THE MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Phase I Final Report

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This is the final report for Phase I of the Midwest Regional Carbon Sequestration Partnership. The MRCSP is one of seven partnerships in the U. S. Department of Energy's (DOE) Regional Carbon Sequestration Partnership Program being conducted in DOE's National Energy Technology Laboratory (NETL).

This report is being submitted by Battelle as a result of research performed under DOE Cooperative Agreement No. DE-FC26-03NT41981, the Midwest Regional Carbon Sequestration Partnership (MRCSP).

A long list of participants in the MRCSP Phase I research contributed to this report. These participants and their affiliations are listed in attached table

Cover: Logo Design by Steve Molnar, Publications Management and Production Group, Battelle.

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About the MRCSP

The Midwest Regional Carbon Sequestration Partnership (MRCSP) is a public/private consortium that is assessing the technical potential, economic viability, and public acceptability of carbon sequestration within its Region. The MRCSP region consists of seven contiguous states: Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia. A group of leading universities, state geological surveys, non-governmental organizations and private companies listed below and led by Battelle, makes up the MRCSP. It is one of seven such partnerships across the U.S. that make up the U.S. DOE Regional Carbon Sequestration Partnership Program. The U.S. DOE through NETL contributes the majority of funds for the MRCSP's research accounting for 68.62% of the total funding or $2.41 million for the current phase of work all under Agreement No. DE-FC26-03NT41981. The next largest contributor is the Ohio Coal Development Office within The Ohio Air Quality Development Authority under Agreement No. CDO/DE-02-17. The MRCSP also receives funding from all of the other members listed below.

Industry Partner	Research Partner
AES Warrior Run	CONSOL Energy
Alliance Resource Partners (Mettiki Coal)	Indiana Geological Survey
American Electric Power	Kentucky Geological Survey
Arch Coal	Keystone Center
Baard Energy	Maryland Geological Survey
Babcock and Wilcox	Michigan State University
British Petroleum (BP)	National Regulatory Research Institute
Center for Energy	Ohio Division of Geological Survey
and Economic Development (CEED)	Ohio Environmental Council
Cinergy	Pacific Northwest National Laboratory
CONSOL Energy	Penn State University
Constellation Energy	Pennsylvania Geological Survey
DTE Energy	Purdue University
First Energy	The Ohio State University
Maryland Energy Administration	University of Maryland
Monsanto	West Virginia Geological Survey
Ohio Coal Development Office	West Virginia University
of the Ohio Air Quality Development Authority	Western Michigan University
Ohio Corn Growers Association	
Ohio Forestry Association	
Ohio Soybean Council	
Ohio Turfgrass Foundation	
Scotts Company	

ABSTRACT

This final report summarizes the Phase I research conducted by the Midwest regional Carbon Sequestration Partnership (MRCSP). The Phase I effort began in October 2003 and the project period ended on September 31, 2005.

The MRCSP is a public/private partnership led by Battelle with the mission of identifying the technical, economic, and social issues associated with implementation of carbon sequestration technologies in its seven state geographic region (Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia) and identifying viable pathways for their deployment. It is one of seven partnerships that together span most of the U.S. and parts of Canada that comprise the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Program led by DOE's national Energy Technology Laboratory (NETL).

The MRCSP Phase I research was carried out under DOE Cooperative Agreement No. DE-FC26-03NT41981. The total value of Phase I was $3,513,513 of which the DOE share was $2,410,967 or 68.62%. The remainder of the cost share was provided in varying amounts by the rest of the 38 members of MRCSP's Phase I project. The next largest cost sharing participant to DOE in Phase I was the Ohio Coal Development Office within the Ohio Air Quality Development Authority (OCDO). OCDO's contribution was $100,000 and was contributed under Grant Agreement No. CDO/D-02-17.

In this report, the MRCSP's research shows that the seven state MRCSP region is a major contributor to the U. S. economy and also to total emissions of CO_2, the most significant of the greenhouse gases thought to contribute to global climate change. But, the research has also shown that the region has substantial resources for sequestering carbon, both in deep geological reservoirs (geological sequestration) and through improved agricultural and land management practices (terrestrial sequestration). Geological reservoirs, especially deep saline reservoirs, offer the potential to permanently store CO_2 for literally 100s of years even if all the CO_2 emissions from the region's large point sources were stored there, an unlikely scenario under any set of national carbon emission mitigation strategies. The terrestrial sequestration opportunities in the region have the biophysical potential to sequester up to 20% of annual emissions from the region's large point sources of CO_2.

This report describes the assumptions made and methods employed to arrive at the results leading to these conclusions. It also describes the results of analyses of regulatory issues in the region affecting the potential for deployment of sequestration technologies. Finally, it describes the public outreach and education efforts carried out in Phase I including the creation of a web site dedicated to the MRCSP at www.mrcsp.org.

EXECUTIVE SUMMARY

The Midwest Regional Carbon Sequestration Partnership (MRCSP) is a public/private consortium that was formed in 2003 to assess the technical potential, economic viability, and public acceptability of carbon sequestration within its Region. The MRCSP region consists of seven contiguous states: Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia. Since its inception, the MRCSP has grown to 38 partners representing leading universities, state geological surveys, non-governmental organizations, state and federal government agencies and private companies across the Region. The MRCSP is the premier resource in the region for identifying the technical, economic, and social considerations associated with terrestrial and geologic CO_2 sequestration and <u>identifying viable pathways for its deployment</u>. The MRCSP is one of seven such partnerships across the U.S. that makes up the U.S. DOE Regional Carbon Sequestration Partnership Program.

This report summarizes results of Phase 1 of the MRCSP's research. While the MRCSP region's geologic and terrestrial sequestration options vary in terms of their technological maturity, costs, available capacity, and potential risks, they are all feasible technologies whose cost-effective, large-scale deployment can be envisioned across the Region in the coming decades.

Immense potential terrestrial and geologic storage potential — Based on the MRCSP's analysis to date, the MRCSP Region's deep saline formations and the conversion of marginal lands hold the greatest potential to store large quantities of CO_2.

- The MRCSP region's geology is diverse, encompassing the Northern Appalachian Basin, the Atlantic Coastal Plain, the Michigan Basin, and the Arches Province. The geologic sequestration options of the region are many and varied, including numerous deep saline formations (DSF) available across much of the region, large active and depleted oil and gas fields in the Michigan Basin and the Northern Appalachian Basin, and one of the nation's largest accumulations of coal in the Northern Appalachian Basin.

- This MRCSP region has more than 500 gigatons of potential geologic CO_2 storage potential ($GtCO_2$). This is an immense natural resource that could accommodate many hundreds of year's worth of current CO_2 emissions from the region's large point sources such as electric power plants, cement plants, and refineries.

- The MRCSP Phase I geologic characterization efforts focused primarily on four reservoir classes: deep saline formations, oil and gas fields, unmineable coalbeds, and organic shales.
  - The deep saline formations, especially the Mt. Simon, St. Peter, and Rose Run sandstones, are, by far, the region's largest assets for long-term geologic CO_2 sequestration. The region's deep saline formations could potentially store 450-500 $GtCO_2$.
  - There is at least 2.5 $GtCO_2$ of potential storage capacity in existing and depleted oil and gas fields. Storing CO_2 in these formations via enhanced oil recovery methods in current and recently abandoned regional oil fields could lead to the production of potentially hundreds of millions of barrels of additional oil production.
  - The Northern Appalachian Coal Basin unmineable coalbeds have the potential to store approximately 0.25 gigatonnes of CO_2. Application of enhanced coal bed methane recovery

technologies could add significantly to the amount of natural gas produced from the deep unmineable portions of this resource while securing millions of tons of CO_2 in place.

   o While still in the laboratory research phase if it proves practical to store CO_2 in deep organic shales, the MRCSP region has one of the richest holdings of these deposits in the world. The theoretical storage potential of these organic shales in the MRCSP region could be potentially as large as 45 GtCO_2.

- The MRCSP region's terrestrial sequestration options are also varied as the MRCSP region embraces a number of major land resource areas such as the Eastern Corn Belt, the Upper Mississippi River Basin, the wetlands of the Chesapeake Bay, and the forests of the Appalachian Region. The MRCSP has focused its terrestrial sequestration research on the following five categories as we believe these have the most potential for our region:

   1. Non-eroded prime croplands
   2. Eroded prime croplands
   3. Marginal lands such as forest, pasture, and severely-eroded croplands
   4. Minelands
   5. Wetlands

The following is a summary of the conclusions of our terrestrial sequestration research for the region:

- The MRCSP region is home to as much as 144 million tonnes of storage capacity available annually (MtCO_2/year) in the five land use classes of terrestrial carbon sinks listed above.
- The conversion of marginal crop lands represents nearly 70% (98.6 MtCO_2/year) of the region's total terrestrial sequestration potential. Regional wetlands offer an additional 14.3 MtCO_2/year of terrestrial sequestration potential. Non-eroded crop lands (13.6 MtCO_2/year), eroded crop lands (11.4 MtCO_2/year), and the restoration of mine lands (5.5 MtCO_2/year) offer smaller but still significant terrestrial sequestration potential.
- The largest concentrations of the MRCSP's terrestrial sequestration potential can be found in Indiana (34 MtCO_2/year), Michigan (30 MtCO_2/year) and Ohio (27 MtCO_2/year). Pennsylvania (19 MtCO_2/year), Kentucky (19 MtCO_2/year), West Virginia (10 MtCO_2/year) and Maryland (6 MtCO_2/year) are also home to significant terrestrial sequestration potential.
- The ancillary, non-climate benefits associated with the potential large-scale implementation of terrestrial carbon sequestration within the MRCSP region would be significant and would include improvement in soil quality, reduction in erosion and sedimentation, bio-filtration of pollutants, and decreased rates of CO_2 emissions. Adoption of recommended management practices may enhance crop yield in some soils by 1 to 2 percent annually, decrease the magnitude of soil erosion and non-point source pollution by 70 to 80 percent, and reduce the transport of pesticides and heavy metal in runoff and percolation water by 70 to 80 percent.

Large potential market for geologic sequestration technologies -- The MRCSP region is home to many large anthropogenic CO_2 point sources that are in close proximity to the region's geologic CO_2 storage formations thus making them potential candidates for employing carbon dioxide capture and storage (CCS) technologies in the future.

- Large, stationary point sources of CO_2 (i.e., more than 100kt CO_2/year) within the MRCSP region annually emit 776 million tonnes of CO_2, with an additional 370 million tonnes from distributed sources such as transportation and agriculture. Large fossil-fired (predominantly coal-fired) power

plants account for 84% of the annual CO_2 emissions from the MRCSP's large stationary CO_2 point sources.

- Of the 294 large CO_2 point source locations within the region, 80 percent of the CO_2 emissions come from only 31 percent (or 85) of the facilities. Of these 85 sources, all but 7 are in close proximity to at least one candidate CO_2 storage reservoir, and all but one are within 50 miles of one or more potential storage options.

- The vast majority (94%) of the region's large CO_2 point sources have at least one candidate geologic storage reservoir within just 100 miles; and many of these core regional industrial and power generating assets are able to access several potential deep geologic CO_2 storage options of various types within a much shorter distance.

Carbon dioxide capture technologies already exist which can be deployed across the MRCSP but continued advancement in CO_2 capture technologies would result in significant cost savings -- According to the MRCSP's analysis of commercially available and prospective CO_2 capture systems, amine scrubbing processes are technically capable of capturing CO_2 from key MRCSP large CO_2 point sources such as power plant flue gas, blast furnace off-gas, and cement kiln flue gas. Physical absorption-based CO_2 capture processes would likely be applicable to capturing CO_2 from high-pressure shifted syngas from future coal-fired IGCC power plants, natural gas steam reforming or partial oxidation plants, as well as from blast furnace off-gas in integrated steel mills, provided that it is first pressurized and shifted. Both of these processes are commercially available and have been used for CO_2 capture.

- Because fossil-fired power plants account for 84% of the MRCSP's total CO_2 emissions from large point sources, if there were a need for deep and sustained CO_2 emission reductions, the application of CCS systems to power plants would likely represent a key CO_2 emissions reduction strategy.

- CO_2 capture opportunities in the iron and steel industry should also receive attention as this industry accounts for 9% of the MRCSP's total CO_2 emissions from large point sources and our research suggests that capturing CO_2 from some iron and steel facilities may be less expensive than capturing it from power plants.

- The MRCSP's analysis also shows that there are a number of emerging technologies that show promise for improving the economics of CO_2 capture. The development of more efficient, cost-effective capture technologies is critical, especially considering that CO_2 capture and compression are estimated to account for as much as 60% of the total costs associated with CO_2 capture, transport and geologic for many of the large CO2 point sources within the MRCSP.

CO_2 transport via pipelines is an established technology with an established regulatory framework -- Within the MRCSP Region, dedicated CO_2 pipelines will be the primary means of transporting CO_2 from the point at which is captured to a suitable, long-term geologic storage site.

- The technology to move CO_2 by pipeline has already been developed and there are currently almost 3000 miles of CO_2 pipeline in the United States. The overwhelming majority of this pipeline exists in the Southwestern U.S. where CO_2 is used to increase oil production from fields in the Permian Basin and other oil-rich areas. A few tens of miles of dedicated CO_2 pipelines can be found in the MRCSP Region in Northern Michigan where they are used to move CO_2 to depleted oil fields undergoing CO_2-driven enhanced oil recovery.

- Acquiring rights of way for CO_2 pipelines do not add much to the overall cost of a large CO_2 capture and storage project but acquiring these rights can take many years of negotiations with landowners, performing environmental impact studies, obtaining permits from various regulatory agencies and public service commissions. Within the MRCSP region, a promising approach to minimizing the cost and accelerating the acquisition of needed CO_2 pipeline rights of way could well center on making "shared use" of existing right of way corridors.

- For each state within the MRCSP region, the state public utility commission or public service commission has jurisdiction over gas pipelines and therefore would presumably have a central role to play in granting permits for CO_2 pipelines including safety related requirements. A number of federal agencies might also play roles in setting the regulatory environment for CO_2 pipelines that might operate within the MRCSP or could even play a role in specific decisions about proposed MRCSP CO_2 pipelines.

Regulatory frameworks exist to guide prospective terrestrial and geologic sequestration projects within the MRCSP but these frameworks are likely not optimal given that potential for large-scale deployment of geologic and terrestrial sequestration technologies within the MRCSP was not envisioned when these rules and regulations were created -- No permits for geologic carbon sequestration injection wells have been formally sought and therefore no permits have been granted yet in the MRCSP region, although there have been several inquires to the appropriate state regulatory bodies in Ohio and West Virginia.

- Currently, there are few laws or regulations that are directly relevant to CO_2 storage in deep geologic formations. Until more tailored laws and regulations are enacted, geologic sequestration projects will most likely be governed by regulations built upon the Underground Injection Control (UIC) program established by the federal Safe Drinking Water Act (SDWA). At the present, it is unclear how CO_2 injection will be dealt with under the UIC program. The most often discussed options are classification of CO_2 injection wells as either Class 1 or Class 5 wells or perhaps the creation of a new class to better address the specific needs and circumstances of CO_2 injection wells. Despite the comprehensive regulatory scheme developed for the UIC program, a possible gap exists in regard to geologic CO_2 sequestration. Specifically, there is no federal requirement for monitoring the actual movement of fluids or gas within the injection zone, nor are there requirements for monitoring in overlying layers to detect leakage. Given the long time frame for geologic sequestration, monitoring for migration will likely be required.

- As with oil and natural gas production, surface and subsurface property rights will affect the regulation of geologic sequestration, the cost of transportation and storage of CO_2, and will be central in determining liability. Because property rights are governed by state law and often develop through state court precedent, it is currently difficult to predict precisely how property issues will affect geologic carbon sequestration.

- To date, terrestrial sequestration has been carried out under private contracts. There is no direct regulation of such private contracts. Due to the public interest of the subject matter, however, there is indirect regulation of private contracts. Although terrestrial sequestration remains largely private, there is still a public interest in encouraging sequestration and monitoring sequestration projects. Thus there will be a role for regulation. Some regulatory issues will involve how to encourage land and forest use that sequesters carbon and discourage practices that release carbon. Regulations could restrict land use practices and require replanting of harvested forests (e.g., via conservation

easements), provide for subsidies and taxes, and/or stipulate how property rights in sequestered carbon are obtained and transferred. In the MRCSP Region, all seven states have conservation easement programs that could be expanded to include carbon sequestration or could be used as a model for new programs.

Key stakeholders have limited awareness of carbon sequestration and the potential role it might play within the MRCSP Region. This finding from the MRCSP's Stakeholder Outreach and Education program holds true across all of the MRCSP states.

- Public officials acknowledged that carbon sequestration was a relatively new and unknown issue both for them and the general public.

- Leaders of environmental groups in the seven states typically appeared more knowledgeable about the topic and expressed interest in MRCSP activities. However, most acknowledged that their resources were limited, that they had more urgent environmental priorities to address, and that carbon sequestration was currently not high on the public's radar screen—although they noted that this could change as the field demonstrations made the issues more immediate and site-specific. Some emphasized that it was important for the MRCSP to demonstrate openness in its activities and in its provision of information.

- In general, the topic of terrestrial sequestration appeared to be viewed favorably as a "green" approach. Where issues were raised about geologic CO_2 storage, they were typically concerned with the containment of injected carbon dioxide in geologic sequestration.

Phase II of the MRCSP will transform the theoretical potential identified in Phase I into high-value added assets for the Region --The upcoming MRCSP Phase II (2005-2009) research program will center on taking the large, theoretical sequestration potential identified in the Phase I research program (2003-2005) and through a series of state-of-the-art field validation tests show how the region's large, well distributed and competitively priced sequestration potential can be utilized to simultaneously advance economic growth and environmental protection. The planned set of activities in the MRCSP Phase II plan include:

- The MRCSP will conduct two or more small scale CO_2 injection field tests in the region's deep geologic reservoirs to demonstrate the safety and effectiveness of geologic storage systems.

- The MRCSP will also conduct small scale field validation tests of terrestrial sequestration across the region to show how the stored carbon can be measured and monitored and how carbon credits could be traded in voluntary greenhouse gas markets.

- Another key component of Phase II will be an innovative "piggyback drilling" program pioneered by Battelle which will allow the MRCSP to leverage the ongoing and extensive investments made by the local oil and gas drilling companies to gather "real world" sequestration-related data such as core samples from deep geologic formations.

- Phase II will continue the crucial work initiated in Phase I to map and define the sequestration potential of the region, seek to understand key regulatory issues and undertake a first-ever systematic approach to en the region, seek to engage and inform stakeholders across the entire region about this important class of technologies.

Key terrestrial and geologic sequestration activities are already happening within the MRCSP — Not only is there tremendous potential for carbon sequestration technologies to deploy in the future within the MRCSP, but at a very real level, one can say this is already happening and that the MRCSP region represents one of the leading locales worldwide for the early implementation of these critical carbon management technologies. The MRCSP Region is home to:

- The world's first geologic storage experiment located at an operational power plant (the Mountaineer coal-fired power plant),

- One commercial power plant that is already capturing CO_2 with an amine scrubber (the AES Warrior Run coal-fired power plant) and at least, three commercial IGCC units in advanced stages of planning are likely to be built in the region.

- More than 10 miles of dedicated CO_2 pipelines serving commercial CO_2-driven enhanced oil recovery in Michigan,

- The region has an extensive history of restoring mine lands and already has commercial experience with implementing no-till agricultural methods and other promising terrestrial sequestration options.

Clearly, terrestrial and geologic sequestration technologies offer the prospect of providing tremendous leverage for the region's economy if deep reductions in greenhouse gases are needed. The remainder of this report focuses more specifically on the potential for terrestrial and geologic sequestration technologies to deploy within the MRCSP region.

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Nomenclature

C	Carbon as elemental carbon as opposed to as CO_2.
CEC	Carbon Exchange Capacity
CH_4	Methane
CO_2	Carbon dioxide
CRP	Conservation Reserve Program
CT	Conventional Till
DPM	Decomposable plant material
ESRI	Environmental Systems Research Institute
FIPS	Federal Information Processing Standards
GIS	Geographic Information System
Ha	Hectare
IPCC	Intergovernmental panel on Climate Change
Mg	Megagrams, 1 Mg $=10^6$ grams or 1000 metric tonnes
Mha	One million hectares
MRCSP	Midwest Regional Carbon Sequestration Partnership
MT	Mulch Till
N_2O	Nitrogen oxide
NLCD	National Land Cover Dataset
NPP	Net Primary Production, Net Primary Productivity
NRCS	Natural Resources Conservation Service
NT	No Till
Pg	Petagram, one petagram $= 10^{15}$ grams or one gigatonne
RPM	Resistant Plant Material
RT	Reduced Till
SMCRA	Surface Mining Control and Reclamation Act of 1977
SOC	Soil Organic Carbon, defined as the total organic carbon of a soil exclusive of carbon from undecayed plants and animal residues (http =//www.fao.org/gtos/tems/variable_show.jsp?VARIABLE_ID =34)
SOCRATES	Soil Organic Carbon Reserves And Transformations in EcoSystems
SOM	Soil Organic Matter, broadly defined as all living organisms (microorganisms, earthworms, etc), fresh residues (old plant roots, crop residues, recently added manures), and well-decomposed residues (humus). (http =//www.akron.ars.usda.gov/fs_soil.html)
STATSGO	State Soil Geographic Data Base
Tg	Teragrams, 1 Tg $=10^{12}$ grams or 1 million metric tonnes
WRP	Wetlands Reserve Program

1.0 INTRODUCTION : CLIMATE CHANGE AND CARBON MANAGEMENT

To date, 189 nations, including the United States, have ratified the 1992 United Nations Framework Convention on Climate Change, which states as its goal, "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[1] While there is general agreement that stabilization of greenhouse gas concentrations is the best way to frame decisions about addressing climate change, there is no scientific consensus yet regarding the ideal levels of atmospheric concentrations or the potential impacts associated with higher concentrations.

Carbon dioxide, or CO_2, is the most important greenhouse gas (GHG) in terms of its contribution to climate change. At the beginning of the Industrial Revolution concentrations of CO_2 in the atmosphere were approximately 270 parts per million (ppm). Currently, CO_2 concentrations are around 370 ppm and rising. Whether the appropriate stabilization level is as low as 450 parts per million or as high as 750 ppm, the goal of stabilization carries with it requirements to produce and sustain *deep reductions* in GHG emissions over the course of this century.[2] Most importantly, stabilization will require fundamentally new and cleaner ways of generating and using the energy that drives the economies of Maryland, the United States, and the world.

The technical literature identifies a number of major options for reducing CO_2 emissions that can be categorized under energy efficiency, renewable energy, nuclear power, fuel switching, and carbon sequestration. In the last few years, a number of technical studies suggest that a broad portfolio of emissions mitigation options will be needed to allow society to address the challenge posed by climate change in a cost effective manner.

The wide-scale deployment of geologic and terrestrial sequestration technologies – in particular – appears to be key to bringing about sustained and significant reductions in CO_2 emissions at least cost.[3] The major geologic sequestration options being considered include sequestration of CO_2 in depleted oil and gas fields, deep saline formations, deep basalt formations, and deep unmineable coal seams. Key terrestrial sequestration technologies under investigation include the conversion of marginal lands to forests, adoption of soil conservation practices in grazing and eroded lands, adoption of low- or no-till agricultural practices, and restoration of degraded mine lands through planting cover crops and other management practices. The adoption and application of these terrestrial sequestration practices often carry with them ancillary positive benefits, such as increased agricultural productivity or reduced run-off.

There is an increasing realization that no single option is universally applicable and that a diverse technology portfolio needs to be available for application based on local conditions. This "no silver bullet" observation is true when applied to the entire world and is true for the State of Maryland. Both the world as a whole and Maryland will need a broad portfolio of energy and carbon management technologies to move forward into the future. While geologic and terrestrial sequestration options vary in

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[1] United Nations Framework Convention on Climate Change. List of Signatories & Ratification of the Convention Parties http://unfccc.int/resource/conv/ratlist.pdf

[2] Wigley, T.M.L., R. Richels., and J.A. Edmonds. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature*, Vol. 379(6562): 240-243.

[3] See for example, Edmonds, J., J. Clarke, J. Dooley, S. H. Kim, S. J. Smith. 2004. "Stabilization of CO2 in a B2 World: Insights on the Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies," *Energy Economics*: Special Issue EMF 19 Alternative technology strategies for climate change policy Edited by John P. Weyant. Volume 26, Issue 4, Pages 517-537.

terms of their technological maturity, costs, available capacity, and potential risks, they are all feasible technologies whose large-scale deployment can be envisioned within Maryland and the surrounding states in the coming decades.

2.0 ABOUT THE MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

The Midwest Regional Carbon Sequestration Partnership (MRCSP) is a public/private consortium led by Battelle. Its mission is to assess the technical potential, economic viability, and public acceptability of carbon sequestration technologies within its region and identify viable pathways for their deployment.

The MRCSP began in late 2003 with a region consisting of five states (Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia) and 22 member organizations. In mid 2004 the region was expanded to seven states by adding Maryland and Michigan. Following expansion, the partnership had grown to 38 members including leading universities in the region, state geological surveys, non-governmental organizations and private companies. Table 2.1 lists the organizations making up the MRCSP at the conclusion of Phase I in September 2005.

Table 2.1.   MRCSP Members (Conclusion of Phase I Research, September 2005).

Industry Partner	Research Partner
AES Warrior Run	CONSOL Energy
Alliance Resource Partners (Mettiki Coal)	Indiana Geological Survey
American Electric Power	Kentucky Geological Survey
Arch Coal	Keystone Center
Baard Energy	Maryland Geological Survey
Babcock and Wilcox	Michigan State University
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DTE Energy	Purdue University
First Energy	The Ohio State University
Maryland Energy Administration	University of Maryland
Monsanto	West Virginia Geological Survey
Ohio Coal Development Office	West Virginia University
of the Ohio Air Quality Development Authority	Western Michigan University
Ohio Corn Growers Association	
Ohio Forestry Association	
Ohio Soybean Council	
Ohio Turfgrass Foundation	
Scotts Company	

The MRCSP is one of seven such partnerships across the U.S. that make up the U.S. Department of Energy (DOE) Regional Carbon Sequestration Partnership Program. The makeup of the seven partnerships at the completion of the Phase I research (September 2005) is shown in Figure 2.1.
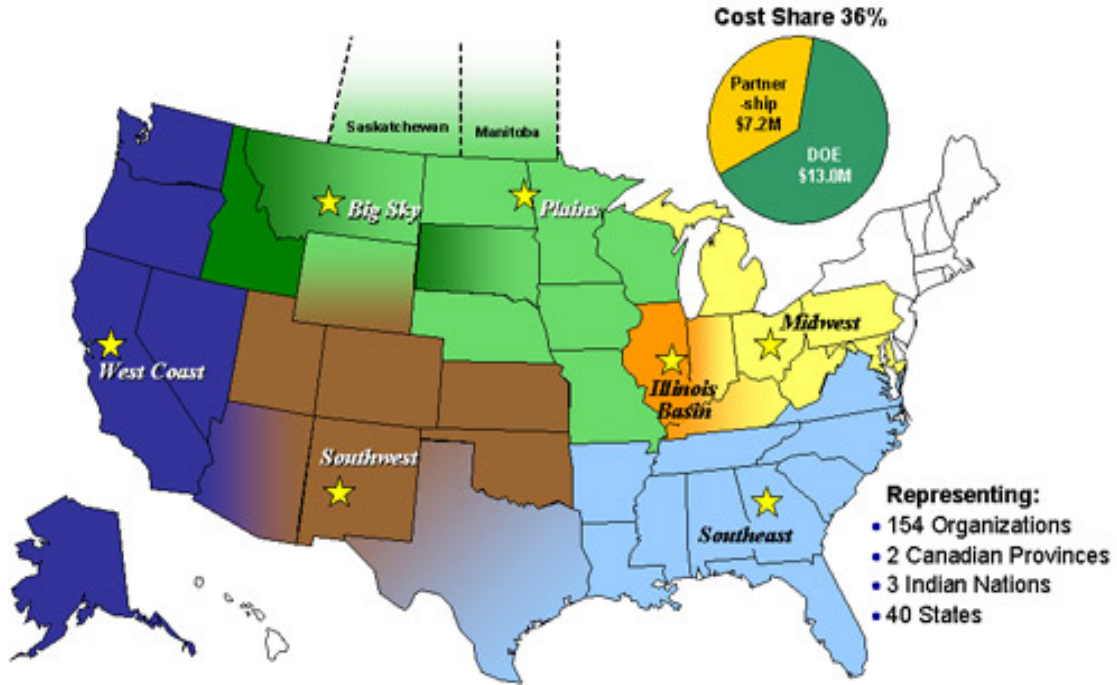
Figure 2.1. Makeup of the Seven DOE Regional Partnerships (c. September 2005).

The U.S. DOE through the National Energy Technology Laboratory (NETL) contributes the majority of funds for the MRCSP's research accounting for 68.62% of the total funding or $2.41 million for Phase I under Agreement No. DE-FC26-03NT41981. The next largest contributor is the Ohio Coal Development Office within The Ohio Air Quality Development Authority under Agreement No. CDO/DE-02-17. The MRCSP also receives funding from all of the other members listed above in Table 2.1.

3.0 ABOUT THE MRCSP REGION

Socioeconomic Characteristics of the MRCSP Region

The MRCSP region encompasses the states of Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia as shown in Figure 3.1. Representing 7% of the total U.S. land mass, this seven-state region is home to almost 18% of the U.S. population, making it one of the most densely populated regions of the country (U.S. Census Bureau, 2005). As shown in Figure 3.2, two-thirds of these 51.5 million people reside in Pennsylvania, Ohio, and Michigan alone.

This region maintains a strong economy, with a 2003 combined gross regional product (GRP) of 1.8 trillion dollars, accounting for 16.5 percent of the total U.S. GDP in the same year (BEA, 2005). Since gross state product is closely linked to the size of the workforce (i.e., population), the composition of GRP by state, which is shown in Figure 3.3, looks very similar to the distribution of population across the region.
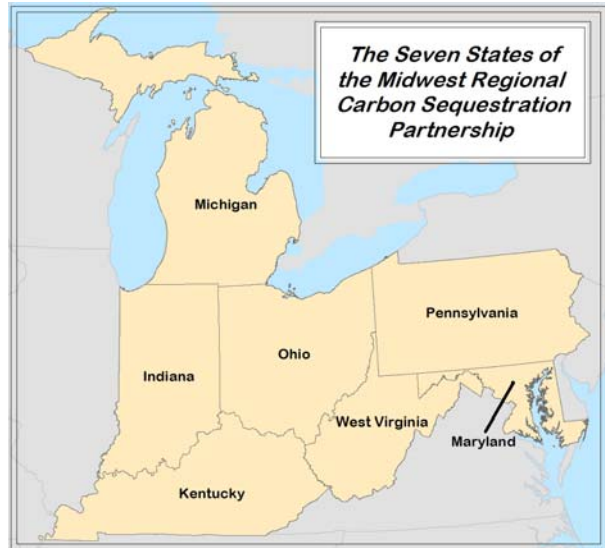
Figure 3.1. The seven states of the Midwest Regional Carbon Sequestration
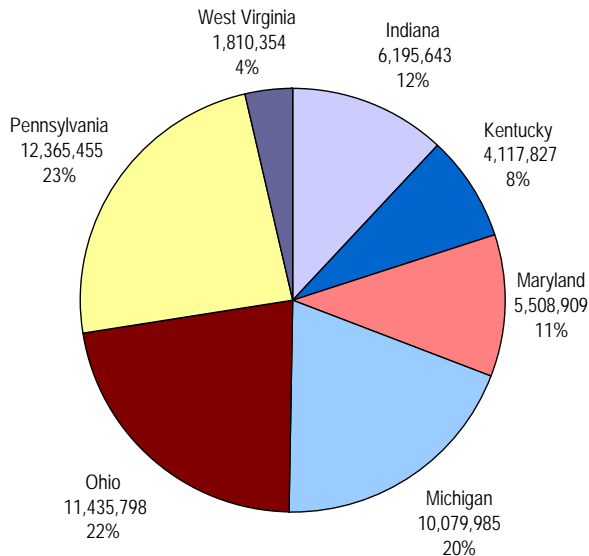
Figure 3.2. Population of the MRCSP Region by state (U.S. Census Bureau).
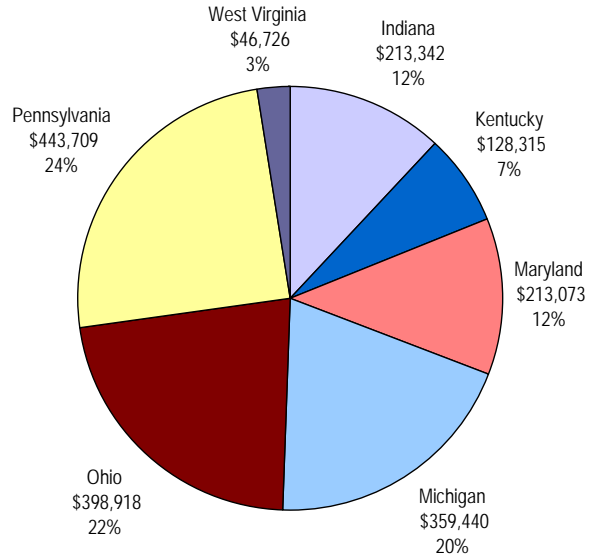
Figure 3.3. Gross state products of the MRCSP Region (U.S. Commerce Department).

Strong Industrial Backbone

Goods-based industries (e.g., agriculture, mining, construction, manufacturing, trade, utilities, and transportation), employ roughly half of the region's workforce (US Census Bureau, 2005). The manu-facturing sector is a driving force of the region's economy, as shown if Figure 3.4, and provides 18.4 percent of the gross regional product (far ahead of the national average). In fact, these seven states account for nearly a quarter of the nation's total manufacturing GDP output, particularly in durable goods, for which twenty-six percent of the U.S. total comes from the MRCSP region. Sixty-one percent of the dollars created by the nation's motor vehicle and parts manufacturing industries come from this region (largely from Michigan). Primary metals manufacturing within the seven MRCSP states, including iron and steel foundries, account for 45 percent of the primary metals income generated in the U.S. Non-oil and gas mining operations within the MRCSP region account for nearly a third of the mining in the entire U.S. (in GDP terms), and is led within the region by West Virginia. These industries are energy intensive and are responsible for a significant percentage of the region's greenhouse gas emissions.
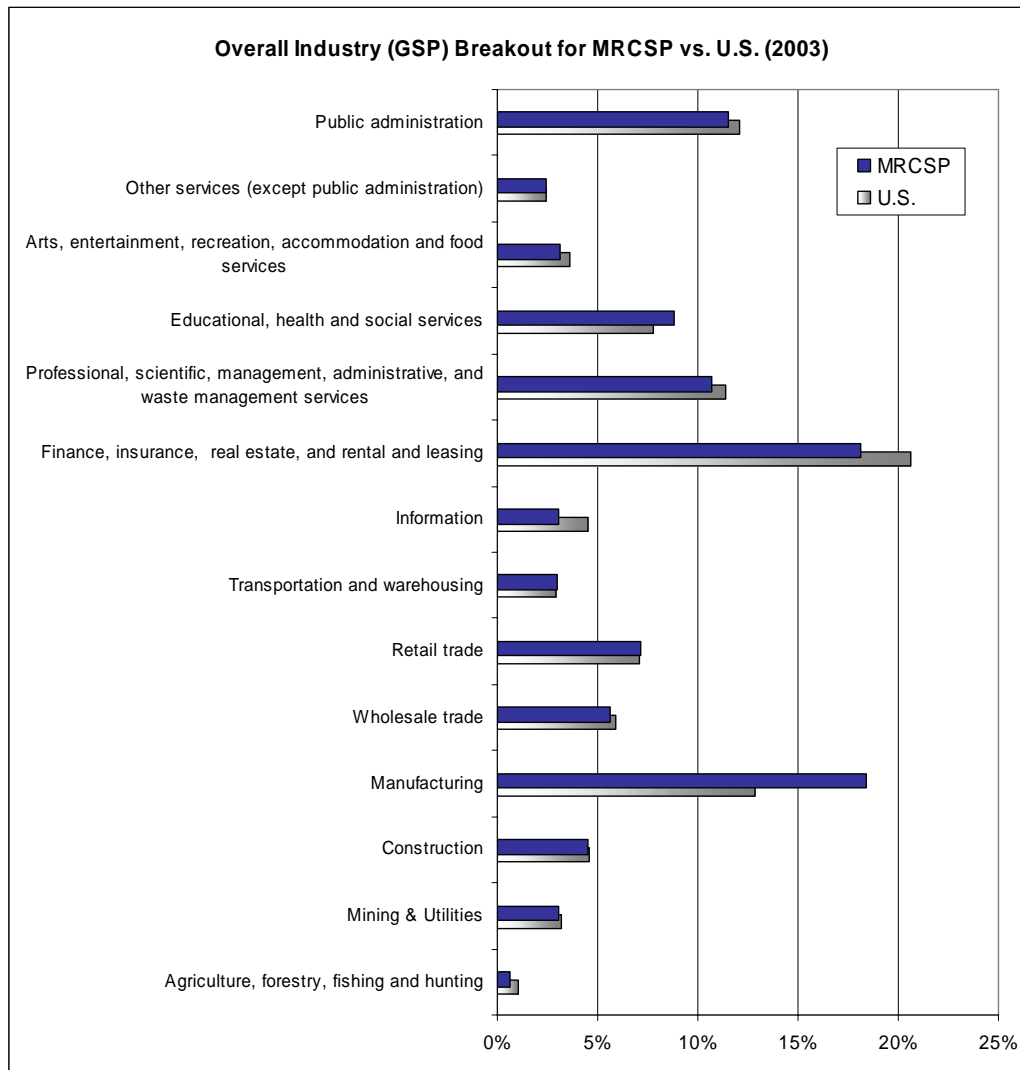
Figure 3.4. Industrial contribution to gross regional product for the MRCSP and the U.S. (U.S. Census Bureau).

Electric Power Sector

Although electric utilities employ only a small fraction of the region's working population, and directly contribute a small fraction of the overall GRP, they enable many of the other economic sectors to thrive and support the quality of life enjoyed by the region's population. However, the generation of electricity does account for largest portion of the greenhouse gases emitted in the seven Partnership states. The region possesses significant indigenous coal resources that allow it to produce some of the least expensive electricity in the nation[1], which, in turn, drives the region's strong manufacturing sector. Burning coal, however, is one of the more carbon-intensive means of generating electric power, and the coal that supports the region's strong economy is also responsible for much of the region's greenhouse gas emissions.
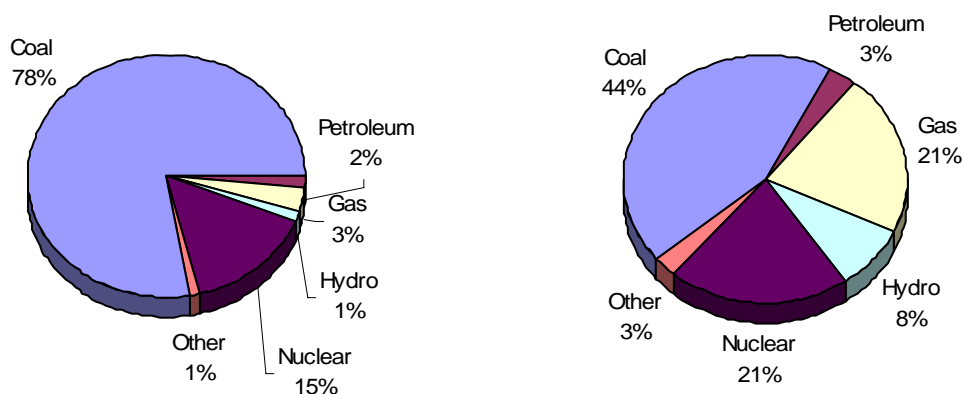
Figure 3.5. Electric power generation fuel mix for (left panel) the MRCSP and (right panel) the U.S. (EIA, 2004).

During 2003, the region's power plants generated 828 million megawatt hours of electricity, 21 percent of the national total (EIA, 2004). Figure 3.5 shows the electric power generation makeup for the region as compared to the rest of the nation, and illustrates the heavy reliance on coal within the region, which contributes 78 percent of the region's total generation as compared to only 44 percent for the rest of the country. The individual generation mix for each of the seven states is shown as Figure 3.6. While nuclear and natural gas-fueled power production makes up a significant portion of electric generation within the MRCSP region, coal-based generation accounts for over half of the electricity produced in each state; and in Indiana, Kentucky, Ohio, and West Virginia, coal fuels over 90 percent of total electric generation. Figure 3.7 presents relative coal consumption and production, along with population and gross state products, for the seven states of this region.

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[1] The average electricity price for 6 of the MRCSP states is below the national average of 7.42¢/kWh. Three of the states – Kentucky, West Virginia, and Indiana – rank among the five least expensive (EIA Electric Power Annual 2003).
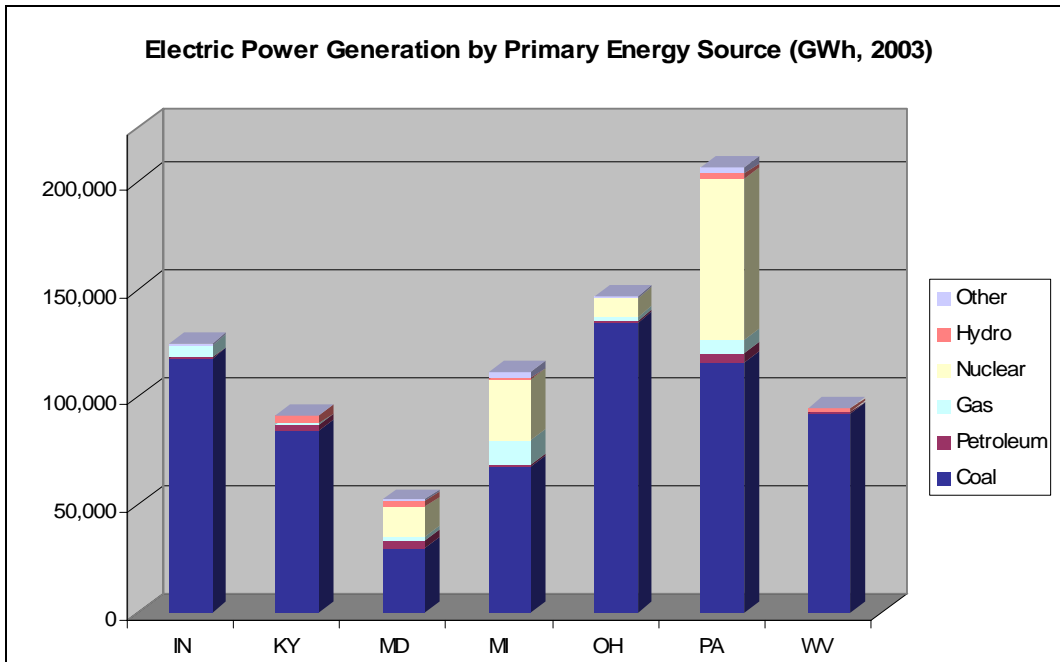
Figure 3.6. Electric power generation by primary energy source (GWh 2003) (EIA Electric Power Annual).
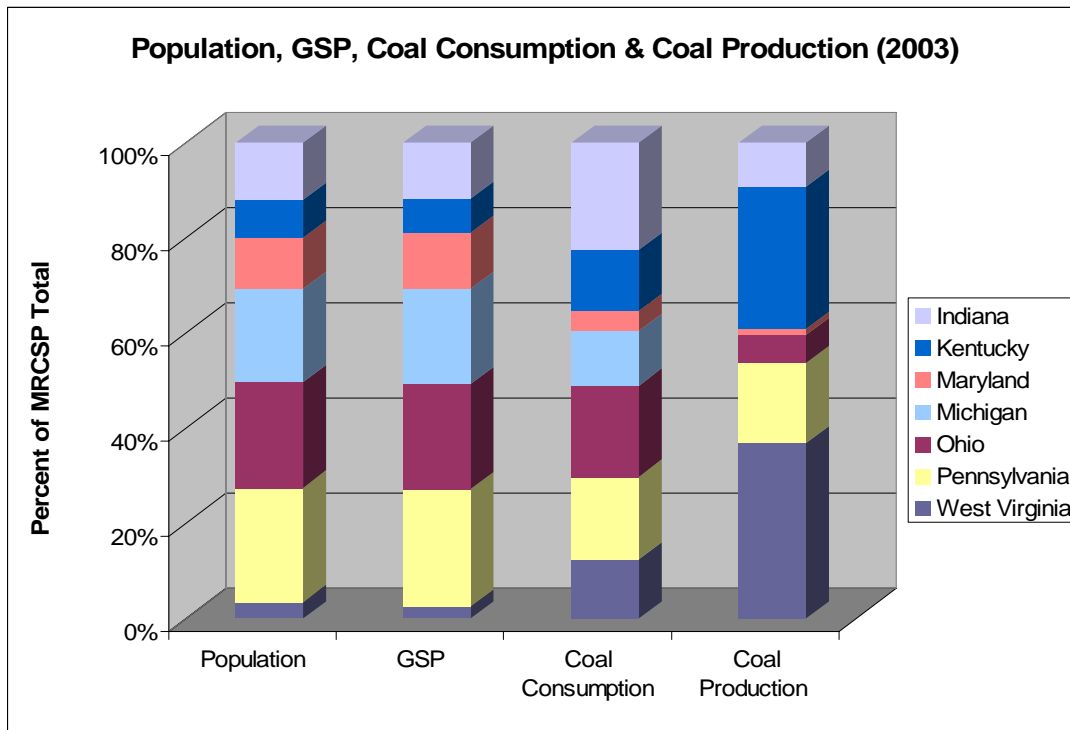
Figure 3.7. Comparison of state contributions to MRCSP Regional values for population, gross regional product, coal consumption, and coal production (U.S. Census Bureau, U.S. Bureau of Economic Analysis, EIA Coal Data Tables).

Emissions of Greenhouse Gases within the MRCSP Region

Greenhouse gases include those gases that trap solar radiation in the earth's atmosphere, including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, and other minor gases. Although carbon dioxide (CO_2) may not be the most potent greenhouse gas when compared molecule per molecule against others such as methane, it is overall the most significant greenhouse gas due to the sheer volume of CO_2 that is produced as a by-product of so many of the combustion and conversion processes that have become key components of modern industrial economies. For this reason, the following analysis focuses primarily on carbon dioxide, and includes methane and other greenhouses gases where data are available.

CO₂ Emissions by Source Type

Distributed Sources
34%

Stationary Sources
66%

Figure 3.8. **Split of distributed vs. stationary source emissions for the MRCSP Region.**

Distributed Sources

Distributed emissions sources are defined as those sources that do not concentrate their emissions at a single, stationary point. Transportation, agriculture, waste disposal in landfills, combustion of fuel for heating homes and offices, and land use practices are all considered sources of distributed emissions. Though these emissions are typically released at lower concentrations and over a larger area than the emissions of a large power plant or industrial facility, distributed emissions account for roughly one third of all the CO_2 emissions in the MRCSP region.

The best state-level estimates for emissions from distributed sources are based on the state emissions inventories published by the United States Environmental Protection Agency (EPA) (EPA, 2003). These inventories are voluntarily submitted by states, and then standardized and formatted by EPA; and as such, complete inventories are unavailable for Michigan and West Virginia. For Michigan, EPA has instead published CO_2 emissions numbers based on state energy fuel consumption data from the Combined State Energy Data System. State inventory data are not published, however for West Virginia, and the values listed here are instead based upon the partial emissions data submitted to EPA, which were obtained directly from EPA officials (Denny, 2004). A description of each major component of the region's distributed emissions, along with their contribution to overall greenhouse gas emissions.

Transportation

Transportation is a major source of greenhouse gas emissions nationwide, comprising 27% of all greenhouse gas emissions and 32% of all CO_2 emissions in the United States (EPA, 2005). In 1990, the most recent year for which individual state level data are available through EPA, transportation accounted for 70.8 million metric tons carbon equivalent (MMTCE) of emissions in the MRCSP Region. In the same year, emissions from transportation made up over half of all distributed-source greenhouse gas emissions in the region (see Figure 3.9) and twenty percent of the region's total emissions, from both distributed and stationary sources. Twenty-three percent of all the CO_2 emissions within the seven states were from transportation. Such emissions are closely tied to the strength of the region's economy. The manufactured goods and resource-based products that the region produces must be moved to market, and the individuals that make up the region's strong labor force must commute to work. According to the U.S.
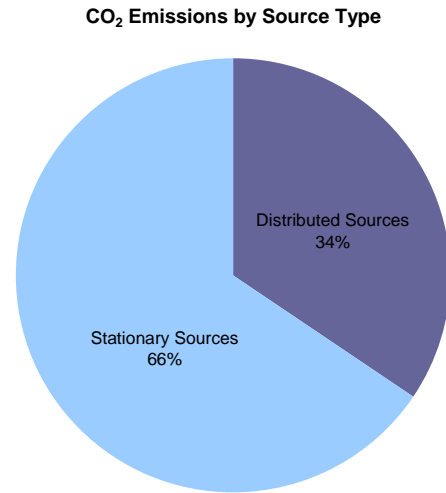
Bureau of Transportation Statistics (2005), as of 2001, there were 44.2 million vehicles registered within the seven states of the MRCSP region (26.5 million autos, 16.6 million trucks, 960,000 motorcycles, and 157,000 buses). In that same year, the seven states of the region accounted for nearly 500,000 vehicle miles traveled or 17.9% of all vehicle miles traveled in the U.S.
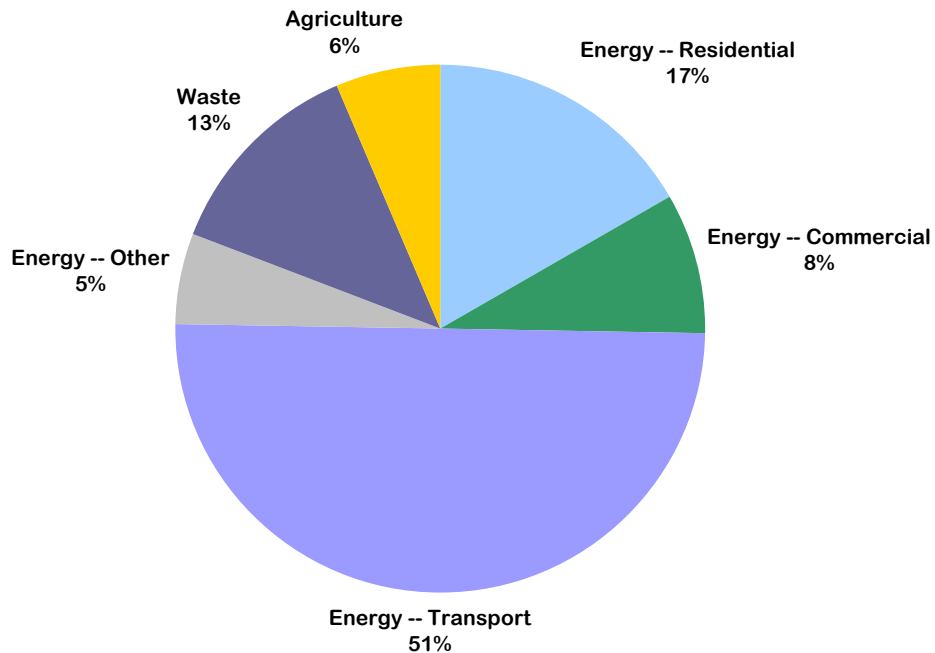
Figure 3.9. Portion of total distributed emissions within MRCSP Region by type (EPA 1990).

Agriculture

Though agriculture only accounts for about 1.4 percent of the region's workforce, 42 percent of the land is used for agricultural purposes, as shown in Figure 3.10 (USDA, 2004). In some states the percentage is much higher; for example, in Indiana 2 out of every 3 acres are used for some sort of agriculture.

Practices associated with agriculture – including animal husbandry and the burning of crop wastes – also produce greenhouse gas emissions. Again, these emissions are spread over large areas, and cannot be identified as distinct points on a map. Still, agricultural emissions accounted for six percent of the region's total distributed emissions in 1990, or 9.0 MMTCE. The primary emissions associated with agriculture are carbon dioxide, methane, and nitrous oxide. Note that no agricultural emissions were reported by Michigan and that for West Virginia the numbers reflect only emissions caused by the burning of crop wastes.

Figure 3.10. **Left panel: Distribution of MRCSP agricultural lands by state; right panel: total land area in each state and in the region with designated agricultural land use (USDA, 2004).**
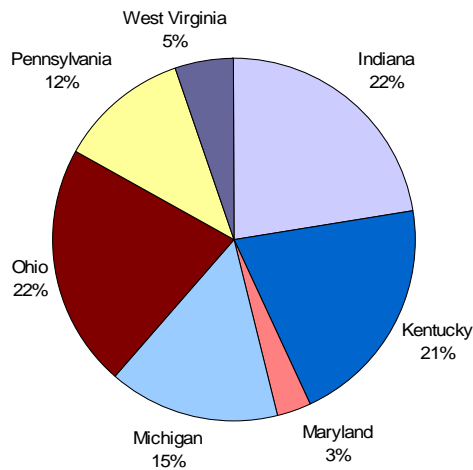
State	Agricultural areas (acres)	% of State's area used for agriculture
Indiana	15,058,700	66%
Kentucky	13,843,700	54%
Maryland	2,077,600	33%
Michigan	10,143,000	28%
Ohio	14,583,400	56%
Pennsylvania	7,745,300	27%
West Virginia	3,584,700	23%
MRCSP	**67,036,400**	**42%**

Residential and Commercial Energy Use

While emissions associated with residential and commercial energy utilization are created at distinct, stationary locations, greenhouse gases produced by burning heating oil, natural gas, and biomass in this way are typically too small to be tracked in the same manner as large, stationary emissions sources. And because the emissions from residential and commercial sources are calculated based on aggregated fuel combustion statistics, they are typically treated as distributed sources. Typically, these emissions are driven by factors including population and economy (number of households and businesses) as well as climate and the fuel mix serving the energy needs of the region. In 1990, residential energy use accounted for 23.7 MMTCE, or seventeen percent of total distributed greenhouse gas emissions. Commercial energy use created another 12.0 MMTCE, or an additional eight percent of total distributed emissions for the region.

Waste Disposal

Methane produced by the anaerobic decomposition of organic matter in landfills makes up the vast majority of greenhouse gas emissions associated with waste disposal.[1] In 1990, waste disposal accounted for 18.1 MMTCE within these seven states, or thirteen percent of the total distributed source emissions for the MRCSP region. Ninety-nine percent of these emissions were methane.

Land Use

"Land use" as defined by the U.S. EPA greenhouse gas emissions inventories, gives states the opportunity to include negative emissions that arise from the natural sequestering of carbon in sinks such as forests and grassland. In 1990, the MRCSP region (exclusive of Michigan and West Virginia, for which

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[1] In fact, landfills are the largest source of anthropogenic methane emissions in the U.S., accounting for 34% of total methane from all sources (EPA 2005).

estimates are not currently available) contributed 10.0 MMTCE of negative emissions, essentially removing this amount of carbon directly from the atmosphere through photosynthesis, and offsetting roughly three percent of the region's total greenhouse gas emissions. It is a goal of the MRCSP to examine a number of ways in which such natural terrestrial sequestration processes can be enhanced within the region, for example via shifting agricultural practices, reclaiming degraded lands, and conserving wetlands.

Stationary Sources and CO_2 Emissions

As part of the ongoing research effort for the MRCSP, a database of large anthropogenic CO_2 point sources located within the region is being compiled. This not only furthers the understanding of the CO_2 emissions profile of the region, but will also feed into various analyses of CO_2 sequestration opportunities that might be examined. The collection and refinement of this point source data is a continuous task within the MRCSP research program, and new and improved data on point sources, their emissions rates and locations, will continue to be updated and as information becomes available. Additionally, due to the changing needs within the region as well as the growing economy of both the region and the U.S. as a whole, outdated facilities are being retired and new ones are being built to take their place as well as to keep up with increasing demand.

As of the publication of this report, there are a total of 565 CO_2 point sources being tracked within the region, with total estimated emissions of nearly 782 million metric tons of CO_2 ($MtCO_2$) per year. As seen in Table 3.1, these include facilities representing a number of key sectors, including electric power generation, iron and steel, chemical, and cement production, and energy products processing and refining. Individual annual plant emissions range from near zero up to almost 17 $MtCO_2$. Beyond those sources listed here, there are an additional 78 sources that have been identified but lack sufficient information to adequately estimate emissions at this time.

Data Development

These data have been compiled from a number of sources. Existing CO_2 source inventories (IEA GHG 2002, IEA GHG 2005) have been augmented with additional and more recent data from a number of other sources. These include updated data on electric generating facilities from the latest EPA Clean Air Markets Division's emissions database (EPA, 2005), data on gas processing facilities from CONSOL Energy (Winschel, 2005) and Western Michigan University (Harrison, 2005), and updated status of ethanol production facilities within the region from the Renewable Fuels Association (2005). Additionally, an effort was made to further refine the locations of these sources with the dataset, as defined by latitude and longitude coordinates; a significant effort was made to enhance the accuracy of this spatial information, in order to provide a better starting point for analyses of potential sequestration opportunities.

Table 3.1.   **Summary of all MRCSP CO$_2$ point sources by sector.**

Type of Facility	Number of Facilities with CO$_2$ Emissions Estimates Available	Minimum Emissions from Single Facility (ktonne/y)	Maximum Emissions from Single Facility (ktonne/y)	Average Emissions from Single Facility (ktonne/y)	Total Emissions from All Facilities (ktonne/y)	Percent of Region's Total Emissions from this Facility Type (ktonne/y)
Ammonia	1	21	21	21	21	<0.1%
Cement	25	78	1,458	594	14,854	1.9%
Ethanol	5	11	278	100	502	0.1%
Ethylene	3	119	492	320	959	0.1%
Ethylene Oxide	1	18	18	18	18	<0.1%
Gas Processing	35	18	3,343	490	17,141	2.2%
Hydrogen	9	3	139	50	448	0.1%
Iron and Steel	33	9	9,047	2,131	70,327	9.0%
Power	435	0	16,839	1,408	657,636	84.1%
Refineries	18	38	3,950	1,104	19,863	2.5%
TOTAL	**565**	**0**	**16,839**	**1,384**	**781,769**	**100.0%**

For all of the sources except electric power plants, annual CO$_2$ emissions were estimated from publicly available production data using appropriate emissions factors, depending on source type and process. In general, these data are current to the latest year of availability, which for most sectors is 2000 or 2001. For the electric power sector, CO$_2$ emissions as reported to DOE and EPA are available for most plants.[1] Initial data current to 2000 were subsequently updated using the latest available data from the EPA (USEPA, 2005), which includes reported emissions current to 2003, plus several additional years of data. Using this data, a representative annual emissions value was calculated for each facility, by eliminating the minimum of the most recent 4 years of available data and averaging the rest. This was performed in order to best represent a typical emissions value for each plant, and avoid assigning data for a year during which a plant may have experienced an extended maintenance shut-down.

Large CO$_2$ Point Sources

Included in this dataset across all source types are a number of rather small point sources, for which the application of CO$_2$ capture technologies would be cost prohibitive at this time. Essentially, there is a point at which a source is just too small (i.e., emits too little CO$_2$) to be considered a feasible candidate for the deployment of CO$_2$ capture and storage technologies. Therefore, the primary focus of the MRCSP research team has been on "large" sources which may be more readily able to consider capturing their CO$_2$, and the same threshold emissions value of 100,000 tons per year of CO$_2$ (100 ktCO$_2$/yr) has been applied as has been established in other CO$_2$ source inventory studies (IEA GHG 2002, IEA GHG 2005).

Therefore, excluding those point sources with annual emissions that are estimated to be less than 100 ktCO$_2$, reduces the set of large CO$_2$ point sources to 294 (as of the time this report was prepared). Total annual emissions from these large point sources are 776 MtCO$_2$. Table 3.2 lists the breakout of these sources within the region by type number of sources, range of emissions, and percent contribution from each type of facility. As shown more clearly in Figure 3.11, the electric generating facilities dominate the CO$_2$ emissions from these large point sources, accounting for 84% of the CO$_2$ emissions from these large CO$_2$ point sources within the MRCSP region. Iron and steel foundries contribute the next largest fraction of CO$_2$ (9%), followed by petroleum refineries, gas processing facilities, and cement plants. Ethylene,

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[1] Note: more detailed unit-level data are available and have been compiled for most of the power plants, and may be utilized for more detailed future analyses. However, at this time, to be consistent with the other sources in the region, data for each generating facility are being tracked and reported here at the aggregate plant level.

ethanol, and hydrogen plants account for the remaining 0.2% of the region's total CO_2 from these large point sources.

Table 3.2.   Summary of large CO_2 point sources (each 100+ ktCO₂/yr).

Type of Facility	Number of Facilities with CO_2 Emissions Estimates Available	Minimum Emissions from Single Facility (ktonne/y)	Maximum Emissions from Single Facility (ktonne/y)	Average Emissions from Single Facility (ktonne/y)	Total Emissions from All Facilities (ktonne/y)	Percent of Total Emissions from this Facility Type (ktonne/y)
Ammonia	0	0	0	0	0	0.0%
Cement	23	313	1,458	639	14,688	1.9%
Ethanol	2	136	278	207	414	0.1%
Ethylene	3	119	492	320	959	0.1%
Ethylene Oxide	0	0	0	0	0	0.0%
Gas Processing	21	101	3,343	788	16,558	2.1%
Hydrogen	1	139	139	139	139	<0.1%
Iron and Steel	23	125	9,047	3,031	69,718	9.0%
Power	207	100	16,839	3,160	654,111	84.3%
Refineries	14	111	3,950	1,402	19,622	2.5%
Total	**294**	**100**	**16,839**	**2,640**	**776,209**	**100.0%**
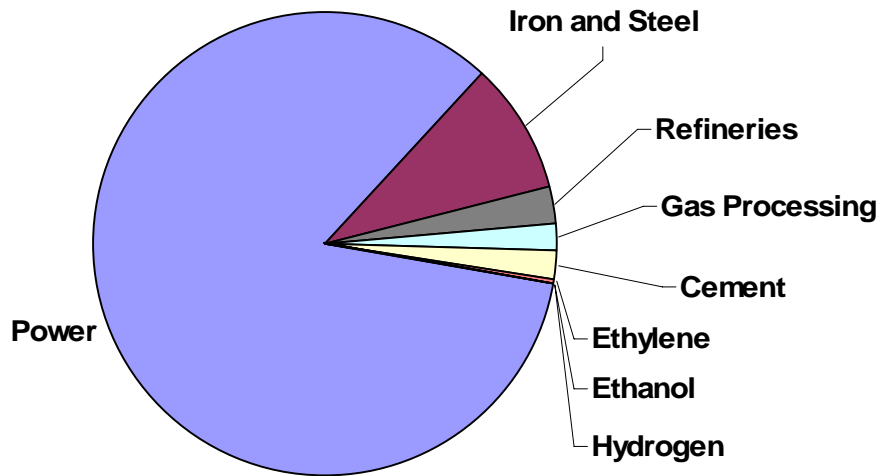
Figure 3.11.   Fuel mix of large CO_2 point sources (each 100+ ktCO₂/yr).

In addition to understanding how many of these sources there are and how much CO_2 they emit, it is also important to understand how they are distributed across the region. A map of these large CO_2 point sources is presented in Figure 3.12. This shows not only the location of each source, but identifies the type of facility by color code and relative size of annual emissions by size of the symbol. This map reinforces the fact that most of the sources are large fossil-fired power plants (most of which, as described earlier, are coal-fired). From the map it is also apparent that certain areas within the region have a

particularly high concentration of these sources (e.g., along the Ohio River, northwestern Indiana, and southeastern Michigan). However, given the high density of sources in such areas, it can be difficult to ascertain the full scope of CO_2 emissions. Figure 3.13 shows the results of a CO_2 density calculation performed on this data to more clearly show the CO_2 emissions intensity of different areas within the MRCSP region. This density map, calculated based on a 50-mile radius from each point across the region, sums all CO_2 emissions within the 50-mile radius and reports the resulting value at its grid point. The dark areas of the figure show areas of highest concentrations of CO_2 emissions from these large point sources, providing further validation of those areas noted from inspection of the previous map. In fact, 74 of the 294 large CO_2 point sources are located along the Ohio River (within IN, KY, OH, PA, and WV), representing 37% of the region's CO_2 emissions from these large point sources, affirming once again the economic lifeblood that this river is to the region.
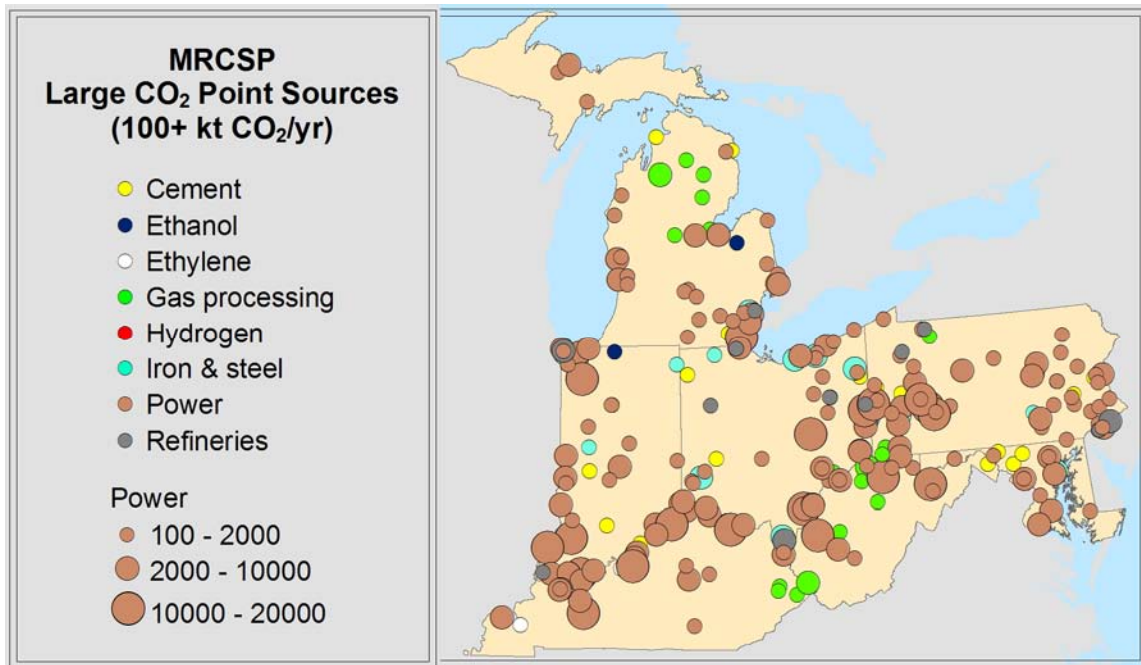
Figure 3.12. Map of large CO_2 point sources (each 100+ ktCO_2/yr).
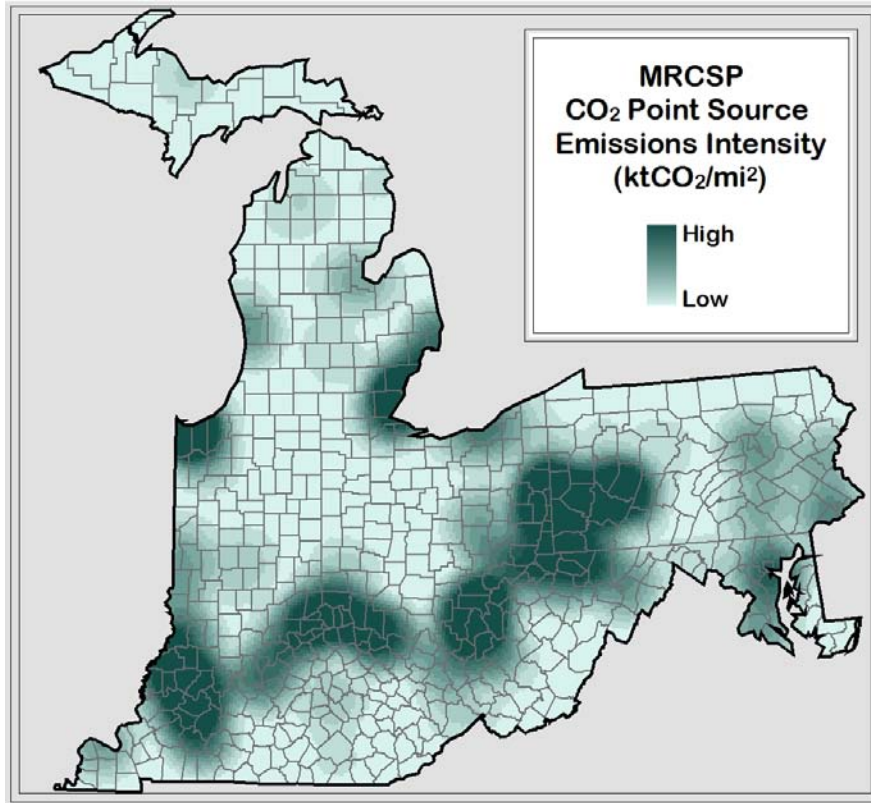
Figure 3.13. CO$_2$ Emissions intensity of MRCSP Region (based on a 50-mile radius at each point).

While these emissions may be concentrated in certain areas, a significant fraction of the total CO$_2$ is emitted within each of the seven states of the MRCSP region. Figures 3.14 and 3.15 show the breakout of emissions from these large point sources by state and source type. While it is again clear that electric generating facilities contribute the largest fraction of CO$_2$ within each of the seven states, it is also apparent that each part of the region has a slightly different makeup leading to its own unique emissions profile.
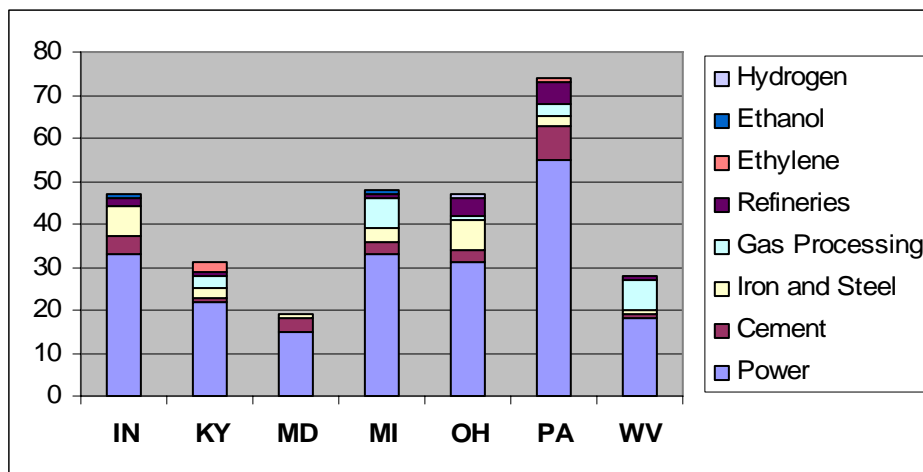
Figure 3.14. Number of large CO$_2$ point sources by state and sector.
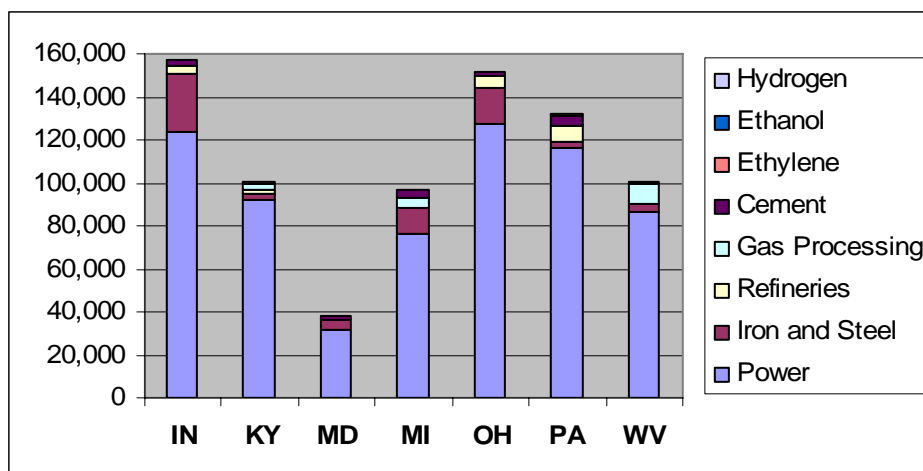
Figure 3.15. Total emissions (ktCO$_2$/yr) by state and sector.

