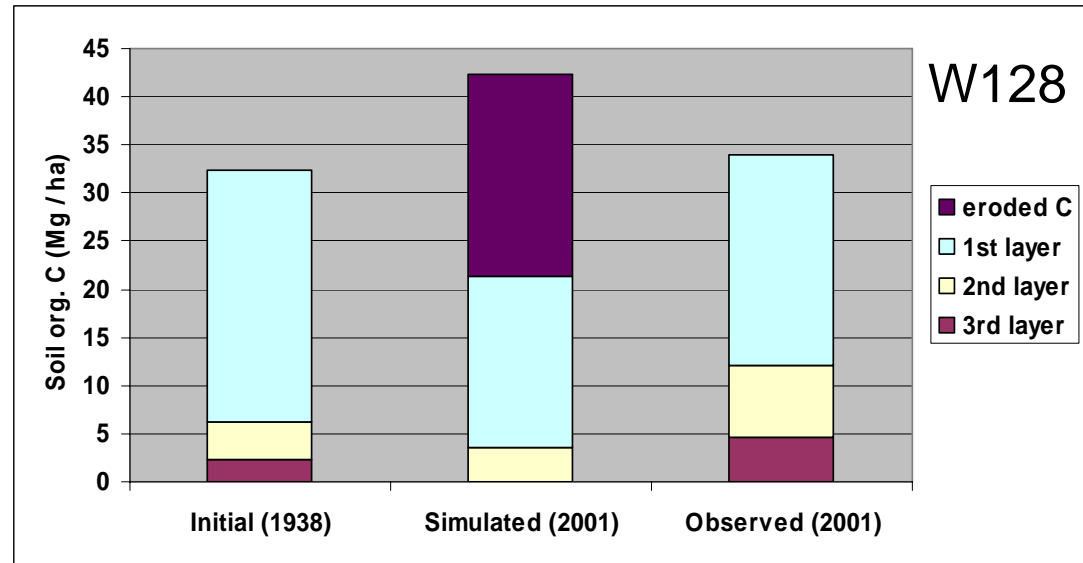
Modeling Results for NAEW

63 year simulation without erosion



Soil C stocks to 20 cm depth in Plow till (W128) and No till (W188) watersheds

- ⇒ Soil erosion altered depth of soil layers
- ⇒ Simulated C stocks were lower than observed values
- ⇒ Eroded C in W188 was $\frac{1}{4}$ that of W128



Data source: Puget et al.

A comparison of annual rates of soil C erosion ($\text{Mg C ha}^{-1} \text{ y}^{-1}$) measured or estimated in NAEW watersheds

