

Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems

*A Collaborative Research Center Among
Investigators from*

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

Argonne National Laboratory

Scientific investigations at multiple scales to
generate the knowledge needed for enhancing
carbon sequestration in terrestrial ecosystems in an
environmentally acceptable manner

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Carbon Dynamics
+
Biogeochemistry

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Terrestrial Biosphere and the Ocean

Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems

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Abstract

The **Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems** is a distributed research center led by Oak Ridge National Laboratory and Pacific Northwest National Laboratory with Argonne National Laboratory as a collaborating partner. The Center conducts new basic research and analyzes existing knowledge and experience to develop the scientific understanding needed to evaluate the feasibility of environmentally sound strategies for enhancing carbon sequestration in terrestrial ecosystems. The Center focuses on scientific advances that could lead to methods to sequester substantial amounts of carbon in terrestrial ecosystems during the next 20 to 50 years. Carbon sequestration can be achieved with the use of existing management practices, particularly forest plantation nutrition, restoration of grasslands and forests on existing cropland, and improved cropping systems management. A primary objective of the Center is to discover the link between the critical pathways and mechanisms for creating longer-lived C pools and ecosystem management strategies. Laboratory and field research is integrated across spatial scales and includes tasks focusing on sequestration processes at the ecosystem/landscape, ecophysiological, and interfacial/molecular scales. Integrated assessment research in the Center uses results of the scientific activities to improve models of carbon sequestration in terrestrial ecosystems, and to predict environmental impacts of that carbon sequestration. Results from Center research have immediate application to other DOE programs, especially Fossil Energy, as well as other federal agencies, and public and private organizations. Center results are communicated to interested organizations in accessible forms.

ABBREVIATIONS

ANL	Argonne National Laboratory
CRP	Conservation Reserve Program
DEM	Digital Elevation Model
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
EMSL	Environmental Molecular Science Laboratory
FTIR	Fourier Transform Infra-red Spectroscopy
GIS	Geographic Information System
GPP	Gross Primary Production
NERP	National Environmental Research Park
NEP	Net Primary Production
NMR	Nuclear Magnetic Resonance
OM	Organic Matter
ORNL	Oak Ridge National Laboratory
Pg	Petagram (10^{15} g)
PNNL	Pacific Northwest National Laboratory
POM	Particulate Organic Matter
SANS	Small Angle Neutron Scattering
SAXS	Small Angle X-ray Scattering
SOC	Soil Organic Carbon
SOM	Soil Organic Matter

1. Introduction and Objectives

Earth's atmosphere is being significantly altered by human activities. Fossil fuel use and land-use changes (most notably deforestation and conversion of natural ecosystems to cropland) are driving the ongoing, rapid rise in atmospheric CO₂ and other so-called greenhouse gases. This rise is causing, or has the potential to cause, regional and global climatic and related environmental changes including global warming, altered patterns of precipitation and cloud cover, sea level rise, and perhaps increased frequency and severity of extreme weather events. The impacts of these environmental changes might be mitigated if the rise in CO₂ and other greenhouse gases can be slowed or stopped. Four nonexclusive strategies to slow CO₂ increase are apparent: (1) reduce fossil fuel emissions and land use changes that result in CO₂ release, (2) capture and sequester CO₂ at point sources, (3) store more C in plants and soils with appropriate terrestrial ecosystem management,¹ and (4) increase C uptake and storage in oceans.

We propose to establish a multi-laboratory (ORNL/PNNL/ANL) distributed **Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems** (the Center). Through collaborative partnerships, the Center will conduct basic research and assess existing knowledge and experience to develop the scientific understanding required to furnish and test the feasibility of environmentally sound strategies for *enhancing* C sequestration in terrestrial ecosystems. Our focus is on approaches to sequester substantial amounts of C in terrestrial ecosystems during the next 20–50 years as a way to offset some fossil fuel releases and “buy time” for the development and implementation of direct solutions to the underlying problem of large CO₂ releases from human activities. The ultimate potential for terrestrial C sequestration is unknown because of fundamental gaps in our understanding of the controls on C fluxes and storage at the global, landscape, ecosystem, and molecular/interfacial scales and how these are interrelated. Nonetheless, we believe that C sequestration in terrestrial ecosystems during the coming decades can be accomplished most expeditiously through the use of existing management practices in forests, crops, and possibly grasslands. Our challenge is determining how to optimize those management practices to enhance C sequestration in the U.S. and elsewhere without significantly diminishing, and perhaps even increasing, forest and crop yield and other desirable ecosystem goods and services.

To meet our goals, Center activities will focus on the scientific basis for ecosystem management strategies directed at

- Enhancing C sequestration through landscape (ecosystem distribution) management
- Partitioning C into longer-lived plant and soil pools
- Increasing the physical, chemical, and biochemical protection of soil C
- Enhancing C storage in living plant biomass

We will use research approaches that help us to

- Understand whole-system (plant and soil) C storage responses to management in various ecosystems
- Determine the molecular-scale mechanisms responsible for C partitioning among pools and the protection of those pools as they are influenced by management
- Quantify effects of microbial community structure and function, especially the ratio of bacteria to fungi, on the recalcitrance of soil C
- Relate management practices to SOM partitioning among alternative pools and SOM transport

Overarching themes are to

- Define the management practices that affect storage and longevity of C in ecosystems
- Compare effects of management for yield and management for C storage in terms of actual quantities of C sequestered
- Use mechanistic understanding and simulation models to extrapolate results of C sequestration experiments to other sites and ecosystems to support fluxes and the scientific bases for implementation of C sequestration strategies

¹ We have already conducted planning work in this area, in part through organization and implementation of the PNNL/ORNL/CAST workshop “Carbon Sequestration in Soils: Science, Monitoring and Beyond” (Rosenberg et al. 1999), 3–5 December 1998, St. Michaels, MD, and through our central contributions to the DOE program planning activity “Working Paper on C Sequestration Science and Technology” (USDOE 1999).

Our research at the landscape scale will use existing data from remote sensing to develop new approaches for characterizing existing C stocks and soil N availability that can identify key properties that correlate with the greatest potential for influencing C sequestration through management. Research initially targets the Oak Ridge NERP, for which adequate extant data and geographical information are available, and experimental agroforestry sites.

Research at the ecophysiological scale will evaluate existing data and make new measurements of plant and soil C changes associated with forest nutrient management, with low-input cropping systems, and with grassland restoration from croplands. The focus will be on process studies. Data will be used to calibrate existing ecosystem models and as input to both landscape and integrated assessment models.

Research at the molecular/interfacial scale will provide mechanistic understanding of results from “higher” levels. It will improve understanding of the influence of microbial and interfacial processes on partitioning of C to labile, recalcitrant, and soluble pools under different ecological conditions and management practices. This research will provide explanations of results at the ecophysiological scale, and also provide new understanding of C partitioning mechanisms (e.g., inorganic C formation, movement of soluble C) that may reveal previously undiscovered pathways that could be exploited to enhance C sequestration.

All Center activities support understanding of environmental impacts of ecosystem management for enhanced C sequestration. Our immediate focus is on U.S. C sequestration potential, but results will facilitate global analyses as well. Center findings will be linked to activities at DOE/Fossil Energy, other agencies, and the broader scientific community.

2. Background and Rationale

Forest clearing for agriculture converts aboveground biomass to CO₂ through burning and/or conversion of living plant biomass to decomposing litter. Moreover, cultivation of soil generally converts a large fraction of the SOM to CO₂ (Davidson and Ackerman 1993). Past agricultural expansion therefore added large amounts of CO₂ to the atmosphere (Wilson 1978). Previous losses of C from terrestrial ecosystems due to land use change can very likely be “recaptured” and C restored in those ecosystems with proper management. For example, the restoration of soil C to pre-cultivation levels in croplands represents one possible target for C sequestration. But cropland soil C pools might even be increased above pre-cultivation levels through improved soil management.

There is considerable information on effects of reduced tillage on soil C recovery in cropland and the C storage that can occur with the reestablishment of native ecosystem types. In addition, forests are presently sequestering C in the United States and other mid-latitude nations (Dixon et al. 1994). This is, to some extent, a recapture of CO₂ released during previous disturbance (logging or conversion to agriculture), but rising CO₂, increased N deposition due to anthropogenic releases to the atmosphere, and even possibly recent climatic changes are stimulating NPP and ecosystem C storage, so that present C sequestration rates may *exceed* rates expected from forest regrowth alone (e.g., Houghton 1996, Houghton et al. 1998).

Our conceptual model says that we can enhance C sequestration in terrestrial ecosystems by (1) increasing the inputs of C (GPP and NPP) to an ecosystem, (2) partitioning C to longer-lived pools, and/or (3) increasing the longevity of (possibly existing) C pools. Science in support of enhanced C sequestration through these three mechanisms is new, but it builds on a rich body of knowledge and decades of research on aboveground and belowground processes in forests, crops, and grasslands. Present information on mechanisms controlling C partitioning and storage at multiple scales is insufficient, however, to decide *a priori* how to enhance C sequestration in terrestrial ecosystems in efficient and environmentally acceptable ways.

2.1 What is the Potential for Carbon Sequestration?

Our lack of quantitative understanding is illustrated by the wide range of some recent estimates of C sequestration potential through forest, crop, and pasture management in the U.S. (Table 1). This is complicated by the fact that values for forests ignore soil C. Nonetheless, the potential for increased C storage in the U.S. through ecosystem management is certainly quite large. Existing forestry practices might be able to sequester 0.28 to 0.53 Pg C/year in wood, and known crop management techniques

might sequester an additional 0.07 to 0.18 Pg C/year in soil. Estimates for enhanced C storage potential through directed rangeland management are less certain, and the 0.01 Pg C/year value for pastureland is greatly limited in precision and generality by a lack of data. For comparison, the U.S. released slightly more than 1.4 Pg C from fossil fuel combustion in 1996 (Marland et al. 1999).

Even without consideration of new technologies (e.g., biotechnology) or the restoration and management of degraded lands and deserts, it is clear that significant quantities of C (and a large fraction of fossil emissions) could be sequestered in presently managed terrestrial ecosystems over the next 20 to 50 years. Similarly, at the global scale, by sequestering C in cropland soils alone at rates thought possible with existing management tools, significant reduction in the rate of CO₂ rise might be realized (Fig. 1). But, these analyses must be improved and the mechanisms of C sequestration must be better understood. Scientific research activities in the Center are focused on providing the knowledge and tools required to refine these estimates and to understand how to realize the highest C sequestration achievable in an environmentally acceptable way.

Table 1. Potential C Sequestration from Forest, Crop, and Pasture Management During the Next 20 to 50 Years in the U.S. (after Birdsey et al. 1992, Hair et al. 1996, Bruce et al. 1998, Lal et al. 1998)

Strategy	Average C sequestration (Pg C/year)	
	Low estimate	High estimate
Forestry		
Converting marginal crop/pasture to forest	0.033	0.119
Increasing timber growth on timber land	0.138	0.190
Growing short-rotation woody crops for energy	0.091	0.180
Increasing tree numbers/canopy cover in urban areas	0.011	0.034
Planting trees in shelter belts	<u>0.003</u>	<u>0.006</u>
Total (wood only)	0.276	0.529
Cropland		
Cropland conversion to CRP (excluding agroforestry)	0.006	0.014
Conservation tillage/residue management	0.035	0.107
Altered cropping systems (fertilizer, cover crops, manures, irrigation)	<u>0.024</u>	<u>0.063</u>
Total (SOC only)	0.065	0.184
Pasture management	0.010	0.010
Soil Restoration (eroded land, mine land, salt affected soil)	0.011	0.025
Total Forestry (wood) and Cropland/pasture (soil)	0.362	0.748

2.2 How Can the Potential Carbon Sequestration be Realized?

Present ecosystem management practices are generally aimed at yield of a desired product, such as wood, grain, or forage. The same management practices may contribute to C sequestration, but they might also limit the potential for *total system* C storage. Center activities will address how management for yield is related to management for whole-system C sequestration, and how management can be optimized for most effective C sequestration. Fundamental understanding of the physiological, microbial, and interfacial processes responsible for changes in C sequestration is critical to development of generalized management strategies across a range of ecosystems. Thus, we will study processes and mechanisms related to gains or losses of C in response to several management practices used to enhance yield as well as manipulations thought to enhance C sequestration.

Results from the long-term Rodale Farming Systems Trial (Liebhardt et al. 1989, Drinkwater et al. 1998) document significant accumulations of soil C under complex rotations including legume cover crops. Significant increases in organic C quality, aggregate stability, and microbial activity resulted from treatments that improved C and N retention. The hypothesis that agricultural practices must simultaneously enhance C and N retention may also be extended from plot or field scales to processes that operate at landscape scales. Conversion of croplands to agroforestry or the production of short-rotation

woody or herbaceous energy crops on once agricultural land offers considerable potential to sequester C in both plants and soils. Conversion of marginally productive, erosive, or otherwise sensitive components of agricultural lands to perennial vegetation or as part of 5-year- to 20-year-long rotations of trees and other crops offers additional opportunities for environmentally friendly C sequestration.

Management strategies to increase soil C storage over the next 20 to 50 years must focus on increasing the size of C pools with intermediate-term residence times (i.e., 10 to 100 years). Active pools turn over rapidly (months to several years) and comprise only a small fraction of total SOC. Although increases in the passive pool (residence times of 100 to more than 1000 years) would be ideal, little is known about the potential for increasing the size of this pool in a given soil. Furthermore, the passive pool may cycle too slowly to respond to manipulations for C accrual over the next half century. The physical basis for the intermediate-term pool must be identified so that its size.

3. Research Framework

Figure 2 conceptually represents the underlying theme of the Center: **Discover the links between the critical pathways and mechanisms for creating larger, longer-lived C pools and thereby optimizing ecosystem management strategies.** Research is focused on the most critical issues and highest priority uncertainties by carefully linking our conceptual model to hypotheses with a direct feedback of scientific results to analyses of C sequestration potential and impacts. To accomplish this linking requires that research at molecular/interfacial scales be related to larger scale analyses. Therefore, our research targets key unknowns in the C allocation pathways that must be understood to improve linkages among adjacent scales. The ultimate focus is on C sequestration at the landscape/regional scale, and this is based on the premise that land-use and ecosystem management offers the greatest potential for enhancing C storage in terrestrial ecosystems.

3.1 Integrated Research Approach

Figure 3 illustrates schematically how the Center will approach the integration of research. Research is guided initially by what we believe to be the most important issues as stated in this proposal. This leads to the identification of key hypotheses that must be addressed at multiple scales. Sites of opportunity having managed ecosystems or chronosequences that can yield insights into management issues are then selected for study. The scientific results are used to refine our models and assessment activities to allow the potential for, and possible impacts of, C sequestration to be addressed. Critical research needs are reevaluated as new insights are gained, so the research direction of the Center will be adjusted as new scientific discoveries dictate.

3.2 Research Sites

Center research will address four broad management strategies that have potential for C sequestration at a particular location. These are (1) fertilization of managed forests; (2) conversion of cropland to native grassland (restoration); (3) conversion of conventional crop management to cropping systems based on legumes, reduced tillage, and/or cover crops; and (4) introduction of agroforestry to croplands. The overall *net* C storage, including externalities involving C fluxes associated with management activities *per se* are considered in part 5 of this proposal.

