Enhancement of soil carbon sequestration in agroecosystems: Field and modeling studies at Coshocton, Ohio

R Lal, Y Hao, P Puget, T Tan, H Blanco-Canqui,
The Ohio State University
RC Izaurralde, JGCRI (PNNL-UMD)
WM Post, ORNL
JR Williams, Texas A&M University
L Owens, USDA-ARS

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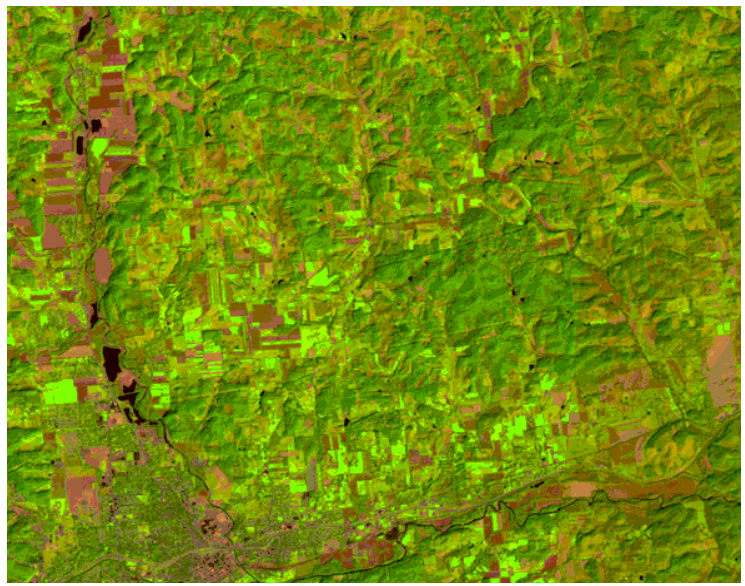
Background

- Landscapes in eastern sections of the U.S. Midwest are dominated by forests, meadows, and cropland
- Estimation of soil carbon sequestration under land use change and alternative practices requires understanding of landscape controls
  - Spatial variability
  - Hydrologic regime
  - Erosion-sedimentation processes
- Hypothesis: An understanding of SCS processes at the landscape scale is crucial to scale up SCS from field to regions



Ground and aerial views of Coshocton, OH

Background (cont'd)

- The impacts of erosion-deposition processes on the carbon cycle remain uncertain
- Eroded C, source or sink of atmospheric C?
  - Sink: Buried sediments, removed from C cycle and/or enhance NPP
  - Source: Eroded soil, enriched in labile C

Date: 3/4/1972
Photographer: Eniz E. Rowland
Location: Whitman County, 6 miles East of Pullman, Washington
Watershed: South Palouse SWCD-25

USDA - Natural Resources Conservation Services

The Northern Appalachian Experimental Watershed (NAEW), a site of opportunity for spatial and temporal research on soil C sequestration

- NAEW at Coshocton, OH is a USDA-ARS research facility with strong collaboration with The Ohio State University
- NAEW contains several long-term experiments reflecting dominant Midwest U.S. cropping practices
  - Corn-soybean rotations
  - No till (NT) vs. plow till (PT) corn systems
- Management history has been kept since 1938
- Historical measurements of soil carbon, crop production, and soil erosion losses are available
- Detailed climate and soils information are available for modeling inputs and parameters

NAEW History and Layout

- Entire watershed divided into small bermed sub-catchments with separate treatments
- Current rotations established in 1976

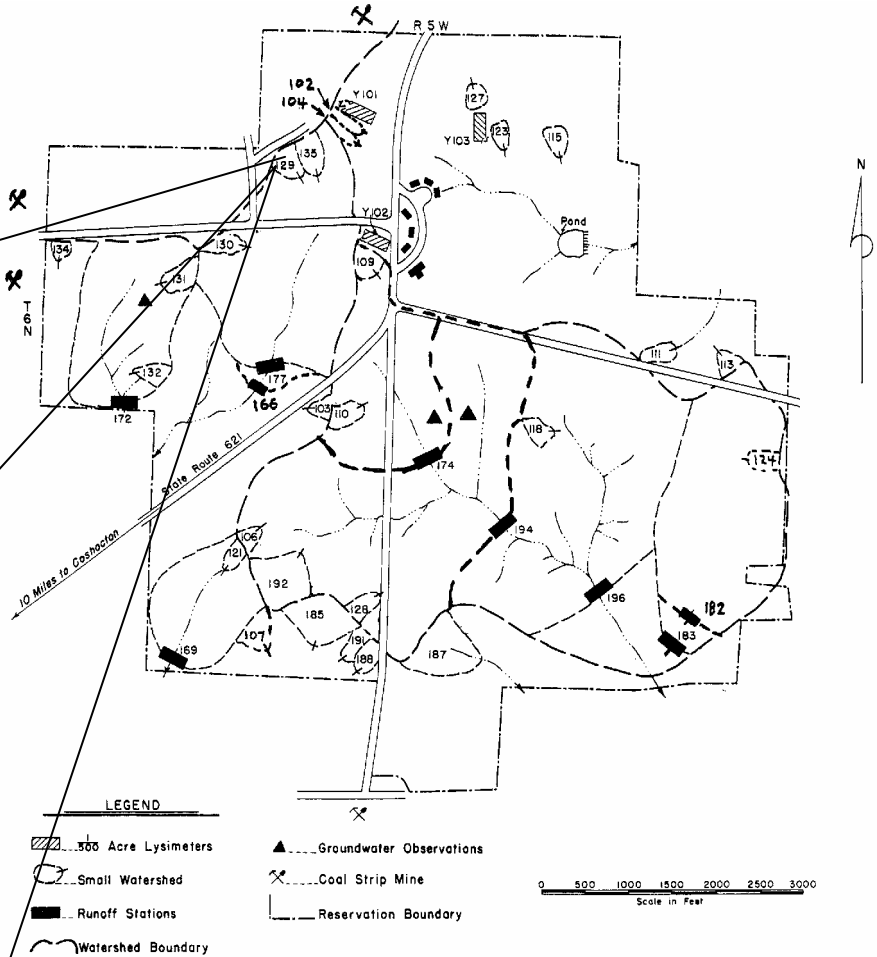


FIGURE 4.—North Appalachian Experimental Watershed, 1,047 acres of government-controlled land.

Five research questions

- 1. What is the influence of eroded C on the C balance of agricultural landscapes?
  (Hao et al. 2001, 2002)
- 2. How do agricultural management and land use affect the stocks, distribution, and turnover rates of soil organic C?
  (Puget et al. 2005)
- 3. What is the role of biochemical protection in soil carbon sequestration?
  (Tan et al., 2004)
- 4. How are the mechanical properties of soil aggregates affected under diverse management systems?
  (Blanco-Canqui et al., 2005)
- 5. Is it possible to model the long-term changes in soil organic C as affected by management and erosion processes?

1. Impacts of agricultural management on soil C stocks and eroded C

- **Background**
  - Soil erosion is usually greater in managed than in unmanaged ecosystems
  - Information on soil C erosion is limited
  - Techniques to quantify soil and C erosion
    - Long-term monitoring of sediments, watershed scale
    - Modeling (e.g., RUSLE)
    - ^{13}Cs analysis
- **Objectives**
  - Evaluate the impacts of agricultural management on soil and C erosion by three methods
    - Sediment measurement
    - RUSLE modeling
    - ^{137}Cs analysis

Materials and Methods

- A 0.79 ha watershed at NAEW selected for the study
  - Slope length: 132 m; slope gradient: 10%
  - Dominant soil: Coshocton silt loam
- Cropping system
  - 1951 – 1970: plow till corn – wheat – meadow – meadow
  - 1971 – 1975: plow till corn
  - 1976 – 1983: meadow
  - Since 1984: no till corn – soybean
- Reference sites
  - Forest
  - Grassland