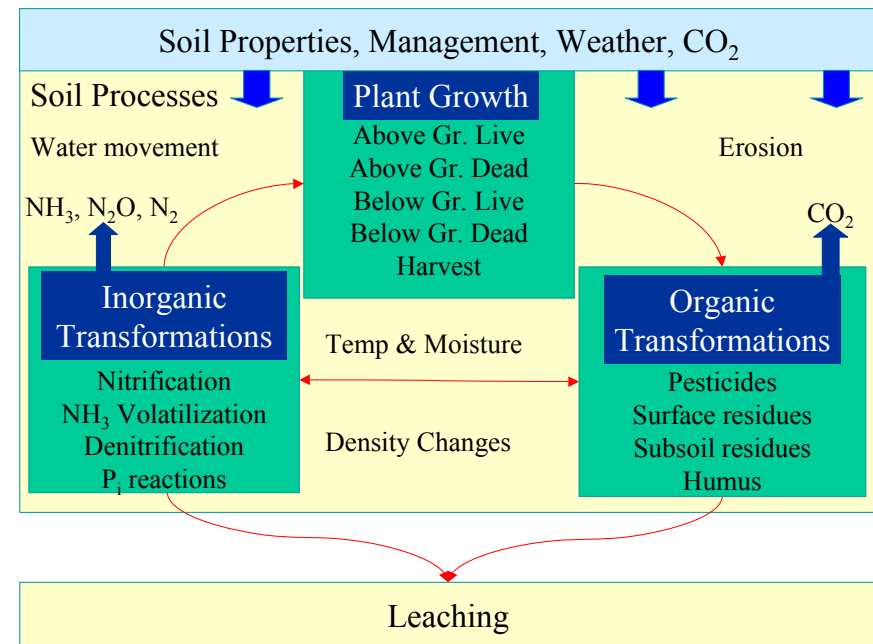


Detail of Coshocton wheel

Source	Period	^{137}Cs	RUSLE	EPIC	Soil sediment collected
Hao et al. (2001)	1951 – 1998	0.041	0.149	-	0.026
This study W128	1939 – 2001	-	-	0.333	-
This study W188	1939 – 2001	-	-	0.084	-

Modeling soil C dynamics in a prairie restoration experiment at Fermilab

- ⇒ The EPIC model was used to study soil C dynamics in prairie restoration experiment
- ⇒ A 25-y weather record was assembled from Aurora, IL
- ⇒ Crop parameters were adapted for modeling big bluestem growth
- ⇒ Soil layer properties for the Drummer soil were obtained from STATSGO database and complemented with site information
- ⇒ A 25-y run (1975 – 1999) simulated the conversion of an agricultural field to a pure stand of big bluestem
- ⇒ N deposition was simulated at a rate of 2.1 mg/L (NADP)



Izaurrealde et al. (2001)

Simulated and observed average above and below ground big bluestem biomass (Mg/ha)

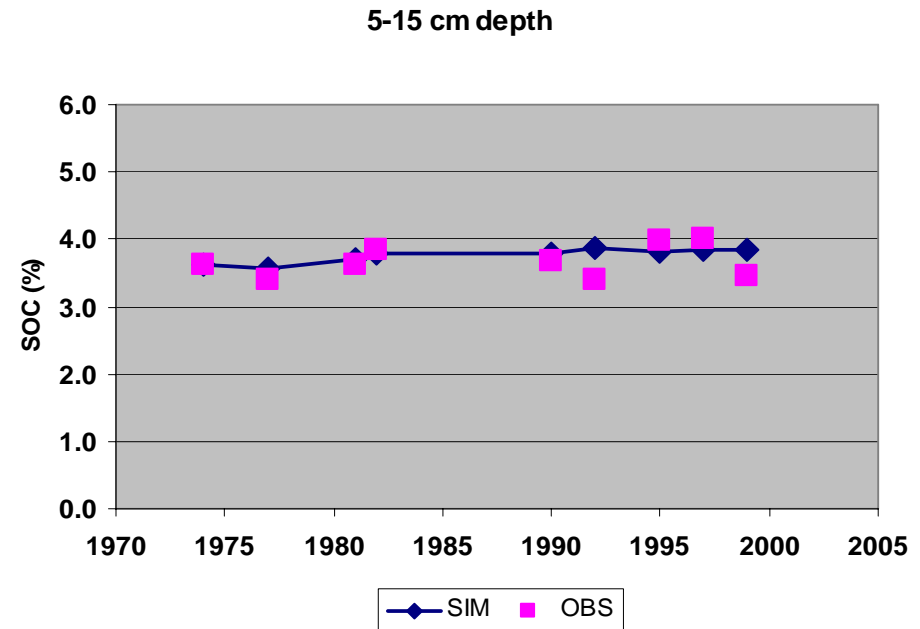
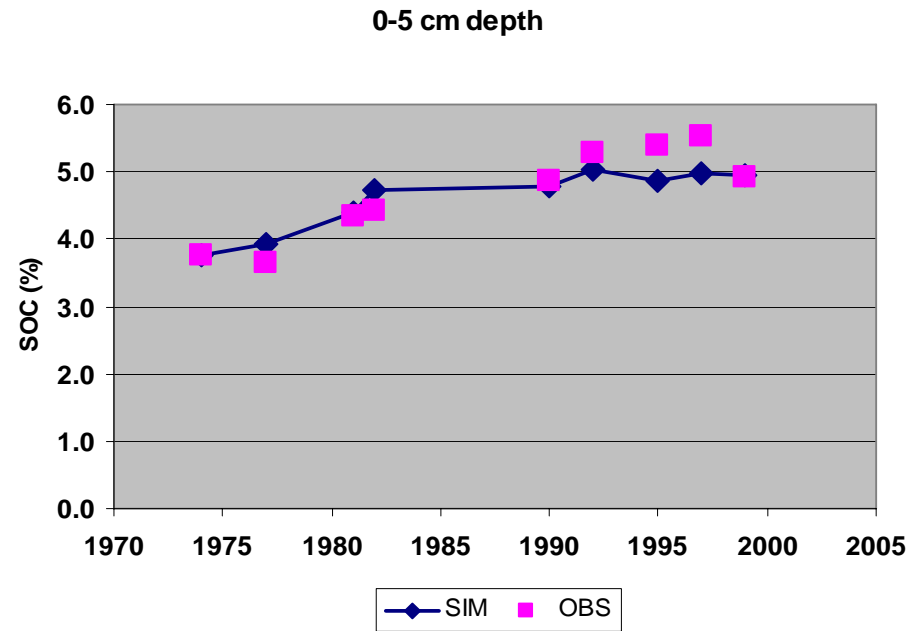