Selection of research sites is driven by our science objectives and our belief that the best opportunities for enhancing C sequestration in terrestrial ecosystems lie in managed forests and croplands and in the restoration of natural ecosystems such as forests, grasslands, and wetlands. We choose to conduct Center research at existing (completed or ongoing) field experimental sites. Using appropriate ongoing experiments for our C sequestration research rather than beginning a series of new experiments has two major advantages: (1) it greatly reduces the cost of conducting the research and (2) it allows us to take advantage of already long-term manipulations (including chronosequences) and hence gain insights into the longer time course of C sequestration responses to management. A key feature of our proposed activities is the linkage of field and laboratory studies and the integration of research across multiple spatial scales. Research sites were, and are being, chosen to concentrate on environmental gradients, ecophysiology and soil biogeochemistry, and chronosequences of land use to aid evaluation of results projected over the coming 20- to 50-year time frame.

Two broad classes of research sites will be used (Fig.4). The first is “Primary sites,” where Center research will span multiple spatial scales and will address several hypotheses. Present primary sites are:

- Industry forest nutrition cooperatives. We will use existing fertilizer trial sites established by industry forest nutrition cooperatives to assess whole-ecosystem C pools and fluxes in response to nutrient management, including leaching of organic C following urea and phosphate applications. Center activities will expand ongoing work directed at wood production to include whole-ecosystem C sequestration. Multiple sites in the Douglas-fir (Pacific Northwest) and loblolly pine (Southeast) cooperatives will be used (see section 4.2.1.1). Extensive soil, vegetation, and climate data are available from the forest industry cooperatives for research sites established on a range of soil types over the last 30 years. Cooperation with the forest industry research sites will be established through subcontracts with the managers of the forest industry cooperatives addressing nutrient management (i.e., subcontracts with Dr. R.B. Harrison, Univ. of Washington, and Prof. H.L. Allen, North Carolina State Univ.).
- Fermilab NERP. We will focus on grassland restoration from cropland at the Fermilab NERP (Batavia, IL), which has a chronosequence of prairie restorations dominated by warm-season C4 grasses on soils cultivated for over 100 years. Plots have been established almost every year since 1975. In addition, plots dominated by cool-season C3 grasses were established in 1971 and 1993, and other areas are maintained in cropland and woodland/forest, allowing comparisons among herbaceous and woody ecosystems. Soils are mostly silt loam Mollisols and Alfisols from closely related series. Center members (J.D. Jastrow, R.M. Miller) have extensive supportive data and experience with the site and restoration program. Dr. Rod Walton of the Fermilab has agreed with the concept of the proposed research and will work with the Center to make this NERP available.
- Rodale Institute. We will carry out mechanistic soil-C-related research at the Rodale Institute (RI) (Kutztown, PA). The RI manages cool-climate, long-term, low-input (organic), experimental crop rotation plots (Liebhardt et al. 1989). Some basic C sequestration research has already been conducted at that site (Drinkwater et al. 1998), but we will extend that research to include studies of C storage/longevity mechanisms at the micro/molecular scale. Our mechanistic research component will facilitate extrapolation to other sites and make possible more precise predictions of long-term C storage with low-input cropping systems. Dr. L.E. Drinkwater of RI is a Center collaborator.
- USDA-ARS National Soil Dynamics Laboratory (NSDL). We will participate in the ongoing NSDL (Auburn, AL) no-till/cover crop experiment. Soil C accumulation and the mechanisms supporting that accumulation will be the focus of Center activities at the site. Two cropping systems on experimental soil bins at the Lab are used: (1) a low C input (conventional) rotation and (2) a high C input (no-till) rotation. The conventional system uses soybean and grain sorghum rotated each year, with conventional tillage and winter fallow. The no-till system also rotates soybean and sorghum, but without tillage and with three fall/winter cover crops (wheat, crimson clover, and sunn hemp) that are also rotated. In addition, the experiment uses open-top chambers to impose ambient and twice-ambient atmospheric CO₂ levels on both cropping strategies. Thus, annual NPP is enhanced both by cover crops and by CO₂ enrichment. Relationships between NPP and C sequestration can therefore be studied through two mechanisms of NPP enhancement that do not involve mineral N fertilization. The experiment is conducted on Decatur silt loam (clayey, kaolinitic, thermic Rhodic Paleudult) in an area with a relatively warm climate. The Principal Investigator, H.H. Rogers, is a Center collaborator.
- Oak Ridge NERP. The Oak Ridge NERP will be used to address mainly landscape scale issues. In 1942, the Manhattan Project selected an isolated area of some 20,000 ha and moved out all the inhabitants within the course of a few weeks. At the time, the landscape was a mosaic of field, pasture, and wood lots. The Oak Ridge NERP is an ideal site for testing and analyzing the spatial and temporal variations in soil N availability and its influence on C sequestration. High quality aerial photographs are available from the 1920s, documenting land-use patterns more than a decade prior to abandonment, at the time of abandonment, and periodically since then, with satellite imagery becoming available in the 1970s. As a result of the site characterization and research, the NERP has become one of the most intensively studied landscapes in the eastern U.S. Since 1942, most of its 20,000 ha have been undergoing forest succession, from a variety of starting points and at a variety of rates. Hardwood stands, pine stands, and old field comprise approximately 51, 30, and 8% of the Oak Ridge NERP (Boyle et al. 1982). Near the center of the area is DOE’s ecosystem project, Walker Branch Watershed,

which is a long-term research site for studies of forest C balance and nutrient cycling (Johnson and Van Hook 1989).

The second research site type is “Specific task sites,” which will be used mainly to study specific hypotheses. Present specific task sites include:

- USDA Forest Service Savannah River Institute. The Short Rotation Woody Crops (SRWC) Cooperative Research Program was established in 1997 at the DOE’s Savannah River Site (Aiken, SC) in cooperation with the USDA-Forest Service Savannah River Institute. A short-rotation plantation is scheduled for planting this year to determine the mechanisms that control above- and below-ground productivity. The project will be a three-way factorial split-plot design including species (loblolly pine, cottonwood, sweetgum, and sycamore), irrigation, and N fertilization. Irrigation will include two levels, irrigated and unirrigated. Eight fertilization treatments will be applied through micro-irrigation. The long-term study will focus primarily on nutrient cycling and the role of water and N in optimizing biomass (wood) production. Currently, neither C sequestration in wood or soils is a primary measure of the DOE/USDA study plan.
- Kansas State University (KSU). A switch from native C4 prairie grasses to C3 Eurasian pasture grasses occurred when a long-term pasture fertilization trial was established in 1945 at KSU. The site will thus enable the use of the natural abundance of stable C isotopes to quantify turnover times for process, mechanistic, and interfacial studies of soil C pools. The nearby Aldus Plots (long-term burn management trials) are located on the same silty clay loam mollisol and are suitable controls. Dr. Clenton Owensby has extensive data on biomass production for both sets of plots. In addition, Dr. Owensby will work with us to identify suitable field sites for later studies by the Center on how grazing management affects whole system C sequestration. Grazing is known to affect plant biomass partitioning; hence, different grazing strategies may influence C storage or release by the system.

Additional research sites may be added to our list of research sites as the Center matures. Such sites have not been chosen, but might include the Arid Lands Ecology NERP (Richland, WA), the Oklahoma ARM site, and the Washington State Univ. Center for Agricultural Systems Evaluation (Richland, WA). Also, Center collaborators are associated with other research sites such as the USDA National Soil Tilth Laboratory (Ames, IA) (see Section 11.4).

4. Research Plan

4.1 Ecosystem and Landscape Scale Studies

Task Leaders: W.M. Post (ORNL), R.C. Izaurralde (PNNL)

Goal. To use landscape-level research to discover how land-use changes and complex land-management systems influence C and N cycling in vegetation and soil. Research techniques will include remote sensing, land cover/use analysis, spatial analysis, direct measurements, and modeling.

Background. Although bound by a considerable degree of uncertainty, the greatest potential for C sequestration in managed ecosystems appears to be through changes and optimization of land use (Table 1). If it is hypothesized that significant increases in total C can be obtained by optimizing the use of landscapes for this purpose, then it is necessary to significantly improve understanding of land use in the context of environmental controls that regulate C sequestration. In this task, research is proposed to make substantial progress in learning how to use improved process-scale knowledge to understand C sequestration potential at landscape scales.

Land-use conversions (e.g., crop/forestry rotations, set asides, reforestation) have different effects on C storage and, even for the same conversion, effects will vary depending on a range of environmental conditions. To identify key issues and processes associated with land-use changes and management controlling C sequestration we will study landscape systems using direct measurements, spatial analysis, and modeling techniques. Aggrading forests exhibit significant spatial variability in properties such as biomass and soil C, even for a single “mature” forest type. It is not clear if transient rates of C sequestration will vary more or less than do long-term “equilibrium” amounts.

For a variety of reasons, land-use changes in the U.S. and large parts of Western Europe may be driving terrestrial C sequestration. The maintenance of soil fertility together with the use of improved cultivars, erosion control, and reduced tillage may have contributed to this effect in crops. These

technologies in combination with global economic factors combine to weaken demand for U.S. agricultural exports. Reduced land demand for agricultural production results in increased land available for purposes such as C sequestration. A return to greater diversity in farm production may also lead to synergistic impacts on C sequestration and improvement of environmental quality with little or no loss in production and profitability. Results from a 15-year study at Rodale Institute revealed substantial soil C storage with the use of complex rotations that included legume cover crops (Drinkwater et al. 1998).

Agroforestry practices also offer opportunities for C sequestration (Schultz et al. 1995) by providing opportunity to develop perennial buffering communities within arable landscapes (e.g., riparian buffers, alley cropping, windbreaks, tree/pasture systems, and forestry farming).

We propose to conduct studies of land-use conversion into forestry and agroforestry to elucidate the mechanisms that control C sequestration at the landscape scale.

Hypothesis 4.1.1 *The rate of C sequestration in an aggrading forest varies in predictable spatial patterns across watersheds as a result of link between ecosystem production and nutrient and water availability that depend on landscape position.*

Approach We will develop a database in the context of our GIS for the Oak Ridge NERP, which will include a high-resolution DEM, historical aerial photography, available satellite imagery, and spatially classified chemical and ecosystem process data based on historical research at the site. We will parameterize a GIS model of soil C storage and soil N availability at the landscape level. The GIS model of nutrient availability will be based on principles of mass balance. Our modeling approach is adapted from a “long-term concept” for calculating excess soil N on agricultural lands (Fried et al. 1976). The following mass balance equation will be solved for each pixel or mapping unit on the Oak Ridge NERP:

$$E = (A + F + M) - (U + P + D)$$

where E is potential excess inorganic soil N, A is atmospheric deposition, F is fertilizer additions, M is mineralization of organic soil N, U is plant uptake of inorganic soil N, P is physical losses (e.g., volatilization, soil erosion), and D is losses through denitrification.

Each of the parameters represents different processes affecting potential excess soil N. They will be quantified for different land-use categories and seasons. Negative values for E indicate N deficiency whereas positive values for E indicate potential excess inorganic soil N. Excess soil N in combination with low existing ecosystem C stocks present the most favorable circumstances for C sequestration. Soil N deficiencies in combination with high existing ecosystem C stocks present the least favorable circumstances.

Data needed to parameterize the mass balance model will be gathered from existing data sets, local monitoring networks on the Oak Ridge NERP, and numerous literature sources. Nitrogen uptake will be calculated from plant productivity and N requirements for different types of vegetation. All of the various determinants of potential excess soil N (E) can be combined using map algebra within the context of a GIS. Each land cover category (e.g., agricultural crops, pasture, forest, and building/road) that is identified on the Oak Ridge NERP will be parameterized to calculate potential excess soil N. Excess soil N also has implications for terrestrial emissions of other greenhouse gases (N₂O). A model based on 2-ft contour intervals is being used on Walker Branch Watershed, and a model with 5-ft contour intervals is available for the entire Oak Ridge NERP. Computer analysis of DEMs can be used to derive a topographic index $\ln(\alpha/\tan\beta)$, where α is the upslope drainage area for a given landscape cell and $\tan\beta$ is the slope across that cell. This has proven to be a good predictor of both hydrologic processes and ecosystem properties. Extensive sampling along topographic gradients has demonstrated that this index is a good predictor of a variety of plant and soil chemical properties (Garten et al. 1994). This research links with section 4.2.4 on coupled C/N cycling mechanisms.

Hypothesis 4.1.2 *Optimizing land use and enhancing biodiversity in a managed landscape through complex rotations and agroforestry methods will enhance C sequestration in soil and vegetation.*

Conversion of agricultural lands to short-rotation agroforestry is a relatively new concept in many areas of the country. Nonetheless, forest industry in the Pacific Northwest (WA, OR) have planted 25,000 ha of short-rotation hybrid poplars in the past decade, and similar activities are currently underway in the southern United States. The DOE's Bioenergy Feedstock Development Program at ORNL has worked closely with industry representatives, universities, USDA, and other federal agencies on these studies

since the early 1970s. These programmatic ties offer excellent opportunities to build on existing studies in order to better understand the C sequestration potential of agroforestry.

Approach. Our initial efforts will be focused on the SRWC at the Savannah River site (section 3.2). Our rationale for this decision is that the SRWC program is a new study and initial soil sampling prior to site preparation will provide a much-needed soil C baseline to which all future measurements can be referenced. Soil samples will be taken from across the study site to a depth of 1m. After site preparation, trees will be planted in late 1999 on a spacing of 2.4×3 m (1345 trees ha^{-1}). Individual plots will be irrigated or unirrigated, and one of eight N fertilizer levels (0 to 350 kg N ha^{-1}) will be applied. After trees are planted, a second series of soil samples will be taken as before which we hope to use to qualify soil C loss due to site preparation. Above- and below-ground measurements of tree productivity will be made annually, and C storage in wood, stumps, and coarse roots will be estimated by allometric equations. Allometric relationships currently exist for predicting leaf dry mass, branch dry mass, total aboveground dry mass, and coarse root dry mass from measured parameters of stem diameter, tree height, and height to live crown.

Also during the first year we will select another site that combines key landscape and production attributes of multiple land use and topography. Candidate sites will be characterized in terms of climate, soil and topographic features, past land use, and current management practices. In addition, several soil properties (e.g., SOM, root penetration, aggregate stability, and bulk density) will be assessed. A special consideration for site selection will be the availability of control management near or within the site selected. It is estimated that this task can be accomplished during a 4-month period in 1999. This activity will be conducted jointly with collaborators at Colorado State University, the Ohio State University, and Rodale Institute.

Upon the selection of this second site, we will characterize the soils and topographic features in detail. The procedure described by Pennock et al. (1994) will be used to identify landscape features associated with indicators of soil quality. For each landscape/use combination, small plots (microsites) will be laid out following the methodology outlined by Ellert et al. (1999), currently used at the farm level in Canada. Replicated microsites with buried markers will be established within each landscape/use combination to facilitate the study of soil and plant biomass. Use of this approach reduces the variability in observations and preserves the structure of the landscape components required for scaling-up C changes.