As is true in most regions, including the entire U.S., a limited set of the large point sources within the MRCSP region contribute a substantial fraction of the total CO$_2$ emitted. Figure 3.16 charts the large CO$_2$ point sources in the region by both individual as well as total cumulative emissions. As this figure illustrates, the 50 largest CO$_2$ emissions sources within the MRCSP region account for fully 61% of the total combined emissions from all of the large sources. This is significant and suggests that a large fraction of the CO$_2$ from these sources can be mitigated by focusing at least initial efforts on a relatively small number of them.

Of these 50 largest point sources, 46 are coal-fired electric power plants, and the remaining four are iron and steel foundries. These are located across the region, with some in each of MRCSP's seven states. Twenty (all coal-fired electric power plants) are located along the Ohio River, as shown in Figure 3.17.

Summary of Greenhouse Gas Intensity

In 1990, the seven states of the MRCSP region emitted a total of 366.8 million tons of carbon equivalent of greenhouse gases. These total emissions were reduced by a 10 MMTCE offset from land use (primarily in Kentucky and Ohio), resulting in net emissions of 356.8 MMTCE. For the region, the largest emitter in 1990 was Ohio at about 90 MMTCE, followed by Pennsylvania at 70 MMTCE and Indiana at 60 MMTCE. In all MRCSP states, the largest portions of greenhouse gas emissions were in the form of carbon dioxide generated from combustion of fossil fuels by electric utilities, industry and the transportation sector. Of these, electric power production was by far the largest contributor, emitting 141 MMTCE. Emissions from transportation and industry came in a distant second and third, at 71 and 69 MMTCE, respectively.

Table 3.3 presents greenhouse gas intensity in terms of emissions per capita, and the more conventional measure of tons of emissions per million dollars of gross state product (or gross regional product for the entire seven-state MRCSP Region). Maryland and Michigan come in well below the regional averages of 7.0 tons CE per capita and 232.7 tons CE per million dollars of GRP. Ohio and Pennsylvania are tightly clustered around the regional mean, while per capita and per income values for Indiana, Kentucky and West Virginia rank well above the regional mean in both intensity categories.
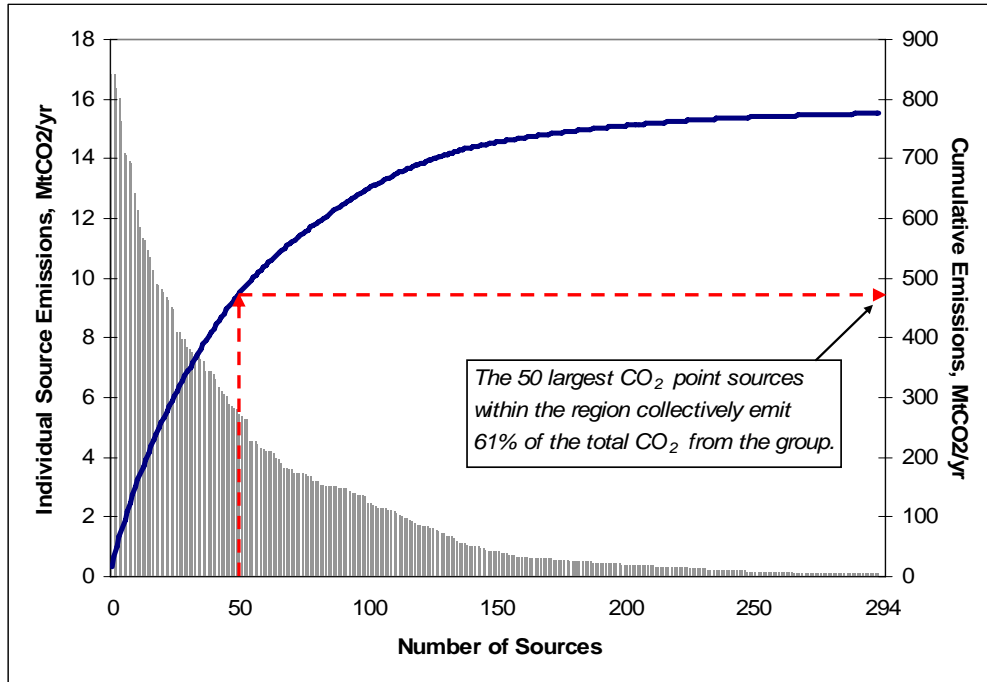
Figure 3.16. Breakout of large CO_2 point sources (each 100+ ktCO_2/yr) by individual and cumulative emissions.
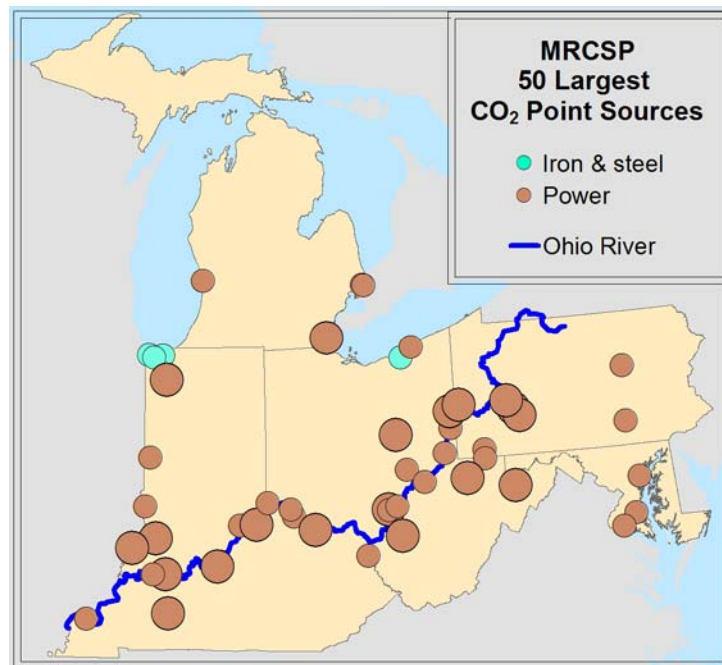
Figure 3.17. Map of the 50 largest CO_2 point sources in the MRCSP Region.

Table 3.3. Two measures of greenhouse gas intensity for Midwest Region states.

State	GHG Emissions per capita (tons of carbon equivalent)	GHG Intensity (tons of carbon equivalent per $M GSP)
Indiana	10.0	336.6
Kentucky	8.8	323.2
Maryland	3.6	111.3
Michigan	4.8	155.7
Ohio	7.8	252.4
Pennsylvania	6.2	203.2
West Virginia	15.8	739.8
All MRCSP States	**7.0**	**232.7**

The following figures highlight the overall greenhouse gas emissions by source, for each state and the total region. Figure 3.18 shows the relative emissions of each of the seven states, as well as the origin of those emissions. Figure 3.19 describes total emissions for the MRCSP region by sector.
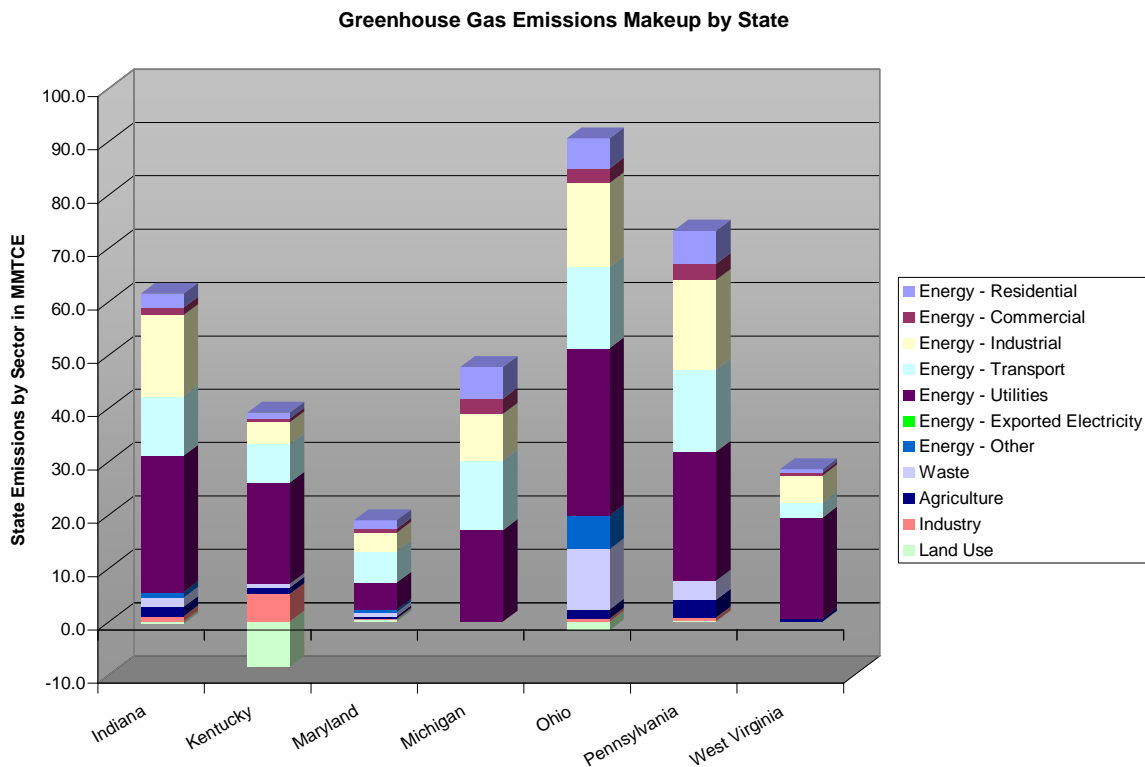
Figure 3.18. Greenhouse gas emissions source makeup by state.

MRCSP GHG Emissions (1990)
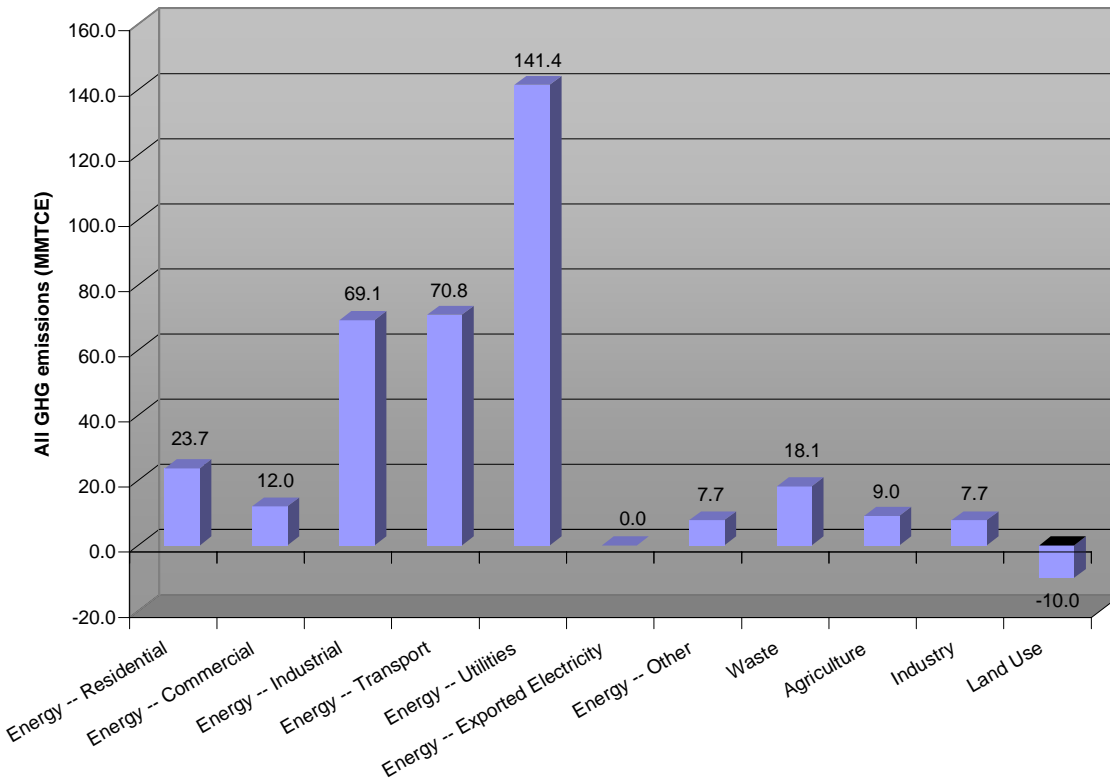
Figure 3.19. Greenhouse gas emissions for the entire MRCSP Region by source.

Looking to the Future

Throughout the history of our fossil fuel-based economy, the production of greenhouse gases has been integrally linked to the economy of each state, region, and nation that relies upon these fuels for energy conversion and feedstock needs. Therefore, the emission of greenhouse gases has been an inescapable byproduct of the industrial age and the continued growth and expansion of our economies. This final section examines trends in regional population, economic strength, agriculture, and energy utilization to assess the potential growth of CO_2 and other greenhouse gas emissions into the future. Additionally, planned power plant projects and capacity additions are examined to further gauge future emissions trends. By examining recent trends and planned growth activities, it may be possible to project future emissions growth.

Socio-Economics and Greenhouse Gas Intensities

Figure 3.20 shows how the relationship between the strength of the economy of each of the seven states, and the greenhouse gases emitted in each state. Though there are many factors unrelated to these emissions that drive GSP, those industries that emit significant greenhouse gases do account for a substantial portion of the economies of these seven states.
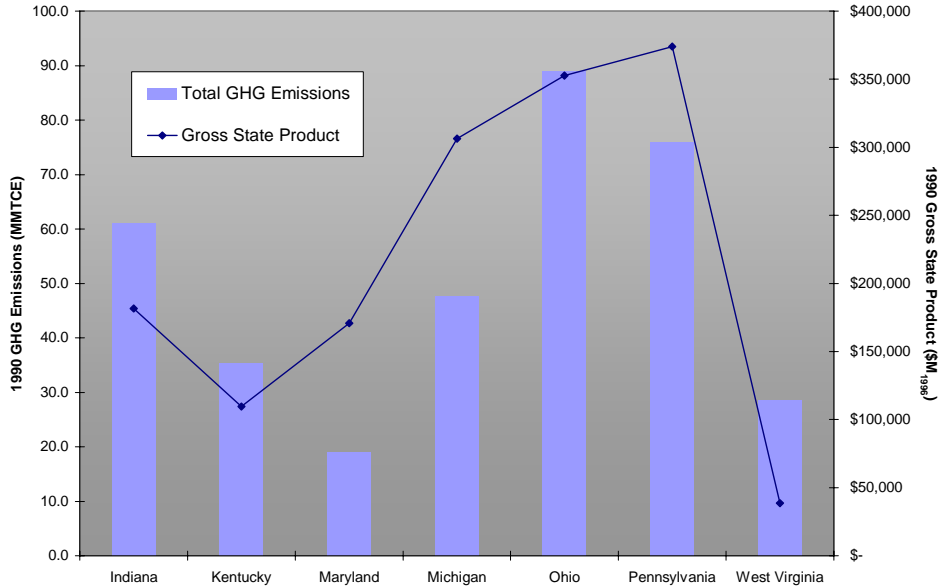
Figure 3.20. The relationship between annual emissions and the strength of a state's economy demonstrates the importance of industry and energy within the region.

While West Virginia's population appears to have been relatively stable over the period between 1980 and 2000 censuses, the populations of the other six MRCSP states have grown over the same time period (Figure 3.21). Because the electricity consumption and industrial output of region is somewhat tied to its population, this increase in population across the MRCSP states (and projected growth through 2010) likely signals an increase in greenhouse gas emissions.
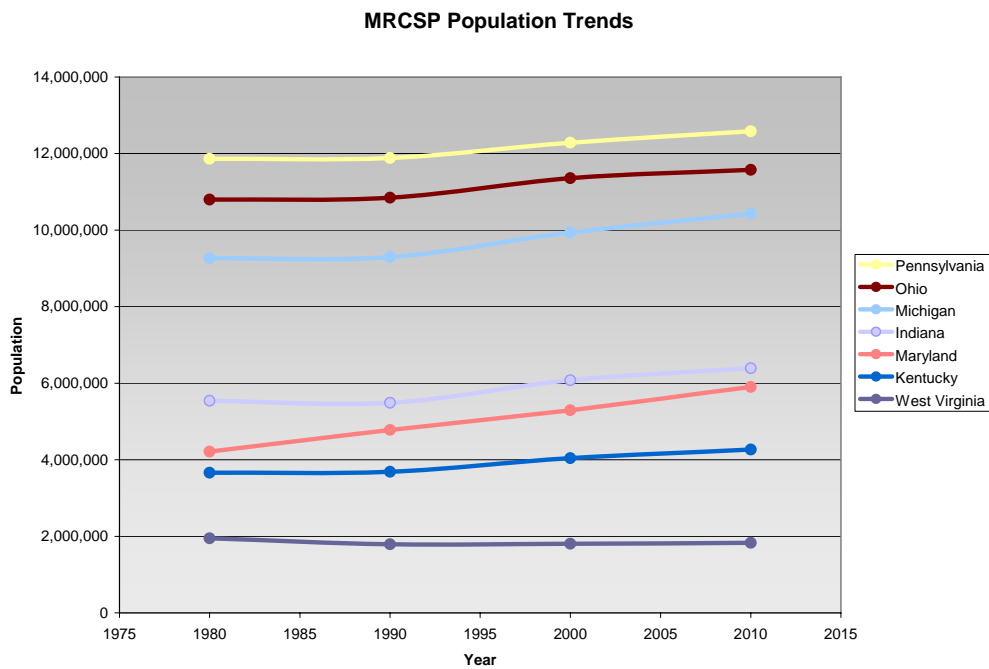
Figure 3.21. Population trends for the states of the MRCSP Region (U.S. Census Bureau).

Land Use and Agricultural Trends

Trends in land use and changes in agricultural practices across the region can also help to assess greenhouse gas trends. For instance, over period between 1974 and 2002, some five million acres of farm land have been lost or converted to some other use (USDA, 2004). This represents an overall reduction in agricultural lands of 3% for the entire region, which is consistent with the national trend. However, some states such as Maryland and Indiana, experienced loss of farm land at about 3 times that rate, while West Virginia reports a slight increase. While the direct impact on emissions is difficult to quantify, particularly since agricultural practices can create both positive and negative greenhouse gas emissions, such changes do provide an interesting look and the changing social and economic landscape that impacts overall trends.

While a reduction in agriculture could lead to lower levels of emissions of this type, one must also consider the new use for this lost farm land and the energy and emissions associated with its likely conversion. Much of this is driven by the region's expanding population centers and industry and result in increased emissions form energy use in the transportation, residential, and commercial sectors, as well as increased landfill emissions and increased emissions from industrial sources. Similarly, if the lost farmland occurs in lands that may offer a sink for greenhouse gases, such as might occur with decreasing amounts of forestland and grassland, net emissions again will experience an upward shift.

Coal Mining and Use of Coal

The trend in coal production and consumption within the region, however, has been mixed, as Figure 3.22 shows. Coal mining within the region has fallen over these eight years, while consumption has been relatively flat, declining slightly until 2000 and increasing again in 2001 where it has remained relatively stable through 2003. Because growing populations create increased demand for total electricity generation, the small and temporary reduction in coal usage likely resulted from an increased reliance on other fuel sources, such as natural gas, for electric generation and other industrial purposes. Given the significant coal resource of this region, and the increasing prices of competing energy sources such as oil and natural gas, a continued increase in the use of coal can likely be expected, along with a similar increase in resulting greenhouse gas emissions, unless means of reducing or mitigating these emissions can be proven and deployed.

It is clear that coal will continue to play a significant role in driving the MRCSP region's economy in the near term. Coal-fired power plants are among the best opportunities for large-scale carbon capture and the large number of existing coal-fired generation facilities represent significant assets that could not be quickly or easily replaced by other technologies. This coupled with a seemingly abundant candidate geologic CO_2 storage resource in the region (which is also being investigated by the MRCSP) implies that this region has many potential opportunities for the deployment of technologies to capture and store the CO_2 from these large coal-fired power plants.
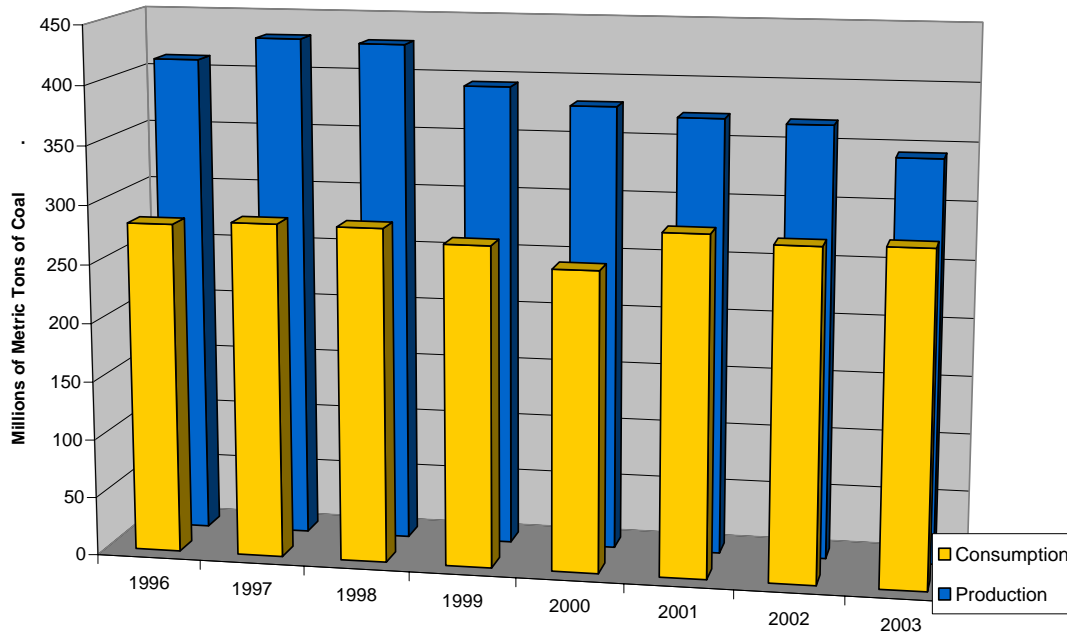
Figure 3.22. **Coal consumption and mining trends in the MRCSP Region between 1996 and 2003 (DOE-EIA).**

Planned Electric Power Generation Projects

Plans for a significant number of electric generating capacity additions are underway for the MRCSP region. As shown in Table 3.4, there are 9 projects currently under construction that will add 1,300 MW of capacity to the region. An additional 32 projects are in various stages of advanced to early development, which would add (if all are completed) an additional 10,900 MW of capacity over the coming decade or more. Figure 3.23 illustrates the breakdown of these projects by development phase (large pie chart) and the fuel mix of projects with each phase (three smaller charts).

Table 3.4. **New electric generation capacity currently under construction or development within MRCSP Region (Platts NewGen, September 2005).**

	Under Construction	Advanced Development	Early Development
Number of Projects	9	19	13
Added Capacity by Fuel (MW)			
Nuclear	0	41	154
Natural Gas	1,312	600	0
Coal	0	2,947	2,772
Wind	24	732	3,314
Hydro	0	232	0
Other	8	200	0
Total	**1,344**	**4,752**	**6,240**

Projects currently under construction are overwhelmingly gas-fired projects, while capacity additions in early and advanced development[1] focus more strongly on coal. Because the siting process for a new generation facility can take a number of years, projects currently under construction were planned and permitted when gas prices were much lower than they are today. Thus, the share of natural gas present in the advanced development stage decreases significantly, and there are no natural gas projects currently in early development.

Coal represents the largest fraction of planned capacity within the advanced development stage, as well as a significant fraction of the early development capacity. While one project in advanced development and two in early development are planning to use integrated gasification combined-cycle (IGCC) technology[2], the majority of these are conventional coal-fired projects. Relative to the new and existing fossil-fired generation in the region, the planned penetrations of wind, hydro, nuclear, and other generation capacity in the coming years, coupled with the retirement of obsolete generating facilities that have exceeded their productive lives, are unlikely to keep emissions from this sector from continuing to increase within the region.
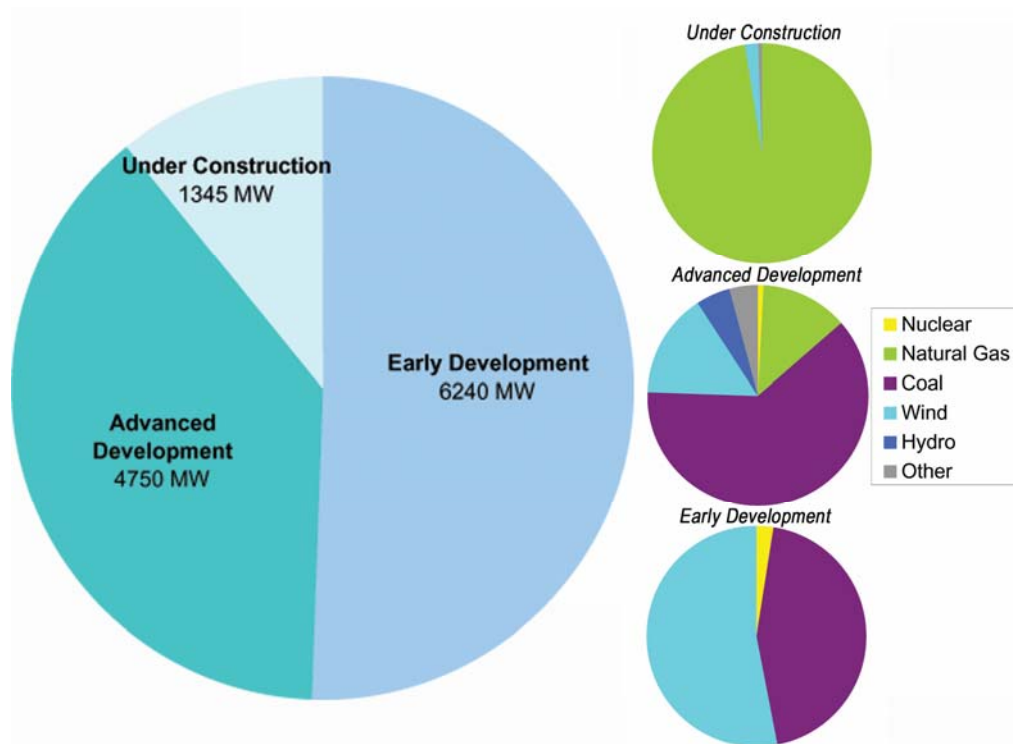
Figure 3.23 Planned generation by phase and fuel mix (Platts NewGen, September 2005).

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[1] To be considered in "Early Development," a project must have taken the beginning steps in the permitting process, or engaged in other preliminary activities including the signing power purchase agreements, securing financing, purchase of turbines, etc. To be considered in "Advanced Development, two or more such criteria must be met. For example, a PPA may have been signed *and* financing secured. (Platts 2005)
[2] IGCC technology operates by gasifying the coal rather than directly combusting it and generally results in higher conversion efficiencies and lower emissions of not only CO_2 but other waste products than conventional plants.

4.0 CO$_2$ CAPTURE AND GEOLOGICAL STORAGE

Until recently, the major options under consideration for mitigation of greenhouse gas emissions included switching to non-carbon-based sources of energy, increased energy efficiency, energy conservation, and terrestrial or biotic sequestration of CO$_2$. However, during the past several years, the concept of capturing CO$_2$ from large point sources (such as electric power plants, cement kilns, and petroleum refineries), followed by injection and permanent storage in geologic reservoirs has gained increased prominence as an element of an overall strategy for mitigating the effects of anthropogenic emissions of CO$_2$. This overall strategy for CO$_2$ sequestration is also known as CO$_2$ capture and geologic storage or CCS.

In some cases the CO$_2$ source may be in close proximity to the target CO$_2$ reservoir. However, in other cases the CO$_2$ may require transporting from the source to the target geologic reservoir. Given the large amounts of CO$_2$ emitted from individual large point sources likely to be involved in CCS (assumed to be at least 100,000 tonnes of CO$_2$ annually for this project) the most likely form of transport is high pressure pipeline.

This section summarizes the MRCSP Phase I research on the technologies and other issues associated with capture technologies and transport of CO$_2$. Finally, this section describes the groundbreaking research conducted by the MRCSP geology research team to define the geological storage opportunities in the region.

CO$_2$ Capture Technologies

An essential first step in the process of CO$_2$ sequestration is capturing the CO$_2$ from the sources that produce it and preparing the captured CO$_2$ for pipeline transmission and injection. A key research activity during the MRCSP Phase I project was to examine CO$_2$ capture options for the MRCSP region's variety of large CO$_2$ point sources. The objectives of this effort were to identify and evaluate, via a comprehensive literature review, commercially-available and emerging candidate technologies for capturing CO$_2$ from gaseous streams, and to assess how these candidate technologies might be most economically matched to the MRCSP region's wide diversity of CO$_2$ point sources.[1]

Available Capture Systems

Based on a review of more than 150 journal articles, conference proceedings papers, and other source materials, the following candidate capture technologies were identified:

- Amine Scrubbing – CO$_2$ is selectively absorbed by chemically reacting with an aqueous amine solvent. The solvent is regenerated by applying heat.

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[1] This part of Section 4.0 is based on the findings of a more detailed report prepared by CONSOL Energy as a part of their research during Phase I of the MRCSP. The report "Carbon Dioxide Capture Options for Large Point Sources in the Midwestern United States – An Assessment of Candidate Technologies" Daniel P. Connell, CONSOL Energy Inc. 2005 can be found on the MRCSP web site (www.mrcsp.org) or on the DOE/NETL website.

- Alkaline Salt Solution Scrubbing – CO_2 is selectively absorbed by chemically reacting with an aqueous solution of an alkaline salt (e.g., potassium carbonate). The alkaline solution is regenerated by applying heat.
- Ammonia Scrubbing – CO_2 is selectively absorbed by chemically reacting with an aqueous ammonia solvent. The solvent is regenerated by applying heat.
- Physical Absorption – CO_2 is selectively absorbed by physically dissolving in a liquid solvent at high pressures and/or low temperatures. The solvent is regenerated by pressure reduction and/or heating.
- Hybrid Absorption – CO_2 is selectively absorbed by physically dissolving in and chemically reacting with a blended solvent. The solvent is regenerated by pressure reduction and/or heating.
- Gas Separation Membranes – CO_2 is separated from other gaseous components because it selectively permeates across a membrane in the presence of a partial-pressure driving force.
- Gas Absorption Membranes – Permeable membrane is used to provide a large surface area for contact between CO_2-laden feed gas and a liquid absorbent. CO_2 is selectively captured by the absorbent; regeneration occurs by altering process conditions as in a typical wet scrubbing process.
- Physical Adsorption – CO_2 is selectively adsorbed onto the surface of a solid sorbent due to intermolecular forces. The sorbent is regenerated by altering pressure or temperature, or by the application of an electrical current or use of a regeneration gas.
- Solid Chemical Absorption – CO_2 is selectively absorbed by chemically reacting with a solid sorbent. The sorbent is regenerated by altering process conditions.
- Cryogenic Separation – CO_2 is captured by condensation or sublimation at low temperatures and elevated pressures.
- Hydrate Formation – CO_2 is captured by adding water at low temperatures and high pressures to form carbon dioxide hydrate crystals.
- Electrochemical Separation – CO_2 is captured using a carbonate ion pump or proton pump.
- Biochemical Separation – Enzymes or photosynthesis are employed for CO_2 capture.

The advantages, limitations, and commercial or developmental status of each of these technologies were assessed, and factors affecting the applicability of each technology, including equipment and material requirements, operating temperature and pressure, feed gas composition and flow rate, and CO_2 separation efficiency, were considered.[1]

Evaluation of Available Capture Technologies

Candidate technologies for capturing CO_2 from large industrial point sources in the MRCSP region were identified and technical and economic considerations regarding the application of these technologies were considered. Table 4.1 integrates these technical and economic considerations, and shows how the candidate capture technologies might best be matched to the MRCSP region's diverse array of large CO_2 point sources. Because many of the candidate technologies are still being researched and developed, multiple candidates are identified for some of the source types. These candidates are rated as *likely*, *attractive*, *plausible*, and *speculative* to provide some indication of their potential applicability. The rating procedure was heuristic and qualitative, but it was based on the technical and economic considerations uncovered by literature research. The terms used to rate the technologies are defined below:

- Likely (L) Most likely candidate for capturing CO_2 among currently available, demonstrated technologies

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[1] The findings of the detailed survey of the literature is described in more detail in the CONSOL MRCSP report.

- Attractive (A) Technology is being actively developed and shows potential for economic or technical improvement over current best-available technologies
- Plausible (P) Technology is available and appropriate but shows no clear advantages over best-available technology, or it is being developed but requires major breakthroughs to become advantageous
- Speculative (S) Technology is in the very early stages of research and development, or has not been specifically proposed for use in the application being considered, but may be appropriate.

According to the data in Table 4.1, amine scrubbing processes are technically capable of capturing CO_2 from each of the major sources in Maryland, which include power plant flue gas, blast furnace off-gas, and cement kiln flue gas. Physical absorption processes are technically capable of capturing CO_2 from high-pressure shifted syngas in IGCC plants and natural gas steam reforming or partial oxidation plants, as well as from blast furnace off-gas in integrated steel mills, provided that it is first pressurized and shifted. Both of these processes are commercially available, and have been used for CO_2 capture. Where they are compatible with the source type, these technologies are designated with an "L" in Table 4.1.

A number of emerging technologies show promise for improving the economics of CO_2 capture. These technologies, which are designated with an "A" in Table 4.1, include ammonia scrubbing and gas absorption membranes for post-combustion CO_2 capture from power plants and similar sources, gas separation membranes for CO_2 capture from a variety of source types, hydrate formation processes for pre-combustion CO_2 capture in IGCC plants, and oxyfuel combustion processes for CO_2 capture in power plants, refineries, and possibly cement plants. Technologies designated as either plausible (P) or speculative (S) do not have practical applications at this time.

Cost Analysis

In some cases, the capture technologies leave appreciable room for improvement. For example, amine scrubbing suffers from a number of limitations, including absorbent losses, corrosion, and large energy requirements for solvent regeneration, which increase the cost associated with applying this technology. The use of amine scrubbing for post-combustion CO_2 capture on a coal-fired power plant is expected to consume about 25% of the plant's output if the technology is installed on a new plant, and 40% of its output if the technology is retrofitted on an existing plant. Moreover, the installation and operation of a currently available amine scrubbing process (including CO_2 compression to pipeline pressure) would likely cause a new PC plant's cost of producing electricity (COE) to increase by at least 40-75%; retrofitting an existing plant with amine scrubbing and CO_2 compression could triple or quadruple its COE. Hence, although it is technically feasible, widespread application of this technology for CO_2 capture is economically unattractive at this point in time.

Table 4.1.   Candidate CO$_2$ Capture Technologies for the MRCSP Region's Large Point Sources Based Upon Technical and Economic Considerations

Source Type	Percent of Total CO$_2$ Emitted by Large Point Sources in the MRCSP Region	Point of Capture	Approximate Cost of Capture ($/tonne Co$_2$) Using Best Available Technologies	Amine Scrubbing	Alkaline Salt Scrubbing	Ammonia Scrubbing	Physical Absorption	Hybrid Absorption	Gas Separation Membrane	Membrane Gas Absorption	Physical Adsorption	Solid Chemical Absorption	Cryogenic	Hydrate Formation	Electrochemical Separation	Biochemical Separation	Oxyfuel + Drying/Compression	Chemical Looping Combustion	Drying/Compression
Power Plants – Post-Combustion	84.3% (654,111 kt/y)	Flue Gas	28-49	L		A			A	A	A	A			S	S		S	
Power Plants – Pre-Combustion		Shifted Syngas	20-33		P		L	P	A	A	P	P			S			S	
Iron/Steel Facilities	9.0% (69,718 kt/y)	Blast Furnace Gas (~60-70% of total CO$_2$)	13-53	L	P		A	P	A	S	P	P		A	S	S			
Refineries	2.5% (19,622 kt/y)	Heater/Boiler Flue Gas (~65-85% of total CO$_2$)	55-80	L		S		S	A	S	S	S		S	S		A		
Cement Plants	1.9% (14,688 kt/y)	Kiln Flue Gas	55-59	L	S	S		S	S	S	S	S		S	S		S		
Gas Processing Plants	2.1% (16,558 kt/y)	Vented CO$_2$	9-10																L
Ethylene Plants	0.1% (959 kt/y)	Process Stream (<100% of total CO$_2$)[b]	9-10																L
Ethanol Plants	0.1% (414 kt/y)	Process Stream	9-10																L
Hydrogen Plants[c]	<0.1% (139 kt/y)	Process Stream	9-10																L

Notes: kt/y = kilotonnes per year.
See text for ranking terms L, A, P, S.
[a] Based on a survey of literature values for technologies highlighted with a double box; includes cost compressing CO$_2$ to pipeline pressure, but not transport or storage costs.
[b] Ethylene plants also produce flue gas with a much lower CO$_2$ concentration; the costs of capturing this CO$_2$ would be comparable to the costs of capturing CO$_2$ from power plant or refinery flue gases.
[c] Assumes a high-purity CO$_2$ stream is produced – i.e., by wet scrubbing. If PSA is used for H$_2$ purification, further CO$_2$ capture may be required, increasing the cost of capture to approximately $53/tonne.

The current leading candidate technologies for capturing CO_2 from power plants are post-combustion capture using commercially available amine scrubbing processes and pre-combustion capture using commercially available physical absorption processes. Literature data were used to prepare preliminary cost estimates for CO_2 capture using these "best available technologies" (Figure 4.1). These estimates were based on a wide variety of technical and economic assumptions. Many of the estimates include the costs of CO_2 dehydration and compression to pipeline pressure (approximately $10/tonne); some also include the costs of pipeline transmission and storage (e.g., $8.50/tonne).[1] In general, all of the capture systems included in Figure 4.1 were designed to reduce specific CO_2 emissions by more than 75% compared to the reference plants.
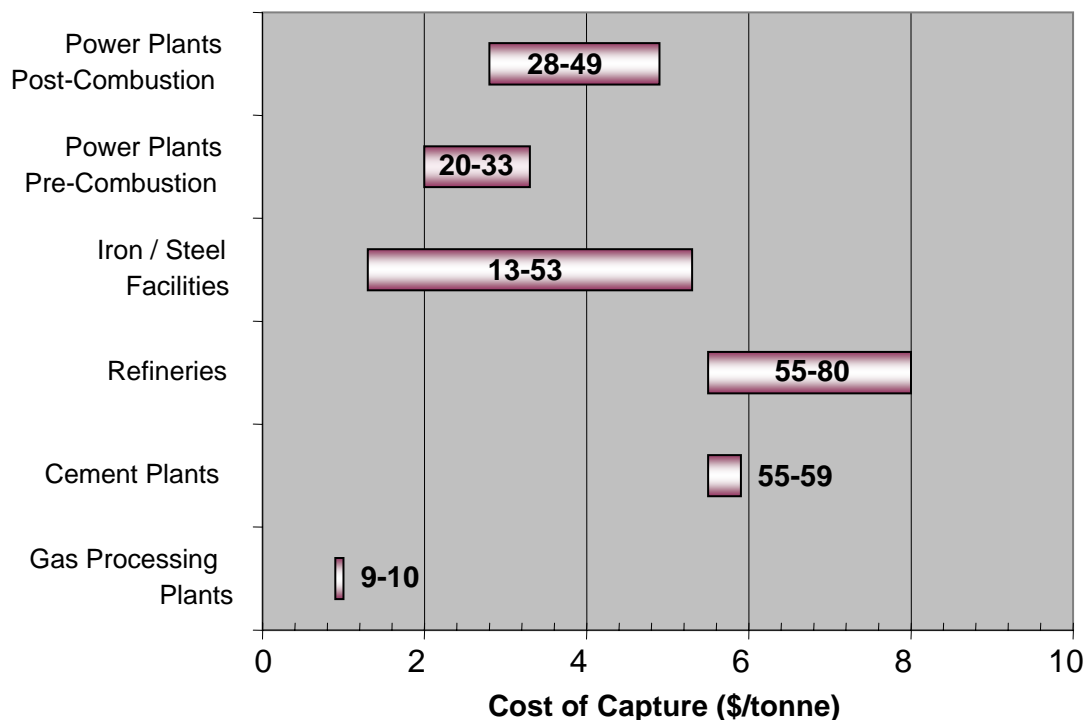
Figure 4.1.   Preliminary cost estimates for CO_2 capture in the MRCSP Region using best available technologies; includes cost of compression to pipeline pressures.

Transportation of Carbon Dioxide (CO_2)

CO_2 may be transmitted via pipeline as a low pressure gas or a supercritical fluid. Pipeline transmission as a supercritical fluid (compressed to 1073 – 3046 psi (7.4 - 21 MPa)) is considered the most reliable and cost effective method for transporting large amounts of CO_2. In the supercritical phase CO_2 has characteristics of both a liquid and gas, maintaining the compressibility of a gas while having some of the properties, such as density, of a liquid. Low viscosity is important for pipeline transport and the viscosity of CO_2 in the supercritical phase is the same as in the gas phase, which is 100 times lower than in the liquid phase. Important from a cost standpoint, supercritical transport allows for substantially higher throughput through a given pipe cross-section than transport as a lower pressure gas.

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[1] The reported costs range from year 1999 U.S. dollars to year 2003 U.S. dollars; however, any variability caused by these different bases is small compared to the uncertainty inherent in each estimate. Hence, no effort was made, during Phase I of the MRCSP, to convert the estimates to a common economic basis.

Special Design Considerations for CO_2 Transmission Systems

Pipelines used for the transmission of CO_2 are very similar to those used for natural gas; however, CO_2 has different properties that must be accounted for in the design of pipelines and other CO_2 handling systems. Additionally, the CO_2 stream captured from point sources and meant for geologic storage would invariably contain some impurities. The gas mixture make-up is also an important consideration in the design of pipelines.

Some of the special considerations in the design of CO_2 pipelines are the following:

- In selecting the materials for use in CO_2 pipelines, the corrosion rate must be established for various temperatures and partial pressures of carbon dioxide. In relatively higher concentrations of carbonic acid, use of corrosion resistant materials provided with erosion protection has been recommended. These areas are typically located downstream of valves and in the vicinity of pumps. (Barrie 2003)
- Water, hydrocarbons and carbon dioxide may also combine to form hydrates that could plug the system. Minimizing the moisture content of the carbon dioxide stream is essential.
- Supercritical CO_2 dissolves into and damages elastomer sealing materials through blistering and cracking; viton valve seats and flexitallic gaskets are recommended for CO_2 pipelines. Ethylene-propylene-diene monomer (EPDM) rubber is also used for CO_2 service, but not recommended in the presence of oils (Watkins, 1983).
- Many lubricants, both synthetic and petroleum-based, harden in contact with CO_2 and become ineffective.
- Dry CO_2 has poor lubricating properties requiring special design features for pumps, compressors, etc.
- CO_2 cools dramatically during decompression so pressure and temperature must be carefully controlled during depressurizing line segments and other routine maintenance activities.
- The CO_2 pipelines require some built-in surge capacities to minimize the potential for "water hammers" that can occur during flow changes.
- Supercritical CO_2 provides favorable conditions for the propagation of fractures requiring counter-measures such as installation of fracture arrestors on the pipeline.
- CO_2 Pipelines are typically buried except at the metering and compressor stations and under deep water. The seasonal temperature variations usually do not affect the fluid conditions in the pipeline. However, if the seasonal temperature variations are likely to impact the pipeline temperature, then those should be accounted for in design.

Pipeline Design

The design of a pipeline needs to take into account the pressure, temperature, and properties of the fluid, dynamic effects such as earthquakes and waves and currents, live and dead loads, thermal expansion and contraction, relative movement of connected components, etc. With the special characteristics of CO_2 accounted for, design methods for natural gas pipelines generally apply also to CO_2 pipelines. Compressibility and density of CO_2 undergo significant non-linear variation in the normal pipeline operating conditions (within normal pipeline pressure and temperature ranges). Design of CO_2 pipelines therefore requires the use of computer codes that allow point-by-point estimation of fluid properties using an equation of state (Farris, 1983). Property correlations may need to be validated with bubble point experiments to ensure accuracy (King, 1982a, 1982b). Also, impurities impact compressibility of CO_2 and result in reduced flows through the pipeline. Table 4.2 shows the effect of some impurities on CO_2

pipeline capacity. It is therefore important to also consider the impurities present in the gas stream and their likely impact on the flow characteristics. The impurities present in the CO_2 stream depend on its source as well as the capture and purification methods used. Specific to the CO_2 sources in the Midwestern region, the levels of impurities left after purification are unlikely to have much detrimental impact on pipeline capacity[1].

Table 4.2.   Effect of impurities on CO_2 pipeline capacity.

Composition of Flowing Fluid	Flow Velocity at Design Pressure Drop (m^3/s)	Flow Loss Relative to Pure CO_2
Carbon dioxide	98.3	1.00
Methane	90.8	0.92
Nitrogen	63.9	0.65
Carbon dioxide plus 5% methane	89.5	0.91
Carbon dioxide plus 10% methane	82.3	0.84
Carbon dioxide plus 5% nitrogen	85.9	0.87
Carbon dioxide plus 10% nitrogen	77.0	0.78

Source: Farris, 1983

The economic operating pressure and temperature ranges for CO_2 pipelines are: 1,250-2,270 kPa and 40-100 ^{0}F, respectively. The lower pressure limit is set by the need to avoid two phase flows, and the upper by the specifications for piping and fittings. The lower temperature limit is set by winter ground conditions and the upper limit by temperature limits on the pipeline coating material.

Temperature changes are accompanied by changes in the pipeline pressure and similarly, pressure swings cause the temperature to change. Therefore, it is necessary to use thermal relief valves to protect segments of pipe that can become isolated by valve closures. A leakage causing rapid pressure drop in the pipeline can cause the temperature to drop to -50 ^{o}F (- 45 ^{o}C). In order to avoid damage to pipeline components from such low temperatures, the system design must include measures to avoid rapid pressure reduction. The blowdown valves need to be carefully sized to limit the rate of release such that the pressure reduction does not cause excessive cooling (Recht, 1986).

For the ease of coordinating the operation of the compressor and the pipeline, some surge storage capacity is also required to control pressure transients during flow changes (similar to water hammer in liquid pipelines). During start-up and shutdown operations, fail safe valves divert the flow to the surge storage tanks; however, due to the high flowrate and high pressure involved, it is not possible to provide enough storage for uninterrupted operation during prolonged outages. Consequently, the pipeline and compressor systems require high reliability to avoid release of CO_2 into the atmosphere or interference with the operations of the CO_2 source (such as a power plant).

Measures are also required to avoid over-pressurization of the pipeline. A "linepack" occurs when the upstream compressor continues to operate even when a downstream valve is closed. Eventually the compressor shuts down when the discharge pressure rises sufficiently. Such accumulation of CO_2 in a section of the pipeline, which can be several miles long, is undesirable because CO_2 cannot be vented or disposed off without some risk to the personnel, equipment or nearby populations. A CO_2 accumulation monitoring system along the pipeline is therefore essential.

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[1] This is based on the characterization of the Midwestern CO2 sources and capture and purification technologies given in Console, 2005.

Pipeline Materials

Selection of pipe diameter, wall thickness, material strength and toughness depends on the fluid temperature, pressure, composition and flowrates. With all else being equal, there is an economic balance between diameter, wall thickness and strength. Fluid flowrates are lower in larger diameter pipes due to lower pressure drops that enable use of smaller compressor systems, with correspondingly lower compression costs; however, installation costs of pipelines rise with increase in diameter. Selection of the pipe diameter therefore involves a tradeoff between compression costs and pipeline installation costs.

Pipeline transport of CO_2 in dense phase requires special considerations to avoid initiation and propagation of cracks. If a crack occurs, CO_2 will flash into vapor accompanied by rapid temperature drop and after the liquid vapor envelope is reached, the rate of pressure drop decreases dramatically (Eagleton, 1980)[1]. This high sustained pressure causes the crack to propagate down the length of the pipe due to the forces of the escaping fluid acting at the tip of the crack. The pipeline design therefore requires measures to minimize the possibilities of brittle and ductile fracture propagation (King, 1981, 1982a, 1982b).

The toughness required is calculated based on pipeline conditions, materials and fluid properties. The pipeline material and associated components must also be able to withstand temperatures as low as -52°F (- 47 °C) that may occur in case of a pipeline rupture. The strength of the pipeline material, however, is not sufficient to stop a propagating fracture, requiring additional crack arrestors and reinforcements along the pipeline. Spacing of reinforcements depends on the location of the pipeline, need to protect public safety and to comply with the codes and standards (e.g., ASME B 31.4 section 402.5), as well as economic considerations regarding the ease of replacing a given section of the pipeline.

The pipelines for CO_2 transportation are likely to be constructed from high strength steel (60000 – 80000 psi yield strength) such as American Petroleum Institute (API) X60 or X80 grade material. Pipelines made of higher strength steel require lower wall thickness and thus selection of the material involves an economic trade-off. The optimum strength and wall thickness are determined based on the aforesaid factors as well as fabrication and handling considerations. Sections of the pipeline that are in contact with higher levels of moisture, such as the section upstream of the dehydration unit, are built using corrosion-resistant alloys. For example, in the SACROC CO_2 pipeline, short sections upstream of the glycol dehydrator were built from 304L corrosion-resistant alloy (IPCC, 2005).

Transmission of CO_2 results in some internal corrosion of the pipeline, as some moisture in the gas stream remains even after dehydration. The de ward/Milliams nomograph is used to estimate corrosion rates of carbon steel under various operating temperatures and CO_2 partial pressures (Barrie et al., 2003). Typically, a corrosion allowance of 1/16 to 1/8 inch is included in similar oilfield applications.[2]

Onshore CO_2 pipelines are buried over most of their lengths, to a depth of 3-4 ft (1-1.2 m), except at metering or pumping stations. Offshore lines are also usually buried in shallow water. In deeper water,

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[1] In a blowdown test with a 9.9 mile (16 km) section of 16" pipe (40.6 cm), with initial CO_2 pressure and temperature of 1500 psi (10.3 MPa) and 40 °F (4.4 °C), respectively, the fluid parameters dropped to the liquid vapor envelope (560 psi and 40 °F or 3.5 MPa and 4.4°C) in 2.5 minutes. After that the rate of pressure drop decreased dramatically and required 10 hours to depressurize the system to 100 psi (0.63 MPa) while the temperature dropped to -52 °F (- 47 °C).

[2] For dry CO2, the corrosion rate of carbon steel is low. At 1300-1750 psi (9-12 MPa) and 320oF-356°F (160°C-180°C) the corrosion rate is in the order of 0.0004 inch (0.01 mm) per year, as measured in short term tests. Field experience with an operating pipeline transporting high-pressure dry CO_2 has shown an even lower corrosion rate: 0.00001- 0.0001 inch (0.00025 - 0.0025 mm) per year. Corrosion rates are much higher in the presence of free water. Tests indicate that the corrosion rate may be 0.0028 inch (0.7 mm) per year or higher, depending on the pressure, temperature and moisture content of the CO2 stream (Siersten, 2001).

only pipelines with a diameter of less than 16 inch (400 mm) are trenched and sometimes buried to protect them against damage by fishing gear (IPCC, 2005). To help reduce corrosion, pipes typically have external coating of fusion bonded epoxy. Internal coatings may also be considered to reduce corrosion and friction loss. Cathodic protection is an essential supplement to protect uncoated areas or areas with damaged coating. The cathodic protection system consists of a sacrificial anode or an impressed current system. The cathodic protection system also requires monitoring stations and ancillary systems.

Booster Pumps

Longer pipelines or hilly terrain are likely to necessitate booster pumps to compensate for the pressure loss. These pumps are likely to be centrifugal pumps designed generally in accordance with the requirements of API 610. The material combinations specified in API 610, column 6 have been used for CO_2 applications. However, due to the differences between CO_2 and the fluids pumped in the petroleum industry, it may be desirable to use low temperature resistant materials for pump casings, and self-lubricating materials such as molded graphite with metal fill for station portions of wearing parts due to the low lubricity of CO_2. Low lubricity of CO_2 would also necessitate the use of double or triple mechanical seals with a lubricating buffer fluid or dry gas seals. Use of sleeve or tilting pad bearing arrangements has proven to be successful in CO_2 service (Eyen, 1986).

The pumping stations are designed for remote operation using the pipeline SCADA system and are equipped with protection equipment such as intake and discharge pressure controllers and automatic shut-off devices in case of departure from design operating conditions.

Other Equipment:

Valves. Valves are typically used for control functions around compressor and metering stations and at the injection sites. Additionally, block valves are used to isolate sections of pipe in the event of a leak or for maintenance. Block valves are spaced at 10-20 mi (16-32 km) depending on the location of the pipe. Block valves are more frequent near critical locations such as river crossings and urban areas.

Valves meant for CO_2 service need to be designed to minimize water traps following hydro testing, in order to minimize corrosion from carbonic acid. Packing materials need to be corrosion resistant and able to withstand extreme low temperatures encountered during blowdown events.

Pig Launchers, Receivers and Batching Stations. CO_2 pipelines also require launchers and receivers for the insertion and removal of so-called "pigs"—tools used for the cleaning or inspection of the inside of the pipes. The utility pigs clean the pipeline of debris and sweep out water and carbonic acid and the smart pigs are used for inspection.

Batching stations used for the inclusion of corrosion inhibiting liquids into the pipeline may also be required.

Instrumentation, Metering, and Supervisory Control and Data Acquisition (SCADA)

Instrumentation along the pipeline is typically used to measure the fluid parameters—flowrate, pressure and temperature—to provide sufficient information for normal operation of the pipeline. The instrumentation is located at compressor and metering stations and sometimes at the block valves.

Metering stations are spaced at 78 – 155 mile (125 -250 km) intervals to report the status of the pipeline. Metering stations typically include the following controls and instrumentation:

- Inlet and outlet shutoff valves
- Inlet and outlet pressure relief valves
- Inlet and outlet pressure and temperature measurement devices
- Strainer
- Turbine flowmeter
- Densitometer
- Moisture analyzer
- Flow control valve
- Piping to a high accuracy flowmeter for inline turbine flowmeter calibration (Warren, 1985)

SCADA systems are used for remote monitoring and operation of the compressor stations and the pipeline. The system is designed to provide the operators located at a central control center with sufficient data on the status of the pipeline, to enable them to control the flows through the compressors and the pipeline as necessary. The system includes multiple programmable logic controllers that monitor flow parameters along the pipeline and set alarms when a departure from normal operating conditions is detected, for the operator to intervene in a timely fashion. Dynamic and static strain measurements, leak detection, fatigue life prediction, and other key indicators are part of the control system design. Design considerations for CO_2 pipeline SCADA systems are similar to those given in the API publication 1113, *Developing a Pipeline Supervisory Control Center*.

Pipeline Transmission Cost Factors

The major items contributing to capital, and operation and maintenance costs are summarized in Tables 4.3 through 4.7. These costs were reported between 1982-2005. Given the approximate nature of these estimates, the costs have not been normalized to a common denominator (to any particular year's dollars).

Compression and Dehydration

In general, the total compressor station construction costs can be subdivided as: labor (28.08%), equipment and material (43.20%), land (0.53%), and miscellaneous (28.20%). The miscellaneous costs include: surveying, engineering, supervision, administration and overhead, interest, contingencies, regulatory filing fees, etc. (Oil and Gas Journal, 2005). Reported high capacity, high pressure compressor costs are contained in Table 4.3.

Table 4.3.   Reported compressor costs.

Type of Unit	Size (MW)	Total Cost ($)	Unit Cost ($/kW)	Source
Centrifugal, motor driven, booster pump, inlet 2275 psi, discharge 2975 psi	1.125	1,500,000[a]	1,333	ND Gasification Company, 2005
Centrifugal multistage, motor driven, 1,000 psi	3	1,620,000[a]	540	Peters and Timmerhaus, 1991
Reciprocating, integral gas engine, natural gas pipeline service (pressure not specified)	4.5	3,780,000[a]	840	Richardson, 1999
Natural gas pipeline service (design not specified)	7.7	12,200,000[b]	1,584	Oil and Gas Journal, 2000b
Natural gas pipeline service (design not specified)	11.2	19,280,000[b]	1,720	Oil and Gas Journal, 2003
Reciprocating, electric motor driven, 2,500 psi	11.2	2,730,000[a]	240	Page, 1996
Centrifugal, carbon dioxide pipeline service	14.6	14,000,000[c]	960	Ormerod, 1994
Natural gas pipeline service (design not specified)	14.9	15,000,000[b]	1,000	Oil and Gas Journal, 2005
Centrifugal, 8-stage, motor driven, carbon dioxide pipeline service, inlet 4 psi, discharge 2975 psi	15	25,000,000[d]	1,667	ND Gasification Company, 2005
Natural gas pipeline service (design not specified)	18.6	23,800,000[b]	1,280	Oil and Gas Journal, 2000b
5-stage centrifugal, 2215 psia, 5 el. motor driven trains, carbon dioxide pipeline service (estimated)	72	40,000,000[c]	555	BP, 2005

(a) Bare equipment cost
(b) Direct and indirect capital cost for installed system
(c) Direct capital cost for installed system
(d) Direct and indirect capital cost for installed system including six air-cooled compressor interstage heat exchangers (22.5 kW [30 hp] each) costing $ 2,500,000.

A large part of the moisture remaining in the gas stream following CO_2 capture from power plant flue gas (or similar sources) will condense as the gas is cooled after each stage of compression (Wiebe, 1941). Condensation during compression would enable physical removal of at least 90% of the moisture from the gas stream, the remainder would have to be removed using gas dehydration systems. Adsorption based dehydration systems are more suitable for removal of moisture from compressed gas streams. (The CO_2 stream at the North Dakota synthesis fuel plant is produced from a low temperature (-90 °F) process and therefore does not contain any moisture and consequently, does not require dehydration.) Reported gas dehydration system costs are contained in Table 4.4.

Table 4.4.   Reported gas dehydration equipment capital costs.

Capacity (metric tons/yr)	Cost[a] ($)	Source
2,100,000	10,600,000	Holt and Lindeberg, 1993
5,060,000	26,000,000	Ormerod, 1994

[a] Direct capital cost for installed equipment

Compression is the largest operating cost for the transmission system. This cost will also vary to some degree on the type of prime mover used. If a diesel engine is used the efficiency of the engine would be around 40%. (Net energy output of diesel fuel is 129,000 BTU/gal.)

Apart from fuel costs, there will be additional costs for the physical removal of water, compressor interstage cooling, regeneration of the adsorbent dryer, and operation and maintenance. Some of these cost factors are listed in Table 4.5.

Table 4.5.   Various operation and maintenance cost factors for compression and dehydration processes.

Item	Cost Factor
Disposal of water separated from the gas stream	$ 0.15 / 1000 gal
Low pressure steam for dehydration of the adsorbent dryer	$ 2.00 / 1000 lbs
Compressor cooling water supplied at 80°F (27°C) and returned at 95°F (35°F)	$ 0.19 / 1000 gal
Maintenance materials	4% of initial material cost
Energy required for compression and pipeline transmission (without recompression) over any distance up to 62 mi (100 km) of CO_2, captured from a typical, conventional 500 MW pulverized coal power plant, totaling 3,364,000 metric tones per year, using a 34 MW compressor plant and an electricity cost of $0.065/kWh *	$33,000,000 per year

1 metric tonne = 2200 lbs.
* Source: Smith et al., 2001.

Depending on the length of the pipeline, recompression of CO_2 may be required. Booster pumping stations may be required at 93 mi (150 km) intervals (Golomb, 1997). Booster pumps may also be required in rocky and/or hilly terrain to maintain sufficient pressure at the high points in order to ensure single-phase flow (Swink, 1982). Typically, centrifugal pumps are used. The pump size depends on the pressure drop along the pipeline and the terminal pressure required.

The cost factors for CO_2 pipelines are considered to be similar to those for natural gas pipelines. These pipelines are constructed from high strength carbon steel. In general, the pipeline construction costs can be subdivided as: labor (44.43%), material (18.51%), Rights of way and damages (10.39%), and miscellaneous (26.67%) (Oil and Gas Journal, 2005). The miscellaneous costs include: surveying, engineering, supervision, administration and overhead, interest, contingencies, regulatory filing fees, etc. The longer the pipeline, the lower the unit cost for construction. Pipelines built near populated areas tend to have higher unit costs.

The size of the pipeline depends on the flowrate. Some reported pipeline diameters for different flow rates are presented in Table 4.6. Table 4.7 contains the reported capital costs for pipelines of different diameters.

Table 4.6.   Reported diameters calculated for carbon dioxide pipelines.

Flowrate (metric ton/day)	Nominal Pipe Diameter (cm [in])	Velocity (m/sec [ft/sec])	Length (km [mi])	Source
2,750[a]	25.4 (10)	0.65 (2.12)	53 (33)	BP Pipelines North America, 2005
5,000	25.4 (10)	2.2 (7.3)	Not reported	Ormerod, 1994
5,753	40.6 (16)	1.1 (3.7)	160 (100)	Holt and Lindeberg, 1993
8,220	40.6 (16)	1.6 (5.3)	250 (155)	Skovholt, 1993
8,400[b]	30.5 (12)	Not reported	160 (100)	ND Gasification Company, 2005
8,400[b]	35.6 (14)	Not reported	192 (120)	ND Gasification Company, 2005
10,000	35.6 (14)	2.6 (8.4)	Not reported	Ormerod, 1994
15,000	61.0 (24)	1.2 (4.2)	100 (62)	van der Meer, 1993
15,850	50.8 (20)	1.06 (3.48)	480 (300)	BP Pipelines North America, 2005
17,400	50.8 (20)	2.2 (7.3)	Not reported	Swink, 1982
27,400	55.9 (22)	2.8 (9.2)	Not reported	Doherty and Harrison, 1996
29,400	61.0 (24)	2.5 (8.3)	Not reported	Swink, 1982
54,800	76.2 (30)	3.1 (10.0)	Not reported	Doherty and Harrison, 1996
54,800	76.2 (30)	3.1 (10.0)	250 (155)	Skovholt, 1993

(a) The figures are from a project estimate developed in 1992.

(b) This is the same pipeline from North Dakota to Saskatchewan, Canada. 14-inch diameter pipes are used for the first 120 miles of the pipeline and the remainder is 12-inch in diameter.

Table 4.7.   Reported costs for pipeline installation.

Diameter (cm [in])	Cost ($/m [$/ft])	Comments Source
15.2 (6)	145 (44)(a,d)	ND Gasification Company, 2005
25.4 (10)*	126 (38)(a,b)	BP Pipelines North America, 2005
30.5 (12)	100 (30)(d)	Oil and Gas Journal, 2003
30.5 (12) & 35.6 (14)**	150 (46)(a,d)	ND Gasification Company, 2005
40.6 (16)	400 (120)(a,b)	Ormerod, 1994
40.6 (16)	415 (125)(b,c)	Ormerod, 1994
40.6 (16)	390 (120)(b)	Chandler, 2000
40.6 (16)	171 (52)(d)	Oil and Gas Journal, 2003
50.8 (20)	620 (190)(b)	Chandler, 2000
50.8 (20)	900 (274)(d)	Oil and Gas Journal, 2005
50.8 (20)	312 (95))(a,b)	BP Pipelines North America, 2005
61.0 (24)	800 (240)(d)	Oil and Gas Journal, 2000b

(a) Rural terrain
(b) Direct capital cost for installed pipeline
(c) Urban terrain
(d) Direct and indirect capital cost for installed pipeline

* The figures are from a project estimate developed in 1992.
**1999 installed cost of 120 miles of 14" and 100 miles of 12" pipeline, including 21 block valves and two metering stations.

Operating Experience with CO_2 Pipelines

CO_2 pipelines have been successfully operated since the early 1970s for enhanced oil recovery (EOR). Worldwide there are 74 active EOR projects employing CO_2 flooding, of which 70 are located in the United States. These pipelines are of varying length. A 505 mi (808 km) long CO_2 pipeline has been in operation since 1971. In addition, there are long lateral pipelines that distribute CO_2 from the main line; for example, the 140 mi (225 km) long Canyon Reef Carriers pipeline. In total, there are some 1,940 mi (3,100 km) of CO_2 pipeline worldwide. The CO_2 pipeline network is very small when compared to natural gas and other hazardous liquid pipelines in the United States that amount to 321,000 mi (514,000 km) and 155,000 mi (248,000 km), respectively. The CO_2 network will have to expand considerably if CO_2 capture and geologic storage is implemented and hence the risk of CO_2 pipeline incidents will have to be seriously considered. The general public is more likely to come in contact with a pipeline network than a capture plant and so, naturally, would be interested in the impact of these pipelines on their personal situation (Gale et al., 2003).

An analysis of CO_2 pipeline incidents over the 1990-2001 period (Gale et al., 2003) shows that there have been 10 incidents or 0.51 incident per 1000 mi (0.32 per 1000 km) of pipeline in the US. None of these incidents involved injuries or fatalities. By comparison natural gas pipelines had 0.27 incident per 1000 mi (0.17 per 1000 km) that involved fatalities and injuries.

Pipeline Rights of Way Considerations

Siting a pipeline entails obtaining the proper regulatory permits and acquiring use of the land that the pipeline will occupy. Depending on the location of the proposed pipeline, environmental impact assessments, permitting, and acquisition of rights of way can take several years. After a pipeline route has been approved, land along the route must be acquired by an easement agreement, by purchase, or via eminent domain.

A pipeline right of way consists of a parcel of land under which a pipeline is buried. Rights of way are often about 50 feet (15 meters) wide. Right of way usually refers to access to a portion of a side of a street or an easement on private property granted to a utility.[1] A right of way agreement between the pipeline company and a landowner is a form of easement (a limited perpetual interest in land that allows the pipeline owner to construct, operate, and maintain a pipeline across the land). An easement does not grant an unlimited entitlement to use the right of way. Pipeline companies are responsible for the right of way. The rights of the easement owner (pipeline company) are set out in the easement agreement.

> **Siting a CO_2 Pipeline in the Real World**
>
> Basin Electric Power Cooperative, the company that secured the right of way for the Dakota Gasification—Weyburn pipeline, worked directly with landowners in obtaining easements for the right of way. Immediate payments were offered for signatures on landowner easement agreements. In addition, a detailed right of way reclamation plan was explained to the landowners. As a result, all 254 landowners in North Dakota granted easements. Although North Dakota law provides for condemnation proceedings, they were not needed.

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[1] Edwin A. Rosenberg and Stella Rubia, "Rights-of-Way and Other Customer-Access Facilities: Issues, Policies, and Options for Regulators," Columbus, Ohio, *NRRI* (1995).

Written easement agreements are filed with other deeds to land, usually in a county recorder's office.

The terms set out in the easement agreement are important in determining its purpose and scope. Like contracts, the terms of the easement agreement control the rights and obligations of the parties inter se. When the terms are ambiguous or the agreement is silent on an issue, general legal principles govern. In interpreting an easement, the intentions of the parties at the time of the grant are taken into account. Generally, use of an easement is limited to what is reasonably necessary to carry out the intended purpose. An easement owner may not materially increase the burden of the easement on the dominant tract of land. In the absence of an express statement otherwise, however, the use of an easement may change in adaptation to new circumstances.

These issues become particularly important when pipelines must be constructed in existing right of way corridors where the easements may be many decades old. Some questions that will need to be asked are:

- Does the original easement grant the right to install and operate CO_2 pipelines? A wide variety of phrases are used in easements, from grants permitting a "natural gas pipeline" to "pipelines for the transportation of oil, hydrocarbons, gas, water, and any other substances whether fluid or solid, any products and derivatives of any of the foregoing, and any combination and mixtures of any of the foregoing…" There is a tenable argument that CO_2 pipelines should not be covered by the former; there is a strong argument that it be covered under the latter.

- How much, if anything, does each landowner or easement holder need to be compensated for the use of the easement?

- Can existing easements be sold or leased to third parties?

Shared Use of Existing Right of Way Corridors

Planning a route for a pipeline involves acquiring easements from individual land owners along the right of way. A new pipeline must either use an existing right of way corridor or create a new one by negotiating with each landowner along the route. Using an existing right of way corridor can reduce the time and expense of acquiring rights of way. However, as noted above, negotiations with easement holders and landowners regarding the scope of existing easements and the amount of compensation due might still be necessary. If an agreement cannot be reached, aggrieved landowners have several legal courses of action: they can ask for compensation for the additional burden the new pipelines put upon their land; they may sue for trespass based on the pipeline exceeding the scope of the easement; they may ask the court for a declaratory judgment to establish the scope of the easement; or they may request an injunction to block construction of the pipeline.

Many of these issues have recently been addressed with the installation of fiber optic lines in existing utility right of way corridors. Fiber optic lines are analogous to CO_2 pipelines in that they are both relatively new technologies that would not have been explicitly included in older easements. The cases that resulted from placing fiber optic lines in existing utility rights of way demonstrate a wide range of variation in both

> **A Real World Example of Shared Use of an Existing Right of Way**
>
> In a Kansas case, the court allowed a telecommunications subsidiary of a gas pipeline company to condemn unused gas pipeline easements to install fiber optic lines. The court determined, however, that the fiber optic lines constituted an additional taking of property because the intended use of the easement was for the transportation of gas. Therefore, the court ordered the company to pay additional compensation to the landowners.

the language of the original easements and the interpretation of this language by the courts.

In a Kansas case, the court addressed the issue of abandonment.[1] When an easement or right of way is abandoned, the easement holder relinquishes the right to use the land. The question raised was whether mere nonuse amounts to abandonment. The court held that nonuse is not abandonment and developed a test for abandonment with two elements: (1) an intentional relinquishment of a right; and (2) an act demonstrating abandonment. Examples of actions that display intent to retain a right of way are plans for future use or upkeep of the right of way. The issue of abandonment may be important for CO_2 pipelines in the Midwest Region for two reasons. First, utilities may want to take advantage of rights of way that they own but are not currently using. Second, CO_2 pipelines might be able to make use of abandoned railroad rights of way.

Condemnation and Eminent Domain

If a landowner and the pipeline company cannot agree to a price, or if a landowner simply refuses to grant an easement, the only option available to the pipeline company is to condemn the land through the power of eminent domain. Thus, an essential question is whether or not pipeline companies will be able to use the power of eminent domain.

Eminent domain is the power of government to take private land for public use. The federal and state governments grant public utilities (also called public service corporations) and common carriers the power of eminent domain to condemn land for a public purpose. For example, the Natural Gas Act grants the power of eminent domain to interstate pipeline companies.[2] Given the newly enacted provisions of the Energy Policy Act of 2005, it seems likely that CO_2 sequestration will be judged to be in the public interest. The issue for transportation of CO_2 is whether the pipelines will be able to take advantage of current state condemnation statutes and regulations that would grant the power of eminent domain. In most cases, this would require that CO_2 pipelines be considered a public utility or a common carrier.

For each state in the MRCSP, the state public utility commission (PUC) or public service commission (PSC) has jurisdiction over gas pipelines. Before constructing a new gas pipeline, the pipeline company must obtain a certificate of public convenience and necessity. In some states, pipelines are also treated as common carriers. A certificate of public convenience and necessity is a permit required by the state PUC or PSC to construct and operate a gas pipeline or other energy facility. The utility must show that the proposed pipeline will serve the public convenience and necessity, and that it follows an acceptable route. A common carrier is required to hold out service to the public without discrimination. State regulators are likewise interested in making sure the pipeline operators who are subject to rate regulation charge reasonable rates. In other words, a common carrier must serve all customers who are willing to pay, and must do so at the same price for all.

Obtaining a certificate of public convenience and necessity would not hinder the development of a CO_2 pipeline, and could actually help because it would mean that the pipeline was being treated as a public utility, and therefore have the authority to condemn a right of way. It can also be helpful in public relations because submission to agency regulation demonstrates a level of public accountability. Conversely, a common carrier requirement might become a difficult issue, particularly if several sources

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[1] Williams Telecommunications Co. v. Gragg, 750 P.2d 398 (Kan. 1988). The court based its decision to allow condemnation on the fact that a Kansas statute authorized condemnation for providers of "electrical current". Although fiber optic cables do not conduct electric current, electricity is used to convert the original electric communication signal to light and to reconvert the light at the end of the line.

[2] 15 U.S.C. §717f(h).

of CO_2 want to use the same pipeline to transport to a common sink. Most natural gas common carrier regulations require that the gas be made available to all customers and therefore such a requirement might be unsuitable for CO_2 sequestration pipelines.