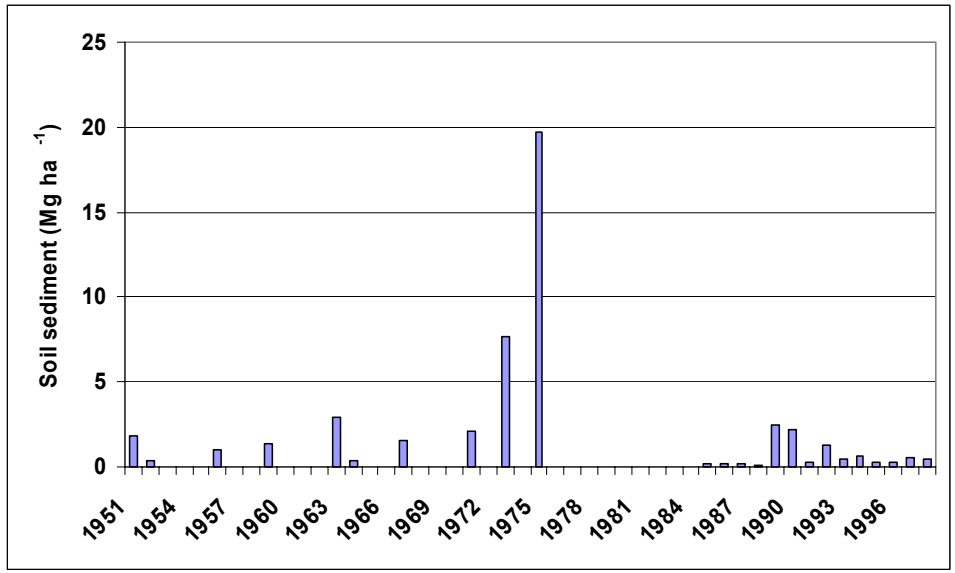
Materials and Methods (cont'd)

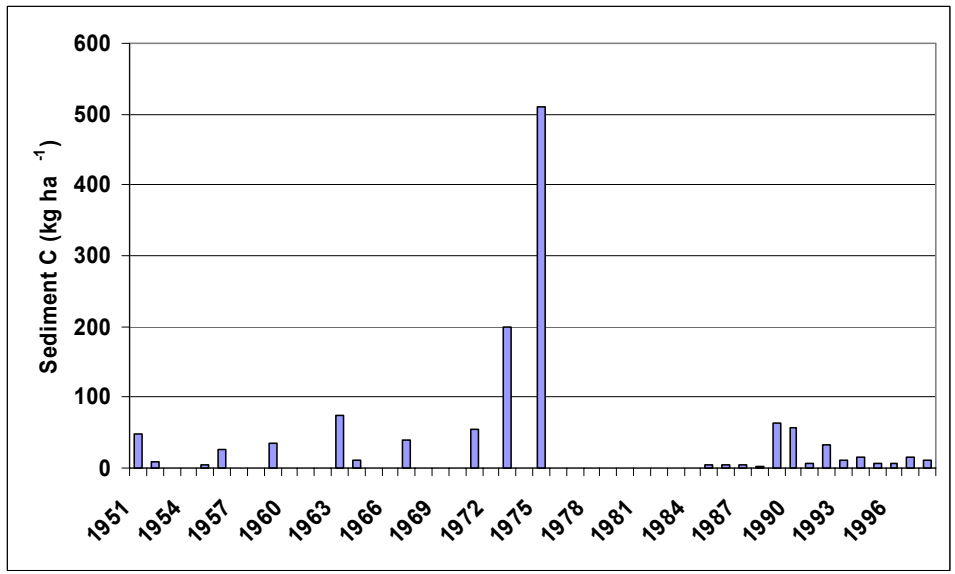
- Soil samples
  - 1970, 1984, 1995, and 1998
  - 1998 for reference site
- Runoff and sediments collected since 1945
- Soil and sediments analyzed for C content
- Air-dry soil samples analyzed for ^{137}Cs radioactivity
- Calculation of soil erosion
  - Sediment method
  - RUSLE method
  - ^{137}Cs method

Detail of Coshocton wheel

Long-term sediment collection

- Soil sediments were
  - High: Plow till corn
  - Low: No till corn – soybean, plow till wheat
  - Nil: Meadow
- C enrichment ratios in sediment ranged from 1.6 to 1.82





RUSLE estimates of soil erosion (Mg ha^{-1}) and C loss (kg C ha^{-1})

	Land use	Soil loss Mg ha^{-1}	C loss kg C ha^{-1}
1951-1970	CWMM, PT	7.2	190
1971-1975	C, NT	22.2	570
1976-1983	M, NT	0.3	7
1984-1998	CS, NT	1.3	34

Soil depth distribution of ^{137}CS radioactivity under three land uses

Depth cm	Watershed kBq m^{-2}	Grassland kBq m^{-2}	Forest kBq m^{-2}
0-10	1.1	1.6	3.1
10-20	1.2	1.9	1.7
20-30	0.6	0.8	0.5
30-40	0.1	0.1	0.2
40-50	0.0	0.0	0.0

Annual soil and C erosion estimated by three methods

Period	Sediment		RUSLE		^{137}Cs – Exp.	
	Soil Mg ha^{-1}	C kg ha^{-1}	Soil Mg ha^{-1}	C kg ha^{-1}	Soil Mg ha^{-1}	C kg ha^{-1}
1951-70	0.5	13	7.2	186	1.5	40
1971-98	1.4	36	4.8	123	1.7	44
1951-98	1.0	26	5.8	149	1.6	41

Summary

- A small but significant amount of C was transported within the agricultural watershed
- Accuracy in soil C erosion measurement was in decreasing order:
  - Sediment collection > ^{137}Cs > RUSLE
- What is the impact of eroded C transported and re-deposited across fields?

2. Agricultural management and land use effects stocks, distribution, and turnover rates of soil organic C (SOC)

- Background
  - Agricultural management effects on SOC stocks and dynamics depend on climate-soil-landscape conditions
  - Reduced tillage (e.g., no-till) usually increases SOC in topsoil
  - Such increases may not occur
    - in fine-textured soils
    - under cold and poorly drained conditions
    - where SOC stocks are high
- Objectives
  - Quantify SOC stocks under different land uses and tillage practices in a silt loam of the Appalachian Piedmont region of Ohio
  - Evaluate the distribution of SOC among different size fractions of water stable aggregates and primary particles (POM, silt and clay)
  - Characterize the turnover rates of different SOC fractions through the use of ^{13}C techniques

Materials and Methods

- Five watersheds
  - Secondary forest (oaks and poplars)
  - Meadow of orchard grass converted from NT corn in 1988
  - PT continuous corn since 1984
  - NT continuous corn since 1970
  - NT corn-soybean rotation with ryegrass as cover crop since 1984
- Soil samples taken in fall 2001
  - By depth increments
  - Soil bulk density
  - C and N analyses

Materials and Methods (cont'd)

- Soil fractionation
  - Fractions > 250 μm and 53 μm by wet sieving
  - Soil slurry < 53 μm by ultrasound
- Water stable aggregates
  - Three nested sieves (2 mm, 250 μm and 53 μm)
  - Floating POM recovered during wet sieving
  - Aggregate fractions analyzed for elemental and isotopic analyses
- Corn C input estimated by ^{13}C analysis

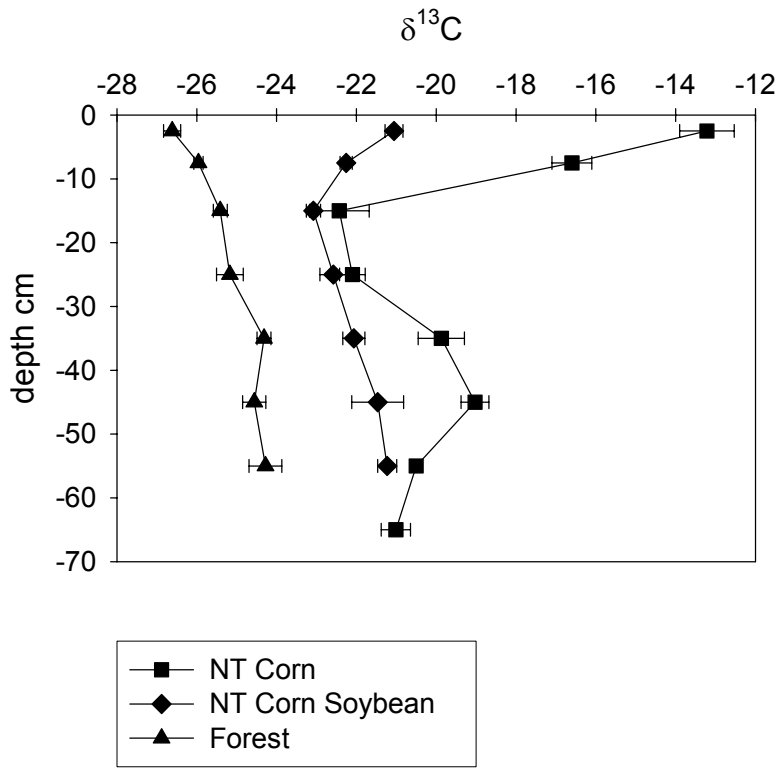
Management effects on C and N stocks in the top 60 cm soil depth