A minimum weather data set (radiation, precipitation, temperature, relative humidity, and wind speed) will be acquired from nearby weather stations or, if unavailable the site will be instrumented to provide the necessary data. We will seek expertise to build a DEM and soil map of the study site(s). Standard procedures will be followed to monitor the growth of herbaceous and woody plant/crop species during two growing seasons beginning in 2000. For woody vegetation these will include the use of allometric methods and direct measurements, alone or in combination. Yield will be recorded in agronomic/biomass species. Leaf area index, crop residue/litter mass, and straw/grain ratios and other relevant parameters will be measured directly or derived from other measurements.

Measurements of soil C and root biomass will follow methodologies outlined in sections 4.2.1 and 4.2.2. These include measurements at incremental depths of C and N in soil (total, light and heavy fractions, microbial biomass) and roots. The results will be expressed on a mass-equivalent basis. Detailed soil sampling will be conducted in spring 2000 and fall 2002. We expect to monitor soil variables of a transient nature. In selected treatments, we will use soil chamber techniques (Hutchinson and Mosier 1981) to investigate the temporal and spatial evolution of N_2O fluxes from soil. Direct measurement and modeling methods to ascertain soil transport and deposition will be selected in close cooperation with our collaborator R. Lal. Soil water content will be assessed periodically by Time Domain Reflectometry.

Emerging results from the microsite studies (e.g., total C) will be summarized and spatially aggregated for each landscape/management combination. We will seek expertise from the remote-sensing group at PNNL (L. Martucci, K. Steinmauss, G. Wukelic) to relate field determinations to remotely sensed data. This will be an important contribution of the project because we need to project landscape/ecophysiological processes correctly at the regional level. All the information collected will be spatially referenced and integrated into GIS layers.

The results will also be used to test and calibrate the simulation models described in section 5.3. We have a modeling system (Section 5.3) capable of representing most of the landscape/ecophysiological processes that will be studied (e.g., weather, topography, water and nutrient cycling, soil erosion, SOM pools, N₂O fluxes, and NO₃ leaching). The field and laboratory results and the simulation studies will be essential in gaining a holistic understanding of C sequestration—together with its ancillary environmental effects—at different levels of resolution.

Anticipated Results. This research will lead to a systematic collection of information on C sequestration rates under varying conditions along with knowledge on how to properly scale-up site measurements into regional and national summaries. We expect to

- Quantify our understanding of interactions between C sequestration and N cycling at landscape scales
- Adapt and demonstrate the applicability of GIS-based biogeochemical models as tools to predict landscape patterns in C sequestration
- Identify soil and environmental conditions that afford the greatest C sequestration potential and associated environmental benefits
- Develop GIS techniques and up-scaling procedures to extrapolate point estimates to regions
- Test the applicability of remote-sensing methods for assessing historical changes in C storage and N availability

4.2 Ecophysiological Scale Carbon Sequestration

Task Leaders: J.S. Amthor, S.D. Wullschleger (ORNL), J.D. Jastrow (ANL), H. Bolton (PNNL)

Goal. To extend fundamental ecophysiological understanding of processes that control C sequestration in managed and restored ecosystems. This research, which is focused at the spatial scale of plots (i.e., 10 to 1000 m²) and includes study of microbial processes and soil aggregation, will support improved landscape models and will direct lower scale measurements.

Approach. We will study three broad management strategies that have potential for enhancing C sequestration at a particular location: (1) fertilization of managed forests, (2) conversion of cropland to grassland (prairie restoration), and (3) conversion from conventional crop management to cropping systems based on legumes, reduced tillage, and/or cover crops.

4.2.1 Forest, Grassland, and Crop Ecosystem Management Options

Goal: To evaluate the capacity of major ecosystem management systems to enhance the amount and recalcitrance of sequestered C.

A key link between these tasks and lower-scale research will be in identifying treatments/plots that resulted in significant soil C sequestration and those that did not. The “best” and “worst” cases will be foci of measurements in 4.2 and 4.3 in order to understand the mechanisms controlling C sequestration potential.

4.2.1.1 Forest Nutrient Management

Task Leaders: R.L. Luxmoore, P.M. Jardine (ORNL), H.L. Allen (NCSU), R.B. Harrison (UWA)

Goal. To evaluate present forest nutrient management as a tool for enhancing C sequestration.

Background. At a given age, managed forests may store more C in trees and soils than unmanaged forests on similar sites, but present management practices are directed at wood production rather than whole-ecosystem C storage. In any case, managed forests offer a significant opportunity to enhance C sequestration over 20 to 50 years. Significant gains in forest productivity have been demonstrated in fertilizer experiments with southern pine species (Fisher and Garbett 1980) and with Douglas-fir stands in the Pacific Northwest (Stegemoeller and Chappell 1990). Increased aboveground biomass may (Johnson 1992) or may not (Harding and Jokela 1994, Canary et al. submitted) be accompanied by a gain in SOM, an issue that we will investigate further. In addition, urea fertilizer increased the movement of SOC by a factor of 2–3 in an eastern deciduous forest (Kelly 1981). The majority of the flux occurred during 3 months following urea application. Phosphate fertilizer is also effective in displacing organic matter from mineral surfaces and increasing mobility through soil profiles. Jardine et al. (1990) showed that a significant component of mobile organic C consisted of hydrophobic organic solutes. These solutes were

selectively adsorbed with depth. The transport of SOC to subsoil can therefore lead to stable organomineral complexes that increase sequestration into a pool with a slow turnover time (section 4.3.2).

Hypothesis 4.2.1.1 *Enhanced whole-ecosystem C accumulation will exceed C accumulation in wood plus roots in response to nutrient management on fine-textured soil, but not on coarse-textured soils. The difference will be a result of SOM accumulation from protection mechanisms more active in fine-textured than coarse-textured soil (relates to 4.2 and 4.3).*

Approach. A chronosequence of six field sites from each of the loblolly pine and Douglas-fir forest cooperative research investigations will be selected from replicated experiments in collaboration with the forest cooperative managers (Allen, Harrison). Forest (wood) growth responses with time following N fertilization are available from field research records of the forest cooperatives. Center-funded research will determine changes in litter, soil, and root C pools with time since fertilization and will determine leaching of SOM at the selected field sites. Leaching of SOM will be estimated from soil solution sampling with lysimeters to be installed at the chronosequence sites. Leaching rates will be estimated from SOM concentration and water budget modeling (Luxmoore 1983). The types of SOM materials (aliphatic, aromatic, hydrophobic) will be determined as described in more detail in Section 4.3.2. The influence of urea and phosphate fertilization on SOM leaching will also be evaluated.

Soil samples from selected chronosequence sites will be provided for microscopic and molecular analyses as part of the Molecular and Interfacial Processes task (section 4.3). Similarly, soil solution samples will be provided for determination of the molecular structure of SOM. Additional field sites from the forest cooperative investigations will be selected to determine the influence of soil type on C sequestration rates in response to nutrient management in loblolly pine and Douglas-fir stands. Soil type effects will be determined at two contrasting times since forest fertilization. The soil types in the Douglas-fir region will be from glacial till and volcanic parent materials, and in the loblolly pine region soils from the coastal plain and Piedmont will be studied.

Data from the forest cooperatives and the new Center research will be summarized in the LINKAGES forest simulation model that was developed for loblolly pine and Douglas-fir stands (Luxmoore et al. in press). Carbon and N dynamics are coupled in LINKAGES. This model will be calibrated to quantify whole-system C dynamics including changes in forest, litter, soil, and leaching with time. A regional assessment with the calibrated LINKAGES model will be initiated in the third year as a contribution to section 5 analyses. This assessment will use multivariate spatial clustering within Major Land Resource Areas (MLRA), following the method of Hargrove and Luxmoore (1998), and will include Monte Carlo methods to account for variation in soil and forest properties (Luxmoore et al. in press).

In addition, we will collaborate with Dr. Carl Trettin and other scientists at the USDA Forest Service National Center for Forested Wetlands Research. That Center supports extensive field experiments in wet landscapes and sites with seasonally high water tables. Their knowledge of anaerobic effects on C accumulation in forest soils will be an important addition to the expertise available for assessment analyses of forested landscapes.

Anticipated Results. This research will contribute to the knowledge base of ecophysiological processes needed to enhance C sequestration in forests. We will develop new conceptual understanding of the relationships between ecosystem management for wood yield and whole-ecosystem C storage. This is needed to optimize management of forests for enhanced C sequestration.

4.2.1.2 Grassland Restoration from Cropland

Task Leaders: R.M. Miller (ANL), J.S. Amthor (ORNL)

Goal. To quantify rates of C sequestration following conversion from crop to grassland (prairie restoration) using a robust chronosequence.

Background. Cultivation of grassland for crop production significantly reduces soil C pools, and the restoration of natural ecosystems from present cropland has the potential to “recover” that previously lost C (as mentioned). Moreover, management of restored ecosystems might increase the C storage potential to levels above those existing prior to cultivation.

Hypothesis 4.2.1.2. *SOM will accumulate continuously over a 25-year period (1975–2000) in the fermilab grassland restoration, showing that this ecosystem management practice can sequester soil C steadily for decades (i.e., not saturating after only a few years).*

Approach. Using the Fermilab NERP grassland restoration chronosequence, we will determine C in grassland plants (including roots), litter, and soil, for comparison with C in the adjacent cropped systems (including roots and litter). We will use detailed chronosequence data to assign rates to C accumulation in restored grassland, recognizing the need to consider spatial heterogeneity. Leaching of SOM will be estimated by soil solution sampling with lysimeters (see section 4.3.2). Soil samples will be collected for microscopic and molecular analyses described below (4.2.2 and 4.3).

Anticipated Results. This research will quantify C sequestration rate and determine the stability of sequestered SOM following grassland restoration. We will relate rates of C sequestration (determined in this task) to the physical and chemical structure of the SOM (determined in 4.2.2). This determined relationship will improve estimates of potential for long-term soil C sequestration in midwestern CRP lands.

4.2.1.3 Cropping Systems

Task Leaders: J.S. Amthor, W.M. Post (ORNL), H.H. Rogers (USDA-ARS)

Goal. To quantify soil C sequestration with a change in crop management toward reduced tillage and legume-based systems. To relate changes in crop management to changes in the stability of SOM, and to related increases in cropland NPP without additional mineral N fertilization to increase in SOM amount and stability.

Background. Most conventional cropping systems rely on some form of tillage and chemical fertilizer inputs (fertilizer production itself produces CO₂; section 5.0). Reduced tillage and/or low-input cropping systems, including the use of cover crops and/or legumes, can enhance SOM (e.g., Drinkwater et al. 1998) and are viable research strategies for C sequestration through ecosystem management. In some situations, however, reduced tillage may not increase SOM for poorly drained fine-textured soils, as reported by Wander et al. (1998) in central Illinois.

Hypothesis 4.2.1.3 *SOM will be increased in response to greater NPP brought about by elevated CO₂ without additional mineral N fertilization (NSDL). Legume-based (Rodale Institute) and no-till (NSDL) systems will increase SOM stabilization in direct proportion to the increase in total SOM.*

Approach. In collaboration with USDA researchers we will sample soil under conventional and no-till/cover-crop systems, with and without elevated CO₂, for quantification of total profile C accumulation. Soil and solution samples will also be collected for microscopic and molecular analyses (4.2.2, 4.3). The latter will be used to assess stability/recalcitrance of SOM throughout the profile in response to management.

The soil profile in the 15-year-old Rodale Institute legume-based and conventional cropping system plots will be sampled by depth for microscopic and molecular analyses to complement extant data on SOM accumulation rate.

Anticipated Results. This research will determine that stimulation of NPP per se enhances the amount and recalcitrance of SOM. We will also find that no-till/cover-crop and legume-based cropping systems, at least at our study sites, enhance the recalcitrance of SOM. This information will be critical to assessing the long-term nature of C sequestration through crop management.

4.2.2 Stabilization of Soil Organic Carbon

Task Leader: J. D. Jastrow (ANL)

Background. The mechanisms responsible for stabilizing SOC may be categorized as (1) biochemical recalcitrance, (2) chemical stabilization, and (3) physical protection (Christensen 1996a). Biochemical recalcitrance may be due to the chemical characteristics of the substrate itself — e.g., lignin derivatives or fungal melanins (Stott et al. 1983, Martin and Haider 1986) — or may result from transformations during decomposition, including incorporation into the excrement of soil mesofauna and microfauna (Kooistra and van Noordwijk 1996). Chemical stabilization occurs because of chemical or physicochemical associations between decomposable compounds and soil mineral components (e.g., organics sorbed to clay surfaces by polyvalent cation bridges or intercalated between expanding layers of clays). Soil structure, however, plays a dominant role in the physical protection of SOC by controlling microbial access to substrates, microbial turnover processes, and food web interactions (Elliott and Coleman 1988, van Veen and Kuikman 1990). Relatively labile material may become physically protected from

decomposition by incorporation into soil aggregates (Oades 1984, Gregorich et al. 1989, Golchin et al. 1994a,b) or by deposition in micropores inaccessible even to bacteria (Foster 1985).

Organomineral associations can occur at a variety of spatial scales with varying degrees of stability against physical, chemical, or biological disruption or degradation. Primary organomineral complexes are related to the primary structure of soils and associated with primary particles isolated after complete dispersion of the soil. Secondary organomineral complexes consist of aggregates of primary organomineral complexes that form the secondary structure of soils and are largely related, either directly or indirectly, to the growth and decomposition of plant roots and the hyphae of mycorrhizal fungi (Tisdall 1996, Jastrow et al. 1998).

According to the conceptual model of Tisdall and Oades (1982), the mechanisms of aggregate formation and stabilization and their relative importance change with spatial scale. Primary particles and clay microstructures are bound together with bacterial and fungal debris into extremely stable silt-sized aggregates (2 to 20 μm diameter), which may be bound together with fungal and plant debris and fragments into larger microaggregates (20 to 250 μm diameter). The organic binding agents involved in stabilizing microaggregates are believed to be relatively persistent and to consist of humic materials or polysaccharide polymers strongly sorbed to clays, with the most persistent clay-organic associations being strengthened by polyvalent cation bridges. Microaggregates, in turn, are bound into macroaggregates (>250 μm diameter) by readily decomposable organic materials and by fine roots, fungal hyphae, bacteria, and algae.

The OM binding microaggregates and other particles together into macroaggregates is believed to be physically protected from decomposition, but it generally turns over faster and, hence, is younger and more labile than microaggregate-associated organic matter (Angers and Carter 1996). Recent studies using the natural abundance of stable C isotopes demonstrate that mean residence times for C in microaggregates are longer than for C in macroaggregates (Skjemstad et al. 1990, Puget et al. 1995, Jastrow et al. 1996). In temperate soils, however, silt-sized aggregates once formed appear to be very stable, exhibiting turnover times that are longer than those of other size fractions, including clays, probably because of the combination of biochemical stability and physical protection afforded by organomineral complexes at this scale (Christensen 1996a, Tisdall 1996). Thus, much of the OM belonging to pools with intermediate residence times is currently thought to be physically or chemically protected from decomposition by incorporation into soil aggregates of various sizes (Elliott et al. 1996).

