ECOLOGY RESEARCH in DOE: An Overview

Jeff Gaffney
UALR
Environment vs Man

Man vs Environment

After taking all of human history for population to reach one billion, it took only a little over a century to reach two billion in 1930. The third billion was added in just 30 years, the fourth in only 15 years.
Keeling Curve.
DIRECT - Carbon Sequestration

DOE Fossil Energy – CO₂ direct sequestration from power plants

Capturing Carbon - Dolomite, Deep Ocean, Using it for Enhanced Oil Recovery, etc.

National Energy Technology Laboratory - NETL

http://www.netl.doe.gov
“Microbes and plants play substantial roles in the global cycling of carbon through the environment. The Office of Science’s Biological and Environmental Research program continues to leverage new genomic DNA sequence information on microbes important to the global carbon cycle by characterizing key biochemical pathways or genetic regulatory networks in these microbes. Research in genomics and biological and environmental research are conducted at the universities and national laboratories supported by the Office of Science.”

http://www.doe.gov/sciencetech/carbonsequestration.htm
Introduction
Gary Jacobs
Oak Ridge National Laboratory
March 19, 2003

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
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
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

\[ C = 59.8 + 59.2(1 - e^{-0.0104t}) \]

\[ r^2 = 0.98 \]
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

- Non-aggregated
  - Slaking $\Rightarrow$ POM, silt & clay
- Inside macroaggregates outside microaggregates
  - Microaggregate isolator $\Rightarrow$ POM, silt & clay
- Inside microaggregates
  - Dispersion $\Rightarrow$ POM, silt & clay
- Acid hydrolysis
  - Silt & clay
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
- Particulate organic matter colonized by saprophytic fungi
- Silt-sized aggregates with microbially derived organomineral associations
- Plant and fungal debris
- Fungal or microbial metabolites
- Biochemically recalcitrant organic matter
- Clay microstructures
Grassland type influences soil C accrual

**P** < 0.05, **P** < 0.01, ***P** < 0.001 based on paired t tests.

Repeated measure of marked sampling sites

**Prairie:**
Warm-season C4 grasses

**Pasture:**
Cool-season C3 grasses

Age (y)
1--15 4--18 7--21 10--24 13--27

1985 1999

*P* < 0.05, **P** < 0.01, ***P** < 0.001 based on paired t tests.

0-10 cm depth

⇒ 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
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

DNA fingerprinting shows bacterial community structures recover faster than fungal communities
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
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: 1,607
- 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

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 CO$_2$ and greenhouse gas accounting

Agriculture
- Tillage
- Fuel
- Fertilizer/pesticides
- Lime, seeds
- N$_2$O, CH$_4$

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

Analyzing economic implications (Agricultural Sector Model)

Management effects on C and N stocks

Puget et al.

<table>
<thead>
<tr>
<th></th>
<th>Soil C (Mg ha(^{-1}))</th>
<th>Soil N (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old growth forest</td>
<td>65</td>
<td>5.8</td>
</tr>
<tr>
<td>Meadow (Hayed field)</td>
<td>49</td>
<td>4.8</td>
</tr>
<tr>
<td>Plow till corn</td>
<td>41</td>
<td>3.5</td>
</tr>
<tr>
<td>No till corn</td>
<td>52</td>
<td>5.6</td>
</tr>
<tr>
<td>No till corn-soybean</td>
<td>47</td>
<td>5.3</td>
</tr>
</tbody>
</table>

- 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
- \(^{13}\)C analysis revealed that corn residues represented about \(\frac{1}{2}\) the C in PT corn while it represented >90% in NT corn
Integrating soil and biological processes at landscape scale through simulation modeling

EPIC 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 (Izaurralde 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.

Representative EPIC modules:
- C, N, & P cycling
- Operations
- Soil layers
- Erosion
- Runoff
- Solar irradiance
- Wind
- Precipitation
- Plant growth
- Pesticide fate

Williams (1995)
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-CO$_2$ gases (e.g. N$_2$O) will be available in near future

Land use pattern in NAEW region:
Forests, meadows and cropland
6. Perform Economic Analyses

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

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

跂 Economic models require a cost per ton calculation

跂 Cost per ton should include:

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

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

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

\[
\text{Social cost per ton} = \frac{(\text{PDC} + \text{PAIC} + \text{MTC} + \varphi*\text{GC} - \text{CB})}{\Delta \text{GHGO}*(1-\text{DISC})}
\]
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
GENOMES TO LIFE- GTL

Simplified Global Carbon Cycle
Atmospheric Carbon Net Annual Increase
3 – 4 GtC/y

Net terrestrial uptake
0 – 1

Fossil fuels, cement, and land-use change
6

Net ocean uptake
2

Physicochemical exchange and biological pump

Surface ocean
(1000)

Deep ocean
(38,000)

Atmosphere
(600)

Plant biomass
(500)

Microbial decomposition

Respiration

Soil carbon

Soil
(2500)

Rock
(70,000,000)

Fossil pool
(20,000)

Reactive sediments
(3000)

Photosynthesis

Carbon Cycling and Sequestration: Goals and Impacts

Improved understanding of key feedbacks and sensitivities of biological and ecological systems and accelerated incorporation into climate models will reduce uncertainties in assessments of climate change.