Nonetheless, even a common carrier requirement would not be a serious obstacle to transporting CO_2. As long as those constructing the pipeline know how it will be regulated, the capacity of the pipeline and the route of the right of way can be planned accordingly. Therefore, regulatory certainty is required. State regulators should decide how CO_2 pipelines are going to be regulated before construction begins.

While safety and environmental issues with pipeline siting are well understood, other issues require some consideration. For example, how many electricity generating plants are in the area? Is there any EOR in the vicinity? How many injection sites are desired (or required) at the particular sink? Will the CO_2 pipeline be treated as a public utility so that is has the power of eminent domain? Will a CO_2 pipeline be treated as a common carrier and be subject to rate regulation?

If state regulators believe they will encounter mostly geographically isolated electricity generating plants transporting CO_2 to large geologic sinks that can handle multiple injection sites, statutes and regulations might be revised to make CO_2 pipelines ancillary to electricity generation so that they would be considered a public utility but not a natural gas pipeline. Thus, they would have the power of eminent domain and such states might require a certificate of public convenience and necessity, but not impose a common carrier requirement.

In states where several electricity generating plants plan to transport to a common sink, particularly one with EOR, then a common pipeline network is desired. Since the CO_2 may be sold to the companies engaged in the EOR, state regulators may be interested in the rates that pipeline operators charge. In this situation, a common carrier requirement might be desired. In fact, the Railroad Commission of Texas, which has explicit authority to regulate CO_2 pipelines, does impose a common carrier requirement. In Texas, land may be condemned for CO_2 pipeline rights of way.

If a pipeline owner has the power of eminent domain, private land can be condemned for the right of way. The primary legal issue in condemnation proceedings is the amount of compensation owed for the taking of the land. The Fifth Amendment of the United States Constitution (and similar provisions of state constitutions) provides that "[N]or shall private property be taken for public use without just compensation." The standard employed for determining just compensation is the fair market value of the land.

Regulation of CO_2 Pipelines

Several aspects of gas pipelines are regulated, including siting, safety, and rates. Siting comprises determining the route of the pipeline and the environmental affects of constructing and maintaining it. Safety involves controlling the risk of injuring people and property or of contaminating the environment. Regulation of the rates charged for transport via pipeline has traditionally been important where the pipelines have been considered a public utility. Siting will be the most important issue for CO_2 pipelines.

Safety regulations are already in place, and accident rates associated with existing CO_2 pipelines do not appear to be significant. [1]

Federal Regulation

The Federal Energy Regulatory Commission (FERC) has broad authority over interstate pipeline matters. For interstate natural gas pipelines, FERC has jurisdiction over tariffs and rights of way.[2] As of January 2005, FERC had not asserted jurisdiction over CO_2 pipelines and moreover, it is unclear whether FERC could assert jurisdiction in the absence of specific legislative authority. Nonetheless, it is unlikely that an extensive interstate CO_2 pipeline network will be constructed in the Midwest Region in the near future.[3] Although pipelines will most likely be used to transport CO_2 from electricity generation plants and other industrial sources to geologic sequestration sites, such pipelines will probably be relatively short given the relative proximity of most of the large CO_2 point sources within the MRCSP region and candidate CO_2 storage reservoirs. Pipelines that fall completely within one state's borders will be under that state's jurisdiction.

> **Permitting.** The Department of the Interior manages land owned by the federal government and its agencies issue various permits related to pipelines that cross those lands. The Department of Agriculture's Forest Service oversees rights of way within national forests lands and the MRCSP states do contain several national forests. The Bureau of Indian Affairs permits rights of way across Native American land with tribal consent and there are tribal lands within some states in the MRCSP.
>
> The Bureau of Land Management (BLM) administers 262 million acres of surface land in the Western United States under the authority of the Federal Land Policy and Management Act of 1976 (FLPMA)[4], and therefore has many utility rights of way within its jurisdiction. Although the BLM does not administer any land in the Midwest Region, it is useful to briefly examine the basic right of way provisions of the FLPMA as well as the Mineral Leasing Act (MLA).[5] The definition of right of way used in the FLPMA includes an easement, lease, permit, or license to occupy, use, or traverse public land.[6] The BLM may grant rights of way under the FLPMA for, inter alia, transportation, electricity, telecommunications, or water infrastructure. A provision of the FLPMA also allows rights of way for pipelines transporting "liquids and gases, other than water and other than oil, natural gas, synthetic liquid or gaseous fuels, or any refined product

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[1] A leading CO_2 pipeline operator, Kinder Morgan CO_2, reports that in over 30 years of experience it has never had a CO_2 pipeline rupture. The Canyon Reef Carriers Pipeline, one of the earliest CO_2 pipelines, had five failures between 1992 and 1984, but no injures occurred. Two of the failures were caused by explosions at compressor stations; three failures were pipeline failures at the injection station. With several decades of experience, and with the promulgation of safety regulations by the Department of Transportation, the transmission of CO2 via pipeline should continue to be a safe activity. See Gemma Heddle, Howard Herzog, and Michael Klett, "The Economics of CO_2 Storage" 16-17 MIT LFEE (2003).

[2] FERC's jurisdiction is based on the Natural Gas Act, the Natural Gas Policy Act of 1978, and 18 CFR 284.

[3] More extensive CO_2 pipeline networks may develop, but over a longer time frame.

[4] Federal Land Policy and Management Act of 1976, Pub. L. No. 94-579 (21 Oct. 1976); 43 U.S.C. §1701 *et seq.* Provisions dealing with rights of way are found in sections 501-511 (43 U.S.C. §§1761-1771).

[5] Mineral Leasing Act, 30 U.S.C. 185 (1988).

[6] FLPMA §103(f).

produced therewith."[1] This exception was made to accommodate the right of way provisions of the MLA, under which the BLM permits oil and natural gas pipelines.[2]

Although the right of way sections of the FLPMA and the MLA are similar, there is one key difference that will be important in determining which statute applies to pipelines involved with geologic sequestration: the MLA imposes a common carrier requirement; the FLPMA does not. Recent BLM practice has been to consider carbon dioxide a natural gas. This has resulted in legal challenges by companies that do not want to be bound by common carrier requirements which allows other companies transporting CO_2 to utilize the pipelines.

In the case Exxon v. Lujan[3], Exxon argued that its application for a CO_2 pipeline right of way should have been granted under the FLPMA rather than the MLA. The crux of the case was the reasonableness of the BLM's classification of CO_2 as a natural gas under the MLA. Exxon contended that natural gas should be taken in a restrictive sense because it implies fuel, however, the BLM maintained that natural gas has a broader meaning, referring to all naturally occurring gases. The Interior Board of Land Appeals, the federal district court, and the Tenth Circuit Court of Appeals all held that the BLM's decision to issue the permit under the MLA rather than the FLPMA was reasonable.

Although the BLM permits existing CO_2 pipelines under the MLA, and therefore imposes a common carrier requirement, it is not clear that pipelines associated with geologic sequestration would have a common carrier requirement. This is because the common carrier requirement of the MLA appears to be aimed at protecting consumers and does not apply to public utilities under the jurisdiction of state public utility commissions that regulate the rates charged for natural gas to consumers.[4] Given that CO_2 destined for sequestration might be considered a waste rather than a consumer product, the BLM and other relevant agencies may determine that a common carrier provision is not necessary. In the case of the BLM, that would mean deciding that CO_2 destined for sequestration is not a natural gas or a refined product of a natural gas, which would enable them to issue pipeline right of way permits for CO_2 destined for sequestration under the FLPMA instead of the MLA.

However, it remains to be seen how pipelines involved in sequestration will be treated by the BLM. Moreover, the BLM rights of way will not be important in the Midwest Region. Nonetheless, similar issues relating to the classification of CO_2 pipelines will arise within the seven states of the MRCSP, and what happens regarding the regulation of CO_2 pipelines, even outside of this region, is likely to have an impact on how such pipelines are treated within the region.

Safety. The Department of Transportation's Office of Pipeline Safety (OPS) administers a national regulatory program to ensure the safety of natural gas and hazardous liquids pipelines. In 1991, the hazardous liquid pipeline regulations were amended to include CO_2.[5] Therefore, CO_2

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[1] FLPMA §501(a)(2); 43 U.S.C. §1761(a)(2). This exception is identical to the grant of authority in the MLA. See note 8 below.

[2] MLA, 30 U.S.C. §185(a), provides that rights of way may be granted for pipeline purposes for the transportation of oil, natural gas, synthetic liquid or gaseous fuels, or any refined product.

[3] *Exxon v. Lujan*, 970 F.2d 757 (10th Cir. 1992).

[4] 30 U.S.C. §185(r)(3)(A).

[5] Carbon dioxide pipelines are regulated under the same rules as hazardous liquid pipelines. Although carbon dioxide pipelines are treated as hazardous, carbon dioxide is not defined as a hazardous substance. It is a Class L, highly volatile, nonflammable, nontoxic material. See 49 CFR 190-199, 49 CFR 195 in particular; the classification is found in Appendix B, Table 4.

pipelines are subject to a high level of scrutiny and are reviewed as high risk hazardous pipelines when they have a diameter greater than 457 mm (18 inches) or when they pass through populated areas.[1]

The OPS regulations are concerned with safety in the design, construction, operation, and maintenance of pipelines.[2] The OPS certifies state agencies to inspect intrastate pipelines and to enforce the safety regulations. For the states in the MRCSP Region, the agency authorized by the OPS in all states is the public utility or public service commission. The states must enforce federal regulations, but are free to supplement these with state-specific regulations, provided they are consistent with federal standards. The authorized agencies are partially funded (up to 50%) by the OPS.[3]

Other federal agencies may have authority over pipeline rights of way. The Army Corps of Engineers control any right of way that crosses navigable waters. The Environmental Protection Agency has the authority to review and consult with other agencies regarding issues of the environmental impact of proposed pipelines. Agencies within the Department of Health and Human Services set limits for the recommended exposure for humans to CO_2.

State Regulation

A majority of the regulations applicable to CO_2 pipelines in the MRCSP Region will come from state agencies. Relevant state level agencies include the following: public utility commissions, natural resource commissions, oil and gas commissions, environmental protection agencies, transportation commissions, and departments of agriculture. Despite the variety of agencies that may be involved, siting is the crux of planning and acquiring a pipeline right of way. The various aspects of siting are often handled by different agencies. Agencies that regulate transportation or utilities are concerned with the physical location of easements, while environmental protection agencies and wildlife agencies focus on the environmental impact of proposed rights of way. One means for making the siting process more efficient is to have a comprehensive planning process that coordinates the permitting of all concerned agencies within a state.

State public utility commissions normally have jurisdiction over electricity and natural gas production and transmission. Accordingly, state public utility commissions will most likely figure prominently in the regulation of the transportation of CO_2. State public utility commissions, also called public service commissions, have jurisdiction over public utilities and common carriers. Public utilities and common carriers are enterprises that have historically been subject to direct government regulation of rates and terms of service. Enterprises in four broad economic sectors are commonly referred to as public utilities—

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[1] 49 CFR 195.303.

[2] The OPS regulations apply to pipelines transporting carbon dioxide—defined as a fluid consisting of greater than 90% CO_2 molecules compressed to a supercritical state. Carbon dioxide is transported in a supercritical state for both safety and economic considerations and in most all cases is presently transported at purities that exceed 90%. For instance, the Dakota Gasification—Weyburn pipeline carries CO_2 at 95% purity, and CO_2 captured from the flue gas of typical coal burning electricity plants can probably be concentrated to about 93% or more. Among other requirements, all new pipelines must have a cathodic protection system. This system should be regularly monitored to ensure the electric current levels are sufficient and that no corrosion is occurring. Pipelines are also required to be equipped with computational leak detection systems. With CO_2 pipelines, one of the primary concerns is the formation of carbonic acid. To prevent nitric acid formation, water in the pipeline must be kept to a very low level. Most CO_2 pipelines are constructed from epoxy coated and polyethylene lined carbon steel.

[3] 49 U.S.C. §60105(a).

energy, telecommunications, transport, and other services such as water and sewage.[1] Common carriers are enterprises that provide transportation for compensation to the public and pipelines and telecommunications lines are often considered common carriers. The common characteristic of public utilities and common carriers (common carriers are usually considered public utilities) is that the services they provide are considered to be essential to the public interest.

Public utility commissions usually have the power of eminent domain, which may be granted to public utilities or common carriers. The state officials consulted within the MRCSP Region are all confident that CO_2 pipelines will be deemed to be public utilities. This will allow land to be condemned for pipeline rights of way if necessary. Furthermore, state public utility commissions are taking the lead in establishing one stop permitting processes. These combine the various permitting steps required in the state by having one agency take the lead and then consulting with the interested parties and agencies.

The Ohio Power Siting Board (OPSB) serves as a model of a lead agency that coordinates all permitting and siting issues within the state of Ohio. The OPSB's mission is to support sound energy policies that provide for the installation of energy capacity and transmission infrastructure for the benefit of Ohio citizens, while promoting the state's economic interests and protecting the environment and land use.[2] The OPSB is comprised of 11 members. The voting members include: the chair of the Public Utilities Commission of Ohio (PUCO), the director of the Ohio Environmental Protection Agency, the director of the Ohio Department of Agriculture, the director of the Ohio Department of Health, the director of the Ohio Department of Natural Resources, and a public member appointed by the governor from a list of nominees provided by the Ohio Consumers' Counsel. The nonvoting members are four Ohio legislators.

The OPSB has jurisdiction over the siting of major utility facilities[3] And someone wishing to construct a major utility facility must obtain a certificate of environmental compatibility and public need from the OPSB before commencing construction. Major utility facilities under the jurisdiction of the OPSB include gas or natural gas transmission lines capable of transporting gas at more than 125 pounds per square inch of pressure.[4] Based on this definition, the OPSB will likely take jurisdiction over the siting of CO_2 pipelines. Carbon dioxide is normally transported at pressures greater than 1200 pounds per square inch. As discussed above, the terms "gas" or "natural gas" should include CO_2, and precedent exists in Ohio courts for employing a broad definition of terms such as "gas" when a restrictive meaning is not explicitly stated.[5] In addition, there is precedent with the OPSB for siting a pipeline for the transportation of a gas not intended for use as a fuel. In January of 2005, the OPSB approved the construction of a pipeline that will transport hydrogen gas.[6] The pipeline will deliver hydrogen from a plant at a Sunoco refinery to a BP North America refinery where the hydrogen will be used in a sulfur removal process to meet low sulfur fuel standards. A CO_2 pipeline would be somewhat analogous in that it would run from a carbon capture site to a storage site.

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[1] James C. Bonbright et al., *Principles of Public Utility Rates*, 7 (1988).

[2] This mission statement comes from the Ohio Power Siting Board's publication "Siting New Energy Infrastructure in Ohio: A Guidance Document" (February 2005). The document is available on the OPSB's website: http://www.opsb.ohio.gov.

[3] See O.R.C. §4906 and O.A.C. §4906.

[4] O.R.C. §4906.01(B)(3).

[5] In *Alexander v. Buckeye Pipeline Co.*, the Ohio Supreme Court refused to apply a restrictive meaning to the terms "gas" or "oil" in a right of way agreement because the parties could have easily qualified the terms. 53 Ohio St. 2d 241 (1978).

[6] The OPSB approved construction of a 12 inch hydrogen gas pipeline that will be constructed and operated by Buckeye Gulf Coast Pipe Lines, L.P. The 3.6 mile pipeline will be buried within or adjacent to existing railway and utility corridors.

Siting in Ohio is a comprehensive process, with the OPSB coordinating the review and permitting processes of the various agencies involved. Even before filing an application which addresses the environmental compatibility and public need for a proposed facility, a pre-application conference may be requested. Relevant agency officials are invited to the conference, which serves to identify potential problems with the project. Before any formal proceedings, the applicant must also hold public meetings to advise affected parties of the proposed project and to gather public input.

Following the public informational meeting, the application may be filed with the OPSB. For pipelines, the application must include at least two fully developed routes. Although one route may be designated as preferred, all routes must be approvable by the OPSB. The OPSB reviews applications within 60 days and consult with relevant state agencies. The staff members then prepare a report which becomes part of the formal record and an opportunity for public comment and then formal legal hearings follow. Based on the staff report and testimony, a hearing officer makes a recommendation to the OPSB which reviews the evidence and makes its ruling. The relevant legal standards the OPSB considers are: (1) the basis of the need for the pipeline; (2) the probable environmental impact; (3) whether the proposed pipeline represents the minimum environmental impact in light of the available technology and the feasibility of alternatives; (4) whether the pipeline will serve the public interest, convenience, and necessity; and (5) the proposed pipeline's impact on agricultural land.[1] Decisions of the OPSB may be appealed to the Ohio Supreme Court.

Other states have similar one stop siting agencies[2], yet the broad scope of the OPSB provides a model within the MRCSP Region. Indeed, in recent legislation, Kentucky has enacted a similar siting process based on the OPSB. A company planning a CO_2 pipeline can approach the OPSB first and receive the guidance on obtaining all proper permits. For example, the OPSB might require that the company obtain permits from the Army Corps of Engineers, the Ohio Environmental Protection Agency, the United States Fish and Wildlife Service, the Ohio Department of Natural Resources, and local governments. The OPSB serves as a lead agency, assisting pipeline companies in meeting Ohio's regulatory requirements.

A one stop siting agency can greatly facilitate all phases of carbon dioxide sequestration as well as the development of other energy facilities. Best practices for a siting agency include[3]:

- A broad jurisdictional scope that encompasses all stages of sequestration, including: electric generation and carbon capture, selection of the sequestration site, transportation, and injection.
- A comprehensive process that incorporates all state and local permitting agencies.
- Clear standards for review.
- Preliminary site studies to facilitate better planning.
- Public participation beginning early in the siting process.
- Formal legal proceedings with the right of judicial review.
- Statutory power of eminent domain.

The power of eminent domain could be included in the enabling statute or regulations of a siting agency. In Ohio, for example, the OPSB must determine whether a proposed facility will serve the public interest, convenience, and necessity. This is the same standard used for granting the power of eminent domain. Thus, rather than having two separate proceedings, one for siting and one for eminent domain, a siting agency could be given the authority to make both determinations at once. An entity that obtains a siting certificate would then automatically have the power of eminent domain. The rights of landowners would

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[1] See ORC §4906.10(A).
[2] See e.g., The Oregon Energy Facility Siting Council and the Washington Energy Facility Site Evaluation Council.
[3] States might also consider financial incentives to decrease carbon dioxide emissions. State siting agencies could play a role in facilitating incentive programs as well as permitting.

be protected by allowing for public participation in siting proceedings and granting affected landowners party status, the right of judicial review, and by requiring good faith efforts to negotiate with affected landowners before requesting condemnation.[1] In essence, the siting process could include condemnation issues.

CO_2 Transport Regulations in MRCSP States

The following is a brief summary of state regulations affecting pipelines, including some comments gathered during meetings with state regulators.

Indiana: CO_2 pipelines would be regulated by the Indiana Utility Regulatory Commission. Commission staff members stated that CO_2 pipelines would most likely be considered public utilities, and therefore would have authority to condemn rights of way under IC 8-1-8-1(a).

Kentucky: The Kentucky PSC has jurisdiction over utilities, as defined in KRS §278.010. Companies transporting oil or gas by pipeline are declared to be common carriers by KRS §278.470. Pipelines may condemn lands under the authority of KRS §278.502.

Maryland: Natural gas pipeline companies may condemn rights of way or easements pursuant to MD Code §5-403. The power of condemnation is conditioned on the company being a common carrier. The granting of a certificate of public convenience and necessity would allow condemnation as a public utility. Staff members of the Maryland PSC stated that a CO_2 pipeline might be able to apply for a certificate of public convenience and necessity under current rules. The staff members also believed that there would be a favorable climate for updating the regulations to specifically provide for CO_2 pipelines.

The Maryland PSC regulates pipeline safety with the U.S. DOT Office of Pipeline Safety. Unlike the federal regulations, MD Code §11-201(d)(1) not only treats CO_2 pipelines as hazardous pipelines, but also defines CO_2 as a hazardous material. For pipeline safety, this makes no difference. It is unclear whether the definition will have any effect beyond the safety regulations.

Michigan: Michigan has a broad eminent domain statute. Michigan statutes §213.23 provides that any public corporation or state agency is authorized to take private property for a pubic improvement or for the purposes of its incorporation or for public purposes within the scope of its powers for the use or benefit of the public. The Michigan PSC has its own rules for condemnation for public utilities.

Ohio: Staff members of the PUC of Ohio stated that CO_2 pipelines will be sited by its Ohio Power Siting Board (see ORC §4906 and OAC §4906). As a result, CO_2 pipelines will be considered public utilities and will have the power to condemn land for rights of way. Several other states in the Midwest are looking to the OPSB as a model of a one-stop permitting process.

Pennsylvania: The Pennsylvania Public Utility Commission has jurisdiction over natural gas utilities and is responsible for enforcing federal and commission pipeline safety regulations as they apply to certificated natural gas utilities in the state. Pennsylvania also has general eminent domain statutes, see 15 Pa. Cons. Stat. Ann. §1511(a)(2) and §1511(a)(6).

West Virginia: The West Virginia PSC would have jurisdiction over CO_2 pipeline siting. Staff members state that CO_2 pipelines could use the PSC's eminent domain authority because they would be considered

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[1] Similar recommendations are made in the *Model State Certification and Siting Code for Electric Transmission Facilities: Final Staff Report of a Keystone Policy Dialogue* (March 1994).

public utilities. The staff members further stated that a certificate of public convenience and necessity would probably not even be required, but they suggest that anyone contemplating a CO_2 pipeline apply for a certificate. See WV Code §54-1-2.

Geological CO_2 Sequestration Opportunities in the MRCSP Region

As described earlier, geologic storage of CO_2 involves first capture of the gas from its source (e.g., power plants and refineries), then purification and compression to transform it to a supercritical fluid, possibly transport to the injection site, followed by its injection into deep geologic formations. A minimum depth of approximately 2,500 feet (762 meters) below the surface is required to maintain the CO_2 in the supercritical phase. This section of the report summarizes the extensive and groundbreaking research carried out by the MRCSP geology team to characterize the geologic sequestration resources in the seven state MRCSP region. A more detailed report focusing on the geological characterization of the MRCSP region is available on the MRCSP website (www.mrcsp.org) or on the DOE/NETL website.

Natural geologic reservoirs have held oil, natural gas, water, and even CO_2, for millions of years with no or minimal leakage. Therefore, these same systems are thought to offer both near-term opportunities and longer-term possibilities for future management of anthropogenic CO_2 emissions (Reichle and others, 1999; Beecy and others, 2002). Various Industries currently use these natural reservoirs for storage of industrial wastes (Class I injection wells) and the disposal of oilfield brines (Class II injection wells). CO_2 is also commercially injected into oil fields in the U.S. and elsewhere today in order to stimulate additional oil production. Such operations are categorized as Class II enhanced oil recovery (EOR) injection wells and is a growing trend in the petroleum industry.

Thus, a substantial quantity of experience currently exists for geologic CO_2 injection. Furthermore, several large-scale projects have been in operation for several years specifically for the purpose of geologic CO_2 sequestration. These include the Sleipner project (injecting into a saline aquifer in the North Sea) (Gale and others, 2001) and the Weyburn project (sequestering CO_2 while performing enhanced oil recovery in western Canada) (Whittaker, 2005; Brown and others, 2001). These projects have been closely monitored and studied, yielding much valuable research for this emerging class of technologies.

Additionally, the injection of anthropogenic CO_2 may be carried out in conjunction with the production of methane from unmineable coal beds or oil and/or natural gas from active or depleted petroleum reservoirs, in both cases the produced fuels may defray some of the cost of capture and injection. While these enhanced recovery options are considered to be near-term opportunities, due to potentially favorable economic conditions, the overall capacity in coal beds or oil-and-gas reservoirs is relatively small compared to the potential of deep saline aquifers.

A key attraction of geologic sequestration is the potential for direct and long-term storage of captured CO_2 emissions in close proximity to the CO_2 source. However, to achieve this objective, the potential capacity of any geologic reservoir needs to be verified by detailed regional assessments as well as by site-specific investigations in order to that decisions makers fully understand the characteristics of the geologic sequestration system. Thus, a major part of the Phase I research was a first-round regional assessment of this capacity.

The MRCSP Phase I geologic team consists of the geological surveys from six of the seven MRCSP states (Indiana, Kentucky, Maryland, Ohio, Pennsylvania, and West Virginia) plus Western Michigan University. In Phase I, the team examined the geology of the seven state MRCSP region, created a regional correlation chart showing the numerous geologic units in the area, and delineated the most promising and prospective geologic reservoirs and sinks for CO_2 sequestration. This early correlation and

broad-brush analysis resulted in the mapping of nine potential reservoir horizons and five potential cap-rock intervals (including organic shales that can also be considered potential reservoirs). In total, the MRCSP geologic assessment resulted in 30 original depth and thickness maps, nine regional thematic maps, and 14 derivative capacity maps, using data from over 85,000 control-points. One of the more significant thematic map layers is a new oil-and-gas-fields map for the region—the first ever compiled for this seven-state area. All of the data and maps collected for this project are stored in a state-of-the-art geographic information system, and are available for interactive use on the MRCSP website at www.mrcsp.org.

Using the maps generated and data collected for this project, estimates of CO_2 storage capacity, by geologic unit, reservoir type (deep saline formations, oil and gas reservoirs, unmineable coals, and carbonaceous shales), and state were calculated. This Phase-1 assessment has shown that the MRCSP region has the following approximate reservoir capacities:

- 450 to 500 gigatonnes of storage potential in deep saline formations; the Mt. Simon, St. Peter, and Rose Run Sandstones have the highest potentials in the region.

- Between 2-3 gigatonnes of CO_2 potential storage may be possible in existing and depleted oil-and-gas fields. Enhanced oil recovery using CO_2 could result in the production of hundreds of millions of barrels of oil that otherwise might be left in the ground.

- Northern Appalachian Basin unmineable coals have the potential to contain approximately 0.2 to 0.3 gigatonnes of CO_2. Using CO_2 for enhanced gas recovery from the coalbeds could help produce trillions of cubic feet of natural gas.

- It may be possible to store over 45 gigatonnes of CO_2 within the region's carbonaceous shales, with potential for additional natural gas production.

This assessment shows that the MRCSP region has the capacity to store hundreds of years worth of CO_2 emissions at our current levels of production. It also indicates that the region has many opportunities—at least in the near term—for value-added production of oil and natural gas associated with CO_2 sequestration.

The estimated CO_2 storage capacity for the region is very large compared to the present-day emissions. Thus, total potential storage capacity for the region is vast. However, that storage capacity is not evenly distributed across the region. Some areas have more-than-ample storage capacity while others have little or no known potential.

Potential Geologic Reservoirs in the MRCSP Region

The U.S. Department of Energy has identified several categories of geologic reservoirs for potential CO_2 sequestration (U.S. Department of Energy, 1999, 2004, 2005). Of these categories, four are considered important for the MRCSP region: (1) deep saline formations, (2) oil and gas fields, (3) unmineable coal beds and (4) carbonaceous shales.

Deep Saline Formations

Saline formations are natural salt-water bearing intervals of porous and permeable rocks that occur beneath the level of potable groundwater. Currently, a number of the saline formations of the MRCSP region are used for waste-fluid disposal (especially in Indiana, Michigan, and Ohio); thus, a long history of technological and regulatory factors exists that could be applied to CO_2 injection/disposal. Saline formations are widespread, close to many large CO_2 sources, and are thought to have large pore volumes available for injection use (Reichle and others 1999, U.S. DOE, 2004, 2005). In order to maintain the injected CO_2 in supercritical phase (i.e. liquid) the units must be approximately 2,500-feet or greater in depth. Maintaining the CO_2 in a liquid phase is desirable because, as a liquid, it takes up less volume than when in the gaseous phase. One tonne of CO_2 at surface temperature and pressure (in gaseous phase) occupies approximately 18,000-cubic feet. The same amount of CO_2, when injected to approximately 2,600 feet in depth, will occupy only 50-cubic feet. These sequestration depths also help insure there is an adequate interval of rocks (confining layers) above the potential injection zones to act as a geologic seal. For the purposes of the MRCSP Phase I Project, no consideration was given to the potential use of shallower saline aquifers for CO_2 sequestration.

In these types of reservoirs, CO_2 is injected, under pressure, down a specially constructed well into the reservoir where it displaces (hydrodynamic trapping) and mixes (solubility trapping) with saline water and fills the pore spaces between the mineral grains of the rocks in the reservoir and is trapped within minerals (mineral trapping) in the rock matrix. Depth, permeability, injectivity, reservoir pressure, reservoir integrity, and water chemistry are some of the variables that control the sequestration potential of deep saline formations (Reichle and others, 1999; Bach and Adams, 2003). In addition to the properties of the injection zone or reservoir, an overlying seal unit, (confining layers), is necessary. The injected CO_2 has a lower specific gravity, and thus more buoyant, than the natural formation fluids and will rise to the top of the porous zones. Hence, all cap rock units must be relatively impermeable and sufficiently thick to arrest any appreciable vertical movement of the CO_2 within the sequestration interval, thereby trapping it in the deep subsurface. The MRCSP geologic team have collected data and mapped several intervals of rocks that would act as satisfactory cap-rock intervals as part of the Phase 1 study.

Storage of CO_2 can be in either subsurface traps, or in unconfined strata. In subsurface traps, the more buoyant CO_2 will occupy the highest portions of any structural (e.g. anticline) or stratigraphic (e.g. pinch-out) feature. These same mechanisms of trapping are found in many of the natural gas and oil reservoirs (i.e., traps) that occur in the MRCSP study area. Within such traps, only the pore volume available in the rock and the size of the trap limits the volume of CO_2 that can be injected. In unconfined storage units, the CO_2 is injected in regional aquifers located in rocks without specific structural closures or stratigraphic traps. Once injected, the CO_2 will migrate to the highest portion of the saline aquifer where it accumulates against the cap rock, which prevents further vertical movement (Bentham and Kirby, 2005). At that point the injected CO_2 then will migrate laterally, following the normal hydrodynamic flow regime of the region (usually towards shallower areas). However, it must be emphasized that flow velocities in deep geologic systems occur at rates measured in feet per hundreds or thousands of years.

Commercial sequestration in saline formations has been successful in the Sleipner field of Norway, and the U.S. Department of Energy is involved in a small-scale demonstration project in the Frio Formation of Texas (Hovorka and others, 2001). Further testing and pilot studies will occur in the United States during Phase II of the Regional Carbon Sequestration Partnerships (U.S. DOE, 2004, 2005).

Oil and Gas Fields

Oil and gas fields represent known geologic traps (structural or stratigraphic) containing hydrocarbons within a confined reservoir with a known cap or seal. In depleted or abandoned petroleum fields, CO_2

would be injected into the reservoir to fill the pore volume left by the extraction of the oil or natural gas resources (Westrich and others, 2002). The injected CO_2 would be trapped by the limits of the reservoir (whether structural or stratigraphic) for secure storage. Volume, permeability, injectivity, pressure, reservoir integrity, water chemistry, the nature of the cap rock or reservoir seal, and the history of production are some of the variables that control the sequestration potential of depleted oil and gas fields (Reichle and others, 1999). This may be an attractive option in many parts of the MRCSP region because vast areas of the region have a long history of oil and gas recovery (exploration for oil began in the 1800's). In addition, the MRCSP region includes four of the top seven, natural-gas storage states in the nation (Natural Gas Monthly, 2002). Such large volumes of gas storage capacity strongly suggest that CO_2 gas can be successfully managed in subsurface reservoirs within the region.

In active oil fields, it has been demonstrated that CO_2 can be used for enhanced oil recovery (EOR). In this process, some of the oil that remains in reservoirs after primary production, is recovered by injecting CO_2 that either (1) repressurizes the reservoir and displaces and drives the remaining oil to a recovery well (immiscible flooding) or (2) directly mixes and chemically interacts with the remaining oil as it pushes it to the producing well (miscible flooding). Approximately 70 oil fields worldwide currently inject CO_2 for EOR (U.S. DOE, 2004) demonstrating the effectiveness of this value-added sequestration option. Moreover, enhanced oil recover, while sequestering CO_2, could provide an economic incentive to storage in several parts of the MRCSP region where CO_2 sources are near oil fields.

Unmineable Coal Beds

The MRCSP region includes the Appalachian basin, which contains the second- (West Virginia), third- (Kentucky), fourth- (Pennsylvania) and fourteenth- (Ohio) leading coal-producing states in the nation (EIA, 2005). Unmineable coal beds offer an out of the ordinary option for geologic sequestration in the region because, unlike the previously described reservoir types, CO_2 injected into a coal bed would not only occupy pore space, but would bond, or adsorb, onto the carbon in the coal itself. The adsorption rate for CO_2 in coals is approximately twice that of methane; thus, in theory, the injected CO_2 would displace methane, allowing for the potential of enhanced gas recovery (Reznik and others, 1982; Gale and Freund, 2001; Schroeder and others, 2002). Because of the adsorption mechanism, concerns of miscibility that occur in oil and gas reservoirs are not an issue. Thus, the injection of CO_2 and resulting enhanced recovery of coalbed methane could occur at shallower depths than for depleted oil reservoirs. Hydrogeologic flow, water chemistry, coal thickness and quality, and subsurface temperature-pressure conditions are some of the variables that control the potential use of coal beds for CO_2 sequestration and enhanced coalbed-methane recovery (Pashin and others, 2003). Although there is currently only limited coalbed methane production in the MRCSP region, rising gas prices have led to growing interest in this energy resource in the last decade, and secondary recovery of methane may provide an economic incentive for sequestration of CO_2 sources in the coal fields.

Carbonaceous Shales

The MRCSP region also contains widespread, thick deposits of carbonaceous shales. These shales are interesting in that they are often multifunctional; acting as seals for underlying reservoirs, as source rocks for oil-and-gas reservoirs, and are unconventional gas reservoirs themselves. Analogous to sequestration in coal beds, CO_2 injection into unconventional carbonaceous shale reservoirs could be used to enhance existing gas production. As an added bonus, it is believed the carbonaceous shales would adsorb the CO_2 into the shale matrix, permitting long-term CO_2 storage, even at relatively shallow depths (Nuttall and others, 2005a).

Geography of the MRCSP Region

The seven-state MRCSP region is an enormous and economically diverse area of the United States that exceeds 255,000 square miles in size (>662,000 square kilometers). The area considered for geologic sequestration (excluding the upper peninsula of Michigan and the Illinois basin portions of Indiana and Kentucky) contains over 201,000 square miles (501,000 square kilometers). The diverse topography, hydrology, and bedrock geology of the region present a variety of geologic sequestration options. Additionally, numerous environmental considerations will be needed in different parts of the seven-state region. The MRSCP region encompasses three physiographic regions (Figure 4.2):

1. Atlantic plain, including the Continental Shelf and Coastal plain (Maryland),
2. The Appalachian highlands, including the Piedmont province (Maryland), Blue Ridge province (Maryland, West Virginia), Valley and Ridge province (Maryland, Pennsylvania, West Virginia), and Appalachian Plateaus province (Kentucky, Ohio, Pennsylvania, West Virginia),
3. Interior plains, including the Interior Low plateaus (Kentucky, Ohio) and Central Lowland (Indiana, Michigan, Ohio).

Bedrock is at or near the surface in much of the Appalachian highlands and is covered by Quaternary sediment in the Atlantic plain and in parts of the Interior plains north of the Ohio River. Variable surface topography, climate, and sediment cover result in varied land uses, surface water, and groundwater conditions across the seven states.

General Geology, Major Structural Features and Target Areas

Because the four reservoir classes being considered all occur in sedimentary rocks, only those areas within the seven states with thickness of sedimentary rocks considered adequate for CO_2 sequestration were evaluated for their geologic sequestration potential. Also, although sedimentary rocks of appropriate thickness occur in a large part of the MRCSP region, the types and depths of potential CO_2 reservoir strata vary. Figure 4.3 is a generalized map of the geologic units at or near the surface that also shows the major geologic structures of the region. Figure 4.4 is a cross section across the map illustrating that the sedimentary rocks thicken into geologic basins and thin above structural arches.

Much of the Appalachian highlands, from the piedmont on the east to the Allegheny front on the west, were not included in this investigation because they are dominated by folded and faulted metamorphic and igneous rocks. Additionally it was not possible, within the scale of this project, to map most of the local sedimentary deposits within this folded section of the Appalachian Mountains because of a lack of any data on the depth and thickness of individual units. Likewise, the upper peninsula of Michigan was not included in the geologic assessment of CO_2 sequestration potential because it consists mostly of metamorphic and igneous rocks. Although a small area of sedimentary rocks, considered to be a part of the Michigan basin, does exist in the Upper Peninsula, these rocks do not obtain depths great enough for consideration as a geologic sequestration target and were not included in this study.

The eastern limit of MRCSP geologic investigations is the Maryland shoreline. Although many offshore sedimentary rocks may have a potential for sequestration, they were not investigated in this Phase I project. The western boundary of the MRCSP region is a multi-county boundary that represents the approximate boundary between the Kankakee arch and Illinois basin in Indiana and the western flank of the Cincinnati arch in Kentucky (Figure 4.3). The Illinois basin, the focus of another DOE-Carbon Sequestration Partnership, was not included in this MRCSP study.
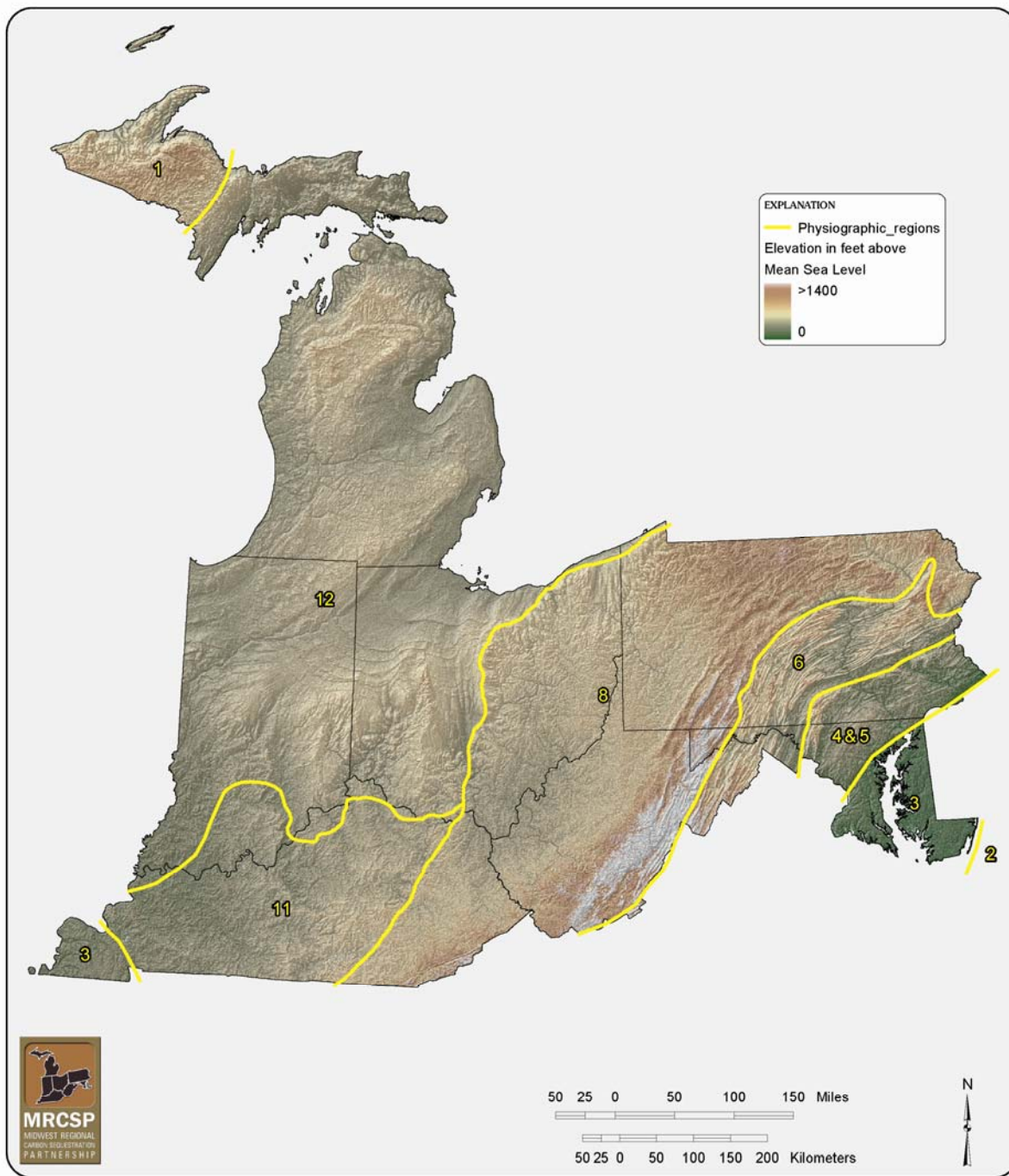
Figure 4.2. **Shaded topographic relief map of the MRCSP study area with boundaries of the general physiographic regions.**

Key: 1 = Superior Upland; 2 = Continental Shelf; 3 = Coastal Plain; 4&5 = Piedmont and Blue Ridge; 6 = Valley and Ridge; 8 = Appalachian Plateaus; 11 = Interior Low Plateaus; 12 = Central Lowland. Physiographic regions from Barton and others (2003); topographic data from NASA (2002).
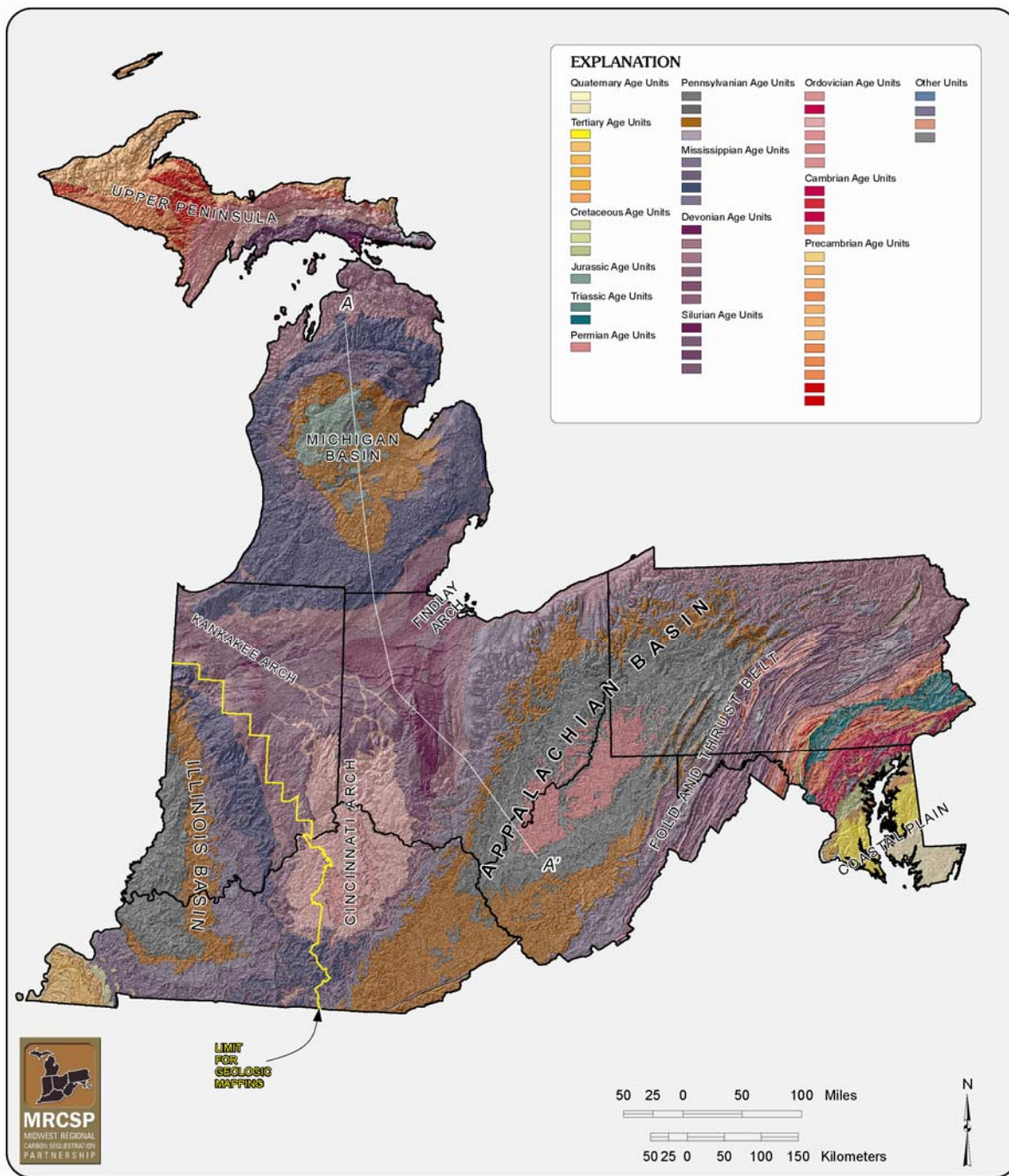
Figure 4.3. **Shaded topographic relief overlain with generalized bedrock geology units (organized by age) found at or near the surface (bedrock contacts from Schruben and others, 1997)**

Note: Some of the major geologic features (folds, arches and basins) of the MRCSP study area are also labeled. A-A' line is location of cross section shown in Figure 4.4.
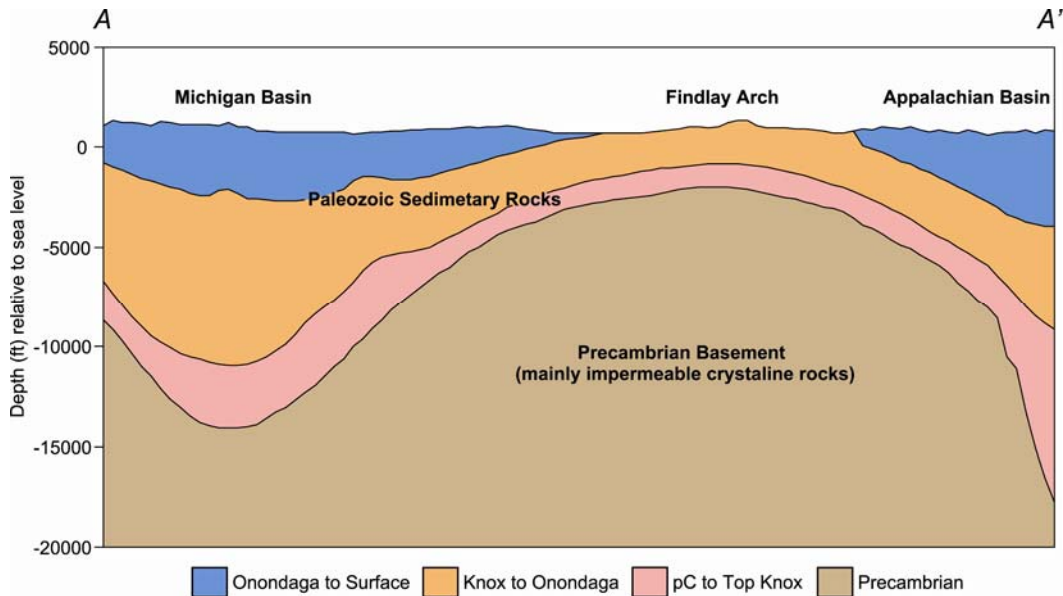
Figure 4.4.   Generalized cross section across the Michigan and Appalachian basins.

> Note: Profile line is shown on Figure 4.3. Layer elevations for this cross section
> were obtained directly from geologic maps produced for this report.

Michigan Basin

The Michigan basin is a nearly circular cratonic basin, occurring mostly within the state of Michigan, but locally extending into northern Indiana and northwestern Ohio. The basin is bordered on the north and east by the Canadian shield, on the west by the Wisconsin highland, to the southeast by the Findlay arch, and to the southwest by the Kankakee arch (Figure 4.3). Interestingly, the basin is situated above a gravity high, a feature that may represent complex basement faulting or a failed rift zone at depth (Hinze and others, 1975). At the center of the Michigan basin, Precambrian basement rocks are overlain by nearly 16,000 feet of sedimentary strata that was deposited from Cambrian through Carboniferous time (Figure 4.5). Although there have been slight shifts in depositional center of the basin with time, the basin has remained essentially circular throughout most of the Paleozoic.

Appalachian Basin

The northern Appalachian basin is an elongate, asymmetric foreland basin, with a preserved northeast-southwest trending central-axis that extends through Pennsylvania, western Maryland, and West Virginia (Figure 4.3). The eastern margin of the basin is concealed beneath thrust sheets in the Blue Ridge province of the Appalachian Mountains. The western margin of the basin occurs in east-central Kentucky and central Ohio. The Cincinnati and Findlay arches separate the Appalachian basin from the Illinois and Michigan basins, respectively (Figure 4.3).
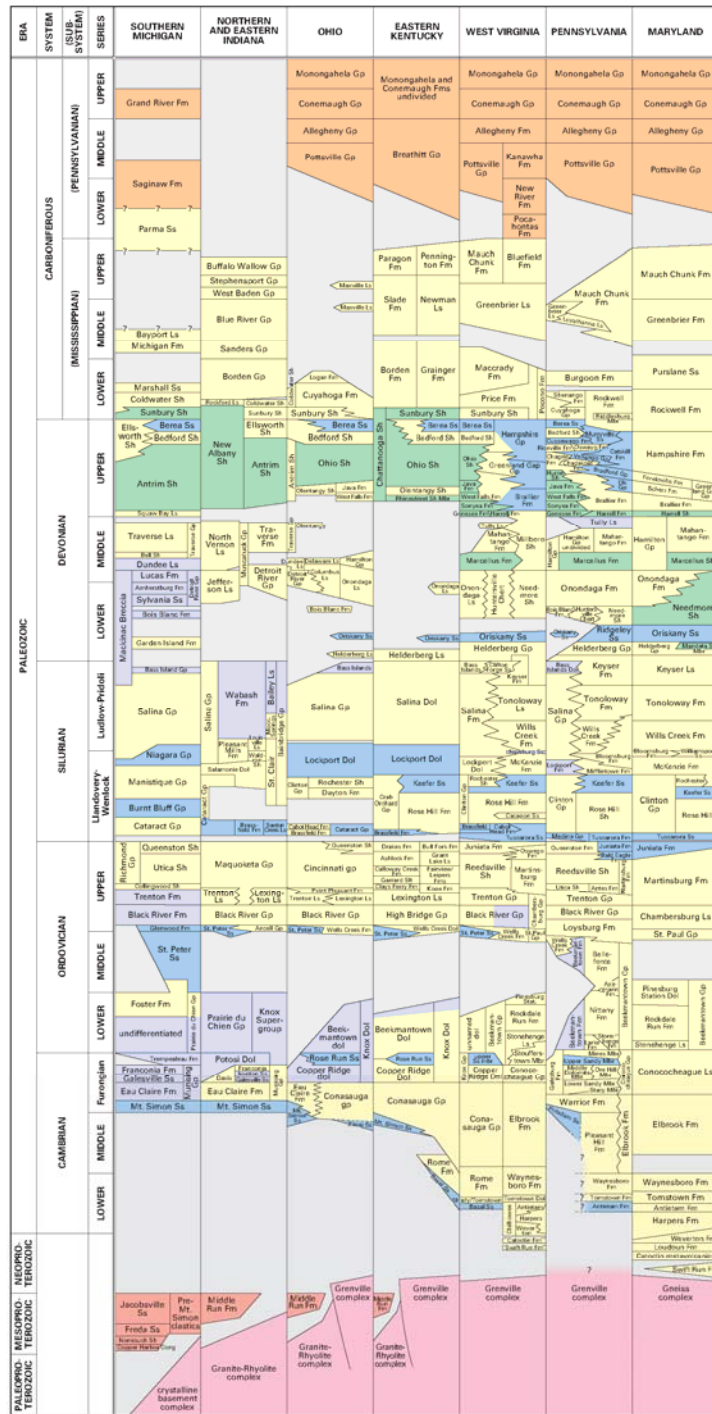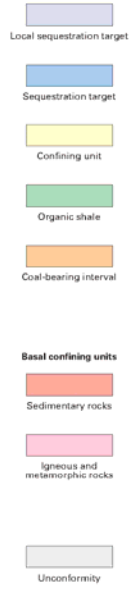
Figure 4.5. Stratigraphic correlation and CO$_2$ sequestration characterization chart of geologic units in the MRCSP region.

The Appalachian basin initially developed during the Cambrian Period and above the Rome trough, a basement aulocogen formed during Iapetan rifting (McGuire and Howell, 1963; Ammerman and Keller, 1979; Shumaker, 1996). The Rome trough extends eastward from Kentucky into West Virginia, thence northeastward, possibly continuing beneath Ordovician and younger age sediments of the northern Appalachian basin. Following Iapetan rifting, the basin enlarged by periodically reactivation of geologic structures that developed in response to collisional tectonics along the eastern margin of North America during the Taconic (Upper Ordovician), Acadian (Middle to Upper Devonian), and Alleghany (Upper Carboniferous) orogenies of the Paleozoic Era (Tankard, 1986; Quinlan and Beaumont, 1984; Thomas, 1995; Shumaker, 1996).

The Precambrian basement is overlain by more than 45,000 feet of sedimentary rocks in the central Pennsylvania portions of the northern part of the basin. Sedimentary rocks of the Appalachian basin range Neoproterzoic to Carboniferous-Permian in age.

Structural Arches

Although the thickest sedimentary cover (and therefore greatest potential for sequestration) are in the basins, portions of several of the broad, structural arches in the MRCSP region also have potential for sequestration of CO_2. The Findlay arch may have started as a positive feature in the late Ordovician during the last phases of the Taconic orogeny (Wickstrom and others, 1992; see Figure 4.3). In northwestern Ohio, the arch forms a broad, shallow platform where there has been significant oil and gas production from the Ordovician Trenton Limestone.

The Kankakee arch, a post-early Ordovician feature, represents a western extension of the Cincinnati arch and separates the Michigan basin from the Illinois basin in northern Indiana. The Indiana-Ohio platform is a broad relatively flat-lying area formed where the Kankakee and Cincinnati arches merge. Several waste-fluid disposal wells have been drilled to the Mount Simon Sandstone (a deep saline aquifer) along this trend in northeastern Indiana. The Cincinnati arch is a late Ordovician positive feature that separates the Illinois from the Appalachian basins in Kentucky, Indiana and Ohio. The western boundary of the MRCSP region, in Kentucky and Indiana, represents the approximate boundary between the Cincinnati arch and Illinois basin. Unlike the previously discussed arches, where Precambrian igneous and metamorphic rocks rise close to the surface, the Cincinnati arch is underlain by the East Continent rift basin, an elongate north-south trending basin filled with a thick sequence of Proterozoic arenaceous rocks (Shrake and others, 1991; Drahovzal and others, 1992).

Geologic Uncertainties

Our knowledge about the sequestration potential in deep geologic units is limited by the availability of data on the various subsurface attributes of the region. For example, in making broad regional assessments, such as in this MRCSP Phase I project, our assessment is constrained, and thus limited, by the availability of oil-and-gas-well data accessibility to seismic data, and our previous experience and working knowledge in and of the region.

In general, the amount of data available for mapping and analysis of any particular unit is directly proportional to its depth below the surface. Thus, the deeper the unit, the less certain is our understanding of the various parameters related to, and needed for, assessing geologic CO_2 sequestration targets in the subsurface of the MRCSP region. Unfortunately, since our primary data set is based mainly on oil and gas wells, the control points used to map the various units discussed herein is limited by where and how deep companies in this industry drills. The deeper the well, the more costly it is to drill; hence, overall, there

are fewer deep wells. This is especially true once the well depth exceeds about 6,000 to 7,000 feet. Consequently, our knowledge on the deepest portions of the region is limited ― to date, no wells are known to have been drilled to the deepest extreme of the Appalachian basin, a depth thought to exceed 45,000 feet. These depths are not practical, in any event, for current sequestration consideration.

Another deep feature of the region that may represent a significant potential sequestration target is the region containing the Rome trough, an inadequately known structural feature in the subsurface of the Appalachian basin (Figure 4.6). The Rome trough is a large, deep feature that occurs in Kentucky, West Virginia, and Pennsylvania and is approximately parallel with the Ohio River (it is thought the current location of sections of the Ohio River are controlled by structural irregularities related to this feature). Seismic data and a limited number of deep wells drilled in this area indicate that the Lower Paleozoic geologic section rapidly expands within this feature. For example, it is known that several thousands of feet of sedimentary rocks occur in the Rome trough proper, that are not known to exist outside the boundaries of the feature. These same data indicate sandstones, some of which may have good storage reservoir potential, occupy portions of this expanded section. However, what is not known is how extensive these potential reservoirs may be. Nonetheless, some of these potential sandstone sequestration targets are within the economic limits of feasibility making them a possible target for consideration as a large injection target (perhaps in the 9,000 to 12,000-foot range).

It is beyond the scope or economic abilities of this project to test these deep regions. However, their presences should be mentioned because, should the Rome trough contains the sandstone intervals that some believe to be there, this deep feature could easily double the sequestration potential within the MRCSP region.

Stratigraphic Correlation

Assessing the regional potential for CO_2 sequestration requires an understanding of the many stratigraphic units (groups and formations) in the MRCSP region and their geologic and stratigraphic relationships between various areas of the partnership (Figure 4.4). Therefore, a regional correlation chart was one of the first, and most significant, undertakings accomplished by the geologic team.

Each state has, over the past 150 years or so, developed its own stratigraphic nomenclature in order to explain the geologic history and stratigraphic succession for rocks within each state ― some of these terms are unique to rocks that occur only in the subsurface. The changing geologic character of many of these rock units, or at least their position within a geologic basin, has created some differences in the nomenclatures used in each state (see Figure 4.4). Other variations between states are related to different methods for establishing the placement of unit boundaries or how a unit is classified (ranked, i.e., group, formation, member) within a specific rock interval or in a different area of the region. Prior to the development of this correlation chart, no detailed chart showing the correlations between the individual MRCSP states existed. We continue to refine this chart as work progresses. More detailed correlation charts, where needed, are presented in the discussions of the individual units/intervals in Appendix A.
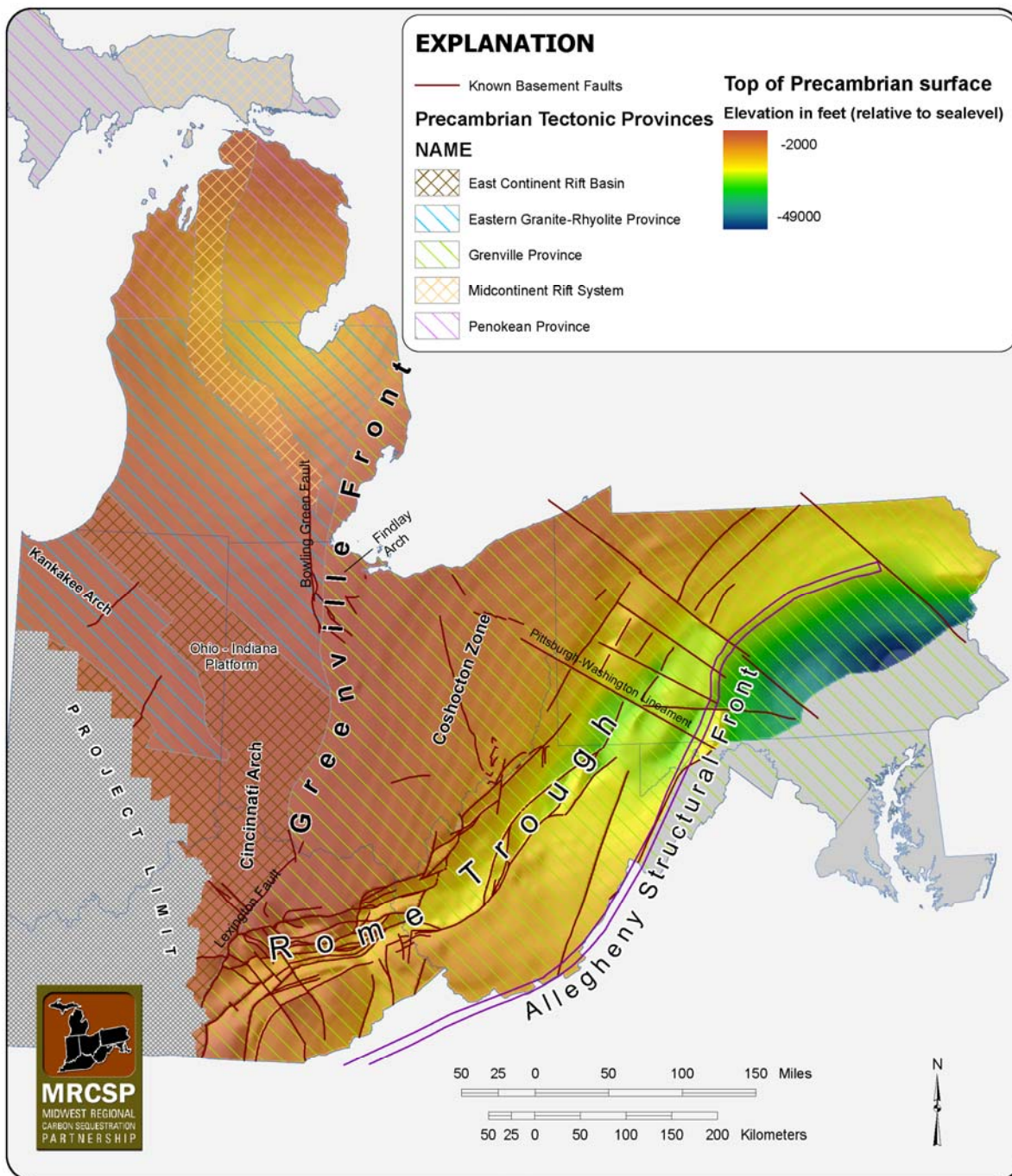
Figure 4.6. **Major geologic structural features of the MRCSP region.**

Note: Map shows major basement faults (known), tectonic provinces of the Precambrian rocks, elevation on top of the Precambrian unconformity, and other structural features.
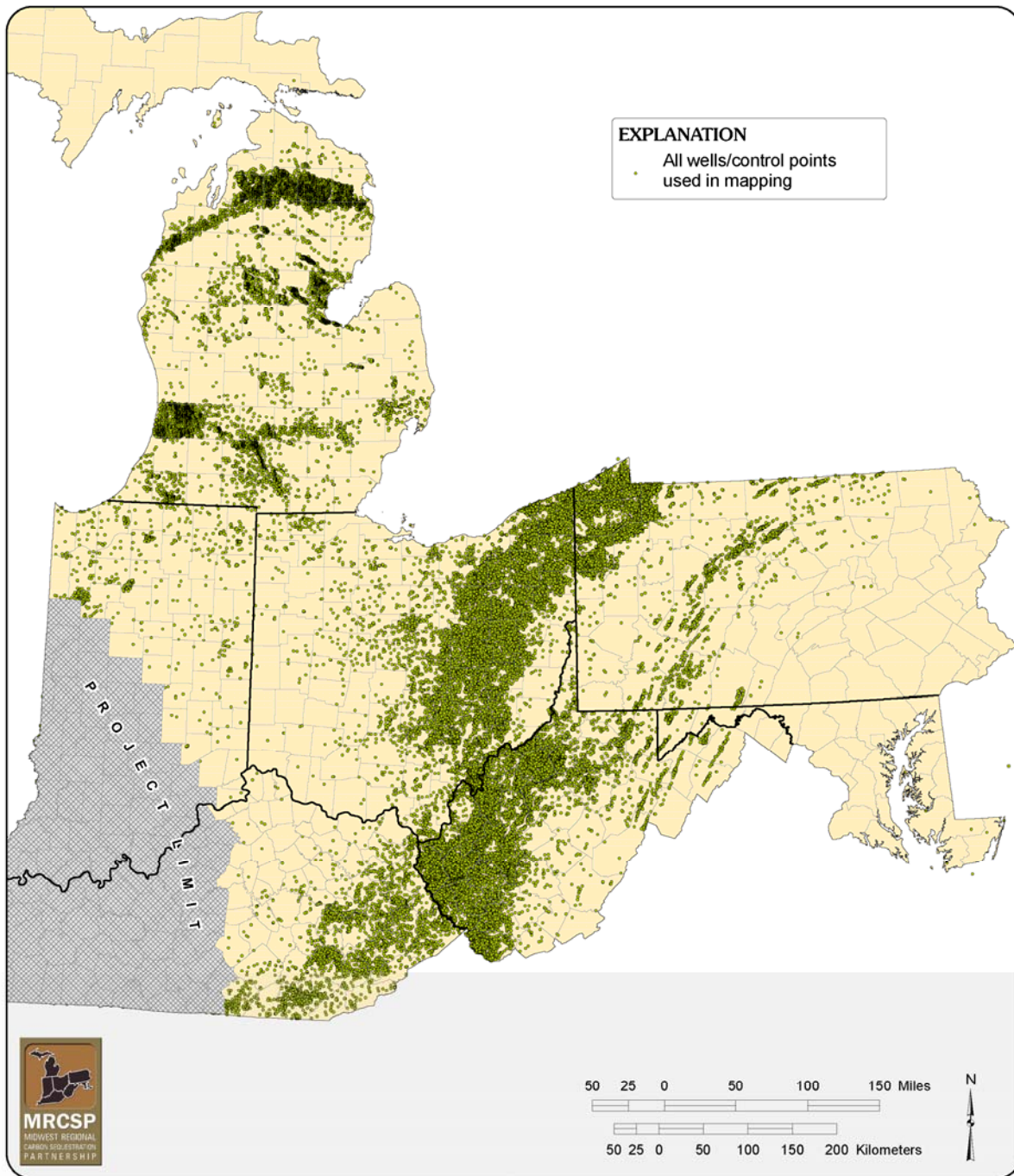
Figure 4.7. Distribution of all wells (85,650 unique wells) used for making the geologic structure and isopach maps for the MRCSP phase I investigation.
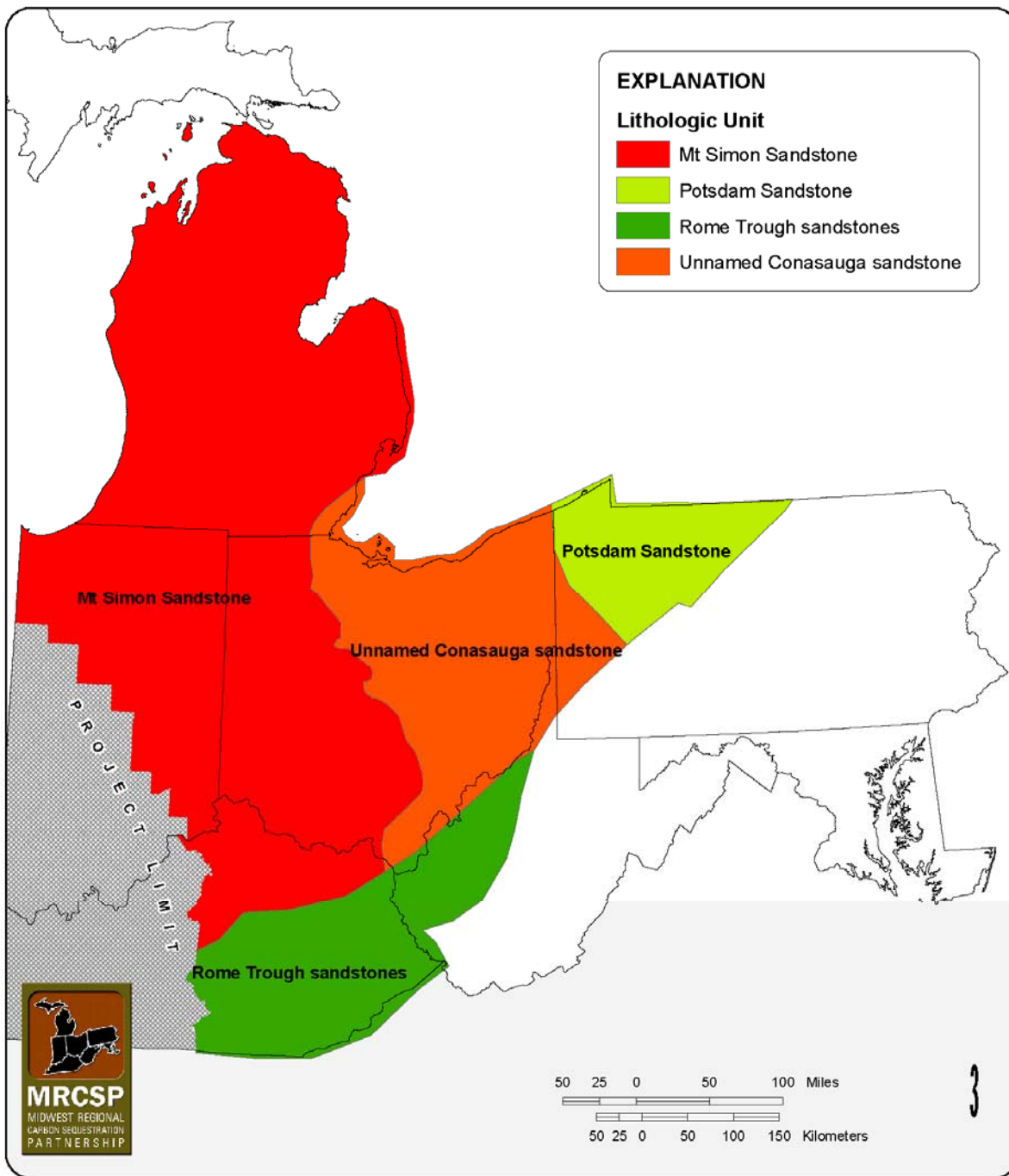
Figure 4.8. Rock units that comprise the Cambrian basal sandstones and the boundaries between them used in MRCSP mapping.