Hypothesis 4.2.2.1. The greatest potential for increasing soil C sequestration will be through physically or chemically protecting labile OM in primary or secondary organomineral complexes. In soils with limited protective capacity, C accumulation will depend more on the biochemical recalcitrance of the OM.

Approach. Major manipulable mechanisms controlling the potential accumulation of SOM pools with intermediate residence times include disturbance, input types and quality (e.g., surface vs. rhizospheric inputs, and C:N and lignin:N ratios), nutrient availability (including effects on productivity and decomposition); and base cation status. In addition, the amounts and types of clays and climate are largely unmanageable but important controlling factors. Our approach is to (1) quantify the amounts and dynamics of C and N in soil fractions representing active and physically and chemically protected SOM pools in the three systems identified in 4.2.1, (2) estimate residence times of SOM in each fraction to ascertain which fractions correspond with the intermediate pool, and (3) determine the extent to which site characteristics, vegetation type, and various manipulations or management strategies influence C accumulation in protected pools. The mechanistic basis of aggregate stability and OM recalcitrance will be examined with respect to the chemical functional composition and structural morphology of organomineral complexes described in 4.3.1.

The size distribution and stability of soil aggregates will be determined using appropriate dispersive energies for each site. After separating light fraction OM (<1.6 g/cm^3) not associated with soil aggregate structure, SOM will be fractionated sequentially with regard to the aggregate hierarchy of the soil. Low-energy techniques will be used to disperse macroaggregates without disrupting microaggregates. Particulate OM (both light and heavy fractions) from inside macroaggregates but external to microaggregates will be isolated by sieving and flotation. Light- and heavy-fraction POM occluded within microaggregates will be isolated after dispersion with appropriate high energies. Mineral-associated OM will be separated into silt and clay fractions.

Initial studies will use natural abundance ^{13}C tracers provided by switches from C4 to C3 vegetation at the Fermilab NERP and also at Kansas State University to evaluate the turnover and residence times of SOM in each isolated fraction. Then, samples collected in 1986 from the Fermilab chronosequence will be used to predict rates of change in pool sizes for this aggrading system with optimum C storage capabilities. These predictions will be tested by resampling the chronosequence at the same original sampling locations. Knowledge gained about the dynamics of the C and N pools in the isolated fractions will then be applied to other core sites (forest management, no till/cover crops, organic crop rotations). Where possible, studies at the core sites will take advantage of baseline or control comparisons, time sequences, and stable isotope tracers to quantify pool dynamics in addition to pool sizes.

Anticipated Results. This research will determine how site factors (e.g., soil type, climate) and management practices expected to sequester SOM affect C pools with varying residence times and will evaluate the potential for long-term storage of accumulated C in protected pools. The chemical composition and morphology of OM fractions isolated with knowledge of their physical location within the aggregated structure of the soil will be characterized as described in 4.3.1. This information combined with data on pool (fraction) residence times (obtained from sites with ^{13}C -labeled inputs and chronosequences) will be used to gain a mechanistic understanding of the factors controlling long-term C stabilization in soils. These results will link to 4.1 and 5.3 by providing data that may be used to better parameterize or refine existing SOM models. Ultimately, the data may contribute to the development of a new generation of models based even more directly on SOM structure and function (Christensen 1996b, Elliott et al. 1996).

4.2.3 Microbial Effects

Task Leaders: H. Bolton (PNNL), R.M. Miller (ANL), J. Zhou (ORNL)

Background. Microbial communities play a key role in the degradation of organic compounds in soil, the conversion of a portion of this organic C to more recalcitrant forms, and the stabilization of soil aggregates (Tate 1995, Lal et al. 1995). Also, the turnover of microbial biomass may contribute to recalcitrant soil C pools. As an example, fungal biomass is more resistant to biodegradation than bacterial biomass because of the presence of chitin and melanin in fungal cell walls (Paul and Clark 1996). Management can influence the role of fungi or bacteria in the decomposition of plant residues in the field. The fungal population is more important in residue decomposition in no-till, presumably because the fungal mycelia can bridge between soil and residue on the soil surface, while bacteria are more important in conventional tillage (Beare et al 1992, Hendrix et al. 1986, Holland and Coleman 1987). Bacteria have a lower efficiency for assimilating C from plant residues than fungi, which can lead to faster decomposition rates and greater OM loss from conventional tillage soils (Adu and Oades 1978). Thus management systems that enhance the fungal population and activity should also enhance the longevity and retention of SOC.

Hypothesis 4.2.3. *Increasing fungal/bacterial biomass and activity ratios will increase the longevity of soil C.*

Approach. The contributions of bacterial and fungal biomass to the production of long-lived soil C pools and OM decomposition in soil will be investigated. Both field and laboratory microcosm studies will be conducted. The field sites will be selected based on information from 4.2.1 on management history and SOC pools. Field studies will include both traditional methods for estimating microbial biomass involving microscopic measurements and the more quantitative chemical methods. Membrane compounds are attractive indicators of living biomass because they are usually degraded rapidly after cell death and because membrane area is assumed to correlate well with cell biovolume of microbes (Tunlid and White 1992). The cell membranes of both prokaryotic and eukaryotic organisms are made up to a large extent of ester-linked phospholipids (PLFA). Specific PLFA molecules are indicative of fungal and prokaryotic biomass. Traditional methods using FDA or acridine orange staining will be used to measure active membranes in mycorrhizal and saprophytic hyphae and bacterial cells (e.g., Baath and Soderstrom 1979, Soderstrom 1977, Miller et al. 1995). We will also use traditional methods to convert PLFAs to quantify of mycorrhizal fungi, saprophytic fungi, and bacteria (Olsson et al. 1995, 1996).

Where ratios of fungal to bacterial biomass are significantly affected by various management approaches (4.2.1) or tied to the production of recalcitrant C pools, molecular methods will be used to study microbial community structure and activities. Both DNA and RNA will be extracted from soil (Hurt

et al. 1999). Microbial community structure will be analyzed via microarray hybridization and quantitative competitive PCR (QC-PCR). We will construct a DNA microarray-containing genes important to C cycling (e.g., xylanase, cellulase, lignin peroxidase, polyphenol oxidases, laccases, glutamate dehydrogenase, methyl coenzyme M reductase, and methane monooxygenases) as described by DeRisi et al. (1997). Phylogenetic microarrays containing probes specific to different groups of fungi and bacteria will be constructed based on rRNA genes as described by Beattie (1997). These microarrays will be used to monitor the changes in both microbial community structure (DNA) and activities (rRNA and mRNA). Since microarray hybridization may not be quantitative, QC-PCR detection methods will be developed (Ferre et al. 1996) and used to calibrate the microarray.

Both field and laboratory microcosm studies will be conducted using soil from the various field sites (see 4.2.1). The bacterial (oxytetracycline) and fungal (captan) inhibitors will be added so that the target population is inhibited with minimal effect on nontarget populations (Beare et al. 1992). Soil C cycling will be investigated in the field at selected sites by adding foliage from plants grown in high-CO₂ open-top-chamber experiments (which provide a ¹³C signal) to the soil surface to follow residue decomposition. Residue decomposition in the lab will use ¹⁴C-labeled organic compounds from both plant residue grown on the soil and model organic compounds thought to be important to the development of recalcitrant organic C pools (e.g., lignocellulose, polyphenol). Populations (DNA) and activity (RNA) of bacteria and fungi would be determined as described. The degradation of ¹⁴C to CO₂ and incorporation of ¹⁴C into various soil C pools will be determined as a function of time. Approaches discussed earlier for soil C pools will be used for both lab and field studies as well as for quantifying microbial biomass C using chloroform fumigation incubation (Horwath and Paul 1994) and substrate-induced respiration (SIR) with selective inhibition to quantify bacterial and fungal biomass (Beare et al. 1990).

Anticipated Results. This research will establish the role of soil microbial structure and function in the partitioning of plant C to labile and recalcitrant pools in soils. Once the importance of the bacterial versus fungal community and metabolic capabilities leading to C sequestration are known, management strategies that select for optimal microbial composition could be used to enhance C storage in more recalcitrant pools.

4.2.4 Coupled C/N Cycling Mechanisms

Task Leaders: H. Bolton (PNNL), J.D. Jastrow (ANL), J. Zhou (ORNL)

Goal. To determine effects of N availability on C sequestration in above- and below-ground pools.

Background. Nitrogen is intimately coupled to the C cycle because it is usually the limiting mineral nutrient for plant growth. Excess N could result in environmental impacts, such as increased decomposition rates of plant residue, leaching of nitrate to groundwater, and loss from soil as the greenhouse gas N₂O. Insufficient N could result in decreased ecosystem productivity and result in mining or degradation of otherwise recalcitrant SOM-N by microorganisms. Because inputs, outputs, and pools of N and rates of transfer between pools can vary during the growing season, N cycling studies in ecosystems have required both long-term (Clark 1977, Jackson et al. 1988, Jones and Woodmansee 1979, Woodmansee and Duncan 1980) and short-term (Jackson et al. 1989, Schimel et al. 1989) studies. Research from tasks 4.1.1 and 4.2.1 will allow us to select sites with low, medium, and high levels of N input where aboveground biomass and C gain are known. It will also provide information on SOM pools and their turnover on sites selected for research. The research in this task will include both short-term and long-term (growing season) studies of the N cycle using ¹⁵N and molecular-based approaches to quantify key microbial groups responsible for N transformations in soil.

Hypothesis 4.2.4. *An increase in N availability in soil (e.g., via fertilization) will enhance C sequestration in soil. However, too little N will decrease C sequestration and potentially lead to mineralization of soil organic N. Too much N will increase soil C cycling and C loss and lead to the gaseous or leaching loss of N from the ecosystem.*

Approach. Short-term studies will quantify transformation rates using ¹⁵N-pool dilution technique as dictated by plant phenology and climate. This technique labels either NH₄-N or NO₃-N with a highly enriched low concentration of ¹⁵N and measures its dilution over 1 to 3 days (Hart et al. 1994, Stark and Hart 1997). This provides a snapshot of inorganic pools of N and their transformation rates in soil including gross nitrification, mineralization, NO₃-N consumption (primarily microbial assimilation), and

NH₄-N consumption (primarily microbial assimilation). Quantitative PCR will be used on these soil samples to evaluate the gene abundance and in situ activity of nitrite reductases (*nir*), nitrous reductases (*nos*), and ammonia monooxygenases (*amo*). These are key enzymes involved in N cycling. We will compare the shift of microbial populations and activities using the microarray hybridization approach discussed in 4.2.3 based on the ratios of mRNA/DNA of a particular enzyme, and the ratios of *nir/amo*, *nos/amo*, *nos/nir*, and heme-containing *nir*/copper-containing *nir*. These comparisons will show if changes in N availability and C dynamics affect population size and gene expression of microbial groups important in the N cycle.

Nitrogen dynamics throughout two growing seasons at selected sites with known C sequestration rates will also be studied using (¹⁵NH₄)₂SO₄ added uniformly at 1 g N/m². Soils will be sampled to quantify soil microbial biomass N by the chloroform direct extraction technique (Davidson et al. 1989), NH₄-N and NO₃-N (Keeney and Nelson 1982), and total soil, root, and shoot N (Bremner and Mulvaney 1982). The quantity of root biomass and its N and C content as well as the distribution of ¹⁵N in the roots and soil at the end of the growing season will also be quantified as a function of depth. The ¹⁵N study will be continued for an additional year to follow the decomposition and mineralization of the ¹⁵N-labeled plant residues. These data will provide estimates of N release from decomposing shoot and root residues and uptake by plants. Rates of N mineralization and ammonification, nitrification, immobilization, and plant uptake will be calculated to determine the N fluxes and pool sizes. Leaching losses of N will be quantified by measurement of nitrate in soil leachates collected in Task 4.3.2 to quantify soluble C leaching. Gaseous losses of N will be quantified by N₂O flux measurements (Mummey et al. 1997). The changes in populations and activities of nitrifiers and denitrifiers will be compared with the rates of nitrification and denitrification to understand how microbial population changes and N dynamics and C sequestration are related.

Anticipated Results. This research will determine how soil N availability is coupled to C sequestration in above- and below-ground pools. Optimal N availability and the underlying microbiological mechanisms controlling N pools and processes will be determined. An amount of N necessary for enhanced plant productivity (e.g., yield) may not be the optimal N level for enhanced C sequestration in above- and below-ground pools. Understanding how the N cycle and N availability influence C sequestration will provide information that will contribute to the development of management principles that can be applied to multiple ecosystems in order to enhance C sequestration.

4.3 Molecular and Interfacial Processes

Goal. To develop a basic understanding of key fundamental interfacial processes that control formation of organomineral complexes and dissolved pools and how these processes govern C sequestration in soil.

Overall Approach. Interfacial and molecular processes governing the formation of long-lived organomineral associations and alkalinity generation will be elucidated using advanced spectroscopic, surface-imaging, and macromolecular structural characterization capabilities at the EMSL (PNNL) and SAN and SAX Center (ORNL).

Background. The C sequestration potential of ecosystems can be enhanced by understanding and manipulating the recalcitrance of organic C, its retention in deeper soil horizons, and its potential for storage through alkalinity production. Whereas the previous section dealt with process-level understanding of sequestration of organic C in protected pools, this section seeks mechanistic understanding of the chemical and structural determinants of the recalcitrance of organic C. We postulate that recalcitrance arises from the structural morphology of the OM, which determines its accessibility for microbial metabolism and contributes to formation of physically protected soil aggregates. Further, we seek to expand descriptions of C sequestration in soil to include the fate of organic and inorganic C that migrates downward from the uppermost soil horizons. Dissolved organic C released from the upper soil horizons can be retained in lower horizons by adsorption to mineral surfaces and diffusion into protected fine pores in the soil. In addition, mineralization of labile organic C, along with weathering of minerals by dissolved organic acids, generates alkalinity that will increase the net flux of bicarbonate out of soil and into longer-term C storage in pools such as groundwater and the ocean. Opportunities exist to manipulate and optimize all these processes through management of organic source material, alteration of microbial

communities, and modification of fertilizer treatments that affect the adsorption and release of organic C from mineral surfaces.

4.3.1 Organomineral Complexation and the Morphology of Soil Organic Carbon

Task Leaders: J. F. McCarthy (ORNL), J. E. Amonette (PNNL)

Background. Natural SOM is a chemically heterogeneous mixture of solutes and macromolecules arising from the degradation and repolymerization of plant inputs to soil and litter. Many advances in understanding of the chemical functional composition of SOM have resulted from new analytical techniques such as ^{13}C - and ^1H - NMR spectroscopy, FTIR, and pyrolysis-gas chromatography-mass spectroscopy (pyrolysis-GC/MS). These techniques provide information on the relative abundance of specific functional groups, such as aromatic, aliphatic, and carboxylic functionalities, in the SOM. But, these data reflect the average composition of the OM and provide little insight into the composition and configuration of individual molecules associated with mineral surfaces. Recent work indicates that the physical morphology of organic macromolecules may be a critical feature in their retention by soil surfaces and, thereby, their role in the formation of soil aggregates. The morphology stems from interactions between individual functional groups separated spatially in the same molecule and from associations between organic clusters as they form macromolecular complexes.