Knowledge of the carbon cycle will allow evaluation of carbon-sequestration strategies and alternative response options.

Development of sensors and monitoring techniques and protocols will allow use of these sensitive ecosystems as sentinels for the effects of climate change.
Ocean Microbes...Monitors of Change
Gaps in Scientific Understanding

- What happens to carbon in the oceans, and how is it portioned among various life forms?
- How does this portioning vary in rate as a function of location, depth, salinity, nutrient availability, temperature, proximity to population centers and coastlines, currents, and seasons?
- How far do carbon and carbon dioxide migrate from their “points of entry” into the ocean, and what impacts their travel and processing?
- What are the elements of the biological pump?
- What happens to growth rates of phytoplankton as a function of carbon entry into the oceans in light of the variables noted above?
- What would happen to carbon absorption if growth rates for phytoplankton were altered either up or down?
- What are the dynamic community structures of ocean microbes, and how do they impact carbon processing?
- How reversible would be the effects of actions that we might take to alter ocean carbon sequestration (and on what time scales)?

http://genomicsgtl.energy.gov/benefits/microbialocean.shtml
Scientific and Technological Capabilities Required

- Metagenomic approaches to aid in sifting through millions of genes and determining which proteins are produced by ocean communities and when.
- Capacity to make and study the proteins determined by the ocean’s metagenome to understand ocean microbial functionality and processes. Because these microbes are essentially unculturable, protein analysis initially will be achieved only by synthesis directly from genome sequence. A high-throughput approach would permit simultaneous, highly parallel production and characterization tests on hundreds of thousands of proteins.
- Molecular tags (or affinity reagents) for proteins with established critical roles to use as probes for determining the structure and function of natural ocean ecosystems.
- New sampling and analysis tools to investigate the natural dynamics of relationships among microbial, biogeochemical, and physical processes.
- Technologies to measure environmental responses, including ecogenomic sensors of sentinel organisms; biochemical assays of cells, communities, and ecosystems; and environmental assays.
- Detailed studies of proteins, multimolecular machines, and metabolites to aid in understanding key microbial responses in terms of photosynthesis, transporters, and biomineralization processes; development of functional assays and technologies, including imaging, to measure system responses.
- Information on microbial mechanistic behaviors (cellular, community, ecosystem) for incorporation into more-accurate climate models.
- Database of genes, pathways, microbes, and communities to explore the structure and function of ocean ecosystems, and, in particular, the roles of ocean microbes in carbon processing and their impact on global climate processes.

Terrestrial Microbial Communities

Diagram showing the flow of CO₂ from plant respiration, soil respiration, and photosynthesis, and the interaction with organic matter, microbes, and soil organic carbon.
Gaps in Scientific Understanding

- How do microbes contribute to carbon transformation in soils, and what is their potential for sequestering meaningful amounts of carbon (gigatons per year) in more stable forms? This knowledge will provide decision makers, including the public, with information on designing and evaluating options for responses to potential climatic effects of future carbon-based energy production.

- How do microbial genomes adjust mechanistically to climate change? This understanding will allow more realistic prediction of future climate-change effects (or explain effects of recent climate change) on the structure and functioning of ecosystems.

- What is the genomic-mechanistic basis for biological feedbacks to the climatic system brought about through the terrestrial carbon cycle? The potential exists for significant releases of CO2 or CH4 to the atmosphere in response to rising temperatures and changes in precipitation.

- With a “simple” understanding of the underlying biology of ecosystems, how can we develop a modeling framework to put systems biology information into a usable context for predicting feedbacks to climate and atmospheric CO2?
Scientific and Technological Capabilities Required

- Methods to understand processes by which carbon is transformed into long-lived forms and to design technical and management strategies for enhancing advantageous processes and mitigating negative responses.

- Methods to measure biomolecular inventories correlated with environmental conditions; characterizations of microbial-system interactions with soils, rhizosphere, and plants; and imaging of microbial functional activities (e.g., proteomes and metabolomes) at cellular and community levels—all to understand processes that impact production of GHGs (CO2, methane, nitrous oxide, and dimethyl sulfide).

- Methods to detect and measure microbial responses to manipulation of plant inputs to the carbon cycle, to human inputs to soils, and to other environmental changes.

- Methods to use microbes as sentinels of climate-induced change in the environment. Research will determine the biomarkers that correlate with specific environmental parameters. Biomarker signatures include combinations of RNAs, proteins, metabolites, and signaling elements; community genomic makeup brought about by population shifts; and functional assays.

QUESTIONS?