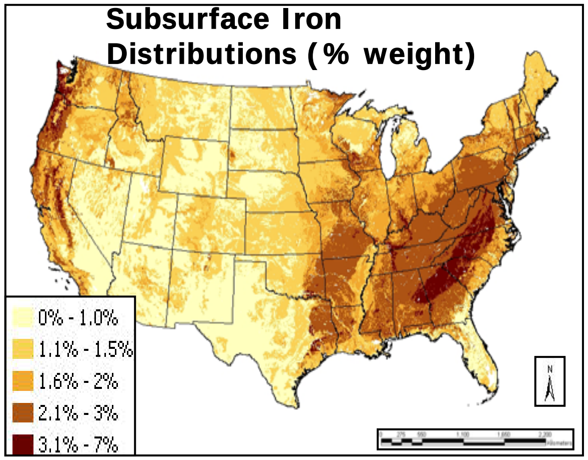
# This CSiTE project is composed of two integrated tasks that began October 2001

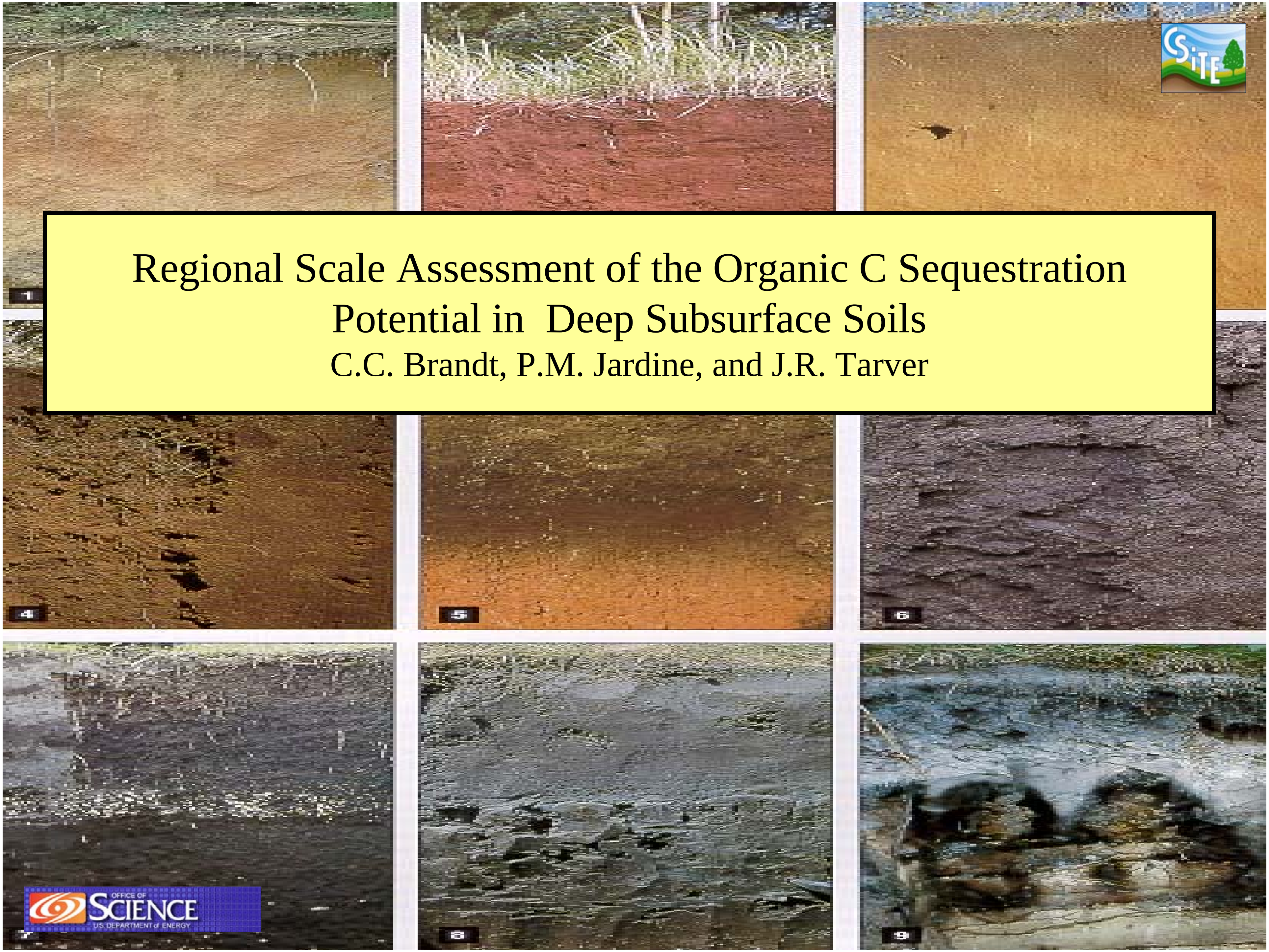
## Regional Scale Assessment of the Organic C Sequestration Potential in Deep Subsurface Soils




**Our goal is determine the value of deep subsurface soils in the long-term sequestration of organic C and develop a geographical method for estimating the carbon storage capacity of subsurface soils (B-horizons) within the United States. This effort will allow us to identify regions and field sites which offer the greatest potential for enhanced subsurface organic C storage and thus most deserving of manipulation or improved management.**

## Manipulations to Enhance Subsurface Organic C Pools

**Our goal is to test and resolve the hypothesis that deep subsurface soils can accumulate organic C as a result of near surface manipulations. The effort involves the use of two highly instrumented *in situ* soil blocks on contrasting soil types and quantifies the impact of coupled hydrological, geochemical, and microbial processes on enhanced subsoil organic C sequestration.**



# Regional Scale Assessment of the Organic C Sequestration Potential in Deep Subsurface Soils

C.C. Brandt, P.M. Jardine, and J.R. Tarver

# Objectives

- **Quantify the relationship(s) between subsoil organic C sequestration and soil physical, hydrological, and geochemical properties.**

- **Develop a geographical method for estimating the carbon storage capacity of subsurface soils (B-horizons) within the United States.**

- **Identify regions and field sites which offer the greatest potential for enhanced subsurface organic C storage and thus most deserving of manipulation or innovative management.**

# Rationale

**Organic C pools within the upper soil horizons (O and A horizons) are highly dynamic and strongly influenced by changes in land use and manipulation (deforestation, agricultural production, fertilization). Turnover times are on the order of years to decades.**

**Organic C pools in subsoils (B and C horizons) are much less dynamic due to mineral stabilization. Turnover times are estimated at millennia and longer.**

**Widespread, highly developed mature soils such as Ultisols, Oxisols, and Alfisols have deep soil profiles that have a tremendous capacity to sequester organic C that has been solubilized from surface horizons.**

**Relationships linking key geochemical and physical properties to the sequestration of organic C in deep subsoils have not been fully investigated.**

**Regional-scale evaluation of the potential storage capacity of these and other soils has not been investigated.**

# An example of sustained subsoil organic C sequestration

**Anthropogenically enriched soil of the Amazon** | **Adjacent nonenriched soil**

**These xantic Ferralsols are from the same physiographic position and have the same clay content and clay mineralogy. The soil on the left was purposely enriched by ancient human occupation centuries ago. This provides an indication that such enrichments can be maintained at a minimum of several centuries.**

# Approach

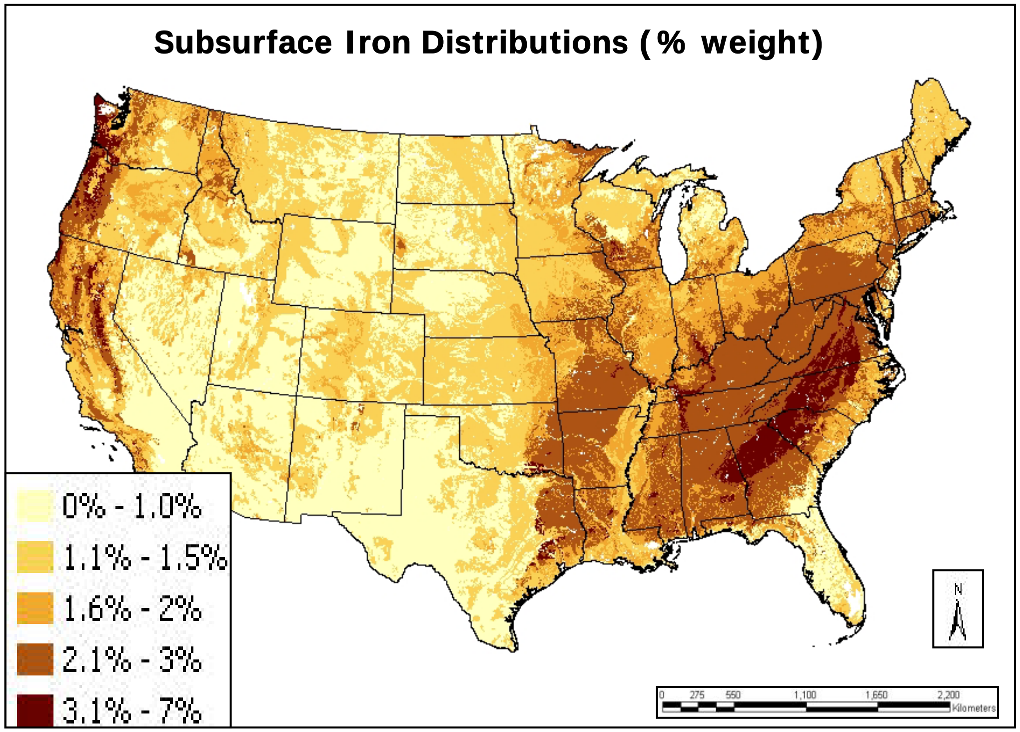
- **Develop and validate statistical models for estimating deep soil carbon storage based on soil chemical and physical parameters.**
  - **Use USDA National Cooperative Soil Survey (NCSS) database to acquire pedon information associated with designated soil series.**
  - **Acquire actual soils associated with selected NCSS pedons to perform C sorption experiments. Also use existing CSiTE field plots across country (e.g. Fermi, Rodale, U. Washington, Richland, SRL, NCSU, ORNL).**
  - **Develop multivariate statistical models to estimate carbon storage using NCSS data and carbon sorption capacity data generated in our laboratory.**
- **Design and implement a GIS database of subsurface soil organic carbon storage capacity.**
  - **Acquire STATGO soil survey database and related attributes.**
  - **Aggregate NCSS pedon characterization data to horizon compartments within great groups and link the aggregated data to the STATSGO database.**
  - **Estimate carbon storage capacity for soil map units.**

# Approach (continued)

- **Regional estimation under various scenarios**
  - Use modified carbon cycle model (linkage to Post and others) to estimate carbon input to soil under current and various alternative scenarios (linkage to West)
  - Overlay model estimates with soils map to estimate carbon input by map unit.
  - Generate regional estimates of changes in C storage in deep subsoils (mean and uncertainty).
  - Visualize results (mean and uncertainty).