Andropogon gerardii

	Above ground biomass	Roots 0-5 cm	Roots 5-15 cm	Roots 15-25 cm	Root / Shoot ratio
Simulated	8.5	6.9	3.7	1.1	1.38
Observed	8.3	9.0	3.1	1.8	1.67

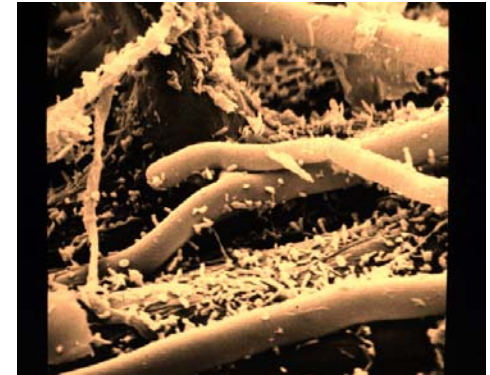
Simulated and observed soil C (%) under big bluestem vegetation

- ⇒ Overall, EPIC captured the soil organic C dynamics observed during 25 years in the Fermilab chronosequence experiment
- ⇒ Most of the observed increase in soil C occurred in the top 5 cm soil depth
- ⇒ The simulated annual rate of soil C accrual to 15 cm depth was lower than the one observed:
 - Simulated: 0.34 Mg/ha
 - Observed: 0.54 Mg/ha
- ⇒ The under prediction of soil C by the model may be related to the under prediction of root and rhizome biomass in the top 5 cm soil depth



Initial and final soil microbial biomass C (%) in Fermilab chronosequence

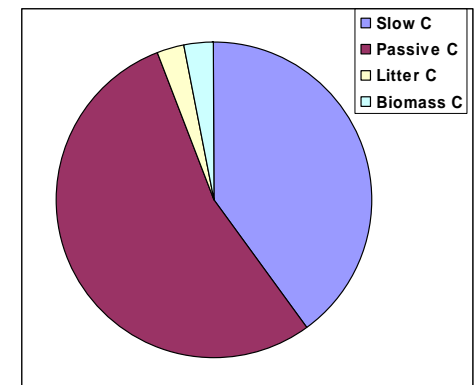
	0-5 cm	5-15 cm	15-25 cm
Initial (1974)	1.0	1.0	1.0
Final (1999) Simulated	3.2	2.7	2.6
Final (1999) Observed	3.1	2.7	2.5



Credit: R. Campbell. 1985. Plant Microbiology. Edward Arnold, London. p. 149.