EXPLANATION

• Lockport to Onondaga interval control points

SILURIAN OUTCROP

ORDOVICIAN OUTCROP

PROJECT LIMIT
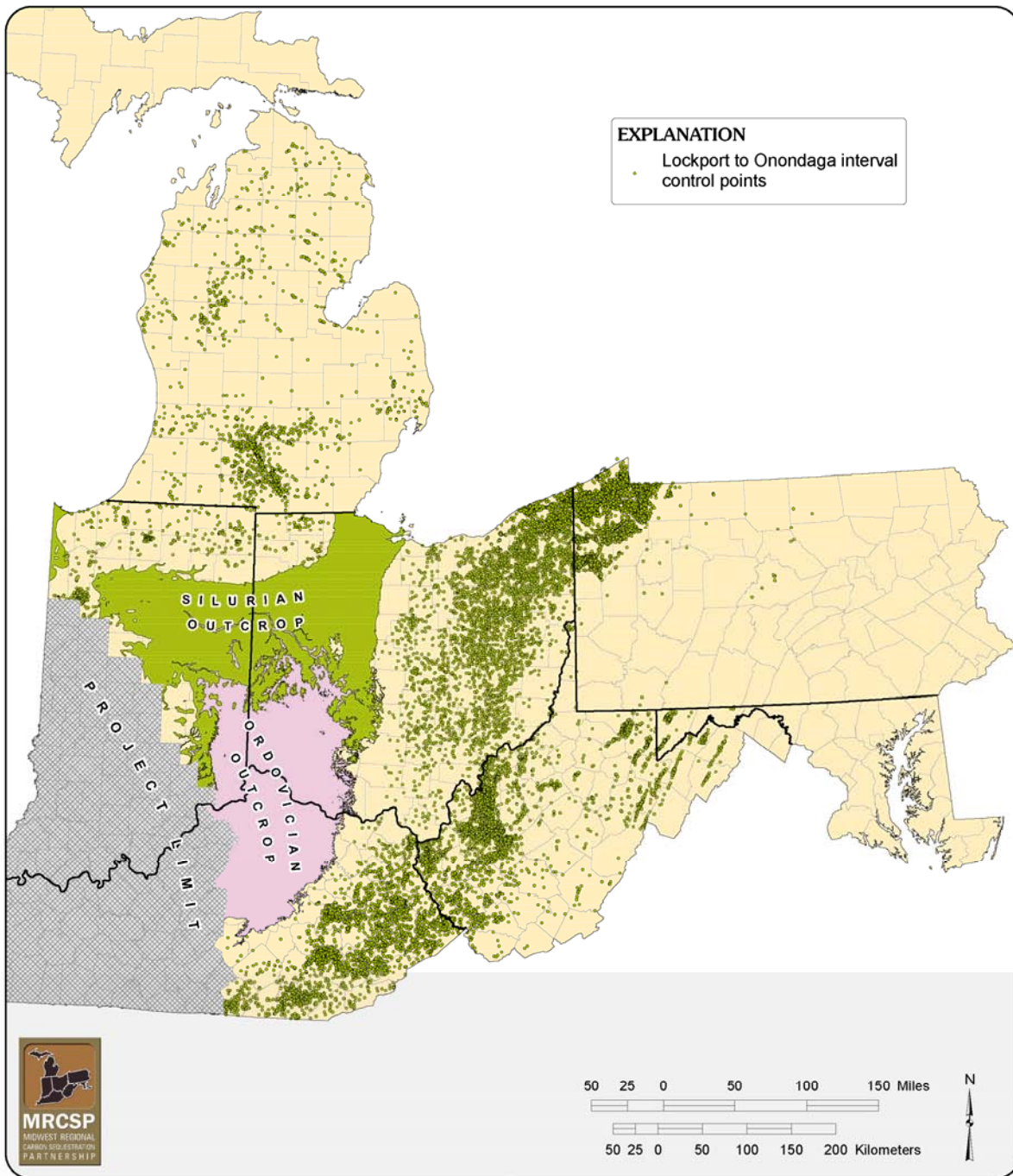
Figure 4.9. **Distribution of control points (wells) used for the Lockport to Onondaga interval.**

Note: This layer has 23,485 wells.
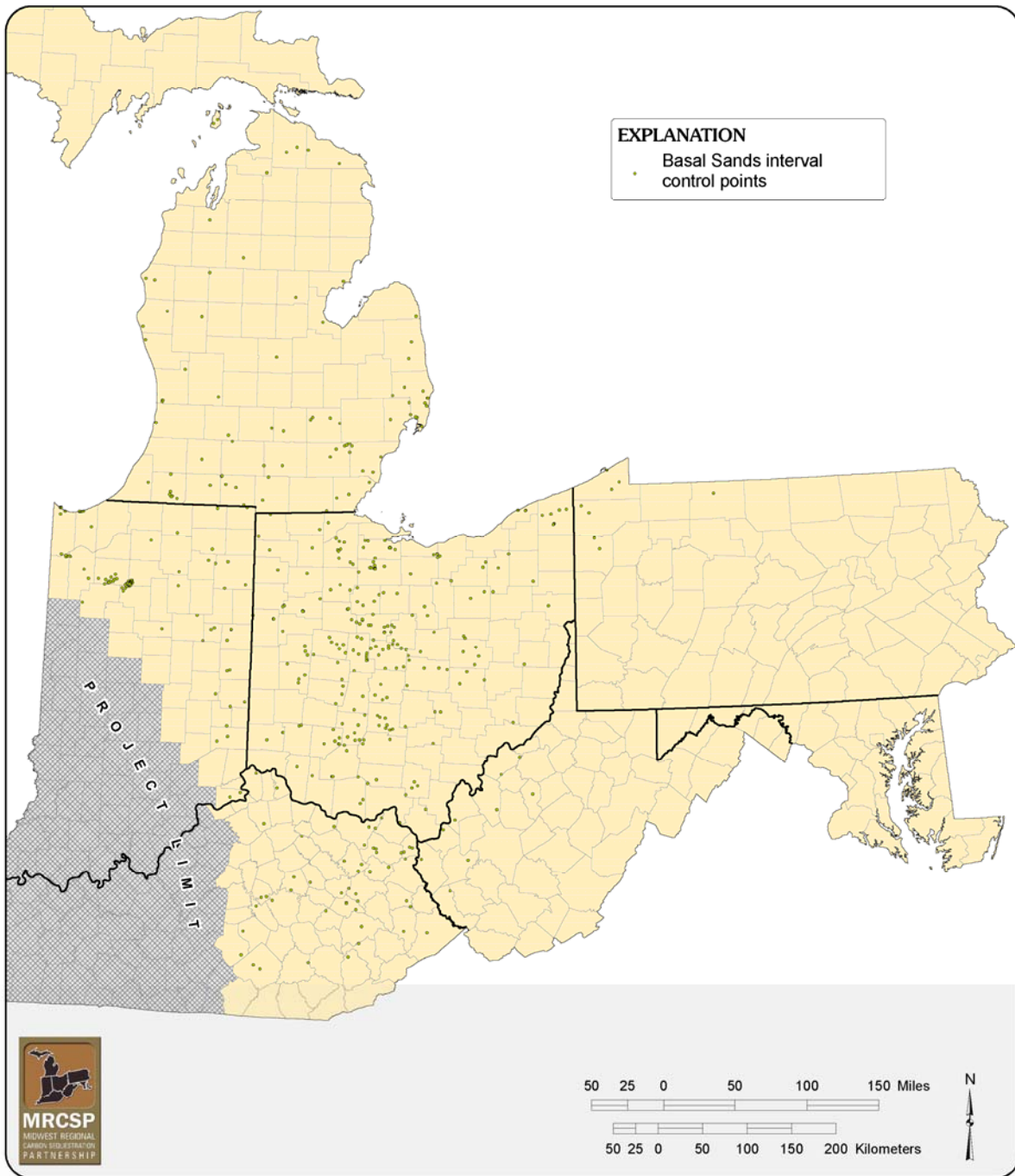
Figure 4.10. Distribution of control points (wells) for the Cambrian basal sandstones.

Note: This layer has 510 wells.
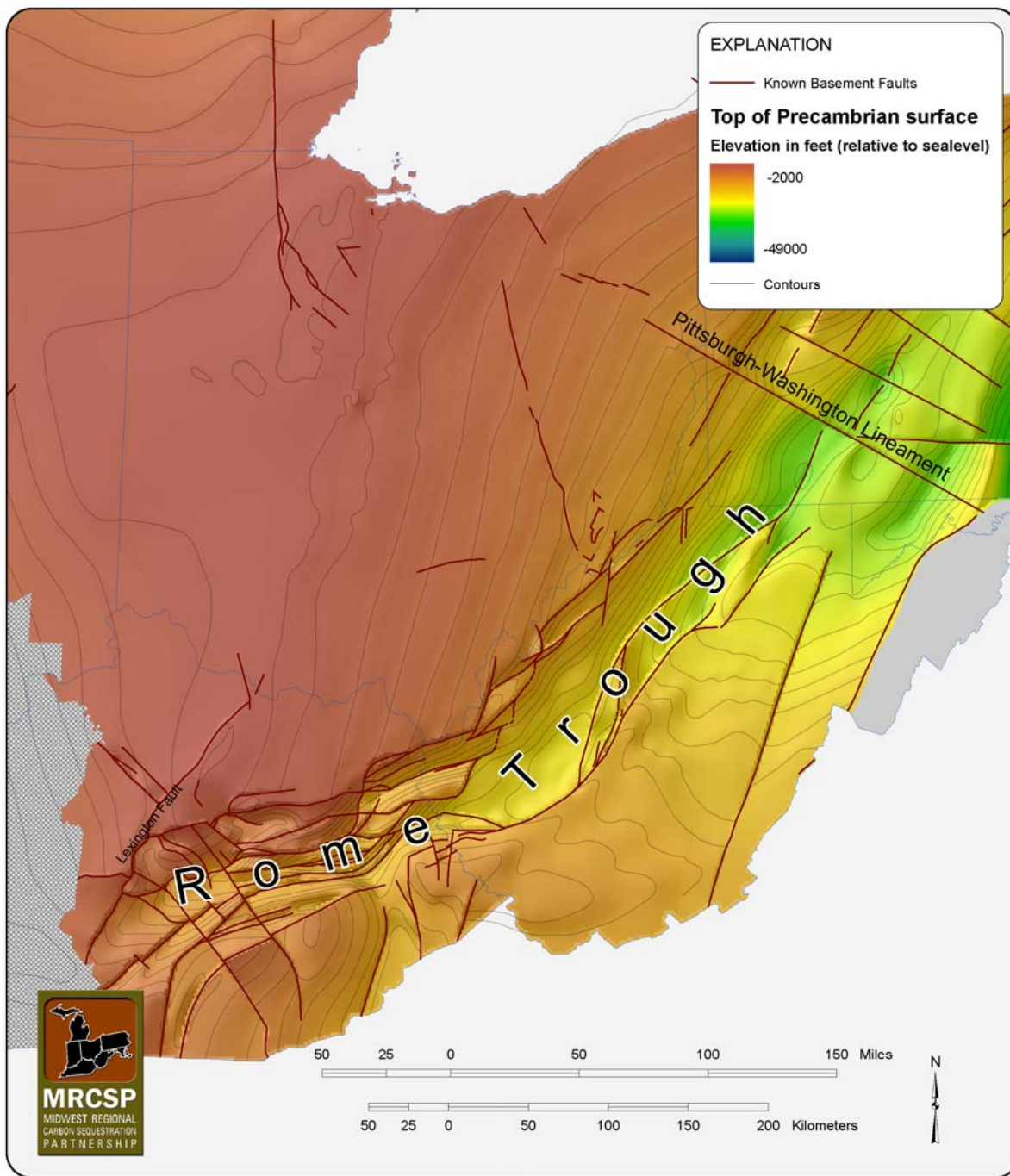
Figure 4.11. **Structure map on the top of the Precambrian unconformity illustrating the complexity within the Rome trough area.**

Note: Hand-contouring was used within the heavily faulted portions of the Rome trough and computer-based contouring was employed in less faulted areas.

Selection of Mapped Units and Limitations

Using the regional correlation chart and our knowledge of these units as a basis, an initial list of potential CO_2 sequestration reservoirs and seal (cap rock) intervals were chosen for further consideration. Known stratigraphic intervals of saline reservoirs, petroleum-producing units, gas-generating (source rock) carbonaceous shales, and coal-bearing units were identified in each state. Many of these intervals can be readily correlated between states or basins, however, others are restricted to a single basin or regions with a basin and determining their relationship of other more established units is problematic.

Phase I of the DOE regional partnership projects called for a regional assessment of the CO_2 sequestration potential of each partnership area within a defined time frame. To expedite our evaluations, a list was developed that consisted of wide-ranging stratigraphic intervals (often composed of multiple groups and formations) and was the basis for an initial assessment of potential reservoirs and cap rocks that could be regionally mapped using existing data sources. Maryland and Michigan were later added to the partnership and the process and list had to be repeated and slightly modified. Where possible, we adapted the chosen mapping units to be used within the new states. However, the added geology of the coastal plain and inclusion of the complete Michigan basin required adding additional units to the selection list.

After the list of geologic intervals and/or individual units to be mapped was finalized and a database schema devised, individual states of the team started collecting the data available to them. This included, amount other things, oil-and-gas-well data files (both electronic and paper), previously completed geologic mapping databases, published and unpublished studies within individual states, and miscellaneous data (i.e., core and sample records, geochemical analyses, miscellaneous geologic data files). As time permitted and as data sources were discovered, some individual units were added to the mapping list ― an example of this addition is the inclusion of the Niagaran reefs and Sylvania Sandstone. Table 4.8 is a final list of all mapped units in the MRCSP project.

Nine potential reservoir horizons and five potential cap rock intervals (including organic shales that can also be considered potential reservoirs) were chosen for regional mapping and further analysis after our initial screening. Our selections of which reservoir and seal intervals to map is by no means all-inclusive for the region. On the contrary, throughout our Phase I analysis, several other prospective reservoirs were noted. Additionally, the selected intervals do not necessarily represent laterally continuous zones of homogenous reservoirs or seals. Many assumptions are necessary when mapping at such a regional scale. Considering the magnitude of this project, the calculated volumes of potential CO_2 that can sequestered may vary depending on the detail, and scale, of an individual analysis. Rather, this Phase I analysis delineates stratigraphic intervals that have the potential to be used as reservoirs and seals for CO_2 sequestration across the region and provides a basis for approximating the carbon storage potential of the region in much the same way as the availability of future energy resources are assessed throughout the world. Over time, with the application of new technology and a refinement of those that now exist, coupled with an increase of available data, the reserve/sequestration potential numbers will inevitably change for many years to come following an areas initial assessment.

Table 4.8.   Summary of basic geologic maps created, responsible state for each layer, interpolation methods and software used to create the maps.

Geologic layer(s) mapped	Map(s) created	State Responsible	Methodology	Software
Precambrian Structure	Structure	Ohio	Kriging with extensive hand interpolation	ArcGIS
Cambrian basal sandstones	Structure & thickness	Ohio	Kriging, hand interpolation in Ky	Geostatistical Analyst (ArcGIS)
Top of basal sands to Copper Ridge interval	Structure & thickness	Indiana	Local polynomial interpolation	Geostatistical Analyst (ArcGIS)
Rose Run Sandstone	Structure & thickness	Ohio	Kriging, with extensive hand interpolation in Ky and Pa portions	Geostatistical Analyst (ArcGIS)
Knox to Lower Silurian interval	Structure (2) & thickness	Ohio	Kriging	Geostatistical Analyst (ArcGIS)
St. Peter Sandstone	Structure & thickness	Indiana	Local polynomial interpolation	Geostatistical Analyst (ArcGIS)
Medina Sandstone	Structure & thickness	Pennsylvania	Proprietary method, "Highly Connected Features" setting in "Create Contour Grid" procedure, and manual editing	Petra (geoPLUS, 2005)
Lockport to Onondaga interval	Structure & thickness	Indiana	Local polynomial interpolation	Geostatisical Analyst (ArcGIS)
Niagaran Reefs	Structure	Michigan	Kriging	Surfer
Oriskany Sandstone	Structure & thickness	Pennsylvania	Proprietary method, "Highly Connected Features" setting in "Create Contour Grid" procedure, and manual editing	Petra
Sylvania Sandstone	Structure & thickness	Michigan	Kriging	Surfer
Needmore Shale	Structure & thickness	Maryland	Kriging	Geostatistical Analyst
Devonian Shales	Structure & thickness	Kentucky	Kriging	Geostatistical Analyst
Appalachian Basin coal thickness	Aggregate thickness	Ohio/ Kentucky	Kriging and hand editing	Geostatistical Analyst
Saginaw Coal	Structure & thickness	Michigan	Kriging	Surfer
Waste Gate	Structure & thickness	Maryland	Kriging	Geostatistical Analyst

Geologic Mapping Procedures, Data Sources and Methodology

The central product of the MRCSP Phase I geologic tasks was a series of regional-scale, digital spatial models and maps with the overall goal to create a GIS to support regional planning for carbon sequestration. The GIS provides spatial data that can be used to evaluate the potential for geologic sequestration of CO_2 at any particular site within the MRCSP study area by digitally analyzing which underlying geologic units might be suitable for further analysis as a CO_2 reservoir and/or seal, their depths and overall thickness, and to provide an estimate of sequestration capacities. Selected sites that appear suitable provided must still be subjected to further, more detailed studies and site-specific testing and analysis. Digital maps were compiled for the depth and thickness of target and confining geologic layers, the extent of major oil and gas fields, the location of industrial injection wells, as well as for other geochemical and petrophysical data needed to calculate CO_2 sequestration capacity.

Most of the mapping effort focused on generating structure and isopach maps for nine regional geologic sequestration targets and five confining layers. The mapping also represents one of the first attempts to create regional-scale geologic maps using quantitative methods with rigorous error assessment. Geologic structure and isopach maps were created by interpolation of formation tops from oil-and-gas-well records that were compiled by the individual partnership states. The MRCSP geologic database contains a total of 85,650 individual wells (Figure 4.7) and approximately 162,000 formation tops. Control points (wells) available for mapping individual layers ranged from less than 500 points for very deep layers (Lower Cambrian rocks), to in excess of 23,000 points for shallower layers such as the Lockport-Onondaga interval. Point data were converted to isoline maps using a couple of different, commercial-available software packages that utilize a range of interpolation methods/algorithms. Unfortunately, computer interpolation occasionally resulted in the generation of surface trends that contradicted known geologic surfaces. In such cases, isolines were manually edited. Grids (rasters) were created for every layer to facilitate spatial analysis, modeling, and cartographic display. The accuracy of the maps was evaluated rigorously. Root Mean Square Errors (RMSE) range from 20 to 500 feet for the structure grids and 20 to 600 feet for isopach grids. Such error ranges stress the previous statements that the maps of this project are of sufficient quality for regional planning, but cannot be used in place of detailed site studies.

Methodology for Structure and Isopach Mapping

Maps in this project were created to identify major regional sequestration target and confining layers. The definition of mapping units reflects these goals rather than traditional stratigraphic-use customs. Hence, in many cases the mapped layers do not follow formal lithologic units or sequence stratigraphy definitions as currently used by many workers. For some map layers, several lithologic units that are considered diachronous were merged together. For example, the Cambrian basal sandstones include the Mt. Simon Sandstone, the basal sandstones of the Rome Trough, the Potsdam Sandstone, and unnamed sandstones of the Conasauga Group (Figure 4.8). These units range from the Furongian(upper) to the lower Cambrian in their occurrence, yet have little genetic relationship to one another. However, the grouping of these units together is useful in and of itself since all sandstones directly overlying the Precambrian unconformity can now be found on one map thus reducing the complexity for the uses of using multiple maps for a like stratigraphic unit.

The mapping workflow for this project included six steps: (1) data gathering, (2) data filtering to remove erroneous wells, (3) interpolation and contouring of gridded data, (4) manual editing of digital contour maps, (5) peer review and adjustments, and (6) creation of grids from final contour maps. The various MRCSP geologic teams divided the mapping responsibilities amongst themselves based on individual

areas of expertise. Each organization was responsible for the aforementioned steps 1 thru 5 for each selected interval and each team was allowed the freedom to use the mapping software of their choosing. After review, the final contour map files were sent to the Ohio Division of Geological Survey, where final gridding was applied for use in the CO_2 capacity calculations.

Original Data

The primary dataset consisted of well data provided by each MRCSP member state. The bulk of the data originated from oil-and-gas-well completion records. Also, each organization supplemented the datasets, where possible, with data created from previous work containing detailed geophysical-log-based interpretations. The resultant data files for this project used, for each structure maps creation, the geographic position of the well, its elevation, and the depths of the top of each map interval. Due to the range of data sources, the quality of depth data varied across the region. For example, some formation tops were determined by experienced drillers, others or by industry or government geologists, while others had an unknown origin. Because of this, filtering procedures were needed to remove errors and irregularities from the dataset.

Data filtering was accomplished by a variety of methods. For example, for layers created by the Ohio Division of Geological Survey (see Table 4.9), a geostatistical approach was adopted using Geostastistical Analyst (ArcGIS). A preliminary variogram was modeled and an initial surface created. Cross validation was conducted and points with residuals two standard deviations or more from the mean residual value were flagged as potential outliers. Then, flagged points were inspected; those deemed valid, yet flagged because of the influence of bad neighboring points were left in the system; erroneous data were removed. The data sets were also corrected by searching for output that did not conform to projected geologic trends across a region. If the error could not be resolved using just the data and map, geophysical-log cross sections were constructed to investigate and reconcile the areas of conflict. The filtering and inspection process was repeated until all erroneous wells were removed or resolved. The accuracy of the resultant interpolated surfaces is directly proportional to the amount and distribution of well control use to construct any particular map surface.

As briefly mentioned above, the amount of data available for mapping and analysis of any particular unit is directly proportional to its depth below the surface. Thus, the amount of data available for each layer varied with depth. Layers in the Devonian and Silurian can have over 10,000 control points (for example, the Onondaga, Figure 4.9). The amount of control drops precipitously as depth to the formations increases. For the deepest target layer, the Cambrian basal sands, there were only 510 wells deep enough to be used as control points (Figure 4.10). The amount and distribution of well control has a marked effect on the accuracy of the resultant interpolated surfaces (Table 4.9).

Other datasets were also used to supplement the point data and to improve the geologic quality of the maps. In Kentucky, hand-drawn structure contour and isopach maps were provided for units below the Knox unconformity. This was mainly because of the complex normal faulting (Figure 4.11) associated with the Rome trough (Gao and others, 2000) and the limitations of computer mapping software to portray these areas in a geologically acceptable manner. In addition, geologic maps from the literature were digitized and used to constrain interpretations in data-poor portions of the study area (Figure 4.12 illustrates one example).

Table 4.9. Summary of data and error statistics (5,000-foot grid resolution) for the major regional maps of this project.

Mapping Unit	Number of Wells	Square Miles/ Well	Cross Validation error (RMSE ft)	Grid Error (RMSE ft)	Range of values (ft)
Basal Cambrian Injection Targets Structure	510	323	595	361	17,210
Basal Cambrian Injection Targets Isopach	373	441	123	100	2,022
Copper Ridge Structure	641	321	385	390	15,691
Copper Ridge Isopach	337	610	658	567	9,751
Rose Run Structure	1,786	40	236	259	17,933
Rose Run Isopach	1,756	41	32	27	611
St Peter Structure	502	162	362	474	10,709
St Peter Isopach	254	321	60	84	1,156
Knox Structure	2,424	77	161	183	13,806
Knx Silur Isopach	2,051	90	86	47	5,202
Queenston Structure	11,327	15	74	55	10,431
Medina Structure	6519	13	58	78	9,299
Medina Isopach	6976	12	23	25	627
Oriskany Structure	11724	5	216	154	7,907
Oriskany Isopach	11024	6	21	10	386

Interpolation Methods

Computer-based and manual interpolation methods were needed to convert the point data into isoline maps and grids. Each state chose an interpolation algorithm that gave the best representation of the geologic layer to be mapped and fit within the individual software capabilities of each state mapping team (Table 4.8). For all methods, the end result was a set of digital isolines that required considerable manual editing in GIS software to remove edge effects, to repair errors caused by data scarcity, and to rectify match-up errors with pre-existing digital surface and near-surface geologic maps of specific map intervals.

Manual Isoline Editing

Considerable manual manipulation of contour lines was needed to create geologic maps that conformed to both the data and geologic knowledge. Line editing was generally accomplished digitally using ArcEdit (a module of ArcGIS). The bulk of the editing was done to fill in data gaps and to rectify contour line variations as these lines approached crop lines of those units eroded by surface processes (Figure 4.12). More extensive editing and interpretation were conducted in the faulted areas of Kentucky, especially
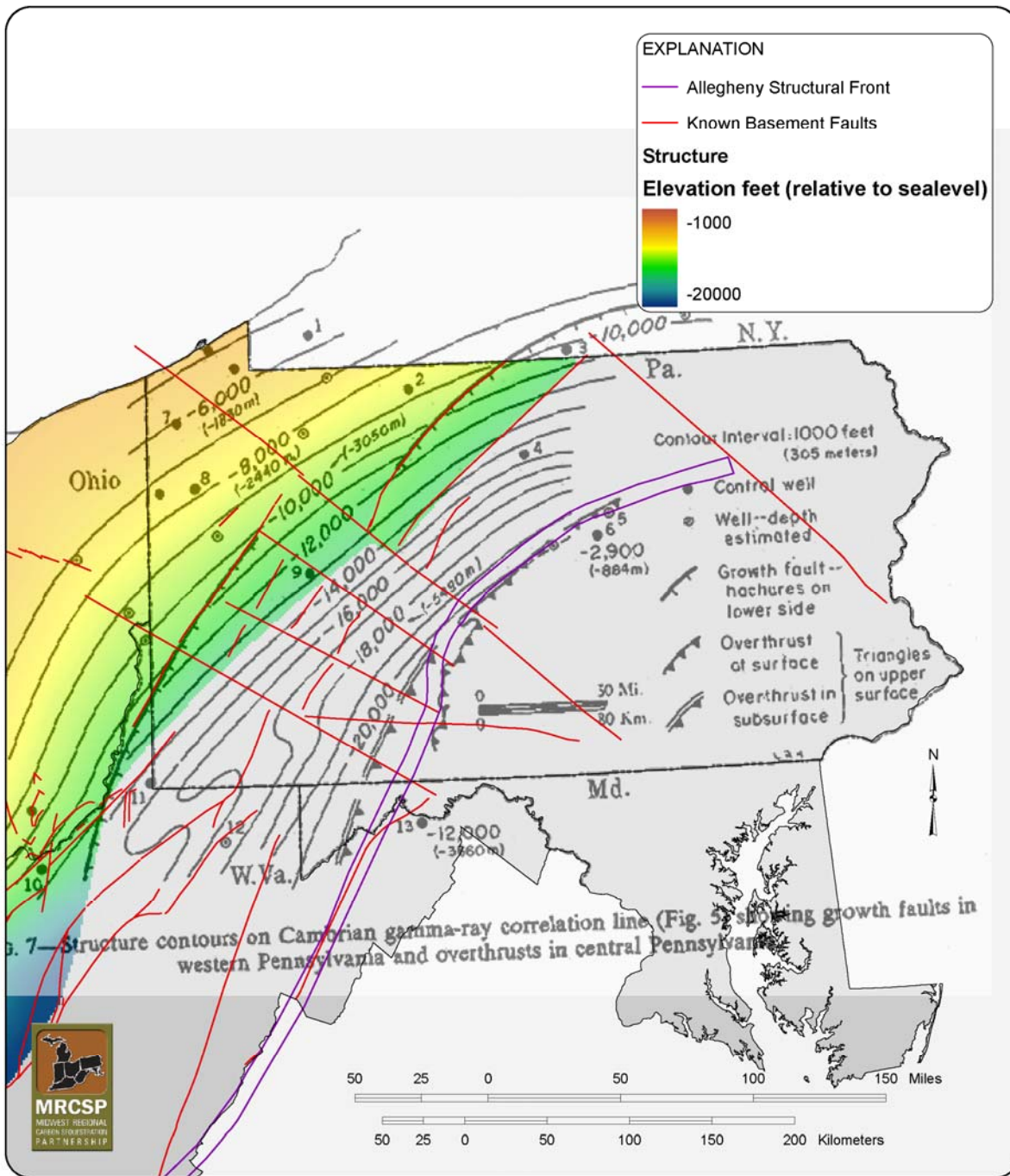
Figure 4.12.   Elevation of a gamma ray pick within the Cambrian, overlain on and georeferenced to, the MRCSP base map with faults for the same interval.

> Note: A copy of Figure 7 from Wagner (1975) was used to aid interpolation/ interpretation in data-poor areas.

on the deeper units (Precambrian thru Rose Run). This mapping, to account for the structurally complex Rome trough (Figure 4.7) followed a separate procedure. Initial isolines were created using Inverse Distance Weighting in Spatial Analyst (ArcGIS). Next, the contour lines were manually adjusted to account for known offsets along the faults. These lines were blended and joined with contours from the rest of the study area. Final contour intervals were based mainly on cartographic and ArcIMS display considerations rather than on data accuracy.

Geologic Map Review

Each map was subjected to peer review by various members of the geologic team. Maps were made available digitally for all members to review through a web-based comment system. In addition, two group meetings were held to review large format prints of each of the maps and to also evaluate each map for geologic correctness and cartographic quality; noted corrections and changes were applied as needed.

Gridding Method

A consistent method to convert both computer-generated and hand-edited contour lines back into a grid format was essential for sequestration capacity modeling, GIS analysis, and cartography. Capacity calculations and many analyses within the GIS environment must have the data in grid format, and in some cases, use grid-to-grid operations. Gridding algorithms for this project must be able to handle both smoothly varying and faulted regions. Two methods were compared as part of this project. Contours were converted to a TIN, which was converted to a grid using 3-D Analyst (ESRI, 2005). In the TIN model, contours were modeled as mass points, and faults as hard break-lines. Contours were also converted to grids using a software package named ANUDEM (version 5.1; Hutchinson and Gallant, 2000), which combines localized splining with an ability to introduce vertical discontinuities (cliffs) into the final grids. Hence, ANUDEM can be used for geological modeling where faulting can be assumed vertical. A comparative study (Venteris and others, 2005) found that the ANUDEM-based method was superior to the TIN-conversion method as long as high grid-resolutions (<15,000 feet grid squares) were used. The study also found that the optimal grid resolution for these data sets was best between 2,000 and 10,000 feet. Based on these results, a grid cell resolution of 5,000 feet was adopted for all the layers in this study, which also provided a consistent grid size for grid-to-grid operations.

Map Accuracy

The uncertainty in the structure and isopach maps was calculated and is provided here as a useful guide when using the maps of this project. Rigorous measures of map accuracy have been obtained for most of the major regional-scale maps in this study. Uncertainty was estimated using two approaches described below.

How good are the interpolations at unsampled locations? This question was evaluated using geostatistical cross-validation based on ordinary kriging. Grids that obey well points exactly may provide a poor prediction at unsampled locations (which is the majority of the area being considered). Consequently, the surfaces were estimated by kriging at each point location, but without using the value at that point. Summary statistics (RMSE) were generated using the differences between the actual data values at a known point versus the interpolated (kriged) values at that same point (Table 4.9). The resultant RMSE values provide a general estimate of the systematic and random error of interpolation at unsampled locations. The value is an average error for the map; actual error at any specific location on the map can be smaller or larger than the RMSE value. Not all final maps were created using geostatistics (Table 4.8);

however, cross validation was calculated for all layers as a method to compare the strength of geostatistical interpolation between mapped layers. The results of this analysis are provided in the column labeled "Cross-validation error" in Table 4.9.

How accurately do the final grids obey the well values? This question was evaluated by calculating the difference between the value at the control point (well) and the value of the nearest calculated grid cell. Results were summarized using RMSE method. Faithfulness of the grid (Table 4.9) was partly a function of grid cell size, as finer grids were more able to accurately model complex trends. Analysis found that a cell resolution of 5,000 feet provided a reasonable compromise between grid accuracy and computational efficiency (Venteris and others., 2005). However, increasing cell resolution of up to 2,000 feet further reduced grid errors for many of the map layers. There was little to be gained from using resolutions greater than 2,000 feet. The results of this analysis are provided in the column labeled "Grid error" in Table 4.9.

Accuracy Discussion

There were considerable differences between the accuracy of the various structure and isopach surfaces. RMSE values range from 10 to 658 feet. Several factors contribute to the uncertainty of the maps.
1. Accuracy is expected to increase with the number of wells per unit area. Ultimately, the values and geometry of the point data have the biggest influence on the final surface produced by computer interpolation, regardless of the method used. Increased numbers of data points lead to more robust statistical prediction.
2. Increased range can have negative and positive influences on spatial modeling. Large trends in areas of sparse data result in errors for non-exact interpolators, such as kriging, that relies heavily on neighboring values. Large trends can also increase the strength of the prediction model (variogram) by decreasing the signal to noise ratio.
3. The shape of the surface and the amount of faulting affect accuracy. Surfaces that are smooth, predictable trends are easier to model than those with abrupt discontinuities (faults, breaks in slope). These discontinuities violate the basic assumptions of geostatistical interpolation. Also, spatial data often have a component of spatial variability below the scale of sampling. The greater this variability (the micro-variance component of the nugget effect), the less the interpolated values will agree with the proximal data values.
4. The well data set is also a source of error. Individual data points should be very accurate (within 10^1 feet). However, misidentified horizons are common and can result in errors greater than 100 feet. Such cases are usually detected by the screening method and removed.
5. Gridding (ANUDEM) in areas of intense faulting may introduce additional errors. In areas of very steep slope (as found in the Rome trough) small errors in gridding can result in large differences between well and grid values.

For this data set, error sources one and two had the most influence on the accuracy of the final grids. The correlation coefficient between cross validation error and data density was 0.51 and the coefficient between cross validation error and the range was 0.39 (for these data, increased range was associated with increased error). Data density and range were combined in a multi-variate linear regression model that explained 81 percent of the variance in cross validation error and predicted the amount of error within 100 feet (RMSE). The maps could be improved by more well control, especially in deep and faulted areas of the Rome trough and Appalachian basin.

Comparisons between cross-validation error and gridding error provided additional discernment on uncertainty issues. In general, if the two error measurements showed good agreement, it confirms the gridding method was creating surfaces with error levels compatible with those expected from direct

gridding from kriging (block kriging). However, the gridding error was much smaller for the Cambrian basal sands structure map and showed the improved fit of the hand-contoured map in the Rome trough area. Yet, such improvement was not observed on other Lower Paleozoic maps. The gridding error was much larger than the cross validation error for both the Oriskany and Medina structure maps, which were interpolated using Petra. One possible interpretation was that the gridding method (ANUDEM) found it difficult to fit the small closed-contour features present on these maps.

Both the computer interpolation and final gridding routines were expected to have difficulty in the faulted regions of the study area. Faults violate the basic assumptions of kriging and are difficult to represent in a grid. RMSE grid errors were compared between the faulted area and the rest of the basin (Table 4.10). The faulted area has much larger errors in the Cambrian basal sands structure and the Copper Ridge Dolomite isopach maps. These layers contained many wells that occurred directly on faults (the Cambrian basal sands isopach was very thin in the faulted area and had a small RMSE value). Otherwise, the magnitude of error was similar for the two regions and the faulted area did not consistently contain increased error over the rest of the region. However, the user should be particularly cautious when using the maps in the faulted regions of the Lower Paleozoic.

Table 4.10. Comparison between uncertainty in faulted and "non-faulted" areas.

Mapping Unit	Faulted Area (RMSE ft)	Rest of Basin (RMSE ft)
Basal Cambrian Injection Targets Structure	754	297
Basal Cambrian Injection Targets Isopach	33	402
Copper Ridge Structure	359	401
Copper Ridge Isopach	1,141	332
Rose Run Structure	211	263
Rose Run Isopach	26	27
Knox Structure	130	185

Methodologies for Other Maps

Oil and Gas Fields Map

The mapping and compilation of state oil and gas fields maps into one regional GIS layer for this project has greatly advanced our ability to assess energy and sequestration resources at regional and state scales. The map represents the first digital petroleum field data for the states of Maryland, Michigan, Pennsylvania, and West Virginia. Moreover, Michigan and Maryland were able to significantly update their petroleum fields maps, and in Pennsylvania and West Virginia, their current oil and gas field digitization projects were completed as a result of the MRCSP project. Digital layers from these states were combined with updated existing digital maps from Indiana, Kentucky, and Ohio to make the first seamless regional map and database of oil and gas fields. The resultant map/GIS layers will have many uses for CO_2 sequestration, oil and gas exploration and development, regional planning, general public education, and uses by other sectors.

Methodologies used in creating and storing oil and gas field tabular data and field boundary maps differed widely from state to state. The biggest challenge to making an integrated, regional map was to conform the tabular field data from each state into a common format. Ohio Division of Geologic Survey personnel designed a data structure that allowed tabular attributes to be populated with data from each state (data

tables can be found on the accompanying GIS CD). The oil and gas fields database contains basic attributes and those necessary for calculation of CO_2 sequestration potential (average depth, porosity, thickness). The main challenge in creating the system was gathering data from geologically similar units into common regional plays. Common plays were developed by combining geologic units of similar age and lithology using the stratigraphic correlation chart created by the MRCSP team as guidance (Figure 4.6). For instance, the "Clinton"/Medina play map locally contains fields that produce from the Silurian "Clinton" sandstone of Ohio (Cataract Group on Figure 4.6), the Medina Group sands of Pennsylvania and the Tuscarora Sandstone of West Virginia (see Figure A7-2 in the MRCSP detailed report on Geological Characterization of the MRCSP Region (www.mrcsp.org)).

The method of drawing the oil-and-gas-field boundaries (polygons) varied from state to state. The most common method was to sort the well data by play or individual producing formation, and draw the field boundaries by hand. Usually a buffer of less than one-quarter to no more than one-half mile was used to define the boundary near the outmost wells of a pool or field. Within larger fields, holes will be found within the interior of the polygon where dry holes are encountered, or where producing wells have been drilled farther apart than the established minimum buffer. Such hand-drawn maps existed as legacy data for most of the states and were used as a starting point in Pennsylvania, Indiana, West Virginia, Kentucky and Ohio; in these instances the field boundaries were simply digitized and attributed. These new digital maps can, and are, digitally updated as needed by automatic or semi-automatic buffering methods (using a GIS package) when new wells are drilled in Indiana, West Virginia, and Ohio. Field maps for Michigan were made solely using GIS buffering of the well locations for Phase I, but will be augmented by hand-digitizing in the future. Field boundaries were merged into a common GIS layer, but blending of oil and gas field boundaries between the states was not done. The individual state maps were compiled from a variety of base map that were at different scales (see metadata in the oil and gas fields layer on the accompanying GIS CD); users should be cognizant of the accuracy differences from state to state because of this.

Injection Wells

The different injection well types gathered for the MRCSP region are categorized into the following types: 1) Class I – hazardous and industrial waste injection wells, 2) Class II –brine injection wells, and 3) Class III - solution mining wells. Collecting the locations of all these wells had not been accomplished before by all of the MRCSP project members. This information is usually kept by state or federal regulatory agencies. However, information from these wells, especially the Class I and II wells (Figure 4.13) will be crucial to understanding the injection characteristics of many of the target formations under consideration. Therefore, under Phase II of the MRCSP Partnership, the geologic team will obtain as much information as possible from these injection operations.

Salinity Grid

A salinity grid can be generated from mapping, either from direct interpolation (Kriging etc.) or by exploiting the general relationship of salinity increasing with depth. Mapping salinity accurately in this region is difficult because the data is not routinely gathered and submitted to state agencies; therefore the coverage is sparse. For example, the Mount Simon Sandstone has only 18 measurements of salinity scattered across the MRCSP area. In addition to a paucity of data, formation waters are continuously modified by filtration through clay membranes, ion exchange reactions, precipitation of minerals, and by solution of the surrounding rocks (Blatt and others, 1980), causing further uncertainty. For these reasons a statistical salinity verses depth model was used to create the salinity grids used in capacity calculations
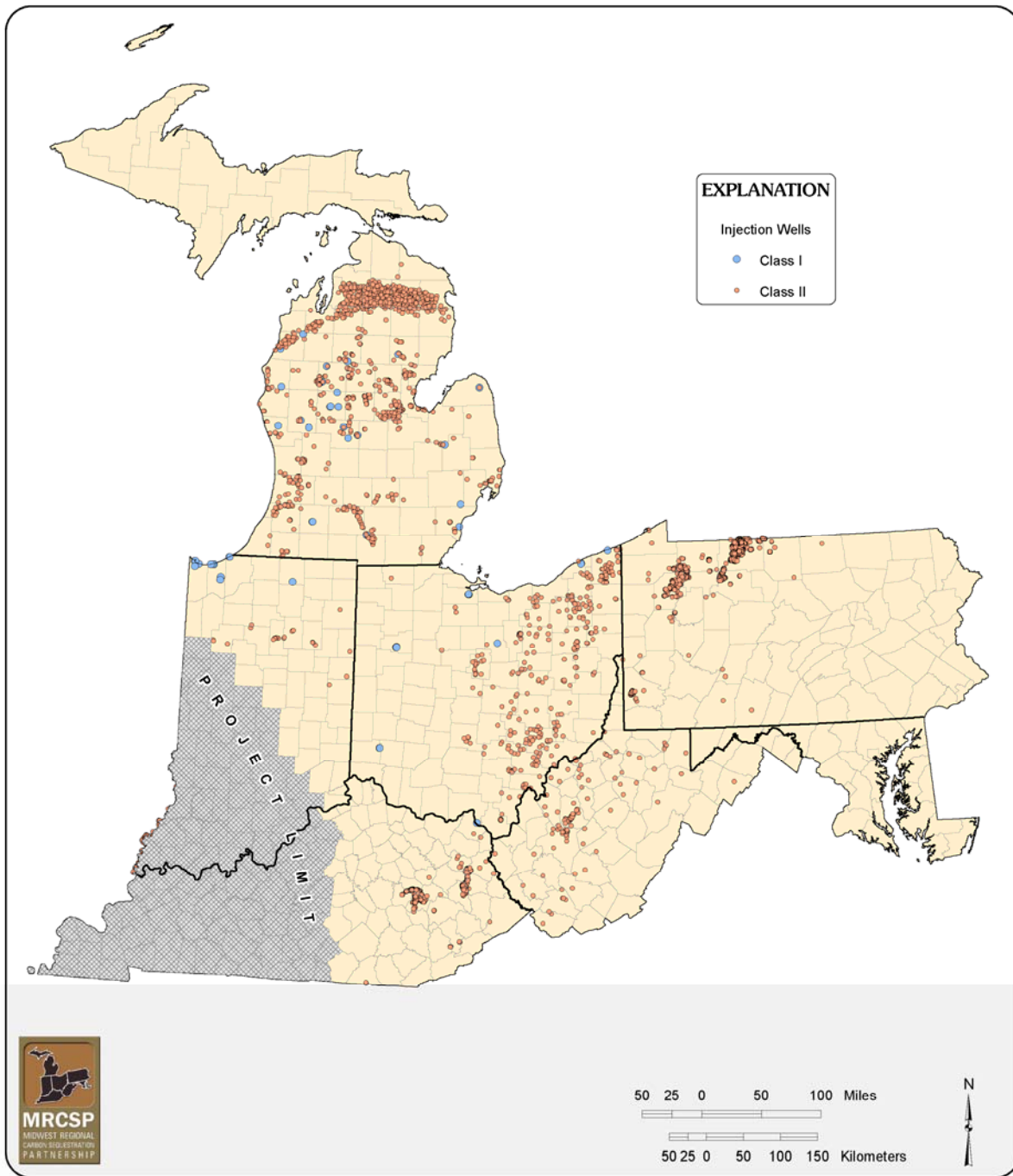
Figure 4.13. Locations of Class I (hazardous and industrial waste) and Class II (oilfield brine) injection wells.

for this investigation. The model was constructed from existing well data using least-squares regression. Individual models were created for each formation. The regression models were used with the overburden (depth) maps to make a continuous salinity grid for each formation.

Geothermal Gradient and temperature

Models of the surface temperature and geothermal gradient were created to calculate the temperature at depth for use in the capacity calculations. For the surface temperature, a thirty-year average for 300 cities was obtained for the conterminous United States (NOAA, 2000). The temperatures were interpolated into a grid using a minimum curvature algorithm.

For the geothermal gradient, a number of datasets were investigated. These datasets included the American Association of Petroleum Geologists (AAPG) bottom hole temperature dataset (AAPG, 1994), and the Southern Methodist University (SMU) dataset (Blackwell and Richards, 2004a), and the 2004 AAPG heat flow dataset (Blackwell and Richards, 2004b). Each dataset was evaluated for data quality and spatial distribution. The AAPG heat flow dataset (Blackwell and Richards, 2004b) was not used because the data distribution was considered too sparse in the project area — only three heat flow measurements were for Ohio. The 1994 AAPG geothermal dataset was unsatisfactory because it was uncorrected for thermal equilibrium and, when analyzed using spatial statistics, the spatial variance was quite large. Of those evaluated, the SMU dataset (Blackwell and Richards, 2004a) was the best for this project by combining a good combination of data coverage and data quality. A regional correction was applied, which significantly reduced the spatial variance. In areas where the SMU dataset was missing data, such as Pennsylvania, data from the AAPG bottom hole temperature dataset (AAPG, 1994) was used however, to augment the SMU dataset. The augmented SMU dataset was used to create the geothermal gradient grid for the region using kriging in Geostatistical Analyst.

Screening Maps

The large number of maps, data grids, and calculations generated in this regional assessment make it difficult for the public, or any other user, to interpret the various attributes related to CO_2 sequestration in geologic units in the MRCSP study area.. Therefore, the geologic team has devising several methods to condense the various types of information contained herein into a smaller number of summary maps for quick reference, by both technical and non-technical audiences.

Several techniques for creating summary maps were investigated. Approaches ranging from complex expert systems models, which codify qualitative geological knowledge through numerical algorithms, to simple screening maps were investigated. Because the expert systems models rely on so much soft information (knowledge rather than data), it was decided, at this stage of the project, that simple Boolean screening maps was the best approach to presenting meaningful summaries. Quantifying geologic knowledge through expert systems approaches must be done with care and can be time consuming if realistic algorithms are to be developed. Research into more advanced techniques will continue in Phase II.

A screening/planning map was produced using grids for all deep saline formations. Structure and isopach grids were reclassified into binary grids showing where the geology was appropriate and inappropriate for CO_2 injection and then reclassified to show areas where overburden thickness were greater than 3,000 feet (using the 2,500-foot rule of thumb for miscible injection, with 500 feet added to account for potential map error). Isopach grids were reclassified to show thicknesses greater than 50 feet. The reclassified grids were recombined into a single grid showing the number of appropriate targets and the name of the targets

(Figure 4.14). This map can also be viewed as a 3-dimensional scene (Figure 4.15). The map is presented herein and will be discussed further with various stakeholder groups, including the partnership sponsors, to elicit input on its usefulness, clarity, and how it can be improved and added-to for development in Phase II.

Data Storage and Distribution

Geologic data for this project is provided in both digital and as hard copy (paper) map formats. This was done to ensure that the needs of a wide range of stakeholders were met. The approach allows information to be distributed to individuals ranging from sophisticated GIS modelers to non-technical users who just need a map for a planning meeting.

Data Storage

All GIS data is being stored in a centralized ArcSDE database maintained by the Ohio Division of Geological Survey. For geologic target and confining layers, there are contour and grid data, geologic unit crop lines, and fault locations stored. Point data used in mapping are stored as a database containing all formation tops with listing basic well-header data (i.e., well operator, location, producing formation, well status, etc.). The database also contains all GIS layers created in this project including layers from the terrestrial studies, CO_2 sources, surface digital-elevation model, oil and gas fields, and the various data and grids needed for capacity calculations. The database may be queried to obtain data for an individual geologic layer, by formation, depth, location, or any combination the user requires.

Data can be provided to the public as ESRI shape files (vector) and ESRI grids (Raster). A myriad of other GIS formats exist and can generally be accommodated. Requests of non-ESRI GIS data formats will be handled on a case-by-case basis.

Metadata

Metadata was an essential part of this GIS data compilation and was created for all layers using the Federal Geographic Data Committee (FGDC) format for guidance. Metadata is provided in html format and can be read in any standard web browser. The metadata provides information on the data sources, compilation procedures, accuracy, projection parameters, and who to contact to ask questions about or obtain copies of the data.

Web-based Map Browser

An ArcIMS (Internet Mapping System) web-based GIS application was created to allow the contents of the ArcSDE database to be browsed using a simple web browser such as Microsoft Internet Explorer or Netscape. The site allows the users to make custom map views that are flexible as to content and scale. The ArcIMS site provides a convenient way to inspect the data created and used in this study and to print the custom maps. The website does not allow the direct downloading of GIS data; rather, it is envisioned as a tool for stakeholders to inspect our data holdings. A data request can then be generated by e-mail or telephone. The universal resource locator (URL) to visit the site is:

http://www.dnr.state.oh.us/website/geosurvey/mrcspgeo/
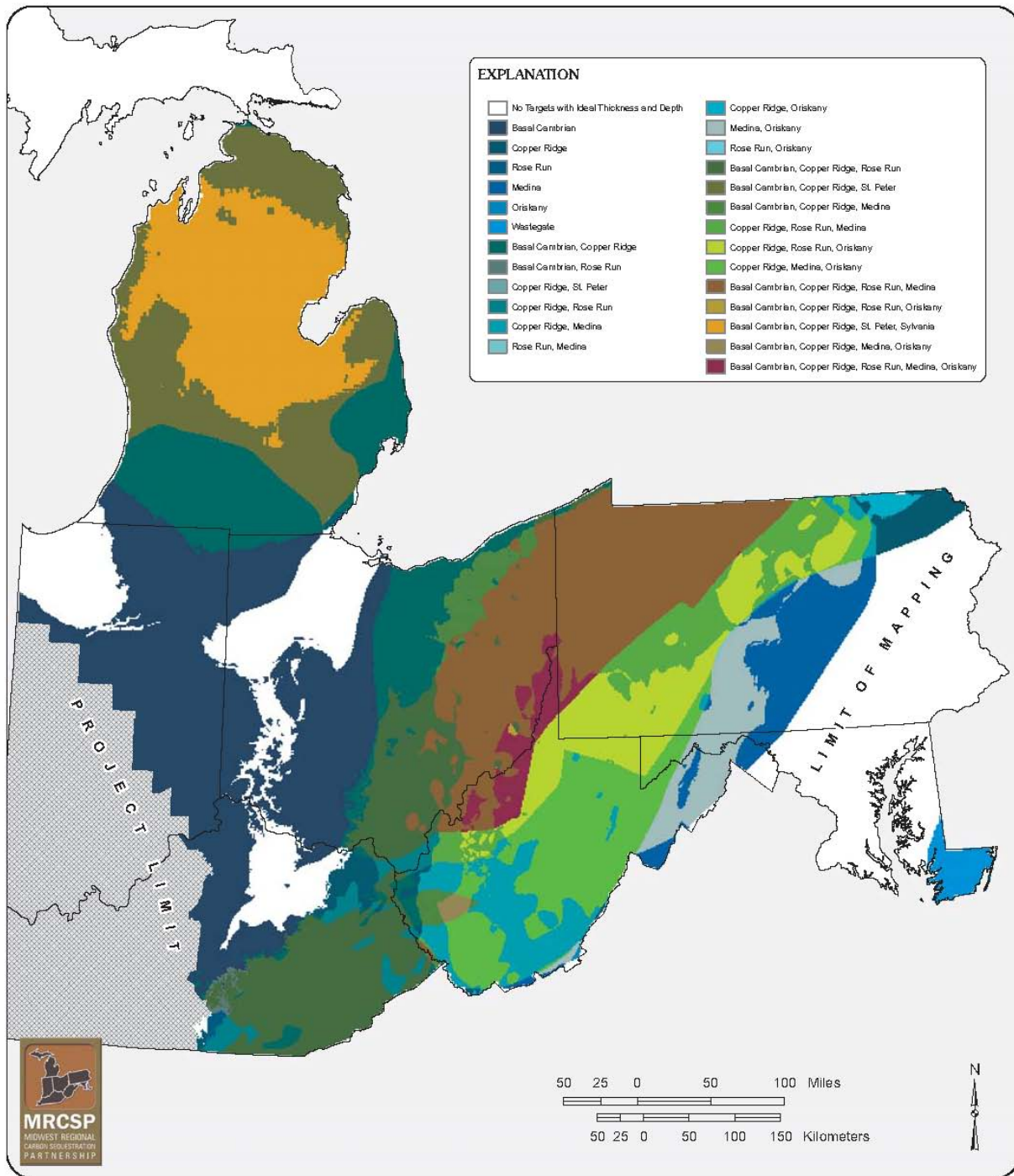
Figure 4.14. Screening map summarizing the geologic mapping done for this report.

Note: The map shows which reservoir or combination of reservoirs meet the criteria of 3,000 feet or greater overburden thickness and CO_2 sequestration target layer thickness greater than 50 feet.
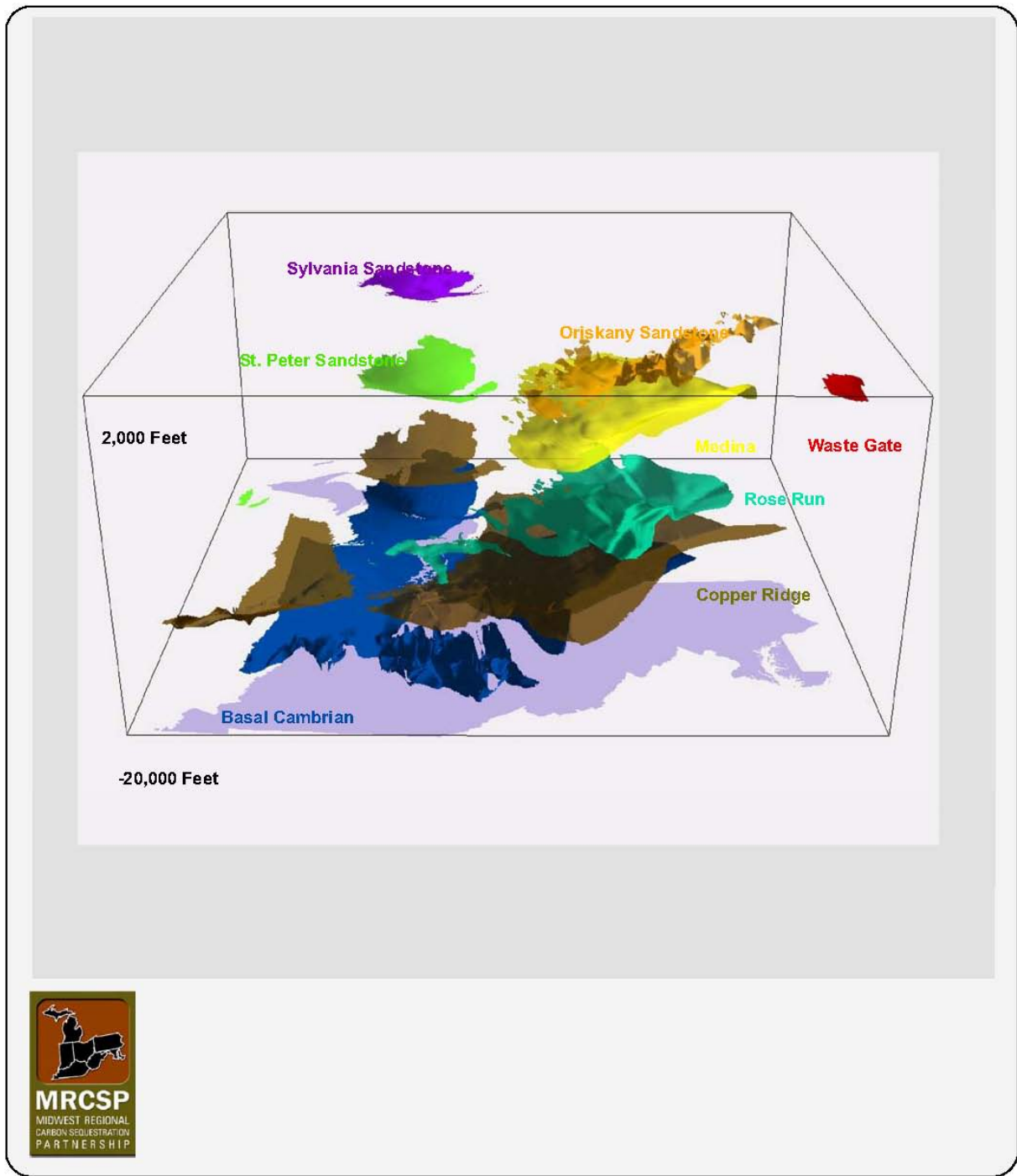
Figure 4.15. Three-dimensional view (looking from the south) of the screening map presented in Figure 4-14.

Hard copy maps of geologic targets and other GIS data are available as page-sized copies as found elsewhere in this report. Maps are also available as large format (36" x 36") prints for more detailed inspection. Maps can be provided as paper copies or as Adobe portable document format (PDF) files for electronic distribution.

Natural Gas Storage

Consumer demand for natural gas is seasonal; higher demand during extreme cold periods for home heating purposes and lower demand during the warmer summer months. In general, natural gas supplies are fairly constant. Thus, natural gas distributors utilize underground gas-storage fields to maintain a reserve of gas for use during peak demand periods.

The MRCSP region has more natural gas storage potential than any other region of the country. In fact, four of the top seven states in gas storage capacity are in the region — Michigan is the national leader. These statistics unequivocally indicate the region contains exceptional geological formations for the underground storage of both natural gas and CO_2 for that matter.

Most of the region's storage fields were once producing gas fields. Later, many of these fields were converted to storage reservoirs by drilling wells designed specifically for injection operations and also by building pipeline and compressor station infrastructures to support the conversion. Gas storage fields are designed to allow their entire amount of working gas to be cycled in and out of the field once each year. Typically, the storage fields are filled from pipelines in the summer months for withdrawal when demand peaks in the winter months.

The gas storage fields provide a great analogue for study when examining CO_2 storage. By analyzing these fields, we can better model the amount of CO_2 that can be stored in similar strata or reservoirs and learn more about the injectivity rates that different reservoirs can be expected to handle. Such investigations will allow us to better forecast how many wells, and over what size of an area, will be needed for a specific CO_2 project. Furthermore, gas storage fields may be a viable means for future use as CO_2 storage fields; either permanent storage from a large CO_2 source, or as a CO_2 buffer operation for a larger CO_2 EOR operation. Occasionally a gas storage field will be offered for sale, any future CO_2 producer or EOR operator might find purchasing such a field cost efficient for storage of CO_2, especially if any preexisting infrastructure could be used for transporting the CO_2. The MRCSP Phase II Project will examine storage fields in greater detail for these reasons.

CO_2-Sequestration Storage Capacity for the MRCSP Region

Carbon dioxide sequestration in geologic strata relies upon a number of different storage mechanisms that are based on the site-specific geologic conditions. Based on the geologic sequestration research conducted over the last decade by a number of researchers, these mechanisms are now fairly well described in published papers and proceedings of conferences such as the Greenhouse Gas Control Technology (GHGT) series organized by the International Energy Agency Greenhouse Gas R&D Programme (see www.ieagreen.org.uk for conference proceedings information) or in the Special Report on Carbon Dioxide Capture and Storage prepared by the Intergovernmental Panel on Climate Change (IPCC) (e.g.

Houghton and others, 1996; 2001). The commonly discussed storage mechanisms are volumetric storage, solubility storage, adsorption storage, and mineral storage. Volumetric storage refers to the amount of CO_2 that is retained in the pore space of a geologic unit, generally as a supercritical phase retained by structural or stratigraphic traps or by the overlying cap rock layers. Solubility storage involves dissolution of a part or all of the CO_2 into the formation waters of the geologic unit. Adsorption storage involves the holding of CO_2 molecules onto the fracture faces and into the matrix of organically rich rock units, such as coal or black shales. Mineral storage involves the chemical reaction of CO_2 with the minerals and brine in the geologic unit. Under appropriate conditions, some chemical reactions may form a solid precipitate, permanently binding the carbon to the geologic unit. Mineral storage is not investigated as part of this report because the complex nature of the reactions and the uncertainty in reaction rates makes it difficult to determine the storage volumes on a regional-scale. In addition to the types of formations and storage mechanisms evaluated in this report, basalt layers and salt caverns are also potential repositories for CO_2 storage; however, due to the early state of research for these options, they have not been evaluated at this time for MRCSP region.

CO_2 Properties

Before the description of the calculations of the CO_2-storage capacity can begin, it is important to briefly review the physical properties of CO_2, since the physical properties affect how much CO_2 can be placed into storage. The phase behavior of CO_2 is well understood and can be found in general chemical references such as Lemmon and others (2003) or in the literature on enhanced oil recovery (e.g., Jarrell and others, 2002). Carbon dioxide can exist as four different phases, as a solid, liquid, gas, or as a super-critical gas. The triple point for solid, liquid, and gas is at -69.826 F (-56.57 C) and 75.2020672 psia (0.5185 MPa). At temperatures greater than 87.8° F (31.1 C) and pressures greater than 1,071 psia (7.38 MPa), CO_2 is in a super-critical state, behaving similar to a gas by filling all available space, while having the density of a liquid. Using typical parameters for the MRCSP area, such as a geothermal gradient of 0.01 F/ft (0.0182° C/m), a surface temperature of 56 F (13.33 C), and a pressure gradient of 0.433 psia/ft (9,792.112 Pa/m), a line representing the typical pressures and temperatures with depth can be superimposed on the phase diagram. This line shows that at shallow depths (less than ~ 2,500 ft), CO_2 would be stored in a gaseous phase, while at deeper depths (greater than ~ 2,500 ft), most of the CO_2 will be in the super-critical gas phase, with some storage as a liquid. The recognition of the super-critical gas phase is important since, under most geologic storage scenarios being evaluated, CO_2 storage will occur as a super-critical gas.

One of the most important properties for the sequestration of CO_2 is density. At low pressures, similar to conditions in shallow reservoirs, CO_2 density is low, so the relative volume of a given amount of CO_2 will be large. Hence, at low pressure, low temperature, and low density, the amount of CO_2 that could be stored in a given space will be relatively low. At increasing depths, density rapidly increases as CO_2 changes phase to first a liquid and then a super-critical gas. In fact, the density of CO_2 at standard temperature and pressure is only 0.1124 lbs/ft^3 (1.8 kg/m^3) while the density at the critical point is 29.09 lbs/ft^3 (466 kg/m^3) – an increase of about 260 times! At very high pressure and temperature conditions found in very deep geologic layers the density of CO_2 may be as high as 62.43 lbs/ft^3 (1000 kg/m^3). Thus, the amount of CO_2 that can be stored in the liquid or super-critical gas phases, in a given space, will be several hundred times larger than storing it in the gaseous phase. At shallow depths, CO_2 is in a gaseous phase, and so the density is low. As the depth increases to approximately 2,500 ft (762 m) below surface, the density rapidly increases because the CO_2 changes phase to a liquid and then a super-critical gas. This high density at depth provides a much larger storage capacity than the gas phase storage and is the primary reason that 2,500 ft (762 m) is considered to be the approximate minimum depth for CO_2 storage.

The primary reason why the petroleum industry is interested in injecting CO_2 is because its physical properties make it a good media for enhancing the recovery of oil. Where CO_2 injection has already been used for secondary recovery, for example in Texas, it has been used as either a liquid or super-critical gas, and its density and viscosity make it ideal for enhanced oil recovery (Jarrell and others, 2002). The density of CO_2 is similar to that of oil, but its viscosity is lower.

For the storage of CO_2 in brine solution, it is important to examine the physical properties of CO_2 in solution. Conversely, CO_2 solubility decreases with increasing salinity. NaCl is used here as a proxy for overall brine compositions (Duan and others, 1995, Jarrell and others, 2002). For example, it shows a more than a 50 percent reduction in solubility as salinity increases to 200,000 parts per million. Because high salinity brine is likely to be present in most deep geologic storage reservoirs, especially in the MRCSP region, solubility related storage will not provide a large fraction of the total storage capacity in the short-term. Slowly, over time, the CO_2 will dissolve into the brine-bearing formation fluids. However, the rate of this dissolution and concurrent mineralization-based storage will be controlled both by the total salinity, reaction rates, and the slow hydrodynamic flow in these layers that will inhibit mixing.

In order to correctly model the density of CO_2 in the MRCSP area, it was necessary to understand the distribution of the fluid pressure gradient, surface temperature, and geothermal gradient. For the fluid pressure gradient, a value of 0.433 psia/ft (9,792.112 Pa/m) was used for the entire region. This value was calculated from a fresh water pressure gradient, because adequate data is not regionally available to determine brine density with depth in the MRCSP project area. Limited numbers of available data indicate a pressure gradient range of 0.38 to 0.48 psi/ft (8,595 Pa/m to 10,858 Pa/m) is representative of the region (Gupta and others 2004a; Gupta and Bair 1997; Russell, 1972). Using these relationships and the temperature and pressure grids described earlier in this report, the CO_2 density at any particular depth is calculated.

Estimating Storage Capacities

Calculation of the storage capacities in various geologic formations has been attempted by a number of research projects during the last ten years. However, despite these efforts, there is no single accepted methodology for determining capacities at local, regional, basin, or global scales. The estimates in existing studies vary over a large range. This uncertainty is a result of the lack of detailed geologic data on formation thickness, lithology, pressure, fluid density, salinity etc for most of the sedimentary basins, except in areas where extensive oil and gas exploration has occurred. Almost of all of the methods involve estimating the total pore volume for the subject formations and using assumptions for the storage efficiency and mechanisms to evaluate the fraction of the total capacity that may be available for actual storage. An early estimate of the global storage capacity developed by Hendricks and Blok (1993) ranges from 400 to 10,000 gigatonnes CO_2. Similarly Bergman and Winter (1995) estimated U.S. saline reservoir storage capacity range of 5 to 500 gigatonnes CO_2. Several other approaches are cited in the following sections. In addition to the regional rock volume based approaches, detailed reservoir simulations (e.g. Gupta and others 2004a) have also been used to more accurately determine site-specific storage and injection rates. Such detailed studies based on site characterization (e.g., Gupta and others, 2004b) will certainly be a requirement for actual project implementation. The following sections discuss the methods used in this study for estimating total pore volumes and possible storage capacity for volumetric, solubility, and adsorption based storage in the MRCSP region.

Volumetric Storage.

Storage of CO_2 in pore spaces as a free phase is herein referred to as volumetric storage. The CO_2 is injected into the geologic unit and occupies some portion of the pore space. For the saline formations in the MRCSP project, it is initially assumed that CO_2 will completely displace the brine pore waters. While not realistic, it does give the maximum amount of CO_2 that can be placed into storage. A wide range of factors including reservoir chemistry, heterogeneity, cementation, and structure will further constrain the actual amount of CO_2 that can be stored at any site. For depleted oil-and-gas fields, it is assumed that there is residual-water saturation occupying pore space, which decreases the amount of pore space available for CO_2 to occupy. The volumetric capacity calculation is modified to reflect the residual-water saturation.

Injection into the geologic unit's pore space will initially displace the pore fluids. These pore fluids include brine waters, oil, and gas. The injection will initially be as a separate phase of CO_2 liquid or super-critical gas. Only over a long period of time will CO_2 dissolve into the formation fluids and possibly react with the matrix and formation fluids to precipitate carbonate minerals. In addition, the amount of CO_2 that dissolves into the pore fluids will be limited by temperature and the salinity of the fluid. Due to the long time intervals for the CO_2 to react with the geologic unit and its formation fluids, volumetric storage will be the primary storage mechanism considered for the CO_2 sequestration capacity calculations.

The general equation for volumetric storage CO_2-sequestration capacity essentially provides an estimate of the total pore volume in the formation:

$$Q_{CO_2} = \rho_{CO_2} * \theta * A * H \tag{1}$$

where:

Q_{CO_2} = CO_2-sequestration capacity for total pore volume
ρ_{CO_2} = Density of CO_2 under reservoir conditions
θ = Porosity
A = Area
H = Thickness of the geologic sequestration unit

For the MRCSP project, the equation is slightly modified, due to the use of English units of measurement.

$$Q_{CO_2} = \rho_{CO_2} * \theta * A * H / 2200 \tag{2}$$

where:

Q_{CO_2} = CO_2 sequestration capacity (metric tonnes)
ρ_{CO_2} = Density of CO_2 under reservoir conditions (lbs/ft^3)
θ = Porosity (%)
A = Area (ft^2)
H = Thickness of the geologic sequestration unit (ft)
2200 = Conversion from lbs to metric tonnes

Other variations of this volumetric approach have been used by Van der Straten (1996) to estimate saline reservoir capacity in Europe and by Gupta and others (1999; 2001) to estimate storage capacities for the Mt. Simon Sandstone and the Rose Run Sandstone in the U.S. Both of these use factors such as storage efficiency (6 percent) and net-to-gross-ratios to adjust the calculated pore volumes.

The calculations for the saline formations were conducted using GIS software, using the raster-based Spatial Analyst extension of the ArcGIS software system. The general procedure for performing the calculations is to first create a structure contour grid and an isopach grid for the saline aquifer sequestration unit (Venteris and others, 2005). The structure elevation grid is then subtracted from a surface DEM grid to obtain a depth grid. This depth grid is used to obtain the pressure and temperature of the saline aquifer at depth. The reservoir pressure is obtained by multiplying the fresh water pressure gradient of 0.433 psia/ft (9,792.112 Pa/m) with the depth grid, which results in the formation fluid pressure at depth. To obtain the reservoir temperature, the geothermal gradient grid is multiplied with the depth and the surface temperature grid is added to this result. Using a custom created macro (modified from Radhakrishnan and others, 2004) to determine the CO_2 density from a database table, these new reservoir pressure and temperature grids are then used, along with the isopach grid and the average porosity for the sequestration unit, to calculate the CO_2-sequestration capacity. For the saline formations, the resultant CO_2 capacity grid can be displayed to illustrate where any particular unit has higher and lower capacity potential.

Volumetric sequestration capacity in depleted oil-and-gas fields has an equation similar to the saline aquifer capacity calculation, except that the volumetric capacity calculation is modified to reflect the residual-water saturation. The residual-water saturation is expected to reduce the amount of pore space initially available for CO_2 to occupy.

$$Q_{CO_2} = \rho_{CO_2} * \theta * A * H * (1 - S_w) / 2200 \tag{3}$$

where

Q_{CO_2} = CO_2 sequestration capacity (metric tonnes)

ρ_{co2} = CO_2 density (lbs/acre-ft)
θ = Porosity (%)
A = Area (acres)
H = Net thickness (ft)
S_w = Water saturation (%)
2200 = Conversion from lbs to metric tonnes

The calculation methodology used for oil-and-gas fields is different than the method used for saline formations. The calculations are conducted using database techniques, as opposed to the calculations being conducted in a GIS using raster-modeling techniques. The reservoir temperature, pressure, thickness, porosity, and irreducible water saturation for the oil and gas field are calculated from available data for the wells that are associated with the oil-and-gas pool or field. The assumptions for missing temperature and pressure data, which are incorporated in equations (4) and (5), is a surface temperature of 61° F (16.11° C), geothermal gradient of 0.007° F/ft (0.01276° C/m), and hydrostatic pressure gradient of 0.433 psi/ft (9,792.112 Pa/m). The assumptions for missing thickness, porosity, and irreducible water saturation data are located in Table 4.11.

$$T\ (F) = 61 + 0.007\ (F/ft)\ x\ depth\ (ft) \tag{4}$$
$$P\ (psia) = 0.433\ (psi/ft)\ x\ depth\ (ft) \tag{5}$$

Table 4.11. Assumptions for missing data in oil-and-gas field CO_2-sequestration calculations.

Formation	Net Thickness (ft)	Porosity (%)	Sw (%)
Clinton sandstone	18	8	5
Trenton Limestone	12	10	5
Beakmantown dolomite	10	15	5
Rose Run sandstone	35	8	5
Copper Ridge sandstones	13	9	5
Copper Ridge dolomite	13	8	5
Krysik Sandstone	14	14	5
Knox "B" zone	14	6	5

The area for the pool or field is taken from the polygon area from the oil-and-gas fields GIS, with the unit of measurement converted from ft^2 to acres. Once all the information on the oil and gas field has been populated in a database table, the calculations are performed. The reservoir pressure and temperature are used as part of an SQL look-up, to find the density of CO_2 in the reservoir. The density along with the other reservoir parameters of thickness, porosity, irreducible water saturation, and area of the oil-and-gas pool or field, are then used to calculate the CO_2-sequestration capacity of the oil-and-gas field.

The equations used in this section provide an estimate of the total pore volume available for storage. The actual volume of storage will depend on factors such as storage efficiency, porosity, and net-to-gross-ratio. Each of these factors will reduce the amount of CO_2 that will be sequestered at any specific site, so the total pore volume needs to be further adjusted for these factors. Tables 4.12 to 4.27 show the total CO_2-sequestration capacity at the 10 percent level. This is an estimate of the amount of CO_2 that will ultimately occupy the pore space. Modeling studies by van der Meer (1995) and Holt and others (1995) have modeled storage efficiencies ranging from 1 to 6 percent (van der Meer, 1995) to 30 percent (Holt and others, 1995). Thus the 10 percent total sequestration capacity represents an estimate that the MRCSP project anticipates is more realistic for the actual amount of CO_2 that could actually be sequestered in the region's reservoirs. Given the spatial variability in parameters and the lack of detailed data on the deep formations, for the purpose of the current study it is assumed that 10% of the pore volume in these will be available for actual storage within any individual reservoir.

Table 4.12. Summary of estimated effective CO_2-storage capacity by geologic interval or reservoir type (in gigatonnes).

Sequestration Target	Porosity (%)	Density (g/cc)	Gas Content (scf/ton)	Area (mi²)	Total
Oil and Gas Fields					2.51
Waste Gate Formation	10			1,342	4.38
Coal beds (net thickness)		1.32	100	25,578	0.25
Antrim and Ohio shales		2.62	42.9	109,043	45.3
Needmore Shale		2.62	42.9	850	0.05
Sylvania Sandstone	10			25,324	15.11
Oriskany Sandstone	10			57,313	19.43
Medina/Tuscarora SS	8			72,328	70.53
St. Peter Sandstone	10			41,796	88.13
Rose Run sandstone	8			57,493	49.27
Potsdam Sandstone	2			9,298	1.71
Conasauga Formation	2			24,973	4.25
Rome trough sandstones	1			18,452	1.23
Mt. Simon Formation	8			85,916	217.18
Total					519.35

Table 4.13. Estimated effective CO_2-storage capacity by reservoir type and state (in gigatonnes).

State	Saline	Coal	Shales	Oil & Gas	Total
Eastern Indiana	80.7	0	0	0.01	80.7
Eastern Kentucky	10.9	0.02	1.7	0.65	13.2
Maryland	9.5	0	0.009	0	9.5
Michigan	216.1	0	4.2	0.05	220.3
Ohio	37.3	0.04	8.5	0.4	46.3
Pennsylvania	75.6	0.08	12.0	0.8	88.5
West Virginia	41.1	0.11	19.0	0.6	60.8
Total	471.2	0.25	45.4	2.5	519.3

Table 4.14. Oil and gas fields. Estimated CO_2-storage capacity by state (in gigatonnes).