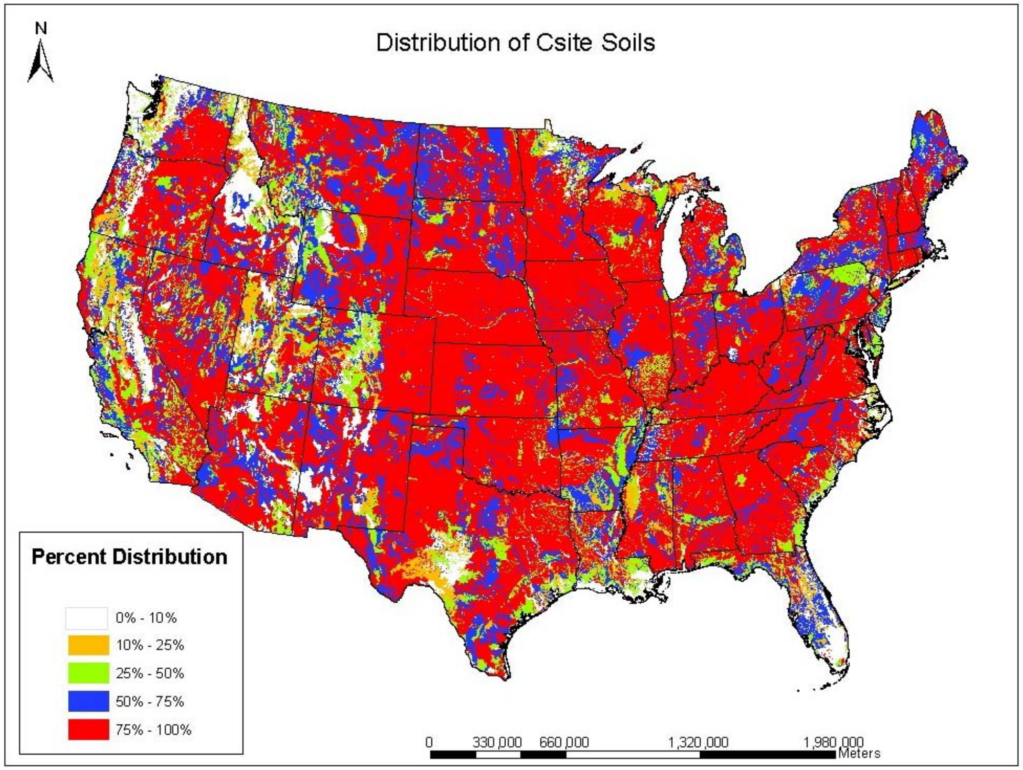
# Results and progress – Soils database

- Screened NCSS pedon data for anomalous values.
- Estimated bulk density of NCSS soils based on physical and chemical properties.
- Aggregated pedon data to great group and horizon compartment.
- Linked aggregated data to STATSGO soil survey database.



# Results and progress – Soil sampling

- Calculated area of each series in STATSGO database.
- Selected an area-weighted sample from list of series.
- Identified most recently characterized pedon in NCSS database.
- Compared chemistry of selected series to all series in great group to ensure that selected series was representative.



## Results and progress – Soil sampling

- Initiated requests with USDA state and county agents to acquire 100 soil series from around the country to perform C sorption isotherms.
- USDA Headquarters suggested that the effort was of such a magnitude that a formal collaboration was needed.
- A memorandum of understanding between DOE/ORNL and USDA has been established and cost estimates are being negotiated for obtaining additional soils.
- Thus far, hundreds of soils from 34 soil series (12 pending) have been obtained and carbon sorption and soil characterization has been completed.

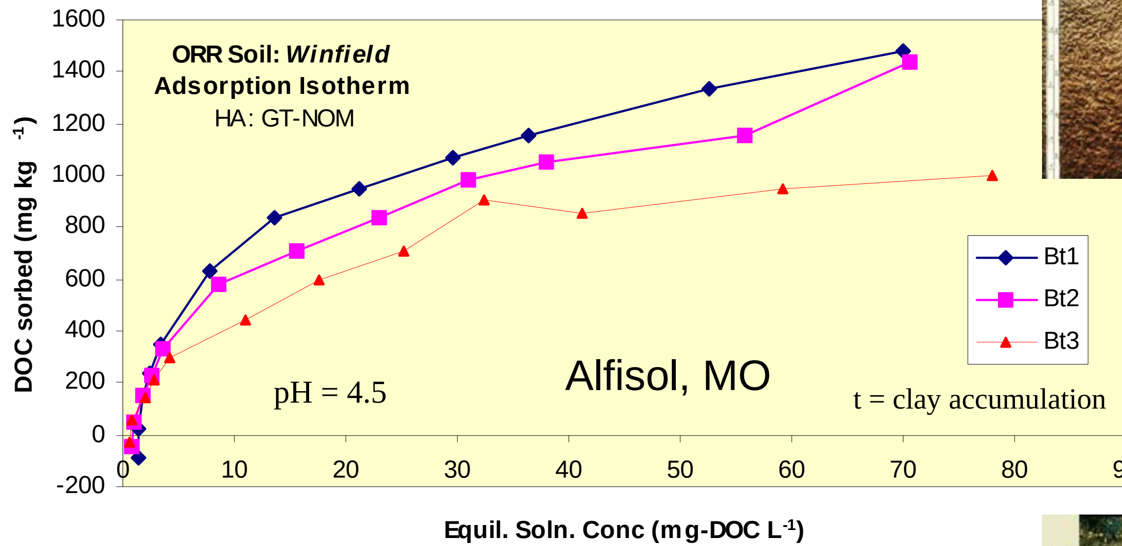
# Organic C sorption isotherms on Alfisols and Ultisols

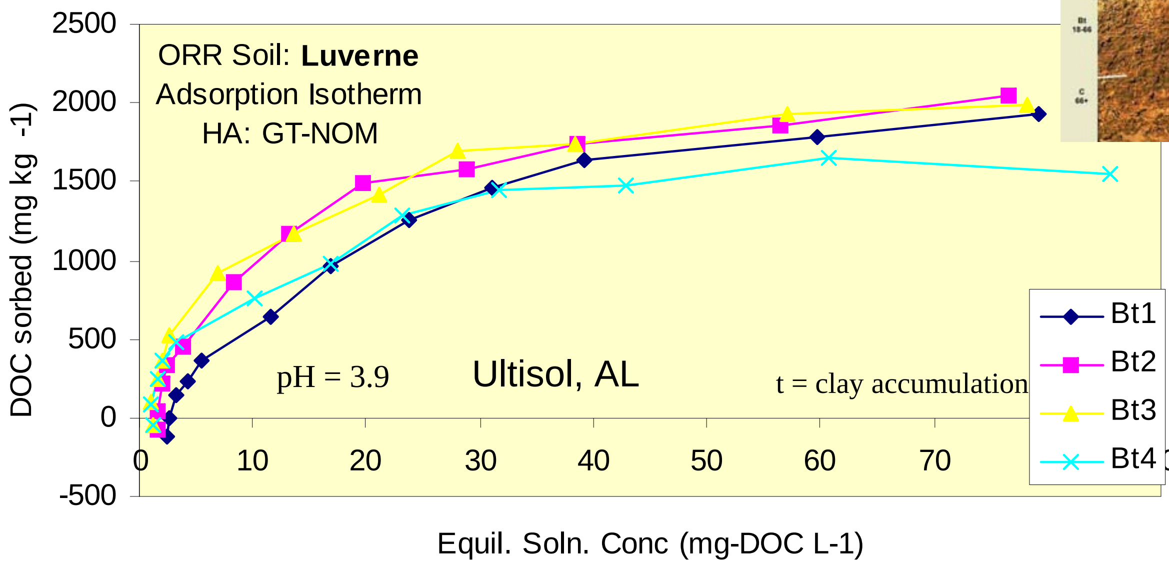
Alfisols and Ultisols B horizons had good sorption capacity for sequestering organic C.

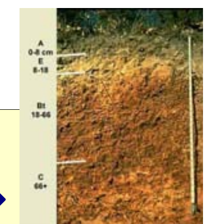
This is likely due to their large clay content that is often coated with Fe-oxides.