Both SANS and SAXS are well-established probes of the morphology of organic and inorganic macromolecules. The scattering curve (i.e., plotting the intensity of the scattered beam as a function of scattering angle) yields information about the shapes of the macromolecular assemblage and about the subparticles from which those assemblages are formed. A productive approach to understanding structure of natural OM derives from the random-walk manner in which these organic assemblages are likely to be formed as new organic moieties are produced by microbial processes and as organic moieties percolate through soils. Random-walk systems have been found to often form fractal structures, and the concept of fractal dimension, D_f , has proven a useful tool in understanding the morphology of natural OM (Homer et al. 1992a, b, Homer 1998, Osterberg et al. 1994, Rice and Lin 1992, 1993, 1994). These approaches have helped to conceptualize different ways small species organize into large ones and to understand how the “effective porosity” inherent in the fractal dimension can vary with chemical factors such as pH (Senesi et al. 1994), source or physical form (mineral-bound or in solution; Rice and Lin 1992, 1993, 1994), concentration, source, or availability of metal ions (Homer et al. 1992, 1994, 1998), or temperature (Osterberg et al. 1994). For example, the combined fractal dimension and concentration-normalized scattering intensity were used to infer the effect of iron on the degree of compaction of the humic structure. Correlations were also observed between the chemical composition of different humics and their likely configuration on surfaces. Compared with aromatic-rich humics, OM with higher aliphatic content exhibited higher fractal dimensions, indicating that it might be expected to form dense surface coatings, with significant interpenetration of constituent moieties (Homer et al. 1992, 1994, 1998). This interpretation is consistent with observations that long-chain aliphatic moieties seem to dominate clay fractions in soils (Christensen 1992).

Most of the mentioned studies have dealt with organic macromolecules in solution, but similar techniques can be applied to organics adhering to soil particles or within soil aggregates. Using SANS, it is possible to match the scattering length density (equivalent to the refractive index in light scattering) of the solvent to that of the mineral component in a soil aggregate. This makes it possible to examine the morphology of the organic C within these structures (i.e., is the OM of recalcitrant organomineral C adhering as a highly condensed coating on the mineral surface, or as a loose, open assemblage indicative of labile OM with a rapid turnover?).

Hypothesis 4.3.1. *Long-term recalcitrance of SOC is promoted by formation of condensed-morphology organic structures on mineral surfaces.*

Approach. This task will focus on soil from sites sampled in Section 4.2. Two complementary approaches will be pursued:

4.3.1.1 Correlations will be sought between the recalcitrance of OM associated with soil aggregates or primary organomineral complexes (as determined by Section 4.2.2) and the chemical composition and morphology of that OM. Soil aggregates and primary organomineral complexes provided by Section 4.2.2. will be analyzed as follows:

- Chemical functional composition of SOC using ^{13}C cross-polarization magic-angle spinning (CPMAS) NMR and FTIR spectroscopy will provide information on the overall distribution of the OM extracted from soils (Clapp et al. 1993). For aggregate fractions with limited sample mass, elemental composition provides “most probable” estimates of the proportions of aliphatic C, aromatic C, and other sp^2 -hybridized C in DOC (Perdue 1984; Wilson et al. 1987).
- The morphology of the OM in the soil aggregates will be characterized using SANS and SAXS (which probe different structural dimensions). The scattering curve provides information on the radius of gyration of primary structures, the fractal dimension of the organic macromolecule, and the cluster geometry of the organic macromolecule within the soil aggregate. These data can be used to interpret whether the OM with the aggregate or on a mineral particle is in open, extended configuration or a low-porosity condensed configuration that forms dense coatings on surfaces. The morphology of the entire soil aggregates will also be examined to test whether the recalcitrance of OM within soil aggregates arises from the absence of open porosity that may exclude microbiota or limit diffusion of oxygen to create anaerobic pockets that protect the organic C.
- The morphologic interpretation will be supplemented in some cases by visualization of the micromorphology of the aggregate structure. The minerals will be characterized, and microscopic spatial relationships between intact particles and organic coatings will be examined using scanning electron microscopy with energy-dispersive X-ray spectroscopy, transmission electron microscopy, and atomic force microscopy.

4.3.1.2 Mechanistic hypotheses will be formulated based on these observations and will be tested in the laboratory to confirm understanding of the morphological basis of SOC recalcitrance. Hypotheses will be tested by one or more of the following approaches:

- Manipulation of the morphology of the OM through changes in pH or metal ion content, along with microbial mineralization experiments to examine the effects of changes in morphology and the bioavailability of the SOC on mineral surfaces.
- Use of model systems with both natural organics and surrogates with defined composition [e.g., polyacrylic acid as a model long-chain, carboxyl-rich structure postulated to form a condensed coating on mineral surfaces (Gu et al. 1996a, b)].

Anticipated Results. The morphology of the organic macromolecules will be demonstrated to be the critical determinant of the recalcitrance of chemically protected SOM associated with mineral surfaces and to play a key role in the formation and stability of soil aggregates that physically protect organic C. Manipulations based on physico-chemical principles governing intermolecular and intramolecular interactions will lead to generic strategies to enhance soil C sequestration.

4.3.2. Sequestration of Dissolved Organic and Inorganic Carbon

Task Leaders: J. F. McCarthy (ORNL), J. E. Amonette (PNNL)

Background. Biological processes in the upper horizons of soil release organic C and H_2CO_3 to the soil solution. As the solution percolates downward through the soil, changing conditions may lead to sequestration of the dissolved C by either (1) storage in the soil as recalcitrant organic C and carbonate or (2) generation and export of aqueous alkalinity (primarily HCO_3^- ion) to other long-term C-storage pools. While the fundamental processes, such as competitive sorption, microbial degradation, oxidative polymerization, and mineral dissolution, are recognized, the manner in which they interact to enhance or suppress sequestration of dissolved C is poorly understood. As the soil solution percolates below the litter and A horizons, the concentrations of DOC usually decrease dramatically whereas the alkalinity of the solution increases. The decrease in DOC in the lower horizons is largely the result of adsorption to the mineral soil rather than microbial respiration (Qualls and Haines 1992, Guggenberger and Zech 1993) and represents the primary mechanisms for long-term storage of C in soil. Movement of DOC into the small pores of the soil matrix because of hydraulic and concentration gradient differences between the pore classes (Jardine et al. 1989a, 1989b, 1990) can further enhance the retention of organic C in the soil profile. The increase in alkalinity likely stems from enhanced dissolution of minerals in the lower horizons (Dethier 1986, Pavich 1986) stimulated by DOC with chelating functional groups (Raulund-

Rasmussen et al. 1998, Antweiler and Drever 1983, Wogelius and Walther 1991, Welch and Ullman 1993).

Soils have a finite capacity for sorbing DOC, and upper soil horizons with high levels of OM are a source rather than a sink for DOC (Kaiser et al. 1997). Jardine et al. (1989b) reported that adsorption of DOC is greater on samples from lower soil horizons with lower levels of indigenous SOC. Furthermore, removal of the indigenous SOC increased adsorption of DOC fourfold. Whether components of DOC bind to soil by physical adsorption (Jardine et al. 1989, Baham and Sposito 1994) or by ligand-exchange mechanisms (Gu et al. 1994, 1995), DOC is chemically fractionated by adsorption during transport through mineral soil horizons (McCarthy et al. 1993, 1996, Gu et al. 1996a, b). Components of DOC that have higher molecular mass or contain higher amounts of either hydrophobic, aromatic, carboxylic, or lignin-derived moieties are preferentially adsorbed (Jardine et al. 1989, Gu et al. 1994, 1995, Kaiser et al. 1998, Wang et al. 1997).

The generation of aqueous alkalinity can also be a significant sink for atmospheric CO₂. Watershed catchment studies (Routson et al. 1977, Creasey et al. 1986, Dethier 1986, Velbel 1993) show that C sequestration by soil as a result of alkalinity production and export to other storage pools is small in any given year. But, when considered over, for example, 50 years, it can be comparable to an increase in stored organic C of about 0.1% in the top 15 cm of soil (i.e., about 225 g C/m²). Large differences in alkalinity production are seen with differences in vegetation (Cochran et al. 1994), DOC quantities (Rauland-Rasmussen et al. 1998), and soil mineralogy (Colman and Dethier 1986). Sequestration strategies that manipulate vegetation types or convert arid and degraded lands to more intensive use with irrigation will likely increase alkalinity production as well as storage of recalcitrant organic C.

Competition between sorption, oxidation, and mineral-weathering processes will control the depth and type of organic carbon accumulation and the amount of alkalinity produced. Master variables dictating which process will dominate include (1) size, morphology, and chemical functional groups of the OM; and (2) composition, redox state, and surface properties of the soil minerals. Sequestration as organic C will be favored by large, condensed, aromatic-rich organics and high-surface-area, low-charge-density minerals. Within a given profile, the composition of DOC and SOC will change with depth, with decrease in the proportion of preferentially adsorbed organic moieties with depth. Furthermore, manipulations that result in enhanced C storage in soil will result in a deepening in the soil profile for organic C, with deeper penetration of preferentially adsorbed DOC and SOC moieties, compared to untreated plots. Generation of alkalinity will be favored by small, carboxylated organics and slightly weathered soils containing easily weathered mafic and anorthitic minerals. For example, greater alkalinity production would be favored in Douglas-fir plantations in volcanic—compared with glacial till—soils in the Pacific Northwest.

Hypothesis 4.3.2. Enhanced downward translocation of DOC from surface horizons increases C sequestration by sorption and weathering mechanisms.

Approach. This task will use samples collected at sites studied in 4.2.1. The concentration data in soil solution will be used to estimate the downward flux of DOC and DIC based on water infiltration rates estimated using water balance models for the sites. More detailed studies will be conducted at selected “test cases” of C sequestration success/failure as described in Section 4.2. Sites having stable isotope inputs that can be used to quantify C pool turnover (as discussed in Section 4.2.2) will be of particular interest.

Multilevel tension lysimeters will be installed and soil water collected at different depths. Soil cores recovered during lysimeter installation will provide SOM from locations corresponding to that of the soil solution samplers.

- At selected sites/treatments, the alkalinity will be measured as a function of depth, and the DOC and SOC characterized with respect to quantity, chemistry, size, and structure/morphology with depth. Characterization will include pyrolysis-GC/MS, NMR, and FTIR. DOM will be fractionated using adsorption and ion exchange chromatography into fractions that differ in polarity and charge density (Leenheer 1981, Aiken et al. 1992) or separated on the basis of molecular mass (Buffle 1988, McCarthy et al. 1993 1996). The relative proportions of these fractions should change as some components of DOM are selectively released or adsorbed during transport through soil horizons (Cronan and Aiken 1985, Jardine et al. 1990). SANS will be used to examine the extent of aggregation of the OM in soil solution as an indicator of its potential strong adsorption to the mineral phase. The

molar volume of the DOM can also be estimated using fluorescence polarization, which measures the hydrodynamic radius of a molecule based on the extent of Brownian rotation during the fluorescent lifetime of fluorophores within the DOM structure (McCarthy et al. 1989).

- At sites with a characteristic $\delta^{13}\text{C}$ signal, the stable C isotope levels in the DOC and SOC will be compared to determine if the mobile DOC is derived from relatively young C or represents release from long-term storage.
- At some sites/treatments, the solid phase will be characterized with respect to the mineralogy and microscopic spatial relationships between intact particles and coatings (i.e., micromorphology, as described in 4.3.1) with depth.
- Laboratory batch studies with analog and natural DOC, whole soils, and mineral isolates will identify structural and chemical factors promoting sorption versus weathering. Because adsorption and weathering may be competing processes, the role of adsorbed DOC coatings on the susceptibility of mineral surfaces for weathering will also be examined.

Anticipated Results. Increased sequestration of organic and inorganic C with depth will be demonstrated. The mechanism of organic C accumulation will be shown to involve competitive displacement of preferentially adsorbed DOC from upper horizons followed by readsorption at lower horizons. The potential increase in C sequestration from alkalinity generation will be quantified. A more focused benefit of this research will be the direct measurement of the effect of nutrient additions (4.2.1.1) on the mobilization of OM in the upper soil horizons. Nitrogen additions using urea or ammonium nitrate will increase soil pH in the upper horizons, and that change in pH will promote desorption of OM. Phosphate acts as a competitive anion for DOC sorption, and is expected to also enhance mobilization of DOC through the soil. Additions of Ca^{2+} might enhance DOC retention by promoting aggregation, but the conjugate anion may counteract this effect. For example, lime (CaCO_3) would increase pH, whereas sulfate in gypsum (CaSO_4) would compete for sorption sites.

5. Assessments of Carbon Sequestration: Potential Net Greenhouse Effects, Environmental Impacts, and Economics

Goal. To incorporate existing and new data on C and N cycling and associated ecosystem processes to derive a national and global inventory of terrestrial ecosystem C sequestration potential and associated understanding of the full range of environmental and economic impacts likely with implementation of strategies to enhance terrestrial C sequestration.

Overall Approach. Assessment of the prospects for changing land-use and management practices to sequester C is needed to clarify the real opportunities for decreasing net greenhouse gas emissions and to identify the ecosystems and land-use strategies with the greatest potential. The assessment will explore the magnitude and the kinds of benefits, risks, and incentives required to achieve greater C sequestration in managed terrestrial systems. Ongoing assessment activities are tightly linked to and modified according to new knowledge and insights from the field and laboratory studies. Similarly, results from the assessment provide guidance for the scientific program in focusing on parameters that could realistically be manipulated or that influence adoption of alternate land- management practices. Insights will be used to improve, refine, and periodically update the kinds of information now summarized in preliminary form in Table 1 and Fig. 5. The data will be summarized in annual reports to be prepared at regional, national, and global scales.

The overall assessment approach is comprised of four discrete analyses that bear on the environmental and economic outcomes of enhanced terrestrial C sequestration. Together these highlight opportunities for net reductions in greenhouse gas emissions and the costs (or ancillary benefits) of achieving them. The analyses are

- Summarization of process understanding and geographical information to produce high-quality, spatially explicit assessments of national terrestrial ecosystem C sequestration potential. Global-scale assessments will be also be completed with less spatial detail.
- Analysis of greenhouse gas emissions. Will fuel and fertilizer inputs required to increase aboveground and belowground C stocks result in greater C emissions to the atmosphere than is sequestered, or will savings of fuel and fertilizer amplify the greenhouse benefits?

- Analysis of environmental effects. Will practices that increase soil C sequestration – such as increased application of N fertilizer or other chemicals on no-till fields – also increase water pollution?
- Analysis of economic incentives and disincentives for land managers. What dollar value for soil C would be sufficient to change land-management practices so that additional C is sequestered?