State	<2499 Feet	>2500 Feet
Eastern Indiana	0.006	0.008
Eastern Kentucky	0.009	0.644
Michigan	0.046	0.003
Ohio	0.366	0.053
Pennsylvania	0.455	0.310
West Virginia	0.533	0.082
Total	1.415	1.100

Table 4.15. Waste Gate Formation estimated effective CO$_2$-storage capacity (in gigatonnes).

State	Area (mi^2)	Total
Maryland	1,342	4.4
Total	1,342	4.4

Table 4.16. Net coal greater than 500 feet deep. Estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Eastern Kentucky	3,751	0.02
Ohio	5,053	0.04
Pennsylvania	4,724	0.08
West Virginia	12,042	0.11
Total	25,571	0.25

Table 4.17. Devonian Shales estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Eastern Kentucky	14,066	1.68
Michigan	38,428	4.18
Ohio	24,693	8.50
Pennsylvania	7,720	12.04
West Virginia	18,323	18.91
Total	109,043	45.3

Table 4.18. Needmore Shale estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Maryland	165	0.010
Pennsylvania	54	0.003
West Virginia	631	0.041
Total	850	0.054

Table 4.19. Sylvania Sandstone estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	10%
Michigan	25,324	15.1
Total	25,324	15.1

Table 4.20. Oriskany Sandstone estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Kentucky	7	0.002
Maryland	1,123	0.981
Ohio	4,896	0.728
Pennsylvania	29,022	7.669
West Virginia	22,265	10.049
Total	57,313	19.429

Table 4.21. Medina Sandstone estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Kentucky	420	0.089
Maryland	1,288	3.382
Ohio	15,647	5.579
Pennsylvania	31,333	36.024
West Virginia	23,642	25.459
Total	72,328	70.534

Table 4.22. St. Peter Sandstone estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Indiana	1,212	0.103
Michigan	39,396	87.967
Ohio	1,187	0.064
Total	41,796	88.134

Table 4.23. Rose Run sandstone estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Eastern Kentucky	13,146	5.443
Michigan	334	0.762
Ohio	16,353	8.100
Pennsylvania	22,222	29.748
West Virginia	5,438	5.215
Total	57,493	49.268

Table 4.24. Potsdam Sandstone estimated effective CO$_2$-storage capacity by state (in gigatonnes)

State	Area (mi^2)	Total
Ohio	18	0.002
Pennsylvania	9,280	1.704
Total	9,298	1.706

Table 4.25. Unnamed Conasauga sandstones estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Eastern Kentucky	25	0.001
Michigan	409	0.164
Ohio	21,185	3.469
Pennsylvania	2,410	0.459
West Virginia	943	0.0161
Total	24,973	4.255

Table 4.26. Rome trough sandstones estimated effective CO$_2$-storage capacity by state (in gigatonnes)

State	Area (mi^2)	Total
Eastern Kentucky	13,157	1.001
Ohio	201	0.006
West Virginia	5,094	0.221
Total	18,452	1.228

Table 4.27. Mt. Simon Formation estimated effective CO$_2$-storage capacity by state (in gigatonnes).

State	Area (mi^2)	Total
Eastern Kentucky	6,661	4.336
Indiana	18,957	80.612
Michigan	40,530	112.839
Ohio	19,768	19.390
Total	85,916	217.177

Solution Storage

Carbon dioxide can dissolve into formation fluids, but it is expected that large amounts of solubility storage will only occur over long time periods due to high salinity, extremely slow mixing rates in the deep formations, limited interaction face between the CO$_2$ plume and surrounding brine, and slow solution rates. For example, Gupta and others (2004a) used compositional reservoir simulations for CO$_2$ injection in the Mt. Simon Sandstone to show that over a period of 500 years, only 8 percent of the total CO$_2$ injected has moved into dissolved phase. As stated above, most salinity measurements from potential storage reservoirs within the MRCSP are highly saline and CO$_2$ solubility is inversely proportional to salinity. Because of the low solution rates, high salinities, and generally increasing salinities with depth in the MRCSP area, solubility calculations were not performed systematically for the phase I project. One representative solution calculation was performed for comparison purposes, and that is described in the Discussion of Results section. For completeness, however, the calculation methodology for solution storage is covered here.

One method of calculating the capacity of CO$_2$ that can dissolve into formation fluids is derived from Carr and others (2003).

$$Q_{CO_2} = 1.1023 * ((7758 * (\theta * A * H)) * S_{CO_2} * B_{CO_2})/(1000 * 17.25) \quad (6)$$

where

Q_{CO_2} = CO₂-sequestration capacity (metric tonnes)

7758 = Conversion from acre * ft to bbl.

θ = porosity (%)

A = area (acres)

H = thickness (ft)

S_{CO_2} = CO₂ solubility in fresh water (scf/bbl water)

B_{CO_2} = CO₂ solubility in brine (%)

1000 = Conversion from ft3 to MCF

17.25 = Conversion from MCF to short tons

1.1023 = Conversion from short tons to metric tonnes

The values for CO_2 solubility in fresh water and CO_2 solubility in brine are derived from Jarrell and others (2002). To determine the CO_2 solubility in fresh water and CO_2 solubility in brine, the reservoir temperature, pressure, and salinity (NaCl in ppm) are needed. Reservoir temperature and pressure are used to determine CO_2 solubility in fresh water using a database look-up table. The salinity data is used in a database look-up table to determine the CO_2 solubility in brine. The CO_2 solubility in brine is multiplied by the CO_2 solubility in fresh water to determine the CO_2 solubility in the formation fluids (Jarrell and others, 2002).

The calculations for the saline formations were conducted using GIS software, in a very similar methodology as with the volumetric calculations. The general procedure for performing the calculations is to first create a structure contour grid and an isopach grid for the saline aquifer sequestration unit (Venteris and others, 2005). The structure elevation grid is then subtracted from a surface DEM grid to obtain a depth grid. This depth grid is used to obtain the pressure and temperature of the saline aquifer at depth as discussed earlier. A custom created macro (modified from Radhakrishnan and others, 2004) is used to determine the CO_2 solubility in fresh water from a database table using the temperature and pressure, and the salinity is used to determine the CO_2 solubility in brine from a database table. These solubility values are then used, along with the isopach grid, and the average porosity for the sequestration unit, to calculate the CO_2-sequestration capacity.

The salinity grid construction was discussed under the methods sections earlier. For the representative calculation performed as part of the MRCSP project, a least-squares relationship was calculated for the salinity values taken from the geologic unit being modeled, which in this case, was the Mount Simon Sandstone. The resulting equation was then used to calculate the CO_2 solubility in brine.

Other solubility-based approaches for capacity estimates include those by Bachu and Adams (2003) for the Alberta basin; Brennan and Burruss (2003) developed a solubility- and saturation-based approach, which, as an example, was used to estimate the storage capacity in the U.S. and Canada by Dooley and others (2004).

Adsorption Storage

CO_2 sequestration in organic-rich rock units, such as coal beds and black shales, could, potentially, provide both long-term CO_2 storage and a method to increase production of a highly usable fossil fuel, natural gas, in a manner analogous to CO_2 enhanced oil recovery. Carbon dioxide, when introduced to a coal bed or black shale, preferentially displaces methane, which is adsorbed on the coal faces within cleats and is adsorbed onto organic matter and clay mineral surfaces in the matrix of the coal or shale.

Previous studies on CO_2 sequestration and methane recovery indicate that, for coals of the type found in the Appalachian and Michigan basins, at least two molecules of CO_2 can be injected for every one molecule of CH_4 released from the coal bed (Gale and Freund, 2001). On average, more than twice as much CO_2 can be stored on a volumetric basis than the amount of CH_4 extracted (Gluskoter and others, 2002; Mastalerz and others, 2004). CO_2 and CH_4 adsorption isotherm data also indicate that that the ratio may be much higher. The use of coal beds and black shales could provide a larger area in which CO_2 can be sequestered or offer multiple options for sequestration at some locations. The production of methane from these organically rich rock units also will help to offset costs of sequestering CO_2.

Sequestration in coal beds is the basis of a proposed efficient null-greenhouse-gas emission power plant fueled either by mineable coal or coalbed methane from deep unmineable coal (Wong and Gunter, 1999). The produced CO_2 from the power plant would be injected into coal beds to produce more methane. In addition, the CO_2 would be geologically sequestered in the coal beds (Wong and Gunter, 1999).

Burlington Resources has demonstrated the success of enhanced gas recovery (EGR) to recover methane by injecting CO_2 into the relatively high permeability coal beds in the San Juan Basin for several years (Schoeling, 1999). Coalbed methane production has been stimulated while injected CO_2 has not broken through to production wells. The injected CO_2 appears to be adsorbed into the coal matrix displacing methane, and remains in the ground. An additional project is underway to further test the EGR process in the relatively low permeability coal beds in Alberta, Canada. These projects and others also show that there are limitations to sustained injection, such as swelling. For the purposes of this project, these limitations are not considered.

The MRCSP project uses GIS technology for computing CO_2-sequestration potential in organic-rich rock units. In this report, a proposed methodology for estimating CO_2 sequestration volumes in coal beds and black shales is presented. Due to the nature of the gas-trapping mechanism of these reservoirs, we are using the standard methodology for *gas in place* calculation in non-conventional reservoirs developed by the Gas Research Institute (Mavor and Nelson, 1997); a different approach than used for volumetric calculations in conventional reservoirs. The CO_2-sequestration potential calculations are basically a series of simple mathematical operations on defined GIS-raster grids. The calculations of coal bed and black shales CO_2-sequestration potential are well suited to using GIS techniques.

In order to calculate the CO_2 storage potential of a coal bed, a number of steps are required. The calculation is basically a series of simple mathematical operations on defined grids. Raster grids were created for the themes listed below:

> H_{coal} = Coal thickness or isopach map (ft)
> G_{coal} = Gas content of the coal, (scf/short Ton)

The calculation of CO_2-sequestration potential in coal beds is based upon the observation that CO_2 preferentially displaces and replaces CH_4 adsorbed on the coal-bed cleats. To calculate the CO_2-sequestration potential, the coal-bed methane (CBM) resources must first be calculated. This calculation involves using the coal-bed gas content values for a given volume of coal at a given density:

> $R_{cbm} = \rho_{coal} * V * G_{coal} / 1000$ (7)

where

> R_{cbm} = Coal-bed methane resources (MCF)
> ρ_{coal} = Coal density (short tons/ft^3)
> V = Volume of coal (ft^3)
> G_{coal} = Coal-bed gas desorption value (scf/short Ton)

1000 = Conversion from scf to MCF

The CBM resources can be expressed as:

$$R_{cbm} = (\rho_{coal} * A * H_{coal} * G_{coal}) / 1000 \ (8)$$

where
A = Area (ft^2)

Initial studies have shown that CO_2 displaces CH_4 at a ratio of 2:1. Further studies (Gluskoter and others, 2002; Mastalerz and others, 2004) show that CO_2: CH_4 adsorption ratios will vary from 2:1 to 16:1, depending on coal rank. The preliminary estimate for CO_2-sequestration potential in coal beds will be at least double the CBM resources:

$$Q_{CO2} = C_{CO2CH4} * R_{cbm} \ (9)$$

where
Q_{CO2} = CO_2-sequestration potential in coal beds (MCF)
C_{CO2CH4} = CO_2:CH_4 Ratio, which for the MRCSP project is 2

The final step in the calculation of the CO_2-sequestration potential involves the conversion of the volume of gaseous CO_2 to short tons. At surface conditions of 60º F (15.55º C) and 1 atm (101,325.01 Pa), the conversion factor is 17.25 Mcf/short ton (8.625 ft^3/lbs).

The full version of the equation to calculate CO_2-sequestration potential:

$$Q_{CO2} = 1.1023 * C_{CO2CH4} * (\rho_{coal} * H_{coal} * A * G_{coal}) / (1000 * 17.25) \ (10)$$

where
1.1023 = Conversion from short tons to metric tonnes

The calculation for organic-rich shales is very similar to the calculation for coal beds. Carbonaceous gas shales of Devonian age underlie the Appalachian and Michigan basins within the study area of the MRCSP. These continuous, low-permeability shales serve as both a sealing interval for deeper reservoirs and a potential sequestration target. In addition, CO_2 injection into fractured gas shales represents a potential method of enhanced natural gas production. The Kentucky Geological Survey, an MRCSP geologic team member, has been investigating the potential use of carbonaceous shales for CO_2 sequestration under a separate U.S. DOE contract (*Analysis of the Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production*, DOE/NETL contract DE-FC26-02NT41442) and much of the following discussion results from that work (Nuttall and others, 2005b).

For estimating sequestration volumes in organic-rich shales, two storage strategies must be considered. Injected CO_2 will occupy the natural fracture system as either a free gas or a supercritical fluid depending on reservoir pressure and temperature conditions. Standard volumetric methods can be used to estimate this capacity, but should only be applied within the extent of known gas-producing areas of the shale.

A much larger volume of CO_2 is likely to be permanently stored as gas adsorbed onto organic matter and clay minerals in the shale matrix (similar to coal). The basic method to estimate this CO_2 storage capacity

is to convert a volume of shale to a weight of shale using its density and then calculate the volume of CO_2 using gas content data.

The shale volume is estimated from gridded isopach data imposing the limitations that the top of the shale must be a minimum drilling depth of 1,000 feet (304.8 m) and the shale is a minimum of 100 feet (30.48 m) thick. The strict application of these conditions eliminated areas in Ohio and Pennsylvania where the shale was shallower than 1,000 feet (304.8 m), but which exceeded several thousand feet in thickness. With this consideration, additional areas in those two states were added for evaluation. These limits were arbitrarily selected to ensure sufficient reservoir and seal capacity for CO_2 sequestration.

Shale density varies inversely with organic matter content (Schmoker, 1993). Clastic-rich gray shales (gray dots) with minimal organic matter generally exhibit a bulk density greater than 2.55 grams per cubic centimeter (g/cc) and gamma ray less than 250 API units. Maximum shale density (minimal organic matter) is approximately 2.82 g/cc. Minimum shale density (maximum organic matter) is approximately 2.35 g/cc. For initial regional assessments, a shale density of 2.62 g/cc is used (Nuttall and others, 2005b).

For determining gas content of the shale, CO_2 adsorption isotherm data were collected as part of the current Kentucky U.S. DOE-funded project. The data indicate the adsorption capacity of the shale averages 42.9 standard cubic feet of CO_2 per ton (scf/ton) of shale (1.134 m^3/tonne) and ranges from 13.9 to 135.7 scf/ton (0.43 to 4.24 m^3/tonne) (Nuttall and others, 2005b). Observed adsorption data are log normally distributed. For comparisons with the other reservoir types, a gas content value of 42.9 scf/ton is used to calculate CO_2 storage capacity herein. This value is a reasonable average for regional calculations based on available CO_2 isotherms (Nuttall and others, 2005b), but actual values would obviously vary with organic content.

Although the methodology used to calculate storage capacity in organic shales of the region is reasonable for a first cut at a regional assessment, it can be improved. Original calculations assumed storage capacity to be proportional to density and suggested increasing density yielded higher sequestration capacities. In actuality, the adsorbed gas capacity (and thus sequestration potential) is inversely proportional to density which itself is a function of total organic content (TOC). Schmoker (1993) described the relationship between density and TOC in his method to determine total organic matter content from density logs. The relation between measured TOC and adsorption capacity is being investigated in current shale research at the Kentucky Geological Survey (Nuttall and others, 2005b).

There are a number of factors that will reduce the amount of CO_2 that can be adsorbed into coal beds. These include the amount of moisture, the heating value and vitrinite reflectance, maceral composition, surface area and pore throat size, and cleat and fracture permeability (Drobmiak and others, 2005). Presumably, these factors will also affect organic-rich shales. Each of these factors will affect the amount of CO_2 that will be sequestered at any specific site, so the total pore volume needs to be further adjusted for these factors. Tables 4.12, 4.13, 4.16, and 4.17 show the total CO_2-sequestration capacity at the 10% level. This is an estimate of the amount of CO_2 that will ultimately be adsorbed by coal beds and organic-rich shales.

Geologic Storage Capacity Results

The primary result of the volumetric storage capacity calculations shows that the MRCSP region has a large amount of potential capacity for CO_2 sequestration. Actual capacity will be limited by a large number of factors that are discussed in the following pages, but is likely less (and more variable) than calculated herein. However, the results calculated provide a basis for comparison between units, states, and other regions using similar methods to determine future storage capacity. The total amount of

potential sequestration capacity for the MRCSP region is estimated at about 520 gigatonnes of CO_2 (Table 4.12). The majority of the CO_2-sequestration capacity in the MRCSP area, about 470 gigatonnes, or approximately 90 percent of the total estimated CO_2 storage capacity, represents the potential of the deep saline formations. The black shales have the next largest storage potential, with a sequestration capacity of about 45 gigatonnes, which is approximately 9 percent of the total estimated CO_2 storage capacity. Oil-and-gas fields have a potential sequestration capacity of about 2.5 gigatonnes, which is approximately 0.5 percent of the total estimated CO_2 storage capacity. The smallest sequestration capacity occurs in coal, with a total of about 0.25 gigatonnes, which is approximately 0.5 percent of the total estimated CO_2 storage capacity (Table 4.12). The reader is referred to the MRCSP web-based interactive maps or the GIS on CD accompanying this report to view the capacity maps per geologic interval mapped to see variations across the area.

Comparisons by State

Each state has their own set of geologic conditions and reservoirs that can sequester CO_2. Tables 4.12 through 4.27 show the breakdown of CO_2 sequestration potential by reservoir and by state.

The largest potential sequestration capacity occurs in the state of Michigan, with a capacity of about 220 gigatonnes (Table 4.13), which corresponds to 42 percent of the total capacity in the MRCSP project area. Almost all of this capacity is in deep saline formations. The Sylvania Sandstone, St. Peter Sandstone, and Mount Simon Formation, provide the majority of the capacity.

The state with the next largest sequestration capacity is Pennsylvania, with a potential capacity of nearly 90 gigatonnes, which corresponds to 17 percent of the MRCSP regional sequestration capacity. Unlike the state of Michigan, the sequestration capacity Pennsylvania is distributed among five different deep saline formations, the Devonian black shales and the Needmore Shale, the oil-and-gas fields, and the coal beds. Pennsylvania also has the largest potential oil-and-gas field sequestration capacity.

The eastern part of the state of Indiana has the third largest sequestration capacity after Pennsylvania. It has a potential sequestration capacity of about 80 gigatonnes. Almost all of Indiana's sequestration capacity is in the Mt. Simon Sandstone. Minor amounts of sequestration capacity are found in Indiana's St. Peter Sandstone and oil-and-gas fields. Indiana's coal fields are outside of the MRCSP boundary, so they were not considered in the calculations.

West Virginia has the fourth largest potential sequestration capacity with a total of about 60 gigatonnes. The deep saline formations have a potential sequestration capacity of over 40 gigatonnes, while the shales have a potential capacity of about 20 gigatonnes. Both the shale and coal bed sequestration capacities are the largest among the states in the MRCSP project. Also, the area in which coal sequestration was considered possible or likely in West Virginia was limited to non-producing areas, so that the total potential coal capacity may be greater.

Ohio has the fifth largest potential sequestration capacity. It has a capacity of over 45 gigatonnes, of which over 35 gigatonnes is in deep saline formations. The saline formations with the largest potential capacity are the Mt. Simon Sandstone (20 gigatonnes) in western Ohio, and the Rose Run (8 gigatonnes) and Medina (5.6 gigatonnes) Sandstones in eastern Ohio. These three reservoirs compose 71 percent of the state's total potential sequestration capacity, and 89 percent of the saline aquifer capacity. The Devonian shales have a potential capacity of 8.5 gigatonnes.

Eastern Kentucky has the sixth largest potential capacity, with over 13 gigatonnes. The potential capacity is only calculated for that part of the state in the MRCSP region. The majority of the capacity is in the

deep saline formations, with a total of nearly 11 gigatonnes (82 percent). The three largest deep saline formations are the Rose Run sandstone, at 5 gigatonnes (41 percent of the total capacity), Mt. Simon Sandstone, at 4 gigatonnes (33 percent of the total capacity), and Rome Trough sandstone, at 1 gigatonnes (8 percent of total capacity). The next largest type of reservoir is the Devonian shale, with a potential capacity of nearly 2 gigatonnes (13 percent).

The estimated total potential storage capacity in Maryland is nearly 10 gigatonnes, of which almost all occurs in deep saline formations of the Waste Gate Formation, Oriskany Sandstone, and Medina/Tuscarora Sandstone. The Waste Gate Formation has the largest capacity, over 4 gigatonnes (46 percent of the total capacity). The next largest is the Medina Sandstone, at 3 gigatonnes (36 percent of the total capacity). There is also a minor amount of sequestration potential in the Needmore Shale. Additional storage capacity may be present in the offshore reservoirs along the Maryland coast; however, these reservoirs were not evaluated due to the lack of data.

Comparisons by Reservoir Type and Unit

The storage capacity in each reservoir is largely a function of its spatial extent, thickness, and the porosity. Given its presence in much of the MRCSP region, the saline aquifer with the largest capacity in the region is the Mt. Simon Sandstone, followed by the St. Peter Sandstone and the "Clinton"/Medina/Tuscarora Sandstone. The deep saline formations with the smallest potential are the Potsdam Sandstone and basal sands in the Rome trough of eastern Kentucky. The low potentials stem from assigning these two aquifers very low porosities, since porosity generally decreases with depth, and both units are deeply buried. In addition, because of the lack of exploratory wells in many areas, such as in the deepest portion of the Appalachian basin in Pennsylvania, such areas had no data to be mapped (see the structure and isopach maps in Appendix A of the detailed MRCSP Geological Sequestration report available on the MRCSP web site (www.mrcsp.org) of the DOE/NETL web site). This also accounts for much of the small potential of these basal sandstones. The unnamed Conasuaga sandstones were also assigned a low porosity, since initial studies have shown that the primary lithology of the Conasauga in eastern Ohio and western Pennsylvanian is a sandy or silty dolomite.

It is perhaps useful to compare the estimated capacities in this study with some other assessments. An assessment of the Mt. Simon Sandstone (including areas outside MRCSP) by Gupta and others (2001) showed a capacity range of 160 to 800 gigatonnes based on porosity range of 5 to 25 percent, net-to-gross-ratio of 50 to 95 percent, and storage efficiency of 6 percent. In the same study, the capacity range for 8.5 percent porosity was 195 to 371 gigatonnes. This compares well with the estimated 10 percent capacity number of 217 gigatonnes for Mt. Simon in the MRCSP region in this study. Similarly, the Rose Run Sandstone capacity range of 9 to 43 gigatonnes of Gupta and others (2001) is comparable to the 49 gigatonnes estimated in the current study.

Estimated CO_2 sequestration capacity in the Devonian Ohio Shale (Cleveland to Lower Huron Members) and equivalents of the Appalachian basin and the Antrim Shale of the Michigan basin ranges between 23.2 and 88.3 gigatonnes, varying between CO_2 adsorption rates of 22 and 84 standard cubic feet of gas per (U.S.) ton of shale. Capacity estimates for the black shales of eastern Kentucky represent only that part of the shale in the MRCSP region. The 90th percentile figures calculated for Ohio, Pennsylvania, and West Virginia seems overly optimistic. The gray shales and intertonguing siltstones characteristic of the Devonian shale in these states may not have sufficient organic matter content to adsorb such large volumes of CO_2. More realistically, the sequestration capacity is likely in the calculated range between the 10th and 50th percentiles. All of these estimates are of course contingent on the injectivity of CO_2 into the shale, which is untested.

For the oil-and-gas fields, the fields are separated into those that are less than 2,499 feet in depth and those that are greater than 2,500 feet in depth (762 m). The 2500-foot depth cutoff roughly corresponds to the predicted transition from the gaseous phase to the super-critical phase, which is approximately 260 times denser than the gaseous phase and, therefore, more desirable.

Solubility Storage

While solubility storage is described in this document, it is not applied in this study, since most of the initial sequestration will occur as volumetric storage. Instead, one representative calculation was conducted for the project. The solubility capacity was calculated for Mt. Simon Sandstone of Indiana, Michigan, and Ohio. The potential CO_2 storage capacity using the solubility calculation is in excess of 83 gigatonnes, while the potential storage capacity using the volumetric calculations is over 217 gigatonnes, an increase by a factor of 2.5. An interesting phenomenon occurs in the solubility calculation. In the center of the Michigan basin, there is no solubility capacity. This is because the modeled salinity is too high to allow CO_2 to dissolve into the formation fluids. The high salinity, generally increasing salinities with depth, and the low solution rates indicate that solubility storage will not be a near-term factor in sequestering CO_2 in the MRCSP area. As a comparison, Dooley and others (2004) used the solubility approach to estimate that the total storage capacity in the Mt. Simon Sandstone, including all of the Illinois basin and the Appalachian basin is approximately 225 gigatonnes.

Conclusions for Geologic Storage

This Phase I assessment has shown that the MRCSP region has approximately 450 to 500 gigatonnes of storage potential in deep saline formations for future deployment of geologic CO_2 sequestration - ample deep subsurface storage space. In fact, our region can easily accommodate many hundreds of year's worth of CO_2 emissions at current or expanded levels within this one type of reservoir. This region also has the potential to store at least 2.5 gigatonnes of CO_2 in existing and depleted oil and gas fields. By using anthropogenic CO_2 in enhanced oil recovery operations in current and recently abandoned oil fields the region could realize hundreds of million of barrels of additional oil production. The northern Appalachian basin unmineable coalbeds have the potential to contain approximately 0.25 gigatonnes of CO_2. The northern Appalachian basin has only recently started to develop the vast amount of coalbed methane found beneath us. Application of enhanced gas recovery using CO_2 early in this endeavor could add significantly to the amount of gas produced from the deep unmineable portions of this resource while securing millions of tons of CO_2 in its place. The use of organic shales as a CO_2 storage medium is still an untested research topic. Should this technology prove practical, the MRCSP region has one of the richest holdings of these deposits in the world.

Although we are herein reporting capacities of reservoirs at 10 percent of total assumed volumes, we do not believe these estimates to be sufficiently conservative. It should also be kept in mind that many other restrictions will be emplaced on the use of any subsurface storage space that have not been accounted for in studies of this type to date. Such restrictions, or access issues, might include: inability to inject below large metropolitan areas or large bodies of water; inability to inject below, or within specific offsets (both vertically and horizontally), of producing oil and gas fields or active mines; inability to inject within specific offsets (both vertically and horizontally) of other injection operations – Class I, II, or III. In addition to these listed possible restrictions, it must be considered that large-scale CO_2 injection operations should not be permitted too close to one another to avoid any possibility of interaction of their related pressure fronts. Many of these restrictions will fall under the purview of regulatory agencies to enact. As with the entire carbon capture and storage technology arena, regulations for CO_2 injection and

storage are still in an early formative stage. Once regulations are known, restrictions can be applied to these capacity maps to calculate potentials including such considerations.

The above-cited storage potential is not distributed evenly over the region. Some areas have very significant storage potential while others have very little known storage potential. Mapping the distribution of this potential is just as significant to the region as calculating the potential for storage. The existing large stationary CO_2 sources of the region are not all situated over sufficient known storage potential. Therefore, it is hoped that this study, and subsequent investigations, will be used by utility and industrial decision-makers to plan future plant locations with necessary subsurface conditions in mind. Further, the maps/results of this investigation can be used to start planning for future pipelines to match existing CO_2 sources with appropriate geologic sinks.

5.0 TERRESTRIAL SEQUESTRATION

Agricultural activities such as clearing of forests, cultivation of crops, expansion of rice paddies, or raising livestock result in the release of carbon dioxide (CO_2) and methane (CH_4) and contribute to the increase in concentrations of these gases in the atmosphere (Ruddiman, 2003). The current atmospheric carbon[1] (C) pool of 760 Petagrams[2] (Pg) is increasing at a rate of 3.2 ± 0.1 Pg of carbon per year (Prentice, 2001; Lal, 2003) due to fossil fuel combustion, land use conversion and soil cultivation. The emission of CO_2 from terrestrial ecosystems is a major contributor to increased levels of CO2 in the atmosphere accounting for an estimated 25% of the annual global emission of CO2 (IPCC, 2001). The historic loss of soil organic carbon[3] (SOC) is estimated to be between 66 and 90 Pg (Lal, 1999).

The quantity and quality of soil organic matter (SOM)[4] are strong determinants of soil quality in terms of biomass productivity and environment moderation capacity (Doran and Parkin, 1994; Bezdicek et al., 1996), and the magnitude and dynamics of the soil organic carbon pool are also indicators of soil degradation because of their influence on numerous physical, chemical, and biological properties and processes which affect the soil's ability to perform its functions (Lal, 1997). Thus, the depletion of the soil organic carbon pool leads to decline in soil quality, reduction in agronomic/biomass productivity, decrease in fertilizer and water use efficiencies, increase in cost of production, increase in soil erosion/sedimentation, reduction in soil biodiversity, and emission of CO_2, methane (CH_4), nitrogen oxide (N_2O), etc.

Rather than a source, soil can be a major sink for atmospheric CO_2. The global soil organic carbon pool of 1550 Pg is about twice the atmospheric pool and three times the biotic pool (Eswaran et al., 1995; Batjes, 1996). Furthermore, carbon lost from terrestrial ecosystems can be put back into soil and biotic pools by restoring degraded ecosystems through natural processes of photosynthesis, humification, aggregation, and calcification. Such restorative processes can be accentuated through adoption of conservation measures and optimization of management practices (Lal et al., 2004). Consequently, soil carbon sequestration can improve soil quality, increase productivity, reduce erosion and nonpoint source pollution, and enhance biodiversity.

A loss of soil organic carbon often occurs upon conversion from natural to agricultural ecosystems due to reduced inputs of organic matter as well as reduced physical protection of soil organic carbon through tillage (Post and Mann, 1990; Davidson and Ackerman, 1993). Other factors which also contribute to a loss of soil organic carbon are a lower fraction of nonsoluble materials in more readily decomposed crop residues (Post and Kwon, 2000) and losses due to soil erosion (Lal, 2003). The conversion of formerly unmanaged lands to agricultural ecosystems can reduce the soil organic carbon pool by as much as 50% in the top 20cm depth and up to 30% in the top meter of depth following 30 to 50 years of cultivation (Post and Kwon, 2000). These results, which speak to how soil organic carbon can be lost from soils also

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[1] The term carbon or (C) is used throughout this and other reports in this terrestrial series to refer to elemental carbon as opposed to carbon in carbon dioxide CO_2.

[2] 1 Pg = 10^{15}g = 1 gigaton

[3] Soil Organic Carbon (SOC) is defined as the total organic carbon of a soil exclusive of carbon from undecayed plants and animal residues (see http://www.fao.org/gtos/tems/variable_show.jsp?VARIABLE_ID=34)

[4] Soil Organic Matter (SOM) is broadly defined as all living organisms (microorganisms, earthworms, etc), fresh residues (old plant roots, crop residues, recently added manures), and well-decomposed residues (humus). See also (http://www.akron.ars.usda.gov/fs_soil.html)

imply a potential for soil organic carbon sequestration when cultivated lands are allowed to revert to a more less intensively managed state such as through afforestation of formerly cultivated lands.

Soils can become a significant sink of carbon following afforestation over the long-term, although the soil organic carbon accumulation rate varies with the age of the forest (Paul et al., 2002). Garten (2002) reported that soil organic carbon increases at a rate of 890 kgC/ha/yr during the first decade following afforestation in the Southeastern U.S. Post and Kwon (2000) estimated a soil organic carbon sequestration rate of 340 kgC/ha/yr by afforestation of cultivated lands. Guo and Gifford (2002) reported an average increase of 18% in soil organic carbon after cropland was converted to woodland plantations.

The above examples suggest that a significant potential exists for terrestrial carbon sequestration in ecosystems via selected land use changes. On the other hand, it has been widely reported (see for example, West and Post, 2002) that the enhancement of soil carbon sequestration through the adoption of recommended management practices can increase crop production costs and cropping complexity.

The capacity of terrestrial carbon sequestration depends not only on the land use distribution, but also on the how much carbon has previously been lost from the land, the specific history of land use change at the site, and which specific cropping systems were employed at the site. Therefore, it is critical that the assessment of terrestrial soil carbon sequestration potential as well as any strategies to realize this potential must be based on a detailed understanding of the history and pattern of land use changes.

The MRCSP's Phase I research on terrestrial carbon sequestration is focused on five dominant land use types characterized by the research team as offering the best opportunities for terrestrial carbon sequestration within the region. Two well-known spatial data sets, the USGS 1992 National Land Cover Dataset (NLCD) (USGS, 2003) and the STATSGO soil map (USDA-NRCS, 1991), were used to identify and delineate the boundaries of these five land use types within the MRCSP region. The five land use types studied within Phase I of the MRCSP's research were:

1. Non-eroded prime cropland: the farming area excluding eroded and marginal areas,
2. Eroded Cropland: the eroded area as defined by STATSGO soil map,
3. Marginal lands: the open area named as bare rock, sand, or clay by NLCD and severely eroded crop and pasture lands defined by STATSGO soil map,
4. Mine Lands: the mine areas defined by 1992 NLCD and the mine area permitted since 1992, and
5. Wetlands: the areas defined by 1992 NLCD.

In addition, an analytical analysis of terrestrial sequestration in the MRCSP region was carried out using the SOCRATES analytical model.

The analysis of each of the five land types listed above and the analytical modeling results are described in detail in six separate Task Reports as part of the MRCSP deliverables. Finally, a separate seventh report titled Methodology describes the process that was developed for this project and employed to assess the terrestrial sequestration potential across these land use categories. All of these reports as well as other MRCSP reports can be found at the MRCSP web site (www.mrcsp.org) as well as through the U.S. Department of Energy.

The specific objectives of the terrestrial research described here were to quantify the carbon sink capacity for major land use components in the MRCSP region and to identify land use and management options to achieve that sink capacity. This research included determination of the hot spots in specific land use scenarios for carbon sequestration with various conservation practices. Finally, efforts were made to develop linkages with industry stakeholders, and to create awareness of terrestrial sequestration among public at large.

Non-Eroded Prime Cropland

Non-Eroded Prime Cropland includes three sub-classes: row crops, small grains, and fallow as defined in 1992 NLCD (USGS, 2003). The net cropland areas exclude the eroded and severely eroded areas as defined by STATSGO soil map (USDA-NRCS, 1991). Therefore, the term cropland used here represents the non-eroded prime cropland.

Estimated Area of Non-Eroded Prime Cropland in the MRCSP States

The area of non-eroded prime cropland is listed for each state in the MRCSP region in Table 5.1.

Table 5.1.   The Area of the Non-Eroded Prime Cropland (USDA-NRCS, 1991; USGS, 2003).

Non-Eroded Prime Cropland	State							MRCSP Total
	IN	KY	MD	MI	OH	PA	WV	
Area (1000 ha)	3,362	1,010	289	2,611	3,047	370	47	10,736
% of total area	35.9	9.7	10.5	17.3	28.5	3.2	0.8	16.2

The distribution of non-eroded prime cropland, illustrated in Figure 5.1, is concentrated in Indiana, Ohio, and Michigan. Note that the cropland "theme" that was used in the MRCSP's geographic information system tool was generated from 1992 NLCD Landsat TM imagery (USGS, 2003) and therefore might contain some eroded areas.

Current Soil Organic Carbon (SOC) Pool in Non-Eroded Prime Cropland

The global agricultural sector has the potential to play a significant role in reducing the build up of greenhouse gases (GHG) such as CO_2, N_2O, and CH_4 in the atmosphere (Cole et al., 1997). Conservation tillage and reduced-tillage practices are effective measures to reduce soil erosion and enhance agricultural sustainability, both concomitant with mitigating GHG emissions (Cole et al., 1997; Schlesinger, 1999; Lal, 2004). Several long-term experiments have demonstrated the CO_2 mitigation potential of conservation tillage practices (Kern and Johnson, 1993; West and Marland, 2002; Lal et al., 2004). Findings reported in the literature are summarized below.

- Conservation tillage management, coupled with diverse cropping systems, have the potential of sequestering carbon at the rate of 30 – 105 Tg/yr in the U.S. (Follett, 2001).
- Lal et al. (1998; 1999) estimated that total potential soil carbon sequestration from improved management on U.S. croplands is 75 to 208 Tg/yr for several decades.
- Bruce et al. (1999) reported a carbon sequestration potential of 75 Tg/yr attainable in U.S. agricultural soils in the next 20 years.
- Using the methodology developed by the Intergovernmental Panel on Climate Change (IPCC) with an emphasis on climatic factors, Sperow et al. (2003) suggested that the U.S. cropland has the potential to sequester 77 - 87 Tg/yr of carbon with widespread adoption of conservation tillage practices and 47 Tg/yr of carbon with adoption of no-till on currently cropped area of 129 Mha, which, however, also varies with climatic regions and specific cropping system.

- Smith et al. (2002) estimated carbon sequestration potential in soils with change in cropping systems in Indiana. Using the CENTURY model, they reported that the soil organic carbon sequestration rates with conversion of conventional tillage to reduced-till and no-till are 350 and 500 kg/ha/yr of carbon in corn-soybean rotation system, respectively.
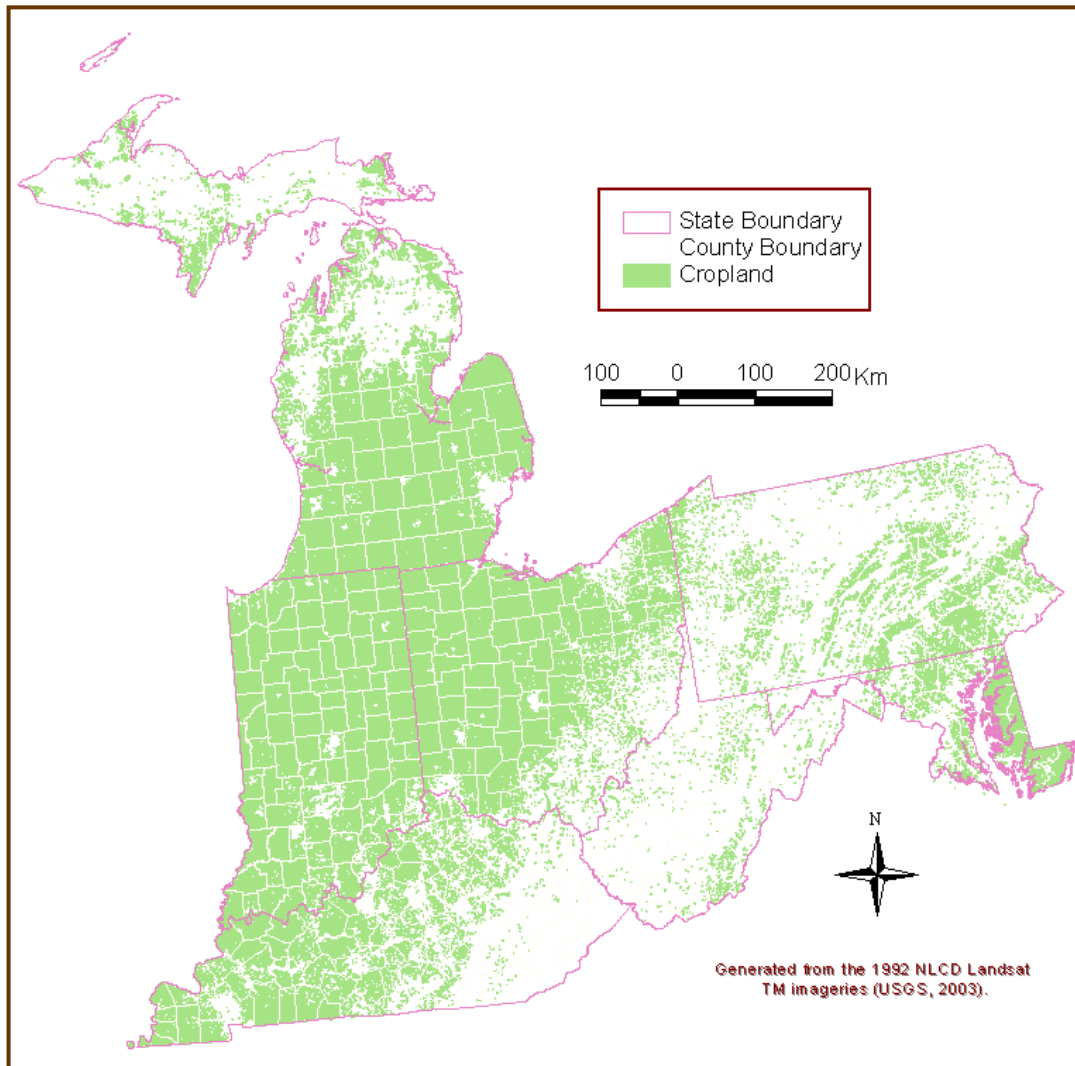
Figure 5.1.   Spatial distribution pattern of croplands in the MRCSP region.

Based on the long-term experimental data from Ohio, Tan and Lal (2005) observed that soil carbon sequestration rates upon conversion from conventional tillage to either no-till or reduced till depends largely upon previous soil organic carbon content and the time scale. Because soil genesis and properties result from interactions of all soil forming factors (Jenny, 1980), the soil organic carbon dynamics and pool size are indicative of such interactions. Therefore, it is possible to use current soil organic carbon pool to predict soil organic carbon sequestration potential with adoption of specific conservation practice through use of empirical models and pedotransfer functions. Following the procedure detailed in the companion MRCSP report in this series titled Methodology, the current soil organic carbon pools for non-eroded prime cropland within the MRCSP were calculated and are summarized in Table 5.2.

Table 5.2.   Estimated Soil Organic Carbon Pool in Non-Eroded Prime Cropland.

SOC Pool	State							Total MRCSP
	IN	KY	MD	MI	OH	PA	WV	
Minimum (Tg)	134.9	19.3	4.7	78.3	110.9	5.9	0.8	354.7
Maximum (Tg)	379.4	66.5	19.6	256.6	349.4	26.4	3.3	1101.1
Mean (Tg)	245.6	40.9	11.1	156.8	217.1	14.7	1.8	688.1
% of Entire Pool	42.4	11.5	10.2	10.3	39.0	4.1	1.2	18.9

Note that the percent of entire pool is obtained from the mean soil organic carbon pool in non-eroded prime cropland for each state divided by the SOCP sum of all land use categories for this state. The value of 18.9% for the MRCSP column represents the total SOCP in the non-eroded prime croplands for the MRCSP region divided by the SOCP sum of all land use categories for this region.

Approach

The potential for carbon sequestration in non-eroded prime cropland was assessed using the approach described below. It included baselining areas of different management practices documented in 1992, estimating changes in areas under conservation practice, and estimating annual rates of soil organic carbon sequestration. Additional information on the overall analysis approach taken by the MRCSP terrestrial team can be found in a separate report in this series titled Methodology.

Baselining Areas of Different Management Practice

The magnitude and rate of soil carbon sequestration that can be expected is a function not only of how much land is potentially available, but also depends critically on the how the land is being used today, how it has been used in the past, and what land use practices are adopted in the future as a means for implementing terrestrial carbon sequestration. Within the MRCSP, the major cropping systems include continuous corn, corn-soybean, and other cropping systems, consisting of corn, soybean, grain crops, small grain crops, and other crops (such as tobacco, vegetable, peanut, winter cover crops, etc). The dominant land management practices include no till, mulch-till (combined with ridge tillage), reduced till, and conventional till. The areas of each management practice associated with specific crops are presented in Table 5.3. These areas were aggregated from the dataset provided by the Conservation Technology Information Center (CTIC, 2004) and adjusted to match the total area of the non-eroded prime cropland derived from both STATSGO soil map and 1992 NLCD land use imagery.

Table 5.3. **1992 Cropland Areas for Different Management Practices in the MRCSP region (CTIC, 2004).**

Crop or Cropping System	Total Cropland[3] ha	Conservation Tillage, ha		Other Tillage Methods, ha	
		No Till	Mulch Till[4]	Reduced Till	Conventional Till
Corn	4,651,583	1,028,589	884,455	894,455	1,950,338
Small Grain[1]	1,439,184	222,953	311,314	278,626	547,810
Soybeans	3,843,430	1,066,627	568,227	643,097	1,365,083
Other Crops[2]	794,202	94,007	78,804	109,706	685,487
Fallow	7,286	3,829	89	1,594	603
Total	10,735,685	2,416,005	1,842,889	1,927,478	4,549,320
% of total cropland area	100	22.5	17.2	18.0	42.4

Note: Areas from the CTIC were adjusted to match those derived from 1992 NCLD.
[1] Including grain sorghum
[2] Other crops include forge crops, vegetable, and truck crops.
[3] Excluding eroded area.
[4] Including Ridge-Till which accounted for about 1% of total planted area.

The areas for different management practices in 1992 was taken as the baseline because only 1992 NLCD land use image is available, which is also comparable with the guidelines established by IPCC for CO_2 emission estimation for land uses and management practices (Houghton et al., 1997).

Future Changes in Areas Under Conservation Practices

For the purposes of the MRCSP's Phase I research, the research team assumed that no-till and reduced till practice would be adopted on respectively 75% and 25% of total cropland area by 2020. Further, it was assumed that the no-till areas that existed in 1992 had become permanent no-till and is thus eliminated from cropland area that is projected for future adoption of conservation practices. The area currently under mulch till will be first converted to no-till. Because the area under reduced till is projected to occupy 25% of total cropland area, if the current reduced till area is < 25% of total cropland area, the difference will be compensated by conversion of conventional till to reduced till and the remainder of the conventional till area will be converted to no-till. If the current reduced till area is > 25%, the fraction in excess of 25% (current RT% - 25%) will be targeted for no-till. The results obtained under this assumption are presented in Table 5.4.

Carbon Sequestration Rates Under Different Management Practices

Rates of soil carbon sequestration with conversion to specific conservation practices vary with geographic location (climate variables), farming operation and production level. West and Post (2002) reviewed and aggregated worldwide experimental data and proposed global average carbon sequestration rates for various conservation tillage practices (on lands that were formerly under conventional tillage) and cropping systems. For example, carbon storage in soils can increase at 57 ± 14 g/m^2/yr following conversion from conventional till to no-till and 20 ± 12 g/m^2/yr by increasing cropping complexity.

Table 5.4. **Non-eroded prime cropland Area Identified for Conversion to Conservation Practices in the MRCSP region.**

Corn or Cropping System	Area for Conservation Tillage, ha	Conversion to No-Till, ha			Conversion to Reduced Till, ha	
		from Mulch Till	from Conventional Till	from Reduced Till	Existing Reduced Till	From Conventional Till
Corn	3,729,248	884,455	1,655,333	0	894,455	295,004
Small Grain	1,137,748	311,314	486,143	118	278,508	61,667
Soybean	2,576,403	568,227	1,097,423	0	643,097	267,660
Other Crops	873,996	78,804	553,192	0	109,706	132,295
Fallow	2,285	89	603	1,594	0	0
Total	8,319,680	1,842,889	3,792,694	1,712	1,925,766	756,626
% of Total Cropland	77.5	17.2	35.3	0.02	17.9	7.0

The IPCC developed the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories to provide methods for signatory countries to the United Nations Framework Convention on Climate Change (UNFCC) to estimate emissions by sources and removals by sinks of greenhouse gases. The Land Use and Land Use Change section of the guidelines provides a method for estimating net carbon emissions from soils. The method estimates average annual carbon emissions and/or sinks from land use and management changes, based on computed soil carbon pool changes over a 20-year inventory period. Default values for baseline soil carbon pools are provided along with a series of coefficients that determine carbon pool changes as a function of climate, soil type, disturbance history, tillage intensity, productivity, and residue management (Houghton et al., 1997). Other researchers have noted that it is difficult to directly quantify the level of uncertainty in this type of analysis because each input data set has an associated level of uncertainty that gets passed through the analysis (Cannell et al., 1999; Houghton et al., 1999).

When one applies this IPCC proposed methodology, it implies that carbon sequestration rates would increase by 5% and 10% with a change from conventional till to reduced till and from conventional till to no till, respectively, the uncertainty in the estimates of greenhouse gas emissions from agriculture or reduction of greenhouse gas emission with land use change may be as high as 50% (Houghton et al., 1997). For example, our preliminary study on the data collected from agricultural experimental stations in Ohio suggested that conversion from conventional till to reduced till and from conventional till to no till can reduce CO_2 emissions respectively by 7% and 17% which are much higher than those proposed by the IPCC. Therefore, the research team elected to use data from literature relevant to the MRCSP region as we believe that this data is of higher quality as it reflects the local conditions within this region better than the general methodology proposed by the IPCC.

Table 5.5a lists data from paired experiments for no-till vs. conventional till, no-till vs. reduced till, and reduced till vs. conventional till from the literature that are relevant to the MCRCSP. In cases where no data were available for a specific management practice, the regional or national average values were used. The method proposed by West and Post (2002) was used to calculate the rates of carbon sequestration (kg/ha/yr) which were adjusted to 30 cm depth if the sampled depth was not 30 cm by assuming that the carbon pool decreases by 40% for each depth increment of 10 cm (Tan et al., 2004b). Note that soil carbon sequestration rates were recalculated from the paired soil organic carbon content data provided by

Table 5.5a. Data Sources for Soil Organic Carbon Sequestration Rate Calculation.

Location	Cropping or Tillage	Treatment	Rate, Kg/ha/yr	Reference
Michigan	NT or MT	NT vs. CT	300	Robertson et al., 2000
Elwood, IL	C-S	NT vs. CT	987	Mielke et al., 1986.
Vienna, IL	C-S	NT vs. CT	881	Kitur et al., 1994; Hussain et al., 1998 and 1999.
Lexington, KY	C (0 N)	NT vs. CT	394	Blevens et al. 1983; Ismail et al., 1994.
Lexington, KY	C (84 N)	NT vs. CT	192	Blevens et al. 1983; Ismail et al., 1994.
Lexington, KY	C (168 N)	NT vs. CT	196	Blevens et al. 1983; Ismail et al., 1994.
Lexington, KY	C (336 N)	NT vs. CT	348	Blevens et al. 1983; Ismail et al., 1994.
Hoytville, OH	C	NT vs. CT	1332	Dick et al., 1997; Dick, 1983
Hoytville, OH	C-S	NT vs. CT	854	Dick et al., 1997; Dick, 1983
Hoytville, OH	C-O-G	NT vs. CT	1215	Dick et al., 1997; Dick, 1983
Wooster, OH	C	NT vs. CT	651	Dick et al., 1997; Mahboubi et al. 1993; Lal et al. 1994
Wooster, OH	C-S	NT vs. CT	825	Dick et al., 1997; Mahboubi et al. 1993; Lal et al. 1994
Wooster, OH	C-O-G	NT vs. CT	844	Dick et al., 1997; Mahboubi et al. 1993; Lal et al. 1994
US Average	NT or MT	NT vs. CT	500	Lal et al., 1998 (Ann Arbor press)
	CT-NT	NT vs. CT	300	West and Marland, 2001
Wooster, OH	C-S	NT vs. RT	693	Dick et al., 1997; Mahboubi et al. 1993; Lal et al. 1994
Wooster, OH	C-S	RT vs. CT	132	Dick et al., 1997; Mahboubi et al. 1993; Lal et al. 1994
Urbana, IL	C-S	RT vs. CT	72	Yang and Wander, 1999.
Urbana, IL	C-S	RT vs. CT	419	Yang and Wander, 1999.
Hoytville, OH	NT	C-O-G vs. C	-7	Dick et al.,1997; Dick, 1983.
Hoytville, OH	CT	C-O-G vs. C	118	Dick et al.,1997; Dick, 1983.
Wooster, OH	NT	C-O-G vs. C	-24	Dick et al., 1997; Mahboubi et al. 1993; Lal et al. 1994
Columbia, MO	CT (fert.)	C-W-Cl vs. C	111	Buyanovsky and Wagner,1998; Balesdent et al. 1998, Buyanovsky et al., 1997.
Columbia, MO	CT (0 fert.)	C-W-Cl vs. C	166	Buyanovsky and Wagner,1998; Balesdent et al. 1998, Buyanovsky et al., 1997.
Columbia, MO	CT (fert.)	C-W-Cl vs. W	111	Buyanovsky and Wagner,1998; Balesdent et al. 1998, Buyanovsky et al., 1997.
Columbia, MO	CT (0 fert.)	C-W-Cl vs. W	152	Buyanovsky and Wagner,1998; Balesdent et al. 1998, Buyanovsky et al., 1997.
Urbana, IL	CT (0 N)	C-O-S vs. C	106	Darmondy and Peck,1997; Odell et al..1984.
Urbana, IL	CT (M, L, P)	C-O-S vs. C	77	Darmondy and Peck,1997; Odell et al..1984.
Urbana, IL	CT (0 N)	C-O-H vs. C	184	Darmondy and Peck,1997; Odell et al..1984.
Urbana, IL	CT (M, L, P)	C-O-H vs. C	284	Darmondy and Peck,1997; Odell et al..1984.
US Great Plain	Fallow	Conservation Till	300-600	Follett and McConkey, 2000.
Canada	Fallow	Conservation Till	200-300	Follett and McConkey, 2000.

CT, RT, NT, and MT refer to conventional tillage, reduced tillage, no-till, and mulch tillage, respectively.
A, alfalfa ; B, barley ; C, corn or maize; Cl, clover; F, fallow; Fert., unspecified fertilizer rate; G, grass; H, hay; L, lime; M, manure; O, oats ; P, phosphorus; S, soybean; W, wheat.

Table 5.5b. Soil Organic Carbon Sequestration Rates Used for SOC Sequestration Potential Estimation in the MRCSP region Based on the Data Presented in Table 5.5a.

Cropping System	Tillage Treatment	Potential Kg/ha/yr		Sample Size
		Rate Mean	Stdev	
Corn	NT vs. CT	518	446	10
	NT vs. RT[†]	419	531	13
	RT vs. CT	288	132	4
Corn-Soybean	NT vs. CT	530	293	11
	NT vs. RT[†]	419	531	13
	RT vs. CT	164	431	7
Other Cropping Syst.	NT vs. CT	492	205	3
	NT vs. RT[†]	419	531	13
	RT vs. CT	209	348	11
All cropping systems	NT vs. CT	520	345	23
	NT vs. RT	419	531	13
	RT vs. CT	209	348	11
Mulch Tillage	NT vs. CT	400	141	2
Fallow	Conservation tillage	350	141	2

References. For example, soil organic carbon rate for no till or RT was compared to CT. In case soil bulk density data are not available for soil organic carbon measurements, the equation provided by Adams (1973) was used to estimate bulk density.

The annual rate of SOC sequestration (kg/ha/yr) was computed using the following equation (Eq. 1):

$$R_{cs} = \{(NT_2 - CT_2) - (NT_1 - CT_1)\}/(t_2 - t_1) \qquad \text{(Eq. 1)}$$

where R_{cs} is the rate of SOC sequestration ($g/m^2/yr$); no till$_{1 \text{ and } 2}$ and conventional till$_{1 \text{ and } 2}$ represent SOC pools under no till and conventional till during the first and second years in which SOC was measured, respectively; and t_1 and t_2 are the number of years since the beginning of the experiment in which SOC was measured. The analysis of paired treatment data in this way reduces the variability in estimates of the carbon sequestration rates caused by deviations in annual precipitation and temperature from the average annual means (West and Post, 2002). The SOC sequestration rates for adoption of specific conservation practices are presented in Table 5.5b and were used in this study for the estimation of annual carbon sequestration rates.

The annual rate of soil organic carbon sequestration for each specific management practice is a product of carbon sequestration rate (Table 5.5b) and respective area (Table 5.4), which is expressed in Tg/yr (1 Tg = 10^{12} g).

Results

The following sections summarize the results and conclusions for the analysis of non-eroded prime cropland.

Soil Organic Carbon Pool in Non-Eroded Prime Croplands

The magnitudes of SOCP in non-eroded prime croplands for each state are presented in Table 5.2. The magnitude varies largely among states due mainly to variation in cropland area. Of the total SOC stock (to 30 cm depth) in all terrestrial ecosystem for each state, the SOCP associated with non-eroded prime croplands accounted for 42.4% in Indiana, 39% in Ohio, and 1.2 and 4.2 % respectively in West Virginia and Pennsylvania. The SOCP for the whole MRCSP region is 18.9%, which is slightly lower than the national average of 20% (Allmaras et al., 2000).

Areas Identified for Implementing Conservation Practices

As shown in Table 5.1, there is 10.74 Mha of non-eroded prime cropland in the MRCSP region, accounting for 16.2% of all land area, of which 81.7% is concentrated in Indiana, Ohio, and Michigan. Predominant crops grown in the region include corn and soybean (Table 5.3). Among all non-eroded prime croplands, land area under different tillage practices in 1992 was 22.5% in no till, 17.2% in mulch till, 18.0% in reduced till and 42.4% in conventional till. It is assumed that the croplands under no till in 1992 have become permanent no till, and the areas under mulch till, reduced till, and conventional till are projected as potential areas for future conversion to no till and/or reduced till (Table 5.4). Meanwhile, of all the non-eroded prime croplands, 25% would remain under reduced till and 75% would be converted to no till. Therefore, 3.79 Mha of croplands would be converted to no till from the current area under conventional till and 1.84 Mha from the current area under mulch till by the year 2012.

Annual Rate of Soil Organic Carbon Sequestration

With increase in area under conservation management practices, especially increasing conversion from moldboard plowing to no till and reduced till, U.S. croplands have shifted from a carbon source to a net carbon sink (Allmaras et al., 2000). The magnitude of annual SOC sink capacity for specific conservation tillage and cropping system depends on the average carbon sequestration rate and the corresponding area.

The data collected from the MRCSP region shows that, upon conversion to no till, SOCP would increase by 18.8% when converted from conventional till and 14.4% when converted from reduced till, and conversion from conventional till to reduced till would increase SOCP by 7.2%. With these assumptions, the average SOC sequestration rate would be 2.79 ($\pm$ 0.89) Tg/yr (1 Tg = 10^{12} g) (Table 5.6) for the whole MRCSP region. This SOC sequestration rate, however, is principally contributed by adopting no till on the current conventional till area, especially for continuous corn and corn-soybean cropping systems. Only 15.8% of the rate is contributed by conversion to reduced till system.

Table 5.6.   Annual Rate of SOC Sequestration (Tg/yr) on Non-eroded prime croplands in the MRCSP region.

Cropping System	No Till > 30% residue			Reduced Till (15-30% residue)		
	from Mulch Till	from Conventional Till	from Reduced Till	Existing Reduced Till	from Conventional Till	Total
Corn	0.09	0.86	0.00	0.26	0.08	1.29
Small Grain	0.03	0.25	0.00	0.06	0.01	0.36
Corn-Soybean	0.06	0.58	0.00	0.11	0.04	0.79
Other Crops	0.01	0.29	0.00	0.02	0.03	0.35
Fallow	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.19	1.98	0.00	0.44	0.17	2.79
Stdev.	0.06	0.63	0.00	0.14	0.05	0.89

Soil Organic Carbon Sink Capacity for 20-Year Period

Assuming that adoption of no till for each cropping system leads to carbon sequestration at a respective average rate (as shown in Table 5.6) between 1992 and 2012, the cumulative carbon sequestered during this period would be 55.8 ($\pm$ 17.8) Tg. In comparison, the total carbon sink capacity over 20 years using the model developed on the basis of the long-term experimental data of paired no till vs. conventional till from this region is estimated at 55.4 Tg for 75% of non-eroded prime croplands with no till (Table 5.7). These two estimates are comparable.

Table 5.7.   Potential SOC Sequestration Capacity (Tg) in Non-eroded prime croplands in 20 Years (1992 – 2012).

Scenario	IN	KY	MD	MI	OH	PA	WV	MRCSP	Stdev
100% NT	23.54	5.16	1.52	19.72	21.44	2.31	0.23	73.92	23.66
75% NT	17.66	3.87	1.14	14.79	16.08	1.73	0.17	55.44	17.74

It is, however, difficult to use this estimation method to identify the spatial distribution patterns of potential carbon sink capacity because there are no spatial associations of the areas presented in Table 5.4 with either STATSGO soil map or non-eroded prime cropland distribution map. In order to visualize the spatial distribution patterns and delineate hotspots, a Soil-Cropland-SOCP theme was created within the MRCSP's GIS model and attempt was made to relate the carbon sequestration rate with no till to the current SOCP of individual STATSGO map units.

Comparison of the paired no-till conventional-till experimental data in the MRCSP region showed a good relationship between the SOCP under no till and that under conventional till, which can be described by following model (Eq. 2):

$$SOCP_{NT} = 1.39 \ (SOCP_{CT})^{0.899} \ (R^2 = 0.94, n = 15) \tag{Eq. 2}$$

According to this empirical model, about 94 % of the variation in the SOCP under no till can be attributed to the previous SOCP level. If all non-no till croplands in the MRCSP region are converted to no till, soil

carbon sequestration would occur at an average rate of 3.7 Tg/yr, resulting in an increase in cumulative SOCP by 74 Tg by the year 2012 (Table 5.7), i.e. an increase in SOCP by about 14% over the 20-year period between 1992 and 2012. The spatial distribution patterns and hot spots for each state of the MRCSP region are depicted in Figure 5.2.

Note that based on the areal proportion, the annual SOC sink capacity increase by adopting no till in the MRCSP region falls in the range suggested by Lal et al. (1998; 1999) and is comparable with the value claimed by Bruce et al. (1999) and Sperow et al. (2003). Donigian et al. (1997) projected an increase in the SOCP with reduced till and no till using CENTURY model along with agricultural practices and production database. They reported an increase in the SOCP with reduced till and no till by about 15% and 50%, respectively, in comparison with that under moldboard plowing in the Corn Belt, Great Lakes region and eastern Great Plains over a 20-year period between 1990 and 2010. Paustian et al. (1997) reported an increase of no more than 20% in the paired no till-moldboard plowing system. The SOC sequestration rate under specific conservation practice varies with antecedent SOC content and the time scale (Tan and Lal, 2005), suggesting that soils with lower antecedent carbon content have greater carbon sequestration potential upon conversion to no till than those with higher antecedent carbon content, and carbon sequestration rate decreases with time. Soils with a SOCP value greater than 26 kg/m2 in top 30cm depth, as indicated by this model, will lose SOC upon cultivation regardless of conservation practices. This would likely happen in Histosols. For example, this model predicts that cultivation of Histosols leads to the SOC loss of 22 Gg /yr from 32,848 ha of cropland in Indiana, and 24 Gg/yr from 56,353 ha of cropland in Michigan.

Conclusions for Non-Eroded Prime Croplands

Based on analysis of the available data, there are nearly 11 million hectares of non-eroded agricultural lands within the MRCSP region. This non-eroded land and therefore the potential to use these lands for soil carbon sequestration is concentrated in Indiana, Ohio, and Michigan. Given the assumptions and methodology described in this report, the soil carbon potential of non-eroded agricultural lands within this region is approximately 3.7 million tons per year or approximately 74 million tons over a hypothetical 20-year period in which these conservation land use practices were adopted.

Adoption of recommended conservation tillage practices on croplands has a much higher potential for soil organic carbon sequestration (SOC) in croplands of the Midwest region than the national average suggested by the IPCC (Houghton et al., 1997). Considering the fact that SOC sequestration rate with each conservation tillage practice not only depends on previous SOC storage level and time scale, but also tends to decrease with an increase in SOC content, the carbon sequestration potential estimated from current SOC storage may be realistic and achievable. The results, especially coupling with spatial visualization of hotspot distribution, will be helpful to policy-makers to geographically specify the carbon credit trading programs with financial support priority.

Cumulative Carbon Gain/Loss In Non-Eroded Prime
Croplands Under No-Till Between 1992 and 2012

SOC Gain/Loss (Tg)
-0.10 - -0.01
-0.01 - 0.01
0.01 - 0.10
0.10 - 0.20
0.20 - 0.40
0.40 - 0.80
>0.80
State Boundary
County Boundary
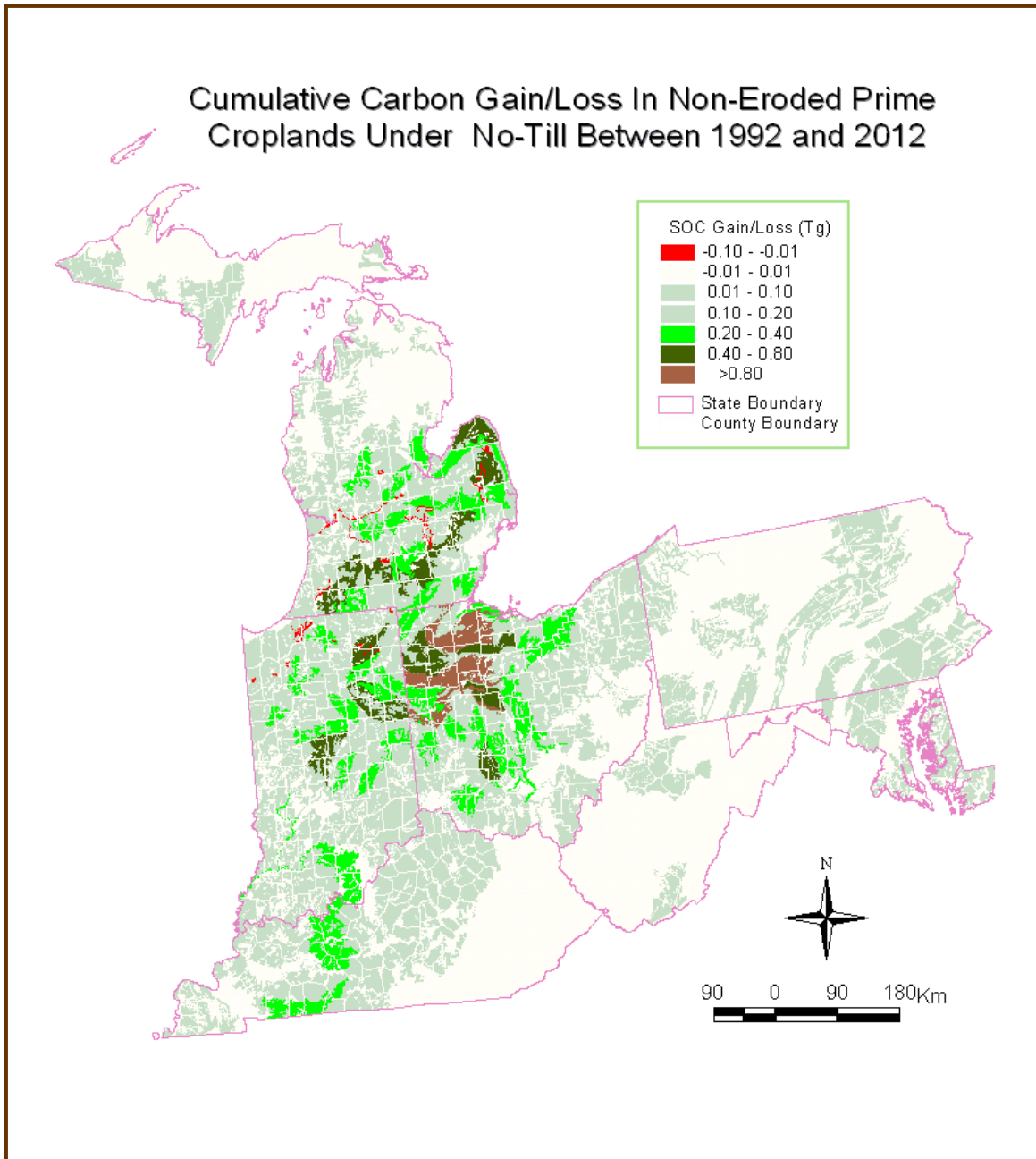
Figure 5.2. **Spatial distribution patterns of cumulative SOC gain/loss (Hot Spots) in non-eroded prime cropland under no-till between 1992 and 2012.**

Eroded Cropland

Eroded cropland is land designated in the 1992 National Land Cover Dataset (NLCD) as cropland in categories such as row crops, small grains, and fallow that is labeled as prime land and eroded in the State Soil Geographic Database (STATSGO). Eroded land is defined as land that has lost 25 to 75% of the surface horizon. Consequently, this investigation is restricted to eroded prime cropland. Severely eroded prime land as defined in the STATSGO database is considered with marginal land, which is covered in a separate report in this MRCSP terrestrial series.

Estimated Area of Eroded Cropland in the MRCSP States

The STATSGO database identifies only the portion of the soil components within a mapping unit as being not-eroded, eroded, or severely eroded, not the actual location. Consequently, an estimate of the area of prime-eroded cropland was made by taking into account the other land use categories in the STATSGO mapping unit, particularly Urban and Pasture. The procedure for this estimate is given in a separate report in the MRCSP terrestrial series titled Methodology. The estimated areas for each state in the MRCSP region for prime-eroded cropland are presented in Table 5.8.

Table 5.8.   The estimated area of the eroded prime cropland (USDA-NRCS, 1991; USGS, 2003).

Eroded Prime Cropland	State							MRCSP Total
	IN	KY	MD	MI	OH	PA	WV	
Area (1000 ha)	933	39	0	80	513	0	0	1,565
% of total area	10.0	0.4	0	0.5	4.8	0	0	2.4

The distribution of eroded, prime cropland, illustrated in Figure 5.3, is concentrated in Indiana, Kentucky and Ohio. The distribution shown in Figure 5.3 is influenced by a difference in the procedures that were used by the various state NRCS offices when the soils were mapped and compiled into the STATSGO data base. Note that the STATSGO data base does not identify any land as being prime and eroded in Maryland, Pennsylvania or West Virginia.

All eroded (and severely eroded) land in these states is classed as non-prime or marginal land (see Table 2.3 in the separate report in this series titled Methodology). Marginal land is considered in a separate report of this MRCSP terrestrial series titled Marginal Land.
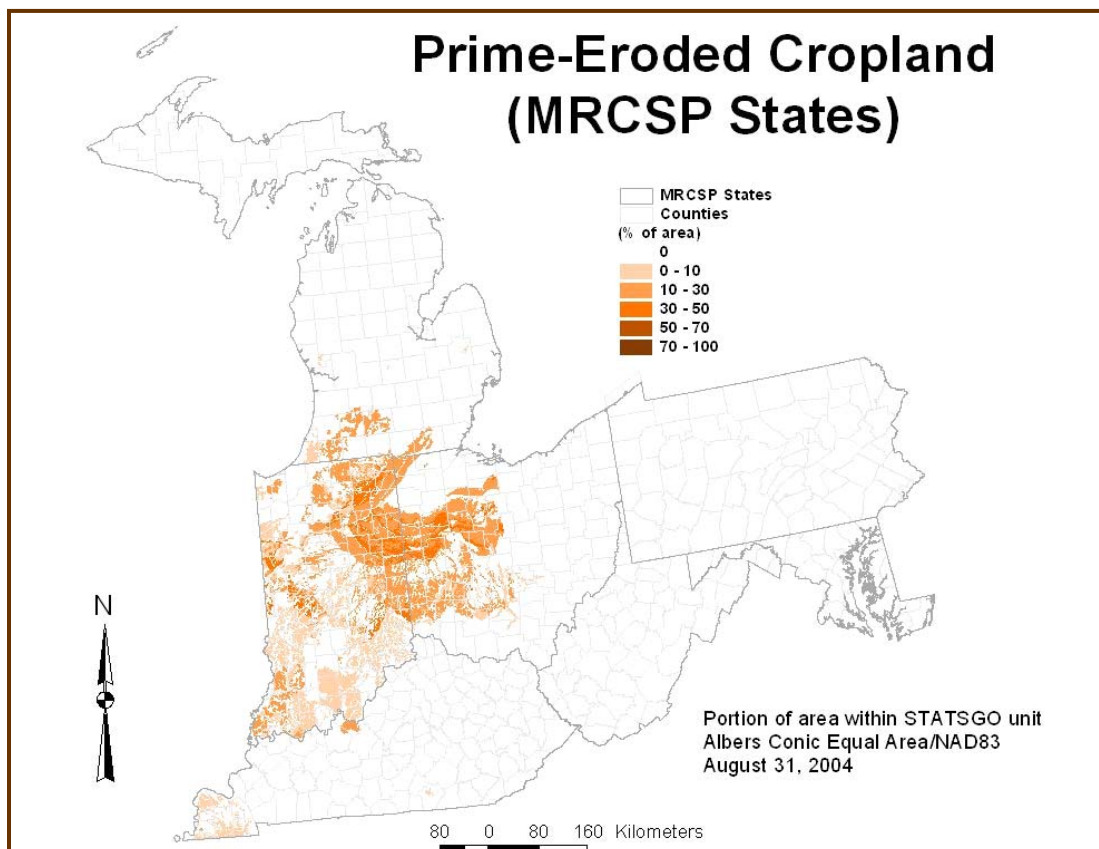
Figure 5.3. Spatial distribution for eroded-prime cropland as a percentage of the STATSGO mapping units in the seven MRCSP states.