- Plow till corn soil contained 66% 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

	Soil C ($Mg\ ha^{-1}$)	Soil N ($Mg\ ha^{-1}$)
Old growth forest	75	7.5
Meadow (Hayed field)	56	5.8
Plow till corn	50	4.4
No till corn	62	6.8
No till corn-soybean	56	6.8

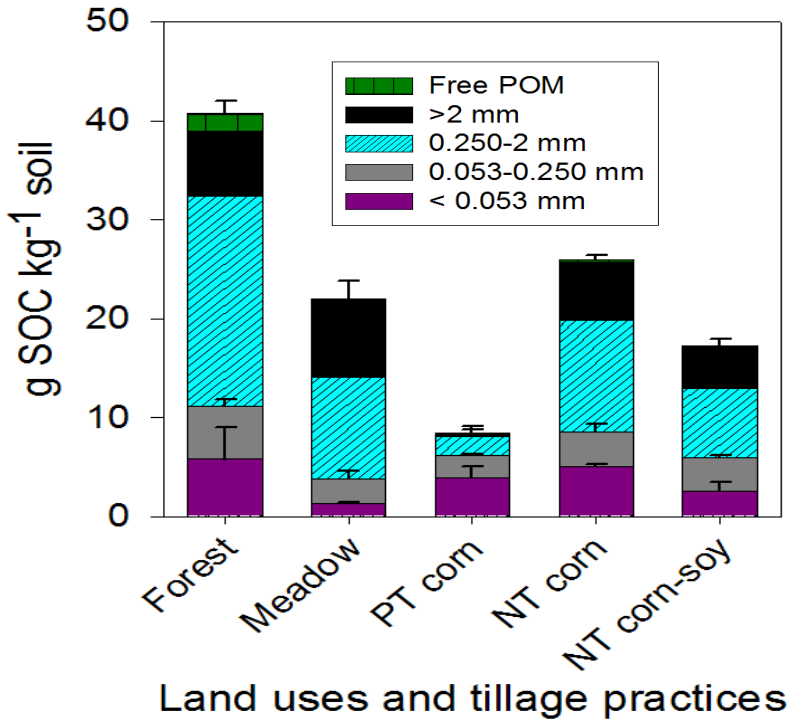
$\delta^{13}C$ signatures in bulk soil

- $\delta^{13}C$ values in soil under forest ranged from –26.9 to –24.3 ‰
- Corn crops increased the $\delta^{13}C$ signal
  - Highest under NT corn
- SOC derived from corn residue in 0-5 cm layer under
  - NT corn: 93%
  - NT corn-soybean: 40%



Carbon and soil aggregates

- Carbon distributed differently among soil aggregate fractions
- Larger aggregates contained more C than smaller aggregates, except in PT corn
- The SOC distribution pattern among WSA confirmed that high C residue input and reduced soil disturbance favor aggregation and the physical protection of aggregated SOC

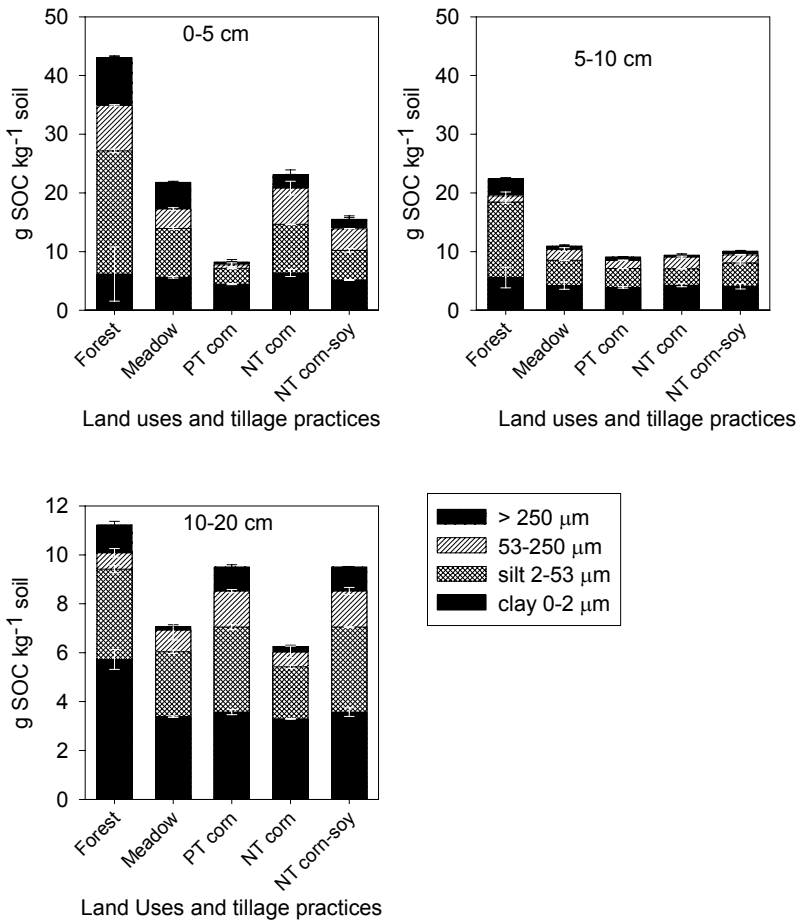


0-5 cm soil depth

Carbon in primary size fractions

- SOC concentrations varied among primary particle size fractions
- As much as 65-80% of SOC was associated with the silt and clay fractions
- About 36% of the total SOC was contributed by POM in the 0-5 cm depth

Figure 8 Amount of SOC in primary particle fractions

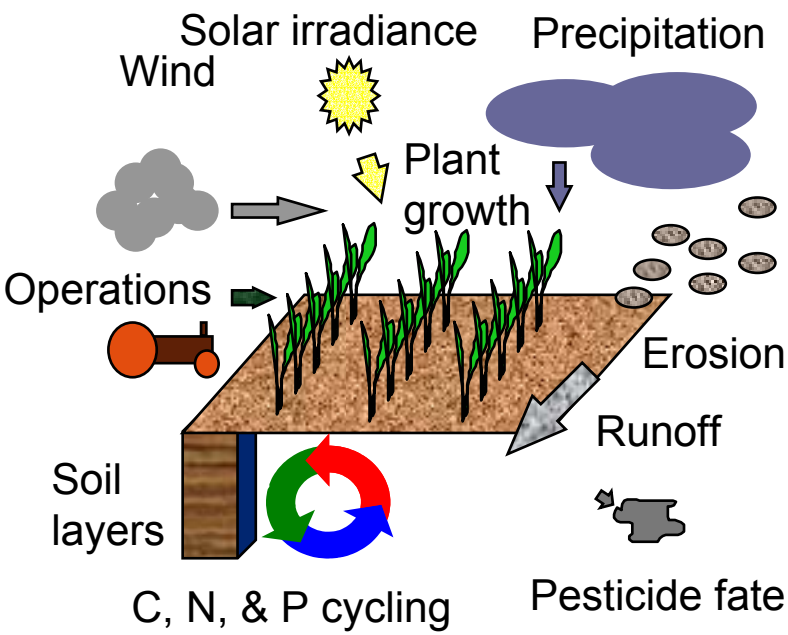


Summary

- Land use, soil tillage, and crop rotations had strong influences on SOC amounts and distribution
- There were significant differences among treatments in aggregation, aggregate size distribution, and in total C and N stocks
- Compared to forest, SOC stocks in the 0-30 cm soil layer were reduced by
  - 15.5 Mg C ha^{-1} in meadow
  - 12.7 Mg C ha^{-1} in NT corn
  - 17.3 Mg C ha^{-1} in NT corn soybean
  - 23.3 Mg C ha^{-1} in PT corn
- Average SOC sequestration rate was 280 kg C ha^{-1} y^{-1}
- The proportion of SOC-derived from corn residue was 96% in 0-5 cm layer of the NT corn, and the proportion decreased with depth
- Some soil fractions were more susceptible to losing and accumulating SOC such as small POM and silt fractions and small macro-aggregates (2-0.250 mm)
- Macroaggregates were enriched in SOC vs. microaggregates
- Formation of stable aggregates is the predominant mechanism of stabilization of soil organic C