Background. Field and laboratory research in section 4 will lead to improved understanding of the potential for enhancing C sequestration in terrestrial ecosystems. Nonetheless, fundamental questions remain regarding the practical opportunities for increasing C sequestration in the “real world” in which land is managed to provide a variety of goods and services and land-use practices reflect many decision criteria. Therefore, we must understand (1) the magnitude and location of the most promising land-management opportunities for C sequestration, (2) whether required changes in land-management practices would have consequences beyond C sequestration that might impact the net balance of greenhouse gas emissions, (3) whether practices that would improve C sequestration would have other environmental impacts, and (4) how strategies to improve C sequestration would affect overall economics of land management and the delivery of traditional goods from forestry and agriculture.

5.1 National and Global Carbon Sequestration Potential Updates

Task Leaders: J.S. Amthor, W.M. Post (ORNL)

Approach: The Center will produce a science-based, high-quality, spatially explicit assessment of national terrestrial ecosystem C sequestration *potential* every 2 years, with the first assessment due by the beginning of the third year of Center operation. The assessment will be based on a thorough review of the literature related to C sequestration in response to management and land use. The updates will also incorporate knowledge gained between assessments about C sequestration processes from ongoing Center research. The initial assessments will be based on 1-km and county-level spatial datasets for land-cover characteristics (EROS Data Center, crop reporting statistics) and soil characteristics (STATSGO and NSSC from USDA-NRCS). Data will be aggregated into several dozen vegetation-soil classes. Management strategies will be “applied” to the individual classes, accounting for climate and edaphic effects, vegetation type, and vegetation age (or time since land use change) with the use of time-dependent C sequestration response functions developed from existing data and Center research. In this way we can explicitly account for spatial variations in response of terrestrial systems to various C sequestration management methods. This will be a considerable advance over the relatively general and imprecise analyses currently available. Sequestration potential will consider both vegetation and soils. Maps in both digital and graphical form will be available to scientists, policymakers, and the public. A group of external experts will be enlisted to evaluate the methods and results.

Methods developed in performing the national analysis and scientific advances from the Center will be used to estimate global-scale C sequestration potential with lower spatial detail.

5.2 Net Impact on Greenhouse Gas Emissions

Task Leader: G. Marland (ORNL)

Objective: Clarify the extent to which practices that result in increased C sequestration in the terrestrial biosphere produce net decreases in emissions of greenhouse gases.

Background. Enhancing C sequestration in terrestrial ecosystems may involve changes in land use that impact the balance of inputs and outputs from agricultural and forestry management practices. This may be as simple as reducing the amount of fuel used for soil tillage or as complex as decreasing the flow of timber or other product streams. Whereas a decrease in fuel input would likely be reflected simply in a saving in emissions of CO₂, reduced timber output might be reflected in increased timber production elsewhere or in timber being replaced by other products. In either case the net impact on the flux of greenhouse gases to the atmosphere is more complex than is observed in the amount of C physically sequestered in a given ecosystem. As a result, if we want to understand the greenhouse gas consequences of changes in land-management practice we need to examine the full impacted system that supplies the same output of goods and services. To represent the complexity of such systems, Marland and Turhollow (1991) and others examined the net C balance when ethanol is produced from corn to substitute for petroleum fuels, and Schlamadinger and Marland (1996) constructed GORCAM, a C-accounting model

that tracks C flows for different forest management approaches. Izaurre et al. (1998) adjusted the rate of C sequestration under no-till, taking into account the CO₂ and N₂O emissions related to manufacture, transport, and application of N fertilizer. They showed that net C sequestration was smaller but still positive. The rate of C sequestration in agricultural systems is likely to be similar to changes in the rate of greenhouse gas emissions from other parts of the system so that savings that enhance benefits, or losses that diminish benefits, may play an important role in the net greenhouse-gas-emissions.

Research Approach. We propose to examine specific changes in land-use practice that might be pursued to increase C sequestration, to define the full system of impacts from these changes, and to quantify the net impact on C flows to the atmosphere. GORCAM tracks C in the forest ecosystem, forest products, and fossil fuels not burned because biomass fuels are used in their place or because forest products displace other (often more energy-intensive) products. We will adapt GORCAM (or develop a comparable modeling framework) to account for changes in the flow of fuels, plant nutrients, agricultural chemicals, and products when farm practices are altered to improve C sequestration. While emphasis will be on C flows, we will also identify and quantify processes and locations where changes in C management impact the net release of CH₄ and/or N₂O. Output from 5.3 will be used to improve the representation of N₂O emissions.

Our expectation is that detailed analysis of prospective changes in land-use practice will reveal certain changes that are successful in reducing net emissions of greenhouse gases and others of little net benefit, even though C sequestration in the ecosystem is increased (see, e.g., Marland and Schlamadinger 1997). Understanding of the net flows of greenhouse gases and how these are influenced by on-site and off-site processes will be important in implementation of greenhouse mitigation strategies and in ensuring that credits awarded are commensurate with the ultimate objective of reducing net greenhouse gas emissions. In conducting these systems analyses we will be cognizant of the implications for implementation and administration of national objectives or of international agreements.

Anticipated Results. This work will summarize the net C balance for changes in land-management practices that enhance C sequestration in forest and cropland soils and biomass. Summaries will also be made of effects that land-management changes aimed at enhanced C sequestration would have on N₂O and CH₄ fluxes to the atmosphere and of the off-site leakage effects on greenhouse gas emissions that enhance or reduce the net benefit of C sequestration in soils and other components of the terrestrial ecosystems.

5.3 Balance of Environmental Impacts

Task Leaders: R.C. Izaurre, N.J. Rosenberg (PNNL)

Objective. To develop a quantitative understanding of the environmental impacts of C sequestration in soils and vegetation and to create better tools to predict these environmental impacts.

Background. Soil organic matter is an essential attribute of soil quality (Doran et al. 1994). Increases in SOM are associated with improvements in tilth, fertility, and water-holding capacity (Herrick and Wander 1998) as well as ecosystem health and function (Warkentin 1995). Recognized, but not well understood, are possible negative environmental impacts associated with certain candidate management practices to enhance soil C sequestration. Zero tillage, for example, requires increased use of chemicals for weed control and can also increase greenhouse gas emissions from the soil. Linn and Doran (1984), for example, reported greater N₂O emission under zero tillage. This result may be site-specific since others have reported contrasting results (Lemke et al. 1999). The range of total environmental impacts of C sequestration in soils and vegetation can best be understood through model analyses of ecosystem processes, such as plant growth; energy, water and element cycling; transformation processes in soil; wind and water erosion; and land-use management.

Approach. We will use a modeling approach to study environmental impacts of management and land-use changes used to sequester C. We have selected the models Century (Parton et al. 1987) and EPIC (Erosion Productivity Impact Calculator; Williams 1995) because together they can represent most of the ecological processes and management options required for integrated assessments. In related work for the EPA and USDA, our collaborators in CASMGS (Consortium for Agricultural Soils Mitigation of Greenhouse Gases) will rely on these models to project the 1990 C baseline of U.S. agricultural soils. Both models contain algorithms to assess the impacts of CO₂ concentration on plant growth and

ecosystem properties. Researchers at Texas A&M University (J. Williams) and CSU-NREL (K. Paustian) will collaborate in this task.

Century was developed for simulation of long-term –years to centuries– SOM dynamics, plant productivity, and nutrient (N, P, and S) cycling. Soil organic C is divided into three compartments: active, slow, and passive. Rate constants are affected by soil water content, soil temperature, and soil texture. The model runs on weekly time steps.

EPIC is an ecosystem model capable of simulating wind and water erosion processes and their impact on soil productivity. Treatment of soil C in EPIC is connected to nutrient (e.g., N and P) cycling and transport processes (e.g., wind and water erosion). The representation of C flows and allocation in the plant-soil system, however, needs to be improved in order to account for textural effects. EPIC simulates plant growth of annual and perennial species, solar radiation controls on photosynthesis, water and element cycling, transformation processes in multiple soil layers, wind and water erosion, complex management (tillage, fertilization, irrigation), and fate of pollutants (e.g., herbicides).

This research will provide opportunities to examine scientific hypotheses formulated at ecosystem and ecophysiological scales (sections 4.1 and 4.2) as well as to enhance model performance with knowledge emerging from field and laboratory experiments. The selection of a model for predicting changes of ecosystem properties ultimately depends on research and application objectives. In multiple-objective projects, more than one model might be needed to make these projections (Izaurre et al. 1999). Thus, model-to-data and model-to-model comparisons are essential methodological steps toward building robust procedures to estimate C fluxes and other effects at regional or national levels.

The first modeling task will be to improve SOM and denitrification algorithms in EPIC. Several other SOM models will be examined (Century [Parton and Rasmussen 1994], RothC [Jenkinson and Coleman 1994], and DNDC [Li et al. 1994]) and their best features incorporated into EPIC. We plan to incorporate, using information on kinetics from Tasks in section 4, new concepts of extractable SOM fractions (Christensen 1996b, see Figure 6).

We will test the improved algorithms against SOC data from the North America SOM Network (Paul et al. 1997) and SOMNET (Powlson et al. 1996). EPIC SOC algorithms will be compared with those of Century and with DNDC with regard to SOC and denitrification. In the third task, we will conduct case studies using data from Center research sites to assess the impact of management on C sequestration and environmental variables. In the last task we will use EPIC and Century to simulate the scenarios required by the accounting (GORCAM) and economic/energy models (SGM) in order to produce the integrated assessment of the full C accounting, environmental, and economic impacts.

Anticipated Results. This research will develop a modeling system to assess environmental impacts of C sequestration. Metamodels of constructed environmental indices that enable quick evaluation and aggregation of the effects of management practices on C sequestration and associated environmental consequences will also be developed.

5.4 Economic Analysis of Soil Carbon Sequestration

Task Leaders: R.D. Sands, J.A. Edmonds (PNNL)

Goals. To (1) compare opportunities for sequestering C in terrestrial ecosystems against other opportunities to reduce net greenhouse gas emissions in a general equilibrium economic framework and (2) understand the tradeoffs in agricultural and forest production between C storage in vegetation and soils, other inputs to production, and product yield. This will be done in both physical and economic terms to produce supply curves for storing C in terrestrial ecosystems.

Background. The return of previously lost C to vegetation and soils in agricultural lands may have value as part of a least-cost strategy for stabilizing atmospheric concentrations of greenhouse gases. But, as the Second IPCC Assessment (Cole et al. 1996) points out, "...the world's farmers, ranchers and pastoralists will not *volunteer* to implement practices proposed to mitigate greenhouse-forced climate change. This will happen only if the producer is convinced that profitability will improve if these practices are implemented." (See also Rosenberg et al. 1998.)

Two levels of economic analysis are relevant. On a local scale, we must understand the economic incentives facing land managers and how management behavior might change if a value is placed on the amount of C stored. On a global scale, sequestering C in plants and soils will be compared with other

options for reducing net greenhouse gas emissions on the basis of cost. An efficient program for reducing net greenhouse gas emissions will select the least-cost options first. The economic potential to store C in plants and soils depends on what other options are available, and their relative costs. It is important to note that C sequestration in terrestrial ecosystems differs from emissions reduction in one important way - sequestration in the biosphere is not permanent. For direct emissions reduction we can imagine a market in C emissions rights priced in dollars per metric ton. But the valuation of C stored in the biosphere would likely have a time element, for example dollars per metric ton of C sequestered and held for some period of time.

Approach. We will use the Second Generation Model (SGM) as an integrating economic framework to search for the least-cost approach to meeting any given constraint on net greenhouse gas emissions. The SGM, developed by PNNL's Global Climate Change group, has been used extensively as a simulation tool to project baseline C emissions over time and provide an estimate of the overall cost of reducing greenhouse gas emissions (Edmonds et al. 1999, U.S. Council of Economic Advisers 1998). Edmonds et al. (1996) used SGM to conduct a study of commercial biomass and its impact on global C emissions from land-use change. We will compare the net benefit of C sequestration in terrestrial ecosystems with that of other options for reducing net emissions of greenhouse gases.

With SGM, we can address three types of flexibility: "what," "where," and "when." "What" flexibility means being able to compare biosphere C sequestration with other greenhouse gas mitigation opportunities on the basis of cost. "Where" flexibility means looking for the least-cost opportunities regardless of location. "When" flexibility recognizes the high cost of rapid changes to the energy system and that C sequestration may provide a less expensive alternative in the near term. We anticipate that this task will focus initially on activities in the United States.

Opportunities for C sequestration in terrestrial ecosystems cannot be put into an integrating economic framework unless we first construct a relationship between a C price and the amount of C sequestered. Such a supply curve is fundamental to any top-down economic analysis of C sequestration and we require a defensible methodology for deriving supply curves. First, we must understand the physical tradeoffs between stored C, product yield, and other agricultural and/or forestry inputs. Second, these physical relationships must be placed in the economic context facing land managers.

Agricultural or forestry activities have several physical inputs and outputs. Management practices are alternative ways to combine these inputs to produce a crop. Inputs include fertilizer, use of machinery, water, seed, and labor time. We consider C storage as an output along with product yield. We will draw on results of the EPIC simulations obtained in Section 5.3, describing the biogeochemical relationship between soil C, management inputs, and crop yield for a variety of crop-land-management practices. Results from Section 5.2, a life-cycle analysis of land-management practices, will also be helpful in determining the net reduction in greenhouse gas emissions.

We will rely on economic models of land management to determine how the agricultural sector might react to C-management alternatives and the incentives that are created to alter C management. We will parametrically alter incentive systems and/or C targets and generate information on land use, farm economics, and market prices. Dr. McCarl of Texas A&M University will participate in this research, contributing in terms of agricultural and forestry options for C-management. These activities will help us understand the effects of various incentive systems on the adoption of C management systems and the possible offsets throughout the economy when actors not directly affected by the incentives react to market-induced changes (see, e.g., Callaway and McCarl 1996).

Anticipated Results. This research will provide a methodology for deriving supply curves for sequestration of C in terrestrial ecosystems. In addition, using the SGM, an economic analysis will be made of meeting a given greenhouse gas emissions constraint with and without the opportunity to sequester C in terrestrial ecosystems.

6. Center Mission and Partnerships

The Mission of the Center is to advance the fundamental scientific understanding needed to develop and implement environmentally acceptable and economically feasible strategies to enhance C sequestration in terrestrial ecosystems.

To be successful, the Center will:

- Publish research results in the open literature. Other value-added products (e.g., assessment reports, research briefs, general public announcements, etc.) will communicate research and assessment findings to the C sequestration and global change community. Special emphasis will be placed on communicating terrestrial C sequestration potentials to key DOE organizations (e.g., DOE/FE) so that this information can be used widely.
- Update regularly a science-based estimate of the potential for terrestrial ecosystem C sequestration in the U.S. and globally. The biennial and 3-year updates will present projections of potential and likely C sequestration, the latter taking into account environmental and socioeconomic issues.
- Establish collaborations and partnerships that ensure “best in class” capabilities.
- Create an open and inclusive environment to build consensus on research and assessment approaches. The Center will host strategic workshops to identify future research needs and develop methodologies for reducing key uncertainties.
- Leverage opportunities for conducting research by using existing research programs and field sites that are applicable to issues of enhancing C sequestration at several scales.
- Form data alliances that provide immediate access to information for assessment activities and research analysis.
- Communicate Center goals, project activities, partnerships and collaborations, and new research and assessment findings in a timely manner. Information on enhancing terrestrial C sequestration will be distributed (in hard copy and on the internet) in formats most useful to researchers and others.