Their slightly to highly acidic pH condition also enhances the sequestration potential of these soils.

Ultisols are extensive in the southeast and Alfisols are extensive in the midwest. Both soil types are dominant east of the Mississippi river.



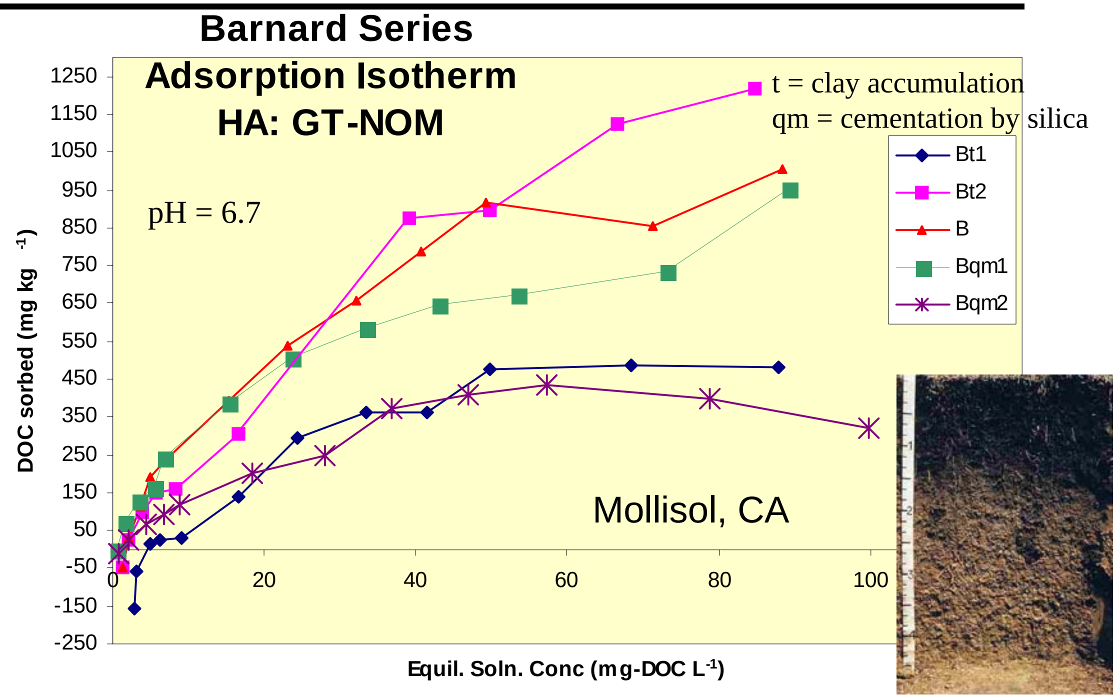



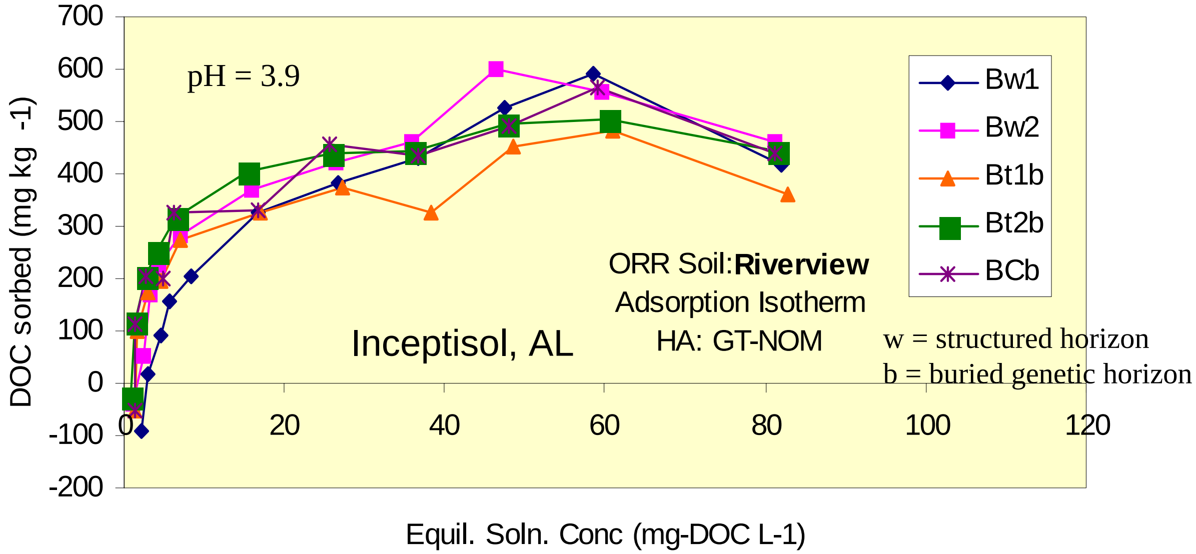
# Organic C sorption isotherms on Mollisols and Inceptisols

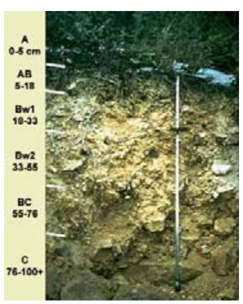
Both Mollisols and Inceptisols generally have sufficient clay and Fe-oxide contents in their B-horizons that serves to sequester organic C.

The pH of the Mollisols can limit sequestration; however their upper horizon organic C stocks are huge whereby they have vast reserves for potential vertical transport and sequestration by lower horizons.

Mollisols are dominant east of the Rocky Mountains and west of the Mississippi river. Inceptisols are scattered throughout the country but are dominant along the Appalachian Mountains.



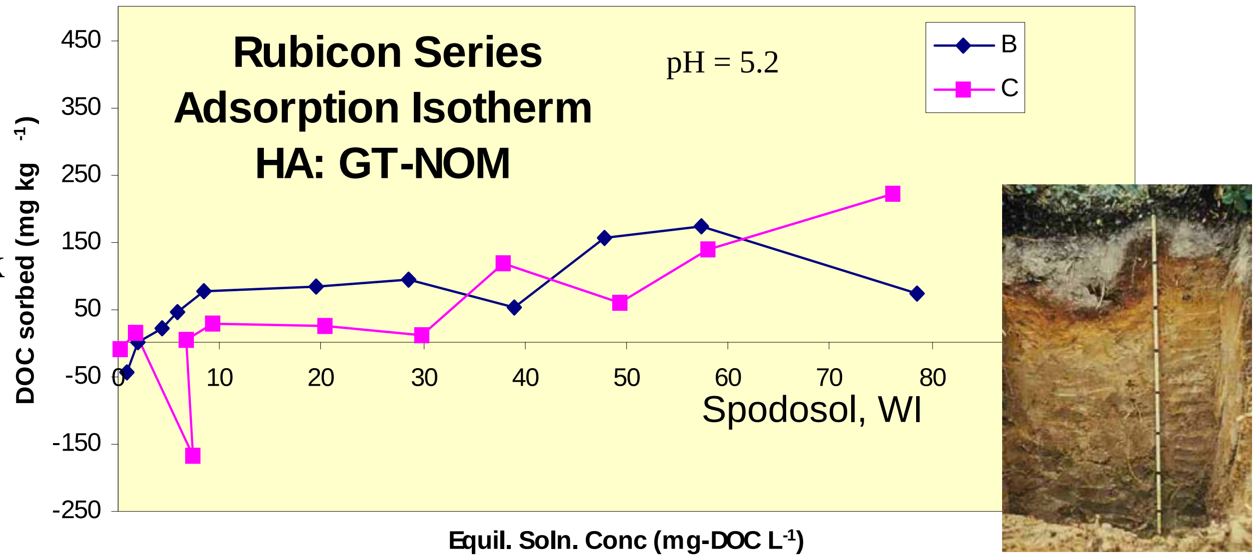



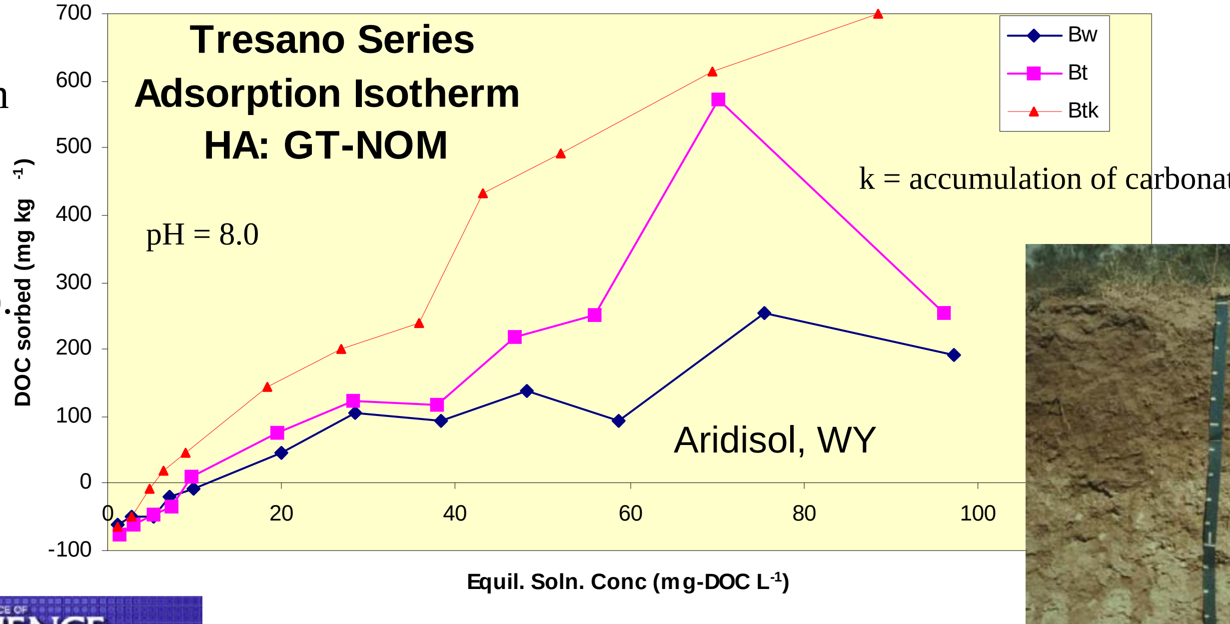
# Organic C sorption isotherms on Spodosols and Aridisols

Spodosols have a subsurface sodic horizon where organic matter accumulates. Below this however, the B-horizons of Spodosols do not appear to significantly sequester organic C due to the lack of sufficient Fe-oxides.