3. Integrating biophysical processes and human interactions at landscape scale through simulation modeling

EPIC Model



Representative EPIC modules

Williams (1995)
Izaurralde et al. (submitted)

- **EPIC is a process-based model built to describe climate-soil-management interactions at point or small watershed scales**
- **Many processes simulated**
  - **Biophysical (weather, plant growth, erosion, nutrient cycling, water balance)**
  - **Management (plant environment control, economics)**
- **CSiTE developed C and N model in EPIC to simulate the full impact of management on ecosystem C**

Simulating soil C erosion at the North Appalachian Experimental Station at Coshocton, OH

- Entire watershed divided into small bermed sub-catchments with separate treatments
- Current rotations established in 1976

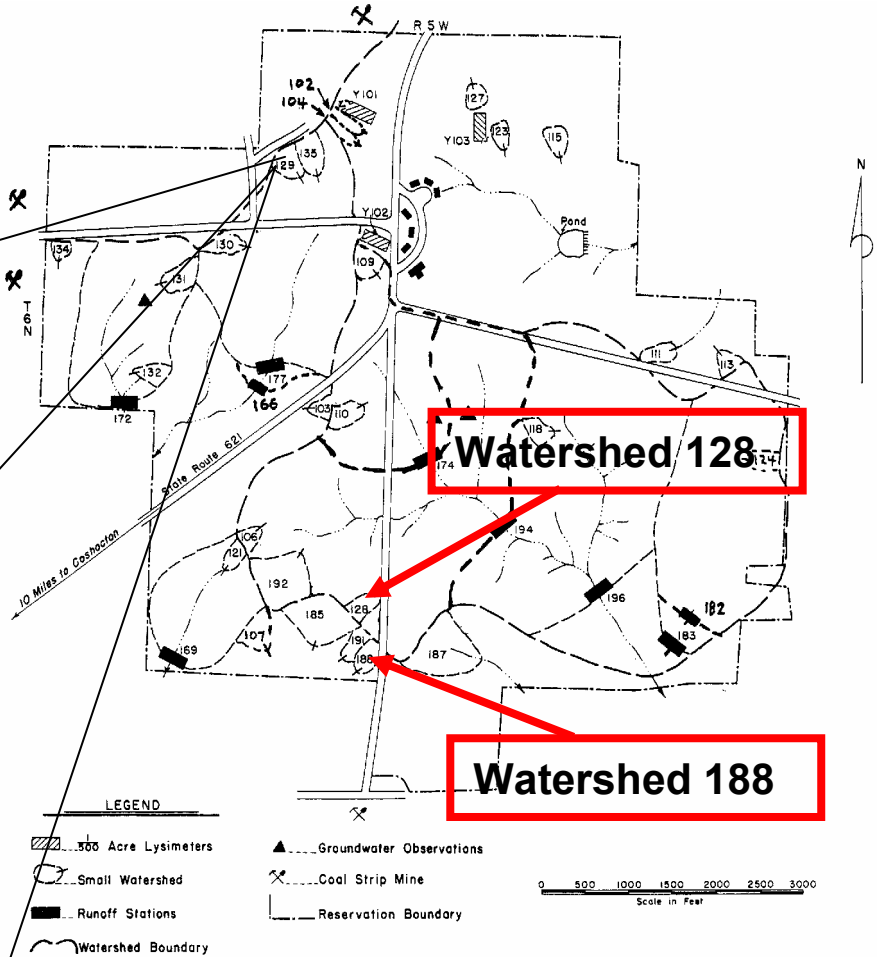
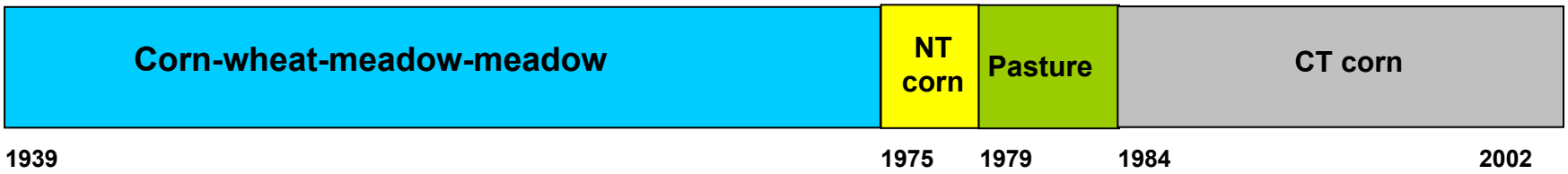


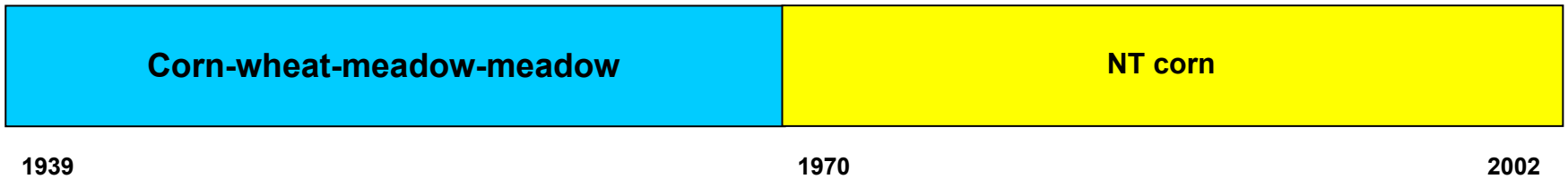
FIGURE 4.—North Appalachian Experimental Watershed, 1,047 acres of government-controlled land.

Land-use history for watersheds W128 and W188

Watershed 128 (W128)



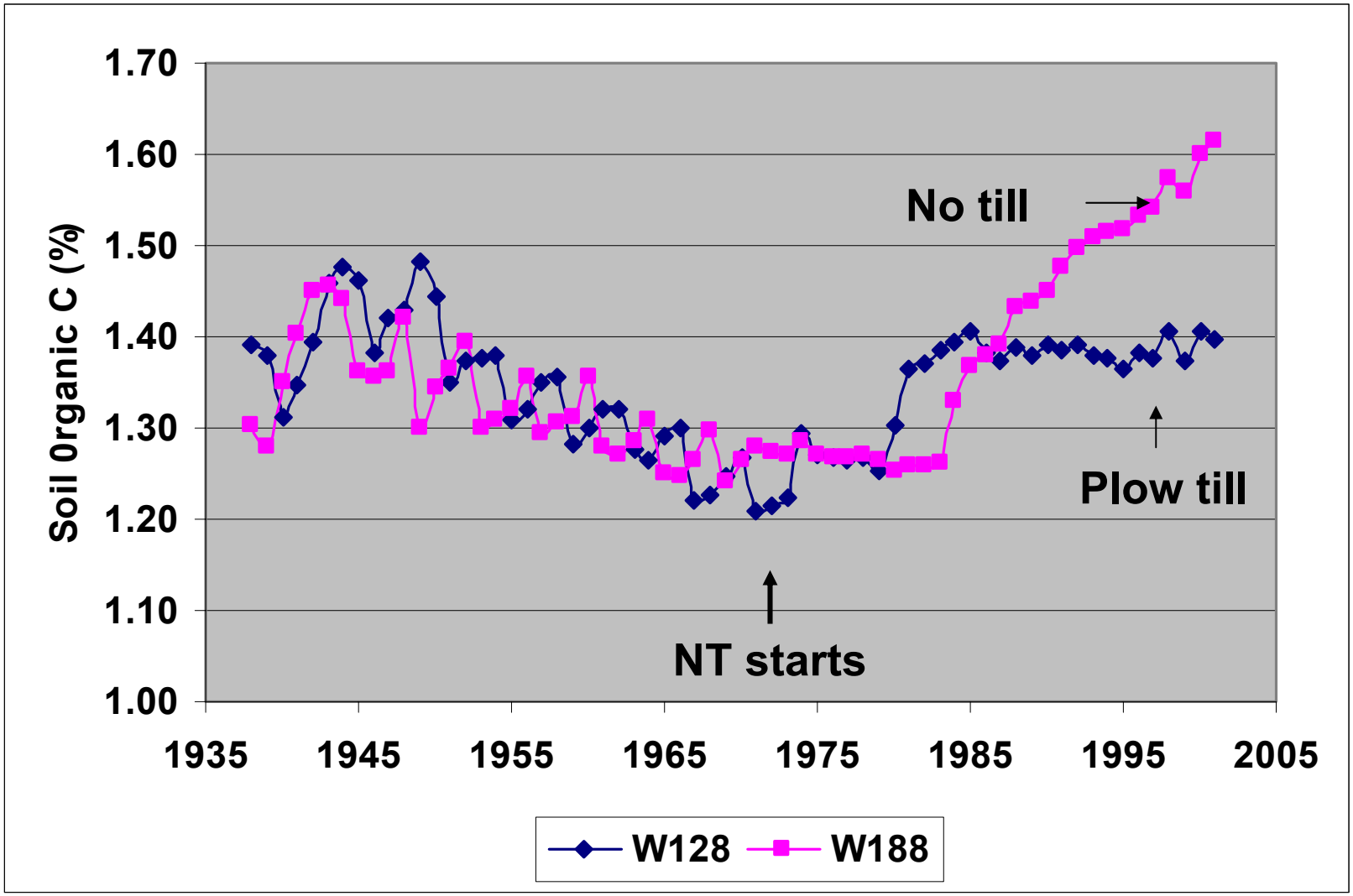
Watershed 188 (W188)