Current Soil Organic Carbon (SOC) Pool in Eroded Prime Cropland

Following the procedure addressed in a separate report on Methodology, the current soil organic carbon (SOC) pools for the eroded prime cropland category were calculated. Table 5.9 lists the estimated values for individual states and the MRCSP region.

Table 5.9. Estimated Soil Organic Carbon Storage in the Eroded Prime Cropland.

SOC Pool	State							Total MRCSP
	IN	KY	MD	MI	OH	PA	WV	
Minimum (Tg)	18.15	0.54	—	1.46	11.77	—	—	31.92
Maximum (Tg)	57.54	1.68	—	5.53	32.88	—	—	97.63
Mean (Tg)	36.11	1.08	—	3.18	21.37	—	—	61.74

The minimum and maximum values were calculated using the low and high values in the STATSGO data base for organic matter, bulk density and particle size distribution to obtain the lowest estimate for SOCP and the highest estimate for SOCP for each soil component.

The potential for carbon sequestration in eroded cropland was assessed using two approaches. Both are based on the tenet that good soil conservation management practices will restore eroded land to a higher state of stored carbon.

1. The first approach proceeds from the fact that "eroded cropland" in the STATSGO database is placed in the class as a consequence of field soil scientists' estimates that 25 to 75% of the top soil (rich in organic carbon) has been removed by erosion. Considering an average loss of 50% of the soil organic carbon (SOC), we analyzed the potential for recovery from depleted SOC status based on two different scenarios, as follows. If the land remains in crop production under good management, using conservation practices that stop or adequately limit erosion (conservation tillage or no-till), we assumed that the area could be restored to 60% of its original SOC content (Scenario 1). Under management practices and land set-aside programs that eliminate row cropping and establish permanent grass/legume cover such as that in the Conservation Reserve program (CRP), we assumed that the eroded land could be returned to its original SOC content (Scenario 2). Our estimates are derived from the mean values for soil organic carbon listed in Table 5.2, based on the assumption that those values are 50% of the original, "noneroded" values.

2. A report prepared by Phil Smith et al.(2002) entitled "Quantifying the Change in Greenhouse Gas Emissions due to Natural Resource Conservation Practice Application in Indiana" includes estimates of potential for storing additional carbon in soils when changes are made in cropping systems. The estimates are generated utilizing the Century model (Metheral, et al., 1993). For example in a corn-soybean rotation (the dominant cropping system in the region considered in this section) the following changes in cropping would produce the indicated rates of carbon sequestration:

Change from conventional till (CT) to reduced tillage (RT)	0.35 mg/ha/yr
Change from conventional till (CT) to no-till (NT)	0.50 mg/ha/yr
Change from conventional till (CT) to grass	0.40 mg/ha/yr
Change from conventional till (CT) to grass/legume	1.32 mg/ha/yr
Change from reduced tillage (RT) to conventional till (CT)	-0.15 mg/ha/yr

    We used three of the estimates for carbon change due to change in management to estimate the potential for carbon sequestration in prime eroded cropland. The assumptions in this approach are that erosion is adequately controlled in each case and that these rates are valid estimates for the first 20 years after the change in management is made.

Potential Sequestration in Eroded Prime Cropland

Table 5.10 presents the results of the analysis for the two scenarios under Approach 1, and Table 5.11 presents the results for the analysis under Approach 2. Considering the errors inherent in both land area measurements and the carbon sequestration rates used in these calculations, all of the values have an uncertainty range of approximately plus or minus 50%.

Table 5.10. Estimate of Carbon Sequestration Potential for 20 Years on Prime Eroded Cropland Using Approach I.

Approach	Cumulative Carbon Sequestered (Tg)							Total MRCSP
	IN	KY	MD	MI	OH	PA	WV	
Scenario 1 (Tg C)	7.2	0.2	—	0.6	4.3	—	—	12.3
Scenario 2 (Tg C)	36.1	1.1	—	3.2	21.4	—	—	61.8

Note: Scenario 1 assumes 50% loss due to past erosion and restoring to 60% of former SOC using good practices; Scenario 2 assumes 50% loss due to past erosion and restoring to former SOC using Best Management Practices, i.e. return to grass/legume.

Table 5.11. Estimate of Carbon Sequestration in 20 Years for Prime Eroded Cropland Using Approach II.

Type Conversion from Conventional Till	Cumulative Carbon Sequestered (Tg)							Total MRCSP
	IN	KY	MD	MI	OH	PA	WV	
Reduced Till (0.35 Mg/ha/yr)	6.5	0.3	—	0.6	3.6	—	—	11.0
No Till (0.50 Mg/ha/yr)	9.3	0.4	—	0.8	5.1	—	—	15.6
Grass/Legume (1.32 Mg/ha/yr)	24.6	1.0	—	2.1	13.6	—	—	41.3

Scenario 1 is based on a shift to conservation practices easily reached without major shifts in current practices. It requires only conversion to no-till practices already in use on a significant part of the cropland. Scenario 2 is based on a shift to grass-legume cover, and requires a shift out of row crop agriculture. Although a period of 20 years is probably an optimistic estimate of time needed to reach 60% and 100% restoration of carbon content in Scenarios 1 and 2, respectively, 30 years is expected to be enough time; the rate tends to be steepest in the early part of the cycle and the approach to the new equilibrium value is asymptotic. Approach II resulted in somewhat lower estimates of carbon sequestration potential in 20 years shown in Table 5.11. These are based on rates of carbon sequestration resulting from changes in management modeled in the Century model (Smith et al, 2002). The total potential for carbon sequestration in the eroded cropland in the region is 11–41 Tg which is similar to the total estimated in Table 5.10 (12-62 Tg).

The estimates in scenario 1 of the first approach gives an estimate of 12.3 Tg and the estimate based on a conversion from conventional tillage to reduced tillage in Approach 2 gives a similar estimate of 11 Tg. In both approaches the maximum sequestration is in the range of 41 to 61 Tg. This would require the eroded prime cropland to be converted to grassland that includes legumes in the mixture.

Identification of Areas for Further Conservation Practices

Indiana and Ohio are the states in the region with large areas of cropland that have been identified as prime eroded land. The distribution of areas with significant potential for carbon sequestration by restoration of eroded cropland is shown in Figure 5.4. The potential for sequestration shown in this figure is calculated by multiplying the rate of sequestration assumed for conversion from conventional tillage to no-till (0.5 Mg/ha/yr) by 20 years and by the fraction of the land area in the class. As expected those

regions with a significant area of prime farm land in the eroded class appear as the regions with the most potential for carbon sequestration.
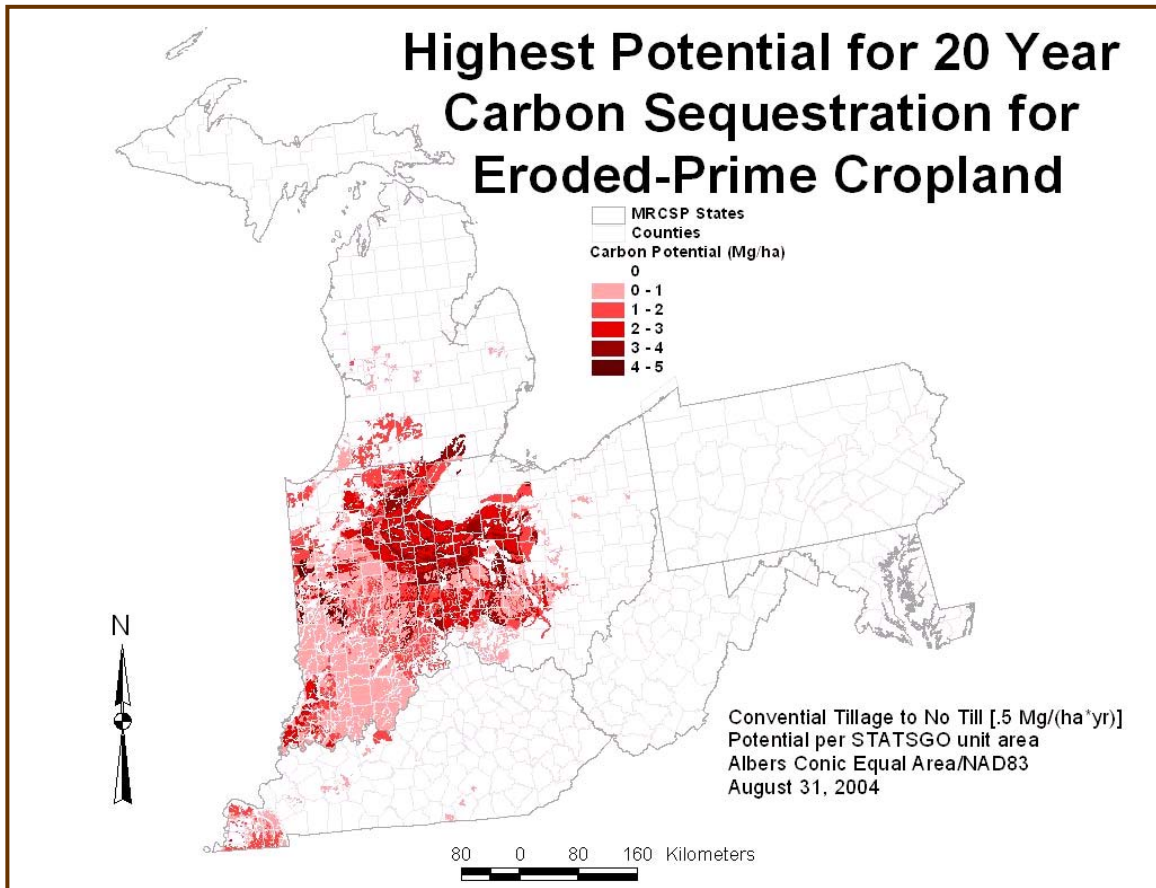
Figure 5.4. The distribution of areas with significant potential for carbon sequestration by restoration of eroded cropland. (The potential represents the average rate for the STATSGO unit.)

Strategies and Policies to Achieve Potential in Eroded Cropland

To achieve maximum sequestration in eroded cropland a policy would need to be in place that encouraged conversion to CRP-type cover (grass/legume).This would require payment to the operator to compensate for lost crop revenue. A lesser degree of sequestration can be achieved by conversion to no-till cropping systems, which are currently encouraged by the farm policy, but could be made more attractive by subsidy or direct payment. In the states with most of the eroded cropland IN, OH, and KY, approximately 50% of the cropland is already in conservation tillage systems. Therefore the carbon storage gains available by conversion to conservation tillage are expected to be relatively small.

Marginal Agricultural Lands

Agricultural land in general includes cropland and pastureland, which were derived from the sub-class 82 (row crops), 83 (small grains), 84 (fallow), and 81 (pasture/hay) in the USGS National Land Cover/Land Cover Database (NLCD) of 1992. Agricultural land use was further categorized as prime and non-prime, eroded, severely-eroded, and non-eroded crop- and pasture-land by overlaying the NLCD image with a State Soil Geographic (STATSGO) map. Marginal agricultural land in this study was defined as all land within the MRCSP region categorized as non-eroded and severely eroded marginal cropland and all marginal pastureland.

Barren land and severely eroded prime crop- and pasture-land are also included in this study as part of marginal agricultural land. However, the eroded marginal (non-prime) cropland was excluded in this study and is covered in a previous section of this report titled Eroded Cropland.

Also, no adjustments were made for mine land or for wetlands as described in those sections of this report. Therefore, some overlap may occur between marginal agricultural land and mine land and wetlands described later in this report. The implications of using the adjusted land use data were very small, affecting only four states. Maximum adjustment in total crop and pasture land was 0.8%.

Carbon Pools in a Forest Ecosystem

Carbon in a forest ecosystem was divided into four carbon pools, namely above-ground tree biomass, root biomass, forest floor litter, and soil organic carbon (SOC). The above ground biomass includes all above-ground woody material (dead or living). Root biomass mainly consists of coarse roots and stumps. Forest floor refers to the distinct layer of dead and decaying plant material that accumulates on the soil surface (i.e. organic layer). Soil organic carbon pool includes all organic material and fine roots in mineral soils. Potential afforestation scenarios have differences in forest species selection and management practices. For the purpose of this study, two tree classes (conifer and deciduous) and two management schemes (permanent forest without harvesting and short-rotation harvesting every 20 years) were distinguished to assess the carbon sequestration potential after afforestation (Table 5.12). In the long-term afforestation, the forest stand was assumed to be "permanent" (> 50 years) yielding a stock of carbon in standing trees. In the short-rotation trees would be harvested every 20 years for timber, pulp, or other uses. A 20-year rotation was chosen because our model predicted that tree growth rates would decline afterwards (see the following section). This period also allowed us to use the same study-length used by other partners in the MRCSP study. In practice, however, the time to harvest will depend on the tree growth curve, the harvest method and the purpose for which the harvest is intended.

Table 5.12. Scenarios of afforestation following use as pasture or crop land.

Forest Species	Management Approach	Carbon Pool Location
Conifer	Permanent forest without harvesting	Above-ground Biomass
		Root (stump + coarse roots)
		Forest floor (organic layer)
		Soil organic carbon
	Short-rotation with harvesting every 20 years	Above-ground Biomass
		Root (stump + coarse roots)
		Forest floor (organic layer)
		Soil organic carbon
Deciduous	Permanent forest without harvesting	Above-ground Biomass
		Root (stump + coarse roots)
		Forest floor (organic layer)
		Soil organic carbon
	Short-rotation with harvesting every 20 years	Above-ground Biomass
		Root (stump + coarse roots)
		Forest floor (organic layer)
		Soil organic carbon

Above-Ground Biomass Growth Simulation

A simplified growth model proposed by Marland and Marland (1992) was used to simulate above ground biomass growth, in which carbon accumulates linearly until half of the maximum yield (*Eq. 1*) is reached and slows gradually to reach the maximum yield asymptotically (*Eq. 2*).

$$C_{t+1} = C_t + G \tag{1}$$

when $C_t \le C_{max}/2$

$$C_{t+1} = C_t + G * \frac{C_{max} - C_t}{0.5 * C_{max}} \tag{2}$$

when $C_t > C_{max}/2$

where C_{t+1} and C_t are total above-ground biomass carbon (Mg/ha, Mg = 10^6 g) at year $t+1$ and t, respectively. C_{max} is the maximum yield in carbon content (Mg/ha) a site can potentially support. G represents an optimum growth rate (Mg/ha/yr) in this region.

The values of G and C_{max} were derived from literature reviews. The tree growth rate used/observed in this region (or adjacent area) varies from 2.0 (e.g. Baral and Guha, 2004) to 5.6 Mg/ha/yr (e.g. Graham et al., 1992), largely depending on tree species, rotation length and managements. An average of 3.2 Mg/ha/yr for G and a maximum yield of 160 Mg/ha (for C_{max}) were considered appropriate for a "good site" in the

MRCSP region (Baral and Guha, 2004; Graham et al., 1992; Hall et al., 1991; Marland and Marland, 1992). The same growth rate and maximum yield were assumed in this study for both coniferous and deciduous forest because research indicates that variations of these parameters of the same forest type under different management can be as large as that between the two types (Day Jr. et al., 1996; Deckmyn et al., 2004; Proe et al., 2002). A general above-ground tree biomass growth model based on the proposed growth rate and yield is illustrated in Figure 5.5.
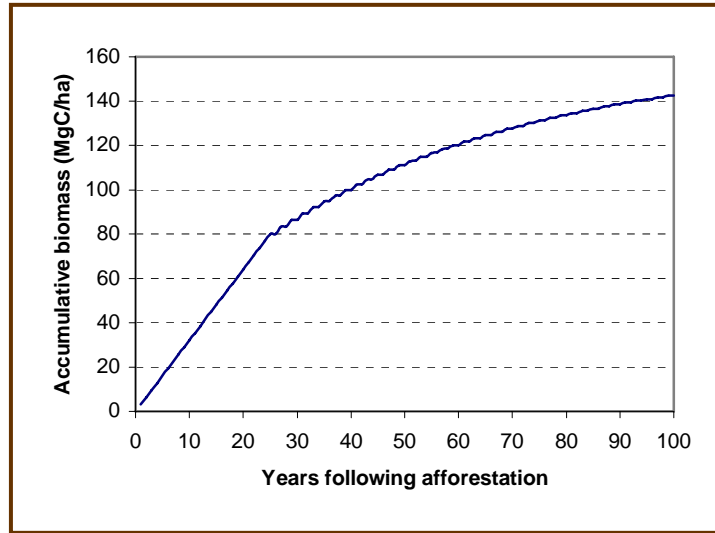
Figure 5.5. General tree growth model with a maximum yield of 160 Mg/ha, and a growth rate of 3.2 Mg/ha/yr.

Note: This maximum yield and rate are considered suitable for a "good" site in the MRCSP region (modified from Marland and Marland, 1992).

Estimation of Root Biomass Growth

Root biomass accumulation (R_{biom}, Eq. 3) was estimated as a function of above-ground biomass growth (C_{t+1}, in Eq. 1 or Eq. 2) and a root/shoot ratio (*RSR*). Mean *RSR* values of 0.22 and 0.21 were used for conifer and deciduous (Table 5.13), respectively, based on the literature.

$$R_{biom} = C_{t+1} * RSR \qquad \text{(Mg/ha)} \qquad (3)$$

Table 5.13. Forest root/shoot ratio (RSR) for coniferous and deciduous forests.

Species	Root/Shoot Ratio (RSR)	References
Conifer	0.18 - 0.26 (mean 0.22)	(Wang et al., 2000), (Laclau, 2003), (Grace et al., 2004)
Deciduous	0.19 - 0.25 (mean 0.21)	

Changes of Carbon in Forest Floor (Litter Pool)

A model proposed by Smith and Heath (2002) was used to simulate change of carbon in forest floor following afforestation. Smith and Heath (2002) developed a forest floor carbon simulation model according to region and forest type after summarizing a large set of published values of forest floor mass across the United States. There are two parts involved in this model. The first part is the net accumulation of forest floor when agricultural lands are converted to forest lands (Eq. 4). The second part is losses of litter when decay exceeds leaf fall (Eq. 5), which happens when forest harvest occurs due to the fact that less new organic material is added than what is being decomposed from previous litter accumulations.

$$FFC = \frac{A * age}{B + age} \tag{4}$$

$$RFFC = C * e^{-(\frac{age}{D})} \tag{5}$$

Where *FFC* is the forest floor carbon accumulation (Mg/ha); *RFFC* is the residual forest floor carbon (Mg/ha); A, B, C, and D are coefficients that are associated with location characteristics and forest type (Table 5.14); *age* is the stand age in years since forest disturbance or afforestation or since reforestation after harvesting.

Table 5.14. Coefficients for calculating forest floor carbon accumulations (FFC) and residual forest floor (RFFC) in the northern U.S. (Data source: Smith and Heath, 2002)

Forest types[1]	Accumulation		Residue	
	A	B	C	D
Pine	19.1	25.6	13.8	8.4
Spruce, fir, hemlock	62.9	57.8	33.7	8.4
Mixed conifer-hardwood	65.0	79.5	29.7	8.4
Aspen, birch	18.4	53.7	10.2	9.2
Maple, beech, birch	50.4	54.7	27.7	9.2
Mixed hardwood, oak	24.9	134.2	8.2	9.2

[1] Scientific names: Pine – *Pinus spp*; Spruce – *Picea spp*; Fir – *Abies spp*; Hemlock – *Tsuga spp*; Aspen – *Populus spp*; Beech – *Fagus spp*; Birch – *Betula spp*; Maple – *Acer spp*; Oak – *Quercus spp*.

Model results show that accumulation of carbon in the forest floor of coniferous species significantly exceeds that in hardwood species (Smith and Heath, 2002). The leaves of deciduous trees are being decomposed much faster than the needles of coniferous trees. The reason for this is probably the more recalcitrant nature of the organic tissues making up coniferous needles, as well as the more acidic nature of the needles themselves and the soil below the coniferous forest. Highly acidic soil ecosystems have lower biological activity and therefore inhibit the decomposition process. The patterns of forest floor accumulation for "permanent" and short-rotation afforestation are shown in Figure 5.6 and Figure 5.7, respectively.
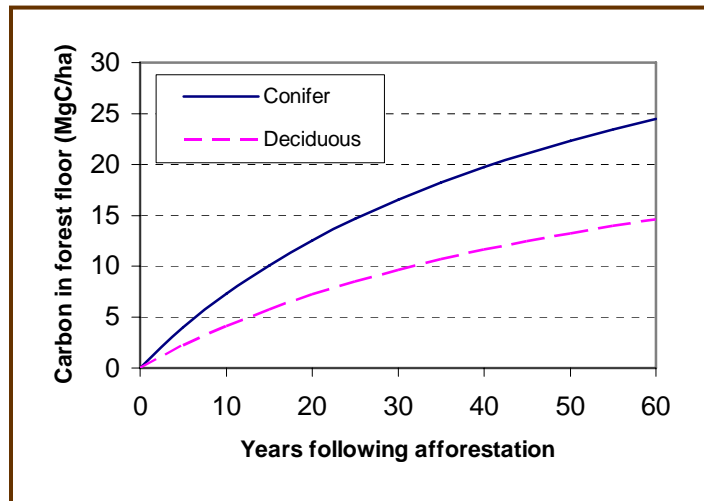
Figure 5.6.   Patterns of carbon accumulation in forest floor following a "permanent" afforestation.

Note: The curve for conifer is plotted from the average of FFC values calculated for pine, spruce, and mixed conifer-hardwood (Table 3). The data for deciduous are the means of FFC values for aspen, maple and mixed-hardwood. (Data source: Smith and Heath, 2002)
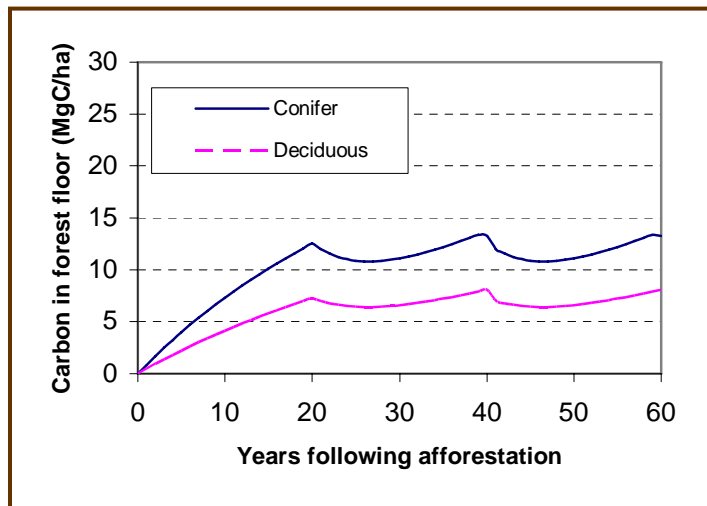
Figure 5.7.   Patterns of carbon accumulation in forest floor following a short-rotation of afforestation (20 years).

Note: During the first 20 years, only carbon accumulations (FFC) are calculated. When harvesting occurs in every 20 years, the residue decay (RFFC) is also added to the calculation. (Data source: Smith and Heath, 2002).

Changes in Soil Organic Carbon

It is well recognized that soils will become a great sink of carbon following afforestation in the long term (Paul et al., 2002; Post and Kwon, 2000). However, findings vary greatly in young forest stands, with soil carbon either increasing (e.g. Garten Jr., 2002) or decreasing (e.g. Paul et al., 2002; Vesterdal et al., 2002). A review of many studies showed that the most important factor affecting changes in soil carbon is previous land use (Paul et al., 2002).

Soils with low initial organic carbon content generally exhibit gains of carbon following afforestation (e.g. Bouwman and Leemans, 1995; Garten Jr., 2002), while other soils such as pasture land (usually with high initial SOC content) generally show an initial decrease in SOC in first 5-10 years following afforestation, which then gradually recovers to the previous level in about 10-30 years (e.g. Paul et al., 2002; Vesterdal et al., 2002).

Given the fact that the amount of soil organic carbon changes are generally small (<10% of total NPP) compared with accumulation of carbon in tree biomass (Paul et al., 2002), the same soil carbon accumulation patterns were applied for all afforestation scenarios.

Although a consistent rate of SOC change was assumed in some studies (e.g. Heath et al., 2002), many others observed a non-linear relationship between SOC changes and time following afforestation (Post and Kwon, 2000; Paul et al., 2002; 2003). Based on simulations of forest growth models and review of literature, Paul et al. (2003) discovered a general trend in SOC changes after afforestation of a pastureland. According to the model, SOC was predicted to decrease at an average rate of -0.79 Mg C/ha/yr during the first 10 years following afforestation, and to increase at a rate of 0.46 Mg C/ha/yr from 10-40 years. The average rate of SOC change after 40 years was predicted to be 0.06 Mg C/ha/yr. The initial decrease of SOC after afforestation was mainly due to the soil disturbance by site-preparation and low organic carbon input from a young forest stand (Paul et al. 2002, 2003). For the purpose of this study, we argue that the initial losses of SOC following afforestation can be prevented if some best management practices, such as maintaining groundcover (crops/grass) between trees and minimizing soil disturbance, are adopted. In addition, low SOC contents in MagLand would normally lead to an increase of SOC after afforestation, as was the evidence in the study of Garter Jr. (2002). We therefore modified the Paul's model by substituting the initial SOC change rate of -0.79 with a value of 0.70 Mg C/ha/yr for a period of the first decade of afforestation. The new SOC change rate was adopted from a parameter used in a U.S. forest carbon budget model for estimating soil carbon dynamics due to landuse changes (Heath et al, 2002). This substitution is also supported by the work of Garten Jr. (2002) in the Southeastern U.S., who observed an average SOC increase of 0.89 Mg C/ha/yr during the first decade after establishment. The SOC accumulation rates in our model after the first decade of afforestation were the same as those in the Paul et al. (2003) model. The modified pattern of soil organic carbon accumulation pattern following afforestation is shown in Figure 5.8.
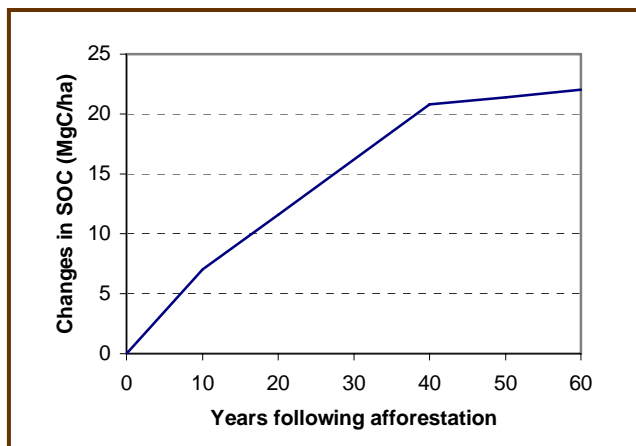
Figure 5.8.   Pattern of soil organic carbon changes following afforestation.

Modified from a model of Paul et al. (2003).

Tree Growth Modifier

In the general above-ground biomass simulation model, tree growth is considered to be uniform throughout the MRCSP region. In reality, tree growth varies depending on species, climate, site qualities, and management. The effect of species and management (i.e. rotation length) was incorporated in the tree growth model by applying different growth rates to young and mature forest stands (Eq. 1 and Eq. 2). To address the impacts of climate and site factors, we developed a growth modifier, which includes three independent components: temperature (Ftemp), precipitation (Fprcp) and soil quality (Fsoil). Each of these components was scaled from zero to one. The lower the value, the more serious limitation that particular factor could impose. $F_{temp,}$ (*Eq. 6*) and $F_{prcp,}$ (*Eq. 7*) were calculated based on the relationship between net primary productivity (NPP) and mean annual temperature (^{o}C) and the relationship between NPP and total annual precipitation (mm), respectively, as in Lieth (1975).

$$F_{temp} = \frac{1 + e^{1.315 - 0.0119 T_{base}}}{1 + e^{1.315 - 0.0119 T}} \tag{6}$$

$$F_{prcp} = \frac{1 - e^{-0.000664 p}}{1 - e^{-0.000664 p_{base}}} \tag{7}$$

where T_{base} and P_{base} are mean annual temperature (°C) and total annual precipitation (mm), respectively, in a location where the optimum growth rate is observed.

The site-quality factor was derived from a "Site-Index" in the STATSGO database. Site index is the total height to which dominant trees of a given species will grow on a given site at some predetermined age, usually 50 years in the Eastern U.S. (USDA-NRCS, 1995). Foresters use the "Site Index" to obtain an estimate of forest productivity. Factors affecting site index include topsoil depth, soil texture, limiting layers, fertility, and internal drainage. Site index reflects the combined effect of all environmental factors and is therefore a good index of forest stand productivity. STATSGO includes the site index for dominant tree species for each STATSGO component.

Because site index values vary depending on species, and because not all species are listed in every STATSGO mapping unit, a generic site quality modifier was built based on listed site index values. For each STATSGO component within a mapping unit, the maximum value of site index (potentially highest yield) was selected from different tree species. One site index for the STATSGO mapping unit was then calculated as an area weighted average of all components in that STATSGO unit ($\sum$ fraction of component area times the max site index of component). Subsequently, the weighted site indices for each mapping unit were ranked for the entire region. The assumption was made that sites in the top 10 percent site index were excellent for tree growth. The 90 percentile of the ranked site indices was taken as a base value (SI_{base}), and the ratio of a mapunit-site index (SI) to SI_{base} was calculated as a site-quality factor (F_{soil}, Eq. 8). A minimum function was applied to set the range of F_{soil} to be between 0 and 1. A map of site quality modifier for the MRCSP region is shown in Figure 5.9.

$$F_{soil} = \min\{\frac{SI}{SI_{base}}, \quad 1\} \tag{8}$$

The effects of these factors were calculated independently, and Liebig's law of the Minimum was applied to derive a general modifying factor (F_{mput}, Eq. 9) for each STATSGO mapping unit using a minimum function (min). This method assumes there are no interactions between factors of average annual temperature, average annual precipitation, and site index, and that forest growth is only affected by the most limiting factor and not by the other two.

$$F_{mput} = \min\{F_{temp}, F_{prcp}, F_{soil}\} \tag{9}$$
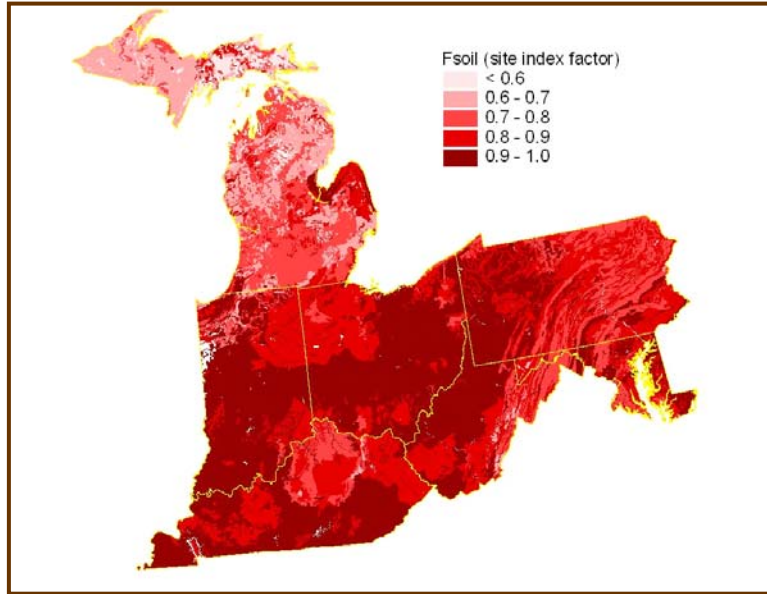
Figure 5.9.   A map of tree growth modifier derived from site indices within the STATSGO database.

Estimation of Carbon Pool Changes for Each STATSGO Mapping Unit

The aboveground biomass for each STATSGO mapping unit was estimated using *Eq. 1* and *Eq. 2* with a site-specific tree growth rate (G_{mput}) and a site-specific maximum yield (C_{max_mput}), which were adjusted from the respective optimum values of G and C_{max} by multiplying a tree growth modifier, F_{mput} (*Eq. 10* and *Eq. 11*). The values of the constants (i.e. the optimum tree growth rate and the maximum yield) were discussed earlier.

$$G_{mput} = 3.2 * F_{mput} \qquad \text{(Mg/ha/yr)} \qquad (10)$$

$$C_{max\_mput} = 160 * F_{mput} \qquad \text{(MgC/ha)} \qquad (11)$$

Assuming that a lower tree growth rate would also result in lower forest floor and soil organic carbon accumulations, changes in forest floor (FLR_{mput}, *Eq.12*) and soil organic carbon (SOC_{mput}, *Eq.13*) for each mapping unit were therefore modified accordingly. The calculations of *FFC* and *SOC* were discussed in sections earlier.

$$FLR_{mput} = FFC * F_{mput} \qquad \text{(Mg/ha/yr)} \qquad (12)$$

$$SOC_{mput} = SOC * F_{mput} \qquad \text{(Mg/ha/yr)} \qquad (13)$$

Results

Table 5.15 lists the abbreviations used in the tables, figures, and discussion in this section.

Table 5.15. Abbreviations used in the discussion of results.

Abbreviation	Descriptions	Unit
MRCSP	Midwest regional carbon sequestration partnership	
MagLand	Marginal agricultural land	
MGNL%	Percentage of marginal land over all land area	%
AREA	Total area of marginal land in thousand (103) hectare	Kha
CSP	Carbon sequestration potential	
BIOM	Above-ground biomass in carbon	Tg C for CSP capacity;
ROOT / RT	Root biomass carbon	
FLOOR / FLR	Forest floor carbon	
SOIL	Soil organic carbon	kgC/ha/yr for CSP rates
TOTAL / TTL	Total terrestrial carbon (sum of BIOM, RT, FLR, and SOIL)	
W/O_HVST	A "permanent" forest stand without harvesting	
W_HVST	Short-rotation afforestation with harvesting every 20 years	
CNF20 / 50	Afforestation of coniferous forest over 20- or 50-years, respectively	
DCD20 / 50	Afforestation of deciduous forest over 20- or 50-years, respectively	

Marginal Agricultural Land in the MRCSP Region

Figure 5.10 shows the spatial distribution of marginal agricultural land (MagLand) in the MRCSP region. The total area of MagLand is 6.5 million hectares (Mha), representing about 10% of the total land area or about 24% of the total agricultural land in this region (Table 5-16). Largest concentrations of MagLand are located in the southern part of Michigan, along the borders between Indiana, Ohio and Kentucky, the Allegheny plateau across the borders of Ohio, West Virginia, and Pennsylvania, and the Northern Appalachian Ridges and Valleys of Pennsylvania. Indiana, Ohio, Pennsylvania, Michigan and Kentucky have similar large total amounts of MagLand (1 ~ 1.2 Mha, see Table 5.16), whereas Maryland and West Virginia have smaller areas (0.2 ~ 0.5 Mha). The proportions of MagLand to the total land area in each state are quite similar (about 10%). However, the percentage of MagLand over total agricultural land varies dramatically from state to state (ranging from 18% to about 60%), suggesting that some states (e.g. West Virginia, 60%) would loose a significant amount of agricultural land if all MagLand were converted to forest. The social implications of a policy to stimulate such afforestation should be carefully studied before it is implemented.
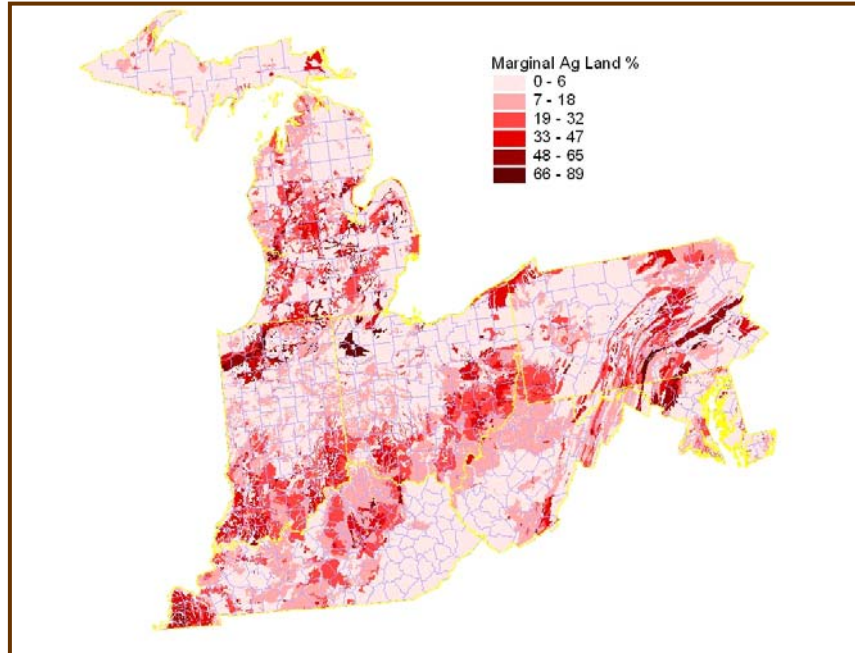
Figure 5.10. **Distribution of marginal agricultural land (MagLand) in the MRCSP region. The legend is percentage of MagLand over total land area within a STATSGO mapping unit.**

Table 5.16. Area of marginal agricultural land in thousands of hectares (Kha) and as percentage of total and agricultural land for each State.

State	Marginal Agricultural Land		
	Area (Kha)	% of Total Land	% of Agricultural Land
IN	1238	13.2	17.9
KY	1012	9.7	28.5
MD	246	9.6	25.0
MI	1230	8.2	24.7
OH	1156	10.8	18.1
PA	1181	10.1	36.6
WV	481	7.7	59.7
Sum / Mean	**6543**	**9.9**[*]	**24.4**[*]

[*] Mean weighted by total land area of each state.

The results show that proportions of MagLand to the total land area in each state are quite similar (about 10%). However, the percentage of MagLand over total agricultural land varies dramatically from state to state (ranging from 18% to about 60%), suggesting that some states (e.g., West Virginia, 60%) would loose a significant amount of agricultural land if all MagLand were converted to forest. The social implications of a policy to stimulate such afforestation should be carefully studied before it is implemented.

Potential Carbon Sequestration Capacity in the MRCSP Region

Total potential carbon sequestration capacity of afforestation of MagLand in the MRCSP region was estimated to be 539 Tg of carbon with coniferous and 508 Tg of carbon with deciduous forest over a 20-year period (Table 5.17). The CSP are 1025 - 1080 Tg C over a 50-year period without harvesting wood. If forest is harvested every 20 years, more carbon is sequestered in a 50-year period then without harvesting, with a total of 1205 and 1173 Tg of carbon accumulated in coniferous and deciduous forest, respectively. Assuming many existing forests are older than 50 years in the MRCSP region, this finding compares well with estimates of carbon sequestered in mature forest in the region. Birdsey and Lewis (2003) estimated that the average storage of carbon in mature forests in the MRCSP region ranged from 170 Mg/ha to 228 Mg/ha, which translates into a total of 1113 to 1494 Tg of carbon that could eventually be sequestered by afforestation of all MagLand in the area. The advantage of short-rotation over a permanent forest on carbon sequestration is mainly due to the fast tree growth rate in a young forest stand.

Table 5.17. Potential carbon sequestration capacity of afforestation of marginal agricultural land with coniferous or deciduous forest over 20- or 50-year periods under two management scenarios.

Forest Type MRCSP State	Potential Capacity (Tg)		
	20 Years	50 Years	
		W/O_HVST[1]	W_HVST[2]
Conifers			
IN	105.3	210.9	235.4
KY	91.6	183.4	204.7
MD	20.8	41.5	46.4
MI	87.9	176.1	196.6
OH	95.3	190.8	213.0
PA	96.8	193.7	216.3
WV	41.6	83.2	92.9
Total	**539.3**	**1079.6**	**1205.3**
Deciduous			
IN	99.3	200.3	229.2
KY	86.3	174.2	199.3
MD	19.6	39.5	45.2
MI	82.9	167.2	191.4
OH	89.8	181.2	207.4
PA	91.2	184.0	210.6
WV	39.2	79.0	90.4
Total	**508.2**	**1025.4**	**1173.3**

[1] W/O_HVST – without harvesting

[2] W_HVST – with harvesting every 20 years

Overall, Indiana has the greatest potential for carbon sequestration by afforestation of marginal agricultural lands, followed by Pennsylvania, Ohio, Kentucky, and Michigan. West Virginia and Maryland have a significantly lower carbon sequestration capacity, mainly because there is much less MagLand available to be converted to forest than in the other states (Table 5.17). It should be noticed that this calculation was based on the assumption that all MagLand would be converted to forestland. No economic and social factors are considered here.

Potential Carbon Sequestration Rates

One way to evaluate the effectiveness of a technique for carbon sequestration is to measure how much carbon can be sequestered per unit area over a certain period of time, i.e. carbon sequestration rate (CSR). The average carbon sequestration rate by afforestation of MagLand was estimated to be 3884 - 4121 kg/ha/yr over a 20-year period, 3134 - 3300 kg/ha/yr over a 50-year period without harvesting, and 3586 - 3684 kg/ha/yr over 50 years with a 20-year rotation (Table 5.18). The magnitude of CSR in this study falls in the middle of a range of CSRs compiled from many studies in the United States (2000 – 10000 Kg C/ha/yr, Richards and Stokes, 2004). A slight drop in CSR for a 50-year short-rotation scenario, when compared with that for the initial 20-year period, is the result of carbon losses from the net decomposition of the forest floor immediately following harvesting and a slow soil carbon accumulation when SOC approaches a new equilibrium after 20 years. A lower CSR for a 50-year permanent forest scenario is mainly due to the decline of tree growth rate when a forest is approaching maturity. This finding is consistent with the results reported by Birdsey and Lewis (2003), who estimated the average annual change of carbon stock of a relatively "mature" forest in Pennsylvania to be only about 500 kg/ha/yr during the period of 1987-1997 (data are calculated from tables in Appendix 5 of Birdsey and Lewis, 2003).

The spatial pattern of carbon sequestration rates following afforestation of MagLand is shown in Figure 5.11. The rates are generally high in the southern part of the MRCSP region and gradually decline northward across the region because of changes in climate (i.e. temperature and precipitation). Site quality (mainly soil properties) also added spatial variability within each climate zone.

Forest Carbon Pool Partitioning

Among four carbon pools in a forest ecosystem, carbon is primarily stored in above-ground tree biomass, which accounts for about two thirds of total carbon sequestration potential (Table 5.19). The other one third of carbon capacity is made up of approximately equal proportions of carbon in root, forest floor, and soil organic carbon pools. During the first 20 years, we estimated that a total of about 2555 kg of carbon can be sequestered per hectare per year in above-ground tree biomass under both coniferous and deciduous forest. This is within a range of growth rates found in other studies. Updegraff et al., (2004) found that the yields of a short rotation plantation of hybrid poplar (*Populus spp*.) in Minnesota ranged 1800 – 3100 kg C/ha/yr. Wang et al. (2000) observed a growth rate of 2377 kg/ha/yr of carbon for a 35-year-old paper birch (*Betula papyrifera*) in Canada, while Day Jr. et al. (1996) estimated that a Mexican mangrove forest accumulated carbon on average of 2850 kg/ha/yr.

Table 5.18. Potential carbon sequestration rates by afforestation of marginal agricultural land with coniferous or deciduous forest over 20- or 50-year periods under two management scenarios.

Forest Type MRCSP State	Potential Sequestration Rate (Kg C/ha/yr))		
		50 Years	
	20 Years	W/O_HVST[1]	W_HVST[2]
Conifers			
IN	4254	3407	3803
KY	4526	3624	4046
MD	4227	3385	3779
MI	3576	2863	3197
OH	4124	3302	3687
PA	4097	3281	3663
WV	4319	3458	3861
Average	4121	3300	3684
Deciduous	4009	3236	3702
IN	4266	3442	3939
KY	3983	3215	3678
MD	3370	2719	3112
MI	3887	3137	3589
OH	3861	3116	3566
PA	4070	3284	3758
WV	3884	3134	3586
Average	4009	3236	3702

[1] W/O_HVST – without harvesting

[2] W_HVST – with harvesting every 20 years
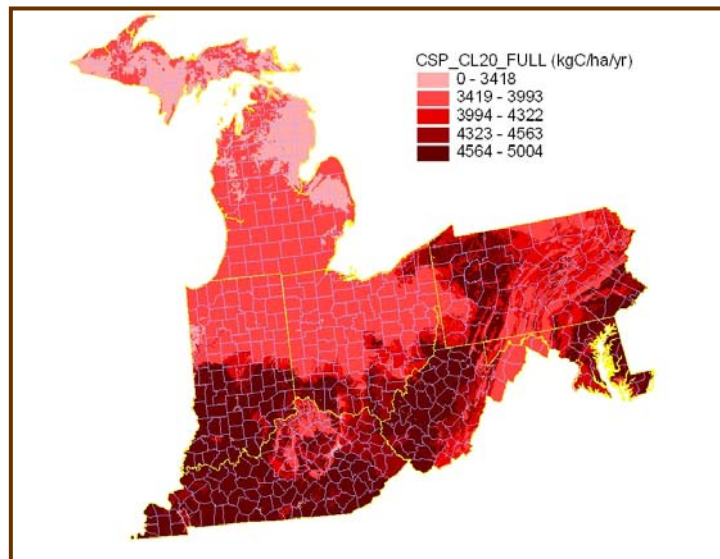
Figure 5.11. Spatial variability of average carbon sequestration rates (kg carbon per hectare per year) in MRCSP region under a coniferous forest over a 20-year period.

Table 5.19. Forest carbon pool partitioning and effects of harvesting on carbon accumulations following afforestation of coniferous and deciduous forest

Forest Type Carbon pools	Carbon Partitioning (kg C/ha/yr		
	20-years	50 Years	
		W/O_HVST[1]	W_HVST[2]
Conifers			
BIOM	2555	2094	2555
ROOT	562	461	562
FLOOR	501	356	177
SOIL	503	390	390
Total	**4121**	**3300**	**3684**
Deciduous			
BIOM	2555	2094	2555
ROOT	537	440	537
FLOOR	289	211	105
SOIL	503	390	390
Total	**3884**	**3134**	**3586**

[1] W/O_HVST – without harvesting

[2] W_HVST – with harvesting every 20 years

Root biomass was predicted to be between 537 – 562 Kg C/ha/yr (or about 14% of the total CSP) over 20 years, which is similar to the observation made by Laclau (2003) under a 20-year-old pine stand (614 Kg C/ha/yr). During the first 20-year period following afforestation, forest floor accumulates 289 - 501 kg/ha/yr (or 7 – 12% of the total CSP) of carbon. A low forest floor accumulation under deciduous forest is primarily due to the fast decomposition rate of deciduous leaf materials. Vesterdal et al. (2002) also observed that forest floors in a spruce stand (conifers) sequestered carbon at a significantly higher rate (360 kg/ha/yr) than in an oak (deciduous) stand (80 kg/ha/yr) over 30 years in Denmark.

In our study, soils were estimated to gain 503 Kg C/ha/yr, which accounts about 10 ~ 12% of the total carbon sequestered during the first 20 years following afforestation. The soil carbon sequestration rate is relatively high compared with other studies. Paul et al. (2002) reviewed 43 published studies on 204 sites worldwide and found that the average change in soil carbon (<30 cm) following afforestation was about 141 Kg C/ha/yr. Post and Kwon (2000) found an average SOC sequestration rate of 340 Kg C/ha/yr in 18 studies in the U.S. The relatively high soil carbon sequestration rate in this study is probably due to our assumptions of low initial soil carbon content in marginal agricultural land (crop + pasture) and limited soil disturbance during plantation and harvesting practices, both of which would result in an immediate soil carbon increase after afforestation. The SOC increase rates may have been underestimated in some studies using long-term average values in the reviews by Paul et al. and Post and Kwon.

The carbon partitioning among carbon pools after 50-year afforestation has a very similar pattern as that during the first twenty years (Table 5.19).

Effects of Forest Species and Harvesting

Our results indicate small differences in carbon sequestration potential between coniferous and deciduous forests, with the former sequestering slightly more carbon than the latter in all scenarios (Table 5.19). Carbon pool partitioning suggests that the major difference between the two forest types come from the carbon accumulation in forest floors and root biomass. Aboveground biomass production is the same for both forest types because the same tree growth rate was applied. For the same reason, no differences are found in SOC, as is supported by the work of Vesterdal et al. (2002). The effect of species on total ecosystem carbon is subject to great uncertainty, as observed in several studies. For example, Moulton and Richards (1990) found that mixed hardwoods (oak) would sequester more carbon than mixed softwoods (pine) forest in the Corn Belt. However, in the same study, they also reported that some coniferous species (e.g., Norway spruce) would sequester more carbon (8.20 – 10.44 Mg C/ha/yr) in the Northeast and Lake States regions than oaks (6.47 Mg C/ha/yr, data only available for the Corn Belt). This suggests that although the site-quality factor in this study gives a reasonable adjustment on tree growth rate for a particular location, using site-suitable (or native) species in future studies may result in a more realistic and precise estimate across the region.

Harvesting activity has both positive and negative effects on forest carbon accumulations. A short-rotation forest accumulates more biomass carbon than a permanent forest, primarily because the "young" forest stand (when periodically harvested) has a high average growth rate. On the other hand, harvesting also causes a loss of carbon on forest floor due to the fact that less carbon would be added from a young forest stand immediately after harvesting than what would be lost from decomposition of existing forest floor residue (Smith and Heath, 2002). However, the loss of forest floor carbon is relatively small when compared to the gains from above ground biomass accumulation. Overall, a scenario of short-rotation forest would produce 11-14% more carbon than that of a "permanent" forest over 50 years (Table 5.19). Note that the fate of wood carbon after harvesting was not considered in this study, which largely depends on the usage of wood products.

Hot Spots for Potential Afforestation Activities

Hot spots refer to locations of high potential carbon sequestration potential. Two factors are critical to determine the hot spots: land availability and the CSP rate. The MagLand-area weighted CSP rates for each STATSGO mapping unit were calculated to combine the effects of both factors (Figure 5.12). Locations (i.e. mapping units) with higher MagLand-area-weighted CSP rates are expected to sequester more carbon through either higher CSP rate or with larger available MagLand.

To better visualize the hotspots and to facilitate future policy analysis, county-level CSP capacity maps were created from the MagLand-area weighted CSP rate maps (Figure 5.13, an example for a 20-year coniferous forest scenario). For illustration purposes, all counties within the MRCSP region were grouped into five different levels of CSP capacity, with the higher level (darker in color) indicating greater potential for carbon sequestration through afforestation of marginal agricultural lands. The result shows that hot spots primarily concentrate along a west-east axis across the southern parts of IN, OH, and PA, and an area covering southern MI and parts of northern IN and OH. This pattern largely mirrors that of the MagLand map in Figure 5.10, suggesting that although the CSP rate varies across the region, the availability of MagLand plays a dominant role in determining the total CSP capacity.
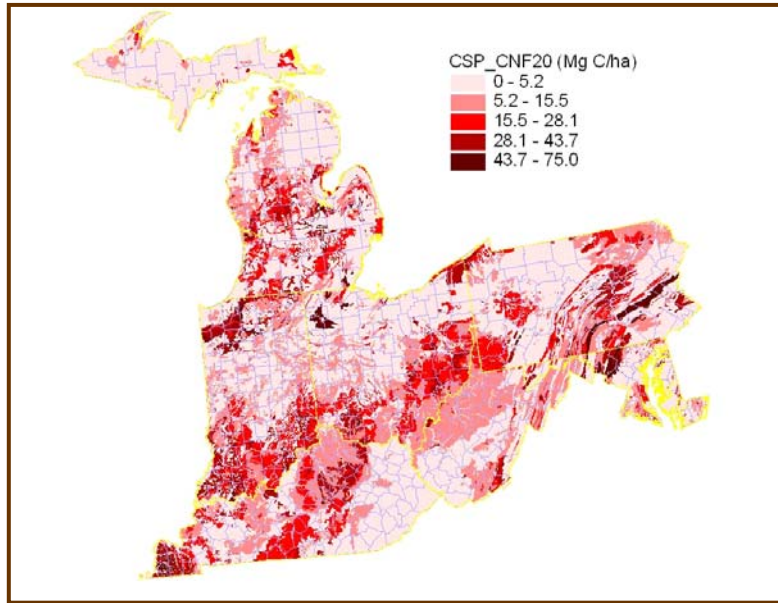
Figure 5.12. **Map of marginal agricultural land area-weighted carbon sequestration rates (kg C per hectare total land per year) under coniferous forest over 20 years.**

Note: This map reflects a combined effect of tree growth rate and the availability of marginal agricultural lands.
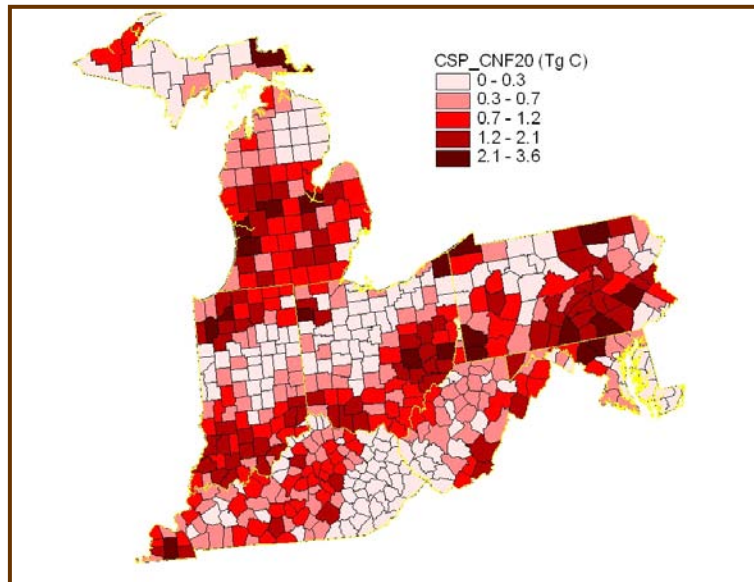
Figure 5.13. **Map of total carbon sequestration potential capacity (TgC) under coniferous forest over 20 years at a county level.**

Based on the hotspots maps, scenarios of afforestation at different CSP levels can be generated for future economic and policy analysis (Table 5.20). This table helps policy-makers and scientists determine where and how many states/counties should be involved in order to sequester certain amount of carbon in this region. For example, if a goal is set to sequester about 100 Tg of carbon over 20 years in the MRCSP region, the policy-makers may only consider to implement an "afforestation regulation" to those counties

that fall in Level 1 (3.1-5.4 Tg of carbon), which include 11 counties in Pennsylvania, 8 each in Indiana and Ohio, and 1- 4 counties in Michigan, Maryland, Kentucky and West Virginia. Meanwhile, we notice that to realize this carbon potential, a total of about 1.4 million hectare agricultural land or about 5% of total agricultural land in this region has to be converted to forest.

Table 5.20. Afforestation scenarios at different carbon sequestration potential levels.

Level	MRCSP State							MRCSP Total
	IN	KY	MD	MI	OH	PA	WV	
Level 1 (3.1 - 5.4)[1]								
# COUNTIES	8	1	2	4	8	11	1	35
%Agland[2]	3.7	1.2	10.5	3.5	4.5	14.6	3.9	5.1
MGNLag[3]	256	43	103	175	290	471	31	1369
CSP_CNF20[4]	21.6	4.2	8.7	13.1	24.6	37.9	2.6	112.8
Level 2 (1.9 - 3.1)								
# COUNTIES	23	13	1	15	18	18	4	92
%Agland	7.5	7.2	2.1	8.1	6.6	13.6	10.4	8.0
MGNLag	519	255	21	405	422	437	84	2143
CSP_CNF20	44.8	23.9	1.8	29.0	35.0	36.1	7.1	177.7
Level 3 (1.1 - 1.9)								
# COUNTIES	18	34	3	25	15	12	13	120
%Agland	3.5	12.5	4.3	8.1	3.3	5.1	20.9	6.3
MGNLag	245	445	43	403	213	163	168	1680
CSP_CNF20	21.1	39.7	3.5	28.9	17.6	13.9	14.2	138.8
Level 4 (0.5 - 1.1)								
# COUNTIES	21	27	9	17	18	11	23	126
%Agland	2.2	5.5	5.8	3.3	2.2	2.4	20.6	3.6
MGNLag	153	194	57	166	138	79	166	954
CSP_CNF20	12.7	17.3	5.0	11.8	11.0	6.4	14.8	79.0
Level 5 (0 - 0.5)								
# COUNTIES	22	45	9	22	29	15	14	156
%Agland	0.9	2.2	1.9	1.4	1.4	0.9	3.9	1.4
MGNLag	66	78	19	69	87	29	31	378
CSP_CNF20	5.2	6.4	1.6	4.6	6.8	2.4	2.8	29.8
Total								
# COUNTIES	92	120	24	83	88	67	55	529
%Agland	17.9	28.6	24.6	24.5	18.0	36.6	59.7	24.3
MGNLag	1238	1016	242	1217	1150	1179	481	6524
CSP_CNF20	105.5	91.5	20.6	87.4	95.0	96.7	41.5	538.2

[1] Levels of carbon sequestration potential (CSP) corresponding to the legend in Figure 9.
[2] Percentage of marginal agricultural land (MagLand) over the total of agricultural land in the MRCSP region within each CSP level.
[3] Total MagLand area (kha = 1000 hectare) of counties within each CSP level
[4] Total CSP (Tg C) over 20-year period under coniferous forestry of counties within each CSP level.

It should be noticed that identification of hotspots for potential afforestation activities in this study was based only on the CSP. When economic and social factors, such as land values, costs/benefits, as well as agricultural production demands, are considered, the hotspots might change. The scenario-generating technique provides a framework to readily incorporate such constraints.

Conclusions for Marginal Agricultural Lands

Based on analysis of the available data, we estimate that there is a total of 6.5 Mha of marginal agricultural land (MagLand) available for afforestation, representing about 24% of total agricultural land in the MRCSP region.

The total regional potential carbon sequestration capacity following afforestation ranged from 508 to 540 Tg of carbon over 20 years, and from 1025 to 1205 Tg of carbon over 50 years under different afforestation scenarios. The results indicate that in a forest ecosystem about two thirds of carbon will be stored in the above-ground tree biomass, while the other one third of the carbon pool would be nearly equally split between roots, forest floor and soil organic carbon pools. Overall, the states of Indiana, Kentucky, Michigan, Ohio and Pennsylvania have almost equal capacity for carbon sequestration, while states West Virginia and Maryland have only half the capacity of the other states.

Coniferous forest shows a slight advantage over deciduous forest in total carbon sequestrations mainly due to greater accumulation of carbon in its forest floor. Harvesting results in more above-ground tree biomass accumulation but also causes losses of forest floor carbon due to faster residue decay. Overall, a forest harvested every 20 years accumulates about 11-14% more carbon than a "permanent" forest stand over 50 years.

The hot spots for potential afforestation activities were found to be concentrated along a west-east axis across the southern parts of Indiana, Ohio, and Pennsylvania, and an area covering southern Michigan and parts of northern Indiana and Ohio, which largely mirrors the pattern of availability of MagLand in the MRCSP region.

It should be noticed that the carbon fate of harvested forest products was not included in this study. A full-life cycle analysis, including the carbon fate in pre- and post-harvest forest biomass, is needed in the future to determine the net carbon impact of afforestation. This analysis assumed that all suitable MagLand in the MRCSP region was converted to forest. The actual CSP would likely be less if economic and social factors are taken into account. Although further investigations are needed on its economic feasibility, social acceptability, operation and maintenance capability, this study provides a guideline for policy-makers and scientists of the potential for carbon sequestration by afforestation of MagLand in the MRCSP region.

Mine Lands

Estimation of carbon sequestration potential on mine lands and other degraded lands involved two steps:

1. The area of mine land in the MRCSP region is identified and spatially accounted for in conjunction with the other land uses analyzed by the MRCSP team.

2. The potential for carbon sequestration is then estimated by multiplying the area in mine land by literature-derived coefficients for annual carbon accumulation in forest or pasture, the two

predominant reclamation activities. The change in carbon pools for above-ground biomass, below-ground biomass, the litter layer in forest, and soils are estimated. The soil carbon pools on mine lands are also estimated using soil carbon estimates from soil surveys. These soil carbon pools represent the baseline against which annual accumulations may be compared to assess total soil carbon stock from mine land over time.

Source Data

The 1992 National Land Cover Dataset (NLCD), State Soil Geographic information (STATSGO), and county boundary GIS shape files are combined with specific data for mine lands in each MRCSP state, when available, to identify and spatially locate surface mine lands. Use of common datasets ensures that the total area analyzed by the MRCSP team and assignment of land uses accounts for the total MRCSP area in a systematic and consistent manner. A limitation of the NLCD data is that it only identifies surface mine area for 1992. Carbon accumulation on mine lands active prior to 1992 is not estimated in this analysis, but land area under mining after 1992 is addressed. To account for land in mining activities after 1992, area defined as mine land from the 1992 NLCD is combined with mine permit data from other sources such as a state governmental agency and state geological surveys. The additional data allow development of a more accurate assessment of the area of mine lands within the region.

The general data sets and permit data sets used to analyze carbon sequestration on reclaimed mine lands are described below.

1. **1992 National Land Cover Dataset (NLCD)** – The U.S. Geological Survey (USGS) 1992 NLDC GIS Raster dataset is used to identify the land cover for all seven states. As described in Table III-2.1, categories 31 (bare rock) and 32 (quarries and mines) of the NLCD data are designated as mine lands. The NLCD datasets and files are available in a GIS grid file format from http://seamless.usgs.gov/.

2. **State Soil Geographic Database (STATSGO) –** A separate report in the Task 2.2. series called "Methodology" describes the STATSGO dataset used in the analysis is available from the USDA - Natural Resources Conservation Service (USDA-NRCS). The STATSGO soil database contains a GIS map with a database of soil characteristics. Soil organic carbon pools (SOCP) are calculated using STATSGO data for the land uses considered by the MRCSP team, as described in Section 2-2 of the Methodology report in the MRCSP terrestrial series. The SOCP for mine lands may represent an initial soil carbon stock which may be used as a baseline for estimating soil carbon changes over time. The GIS shape files documenting SOCPs are located at http://dynamo.ecn.purdue.edu/%7Ebiehl/MRCSP.html.

3. **County Boundaries Data–** The county boundaries for Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia (described in Section 1 of the Methodology report) are used to organize data and allocate areas to various land uses. County boundary data allow the areas designated as mine land by the 1992 NLCD to be joined with the surface mining permit shape files from other sources. In addition to calculating the area of mine land for each county, county shape files are used to create maps that identify annual accumulation and potential "hot spots" for carbon sequestration on mine lands.

4. **Surface Mining Coal Permits (GIS Format)** – GIS maps of surface coal mine permits are used to identify areas of mining active during or after 1992. Surface mine permit data in GIS format are only available for Indiana, Kentucky, Ohio, and West Virginia. Mine areas for the remaining

states, Maryland, Michigan and Pennsylvania, are derived from the 1992 NLCD. In order to relate surface coal mine permit area with the 1992 NLCD area, only surface mining permits active during and after 1992 are selected for analysis. The following provides a brief description and source of the surface mine data used in the analysis:

- **Indiana:** A GIS shape file containing 2,615 polygons of coal mine locations dating from 1883 to 2000. Only polygons for mine permits issued between 1992 and 2000 are used for this analysis. The data and files are maintained by the Indiana Geological Survey with the file name COAL_MINE_SURFACE_IN (http://igs.indiana.edu/arcims/statewide/download.html).
- **Kentucky:** A GIS shape file containing 1,195 polygons of coal mine permits issued between September, 1999 and April, 2000. Data and GIS files are maintained by the Kentucky Department of Natural Resources with the file name SERIES7PERMIT_BOUNDARIES (http://www.surfacemining.ky.gov/data/gis/spatial/).
- **Ohio:** A GIS shape file containing 3,668 polygons for coal mine permits issued between 1975 and 2002. Data and GIS files are maintained by the Ohio Department of Natural Resources with the file name C, D_Coal_Permit_Maps (http://www.ohiodnr.com/gims/category.htm).
- **West Virginia:** A GIS shape file containing 6,100 polygons of coal mine permits issued between 1972 and 2002. Only polygons for mine permits issued between 1992 and 2002 are used for this analysis. Data and GIS files are maintained by the West Virginia Department of Environmental Protection with the file name PERBD.SHP (http://gis.wvdep.org/).

5. **Surface Mining Coal Permits (Tabular Format)** – Additional documentation for the area of mine land, date of mine permit, permit owner, and county containing the mine land are in Microsoft Excel spreadsheets for Kentucky (Kentucky Department of Natural Resources), Maryland (Maryland Department of Environment), Pennsylvania (Pennsylvania Department of Mining and Reclamation), and West Virginia (West Virginia Department of Environmental Protection). With the exception of Maryland, these data indicate that the 1992 NLCD and available GIS data underestimate the extent of mine lands in the study region. Tabular data are useful for describing the extent of mine lands in the study region; however, as discussed below, they are not robust enough for use in the analysis.

The area of mine land identified in the tabular sets is provided in Table 5.21 along with figures from other data sources. Although all the data sources contain extensive information on mine lands in the MRCSP region, they cannot be combined for the purposes of analysis. Closer examination indicated that the tabular data could not be integrated into the NLCD data because the county location that is listed for the mine lands represents only the primary site (main portion of the mining area). The area of mine land could cross county borders, but the proportion of mine land in each county is not provided. Thus in Pennsylvania, tabular data indicate 200,695 ha of land permitted for mining, a much higher area than the 125,363 ha designated in the 1992 NLCD as mine land. The lower, unadjusted number is used for defining land cover later in this report as well as in Table 2 of the Methodology report.

Table 5.21. Mine land area in MRCSP region states with permit data not reflected in the 1992 NLCD.

Data Source	Mine Land Area, ha			
	Kentucky	**Maryland**	**Pennsylvania**	**West Virginia**
1992 NLCD	52,262	29,081	125,363	73,253
Mining Permits – GIS	15,609	NA	NA	110,220
Mining Permits – Tabular	121,831	2,022	200,695	139,064
OSM Permit Average (1994 – 2002)[1]	716,595	2,294	173,726	115,594
Adjusted Area (NLCD + GIS permits)	67,871	Unadjusted	Unadjusted	183,473

[1] Data from Office of Surface Mining Annual Reports 1994 – 2002.

   NA = Not Available.

Data Manipulation

Area for mine lands is derived from the 1992 NLCD and augmented by mine permit data obtained from state agencies within the MRSCP study region to the extent the data format allowed. The areas of land designated as category 31 (bare rock) and 32 (quarries and mines) by the 1992 NLCD provide the base areas considered in this analysis. When GIS format data on surface mined lands are available (as is the case for Indiana, Kentucky, Ohio, and West Virginia), the data are merged with the 1992 NLCD designated mine lands and shared with all MRCSP participants. This ensures that mine and other land use areas are not double-counted and land uses are accurately assigned by all MRCSP research teams.

Mine lands identified in the state GIS format data that are not included in the 1992 NLCD are incorporated into the NLCD data. Land uses for these areas are then changed from the land use identified in the NLCD to mine lands. Consequently, the area of land used for row crop, urban, water, pasture, etc. for the MRCSP analysis may be less than the area designated by the 1992 NLCD because a portion of these areas were converted to mine lands after 1992.

Method for Filtering Data to Select Post-1992 Mining Activities

The NLCD presents land cover data for a single year; however, the shape files for some of the MRCSP states contain permits with dates ranging from 1970 to 2002. Table 5.22 presents the mine land area added since the compilation of NLCD data for Indiana, Kentucky, Ohio, and West Virginia. The total area encompassed by mine permits issued during or after 1992 is 43% larger than the areas designated as category 31 and 32 by the NLCD.

Table 5.22. Increase in mine land area in MRCSP states since compilation of the 1992 NLCD.

	Mine Land Added During and After 1992	
State	Area (Ha)	Percent Increase over NLCD Data
Indiana	7,994	36
Kentucky	15,609	30
Ohio	37,503	145
West Virginia	110,220	150
Total	**171,327**	**43**

To account for mine areas identified in mine permit GIS files that are not designated as mine lands by the NLCD, and to maintain consistency with the land use areas analyzed by other members of the MRCSP terrestrial group, the data from the GIS mine permit shape files are filtered to select only 1992 to 2002 mine permits using the following steps:

1. Select mine permits that occurred during or after 1992 using the "Select by Attributes" command in ESRI Arc Map using MAP DATE $\geq$ 1992.
2. Create a new shape file of the selected permits above using "Create Layer from Selected Features" command in ESRI Arc Map.

It is not necessary to filter the Kentucky mine permit shape file for permits occurring during or after 1992, because all permits listed were active between 1999 and 2000. However, it is necessary to filter data from the Kentucky mine permit shape file to remove mine permits labeled as "underground." This is accomplished by using "Select by Attributes" command in ESRI Arc Map to restrict the permits included in the analysis to those not labeled "Underground" (Code $\neq$ Underground (UG)).

After filtering the data, the GIS mine permit shape files are incorporated into and evaluated with the 1992 NLCD to develop an accurate and complete identification of the mine land area in each county.

Method for Calculating Mine Land Area per County

The data set provided by the 1992 NLCD is adequate for calculating the mine land area of Maryland, Michigan, and Pennsylvania because no GIS shape files are available for these MRCSP states. In order to calculate the mine land area of Indiana, Kentucky, Ohio, and West Virginia, it is necessary to combine the 1992 NLCD GIS grid data with the GIS mine permit polygon shape files that are provided by those state agencies. The approach to combine the two data sets must address two issues. First, the large number of permits and extent of land cover prevents the use of ArcGIS to merge the different GIS datasets. Second, in order to add the mine area addressed by the GIS mine permit shape files to the 1992 NLCD dataset, it is necessary to adjust the area of the other land use categories in the NLCD. The solution is to use county boundary shape files to calculate the area of mine lands in each county for each dataset and to determine the adjustment needed for other land use categories. Figure 5.14 illustrates the process used to perform the calculations. The five steps are discussed below.

1. ***Identify the spatial location and estimate the area of mine lands in each county as designated in the 1992 NLCD.*** For Maryland, Michigan, and Pennsylvania, the data derived in this step establishes mine land area. The area of mine land in each county for these states is the same as 1992 NLCD because mine permit shape files for these states are not available. The area of mine

land in each county as designated by 1992 NLCD represents the baseline area of mine lands for the states for which GIS shape files are available (Kentucky, Indiana, Ohio, and West Virginia).

The areal extent of each land use designation, and specifically for mine lands, from the 1992 NLCD mine area for county is estimated as follows:

- Overlay the county boundary shape files on top of the 1992 NLCD in ArcView 3.3.
- Use the "Tabulate Area" command in ArcView 3.3 to create a table of the area of land cover within each county. For this table, set the 1992 NLCD land cover as the column theme, the field "Value" for the column field, the county shape file as the county theme and the county FIPS numbers as the county field.
- Export the table created by ArcView 3.3, which presents the county names in rows and NLCD land cover classifications in columns, to Microsoft Excel (or to a database program) to analyze the land cover for each county.
- Sum the NLCD land use classifications 31 and 32 to identify the mine land area defined by the 1992 NLCD for each county.

2. ***Estimate the additional area of mine permits in each county as derived from GIS shape files provided by state agencies.*** When GIS shape files for mine lands are available, as for the mining permit areas for Indiana, Kentucky, Ohio, and West Virginia, additional analyses, as described below, is required.