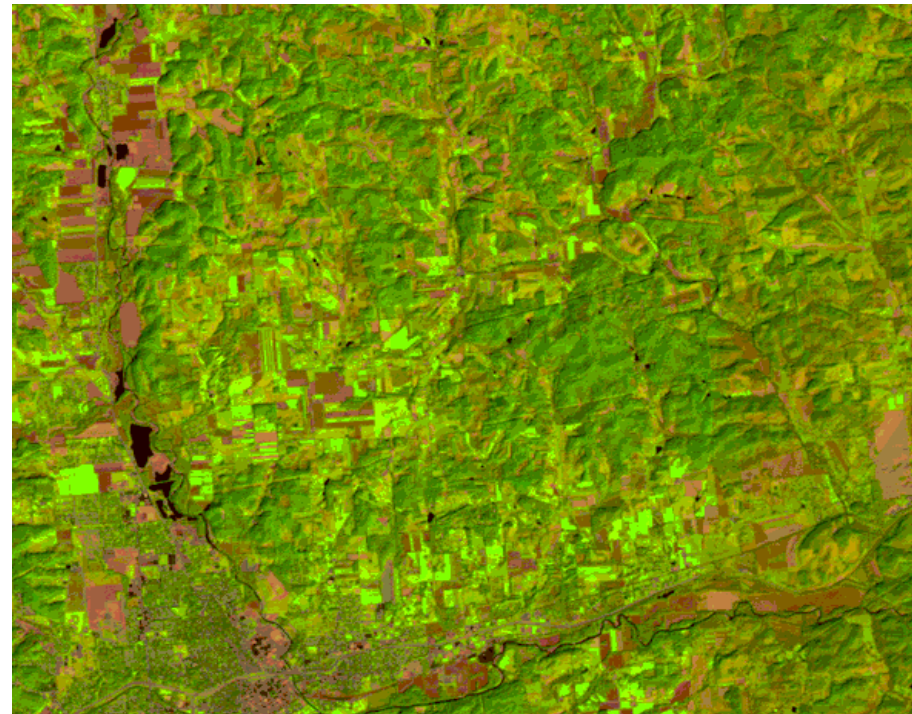
Distribution of C within soil C pools

- ⇒ **Passive C** represented ~54% of the total
- ⇒ **Most of the C accrual** occurred in the slow C pool



Using Model Results to Calculate Regional Soil C Sequestration

- ⇒ **Data from Coshocton and Fermilab and simulation modeling allow estimating**
 - **C sequestration potential over time**
 - **C in eroded sediments**
- ⇒ **The model can be used to extrapolate to regional edaphic and management conditions**
 - **Multi-field version of EPIC**
- ⇒ **Capability to simulate non-CO₂ gases (e.g. N₂O) will be available in near future**



**Land use pattern in NAEW region:
Forests, meadows and cropland**

6. Perform Economic Analyses

⇒ For a management practice to be adopted it must be:

- Cost effective
- Involve tolerable amounts of risk
- Have a market (economic) method or a fair governmental (social) method of implementation

⇒ Economic models require a **cost per ton** calculation

⇒ Cost per ton should include:

- Net cost of practice, amount of GHG offset
- Producer development cost, adoption inducement cost
- Market transaction costs, governmental costs
- Discounts
- Value of co-benefits