Data source: Puget et al. (2005)

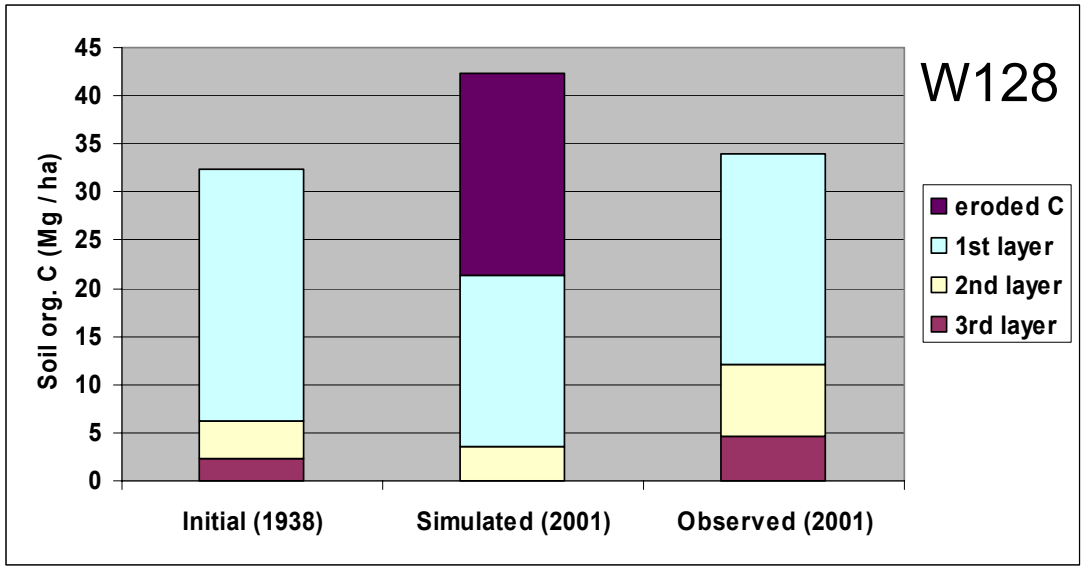
- A 63-y weather record was assembled using data from New Providence, OH
- Crop modeled: corn, wheat, timothy, fescue, and alfalfa
- Soil layer properties were obtained from Kelley et al. (1975) and L. Owens (pers. comm.)
- Two 63-y runs (1939 – 2001) were made with management described above
- CO_2 concentration increased from 296 to 370 ppm (25% increase)

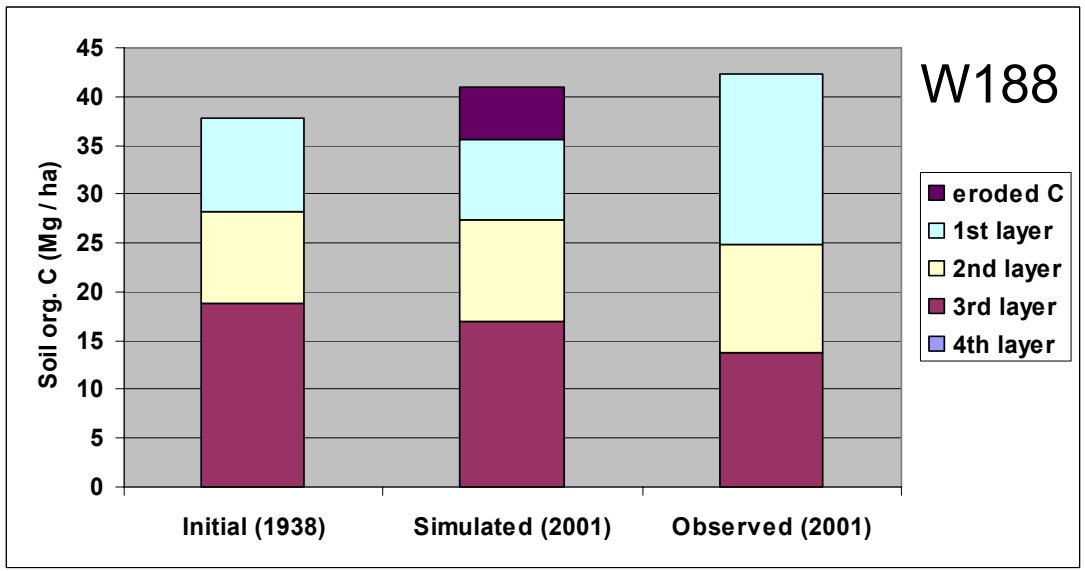
Modeling Results for NAEW
63 year simulation without erosion



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 under no till (W188) was 1/4 that eroded under plow till (W128)





Data source: Puget et al. (2005)

A comparison of annual rates of soil C erosion (Mg C ha^{-1} 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	-

3. Summary

- The 63-y simulations revealed that soil erosion significantly affected the C cycle at field scale
- Simulated losses of eroded C under no till were about 1/4 those under conventional till
- Eroded C under no till simulated with EPIC was the same order of magnitude as that assessed with ^{137}Cs methods or through sediment collection

4. Biochemically Stabile SOC Associated with Aggregates

⇨ BACKGROUND

- Land use and soil management affect the proportions of labile and stabile SOC fractions
- Non-hydrolyzable C (NHC) contribution to total SOC dynamics is significant
- Contribution of NHC relative to total and labile C remains to be documented and explained

⇨ OBJECTIVES:

- Quantify contribution of NHC to total SOC for different land use and soil management
- Identify role of biochemical protection mechanism in SOC sequestration by comparing NHC fractions associated with aggregates

Studied Watershed Histories

Table 1. Schematic overview of the crop rotation in the different cultivated watersheds since 1938.

W128 **CTc** Continuous, conventional moldboard plowed corn since 1984 **Berks silt loam**

4 years rotation : corn/ wheat/ meadow/ meadow
7 y C4 crop (corn) 1945,50,54,58,62,66
28 y C3 crop

corn 5y C4 crop 1974-1978 | pasture 5 y C3 crops 1979-1983 | **conventionally plowed corn** 18 y C4 crops

1938 1939 1946 1950 1954 1958 1962 1966 1970 1974 1978 1982 1984 1990 1994 1998 2002

W188 **NTc** Continuous no-till corn since 1970 **Rayne silt loam**

4 years rotation : corn/ wheat/ meadow/ meadow
8 y C4 crop (corn) 1938,44,48,52,56,60,64,68
24 y C3 crop

no-till corn 32 y C4 crops

1938 1942 1946 1950 1954 1958 1962 1966 1970 1974 1978 1982 1986 1990 1994 1998 2002

W118 **NTcs** No-till corn soybean (rye) rotation since 1984 **Coshocton silt loam**

4 years rotation : corn/ wheat/ meadow/ meadow
8 y C4 crop (corn) 1938,43,47,51,55,59,63,67
25 y C3 crop

corn 5Y C4 crop 1971-1975 | meadow wheat 1976-1982 198 8 y C3 crops | **no-till corn / soybean (rye)** 9 y C4 crops 9 y C3 crops

1938 1942 1946 1950 1954 1958 1962 1966 1970 1974 1978 1982 1984 1990 1994 1998 2002