Aridisols generally are generally lacking in sufficient clay and Fe-oxides and thus have a low capacity for sequestering organic C. Some Aridisols have a significant Fe-oxide content which enhances the sequestration of organic C, however their pH is usually high which decreases the sequestration potential (see graph).

Spodosols are most numerous in New England, the northern Great Lakes, and Florida. Aridisols are prevalent from the Rocky Mountains westward.

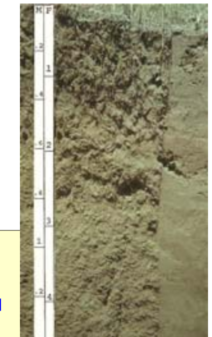


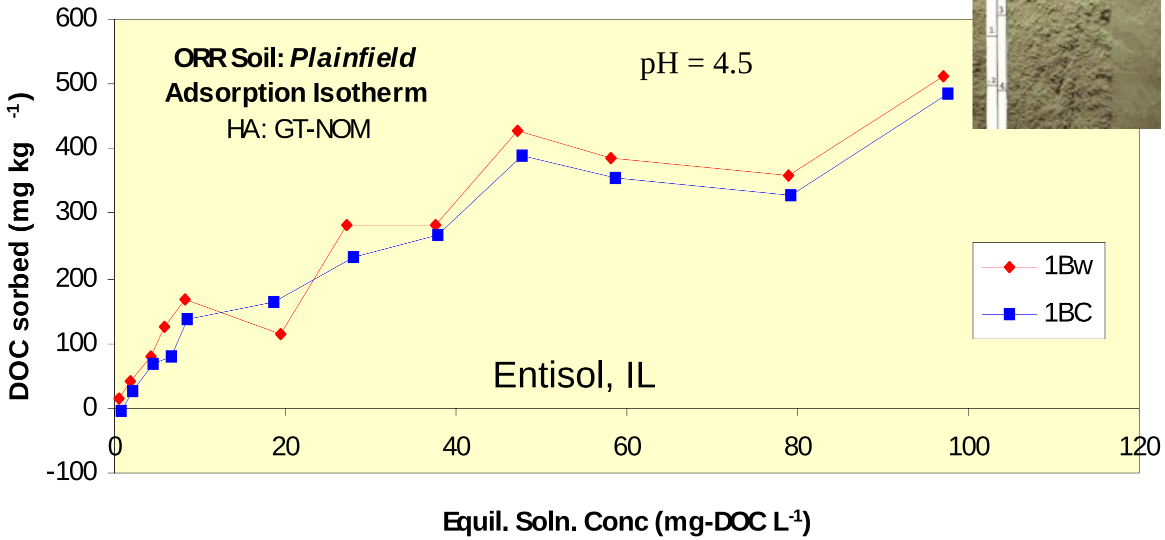



# Organic C sorption isotherms on Entisols

Entisols have no diagnostic horizons and appear to have a moderate organic C sequestration capacity.

Entisols are scattered throughout the country but are more numerous west of the Mississippi.



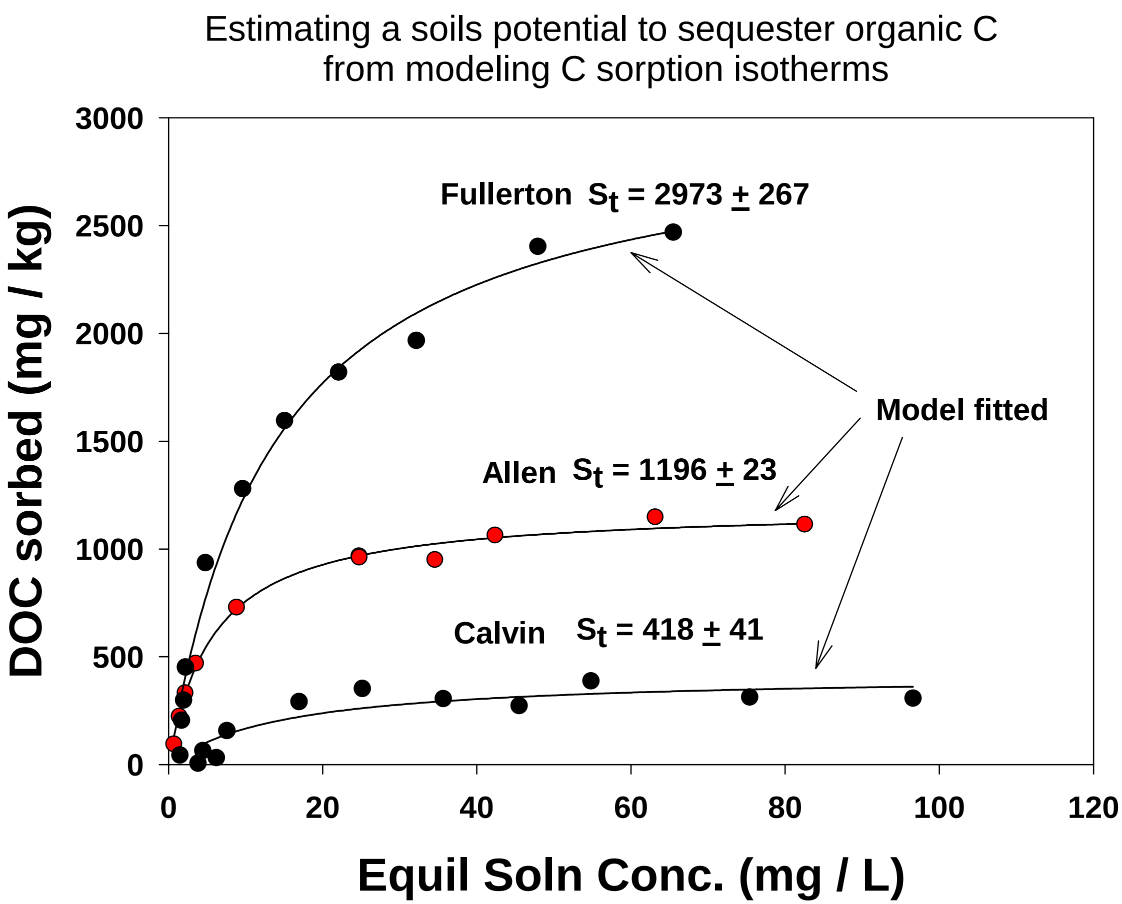


# Obtaining an estimate of maximum organic C sorption for each soil

The langmuir equation is optimized to the observed data where estimates of the maximum organic C sorption ($S_t$) to a particular soil are obtained.

Data fits are generally good with adequate 95% confidence limits for the estimated $S_t$ parameter.

The $S_t$ parameter is used in a multiple regression or neural net modeling strategy where soil physical and geochemical properties serve as the independent variables.



# Measurement of soil physical and geochemical properties

Complete or planned:

- Particle size
- pH (water and KCl)
- Fe-oxide content
- Total organic carbon
- Total inorganic carbon
- Cation exchange capacity
- Anion exchange capacity

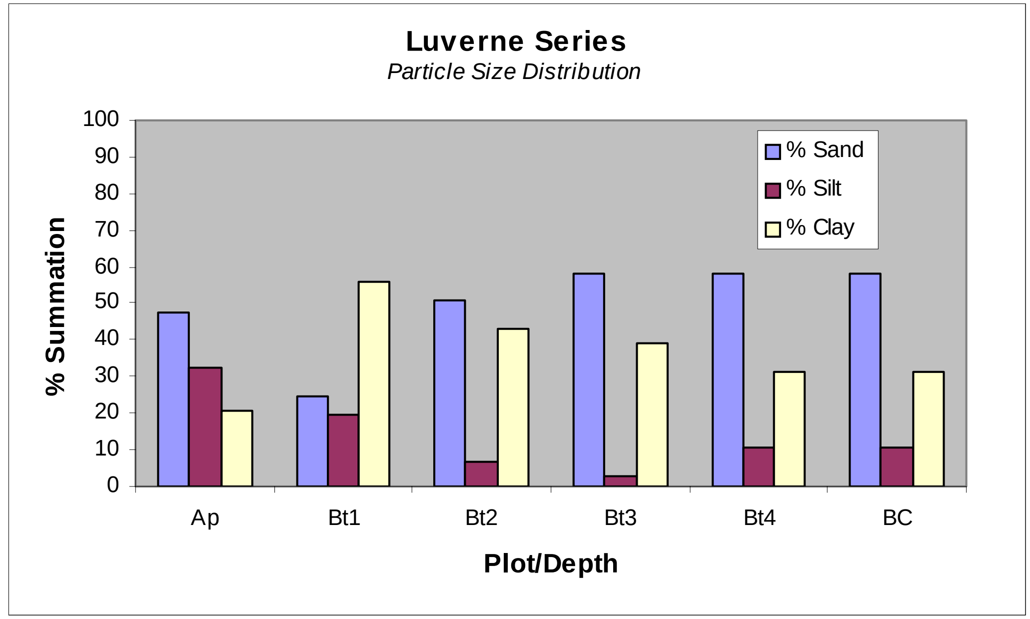
If necessary:

- Amorphous vs. crystalline Fe-oxides
- Exchange phase cations and anions
- Surface area

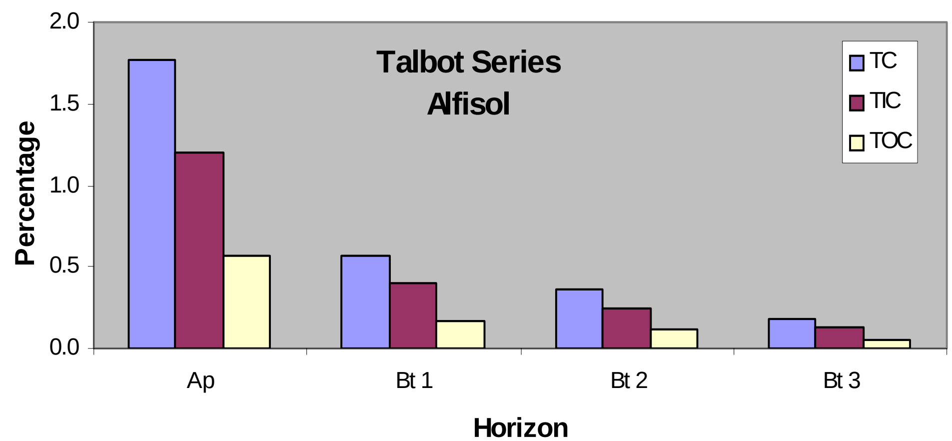
Available data:

- Actual and predicted horizonal bulk density

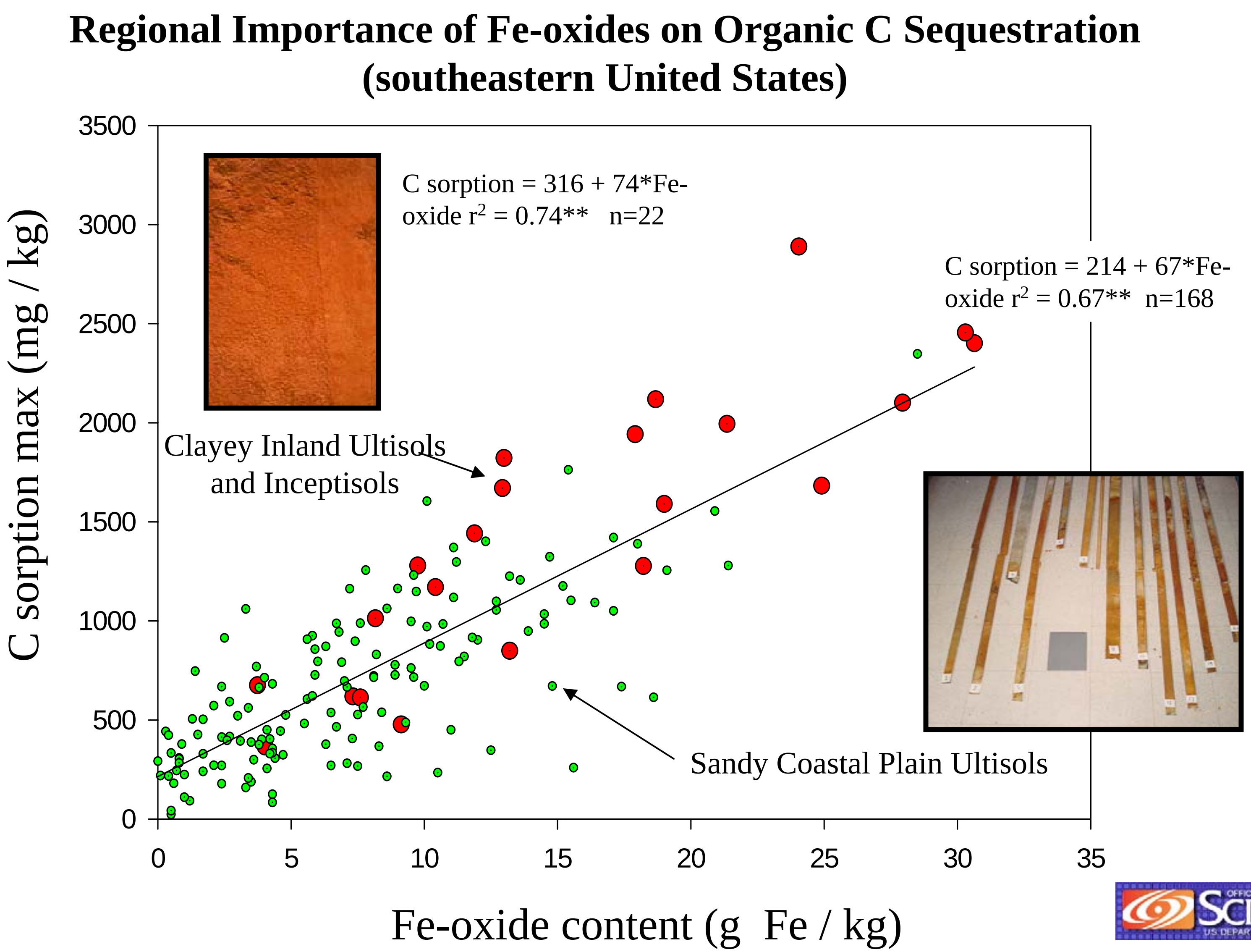
Example particle size distribution on an Ultisol




Example carbon distribution on an Alfisol



# Building multiple regression and neural net models to predict maximum organic C sequestration potential as a function of soil properties

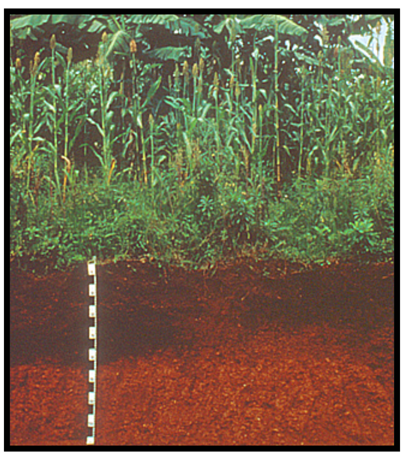


# Benefits

- **Development of a statistically rigorous, geographically-based method for estimating the carbon storage capacity of deep subsurface soils within the United States.**

- **Identification of regions and field sites which offer the greatest potential for enhanced subsurface organic C storage and thus most deserving of manipulation or improved management.**

- **The United States framework for assessing the organic carbon sequestration potential of subsoil could be extended globally.**



**Humic Rhodic Eutrustox – organic rich oxisol with more than 16 kg C / $m^2$ at depths greater than 1 m. Why? Management with low-input agriculture. These soils support some of the largest human population densities in the world.**

# Future Research

- **Calculate uncertainty estimates of aggregated soil properties.**
- **Complete carbon sorption and characterization of soil samples**
  - **Southeastern U.S.**
  - **Soils requested from USDA**
- **Construct multivariate statistical models to estimate carbon sorption from soil properties.**
- **Incorporate modified carbon cycle to estimate carbon input to soil.**

# Manipulation Strategies to Enhance Subsurface Organic C Pools

?

# Objectives

- **Quantify the magnitude of enhanced organic C accumulation in deep Ultisol and Inceptisol subsoils that have been treated with amendment strategies designed to accelerate the mineralization and dissolution of surface organic matter.**

- **Quantify the impact of coupled hydrological and geochemical processes on the fate and transport of solubilized organic C through the soil profile.**

- **Quantify the chemical nature of the sequestered C and the mechanisms responsible for immobilization on the solid phase.**

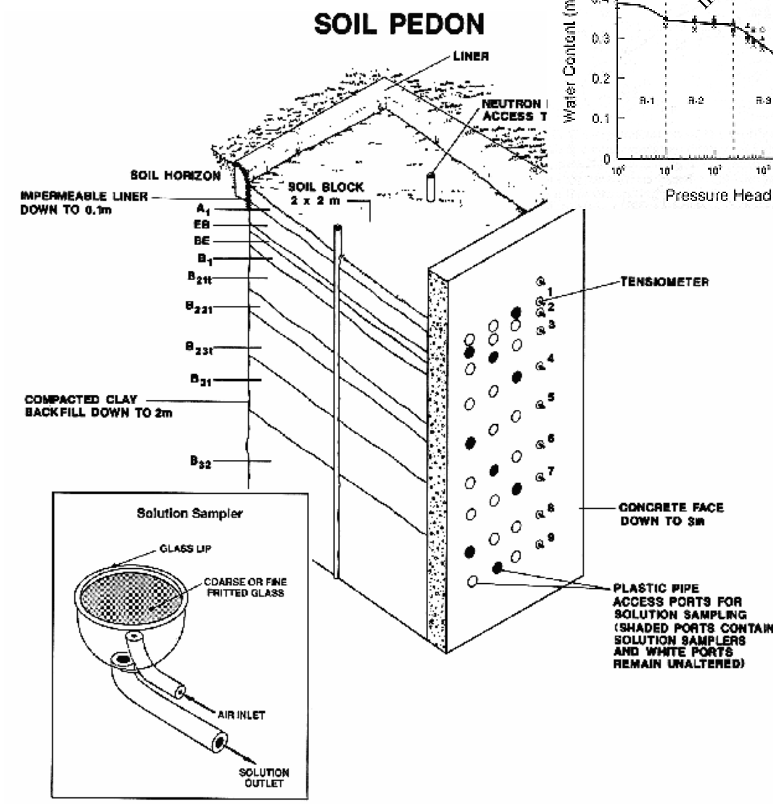
# Rationale

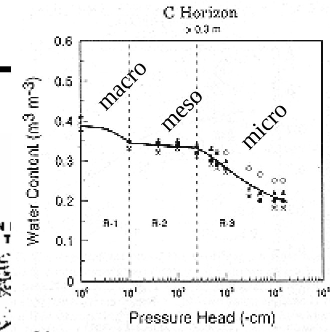
- **There is a need to assess the potential of existing and rapidly expanding commercial fertilization practices in agriculture and silviculture to accelerate natural C sequestration in deep soil profiles.**