6.1 Collaborations and Partnerships

Figure 6 illustrates conceptually how the Center will engage collaborators and partners in the planning and execution of research. There are three components to be addressed.

6.1.1 Research Council

A Research Council will serve to review plans and progress of the Center and to provide direct links to other institutions and agencies involved in C sequestration issues. We envision the Research Council being comprised of lead scientists from the participating laboratories (two each from ORNL and PNNL, one from ANL) and principal scientific collaborators (USDA, Rodale Institute, and one from CASMGS). We would expect that staff of DOE/OBER and David J. Beecy (DOE/FE) would be formal members of the Research Council to help ensure that the research results of the Center are transferred to the needs of DOE/SC and DOE/FE. We would expect to also include staff from the USDA Forest Service on the Research Council. Through more informal interactions, Center research will be linked to activities in the IPCC, Resources for the Future, and others who are engaged in C sequestration issues.

6.1.2 Scientific Collaborations

An important strategy of the Center is to take advantage of other ongoing activities in C sequestration and related research. Therefore, direct scientist-to-scientist collaboration is highly valued. Only in this way will we be able to undertake the necessary studies across ecosystems and multiple scales. For example, we will select research sites where other related work is already in progress. There are also opportunities to complement some of the applied R&D beginning in DOE/FE. For example, ORNL is discussing with DOE/FE staff possible projects addressing the separation and capture of CO₂ at fossil fuel plants with chemical modification to create usable soil amendments on degraded lands. Center research could be blended into some of these studies, should they progress.

Expertise needed to execute the research derives from formal research partnerships among staff at ORNL, PNNL, ANL, and several collaborators. The current collaborators with the Center are listed on the personnel page at the beginning of the proposal. This is a strong multi-institutional research alliance. Many of these partners have worked together on past projects dealing with complex research questions. This partnership ensures a full range of capabilities needed to address the research hypotheses and integrated assessment objectives.

6.1.3 Science and Technology Workshops

Workshops to address scientific issues will be planned as appropriate. Topics that are likely to be considered initially include (1) methods to quantify microbial community structure and function (molecular methods appear to have significant value, but there is controversy as to how effective they are at this time); (2) interfacial scale issues related to soil C transformations and transport (it is especially important to address how to scale up mechanistic information to be useful at landscape and larger scales); (3) quantification of environmental impacts [the complexity of balancing approaches to C sequestration with other issues is not readily handled by existing approaches; as research results appear, workshops will be held to ensure direct transfer of new scientific information to applied R&D programs (DOE/FE) and potential implementers of C sequestration activities (e.g., USDA, private industry)]. The Research Council will organize these workshops. Topics will be determined once the Center is operational. Results of the workshops will be published. They will help guide the scientific agenda of the Center.

6.2 Data Systems

Data support in the Center includes access to key existing databases, both at ORNL (e.g., CDIAC, DAAC, and ARM) and via links to other data centers, universities, and researchers. Functions include integration and documentation of existing and planned measurements from the field research; interaction with modelers to tailor data sets for ingest into C allocation models; and documentation, evaluation, and dissemination of products produced by the Center. ORNL's data archives contain numerous holdings relevant to assessing the potential for sequestering C in the terrestrial biosphere. Examples include long-term climate records, results from CO₂ fertilization experiments, CO₂ flux records from terrestrial sites, records of the atmospheric content of key chemical species (CO₂, C isotopes, N species), SOC and soil N data, and fossil-fuel CO₂ emission estimates. All these holdings are fully documented and available on the Web (<http://cdiac.esd.ornl.gov>).

Environmental data from field sites needs to be gathered and integrated in a consistent manner that permits cross-site synthesis. In addition to basic quality assurance, data will be reformatted as needed to ensure consistent variable names, units, missing-value codes, etc. Data sets will be needed that permit extrapolation from study sites to regional, national, and global scales, and the Center will obtain and quality-assure these data sets to support the analysis, modeling, and assessment tasks. Finally, the Center will thoroughly document these products (methods, data formats, etc.) to ensure their value to a diverse user community and will archive the data products and distribute them via a Web site and appropriate digital physical media.

6.3 Center Management and Coordination

The Center is managed and coordinated by ORNL and PNNL. Responsible Center coordinators are Dr. Gary Jacobs (ORNL) and Dr. F. Blaine Metting (PNNL). Program direction and funding support is the purview of the Office of Biological and Environmental Research, Environmental Sciences Division at DOE.

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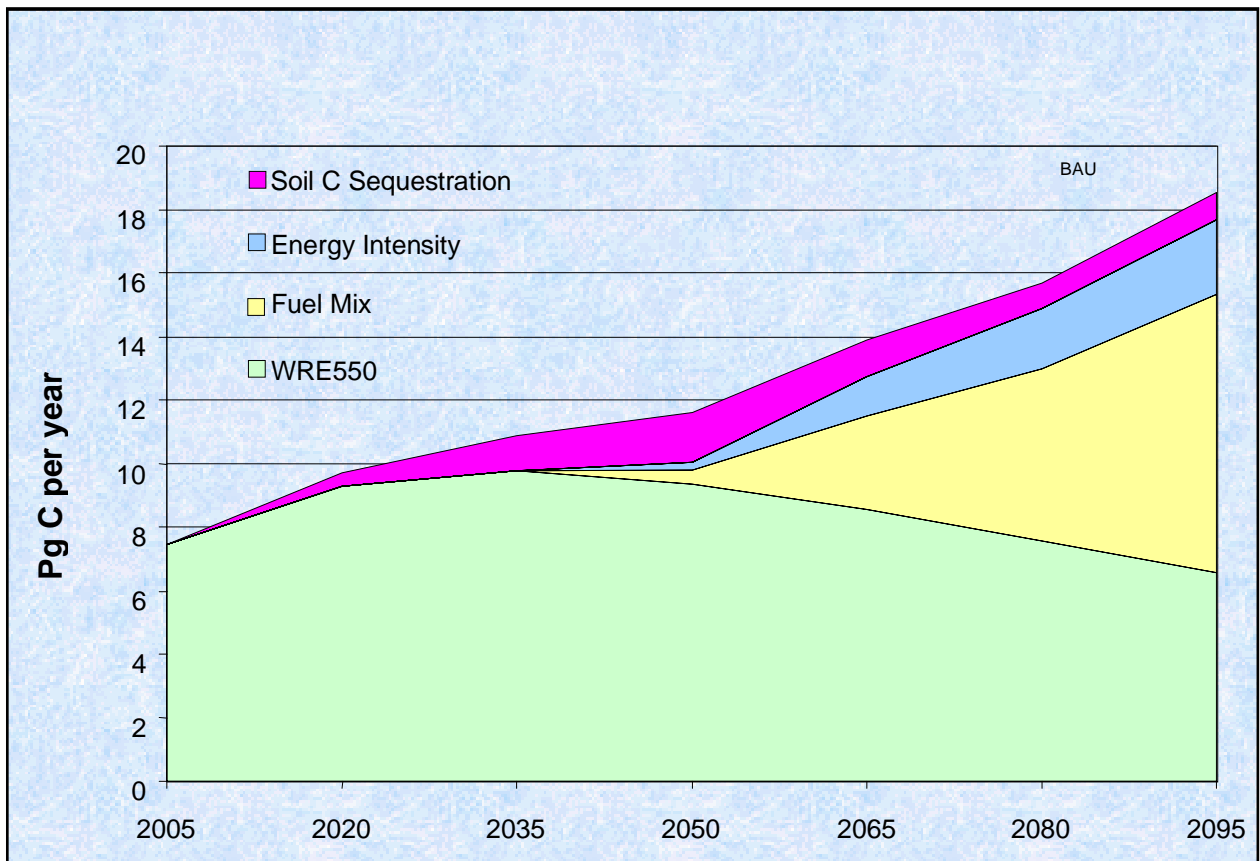


Figure 1. Reduction of global C emissions through cropland soil C sequestration. Edmonds and co-workers at PNNL have analyzed globally the impact of cropland soil carbon sequestration on the concentration of atmospheric CO₂. The integrated assessment model MiniCAM uses of the emissions trajectories of Wigley et al. (1996) that constrain the CO₂ concentration to 550 ppmv (WRE550). This trajectory requires that net carbon emissions peak in the year 2033 and then begin to decline. The analysis shows how cropland soil carbon sequestration and changes in the energy system can reduce global carbon emissions so that the 550 ppmv constraint is not breached. The calculations assume that, from 2000 to 2100, cropland soils will sequester carbon at global annual rates ranging from 0.4 to 0.8 Pg/yr, with rates twice as large in the initial years and half as large in the later years. This analysis indicates that, if the full potential of soil carbon sequestration in croplands alone were realized, the time during which the global energy system can adjust to meet the new constraints would be lengthened up to 35 years. From the middle of the century on, further emissions reductions would come from changes in the energy system such as from switching the fuel mix and reducing total energy consumption (Edmonds et al. 1999).

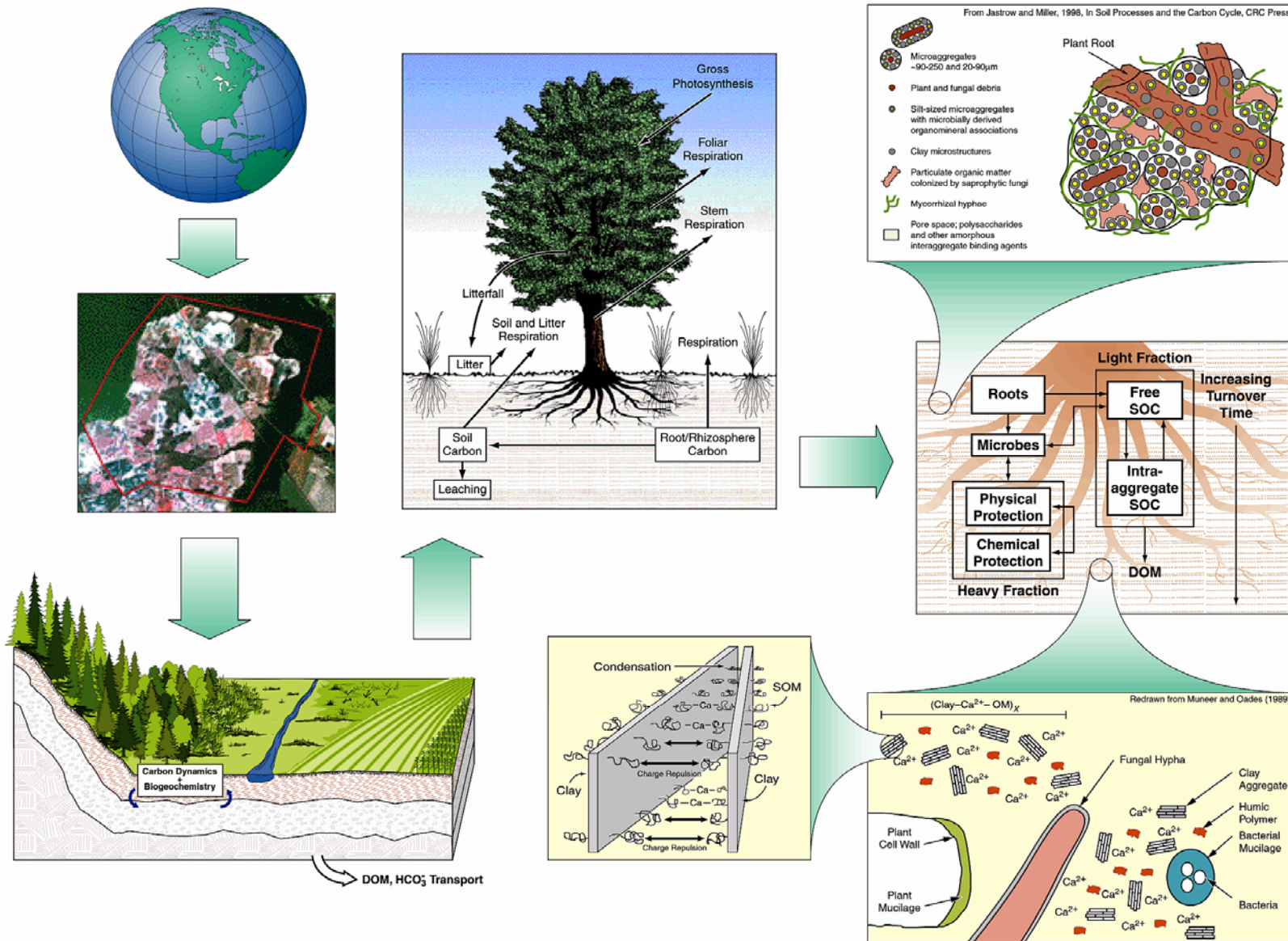


Figure 2. Conceptual representation of the multiple scales to be addressed in this proposal. Research will focus on the critical pathways and mechanisms for enhancing long-lived pools of C in terrestrial ecosystems and on ways to optimize C sequestration through management of certain ecosystems. However, to extrapolate and scale these results to national and global systems requires knowing how much C is allocated into certain pools and what factors control the mean residence time in response to ecosystem management strategies.