W185 **Meadow** Meadow since 1988 **Berks silt loam**

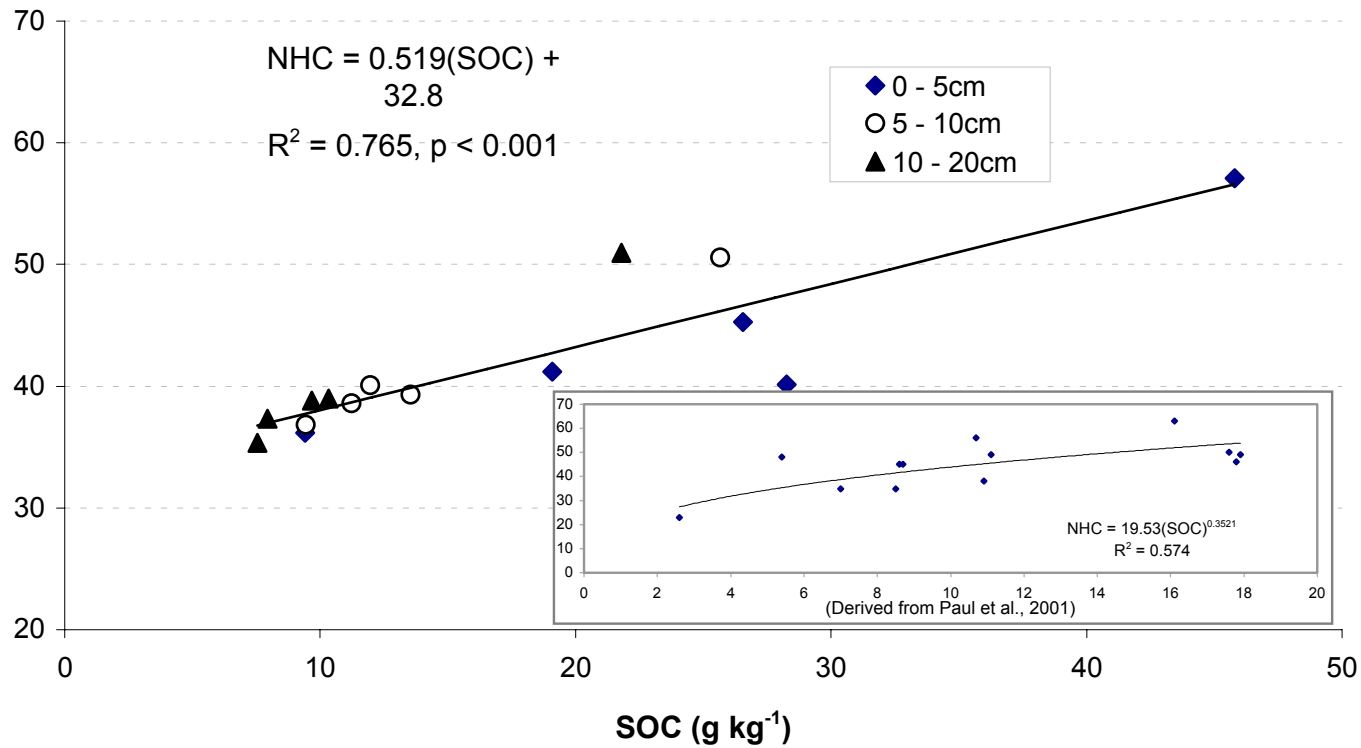
4 years rotation : corn/ wheat/ meadow/ meadow
8 y C4 crops (corn) 1938,42,46,50,54,58,62,66
23 y C3 crops

no-till corn 1969-1987 19 y C4 crops | **meadow** 14 y C3 crops

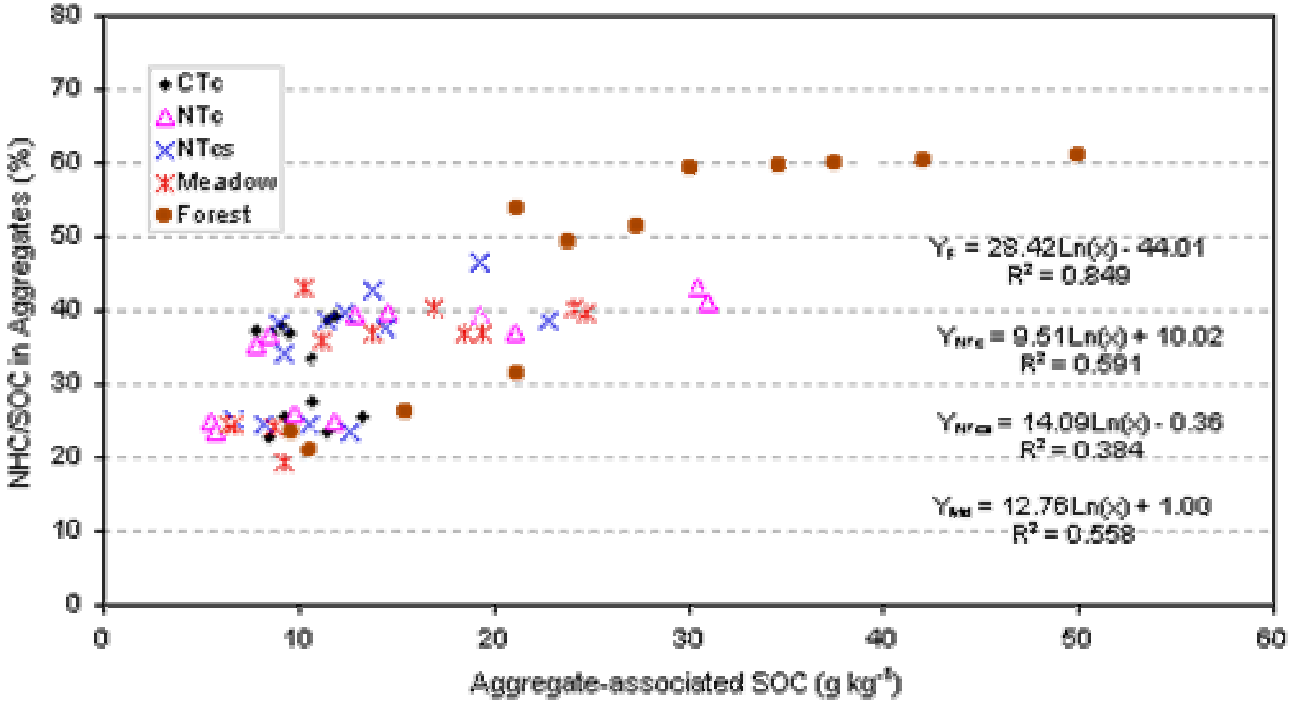
1938 1942 1946 1950 1954 1958 1962 1966 1970 1974 1978 1982 1986 1990 1994 1998 2002

Relationship between total SOC and NHC

- NHC concentration and NHC C/N is correlated with total SOC regardless of land-use, management, depth.
- Average NHC fraction is 42%
  - Forest - 53%, Meadow - 41%, NT - 39%, CT - 37%
  - Range 0-5cm : 57% Forest, 36% Conventional Till corn (CTc)



Management effects on NHC



- ⇨ NHC fraction of SOC increases with aggregate size
- ⇨ Management has impact on the rate of this increase
- ⇨ More NHC under NTc than NTcs suggesting corn residues more resistant than corn-soybean residue

NHC Patterns by Water-Stable Aggregate Size

Table 3. Characteristic comparison of water stable aggregates between landuses grouped by sampling depth.

Depth	Aggregate size	Forest				NT				CT			
		NHC	NHC/SOC	C:N	C:N (nh)[a]	NHC	NHC/SOC	C:N	C:N (nh)[a]	NHC	NHC/SOC	C:N	C:N (nh)[a]
cm	μm	g kg^{-1}	%			g kg^{-1}	%			g kg^{-1}	%		
0 - 5	<53	17.8	59.2	15.3	43.6	6.4	38.6	11.3	22.0	3.5	36.8	8.7	17.6
	53-250	22.5	60.0	16.9	42.9	6.9	38.9	11.6	22.4	2.9	37.2	7.6	17.4
	250-2000	25.4	60.3	20.3	44.1	10.6	43.3	15.6	23.3	4.7	39.5	9.5	19.8
	>2000	30.6	61.2	23.0	45.2	10.4	39.8	14.9	23.1	3.6	33.5	n/a	18.7
5 - 10	<53	11.4	53.7	12.5	40.1	3.3	35.0	7.4	15.9	3.5	38.0	7.5	14.8
	53-250	11.8	49.4	12.9	38.8	3.7	39.3	8.3	20.7	3.1	36.7	7.9	15.6
	250-2000	14.1	51.5	14.9	41.4	4.9	38.3	9.7	21.6	4.4	38.7	9.4	19.6
	>2000	20.6	59.6	14.3	45.2	6.0	39.3	10.3	19.8	2.9	27.6	n/a	13.7
10 - 20	<53	2.3	23.5	9.2	15.8	1.5	24.8	6.6	8.6	2.4	25.6	7.7	12.0
	53-250	2.2	20.9	10.1	15.5	1.6	24.0	7.2	9.3	1.9	22.8	8.4	11.6
	250-2000	4.1	26.2	11.4	21.3	2.4	24.9	8.3	11.3	3.4	25.5	9.1	13.6
	>2000	6.6	31.2	13.4	28.6	2.6	22.6	8.8	12.1	2.7	23.4	7.8	12.9
LSD (0.05)			n/a			1.8	3.4	2.6	4.9		n/a		

: Including NTc, NTcs and meadow and each value is the average of data from these three treatements.