- **Specifically, it is unknown as to the propensity of subsoils to sequester organic C that has been released and transported from surface horizons amended with urea, phosphates, and other manipulations.**

- **There is a need for new quantitative information on the significance of C credits in deep soils resulting from manipulation.**

# Approach:  Intermediate-Scale Setup




**Utilize undisturbed pedons at ORNL. Provides an experimental scaleup closer to field conditions by encompassing new phenomena and allowing for multi-dimensional flow and transport.**

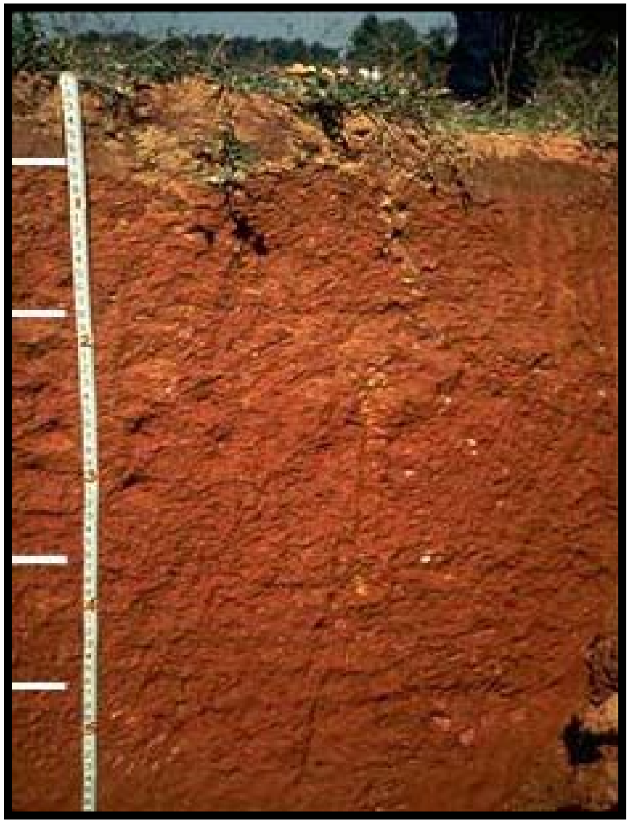
**Allows for manipulation and control of solute transport behavior for defining coupled processes that are operative at the field-scale.**

**Multiporosity sampling capabilities as a function of depth.**

# Instrumented pedons available on two soil orders

Inceptisol

Ultisol



**Undisturbed pedon facilities are available on both an Ultisol and an Inceptisol. They have well structured subsoils that consist of a complex continuum of pore regimes ranging from macropores at the mm scale to micropores at the sub-Fm scale.**

**The pore structure of the media is hydrologically interconnected where water and solute mass can move from one pore class to another. The media is heavily coated with Fe-oxides and thus has a high geochemical reactivity.**

# Initial approach

**Storm event monitoring of indigenous organic C and associated solutes as a function of depth in both the Ultisol and Inceptisol pedons during 2003 and 2004.**

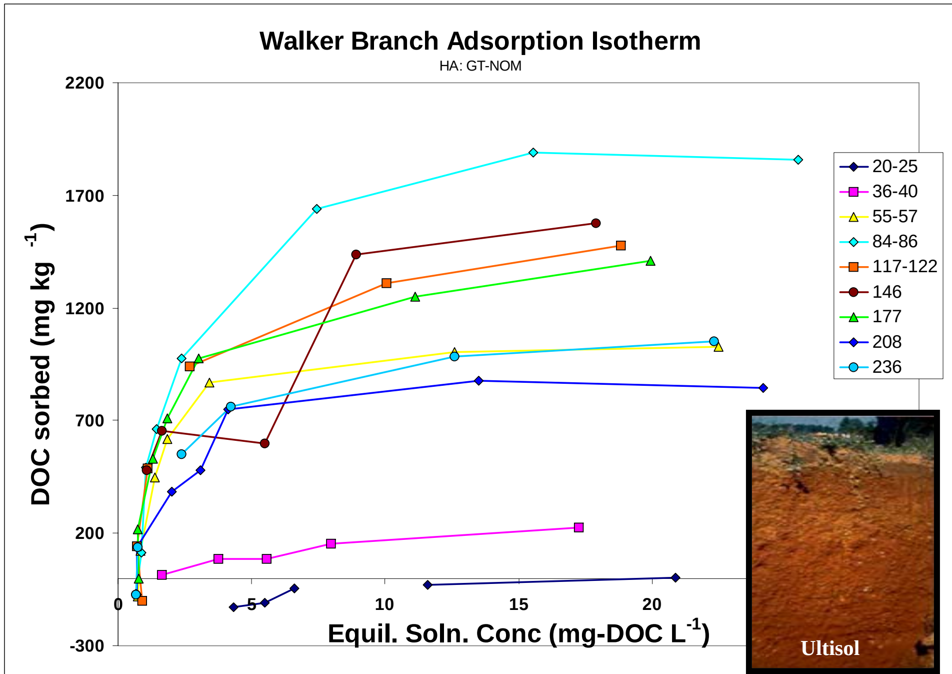
**Organic C and solute fluxes were quantified in macro-, meso-, and micropore domains during storm drainage through the profiles.**

**Pore water was frequently fractionated into hydrophilic and hydrophobic acid and neutral species and analyzed for its aromaticity.**

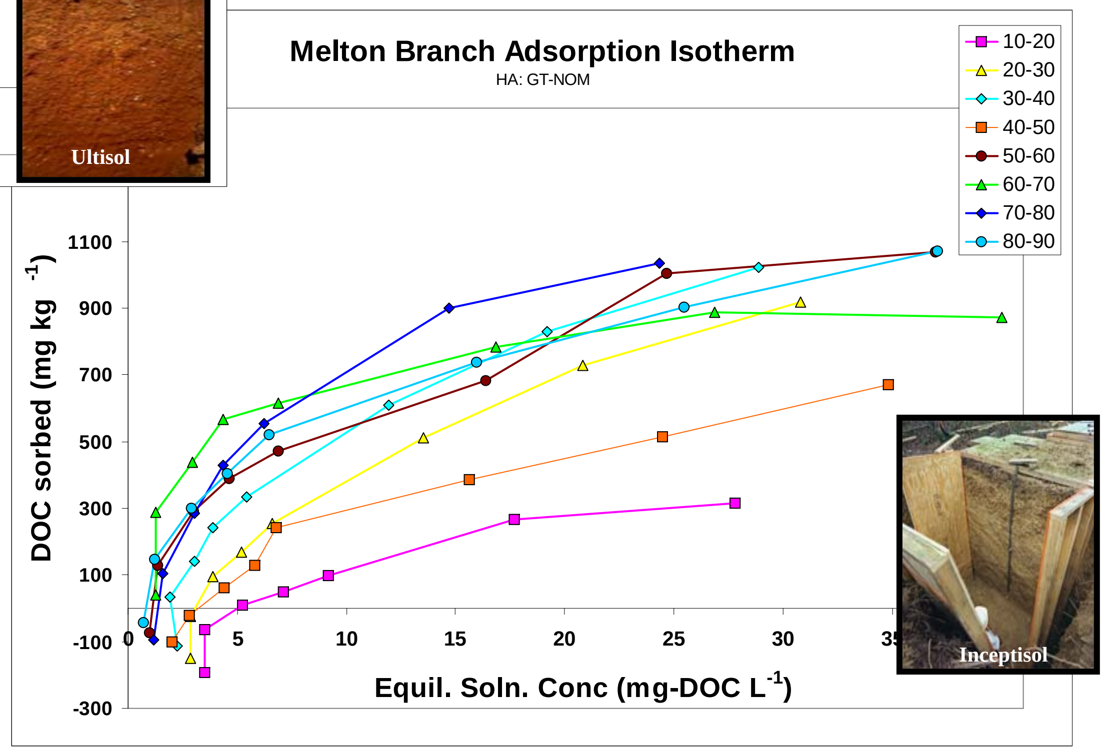
**Characterization of select physical, chemical, and mineralogical properties of the pedons.**