- Overlay the state specific mine permit shape files onto the county boundaries in ArcView 3.3.
- For the database (dbf) files of each state mine permit shape file, add a new column and provide each permit with a unique identifying number. The shape file may already have a unique identifier, but if not, a unique number can be provided in the Arc View "Calculate Field" command using the following equation: rec + 1
- Create a table of permit areas by county using the "Tabulate Area" command. For this table, select the permit shape file as the row theme and the unique permit identifier for the with the row field category. Choose the county shape file for the column theme with the county FIPS code as the county column field. The final table lists each unique permit id and provides the area of a permit that is within a county or counties.
- After ArcView creates the table, export it to Microsoft Excel, sort the mine permits that overlap county boundaries, and create a new table for permits that correspond to two or more county FIPS codes.
- In order to assign a land cover for each permit in a later step, it is necessary to process the data to create a table with the following three columns:
  - o One column listing the unique permit id numbers,
  - o A second column displaying the corresponding county FIPS code,
  - o A third column showing the area for each permit.
- The final products of this step are three column tables for permits within a single county and permits that have area in two or more counties. In the step discussed in section IVa.2c.4, these three column tables listing the permit, corresponding county name, and permit area within a county are joined with a table that lists the land cover for each unique permit id.
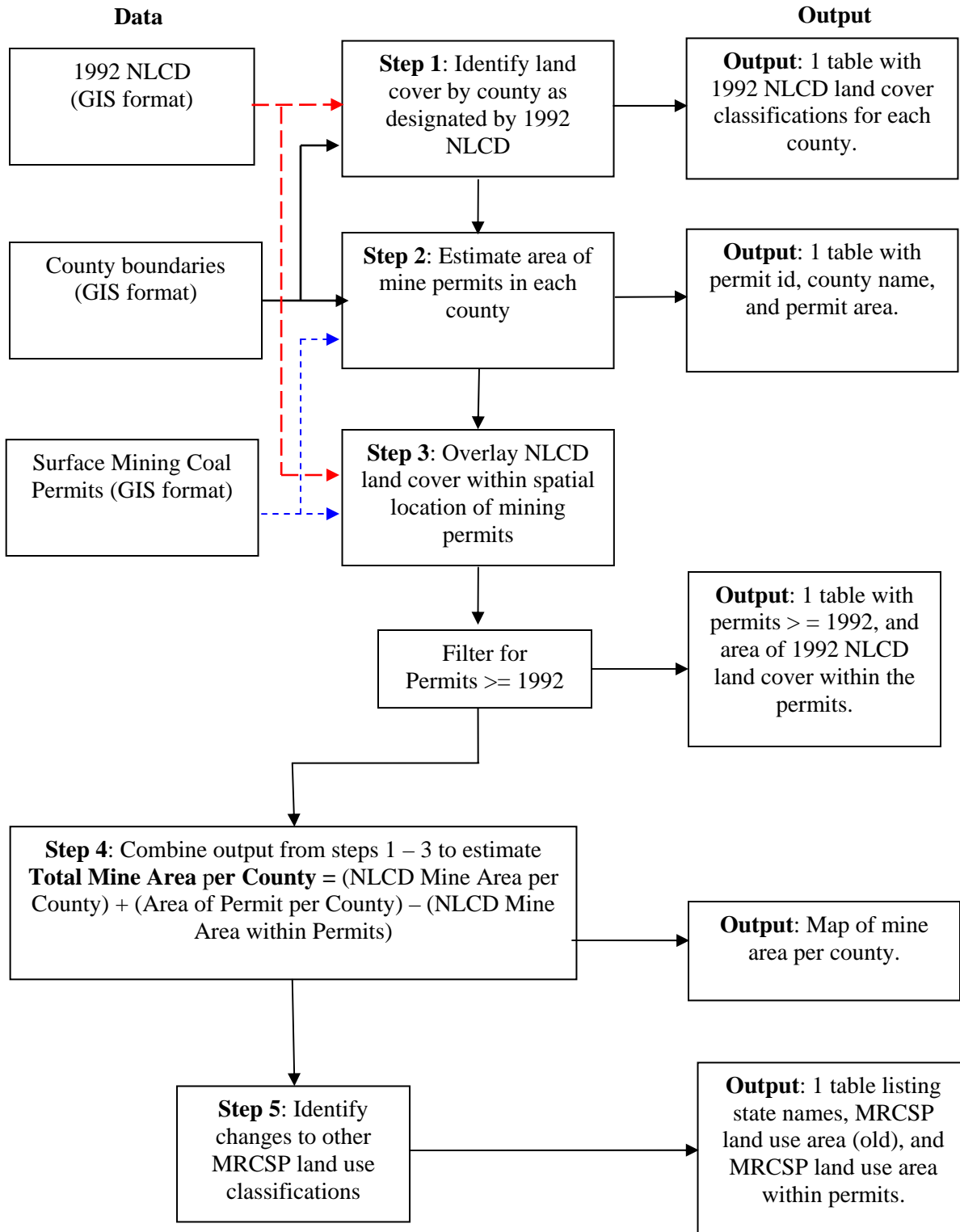
Figure 5.14.   Methodology to establish the area of mine lands in MRCSP region.

3. *Identify 1992 land cover on mine lands added from state specific GIS data by identifying the spatial location of the added mine lands and the 1992 NLCD designated land cover*. The area of land cover classification within each permit is calculated in these steps.

- Overlay the mine permit shape files onto the 1992 NLCD grid dataset using ArcView 3.3.
- Create a table of land cover within each permit by county for Indiana, Kentucky, Ohio, and West Virginia with the "Tabulate Area" command in ArcView 3.3. For this table, select the permit shape file as the row theme and the unique permit identifier for the row field category along with choosing the 1992 NLCD land cover as the column theme and the field "Value" for the column field.
- Export the table to Microsoft Excel or other database management system to systematically report the 1992 land cover from the NLCD for land under mining after 1992.
- The final product for this step is a table listing all unique permit identifiers that shows the area of the NLCD land covers classifications for each permit. For example, Permit 123 could have 50 hectares of NLCD Category 41 (Deciduous Forest), 30 hectares of NLCD Category of 51 (Shrubland), and 20 hectares of NLCD Category 32 (Quarries/ Strip Mines / Gravel Pits).

4. *Estimate the aerial extent of the new mine lands and of the land uses identified in the 1992 NLCD that are changed to mine land*. A table that identifies the 1992 NLDC defined land cover and aerial extent of mine permit areas for each county is created in this step.

- For mine permits within a single county, use Microsoft Excel to combine the three column table, discussed in Section IVa.2.b.2.5 (permit area within a county), with the table created in Section IVa.2.b.3 (land cover per permit). The new table would have a row containing the following information:

  Permit 123, County A, 75 hectares, 30 hectares of NLCD Category 41 (Deciduous Forest), 25 hectares of NLCD Category of 51 (Shrubland), 20 hectares of NLCD Category 32 (Quarries/ Strip Mines / Gravel Pits), and 0 for all other NLCD Categories.

- For the unique permit id numbers that fall within two or more counties, use Microsoft Excel to combine the three column table, discussed in Section IVa.2.b.2 (permit area within a county), with the table created in Section IVa.2.b.3 (land cover per permit), but the NLCD land cover area is multiplied by the percentage of permit area within the county as follows:

  Permit 234, County A: (Area in County A)/ (Total Area of Permit within County A and B) × Area of a 1992 NLCD Category

  For example, if Permit 234 had 100 hectares with 75 hectares in county "A" and 25 hectares in County "B", the 40 hectares of NLCD Category 42 (Evergreen Forest) are multiplied by 0.75 for County "A" and 0.25 for County "B". After these calculations, the table lists two lines:
  - o Permit 234, County A lists 30 hectares for Category 42 and
  - o Permit 234, County B lists 10 hectares for Category 42.

- Combine the table of permits that fall within a single county and the table of permits that cross two or more counties to create a table listing the following:
  1. Permit ID Number,
  2. County FIPS code or name,
  3. Permit Area within County,
  4. Area for NLCD Classifications (including adjusted areas for cross boundary permits)

- Sum the permit area and the area of NLCD classifications for each county and change the NLCD categories to match MRCSP classifications. Now, the table lists all the county names, and the area of NLCD classifications that are within permits. An example is shown

in Table 5.23, but the NLCD classifications have been changed to match the MRCSP land cover classifications.

Table 5.23. Example of how the total area of mine permit data are allocated to the MRCSP land cover classifications by county.

County	Total Area of Permit	Water	Urban	Grass	Rock	Mine lands	Forestland	Shrubs/ Orchard	Pasture	Cropland	Wetlands
Clay	481	7	4	0	0	22	74	4	92	275	2
Daviess	1,049	18	1	0	0	73	86	0	332	539	0
Dubois	113	0	0	0	0	0	4	0	72	36	0
Gibson	714	6	0	0	0	19	59	0	232	397	1

- Calculate the total mine area per county using the following data from previous steps:
  a) Area Designated as Mines by 1992 NLCD By County is summation of NLCD Categories 31 and 32 that is discussed in Section IVa.2c.1.
  b) Area of Permit Per County is the summation conducted in Section IVa.2c.2
  c) Area in Permits Designated by NLCD as Mine Lands is the addition of 1992 NLCD categories 31 and 32 done in this section. Examples of these values are shown in Table 5.22 under the column labeled "Mine Lands".
- Use the following equation to calculate the total mine area per county: **TOTAL MINE AREA PER COUNTY** = (Area Designated as Mines by 1992 NLCD By County) + (Area of Permit Per County) – (Area in Permits Designated by NLCD as Mine Lands). To avoid double counting, the area within a permit that is designated as a mine land by 1992 NLCD is subtracted from the total mine area estimated above.

5. *Identify changes made to the land uses identified in the 1992 NLCD that are changed to mine land.* – This step creates Table 5.24 showing the changes made to other NLCD classifications due to the addition of state specific GIS area of mine land.
   - The following data from previous steps is used to determine the change in area for other NLCD land cover classifications:
     o Area of NLCD per County is discussed in Section IVa.2c.1. This is a table showing the county FIPS codes in rows and listing the 1992 NLCD categories as column headings.
     o Area of NLCD in a Permit By County is discussed in Section IVa.2c.4. Examples of these values are listed in Table 5.23.
   - Calculate the change to other MRCSP land covers using the following equation: **ADJUSTED LANDCOVER** = (Area of NLCD per County) – (Area of NLCD in a Permit By County). For example, County A has 1,000 hectares of Deciduous Forest, but 300 hectares are within mining permit boundaries identified by state GIS data. This means that County A will only have 700 hectares of forest after adding the new mine area and making the adjustments.
     o Create the original land cover values for each state listed in Table 5.24 by summing the land cover for each county. The adjusted values for all land covers except mine lands are found by using the **ADJUSTED LANDCOVER** equation. For Maryland, Michigan, and Pennsylvania, the adjusted values for all land covers are the same as the original values, but for Indiana, Kentucky, Ohio, and West Virginia the adjusted values for mine lands requires summing the numbers calculated by **TOTAL MINE AREA PER COUNTY** equation.

The end product of these activities is a series of tables and maps displaying the total mine area for all seven states. Tables created in this process display information on NLCD land cover within a county, land cover within a permit as defined by the NLCD, the mine permit area per county, and adjustments made to other NLCD land cover classifications due to the additional mine area. The values shown in these tables can easily be transferred into GIS database in order to create a geographical representation for the carbon sequestration calculations performed in the following sections.

Method for Estimating Carbon Sequestration on Mine Lands

A wide variety of vegetative covers are used for reclamation activities that are not explicitly dictated by the Surface Mining Control and Reclamation Act (SMCRA) of 1977. The primary reclamation concern is the legal and short term requirement to provide minimum ground cover and maintain groundwater quality which may not be consistent with the best long term vegetative cover (Holl, 2002).

The landowner generally decides what vegetative cover will be used for reclamation and the mine operator is frequently not the landowner. There is little published documentation on what is planted on reclaimed mine lands after the initial activities to control erosion and establish cover are complete. Of the land that was not in mining according to the 1992 NLCD, which mine permit data indicate is mine land after 1992, over 81% was in forest and nearly 10% in pasture in 1992 (Table 5.24).

These activities likely comprise the predominant land use in the MRCSP study region before conversion to mining. Therefore, mine land is assumed to be reclaimed to either forest or pasture for this analysis. When data are available, reversion to the land use prior to mining activity is analyzed (e.g., cropland or other activity described by the 1992 NLCD when there is overlap between the NLCD and mine GIS data).

These activities likely comprise the predominant land use in the MRCSP study region before conversion to mining. Therefore, mine land is assumed to be reclaimed to either forest or pasture for this analysis. When data are available, reversion to the land use prior to mining activity is analyzed (e.g., cropland or other activity described by the 1992 NLCD when there is overlap between the NLCD and mine GIS data).

The carbon content of the soil that is removed for mining and then placed back onto the site represents a second confounding element in reclaimed mine land. Disturbing the topsoil when it is removed from the mine site to expose the coal seam releases a portion of the stored carbon. However, it is not clear how much carbon is lost to the atmosphere. The IPCC method assumes that "abandoned/degraded" land has lost 50% of soil carbon present under native vegetation (IPCC, 1998), which is the factor used in most of this analysis.

Regulations require that the topsoil be stored separately from the overburden material and protected from wind and water erosion. Annual or perennial vegetation must be planted on the removed topsoil to protect it from wind and water erosion (USDA-FS, 1984). A cover crop that protects the soil will also contribute to soil carbon accumulation and may help mitigate the losses that result from soil disturbance. This analysis, as part of the MRCSP project, does not account for these carbon accumulations, but it is important to recognize that the carbon content of topsoil used for reclamation is likely greater than zero.

Table 5.24 Land cover area (hectares) for each state using MRCSP classifications

			Area Assigned to Use Classification (ha)									
State	Value	Total	Water	Urban	Grass	Rock	Mine Lands	Forest Land	Shrubs/ Orchards	Pasture	Crop Land	Wet Lands
IN	OR	9,376,123	105,912	315,074	55,042	1,025	22,207	1,763,442	37,598	1,770,614	5,141,073	164,136
IN	ADJ	9,376,123	105,825	315,063	55,041	1,025	30,201	1,761,721	37,582	1,768,645	5,136,906	164,114
KY	OR	10,461,312	190,097	191,360	54,372	539	52,262	6,229,925	0	2,147,310	1,412,998	182,449
KY	ADJ	10,461,312	189,918	191,337	54,372	539	67,871	6,214,748	0	2,147,216	1,412,891	182,418
MD	OR	2,738,712	225,942	200,797	14,774	1,038	29,081	1,058,915	0	632,247	354,547	221,371
MI	OR	15,069,929	431,339	475,354	64,199	9,265	68,260	6,169,621	319,246	1,371,366	3,602,932	2,558,347
PA	OR	11,733,011	135,322	482,408	21,648	110	125,363	7,643,828	0	2,644,374	581,759	98,199
OH	OR	10,681,297	120,732	562,199	61,927	32	25,898	3,360,629	384	2,315,073	4,085,227	149,196
OH	ADJ	10,681,297	120,044	562,014	61,927	32	63,401	3,341,938	384	2,303,281	4,079,240	149,036
WV	OR	6,268,806	51,012	81,981	1,498	0	73,253	5,238,932	0	688,709	118,158	15,263
WV	ADJ	6,268,806	50,163	80,654	1,482	0	183,473	5,135,223	0	685,512	117,174	15,126
Total	OR	66,329,190	1,260,356	2,309,173	273,460	12,009	396,324	31,465,292	357,228	11,569,693	15,296,694	3,388,961
Adjusted	ADJ	66,329,190	1,258,553	2,307,627	273,443	12,009	567,651	31,325,994	357,212	11,552,641	15,285,449	3,388,611

OR = original; ADJ = adjusted land cover values. See discussion under **Altering MRCSP Classification** regarding the addition of area of mining permits active on or after 1992 and subtracting the land cover values within the boundaries of permits.

Carbon sequestration in the soil, litter layer, and above-ground biomass are estimated for mine lands in the MRSCP study region. Refereed journal articles, conference presentations, unpublished studies, and government publications are used to derive estimates of the carbon stock and annual rate of change of carbon on mine lands. The literature review focused on studies in or near the MRCSP study region because climate and native vegetation are critical factors in determining both the stock and change in carbon over time. However, studies of mine land soils from locations throughout the world were analyzed to derive carbon sequestration rates since research in this area is limited. Since existing studies generally do not provide estimates of the carbon stock on mine land soils at the start of reclamation, assumptions are made, when required for analysis, about initial soil carbon stocks prior to re-vegetation.

Carbon Sequestration in Mine Land Soils

Limited research is available that assesses soil carbon sequestration on reclaimed mine land sites. Carbon accumulation in mine land soils for this analysis is estimated using rates derived from Akala and Lal (2000 and 2001), Amichev et al. (2004), Birdsey and Lewis (2003), Insam and Domsch (1988), Paul et al. (2002), Seybold et al. (2004), and Sinclair et al. (2004).

Akala and Lal (2000) develop equations using time as the independent variable to estimate soil organic carbon (SOC) accumulations on mine lands reclaimed to pasture or forest. Data for the equations are derived from southeastern Ohio chronosequence field studies on mine lands reclaimed to pasture and forest at various times over 25 years. Coefficients for the equations are developed by comparing the SOC content on reclaimed sites that were reclaimed at different times. The research indicates that soil carbon accumulations under pasture are greater than the accumulations under forest on reclaimed mine sites. Two equations for pasture and two for forest are derived for the upper (0-15 cm) and lower (15-30 cm) soil horizons. These equations are solved for this analysis by varying time from 1 – 20 years (the expected time until a new equilibrium is met (IPCC, 1997a)):

Pasture: 0 – 15 cm $MgC^{1}/ha = 15 + 29.5/\{1 + \exp[-(t - 10.8)/2.39]\}$
           15 – 30 cm $MgC/ha = 10.7 + 7.67/\{1 + \exp[-(t - 13.3)/2.80]\}$
Forest: 0 – 15 cm $MgC/ha = 12 + 34.1/\{1 + \exp[-(t - 13.0)/3.30]\}$
           15 – 30 cm $MgC/ha = 9.08 + 4.52/\{1 + \exp[-(t - 11.7)/1.28]\}$

The carbon stocks and rates of change derived from these estimates are provided in Table 5.25. Results of the equations indicate that carbon sequestration continues throughout the 20-year period, but the annual rate of SOC accumulation increases at an increasing rate for the first 11 years for pasture and 13 years for forest before declining.

Carbon sequestration rates over twenty years for mine land soils are estimated by summing the per hectare sequestration rates for 0 to 15 and 15 to 30 cm for each land use category. The annual change in SOC for each year is then estimated and the average annual rate of change calculated over the twenty years. For the analysis, total soil carbon sequestration is estimated by multiplying the SOC average rate of change by the area of mine land. Although the study is explicitly for Ohio mine reclamation sites, the soil C sequestration rates are applied to all states in the MRCSP region.

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[1] MgC refers to million grams of carbon.

Table 5.25. Carbon sequestration in mine land soils derived from equations for pasture and forest on reclaimed mine lands. Source: Akala and Lal (2000).

Time (yrs)	Pasture Carbon (Mg/ha)			Pasture Carbon Rate of Change (Mg/ha/yr)	Forest Carbon (Mg/ha)			Forest Carbon Rate of change (Mg/ha/yr)
	Depth 0-15 cm	Depth 15-30 cm	Total 0-30 cm		Depth 0-15 cm	Depth 15-30 cm	Total 0-30 cm	
1	15.5	10.8	26.3	—	12.9	9.1	22.0	—
2	15.7	10.8	26.6	0.3	13.2	9.1	22.3	0.3
3	16.1	10.9	27.0	0.4	13.6	9.1	22.7	0.4
4	16.6	11.0	27.6	0.6	14.1	9.1	23.2	0.5
5	17.4	11.1	28.5	0.9	14.8	9.1	23.9	0.7
6	18.5	11.2	29.7	1.2	15.7	9.1	24.8	0.9
7	20.0	11.4	31.4	1.7	16.8	9.2	26.0	1.2
8	22.0	11.7	33.7	2.3	18.1	9.3	27.5	1.5
9	24.4	12.1	36.5	2.8	19.8	9.6	29.4	1.9
10	27.3	12.5	39.8	3.3	21.8	10.0	31.8	2.4
11	30.4	13.0	43.4	3.6	24.0	10.7	34.8	3.0
12	33.4	13.7	47.0	3.6	26.5	11.6	38.1	3.3
13	36.1	14.3	50.4	3.4	29.1	12.4	41.4	3.4
14	38.4	15.0	53.4	3.0	31.6	13.0	44.6	3.1
15	40.2	15.7	55.8	2.4	34.1	13.3	47.3	2.8
16	41.5	16.3	57.7	1.9	36.3	13.4	49.8	2.4
17	42.4	16.8	59.2	1.5	38.3	13.5	51.8	2.1
18	43.1	17.2	60.3	1.1	40.0	13.6	53.5	1.7
19	43.6	17.5	61.1	0.8	41.3	13.6	54.9	1.4
20	43.9	17.7	61.6	0.6	42.4	13.6	56.0	1.1

Amichev et al. (2004) measure soil carbon stocks on 14 reclaimed mine sites in Illinois, Indiana, Kentucky, Ohio, Pennsylvania, Virginia, and West Virginia that averaged 2.5 ha of forest where mining ceased before 1977 (SMRCA requirements not applicable). Soil carbon stocks in mined sites converted to loblolly pine (*Pinus Taeda*), white pine (*Pinus Strobus*), Scots pine (*Pinus Sylvestris*), and hardwood are assessed and compared to nearby natural sites that were not mined.

Since initial soil carbon stocks are not provided, for this analysis it is assumed that initial stocks are either 25 or 50% of the natural site for each state when mine reclamation began. When it is assumed that initial stocks are 50% of natural sites, the average annual rate of change of carbon stocks on pine and hardwood sites range from losses of -0.19 Mg/ha/yr in Pennsylvania to gains of 0.55 Mg/ha/yr in Virginia.

Illinois and West Virginia also exhibit an average carbon emission from mine lands. The carbon stock at the start of reclamation may be less than 50% of the natural sites because SMCRA requirements were not in place at the time of reclamation of these sites. It is not likely that carbon emissions would continue after forest is established since the soil is not disturbed and carbon inputs from biomass production occurs.

Assuming initial carbon stocks of 25% of the natural sites, all sites exhibit positive soil carbon accumulations that range from 0.12 Mg/ha/yr in Pennsylvania to 1.4 Mg/ha/yr in Virginia with an overall

average rate of change of 0.18 Mg/ha/yr. Soil carbon changes on reclaimed mine land in the MRCSP region is estimated in this analysis using the annual rates of soil carbon (C) changes derived from the assumption of initial carbon stocks being 25% of the natural sites. Soil carbon (C) sequestration rates from adjacent states are applied to the states not included in the study area (Maryland and Michigan).

Birdsey and Lewis (2003) estimate soil carbon stocks in forests for all fifty U.S. states using forest inventory data and models that relate soil organic matter accumulations to temperature, precipitation, age class, and land-use history. These data are compiled with ecosystems data to estimate regression coefficients representing changes in soil carbon over time. The relative age of forests is accounted for in the models using a weighting procedure that compares the average forest age with the reference age.

Therefore, the soil carbon accumulations represent a weighted average based on a broad range of forest age and accumulation rates. The accuracy of the data is enhanced by generating geographically specific results. For the MRSCP study region, estimates of soil carbon (C) for the specific states considered in the analysis are used by applying the following.

1. To ensure that soil carbon estimates are derived only from biomass production, the Birdsey et al. data are first adjusted to remove soil carbon gains generated by land use change.
2. Subtract the soil C stock in 1987 from the soil C stock in 1997 to estimate the change in the soil C stock between 1987 and 1997.
3. Divide the result of step 2 above by 10 to derive the annual change.
4. Convert the data presented in Tg (million metric tons) to Mg (metric ton) by dividing by 1,000,000.
5. Divide by the area (ha) of forest considered in the analysis for each state to estimate the annual rate of change per hectare. The resulting value is then multiplied by the area of mine land in each county of the state where the soil C accumulation rate was derived to estimate soil C gains per year.

Insam and Domsch (1988) analyze soil carbon accumulation on mine sites reclaimed to forest and agriculture in the Federal Republic of Germany. Regression equations are derived to estimate SOC stocks to 15 cm depth using time as the independent variable as follows:

Agriculture: $y = 0.20x^{0.35}$
Forest: $y = 0.12x^{0.78}$

where $y = SOC$ (g/100g soil) and x = time (years).

For this analysis, SOC is converted to Mg/ha assuming a bulk density of 1.35 g soil/cm^3 soil to obtain a per acre soil weight to a 6 inch depth of 2 million pounds (2240.1 Mg/ha to 15.24 cm depth) (Skousen, 2004, *Personal communication)*. For this analysis, the change in carbon stock between years zero and one is not included in the annual rate of change of soil. It could be considered the carbon stock at the start of reclamation, but because it is an artifact of the initial measured carbon values which are greater than zero, the intercept term has less meaning.

The data did not contain soil carbon (C) measurements prior to the reclamation activities. The average rate of carbon accumulation on mine land soils converted to agriculture is 0.41 Mg/ha/yr and conversion to forest accumulates carbon at a rate of nearly 1.4 Mg/ha/yr. These data reflect soil carbon (C) only to 15 cm and are therefore not applied to the areas of mine land. The soil carbon (C) sequestration rates are used to provide a more complete comparison of the results from various studies. The soil carbon (C) sequestration rates when agriculture is the reclamation activity derived from the Insam and Domsch

(1988) data are similar to the results derived from other studies. The soil carbon (C) estimates when forest is the reclamation activity are higher than those derived from other studies.

Paul et al. (2002) reviewed studies of 204 forested sites of various ages to calculate weighted average soil carbon accumulations based on the age and carbon accumulations over previous land use (usually agriculture). The average soil carbon accumulations range from 0.02 Mg/ha/yr for sampling depths greater than 10 cm to 0.11 Mg/ha/yr for sampling depths less than 30 cm over all studies. Soil carbon to a depth of 30 cm is required for this analysis, so the larger value is applied to the reclaimed mine sites in the MRSCP study region.

Seybold et al. (2004) assess soil carbon content on eight reclaimed mine sites in southwestern Indiana. The predominant land use at most of the sites prior to mining was agriculture. The authors determined that the soil quality on the reclaimed mine sites was inferior to either native or agricultural land. Carbon stocks range from 24.4 Mg/ha 16 years after reclamation began to 45.0 Mg/ha 21 years after reclamation. Data from this study are not used in this analysis because initial carbon stocks are not provided, so there is no accurate way to assess annual accumulations of soil carbon (C) from the start of reclamation.

Sinclair et al. (2004) calculate soil organic matter from eight mine sites that had been reclaimed to agriculture in 6 to 17 years in southwestern Indiana. In addition to measurements from the reclaimed sites, the analysis includes data from the National Cooperative Soil Survey Database on similar soils within the same counties as the mined lands. These data provide the pre-mining soil characteristics. Soil organic carbon stocks and rates of change are not included in the analysis, but the percent soil organic matter in the mine sites and the assumed pre-mining soils is provided. Bulk densities of the mine site soils and a range of bulk densities for the pre-mine soils are also included. With these data, soil organic carbon is calculated for this analysis as follows:

1. For the base conditions prior to mining, ranges of bulk density and soil organic matter (SOM) are provided rather than specific values. For this analysis, the average bulk density and percentage SOM are used to establish the pre-mining SOM content of the soils.
2. SOM estimates for the mine sites are not always provided for the 0 - 30 cm region of the soil profile. Adjustments are made to estimate SOM in the top 30 cm by calculating the percent SOM per layer using the coverage that closest approximates the 30 cm required depth (e.g. 0 – 20 or 0 - 33 cm). For example, when the data provide 0 – 20 and 25 – 33 cm, the 0 – 20 measurement is used to estimate the SOM per cm depth and then the rate per cm is applied to the full 30 cm depth.
3. Multiply the per cm depth calculated in step 2 above by 30 to obtain SOM in the top 30 cm of soil.
4. Calculate soil carbon by converting from percent SOM to MgC/ha using the following equation:

$$\text{Soil C} = (\frac{SOM}{100} \times BD \times 100 \times Depth) \times 0.58$$
$$= (SOM \times BD \times Depth) \times 0.58$$

where: Soil C = soil carbon (Mg/ha),
SOM = Soil organic matter (%),
BD = Bulk Density (g soil/cm^3 soil),
Depth = Soil depth of measurement (cm),
0.58 = factor to convert from SOM to soil carbon (SOM is approximately 58% carbon).

5. Subtract the soil carbon from the baseline prior to mining from the soil carbon calculated from the mine sites. For this analysis it is assumed that the soil C at the start of reclamation is 50% of the pre-mining soil carbon level.

6. Divide by the number of years the mine site has been reclaimed (ranges from 6 to 17 years for all study sites) to derive the annual rate of change of soil carbon accumulation.

Using the calculations applied to the Sinclair et al. (2004) data, average annual soil carbon accumulations on mine land reclaimed to cropland in southwestern Indiana are 1.6 Mg/ha/yr. The highest estimate for the rate of accumulation is 3.3 Mg/ha/yr and the lowest estimate is 0.22 Mg/ha/yr (Table 5.26). Mine reclamation to agriculture is most likely only in Indiana, Ohio and Michigan, therefore these soil carbon (C) accumulation rates are only applied in those states.

Stahl et al. (2003) estimate soil carbon accumulations on mine soils in Wyoming. These data are not explicitly used in the analysis because the study region is in a different climatic region than the MRCSP region and there is some concern expressed by the authors that the soil samples contained coal dust, which enhances the measured SOC content. However, it is interesting to note that the authors find that carbon accumulation in mine land soils may be greater than in native sites.

Carbon Sequestration in Above-Ground Biomass (Forest)

Amichev et al. (2004) estimate carbon in above-ground biomass using measurements of tree diameter and regression equations on nearby natural sites and 14 mine sites reclaimed to hardwood and pine forest before SMRCA regulations. Estimates of biomass include stem wood, stem bark, foliage, treetops, branches, stumps, and coarse roots. The authors find that carbon stocks on reclaimed mine sites, especially the litter layer and above-ground biomass, may be greater than on non-mined sites for some hardwood (Kentucky and Ohio) and pine (West Virginia and Kentucky) forests. For this analysis, the above-ground biomass stocks are converted to annual accumulations by dividing the carbon stock by the age of the reclaimed mine site. It is assumed that the initial carbon stock of above-ground biomass is zero since forest was not present at the start of reclamation. Average carbon accumulations in above-ground biomass for pine and hardwood forests range from 1.3 Mg/ha/yr in Indiana to 3.3 Mg/ha/yr in West Virginia (Table 5.26); the average at all sites is 2.4 Mg/ha/yr. Soil carbon (C) sequestration rates from adjacent states are applied to the states not included in the study area (Maryland and Michigan).

Birdsey and Lewis (2003) use forest inventory data to estimate carbon accumulations in above-ground biomass. Carbon accumulation estimates are derived from estimates of the tree growth by general species (softwood and hardwood) using ratios to allocate growth to limbs, roots, and other tree components. The cubic feet of tree volume is then converted to pounds of carbon assuming trees are 45-50% carbon. For the MRSCP study region, estimates of biomass C for the specific states considered in the analysis are used by applying the following.

1. Land-use changes in forestry result in biomass loss due to forest clearing or other tree removal. To ensure that biomass carbon estimates are derived only from biomass production, the Birdsey et al. data are first adjusted to remove biomass carbon losses generated by land use change.
2. Subtract the biomass C stock in 1987 from the biomass C stock in 1997 to estimate the change in the biomass C stock between 1987 and 1997.
3. Divide the result of step 2 above by 10 to derive the annual change.
4. Convert the data presented in Tg (million metric tons) to Mg (metric ton) by dividing by 1,000,000.

5. Divide by the area (ha) of forest considered in the analysis by state to estimate the annual rate of change per hectare. The resulting value is then multiplied by the area of mine land in each county of the state where the biomass carbon accumulation rate was derived to estimate biomass carbon gains per year.

Annual accumulations of carbon in above-ground biomass represent the average of all tree species in each of the states and range from 0.1 Mg/ha/yr in Pennsylvania to 2.2 Mg/ha/yr in Indiana (Table 5.26). The predominant forest cover in Kentucky (77%), Maryland (63%) and West Virginia (76%) is oak (*Quercus* family Fagaceae) – hickory (*Carya* family Juglandaceae) forest. Oak – hickory and Maple (*Acer* family Aceraceae) –Beech (*Fagus sylvatica* L.) – Birch (*Betula* family Betulaceae) species mixes represent the predominant forest cover types in Indiana (37 and 39% respectively), Ohio (39 and 27% respectively) and Pennsylvania (47 and 39% respectively). The greatest variety of tree species are found in Michigan forests with spruce (*Picea* family Pinaceae) – fir (*Pseudotsuga* family Pinaceae) (15%), maple (*Acer* family Aceraceae) – beech – birch (38%) and aspen (*Populus* grandidentata Michx.) – birch (27%) (Birdsey and Lewis, 2003).

Carbon Sequestration in the Forest Litter Layer

Amichev et al. (2004) estimate litter layer carbon assuming that there is a direct relationship between the cumulative leaf area of a forest and the litter layer carbon pool. The primary components used in the regression analysis are a site index and stand age. Average rates of carbon accumulation in the litter layer are estimated by dividing the litter layer carbon stock by age of the mine site for this analysis. Litter layer carbon stocks range from 0.1 Mg/ha/yr at a number of sites (Table 5.26) to 0.4 Mg/ha/yr in Virginia with an overall average for all sites of 0.18 Mg/ha/yr. Soil carbon sequestration rates from adjacent states are applied to the states not included in the study area (Maryland and Michigan).

Birdsey and Lewis (2003) use forest inventory data and research methods to estimate carbon accumulations in the forest litter layer. Birdsey and Lewis (2003) assume that initial forest floor carbon is zero when reforestation from cropland or pasture is estimated. Their research indicates that the carbon in litter layers is similar to reference sites after 50 years of forest establishment. The assumption that there is no carbon in the litter layer fits well with the litter layer or reforested mine lands since there are no biomass inputs at the start of reclamation. Data are available for a broad class of forest ecosystems, but only general data are used for this analysis. For the MRSCP study region, estimates of carbon in the forest litter layer for the specific states considered in the analysis are used by applying the following.

1. Land-use changes in forestry result in forest litter layer losses due to clearing or other tree removal. To ensure that the forest litter layer carbon estimates are derived only from biomass production, the Birdsey and Lewis (2003) data are first adjusted to remove forest litter layer carbon losses generated by land use change.
2. Subtract the forest litter layer C stock in 1987 from the forest litter layer C stock in 1997 to estimate the change in the forest litter layer C stock between 1987 and 1997.
3. Divide the result of step 2 above by 10 to derive the annual change.
4. Convert the data presented in Tg (million metric tons) to Mg (metric ton) by dividing by 1,000,000.
5. Divide by the area (ha) of forest considered in the analysis by state to estimate the annual rate of change per hectare. The resulting value is then multiplied by the area of mine land in each county of the state where the forest litter layer C accumulation rate was derived to estimate forest litter layer C gains per year.

Carbon accumulations in the litter layer using these calculations range from -0.05 Mg/ha/yr in Kentucky to 0.2 Mg/ha/yr in Maryland, Michigan and Ohio. In addition to Kentucky, carbon losses are also estimated for Pennsylvania and West Virginia using the Birdsey and Lewis (2003) estimates (Table 5.26). All estimates indicate that carbon accumulations in the litter layer are relatively small compared to soils and above-ground biomass.

Carbon Estimates Using the IPCC Method (Pasture, Forest, or Cropland)

The Intergovernmental Panel on Climate Change (IPCC) method is used to estimate carbon accumulation in soils when the land use prior to mining activities is known. The IPCC developed the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories to provide methods for signatory countries to the United Nations Framework Convention on Climate Change (UNFCC) to estimate emissions by sources and removals by sinks of greenhouse gases. The Land Use, Land Use Change and Forestry section of the guidelines provides a method for estimating net carbon emissions from soils. The method estimates average annual carbon emissions and/or sinks from land use and management changes, based on computed soil carbon stock changes over a 20-year inventory period. Default values for baseline soil carbon stocks are provided along with a series of coefficients that determine carbon stock changes as a function of climate, soil type, disturbance history, tillage intensity, productivity, and residue management (IPCC, 1997a). Documentation of the inventory methods for land use and management change are in the IPCC Workbook Module 5 (Land-Use Change and Forestry; IPCC, 1997a) and Reference Manual, Chapter 5 (Land-Use Change and Forestry; IPCC, 1997b).

The IPCC Guidelines are developed for use by all member countries of the UNFCCC, including countries lacking detailed data on land use and management changes. Thus the data requirements represent a compromise between the level of detail required to conduct the most accurate inventory estimates for each country and the input data likely to be available in most countries (IPCC, 1997a). The uncertainty in the estimates of greenhouse gas emissions from agriculture and from land-use change and forestry may be as high as ± 50% (IPCC, 1997a). However, because each input data set has an associated level of uncertainty that gets passed through the analysis, it is difficult to directly quantify the level of uncertainty in this type of analysis (Cannell et al., 1999; Houghton et al., 1999).

The IPCC method involves the stratification of land area into major climatic regions and soil types to determine reference soil carbon stocks. Within each climate-soil stratum, the areas associated with different land use and land management systems are categorized at the beginning and end of the inventory period. Soil C stock changes are then computed based on changes in land use and management that occur within the inventory period, for the entire land area included in the inventory.

The average change in soil carbon stock for each climate-soil-land use/management category is computed with the following equations:

$$d\text{C} \;=\; \sum_{FIPS=1}^{N} (SC_{End} \;-\; SC_{Init}) \tag{1}$$

$$SC_{End} = (Ha_{End} \times SC_R \times BF \times TF_{End} \times IF_{End}) \tag{2}$$

$$SC_{Init} = (Ha_{Init} \times SC_R \times BF \times IF_{Init}) \tag{3}$$

where   δC   =   the change in C stocks for that land use scenario between the start of reclamation and 20 years later,

   N   =   the MRCSP counties

   Ha_{End} =   hectares in that land use (pasture, forest, etc.) 20 years after reclamation begins,

   SC_{End} =   soil carbon stock 20 years after reclamation begins,

   SC_{Init} =   soil carbon stock when reclamation begins,

   SC_R =   the IPCC default estimate of soil carbon under native vegetation - reference level (varies by climatic zone and soil type),

   BF   =   the IPCC base factor,

   TF_{End} =   the IPCC tillage factor (if forest or pasture, =1),

   IF_{End} =   the IPCC input factor based upon residue inputs from land use activities in during reclamation,

   Ha_{Init} =   the number of hectares of mine land in the county,

   IF_{Init} =   the IPCC input factor based upon residue inputs at start of reclamation.

The total change in soil carbon stocks for the climatic region is the sum of soil carbon stock changes for each land use category within the region. Baseline changes in soil carbon stocks were then converted to annual average rates of change of carbon (Tg/yr) for the inventory period for the entire study region.

Soils in reclaimed mine areas are assumed to be low activity (low clay content) mineral soils for this analysis. The IPCC method results in average soil carbon sequestration of 1.8 Mg/ha/yr from forest, 1.4 Mg/ha/yr from pasture and 0.96 Mg/ha/yr from continuous row crop under no-till when it is assumed that mining activities leave the soil with 50% of the carbon available under native vegetation (Table 5.26). These rates of soil carbon accumulation are higher than expected, predominantly because the IPCC method assumes it requires only 20 years to reach a new equilibrium. Therefore, since the carbon stock at the start of reclamation is small relative to the carbon stock under native vegetation, the annual rate of change is large. When the carbon stock at the start of reclamation is assumed to be 60% of the carbon stock under native, the average annual rates of carbon accumulation are 1.4, 1.1, and 0.6 Mg/ha/yr respectively for forest, pasture, and continuous row crop under no-till (Table 5.26).

Table 5.26. Averages (in bold) and ranges of rates of carbon sequestration derived from various studies addressing states within the MRCSP region.

Land Use Category	Carbon Sequestration Rate (Mg/ha/yr) for MRCSP States						
	IN	KY	MD	MI	OH	PA	WV
Hardwood Forest (Study 2: Amichev et al.)							
Total	**2.5**[a]	**3.4**	NA	NA	3.0 – 3.3 **3.0**	NA	NA
Biomass	**1.5**	**2.2**	NA	NA	2.3 – 2.5 **2.4**	NA	NA
Litter Layer	**0.4**	**0.3**	NA	NA	0.03 - 0.04 **0.04**	NA	NA
Soils	**0.6**	**0.9**	NA	NA	0.3 – 0.8 **0.53**	NA	NA
Pine Forest (Study 2: Amichev et al.)							
Total	**1.7**	2.7 – 4.3 **3.4**	NA	NA	NA	1.8	1.8 – 4.9 **3.4**
Biomass	**1.3**	2.7 – 4.0 **2.9**	NA	NA	NA	2.2	2.1 – 4.5 **3.3**
Litter Layer	**0.2**	0.1 – 0.2 **0.1**	NA	NA	NA	-0.2	0.1 – 0.2 **0.2**
Soils	**0.16**	0.2 – 0.4 **0.4**	NA	NA	NA	-0.2	-0.5 – 0.2 **-0.1**
Reclaimed Mineland (Study 1: Akala et al.)							
Forest Soils	**1.1**	1.1	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**
Pasture Soils	**1.2**	1.2	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
General Forest (Study 3: Birdsey et al.)							
General Forest	0.8 – 5.1 **2.3**	-1.5 – 0.8 **0.65**	-2.9 – 1.6 **1.2**	0.07 – 2.5 **1.9**	0.05 – 3.1 **2.3**	-1.3 – 1.7 **0.4**	0.03 – 3.6 **1.8**
Biomass	**2.2**	**0.72**	**0.6**	**1.4**	**1.8**	**0.1**	**1.8**
Litter Layer	**0.05**	**-0.05**	**0.2**	**0.2**	**0.2**	**-0.01**	**-0.006**
Soils	**0.02**	**-0.02**	**0.4**	**0.3**	**0.3**	**0.25**	**0.06**
General Forest (Study 4: Heath et al.)							
Total	0.4 – 1.4 **0.9**	-0.1 – 1.0 **0.4**	0.7 – 1.8 **1.1**	0.4 – 1.4 **0.9**	0.4 – 1.4 **0.9**	0.7 – 1.8 **1.1**	0.7 – 1.8 **1.1**
Biomass	0.7 – 1.0 **0.8**	0.5 – 0.7 **0.6**	0.8 – 1.1 **0.9**	0.7 – 1.0 **0.8**	0.7 – 1.0 **0.8**	0.8 – 1.1 **0.9**	0.8 – 1.1 **0.9**
Soil	-0.3 – 0.4 **0.07**	-0.6 – 0.3 **-0.15**	-0.1 – 0.7 **0.2**	-0.3 – 0.4 **0.07**	-0.3 – 0.4 **0.07**	-0.1 – 0.7 **0.2**	-0.1 – 0.7 **0.2**
General Forest (Study 7)							
General Forest	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Reclaimed Mine Land Soil (Study 5: IPCC)							
Reclaimed Mine Land Soil	1.0 – 7.0 **2**	1.0 – 7.0 **2**	1.0 – 7.0 **2**	1.0 – 7.0 **2**	1.0 – 7.0 **2**	1.0 – 7.0 **2**	1.0 – 7.0 **2**
Mine Land Soil (Study 6: Lal et al.)							
Mine Land Soil	1.0 – 3.0 **2**	1.0 – 3.0 **2**	1.0 – 3.0 **2**	1.0–3.0 **2**	1.0–3.0 **2**	1.0–3.0 **2**	1.0–3.0 **2**

Land Use Category	Carbon Sequestration Rate (Mg/ha/yr) for MRCSP States						
	IN	KY	MD	MI	OH	PA	WV
IPCC Method - Base Factor = 0.5							
Forest Soil	0.9 – 2.7 **1.78**	0.9 – 2.6 **1.75**	0.9 – 2.7 **1.77**	1.0 – 3.0 **1.98**	0.9 – 2.7 **1.80**	0.9 – 2.8 **1.85**	0.9 – 2.7 **1.79**
Pasture Soil	0.7 – 2.1 **1.42**	0.7 – 2.1 **1.40**	0.7 – 2.1 **1.42**	0.7 – 2.2 **1.58**	0.7 – 2.1 **1.44**	0.7 – 2.2 **1.48**	0.7 – 2.1 **1.43**
Cropland Soil	0.5 – 2.1 **0.96**	0.5 – 2.1 **0.94**	0.5 – 2.1 **0.96**	0.5 – 2.4 **1.07**	0.5 – 2.2 **0.97**	0.5 – 2.2 **1.00**	0.5 – 2.1 **0.96**
IPCC Method - Base Factor = 0.6							
Forest Soil	0.7 – 2.1 **1.43**	0.7 – 2.1 **1.40**	0.7 – 2.1 **1.42**	0.8 – 2.8 **1.58**	0.7 – 2.2 **1.44**	0.7 – 2.2 **1.48**	0.7 – 2.1 **1.43**
Pasture Soil	0.5 – 1.6 **1.07**	0.5 – 1.6 **1.05**	0.5 – 1.6 **1.06**	0.6 – 1.8 **1.19**	0.5 – 1.6 **1.08**	0.6 – 1.7 **1.11**	0.5 – 1.6 **1.07**
Cropland Soil	0.3 – 0.9 **0.60**	0.3 – 0.9 **0.59**	0.3 – 0.9 **0.60**	0.3 – 1.0 **0.67**	0.3 – 0.9 **0.61**	0.3 – 0.9 **0.63**	0.3 – 0.9 **0.61**
Reclaimed Soil after Surface Mining (Study 8: Sinclair et al.)							
Cropland Soil	0.2 – 3.3 **1.6**	NA	NA	NA	NA	NA	NA

Study 1   Akala, V.A. and R. Lal, 2000. Potential of Mine Land Reclamation for Soil Organic Carbon Sequestration in Ohio. Land Degradation & Development. 11: 289-297.

Study 2   Amichev, B., J. A. Burger, and J.A. Rodrigue, 2004. Presentation at the 2004 National Meeting of Mining and Reclamation and the 25th West Virginia Surface Mine Drainage Task Force, April 18-2, Lexington, KY.

Study 3   Birdsey, R.A. and G.M. Lewis. 2003. Carbon in United States Forests and Wood Products, 1987-1997: State-by-State Estimates. Gen. Tech. Rep. NE-310, U.S. Department of Agriculture, Forest Service, Northeastern Research Station. Newtown Square, PA.

Study 4   Heath, L., J. Smith, and R.A. Birdsey. 2003. Carbon Trends in U.S. Forestlands: A Context for the Role of Soils in Forest Carbon Sequestration. In Kimble, J.M., L.S. Heath, R.A. Birdsey and R. Lal, (Eds.), The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect, CRC Press, Boca Raton, FL.

Study 5   IPCC, 1998. Special Report on Land-Use, Land-Use Change, and Forestry. http://www.grida.no/climate/ipcc/land_use/

Study 6   Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1999. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press LLC., Boca Raton, FL.

Study 7   Parks, P.J. and I.W. Hardie, 1996. Forest Carbon Sinks: Costs and Effects of Expanding the Conservation Reserve Program. Choices, Second Quarter.

Study 8   Sinclair, H.R., Jr., K.M. McWilliams, S.L. Wade, and G.R. Struben. 2004. Characterization of Reclaimed Soils in Southwestern Indiana after Surface Mining for Coal. Proceedings of the 2004 National Meeting of the American Society of Mining and A103Reclamation and the 25th West Virginia Surface Mine Drainage Task Force, April 18-24. American Society of Mining and Reclamation, Lexington, KY, pp 1674-1699.

[a]   A range of carbon sequestration rates could not be provided for all sites because some studies contained estimates or measurements from a single site.

Carbon Accumulation for Various Land Use Categories

As presented in Table 5.24, mining activities occurred on over 567,000 ha in the MRCSP region after 1992. The largest area of mine lands is in West Virginia, with over 183 thousand ha, followed by Pennsylvania with over 125,000 ha. The area of mine land by county in the MRCSP study region is shown in Figure 5.15.
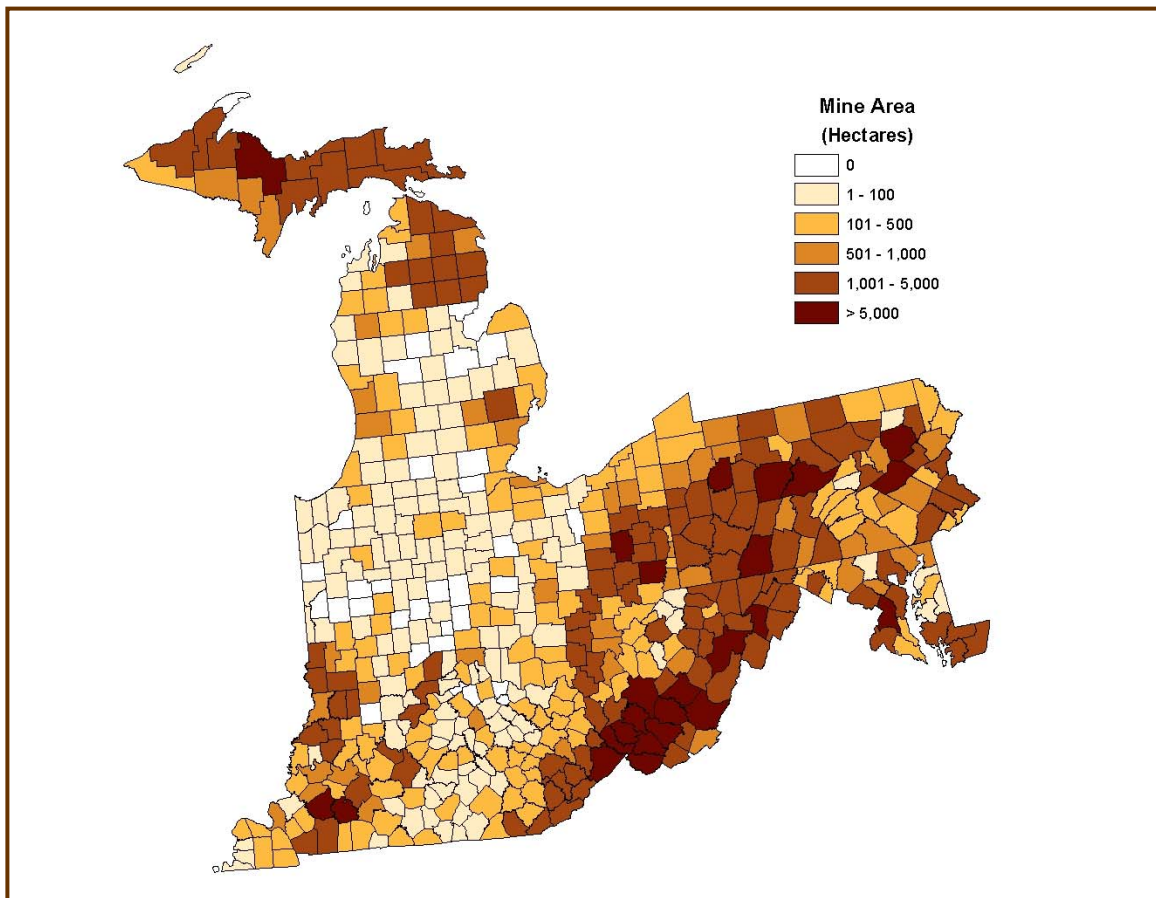
Figure 5.15.   Mine land area (ha) by county for the MRCSP region.

There is considerable variability in literature derived rates of carbon sequestration in above-ground biomass, forest litter layer and soils. For this analysis, total carbon sequestration on reclaimed mine land is estimated using the average rates of sequestration derived from the literature and area of mine land, by state (Table 5.27). The annual rates of carbon accumulation from all studies are combined to provide a single value. For example, the average carbon change in forest soils is calculated as the average of all forest soil carbon studies. Note that forest litter in Pennsylvania exhibits carbon emissions rather than carbon sequestration gains. Both studies used to derive the average rate of carbon accumulation in forest litter for Pennsylvania showed carbon losses.

Table 5.27. Range and average (in bold) annual rates of carbon sequestration by carbon sink components of different land uses during mine reclamation in different states.

Land Use Component	Carbon Sequestration Rate (Mg/ha/yr) for MRCSP States						
	IN	KY	MD	MI	OH	PA	WV
Forest Total	1.4 – 4.3 **2.6**	2.2 – 5.2 **2.7**	1.5 – 4.5 **2.2**	1.7 – 4.1 **2.5**	2.2 – 5.0 **3.1**	1.5 – 4.5 **2.0**	2.1 – 5.4 **3.0**
Forest Biomass	0.8 – 2.2 **1.4**	0.6 – 2.4 **1.5**	0.6 – 1.1 **0.8**	0.4 – 1.9 **1.1**	1.5 – 1.8 **1.7**	0.8 – 2.0 **1.1**	1.5 – 2.8 **2.0**
Forest Litter	0.05 – 0.4 **0.2**	-0.05 – 0.3 **0.1**	**0.2**	**0.2**	**0.2**	**-0.1**	**0.1**
Forest Soil	0.7 – 3.3 **1.0**	0.5 – 2.7 **1.0**	0.7 – 3.4 **1.2**	0.7 – 3.4 **1.2**	0.7 – 3.3 **1.2**	0.7 – 3.4 **1.0**	0.6 – 2.6 **0.9**
Pasture Soil	0.7 – 2.1 **1.3**	1.2 – 1.4 **1.3**	0.7 – 2.1 **1.3**	0.7 – 2.2 **1.4**	0.7 – 2.1 **1.3**	0.7 – 2.2 **1.3**	0.7 – 2.1 **1.3**
Cropland Soil	0.5 – 2.1 **1.3**	0.7 – 2.1 **0.94**	0.7 – 2.1 **0.96**	0.5 – 2.4 **1.1**	0.5 – 2.2 **0.97**	0.5 – 2.2 **1.0**	0.7 – 2.1 **0.96**

Annual rates of carbon sequestration for pine and hardwood forests are combined to estimate a single carbon sequestration rate for general forests. Only Birdsey and Lewis (2003) and Amichev et al. (2004) analyze pine and hardwood forests separately. Average total carbon sequestration from all three forest components (above-ground biomass, litter layer, and soils) range from 2.0 Mg/ha/yr in Pennsylvania to a high of 3.1 Mg/ha/yr in Ohio. The carbon sequestration rate for above-ground biomass is largest in West Virginia, 2.0 Mg/ha/yr and lowest in Maryland, 0.8 Mg/ha/yr. The lower rate of carbon accumulation for Maryland is partially due to the limited number of studies available for the sate. When the only available literature contains small sequestration rates for the state, the total carbon sequestration possible for the state is limited.

The carbon accumulation rates in forest soils are within the range of previous research. Forest soil carbon sequestration rates derived for this analysis range from 0.9 Mg/ha/yr in West Virginia to 1.2 Mg/ha/yr in Maryland, Michigan, and Ohio. The rates of soil carbon gain from pasture are the most consistent across all states, averaging close to 1.3 Mg/ha/yr. Rates of soil carbon sequestration on cropland soils are lower than forest and pasture soils, except in Indiana where cropland soils sequester the same amount as forest soils. Cropland soils accumulate less carbon than forest and pasture because biomass is removed when a crop is harvested, so carbon inputs to the soil are made only by the root structure and plant litter remaining after harvest.

Total carbon sequestration in the MRCSP region is estimated by multiplying the annual rate of change of carbon sequestration, by the area of mine land in each county. All mine land is assumed to be reclaimed to the same use (forest, pasture, or cropland). When all mine land is reclaimed to forest, total sequestration is estimated to be nearly 1.5 Tg/yr with over a third (nearly 0.54 Tg/yr) from forest in West Virginia (Table 5.28 and Figure 5.16). The data indicate that, in addition to having the largest area of mine land in the MRCSP region, combining the carbon in biomass, litter layer and soil derived from West Virginia forests also provides the second highest rate of carbon sequestration of any MRCSP state. Carbon accumulation in forest is predominantly derived from above-ground biomass in all MRCSP states. Forest litter contributes the least of the forest components to carbon sequestration in forests. Carbon sequestration on forest soils also contribute significantly to overall forest carbon sequestration (0.51 Tg/yr).
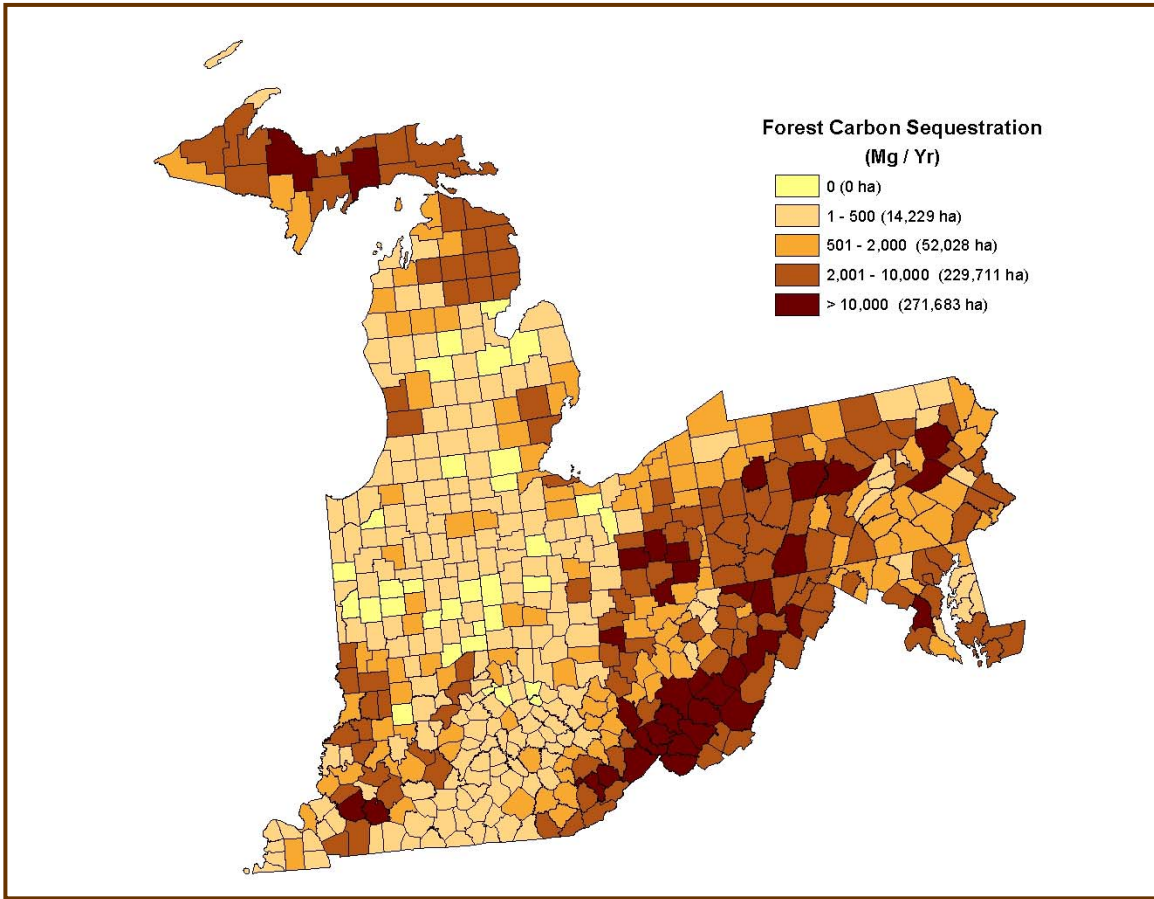
Figure 5.16. Annual carbon sequestration (Mg/yr) by MRCSP counties when all mine land is reclaimed to forest.

Table 5.28. Range and average (bold) rates of annual carbon accumulation from different land use activities.

| Land Use Category | Annual Carbon Accumulation for MRCSP States (1,000 Mg/yr) | | | | | | | Total |
	IN	KY	MD	MI	OH	PA	WV	(Tg/yr)
Total Forest	41-129 **78.6**	149-354 **177.4**	44-129 **69.2**	114-277 **178.0**	132-287 **178.1**	188-561 **256.8**	376-987 **537.2**	1.0-2.7 **1.48**
Forest Biomass	24-66 **42.9**	42-45 **104.8**	23-32 **27.1**	75-82 **79.6**	95-111 **99.9**	138-150 **141.0**	266-514 **334.8**	0.7-1.1 **0.83**
Forest Litter	**6.5**	**7.9**	**5.8**	**13.7**	**7.6**	**-13.2**	**17.8**	**0.05**
Forest Soil	20-99 **29.2**	34-181 **64.7**	20-97 **36.2**	46-229 **84.8**	37-176 **70.6**	88-423 **128.9**	110-473 **184.5**	0.4-1.7 **0.60**
Pasture Soil	21-82 **39.6**	48-143 **88.2**	20-61 **38.1**	48-150 **94.9**	44-133 **83.7**	88-276 **168.0**	128-386 **241.3**	0.4-1.2 **0.75**
Cropland Soil	15-63 **29.0**	34-143 **65.6**	14-61 **27.5**	34-164 **67.5**	32-140 **69.9**	63-276 **140.2**	92-386 **149.8**	0.3-1.2 **0.55**

The Birdsey and Lewis (2003) data show very low rates of carbon accumulation in above-ground biomass between 1987 and 1997 for forests in Maryland (0.7 Tg from 1.1 Mha), and Pennsylvania (0.1 Tg from 6.8 Mha). It is possible that the forests analyzed in these states are more mature and therefore accumulating less carbon, but a reason for the lower carbon values is not included in the literature.

When all mine land in the study area is planted to pasture, a total of 0.75 Tg/yr of carbon may be stored in the soils. The largest carbon accumulations on pasture soils occur in West Virginia and Pennsylvania, the states with the largest areas of mine land (Table 5.28 and Figure 5.17). Reclaiming mine land to cropland provides the lowest annual rate of carbon accumulation, 0.55 Tg/yr, with most gains in West Virginia and Pennsylvania (Figure 5.18). The higher rate of accumulation, particularly for West Virginia, is strictly a function of the large amount of mine land in the state. It is not likely that most of the mine land in West Virginia would be reclaimed to cropland because the terrain is not conducive to agricultural production.

A comparison of the 1992 NLCD data to mine permit data for permits issued after 1992 indicates that nearly 51% (4,167 ha) of Indiana and 15% (5,987 ha) of Pennsylvania mine land was in cropland before mining activities. Mine land that was in cropland prior to mining is less than 1% for Kentucky and West Virginia. Therefore, it is likely that the total annual accumulation of carbon from mine land reclaimed to cropland is closer to the 0.17 Tg/yr that may be sequestered when mine land in Indiana and Pennsylvania is reclaimed to cropland.
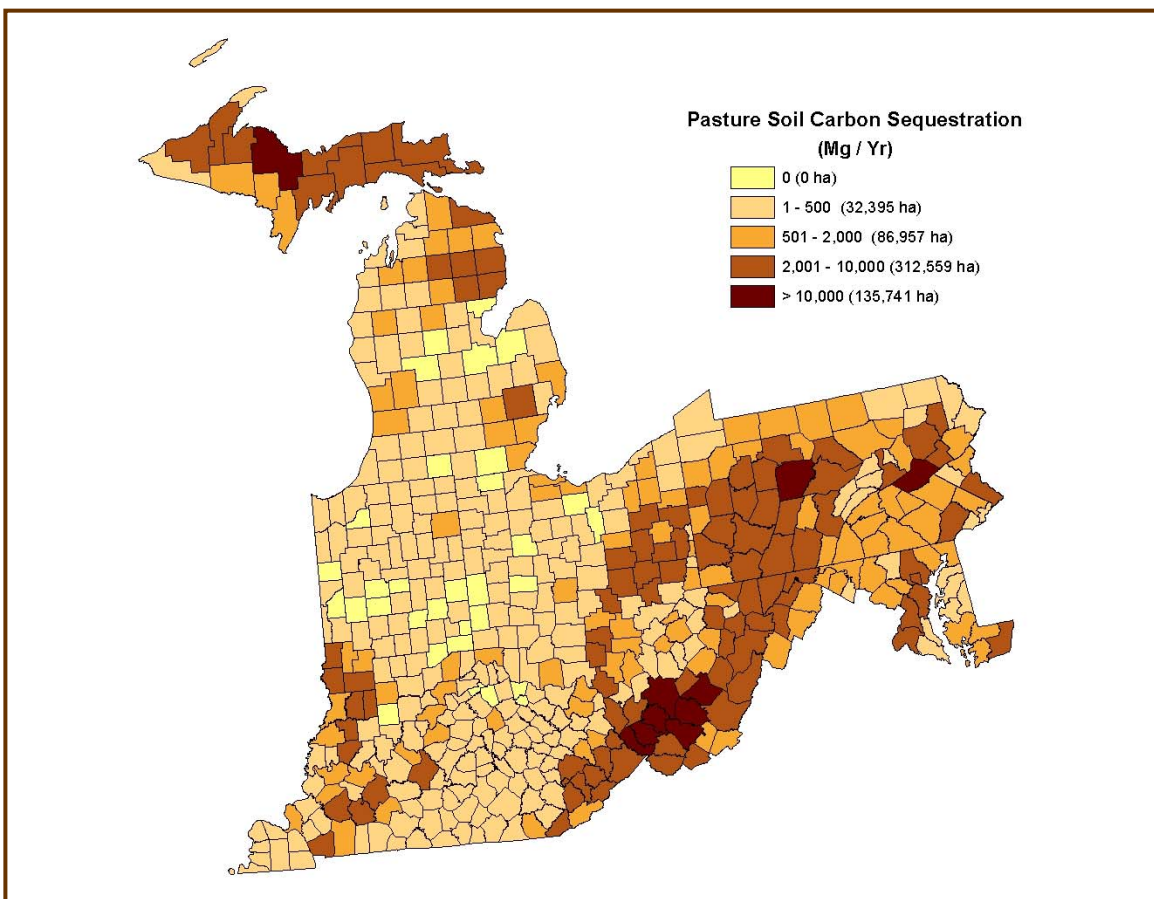
Figure 5.17.   Annual carbon sequestration (Mg/yr) by MRCSP counties when all mine land is reclaimed to pasture.
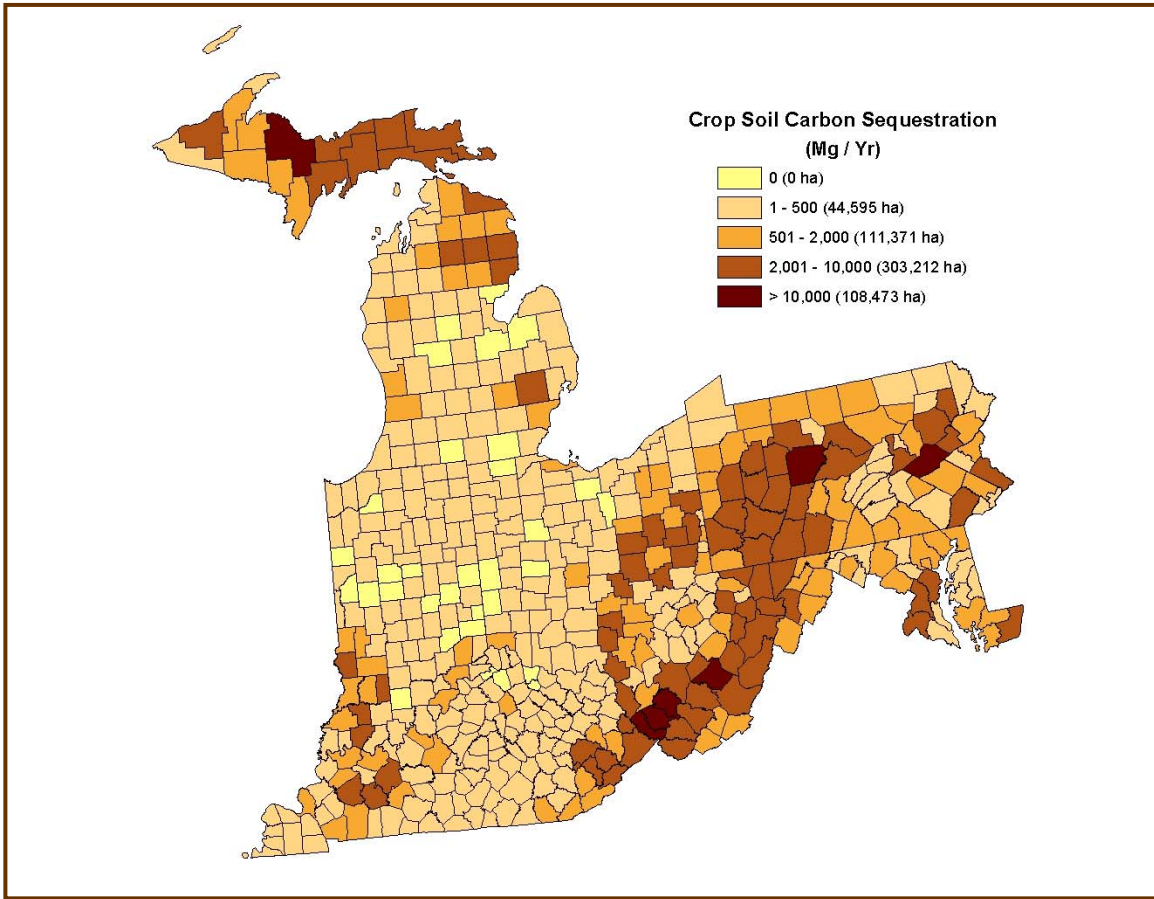
Figure 5.18. Annual carbon sequestration (Mg/yr) by MRCSP counties when all mine land is reclaimed to cropland.

Reclaiming all mine land to forest provides a biophysical potential carbon sequestration of 29.5 Tg over twenty years (Table 5.29 and Figure 5.19). The largest carbon pools are attained from mine land reclaimed to forest in West Virginia (10.7 Tg) and Pennsylvania (5.1 Tg). The litter layer in Pennsylvania does not sequester any carbon during the twenty years.

Table 5.29. Range and average, in bold, rates of carbon accumulation in MRCSP states from different land use activities over 20 years.

| Land Use Category | Carbon Accumulation for MRCSP States (Tg) | | | | | | | Total Tg |
	IN	KY	MD	MI	OH	PA	WV	
Total Forest	0.8-3	3-7	0.9-3	2-5	3-6	4-11	8-20	21-54
	1.6	**3.5**	**1.4**	**3.6**	**3.6**	**5.1**	**10.74**	**29.5**
Forest Biomass	0.8-0.9	2-3	0.5-0.6	1-2	2-2	2.8-3	5-10	15-22
	0.9	**2.1**	**0.5**	**1.6**	**2.0**	**2.8**	**6.70**	**16.6**
Forest Litter	**0.1**	**0.2**	**0.1**	**0.3**	**0.2**	**-0.3**	**0.36**	**0.9**
Forest Soil	0.4-2	0.7-4	0.4-2	0.9-5	0.7-4	2-9	2-10	7-34
	0.6	**1.3**	**0.7**	**1.7**	**1.4**	**2.6**	**3.69**	**12.0**
Pasture Soil	0.4-2	1-3	0.4-1	1-3	1-3	2-6	3-8	8-25
	0.8	**1.8**	**0.8**	**1.9**	**1.7**	**3.4**	**4.83**	**15.1**
Cropland Soil	0.3-1	0.7-3	0.3-1	0.7-3	0.6-3	1-6	0.8-8	6-25
	0.6	**1.8**	**0.3**	**1.4**	**2.3**	**3.7**	**1.0**	**10.9**

Potential Carbon Gains on Reclaimed Mine Lands ("Hot Spots")

The biophysical potential carbon sequestration for the MRCSP region is estimated using the land use in each county that provides the highest annual rates of carbon accumulation and the area of mine land. Reclaiming mine land to forest provides the largest annual carbon accumulation in the MRCSP region.

The total annual carbon sequestration potential from all counties is almost 1.5 Tg/yr (Table 5.30). Nearly 59% of the total carbon sequestration potential may be attained through reclaiming mine land to forest in 10% of the MRCSP region counties. Selecting areas where carbon sequestration is greater than 7,500 Mg/yr allows 51 counties to contribute to total carbon sequestered. The largest area of mine land in these counties is in West Virginia (49%), Pennsylvania (18%), and Kentucky (10%), which, combined, account for nearly 80% (0.66 Tg/yr) of the total carbon sequestration potential (0.85 Tg/yr). Over 85% of the total potential carbon sequestration in West Virginia and nearly 50% of the total in Kentucky, Ohio, and Pennsylvania is captured in the designated "hot spots" (Table 5.30). Carbon sequestration "hot spots" are identified by determining the areas of mine land that provide the highest annual accumulation of carbon and the county location for those sites (Figure 5.20).

Table 5.30. Highest estimated annual carbon gains for "hot spot" counties (>7,500 Mg/ yr) in MRCSP states.