ą: non-hydrolyzable fraction.

- ⇨ **C:N ratio of NHC differs strikingly from total SOC Forest - 43, NTcs, Meadow - 21, NTc - 18, CTcs - 17**
- ⇨ **NHC content increases with aggregate size**
- ⇨ **NT and CT different only in 0-5cm depth**

4. Summary

- Contribution of NHC fraction increases with soil SOC concentration and with water-stable aggregate size - suggests important role for NHC in soil aggregation and aggregate stability
- Conversion from CT to NT increased NHC in all aggregate fraction especially the 250-2000μm and >2000 μm sizes.
- Large amounts of NHC and its large C/N in association with >2000 μm in forest and meadow indicates large sequestration potential in biochemically resistant compounds.

5. Mechanical Properties of Soil Aggregates under Diverse Management Systems

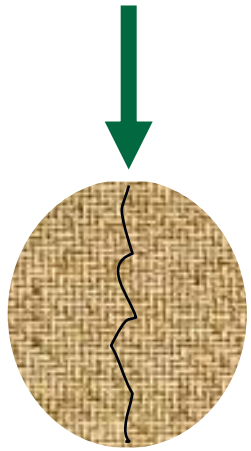
- ⇨ Aggregates: basic units of soil structure
- ⇨ Mechanical properties of aggregates define the soil behavior to tillage, compaction, and plant growth
- ⇨ Aggregate attributes ≠ attributes of the whole soil

Objectives

- Assess the aggregate mechanical properties for diverse land use and management systems.
- Compare the bulk densities of aggregates with those of bulk soil.
- Study the interrelationships among aggregates properties.

Tensile Strength

Tensile strength (TS) is a dynamic property - force required to break an aggregate, a sensitive indicator of the structural stability.



$$TS = 0.576 \left(\frac{F}{D^2} \right)$$

where *F* is breaking force (N), *D* aggregate diam. (Rogowski et al., 1968; Horn and Dexter, 1989).

Study Site

- North Appalachian Experimental Watershed, Coshocton, OH.
- Seven (>15 yr) watersheds (6 to 12% slope).

1. Moldboard plow (MP)
2. Chisel plow (CP)
3. Disk with cattle manure (DM)
4. No-till with cattle manure (NTM)
5. No-till without cattle manure (NT)
6. Pasture
7. Forest

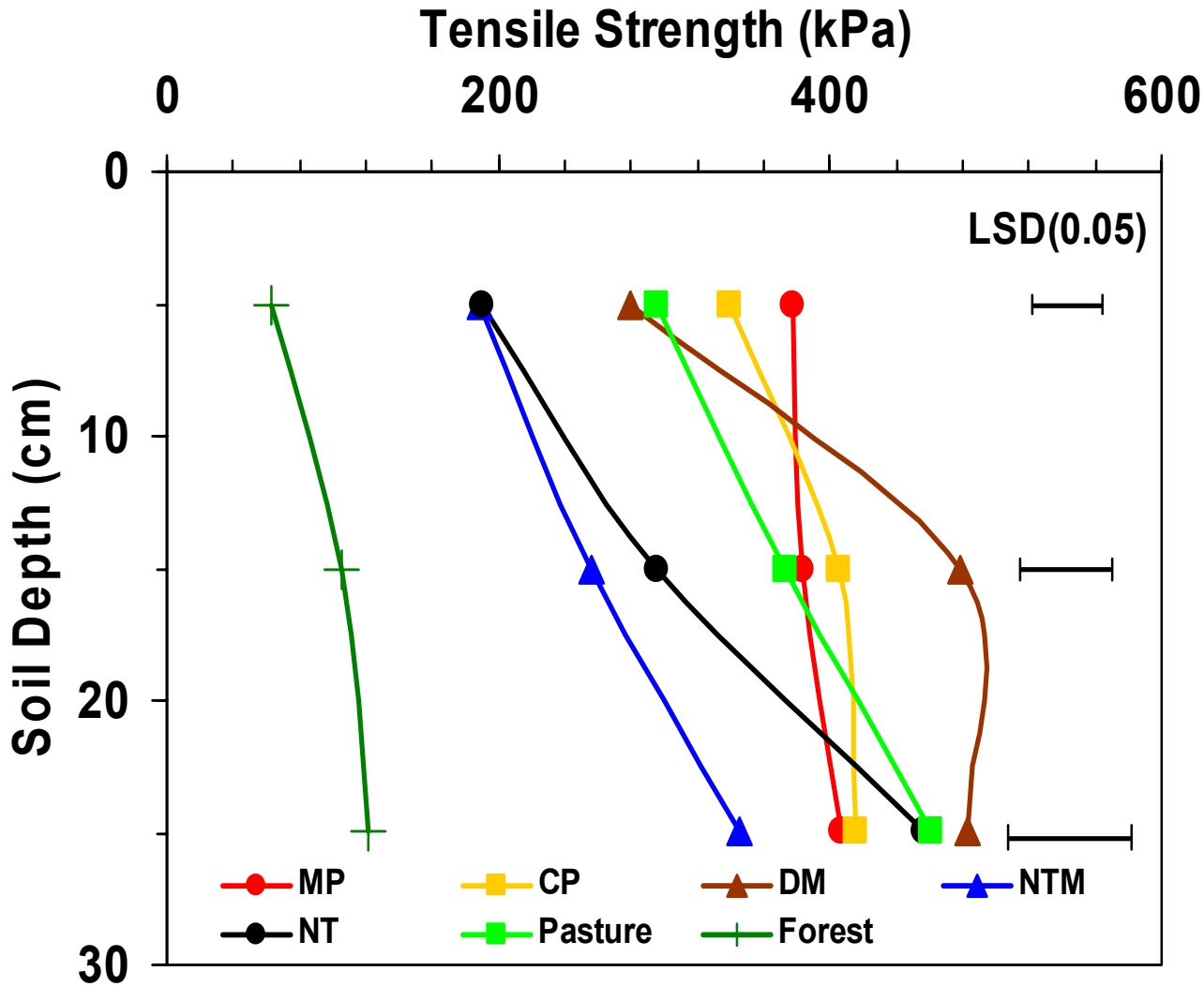
Watershed Treatments

Watershed	Management	Area, ha
MP	corn (*Zea mays* L.)	~0.12
CP and DM	corn-soybean [*Glycine max* (L.) Merr.] rotations	<1
NTM and NT	continuous corn	<1
Pasture	Perennial pasture grass	>1
Forest	Perennial hardwood forest	>1