**Organic C sorption isotherms were also performed on soils acquired from the pedons as a function of depth.**

# Organic C sorption on pedon soils

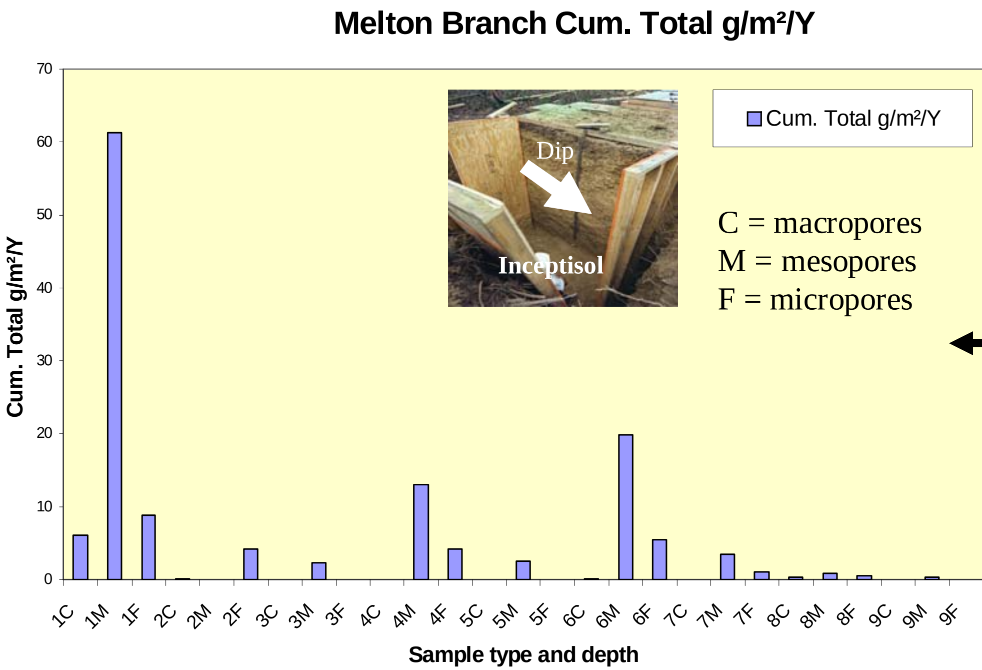



Batch sorption isotherms on soils from the pedons suggested that Ultisols tended to sorb more organic C as a function of depth relative to Inceptisols.



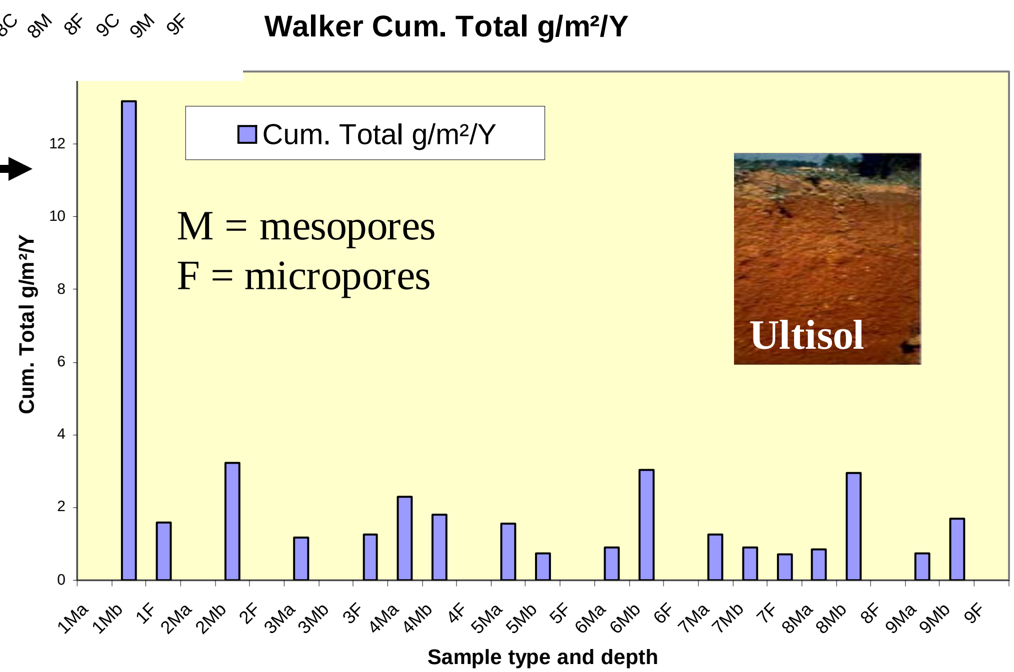

Variability in organic C sorption was a function of solid phase pH, indigenous sorbed organic C, and clay content.

# Organic C flux through pedon soils




**The highly fractured Inceptisol exhibited the highest C flux during storm events which is consistent with its more rapid flow and transport characteristics and lower organic C retention capacity.**

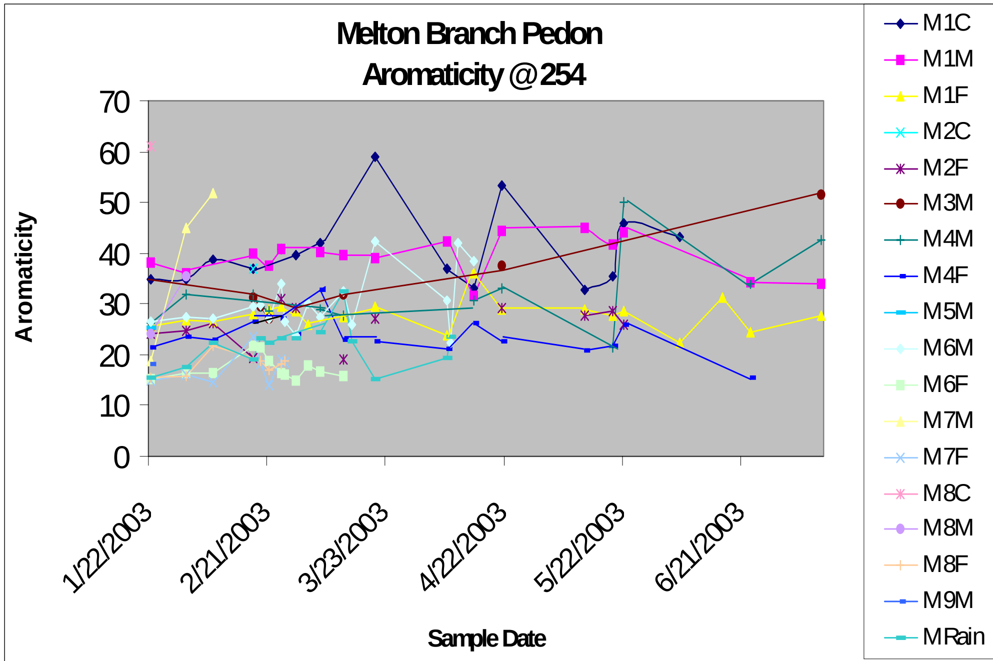
**Mesopore domains along dipping bedding planes served as conduits for organic C movement through the profile.**




**The more highly weathered Ultisol exhibited significantly lower organic C fluxes which may be related to their higher organic C retention capacity.**