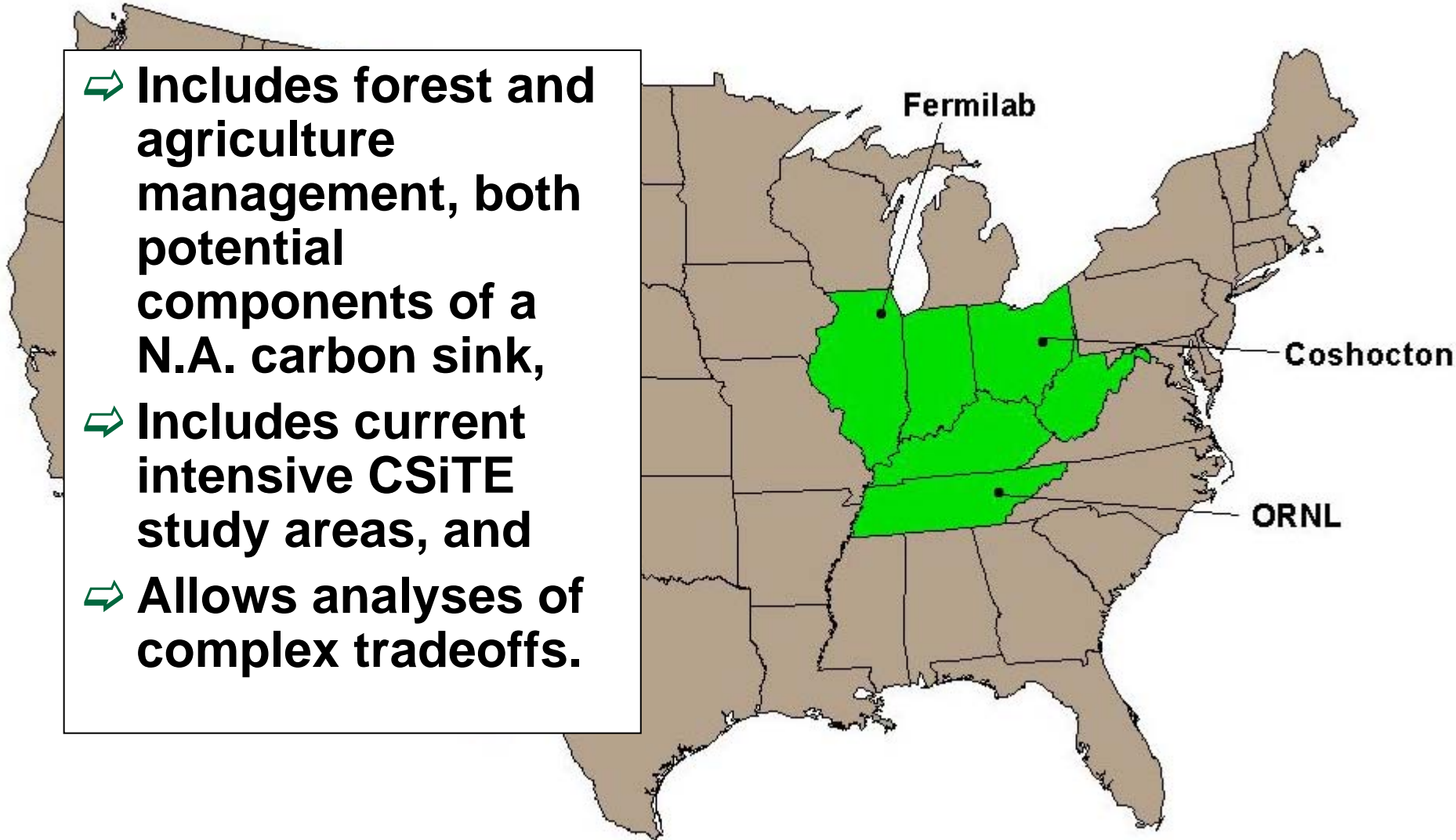
$$\text{Cost per ton} = \frac{\text{net cost of practice}}{\text{amount of GHG offset}}$$

$$\text{Private cost per ton} = \frac{(\text{PDC} + \text{PAIC} + \text{MTC} - \text{GC})}{\Delta\text{GHGO} * (1 - \text{DISC})}$$

$$\text{Social cost per ton} = \frac{(\text{PDC} + \text{PAIC} + \text{MTC} + \phi * \text{GC} - \text{CB})}{\Delta\text{GHGO} * (1 - \text{DISC})}$$

CSiTE Integration Activity: Potential Region

- ⇒ Includes forest and agriculture management, both potential components of a N.A. carbon sink,
- ⇒ Includes current intensive CSiTE study areas, and
- ⇒ Allows analyses of complex tradeoffs.