Materials and Methods

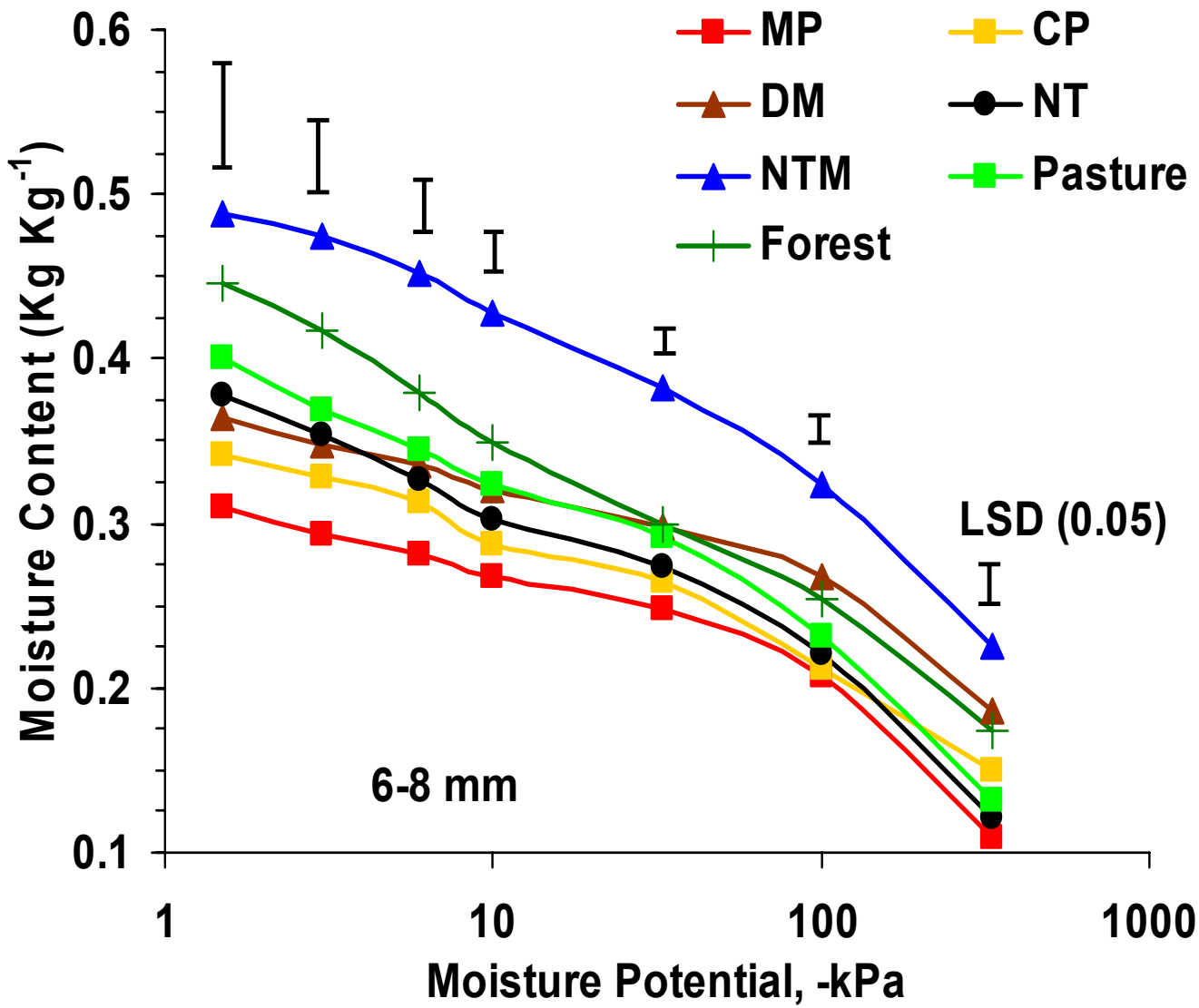
- Soil samples collected in April, 2004.
- Depths: 0 to 10, 10 to 20, and 20 to 30 cm.
- Air-dry aggregates: 2-1, 2-4, 4-6, and 6-8 mm.
- TS: crushing method.
- Aggregate Density (ρ_{agg}): Clod method.
- Bulk soil density (ρ_b): Core method.
- Soil moisture retention (SMR): 0 to 300 –kPa.
- Total SOC content : Dry combustion method.

Geometric mean TS



Forest < No-till < DM < CT for 0- to 10-cm depth.

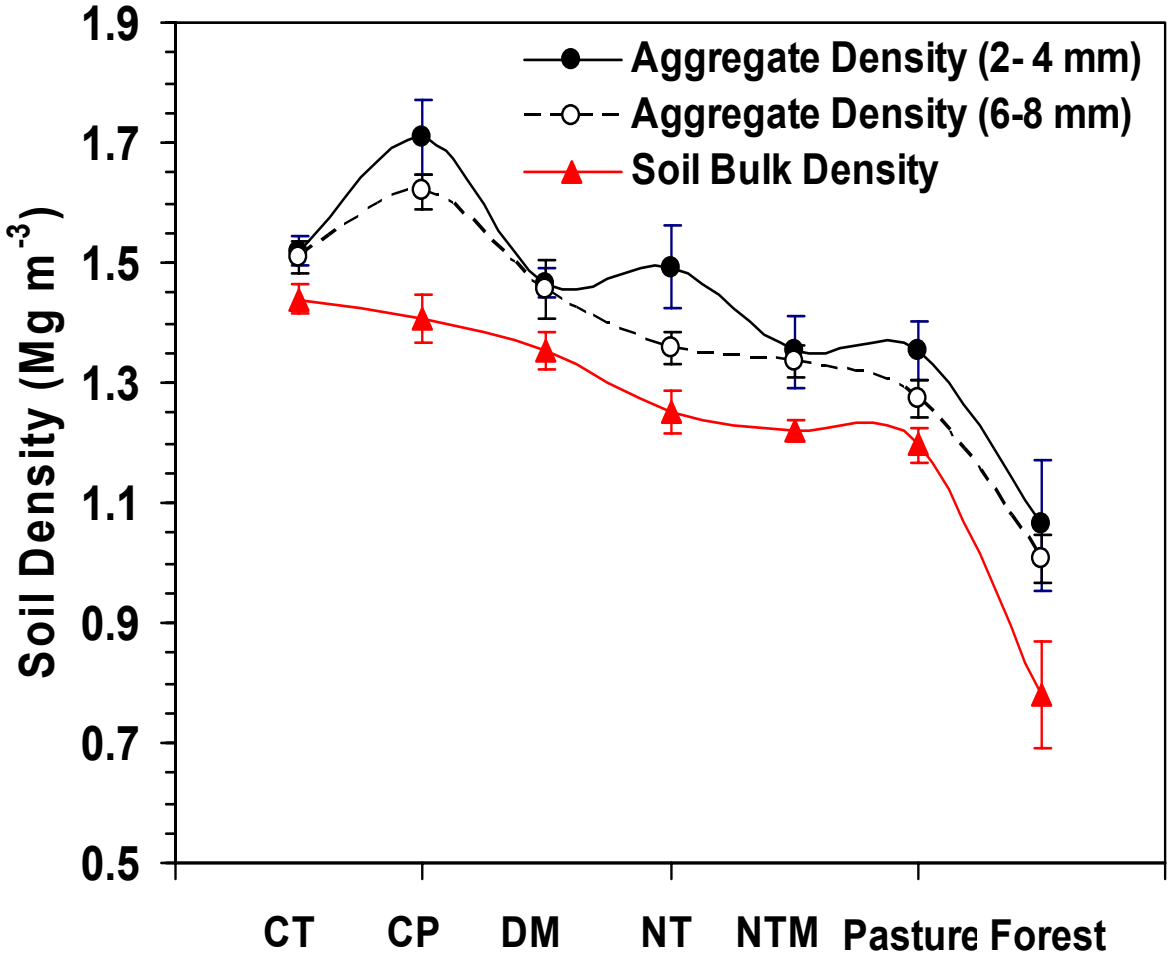
Soil Moisture Retention



Results

- Forest had the highest SOC concentration and lowest ρ_{agg} followed by NTM
- NTM: highest SMR (0 to 300, -kPa)
- MP had the highest TS and ρ_{agg}, and the lowest SMR (0 to 300, -kPa) and SOC content
- Excessive tillage had negative impact on aggregate properties

Comparison of Densities



$\rho_{agg} > \rho_b$

($P<0.05$)

Reduction of macroporosity and increase of cohesion forces increase ρ_{agg} (Horn, 1990)

5. Conclusions

- Long-term management practices cause significant changes in aggregate properties
- Increasing SOC content reduces TS and ρ_{agg}, improves soil moisture retention of aggregates
- Tillage not only reduces SOC but increases aggregate TS and ρ_{agg}
- Aggregates have higher density than bulk soil
- Size, SOC content, and ρ_{agg} explain 71% of the variability of LogTS
- Aggregate physical properties interact dynamically with carbon processes and should be captured in the next generation of soil C models

Overall 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
    - Yielded information on the role of stable aggregates in the formation of stable SOC
    - Provided new insights into the role and dynamics of microbially-resistant organic matter
    - Indicated that aggregate physical properties are dynamic and respond to land-use and soil management
- Site offers unique possibility for integration of soil carbon, hydrology, and management impacts of dominant U.S. agricultural practices