**Micropore storage capacity similar to Inceptisol which may be related to similar clay content of the two soils.**

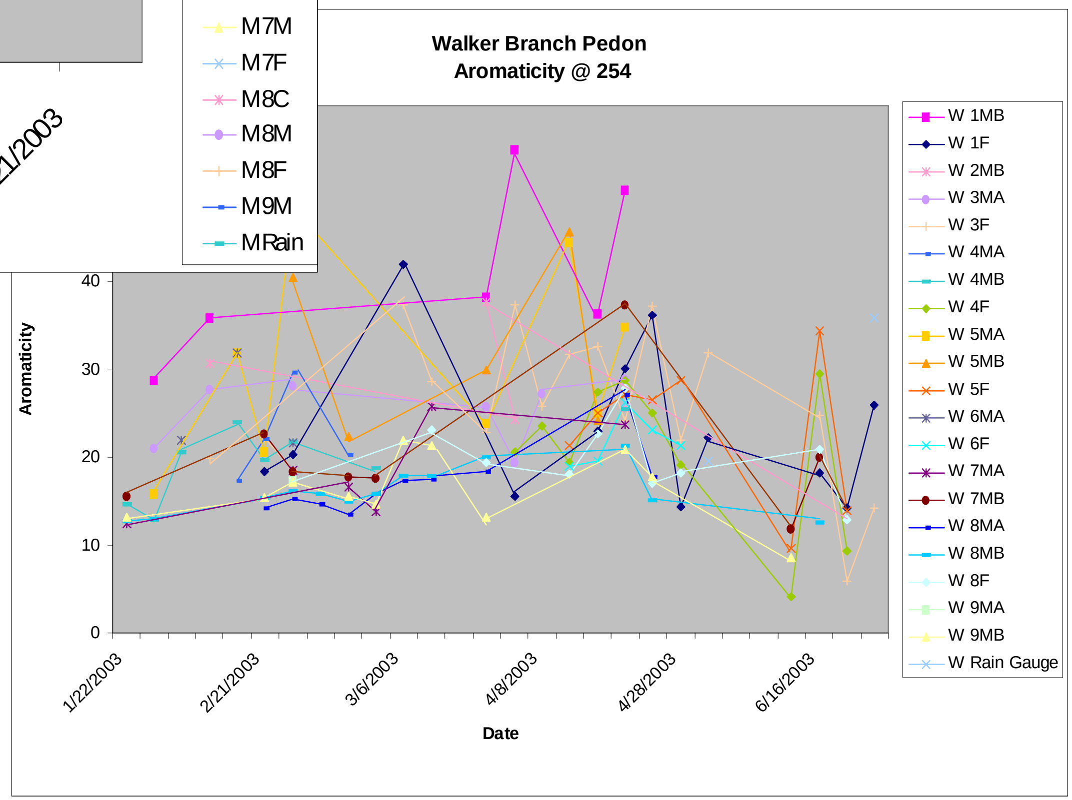
# Pore water organic C aromaticity



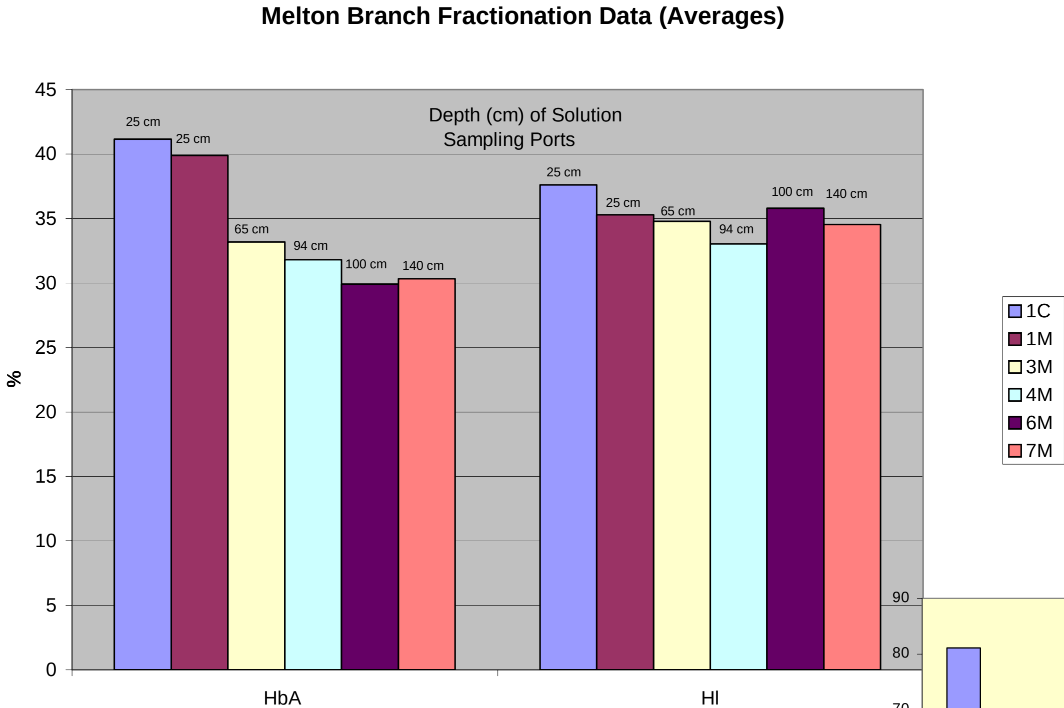

Lower aromaticity indicates less humic rich organic C in the pore water suggesting that these larger organic molecules are being preferentially adsorbed by the solid phase during movement through the profile.

Similar pore water aromaticity values observed for both the Inceptisol and Ultisol.

Both soil types show decreasing aromaticity with increasing depth suggesting preferential loss of larger organic molecules during transport.

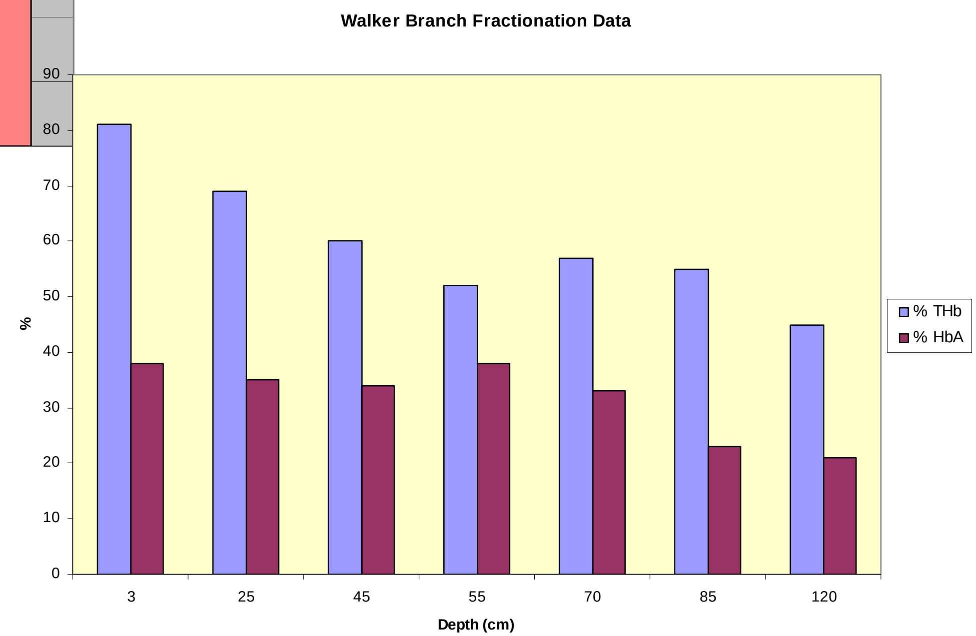


# Pore water organic C fractionation

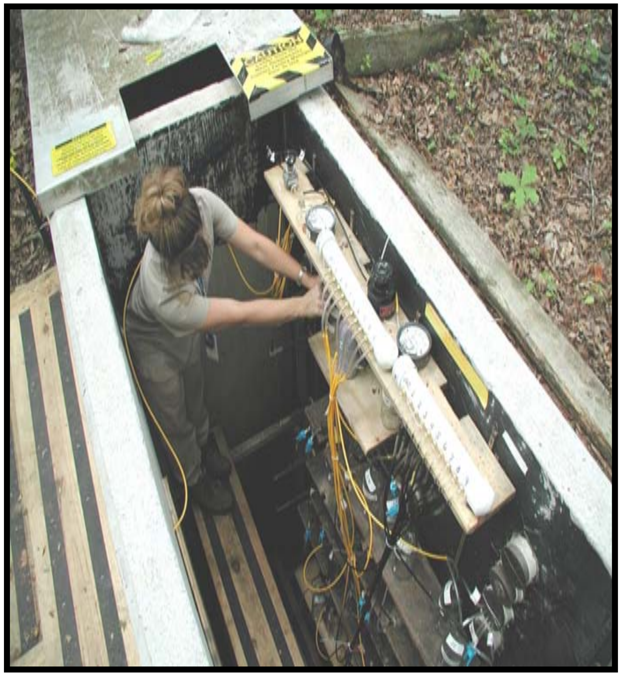



Both the Inceptisol and Ultisol show a decreasing pore water hydrophobic acid content indicating that larger organic C molecules are being preferentially adsorbed by the solid phase during movement through the profile. These results are consistent with the aromaticity results.

The Ultisol also shows a decreasing total hydrophobic content with depth suggesting preferential sorption of both acidic and neutral organic macromolecules.



**It is time for manipulation of the active organic C pools in an attempt to enhance passive organic C pools deeper in the profile (i.e. Concept 4)**



# Benefits

- Provide fundamental knowledge of the key hydrological and geochemical processes governing the fate and transport of solubilized organic C in deep subsurface environments.

- Significant advances in the current conceptual understanding and quantitative relationships needed to predict organic C inventories and budgets in soil systems.

- Provide new experimental data for quantifying the environmental and economic impacts associated with various manipulation strategies.

- Provide new quantitative information on the significance of carbon credits in deep soil resulting from manipulation.

# Publications

Peer-reviewed publications:

Mayer, L.M., L.L. Schick, K.R. Hardy, R. Wagai, and J. McCarthy. 2004. Organic matter in small mesopores in sediments and soils. Geochim. Cosmochim. Acta. 68:3863-3872.

Heuscher, S.A., C.C. Brandt, and P.M. Jardine. 2004. Using soil physical and chemical properties to estimate bulk density. Soil Sci. Soc. Am. J. (in press).

Jardine, P.M., T.L. Mehlhorn, R.M. Nesbit, D.E. Todd, J. Tarver, and C.C. Brandt. 2004. Physical and geochemical processes controlling organic C sequestration in highly weathered subsurface soils. Soil Sci. Soc. Am. J. (in preparation).

Planned:

Brandt, C.C., S.A. Heuscher, P.M. Jardine, and G.K. Jacobs. 2004. Regional scale assessment of organic C sequestration potential in deep subsurface soils.

Jardine, P.M., J. Tarver, D.E. Todd, and G.K. Jacobs. 2004. Fate and transport of storm driven organic C in structured humid region soils.

# Presentations

Adams, A., R. Harrison, C. Garten, P. Jardine, and C. Licata. 2002. Accounting for Carbon Movement and Storage in Pacific Northwest Forests. Soil Science Society of America, Nov. 10-14, 2002. Indianapolis, IN.

Kinsall, B., C. Brandt, H. Gibbs, M. Post, and P. Jardine. 2002. Regional Estimation of Carbon Immobilization in Subsurface Soils. Soil Science Society of America, Nov. 10-14, 2002. Indianapolis, IN.

Adams, A., R. Harrison, R. Sletten, J. Amonette, P. Jardine, C. Licata, and F. Bouroncle. 2002. Carbon Movement and Sequestration in Fine- vs. Coarse-grained Soils of Managed Douglas-fir Stands. Soil Science Society of America, Nov. 10-14, 2002. Indianapolis, IN.

Traver, J., J. Palmer, D. Todd, and P. Jardine. 2003. Fate and Transport of Dissolved Organic Carbon in Soils from Two Contrasting Watersheds. Soil Science Society of America, Nov. 2-6, 2003. Denver, CO.

Kinsall, B., C. Brandt, J. Palmer, and P. Jardine. 2003. Estimation of Carbon Immobilization in Subsurface Soils Using Historical Data. Soil Science Society of America, Nov. 2-6, 2003. Denver, CO.