Regional Integration Activity Summary

- ⇒ **Integrated approach allows full evaluation of merits of a proposed C sequestration practice.**
- ⇒ **Series of steps for evaluating C sequestration enhancement method involve:**
 - 1. Identify promising techniques**
 - 2. Understand controls and basic mechanisms**
 - 3. Perform sensitivity analysis**
 - 4. Include full C and greenhouse gas accounting**
 - 5. Evaluate environmental impacts**
 - 6. Perform economic analyses**
- ⇒ **CSiTE is completing a concept paper and developing an approach to analyze a diverse region of the U.S.**
- ⇒ **Integrated evaluation framework can**
 - **Reveal gaps in our data and knowledge base.**
 - **Guide evaluation of proposed new soil C sequestration methodologies.**



Summary

⇒ Long-term experiments at Coshocton

- Have historical record needed to study temporal and spatial dimensions of soil C dynamics
- Provided opportunity to study processes that control soil C accumulation or loss under traditional and alternative management
- Improved our understanding of the role of erosion in soil C sequestration

⇒ CSiTE investigators

- Enhanced modeling tools to conduct comprehensive evaluations of soil C sequestration
- Conducted extensive tests of model performance using data from Coshocton, Fermilab and other experiments worldwide



Summary

F. Blaine Metting, Pacific NW National Laboratory
and **CSiTE Team**

CSiTE Mission: Fundamental science supporting approaches for enhanced C sequestration in terrestrial ecosystems

CSiTE Goal: Establish the scientific basis for enhancing C capture and long-term terrestrial sequestration

via Discovery and characterization of critical pathways and mechanisms to create larger, longer-lasting C pools

Accomplishments to date:

- New R&D tools – Experimental & modeling approaches
- Insights – Biological & physical controls of C seq., economic & environmental impact potential
- Emerging manipulation concepts

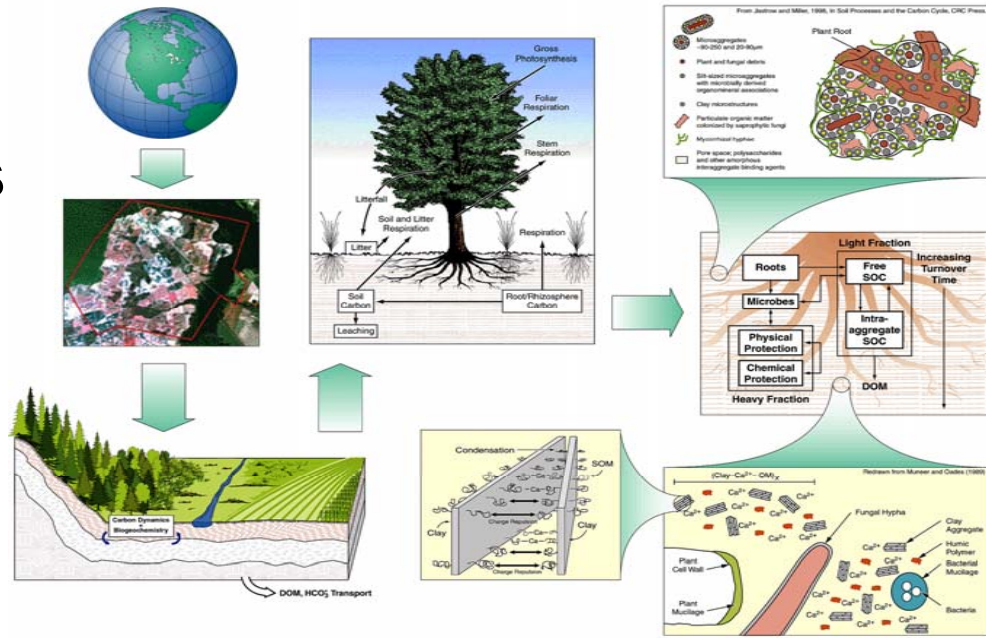
Future CSiTE Directions

⇒ Continue

- Multi-scale/multi-disciplinary research
- Model development & landscape extrapolations

⇒ Explore

- New manipulations
- Regional analyses



Questions ?