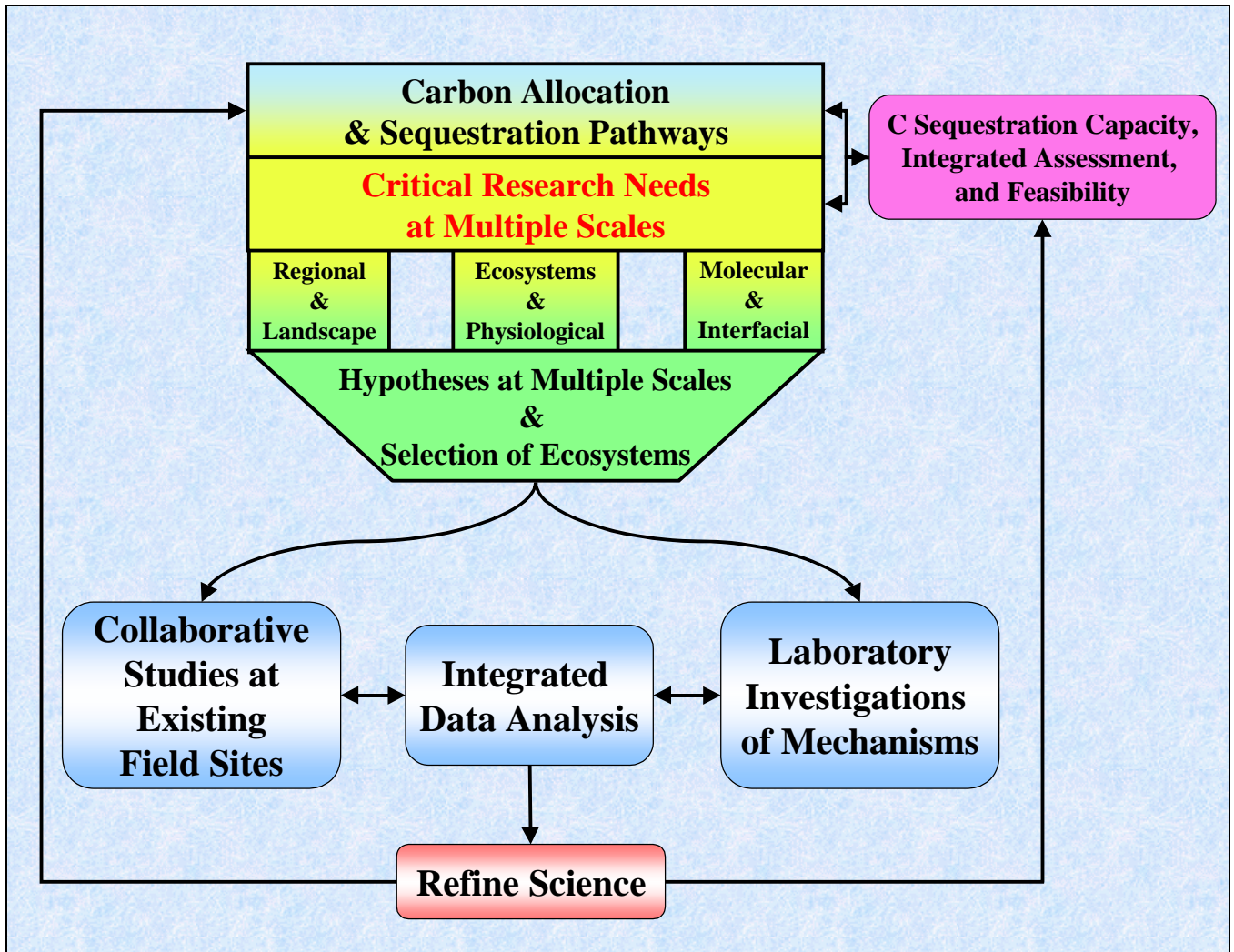


Figure 3. The proposed research will use a conceptual model of carbon sequestration pathways to determine research needs at multiple scales and to formulate hypotheses. The hypotheses will be tested through observations, measurements, and sampling at field sites. Selected characteristics of the samples will be analyzed at molecular and interfacial scales to determine the most important mechanisms controlling carbon sequestration. Research results will help refine scientific concepts and in turn allow researchers to improve conceptual models, assessments, and evaluations of feasibility of carbon sequestration.

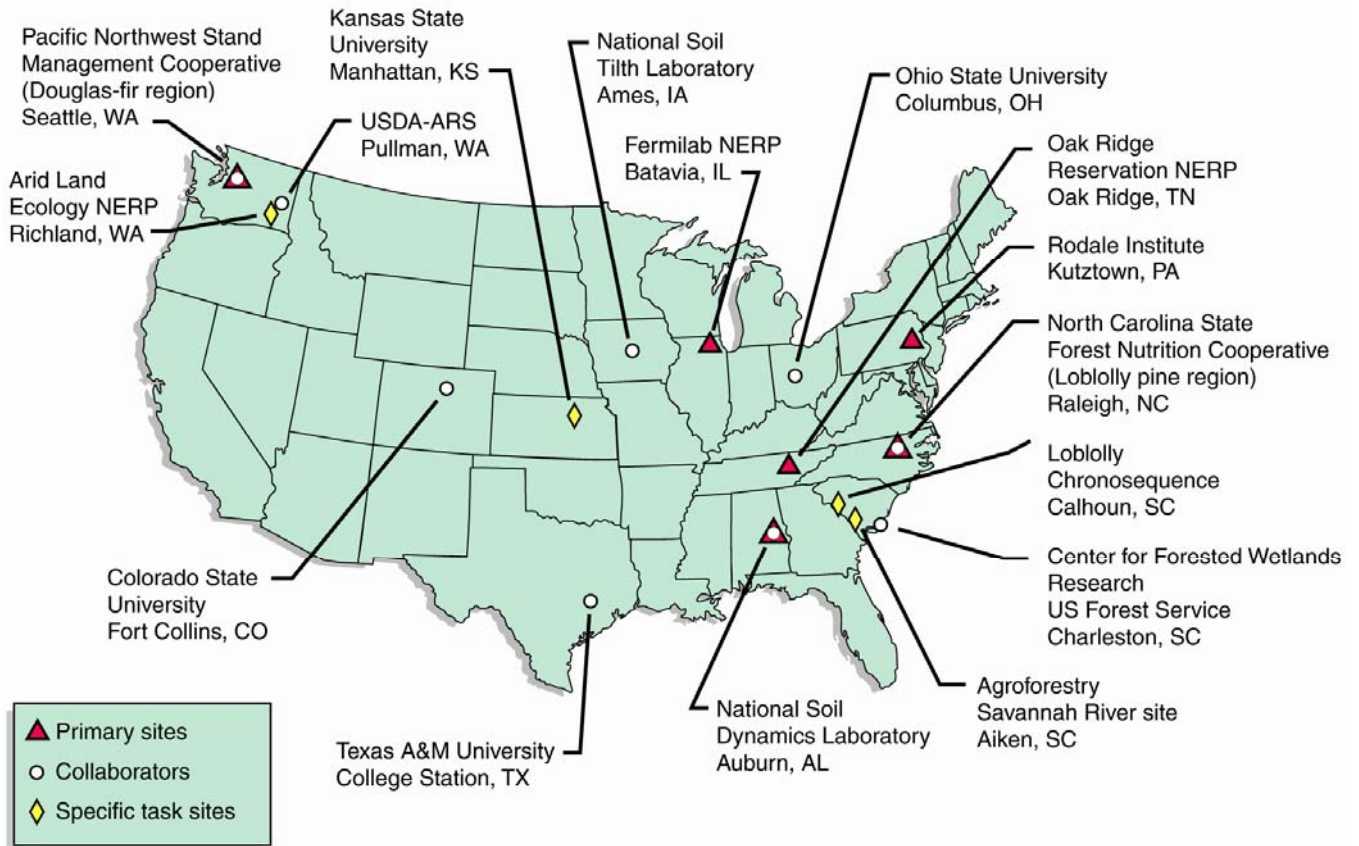


Figure 4. Map showing the location of primary field research sites, collaborators with the Center, and sites where specific research questions will be addressed. Research at primary sites will cut across several spatial scales and tasks.

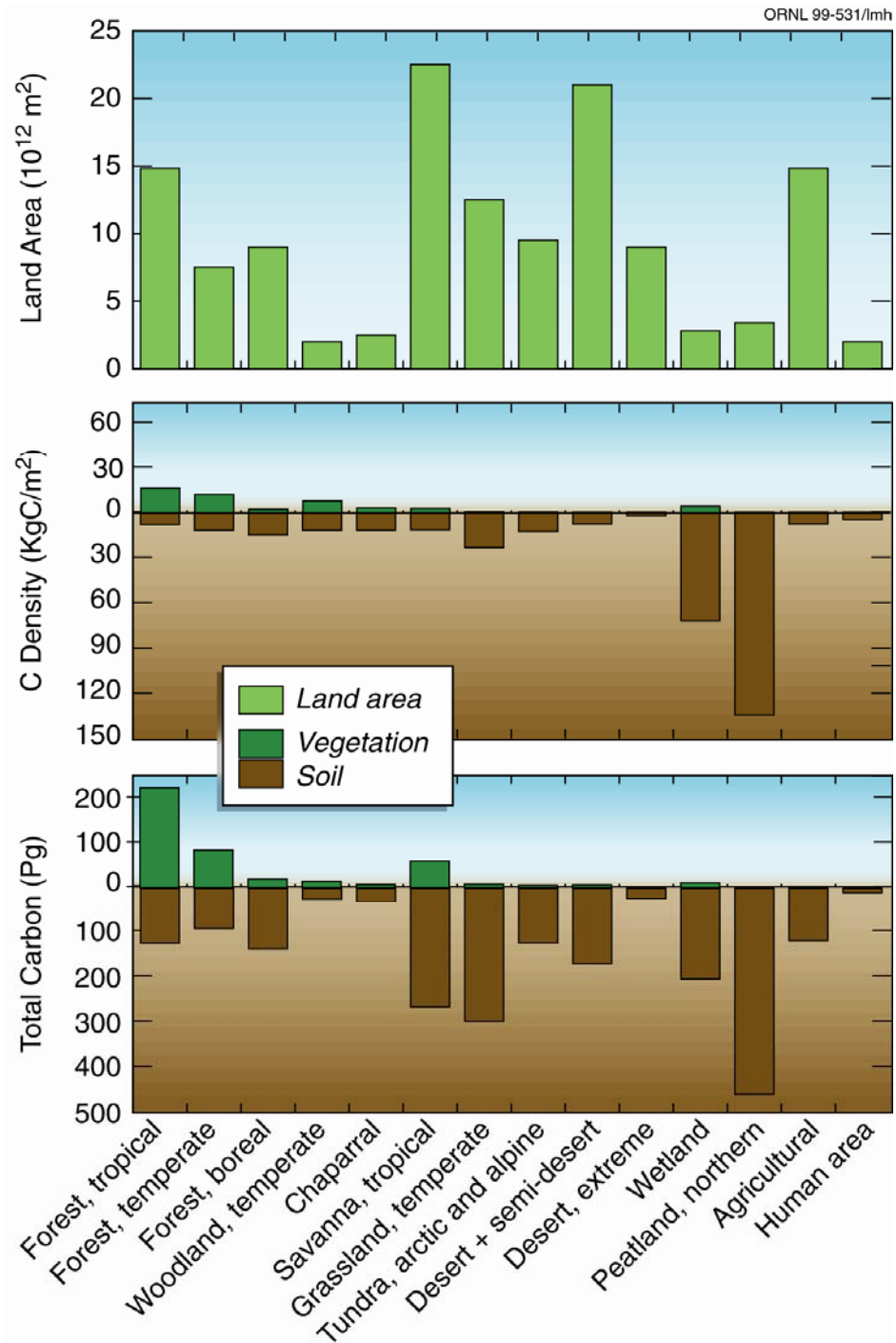


Figure 5. (Top) Estimated global area of land in 14 broadly defined terrestrial biomes (excluding lake/stream and perpetual ice); **(middle)** estimated average organic carbon area density in living plants and soils in the 14 biomes; and **(bottom)** estimated global total organic carbon in living plants and soils in the 14 biomes (based on Amthor and Huston 1998). Soil organic carbon is for the top meter of "mineral" soil only, except in wetlands and peatlands which include surface litter and extend to the bottom of the "soil" profile. Additional surface litter and standing dead plants may contain from 50 to more than 200 Pg C globally, with relatively large amounts in forests. Jobbágy and Jackson (1999) recently estimated that globally the top 3 meters of mineral soil may contain 55% more organic carbon than the top meter, excluding peatlands and wetlands.

At the regional and national levels, spatially resolved information about ecosystem distributions and C inventories are available to complete similar analyses at those smaller scales. Center missions include using new scientific information to improve estimates of present C stocks, to estimate total potential for C sequestration, and to determine what level of C sequestration might be achieved when environmental impacts of management strategies are considered.

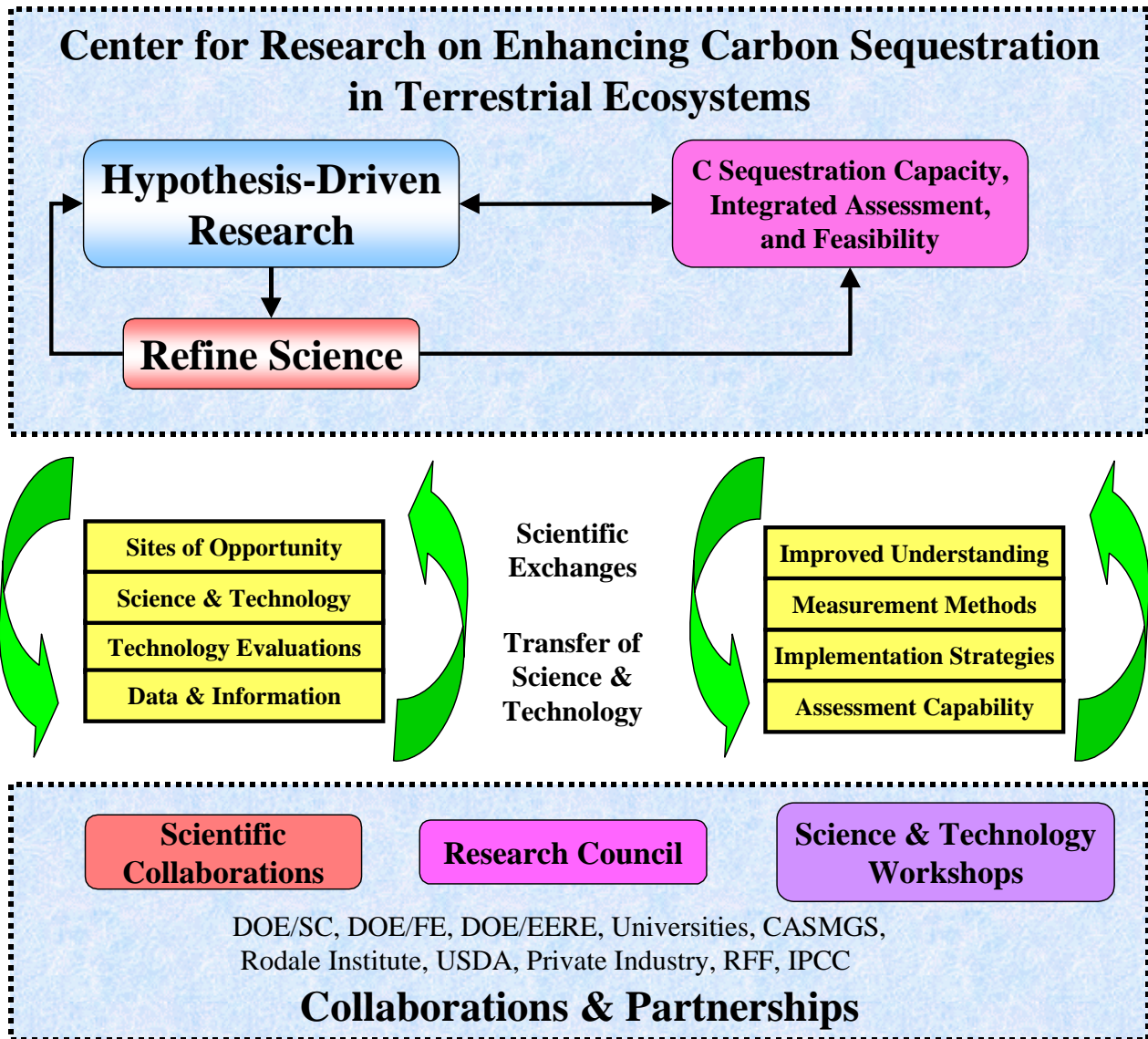


Figure 6. Relationships between Center scientific activities and our partners in developing critical research needs, performing the science, and transferring scientific results to others involved in developing strategies and methods for carbon sequestration.