State	Mine Area (1,000 Ha)		Total Carbon from all Counties (1,000 Mg/yr)	Potential Carbon Gain in "Hot Spot Counties		Percent of Total Potential Carbon
	Total Mine Area	Area in "Hot Spot" Counties		1,000 Mg/yr	Percent of Total	
Indiana	30.2	6.7	78.6	17.4	1%	22%
Kentucky	67.9	31.6	177.4	82.6	6%	47%
Maryland	29.1	9.1	69.2	21.6	1%	31%
Michigan	68.3	26.0	178.0	67.9	5%	38%
Pennsylvania	125.4	57.5	256.8	117.7	8%	46%
Ohio	63.4	30.3	178.1	85.2	6%	48%
West Virginia	183.5	156.9	537.2	459.2	31%	85%
TOTAL	**567.7**	**318.1**	**1,475.3**	**851.8**	**58%**	**58%**

Conclusions for Mine Lands

The analysis shows that the largest carbon sequestration is obtained by reclaiming all mine land in the MRCSP region to forest. Reclaiming all mine land in the MRCSP region to forest provides a biophysical potential of sequestering 1.5 Tg/yr or a total of nearly of 30 Tg over a twenty year period.

Mine land in West Virginia and Pennsylvania provide the largest carbon sequestration potential from forest on reclaimed mine sites (10.2 and 4.7 Tg of carbon respectively). Assuming mine land in Indiana and Ohio are reclaimed to cropland provides 2.2 Tg of carbon, which is less than the 6.9 Tg that could be accumulated if mine land is reclaimed to forest.
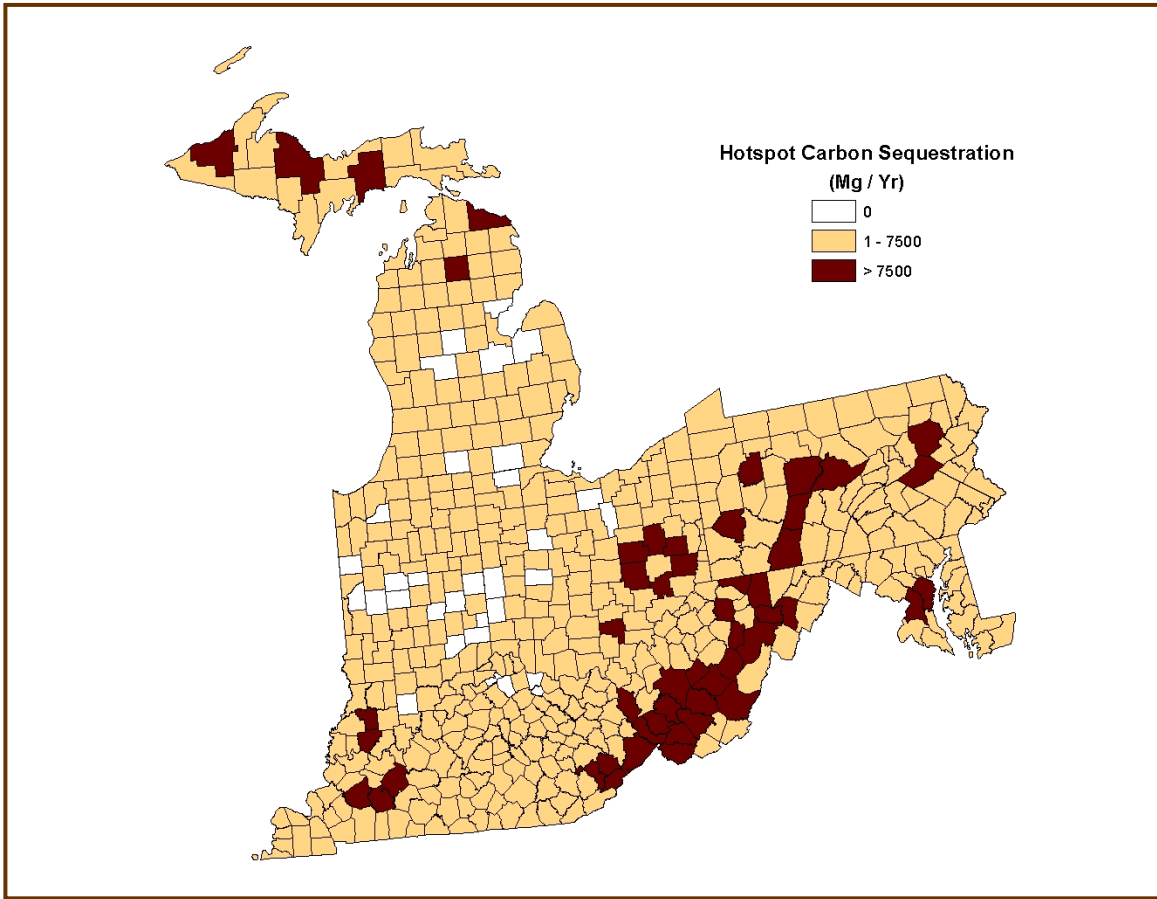
Figure 5.19.   Carbon sequestration "hot spots" showing counties where the annual accumulation of carbon is greatest when all mine land is reclaimed to forest.

Additional research is required to establish the soil carbon stock at the start of reclamation activities. In this analysis, assuming that 50% of the carbon stock was present when reclamation begins results in carbon sequestration rates that are too high in some cases (e.g., the IPCC method results in carbon accumulation rates considerably higher than expected). In other cases, especially in forest soils, the assumption results in soil carbon accumulation rates that are smaller than expected, and even negative. A better understanding of the impact of soil disturbance for mining on the soil carbon stock is required to improve the analyses.

As part of the MRCSP effort, a chronosequence study of reclaimed mine sites in West Virginia is planned. This chronosequence study will provide some data to establish carbon stocks on mine land sites at the start of reclamation. In addition, this study will provide additional data that will allow refinement of the Akala and Lal (2000) equation development to estimate the carbon accumulation on reclaimed mine sites.

The present analysis estimates carbon sequestration on mine lands by assuming all mine lands are reclaimed to the same activity. Estimates are generated using these assumptions for ease of analysis, but may over- or understate carbon gains on mine lands. Additional analyses are required to attribute carbon gains to mine land using the land use prior to mining activities as the base. These data are limited to only

those sites where GIS data provide a geospatial location for the mines that can be compared to the 1992 NLCD to attribute the land use prior to mining.

The rates of soil carbon sequestration derived using the IPCC methods are higher than expected. Additional work is required to determine the value of the IPCC provided coefficients that are most appropriate for this analysis.

Soil carbon sequestration on mine land soils may be enhanced through the addition of materials that enhance the nitrogen content of the soil and increases biomass production. Two such activities are the application of poultry litter and bio-solids, which some research has demonstrated to effectively enhance soil carbon sequestration. A future activity that will be pursued is to analyze the extent soil amendments may increase the rate of soil carbon sequestration on mine land soils. A two-fold benefit could be derived from these activities. First, increasing carbon sequestration helps to mitigate greenhouse gas emissions. Second, applying amendments that must otherwise be disposed of in some way creates a use for a waste product.

Mine lands are not only reclaimed to forest, pasture and cropland, the primary activities analyzed for this project, but also to golf courses, schools, playgrounds, baseball fields and other uses. Soil carbon sequestration on some of these land uses may be greater than the sequestration from forest, pasture or cropland. It may be worthwhile to assess how these other land uses may contribute as greenhouse gas mitigation activities.

Wetlands

Wetlands are seasonally saturated soils under herbaceous or forested natural vegetation. Wetland soils are also used for agricultural and urban land uses. Saturation-induced anaerobic conditions in the upper part of the soil suppress decomposition rates. Decomposition under anaerobic conditions is primarily fermentation and methanogenesis (Mitsch and Gosselink, 2000). With high net primary productivity and low decomposition rates, soil organic matter accumulates. Biomass pools fluctuate minimally under established herbaceous cover and increase in forested wetlands. Methane, a significant greenhouse gas, is produced in non-tidal wetlands.

Wetlands are diverse ecosystems found across climatic regions (Mitsch and Gosselink, 2000). Water saturation may be caused by water-restricting soil horizons or by a near-surface regional ground water. For this analysis, we have divided the wetlands of the MRCSP region into *peatland*, *tidal marsh*, and *other wetland* classes. Other wetlands include all herbaceous and forested wetlands identified in the USGS National Land Cover Dataset that were not identified as either tidal marsh or peatland.

Peatlands

Peatlands are soils with a peat surface layer. Peat is incompletely decomposed organic soil material (fibric material) (Clymo et al., 1998). Note that some researchers (e.g., Gorham, 1991) have also used the term peat to refer to all histosols. Canada has the largest peatland area of any nation with approximately 110 MHa (Mitsch and Gosselink, 2000). Peatlands in the U.S. are primarily along the northern tier from Minnesota to Maine. Within the MRCSP region, peatlands are found only in the state of Michigan, with the greatest area in northern Michigan.

Tidal Marshes

Tidal marshes are high-intertidal environments with vegetated, repeatedly flooded platforms dissected by creek networks (Allen, 1997; Rabenhorst, 2001). Marshes develop and are sustained in environments with protection from storms and waves and sufficient sediment deposition to accrete with sea-level rise. They are among the most productive ecosystems on earth, with production variability related to solar radiation inputs and nutrient availability (Mitsch and Gosselink, 2000). They can be significant carbon sinks under sea-level rise through organic and mineral accretion (Rabenhorst, 1995). However, marsh decline is widespread, with a presumably decreasing carbon sink over time (Cooper et al., 2001; Kearney et al., 2002). The response of marshes to global change remains an uncertainty, making it difficult to integrate marsh carbon dynamics into global predictive models. Sea-level rise and sediment deposition rates are primary factors affecting long term marsh carbon storage and loss. Sediment deposition directly builds marsh soils to assist in accretion rates; organic deposition is also strongly influenced by sediment deposition rates (Mitsch and Gosselink, 2000). Tidal marshes act as dissolved carbon and nutrient sinks and sources under varying settings and conditions (Cai et al., 2000). Tidal marshes also influence estuarine and marine carbon cycles (Stevenson et al., 1985; Cai et al., 2003). The influence of coastal wetlands on atmospheric carbon remains a significant uncertainty (Reed and Cahoon, 1999).

Tidal marshes are extensive in North America along the Atlantic coast, the Gulf of Mexico, and the Pacific coast. There are an estimated 1.9 MHa of salt marsh and 0.8 Mha of freshwater tidal marsh in the United States (Mitsch and Gosselink, 2000). In the Atlantic Coastal Plain, salt marsh tidal range is generally small, which limits sediment deposition. Dominant plant species are *Spartina alterniflora*, *S. patens*, *Juncus roemerianus*, and *Distichlis spicata* (Mitsch and Gosselink, 2000).

Other Wetland Types

Natural soil drainage class (typically referred to as drainage class) is a measure of the frequency and duration of saturation under the conditions of pedogenesis (Soil Survey Staff, 1993). Drainage class is a dominant property considered during the soil mapping process and is therefore among the more accurate and precise data within the STATSGO database. However, drainage class is locally defined and is therefore subject to regional differences.

Drainage class categories are excessively well drained, somewhat excessively well drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained soils. Wetland soils (hydric soils) may be under somewhat poorly, poorly, or very poorly drained soils. Hydric soils are delineated in the field using morphological regionally defined indicators (http://soils.usda.gov/use/hydric/). Carbon content increases dramatically with decreasing drainage class, with organic soils typically forming in very poorly drained series (Trumbore and Warden, 1997). Organic soils have a carbon content greater than 12 to 18 % (depending on clay content) and typically overlie mineral horizons. Organic soil layers range from centimeters to tens of meters in thickness.

The Wetlands Reserve Program (WRP), managed through the USDA Natural Resources Conservation Service, is a voluntary program in which farmers receive payments for wetland restoration efforts (http://www.nrcs.usda.gov/programs/wrp/).

The objectives of the terrestrial research described here for wetlands were to quantify the carbon sink capacity for major land use components in the MRCSP region and to identify land use and management options to achieve that sink capacity. This research included determination of the hot spots in specific land use scenarios for carbon sequestration with various conservation practices. Finally, efforts were made to develop linkages with industry stakeholders, and to create awareness of terrestrial sequestration among the public at large.

The following subsections describe the approach taken in analyzing wetlands in this study. For more information on the general methodology followed by the MRCSP terrestrial research team, see the report in this series titled Methodology.

Source Data

Data sources for the wetland analysis included:

1. Soil maps and attribute data: State Soil Geographic (STATSGO) database (http://www.ncgc.nrcs.usda.gov/branch/ssb/products/statsgo/). See the separate report in the MRCSP terrestrial series titled Methodology for additional details.
2. Land use data: USGS National Land Cover/ Land Use Database (NLCD) (1992 Landsat TM imageries) (http://landcover.usgs.gov/natllandcover.asp), See the separate report in the MRCSP terrestrial series titled Methodology for additional details.
3. Coastal marsh extent data in Maryland derived from the Global Land Cover Facility Coastal Marsh Project (http://glcf.umiacs.umd.edu/data/coastalMarsh/product.shtml).

Method for Calculating Area of Wetlands

Wetland area was calculated for each STATSGO polygon directly from NLCD quantification of cells with values of 91 (woody wetlands) and 92 (emergent herbaceous wetlands). The calculation method is described in more detail in a separate report in the MRCSP series titled Terrestrial Methodology.

Method for Estimating Carbon Sequestration
in Upper 30 cm of Wetland Soils

Soil carbon mass in the upper 30 cm was calculated for STATSGO polygons using STATSGO geographic and tabular data. Note that this methodology is identical to that described in the Methodology report in the Task 2.2 series, except that calculations were restricted to poorly to very poorly drained components. There is significant soil carbon storage below 30 cm in most wetlands soils (Moore and Turunen, 2004). Also, organic layers have lower bulk densities than mineral soils, further underestimating the relative carbon content of wetland soils when calculated on a volumetric basis (Ellert and Bettany, 1995). For example, peat layers in southern Manitoba were calculated to have a bulk density of 0.1 g/cm^3 (Ovenden et al., 1990) while mineral surface soils typically have bulk densities greater than 1.0 g/cm^3. Therefore this carbon storage estimate is within the context of the 30 cm depth used by the MRSCP Terrestrial Working Group and should not be interpreted as a full carbon pool estimate.

The calculation was performed following the procedure described in the separate report in the MRCSP terrestrial series titled Methodology, except that only poorly drained to very poorly drained components were used.

Analysis steps performed in ArcGIS:

1. Begin with state SOCP component tables for each state calculated through section 2-2.C described in the Methodology report. Add to ArcGIS map document as "MD_SOCPCOMP" (where "MD" is the two-letter state code).
2. Select poorly to very poorly drained components using code: "DRAINAGE" = 'P' OR "DRAINAGE" = 'P,VP' OR "DRAINAGE" = 'VP' OR "DRAINAGE" = 'VP,P' OR "DRAINAGE" = 'P,V' OR "DRAINAGE" = 'VP,'. Export as new table "MD_SOCPCOMP_PVP".
3. Add the state comp.dbf table and join it to the MD_SOCPCOMP_PVP.dbf by the variable MUIDSEQNUM.
4. Add a field CPbySOCP and calculate values as equal to: [MD_SOCPCOMP_PVP.CPCOMP]* [COMP.COMPPCT]. Export as "MD_SOCPCOMP_PVP2.dbf".
5. Summarize by MUID with the sum of [COMPPCT] and the sum of [CPbySOCP]. Save as MD_SOCPMUID_PVP.
6. Add a field "WETL_CPCT". Calculate values as: [Sum_CPbySO] / [Sum_COMPPC].
7. Repeat step 1-6 for each state.
8. Join tables to MRCSP STATSGO shapefile and add field WET_CPCT_T (Total) and calculate values as sum of individual state WETL_CPC value so that each polygon with poorly to very poorly drained soils has a WETL_CPCT value.
9. Add field WETL_SOCP2. Calculate values as: 10*[WETL_HA] * [WET_CPCT_T] (units are Mg)
10. Select all rows with WETL_SOCP2 = 0 and calculate values as equal to [WETL_SOCP]. (This corrects for STATSGO map units without P to VP drained soils but with wetlands.)
11. Delete unnecessary fields added through joins.

Method for Estimating Carbon Sequestration Potential in Wetlands

Carbon sequestration in wetland soils occurs through natural processes and may be increased through conversion of lands to wetlands and through improved wetland management and conservation. For this analysis, the following three land use categories were considered as those with the most substantial carbon sequestration potential (Table 5.31):

1. Peatlands – naturally sequester large carbon pools; only present in Michigan within the MRCSP region.
2. Tidal marshes – tidal marshes under rising sea levels have among the highest carbon sequestration rates of any ecosystem; only present in Maryland within the MRCSP region.
3. Land conversion from cropland to wetland – non-prime farmland on poorly to very poorly drained soils throughout MRCSP region

For each land use, high and low carbon sequestration potential was estimated over a 20-year period. Carbon sequestration rates were not determined for wetlands other than peatlands and tidal marshes because of both a likely small sequestration potential and a lack of published research data on these wetlands. Methane production and biomass sequestration were not estimated.

Table 5.31.   Carbon sequestration rate calculation methods, values, and literature sources.

Land Type	Method	Carbon Sequestration Rate (kg/ha/yr)		Literature Source
		Low	High	
Tidal marshes	Range of literature values	2500	5700	Hussein et al., 2005
Peatlands	Range of literature values	230	350	Tornacai (1988) Ovenden (1990)

Land Use Conversion	Method	State Mean (Mg/ha)		Data Source
		Minimum	Maximum	
Cropland to wetland	Difference between current C content and maximum C content in upper 30 cm	9 (KY)	218 (MI)	STATSGO polygon

Method for Estimating Carbon Sequestration Potential Over 20 Years in Peatlands. Peatland area estimates were calculated by determining the map unit percentage of components under a peat surface texture as listed in the STATSGO comp.dbf table. Carbon sequestration rates in peatlands are a function of temperature, with greater rates in boreal and temperate peatlands as compared to subarctic peatlands (Ovenden et al., 1990). For a high sequestration rate, we used the estimate by Ovenden et al. (1990) of 350 kg/ha/yr of carbon determined through an analysis of peat deposits in southern Manitoba, Canada (Table 1). The low estimate of 230 kg/ha/yr of carbon was taken from Tarnocai (1988) (Table 1). This estimation method does not account for loss or harvesting of peatlands or variation in sequestration rates due to ecosystem productivity or carbon dioxide enrichment.

Analysis steps performed in ArcGIS:

1. Select rows in Michigan STATSGO comp table with SURFTEX = "Peat". Summarize MUID with sum of COMPPC. Join to STATSGO shapefile by MUID. Export as mrcsp_statsgo_nlcd3_a83_NewWet4.
2. Create new field Peat_HA. Calculate as [HECTARES] * [Sum_COMP_1] /100.
3. Select rows where Peat_HA is greater than WETL_HA, set Peat_HA equal to WETL_HA in these polygons.
4. Delete unnecessary fields.
5. Add field "Peat_SqC_L", the Mg of C sequestered over 20 years – low estimate. Calculate as 230 * 20 * [Peat_HA] / 1000 (units Mg). Rate of 230 kg/ha/yr from Tornacai (1988).
6. Add field "Peat_SqC_H", the Mg of C sequestered over 20 years – high estimate. Calculate as 350 * 20 * [Peat_HA] / 1000 (units Mg). Rate of 350 kg/ha/yr from Ovenden (1990).

Method for Estimating Carbon Sequestration Potential Over 20 Years in Tidal Marshes. Tidal marsh area estimates were inputted from data available through the Global Land Cover Facility Coastal Marsh Project (Kearney et al., 2002). Kearney et al. (2002) developed a mixed-pixel classification system to estimate marsh extent and condition data using summer Landsat imagery. Pixels are classified using a spectral mixed modeling method. The mixture modeling identifies end members using the Normalized Difference Water Index, the Normalized Vegetation Index, and the Normalized Difference Soil Index. Marsh decline follows a transitional shift to increased soil reflectance upon vegetation thinning, to dominance of water upon transition to submergence. Vegetated platforms are classified from non-

degraded to completely degraded. For the MRCSP analysis, completely degraded marshes were not included. This method has been validated in the Mid-Atlantic region (Kearney et al., 2002).

For the high and low sequestration rates, we used the rates of 2500 and 5700 kg/ha/yr measured in a study of tidal marsh soils in the lower eastern shore of Maryland (Hussein et al., in review). This estimation method does not account for loss or transgression of tidal marshes, sea-level rise scenarios, or variation in sequestration rates due to ecosystem productivity, sediment availability, or carbon dioxide enrichment.

Analysis steps performed in ArcGIS:

1. Import Coastal Marsh data set (available from http://glcf.umiacs.umd.edu/data/coastalMarsh/product.shtml), select polygons with marshes not completely deteriorated using "GRID_CODE" = 1 OR "GRID_CODE" = 2 OR "GRID_CODE" = 3. Export as MD_Marsh123.shp.
2. Intersect with STATSGO file to generate MDMarshIntersection.shp. Add to a geodatabase to add area field.
3. Summarize shapefile by STATE_ID.
4. Add field Marsh_HA, calculate as [Sum_Shape_] /(100*100).
5. Join to STATSGO shapefile by STATE_ID. Export as "mrcsp_statsgo_nlcd3_a83_NewWet3".
6. Select all records with marsh area greater than total wetland area: "Marsh_HA"> "WETL_HA", set the Marsh_HA of these polygons equal to WETL_HA.
7. Delete unnecessary fields.
8. Add field "Mars_SqC_L", the Mg of carbon sequestered over 20 years – low estimate. Calculate as 2500 * 20 * [Marsh_HA] / 1000 (units Mg). Rate of 2500 kg/ha/yr from Hussein et al. (in review).
9. Add field "Mars_SqC_H", the Mg of carbon (C) sequestered over 20 years – high estimate. Calculate as 5700 * 20 * [Marsh_HA] / 1000 (units Mg). Rate of 5700 kg/ha/yr from Hussein et al. (in review).

Wetland Conversion of Cropland on Non-Prime Farmland With Poorly to Very Poorly Drained Soils. The conversion of cropland to wetland by flooding and/or drainage reduction and the establishment of wetland plant communities will decreases decomposition rates and may increase net primary productivity (Roulet, 2000). Methane emissions will also be increased in non-coastal wetlands dependent on water table dynamics. We were not able to obtain appropriate published data or models on carbon sequestration rates following conversion of cropland to wetland through a literature search. There are several initiating projects that may produce suitable data, but these will not be available in the short-term. This is a significant gap in our knowledge and should be identified as a research priority. In the absence of these data, we estimated carbon sequestration potential as the difference between current 0-30 cm pools (estimated in the Methodology report) and the maximum 0-30 cm carbon pool of a component within each STATSGO map unit (Table 1). The logical basis for this calculation is that cropland to wetland conversion would only be conducted if the landscape and soil conditions were conducive to maximum carbon sequestration within the limitations of a soil landscape and climatic region (represented by the STATSGO polygon).

Analysis steps performed in ArcGIS:

1. Calculate percentage of poorly to very poorly drained soils on non-prime farmland in STATSGO map units through analysis of component tables. Join this table to mrcsp_statsgo_nlcd3_a83_NewWet.shp and export as "mrcsp_statsgo_nlcd3_a83_NewWet2.shp". Delete unnecessary fields.

2. Add field "CR_WT_HA_L" (hectares of cropland convertible to wetlands – low estimate). Calculate as: [CROP_ M4HA] * ([SUM_COMPPC]/100) * 0.23. [SUM_COMPPC] is the percentage of poorly to very poorly drained soils on non-prime farmland. 0.23 is the lowest conversion calculated in the SSURGO analysis in counties with greater than 0.5% convertible cropland.
3. Add field "CR_WT_HA_H" (hectares of cropland convertible to wetlands – high estimate). Calculate as: [CROP_M4HA] * ([SUM_COMPPC]/100) * 1.00. 1.00 is the highest conversion calculated in the SSURGO analysis in counties with greater than 0.5% convertible cropland.
4. Select rows with non-zero CROP_M4HA.
5. Summarize each state field MD_SOCPCOMP_PVP by MUID and calculate the maximum SOCP. Save as MD_CMax_PVP. This gives an estimate of the maximum potential carbon that could be sequestered by STATSGO polygon in the upper 30 cm upon conversion of a cropland to a wetland.
6. Join state fields to STATSGO shapefile, export as mrcsp_statsgo_nlcd3_a83_NewWet5. Delete unnecessary fields.
7. Add field MaxCrWt_Cp – calculate as the sum of the newly added fields: [Max_CPCO_1] + [Max_CPCO_2] + [Max_CPCO_3] + [Max_CPCOMP] + [Max_SOCP_1] + [Max_SOCP_2] + [Max_SOCPCO].
8. Add field "CR_WT_CP_L", calculate as (units are Mg): 10 * [CR_WT_HA_L] *([MaxCrWt_Cp] -([CROP_M4SOC]/ ([CROP_M4HA]*10))). Set negative values to zero.
9. Add field "CR_WT_CP_H", calculate as (units are Mg): 10 * [CR_WT_HA_H] * ([MaxCrWt_Cp] -([CROP_M4SOC]/ ([CROP_M4HA]*10))). Set negative values to zero.

Results

Table 5.32 presents the results of the analysis to determine the area and carbon sequestration potential of wetlands in the MRCSP area carried out using the methodologies described in the previous section. The values listed in the table are supported by graphics in the discussion of the different wetland types below.

Wetland Area

We estimate the area of wetlands in the MRCSP region at 3,388 kHa (Item A in Table 5.32). The largest extents of wetlands are found in Michigan, with smaller areas located in Maryland, Kentucky, northern and western Indiana, northern Ohio, and eastern and northwestern Pennsylvania (Figure 5.20).

Wetland Soil Carbon Pools in the Upper 30 cm

The total soil carbon pool in the upper 30 cm of wetlands is estimated at 656 Tg (Item A, Table 5.32), with 589 Tg in Michigan, 27 Tg in Maryland, and 22 Tg in Indiana. Carbon density is greatest in soils with thick organic layers; these soils are concentrated in Michigan and Maryland (Figure 5.21).

Table 5.32.   **MRCSP wetlands analysis summary by state and total.**

Wetland Type	State							Total MRCSP
	IN	KY	MD	MI	OH	PA	WV	
A. Wetlands (Carbon Pool in the Upper 30 cm of Soil)								
Area (Ha)	164,136	182,449	221,371	2,558,347	149,196	98,199	15,263	**3,388,963**
C (Tg)	22.3	5.8	26.8	589.0	7.4	4.0	0.7	**656.0**
B. Peatlands (Estimated Sequestration Potential)								
Area (Ha)	–	–	–	196,454	–	–	–	**196,454**
Low Est. Potential (Gg)	–	–	–	904	–	–	–	**904**
High Est. Potential (Gg)	–	–	–	1,375	–	–	–	**1,375**
C. Tidal Marshes (Estimated Sequestration Potential)								
Area (Ha)	–	–	81,761	–	–	–	–	**81,761**
Low Est. Potential (Gg)	–	–	4,088	–	–	–	–	**4,088**
High Est. Potential (Gg)	–	–	9,321	–	–	–	–	**9,321**
D. Cropland to Wetland Conversion (Estimated Area and Sequestration Potential)								
Low Est. Area (Ha)	22,087	477	2,028	48,295	23,791	3,228	240	**100,145**
High Est. Area (Ha)	96,030	2,072	8,816	209,980	103,439	14,036	1,043	**435,415**
Low Est. Potential (Gg)	3,674	5	307	10,529	1,140	47	4	**15,705**
High Est. Potential (Gg)	15,973	21	1,333	45,780	4,956	204	16	**68,282**
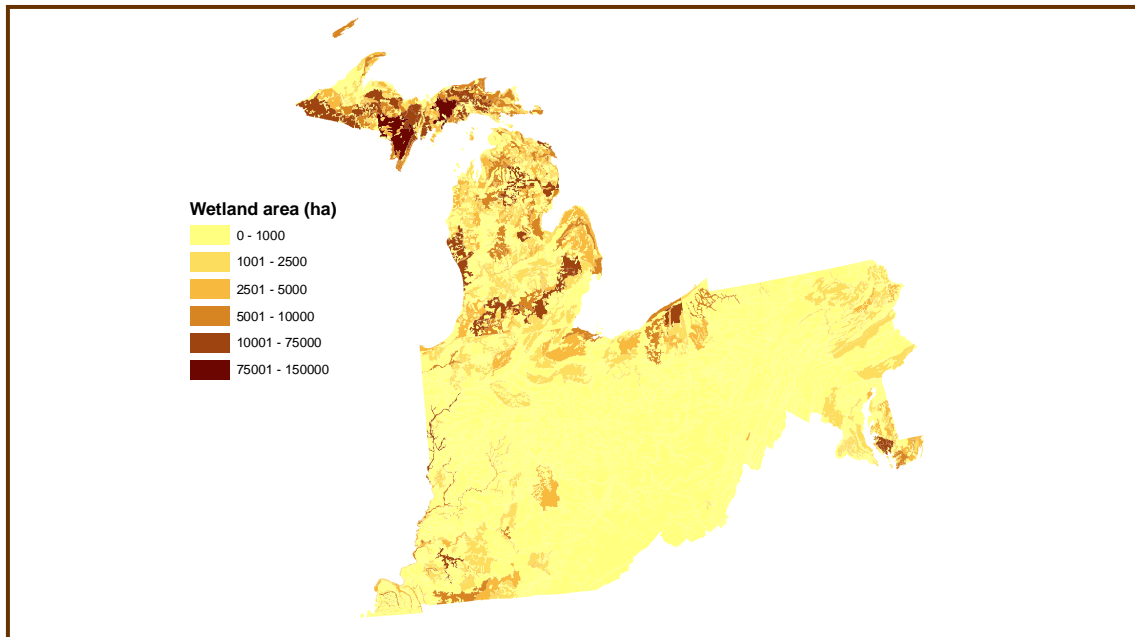
Figure 5.20.   **Area of wetlands in the MRCSP region.**
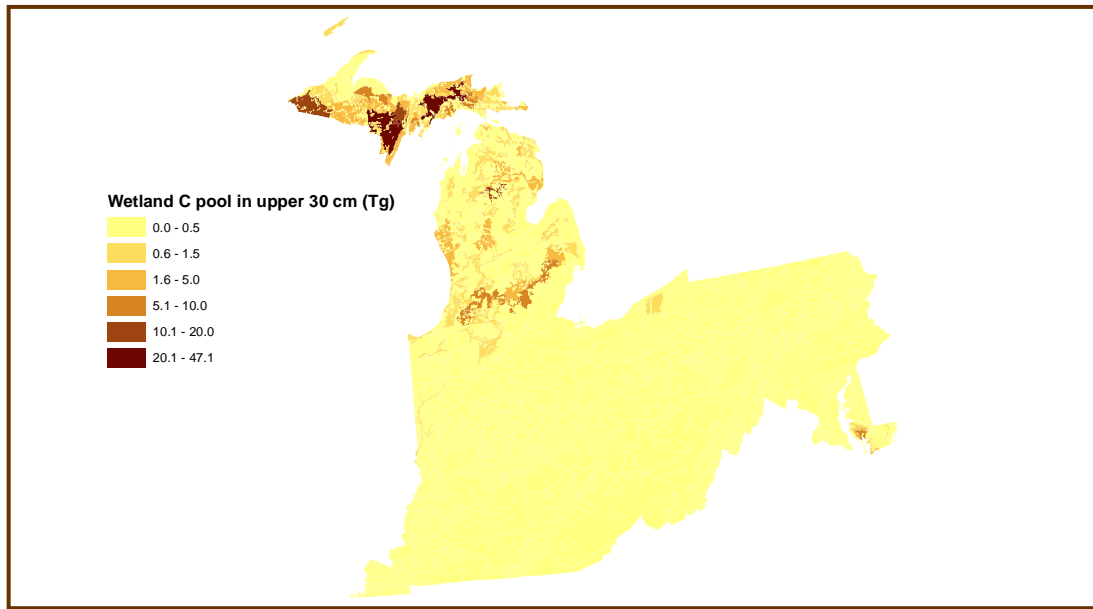
Figure 5.21. **Wetland carbon pool in the upper 20 cm.**

Carbon Sequestration Potential in Wetlands

Table 5.33 presents the results of the analysis to determine the area and carbon sequestration potential of peatlands, tidal marshes, and conversion of cropland to wetland in the MRCSP area carried out using the methodologies described in the previous section. The values listed in the table are supported by graphics in the discussion of the different wetland types below.

Table 5.33. **Summary of wetland carbon sequestration potential.**

	Land Use			
	Tidal Marshes	**Peatlands**	**Cropland to Wetland Conversion**	**Total**
Area (KHa)	82	196	100 to 435	378 to 713
Rate of carbon sequestration (kgC/ha/yr)	2500 to 5700	230 to 350	Rate not used in estimation	230 to 5700
Total potential over 20 years (Tg)	4.1 to 9.3	0.9 to 1.4	16 to 68 (time not specified)	5 to 10.7[a] 21 to 78.7[b]

[a] Without cropland conversion.
[b] Wth cropland conversion, unspecified time.

Carbon Sequestration Potential Over 20 Years in Peatlands

We estimate the area of peatlands in the MRCSP region at 196 kHa (Item B, Table 5.32). Peatlands are present only in one state, Michigan. As Figure 5.22 shows, peatlands are concentrated in northern Michigan, with limited extents in north-central Michigan. Carbon sequestration potential over 20 years was estimated as ranging from 0.9 to 1.4 Tg (Table 5.33). The distribution of carbon sequestration is a direct function of the spatial extent of peatlands under our calculation method (see Figure 5.23 for low case and Figure 5.24 for high case).

Carbon Sequestration Potential Over 20 years in Tidal Marshes

We estimate the area of tidal marshes in the MRCSP region at 82 kHa (Item C, Table 5.32). Marshes are present only in Maryland along both shores of the Chesapeake Bay and in Atlantic Coast estuaries (Figure 5.25). The greatest extents of tidal marsh are found along the eastern shore of the Chesapeake Bay, the lower eastern shore of Maryland.

Carbon sequestration potential over the next 20 years under rising sea-level is estimated to range from 4.1 to 9.3 Tg (Table 5.33). This calculation was based on zero loss of tidal marsh but without targeted management. The distribution of carbon sequestration is a direct function of the spatial extent of marshes under our calculation method (see Figure 5.26 for low case and Figure 5.27 for high case).
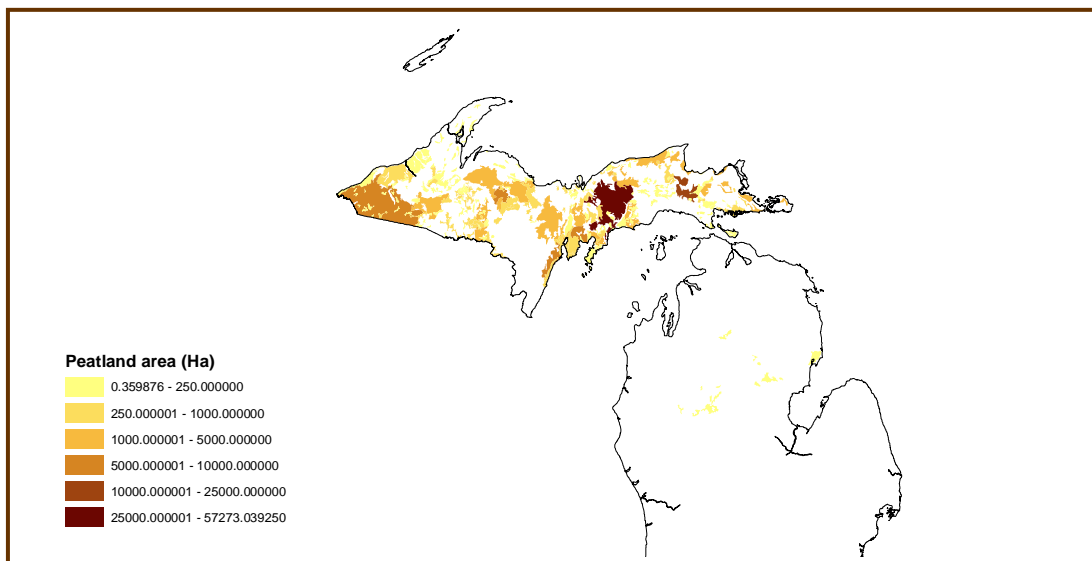
Figure 5.22.   Area of peatlands in the MRCSP region.
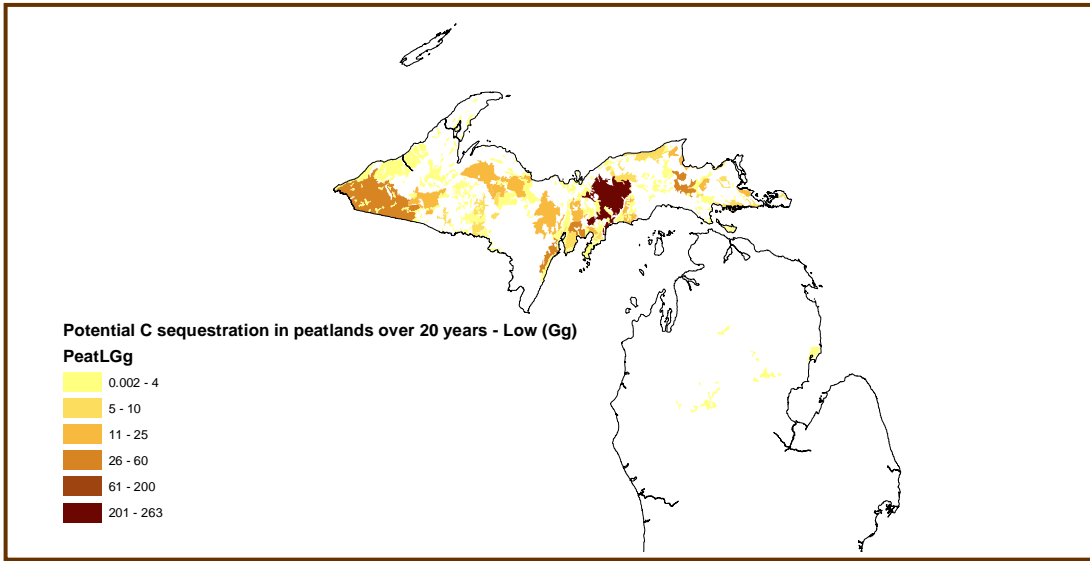
Figure 5.23.   Potential for carbon sequestration in peatlands over 20 years — low case.
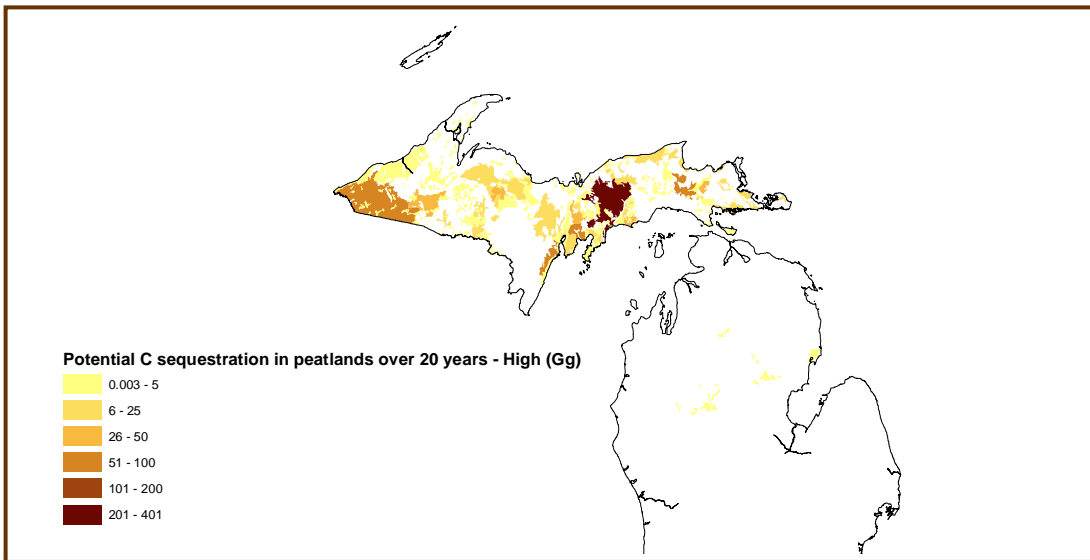
Figure 5.24.   Potential for carbon sequestration in peatlands over 20 years — high case.
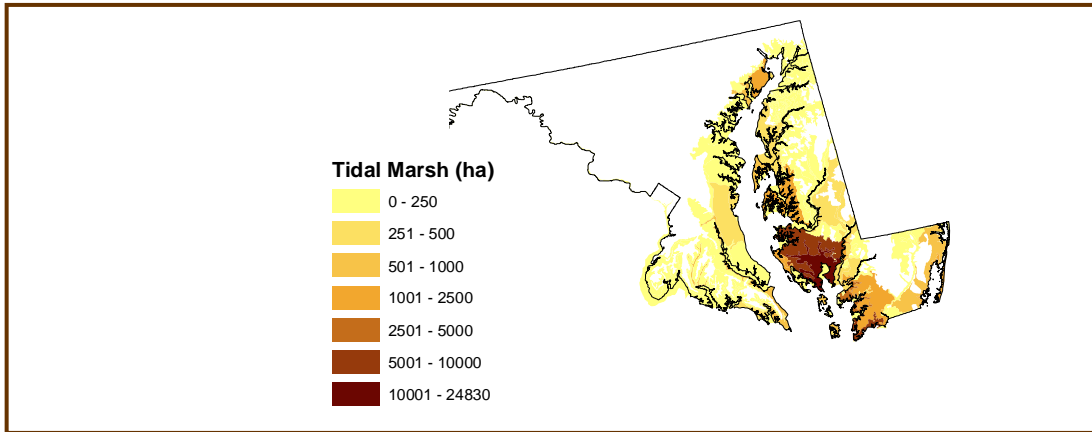
Figure 5.25. Area of tidal marsh in the MRCSP region.
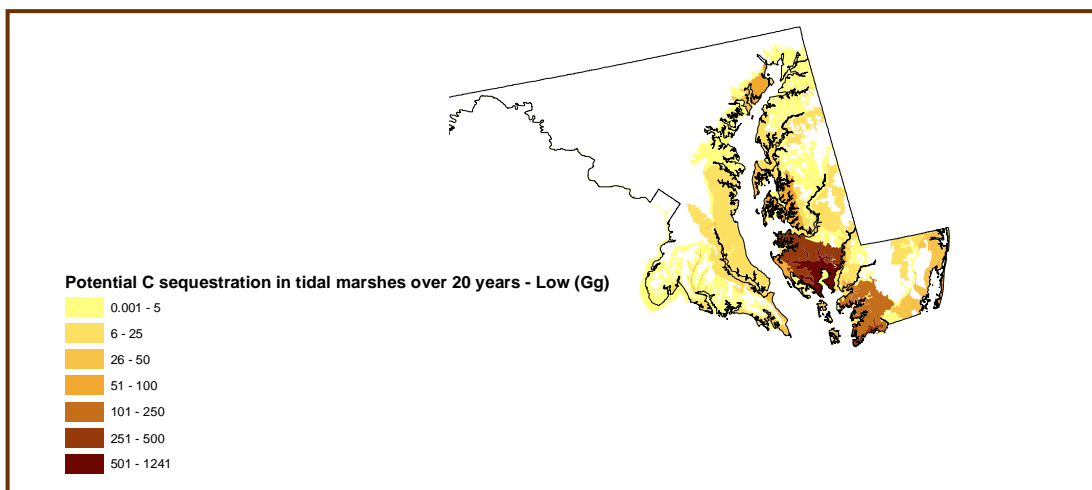
Figure 5.26. Potential for sequestration of carbon in tidal marshes over 20 years — low case.
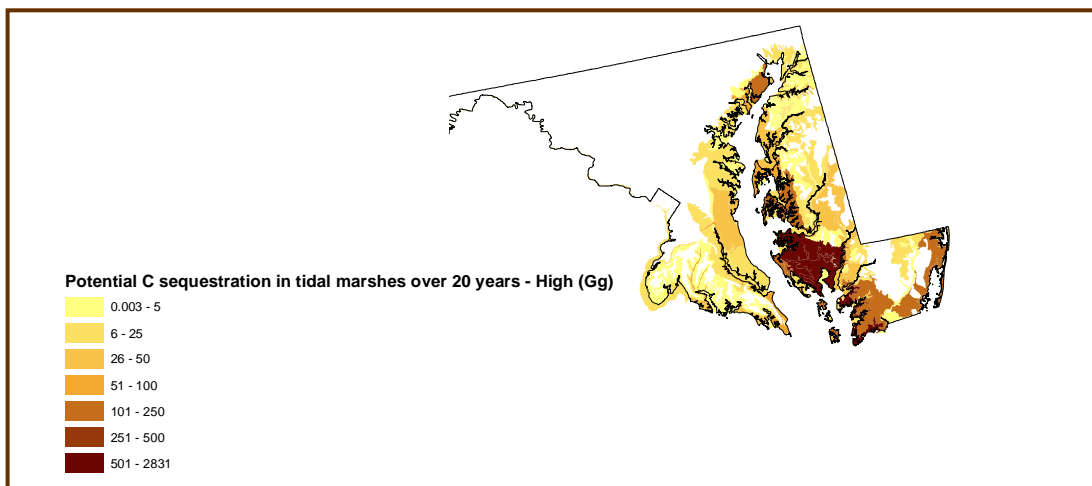
Figure 5.27. Potential for sequestration of carbon in tidal marshes over 20 years — high case.

Carbon Sequestration Potential Through Conversion of Cropland on Non-Prime Farmland With Poorly to Very Poorly Drained Soils

We estimate the area of potentially convertible cropland in the MRCSP region in the range from 100 to 435 kHa (Item D, Table 5.32). These areas are primarily in Michigan, Ohio, and Indiana (Item D, Table 5.32 and Figure 5.28 for low case and Figure 5.29 for high case). Potentially convertible wetlands soils are generally in areas with the greatest extent of existing wetlands. There are areas of concentration in southern Michigan, Ohio, northern Indiana, and eastern Pennsylvania.

Carbon sequestration potential was estimated as ranging from 15.7 to 68.3 Tg, with most of this potential in southern Michigan and northern Indiana (Figure 5.30 for low case and Figure 5.31 for high case). These states have large areas of potentially convertible cropland with organic surface soils. There are also limited areas of cropland with high conversion potential in parts of Ohio and eastern Maryland (Figures 5.30 and 5.31).
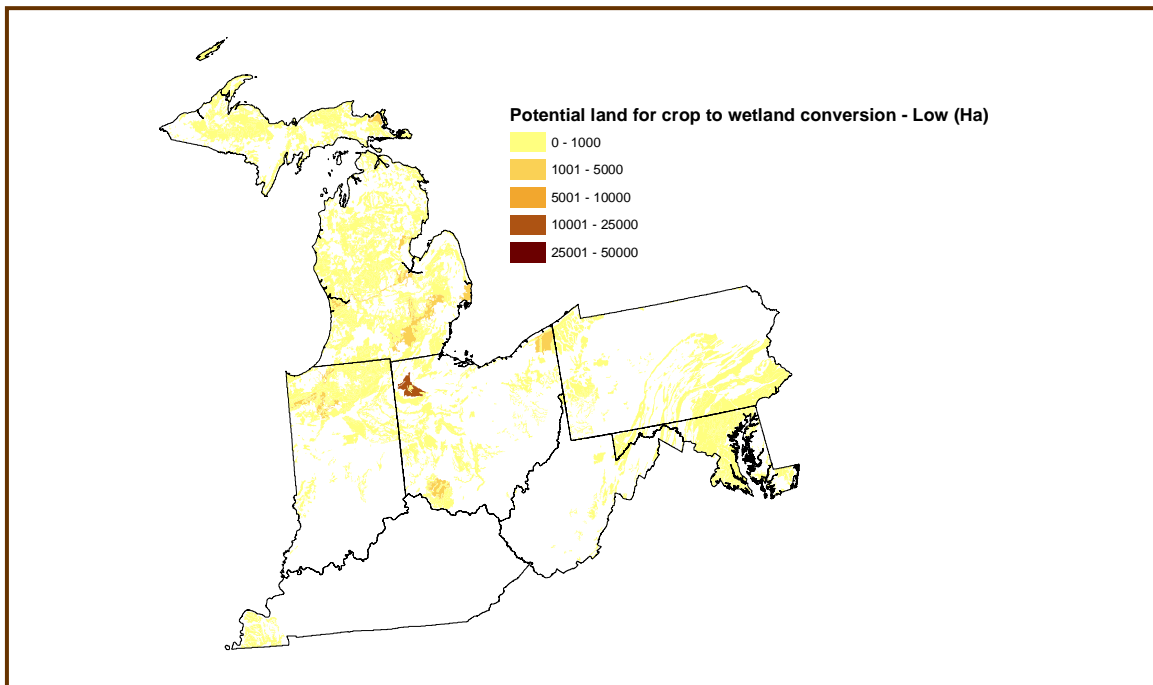
Figure 5.28.   **Potential land for cropland to wetland conversion — low case.**
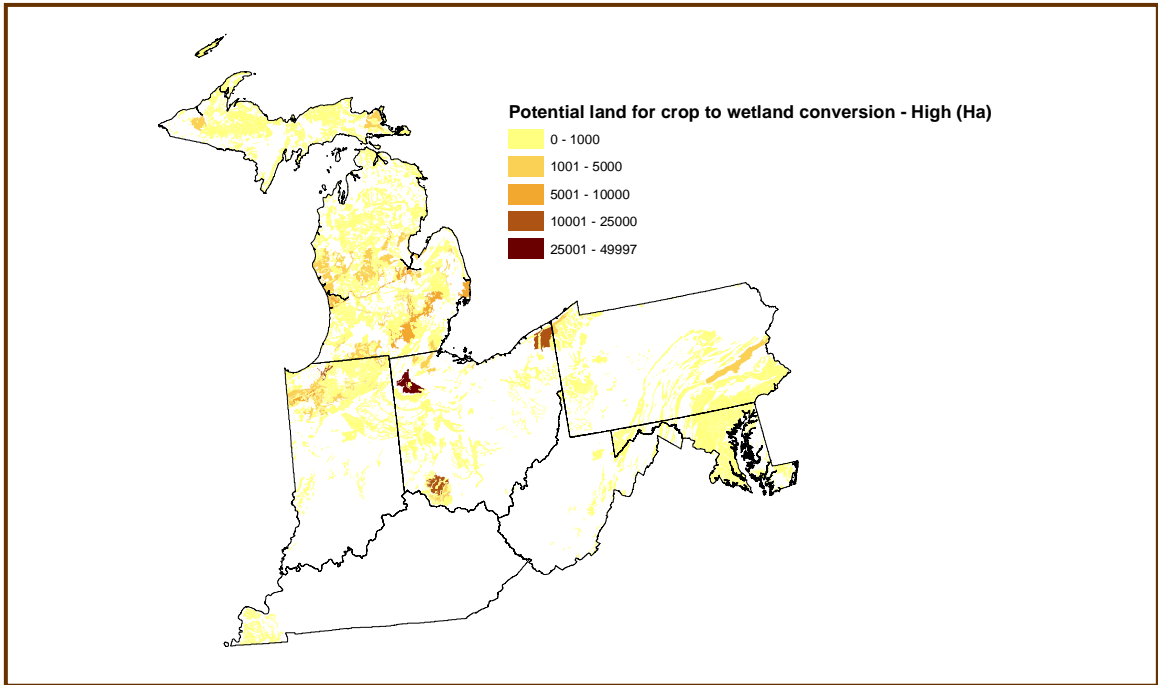
Figure 5.29.   Potential land for cropland to wetland conversion — high case.
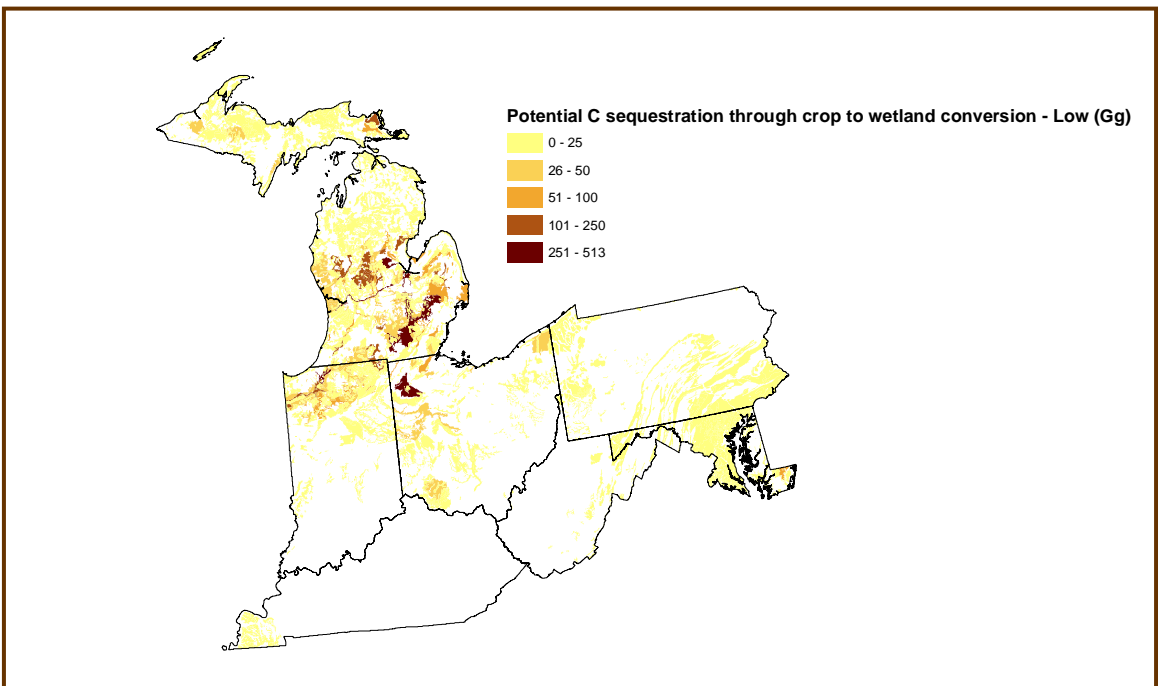
Figure 5.30.   Potential carbon sequestration through crop to wetland conversion — low case.
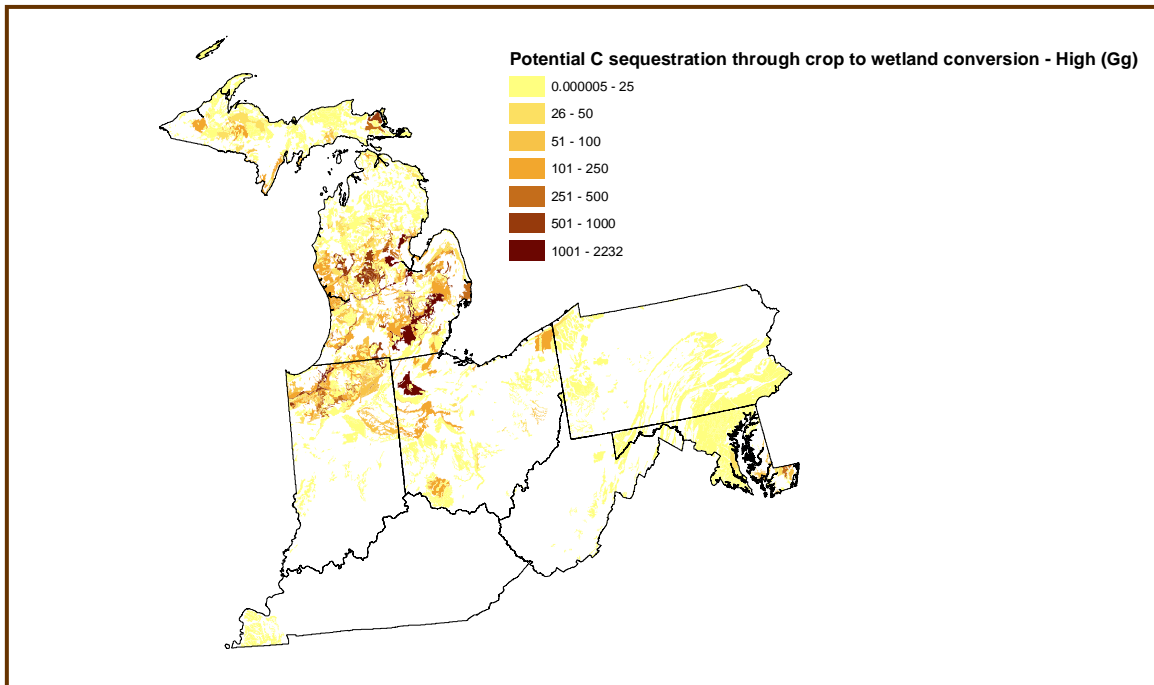
Figure 5.31.   Potential carbon sequestration through crop to wetland conversion — high case.

Conclusions for Wetlands

We estimate the area of wetlands at 3,388 kHa in the MRCSP region, and a total soil carbon pool in the upper 30 cm at 656 Tg, with 589 Tg in Michigan, 27 Tg in Maryland, and 22 Tg in Indiana. Wetland biomass pools and subsoil soil carbon pools were not estimated.

Among existing wetlands, the greatest carbon sequestration potential over 20 years is through tidal marsh conservation, with an estimated range of 4.1 to 9.3 Tg. Tidal marshes are present only in Maryland within the MRCSP region. Realization of this potential will require significant efforts to reverse the current trend of marsh loss under sea-level rise and development pressures (Kearney et al., 2002). Net carbon loss under current marsh losses and degradation rates was not estimated. Peatlands, present only in Michigan within the MRCSP region, are estimated to sequester from 0.9 to 1.4 Tg carbon over 20 years. Existing and future carbon storage in peatlands is threatened by anthropogenic disturbances including drainage, urban and industrial use, energy development, harvesting, and forestry (Garnett et al., 2000; Roulet, 2000).

We estimate that there is the potential to sequester from 15.7 to 68.3 Tg of carbon through cropland to wetland conversion. This estimate was based on limited data availability and was not validated through modeling; additional research is required to quantify this potential. No data sets are currently available to estimate the expected rate of carbon sequestration under cropland conversion. Most of this potential is in southern Michigan and northern Indiana with limited areas in parts of Ohio and eastern Maryland.

Analytical Modeling of Terrestrial Potential

The SOCRATES soil carbon model consists of five linked compartments which represent measureable soil carbon pools and plant-derived litter. These pools undergo first-order decomposition in response to temperature and moisture. All plant material consists of decomposable (DPM) and resistant (RPM) components based on the conceptual fractions initially described by Jenkinson (1990). The respective DPM/RPM ratios for the litter produced from a terrestrial ecosystems are the same as those used by Jenkinson et al. (1991) and are outlined in Table 5.34. The effect of temperature on decomposition is based on a Q_{10} relationship of 2.0 (equation 1) with T representing mean annual air temperature in Centigrade

$$TF = 0.177 \exp (0.069*T) \tag{1}$$

To broaden the range of terrestrial ecosystems that could be simulated, the SOCRATES approach for predicting SOC was modified (Grace et al. a., submitted) by incorporating an empirical moisture factor (equation 2),

$$MF = 0.0598 * P^{0.279} \tag{2}$$

where P is mean annual precipitation in millimeters. A simple net primary productivity (NPP) calculator (Lieth, 1975) was also included to provide an estimate of carbon inputs into the soil. NPP is based on either the mean annual temperature T in Centigrade or average annual precipitation P in millimeters. Explicitly, the minimum value of equations (3) and (4) is utilized.

$$NPP_T = 3000 /(1+e^{1.315-0.0119T}) \tag{3}$$

$$NPP_P = 3000(1-e^{-000664P}) \tag{4}$$

Table 5.34. Parameters used in to partition net primary productivity for major land uses in the SOCRATES soil carbon model.

Land Use	Partition Coefficient				Life Span (yr)				Ratio DPM to RPM[a]	Roots[b]
	Leaf	Branch	Stem	Root	Leaf	Branch	Stem	Root		
Forest	0.3	0.2	0.3	0.2	2	10	60	10	0.2	0.25
Grassland	0.6	0.0	0.0	0.4	1	-	-	1	0.4	0.35
Arable	0.55	0.0	0.0	0.2	1	-	-	1	0.59	0.33
Shrubland	0.5	0.1	0.1	0.3	1	10	50	2	0.4	0.31

[a] Ratio of decomposable to resistant plant material as litter

[b] Proportion of total roots in top 10 cm of soil

SOCRATES uses the same NPP partitioning constants and average life spans for biomass and litter production for the forest, grassland, shrub and arable (cropping) categories (Table 5.34) as outlined in Polglase and Wang (1992), except for arable ecosystems in which we reduced the leaf partitioning coefficient from 0.8 to 0.55 to account for the removal of harvested (e.g. grain) products (i.e. 25% of NPP). As SOCRATES only explicitly simulates SOC dynamics in the top 10 cm, annual root production in this layer was allocated according to Jackson et al. (1996). The carbon density of each plant component at steady state (B) is estimated using equation 5.

$$B = NPPpY \tag{5}$$

where NPP is annual NPP (from equation 3 or 4), p is the partitioning coefficient for each of the plant components and Y is the average life span (in years), for the component. The annual litter carbon (C) input (L) for each plant component is then estimated by equation 6.

$$L = (1/Y)B \tag{6}$$

To convert the 0-10 cm soil organic carbon outputs from the model to 0-30 cm, we used the FAO/UNESCO data as summarized in Kern (1994) to develop a soil carbon distribution profile for extrapolating down the profile to any depth. Excluding organic soils (Histosols), the FAO data maintains that the 0-10 cm layer represents, on average, 43% of the SOC in the top 30 cm.

Basic Calculation Unit and Data Inputs

We used the same mapunits as used in the desk top analysis. The single STATSGO polygon map unit is proposed to be the basic unit for computing SOC pool in kg C/m^2. Each polygon map unit represents a MUID. Each MUID is a unique combination of 1 to 21 soil taxon components. Note that there can be several STATSGO polygon map units with the same MUID.

The calculation of the current soil organic carbon pools involves the use of four STATSGO data base files. The data base (dbf file) for the shape file represents each STATSGO polygon map unit. This shape file data base points to the STATSGO soil association data base (MAPUNIT.dbf) using the MUID field (many to one relationship). The MAPUNIT data base points to the soil component data base (COMP.dbf) using the MUID field (one to many relationship). The COMP data base points to the soil layer data base (LAYER.dbf) using the MUID and MUIDSEQENCE fields (one to many relationship).

Average clay (%) and bulk density (g/cm^3) data was extracted from the STATSGO database for the 0-10 cm layer of each mapunit. An annual precipitation (mm) and mean annual temperature in Centigrade was assigned to each mapunit within the region by overlaying an interpolated climate surface created by the PRISM climate mapping system http://www.ocs.orst.edu/prism/.

Calculation of the Current State of Soil Organic Carbon for Each STATSGO Map Unit

To develop land use dependent soil carbon maps for the top 30 cm of soil we used a similar methodology to that outlined in Grace et al. b. (submitted) and based in part on the work of King et al. (1997). Each STATSGO mapunit was assigned a single dominant pre-historic vegetation type (forest, shrub or grassland) drawn from the potential natural vegetation dataset of Kuchler (1993). In the case of wetlands, we assigned a grassland classification due to the lack of exact information regarding simulation of carbon dynamics in wetland systems. (This aspect of the model will be developed further in the near future). The land use, climatic, and soil physio-chemical information was then used to develop a pre-settlement soil carbon map for the MRCSP region by running the SOCRATES model under the respective land uses (with full litter return) until an equilibrium state of soil carbon was maintained in all map units (approximately 3000 years).

For all pre- and post-history, as well as strategic simulations, we ran the SOCRATES model within The Modeling Applications System Integrative Framework (MASIF) (Gage et al., 2001), a data handling and processing environment, specifically developed to facilitate data intensive, regional-scale long-term simulations. MASIF is characterized by a scalable data management module for rapid and ready access to input and output data; a visualization module for the exploration, description, and analysis of spatial and temporal patterns; a statistical analysis module to conduct and compare model scenarios; an output animation module to produce spatio-temporal time series of model output; and the potential to use web-based interfaces to interact with the model. MASIF has been implemented using Visual Basic, Oracle, MS Access, ArcView, MineSet and S-Plus. These products represent a class of existing upgradeable applications that are inherently useful for the analysis of large data sets, are widely used worldwide, and include libraries that facilitate interconnections.

The respective masses of soil organic carbon in the DPM, RPM, BIO and HUM pools (kg/m^2) of SOCRATES in each map unit for the year 1840 served as initialization values for the post-settlement simulations required to develop a current day soil carbon surface for the project region.

We then used the same database and shape files developed and supplied by the Purdue team which provided the intersection of the STATSGO soil and NLCD land use themes. We subsequently modified the SOCRATES model to accommodate all 16 soil times land use categories found within each map unit: CROP-Prime non-eroded, SHRUB, FOREST, PASTURE-Prime non-eroded, WETLAND, MINE, URBAN, CROP - Prime eroded, CROP - Prime severely eroded, CROP-Marginal not eroded, CROP-Marginal eroded, CROP-Marginal severely eroded, PASTURE-Prime eroded, PASTURE-Prime severely eroded, PASTURE-Marginal, and OTHER (water bodies etc). These formed the basis for the post-settlement simulations estimating land use dependent soil organic concentrations (kg/m^2) and total carbon mass (0-10 cm) for each of the 15 terrestrial soil times the land use classes within a map unit for the present day.

With the rapid expansion of arable agriculture into the Midwest from 1840, we made a number of assumptions to replicate agronomic practice and productivity (litter return, etc.) within the bounds of the SOCRATES input needs and parameters between 1840 and the present based on these land uses and the potential productivity patterns.

The site specific NPP calculation was the basis for carbon inputs into the soil, as well as estimation of forest biomass. In all cropping systems (prime or marginal) we specified an annual crop residue return rate of 5-10% with conventional tillage and a NPP modifier of 1.4 to account for biomass gains with nitrogen fertilizer applications in the latter decades of the 1990s. This is a weighted average to remove the bias imposed by the fact the 1992 NLCD land use values would more than likely have over-estimated the actual area of cropping land in the region in the mid-late 1800's. In the prime cropping and pasture lands, NPP was assumed to be unconstrained (i.e. 100% of potential as determined by temperature and moisture and external fertilizer inputs). For eroded lands, NPP was constrained to 90%, severely eroded and marginal lands the NPP was assumed to be at 65% of potential. Impacts of erosion and farmland suitability were considered additive, e.g. marginal + severely eroded lands would perform at only 30% of potential NPP. Wetlands were simulated using the same parameters as grasslands/pastures at full productivity, whilst for mine sites and urban areas we assumed zero or negligible. The increasing spatial fragmentation of the latter makes it extremely difficult to actually quantify carbon stocks in the regions.

The specific association of the soil organic carbon concentration (kg m^{-2}) with each of the STATSGO soil x NLCD land use intersections within a polygon can then provide the basis for summation of total soil organic carbon within a soil x land use category, a map unit, a state or the entire region. For example, for developing a total soil carbon budget for each map unit, we used a similar summation procedure (equation 7) as used in the desk top analysis, except the soil organic concentration is estimated by the model itself.

$$TSOCP_k = SOCP * LUP_k * POLYAREA \qquad (7)$$

where:

$TSOCP_k$ is the total soil organic carbon pool in polygon map unit (kg)

$SOCP$ is the total soil organic carbon pool to 30 cm depth estimated by SOCRATES (kg m$^{/2}$) for STATSGO soil x NLCD land use category k.

LUP_k is the portion of the area of the polygon unit represented by STATSGO x NLCD land use category k.

$POLYAREA$ is the total area of the polygon map unit (m^2).

Calculation of the Future State of Soil Organic Carbon for Each STATSGO Map Unit

A 20-year time frame was chosen for the simulations to assess the potential impact of carbon sequestration management practices on both soil organic carbon (0-30 cm), and where applicable, forest production, specifically aboveground biomass carbon (stem and branches). For simplification, the average climatic conditions within the region were deemed not to have changed during this time period.

While the SOCRATES NPP estimator can take into account elevated atmospheric levels, we also assumed atmospheric CO_2 concentrations remained stable at current levels (approximately 370 ppm). Potential changes in topsoil organic carbon (and aboveground biomass in the case of afforestation) for the 15 respective terrestrial land uses were then simulated in response to the management strategies which were the same as utilized in the desk top study (Table 5.35). We specifically focused on assessing carbon management strategies in cropped and pasture land and mine sites. Future land use "A" simulates business as usual.

The respective mass of soil organic carbon in the DPM, RPM, BIO and HUM pools (kg/m^2) of SOCRATES for each land use within each map unit at the conclusion of the present day simulation served as initialization values for the future simulations. As before, the site specific NPP calculation was the basis for carbon inputs into the soil, as well as estimation of forest biomass for that particular management option.

In all conventionally tilled cropping systems (prime or marginal) we specified an annual crop residue return rate of 5-10% and a NPP modifier of 1.4 to account for biomass gains with nitrogen fertilizer applications. For reduced and no-tillage strategies, residue returns were specified as 45% and 65% respectively, and the decomposition rate decay constant for the humus (stable organic carbon) pool in SOCRATES, was reduced by 2.5% and 10% respectively, to mimic the on-going reduction in cultivation intensity.

Specific land use areas were assumed not to have changed relative to the NLCD land use data set, however, when imposing a new land use or agronomic strategy, the previous land condition (erosion class and farmland suitability) was deemed to still be in effect when calculating NPP. For example, a shift to forestry on prime cropland which was severely eroded and conventionally tilled, would still be constrained at 65% of potential productivity for the 20 years simulation. While increases in soil organic carbon are known to promote improved soil physical and chemical health, it is beyond the scope of this modeling project to include these assumptions.

Table 5.35. Current and future land uses as simulated by the SOCRATES soil carbon and ecosystem productivity model for assessing carbon sequestration strategies in the MRCSP Region over 20 years.

Current Land Use	Future Land Use			
	A	B	C	D
Shrub	Shrub	n.n.	n.n.	n.n.
Forest	Forest	n.n.	n.n.	n.n.
Pasture				
Prime, Non-eroded	Pasture	n.n.	n.n.	n.n.
Marginal, Non-eroded	Forest	n.n.	n.n.	n.n.
Marginal, Eroded	Forest	n.n.	n.n.	n.n.
Marginal, Severely eroded	Forest	n.n.	n.n.	n.n.
Wetlands	Wetlands	n.n.	n.n.	n.n.
Mine Sites	Forest	Pasture	n.n.	n.n.
Urban	Urban	n.n.	n.n.	n.n.
Crop				
Prime, Non-eroded, Conventional tillage	Conventional tillage	Reduced tillage	No-tillage	n.n.
Eroded, Conventional tillage	Conventional tillage	Reduced tillage	No-tillage	Pasture
Prime, Severely eroded, Conventional tillage	Forest	Pasture	n.n.	n.n.
Marginal, Non eroded	Forest	n.n.	n.n.	n.n.
Marginal, Eroded	Forest	n.n.	n.n.	n.n.
Marginal, Severely eroded	Forest	n.n.	n.n.	n.n.
Other (Water)	n.a.	n.a.	n.a.	n.a.

Current Soil Organic Carbon Stocks

Using the SOCRATES model we developed a pre-settlement (approx. 1840) soil carbon map of the MRCSP region based on the long-term decomposition of litter under the native vegetation. We estimate the soil organic carbon content in the top 30 cm of soil in the MRCSP region prior to the introduction of agriculture to have been 5510 Tg. We estimate that widespread and rapid introduction of agrarian practices and subsequent land use changes across the region since 1840 (Figure 5.32 and Figure 5.33) have reduced the overall soil carbon stocks by 15%. The current day soil organic carbon stock is estimated to be 4709 Tg (including urban soils).

Data and model derived current day soil organic carbon stocks (0-30 cm) for the MRCSP region are summarized in Table 5.36. The difference in regional totals can basically be explained by the disparity between the respective methods for the FOREST class alone. It is not possible to isolate the exact cause; the model may be over-estimating carbon accumulation in FOREST and PASTURE systems, or the STATSGO soil data may not have a diverse enough selection. Also, the STATSGO analysis did not use data specific to particular land uses within a map unit. Simulation of carbon dynamics in wetlands is problematic; this is not a specific to SOCRATES but all models. However, we have made a first approximation and this is an area which will require further development. It is encouraging that the SOCRATES model has produced plausible outputs, well within the limits of the measured data used in the STATSGO analysis, which in itself makes many assumptions. This lends support to the fact that with refinement in an iterative manner, both analysis methods will produce results that continue to converge and increase the accuracy and utility of the outputs method for producing reliable site specific soil carbon maps for accurately assessing management strategies and sequestration potentials.
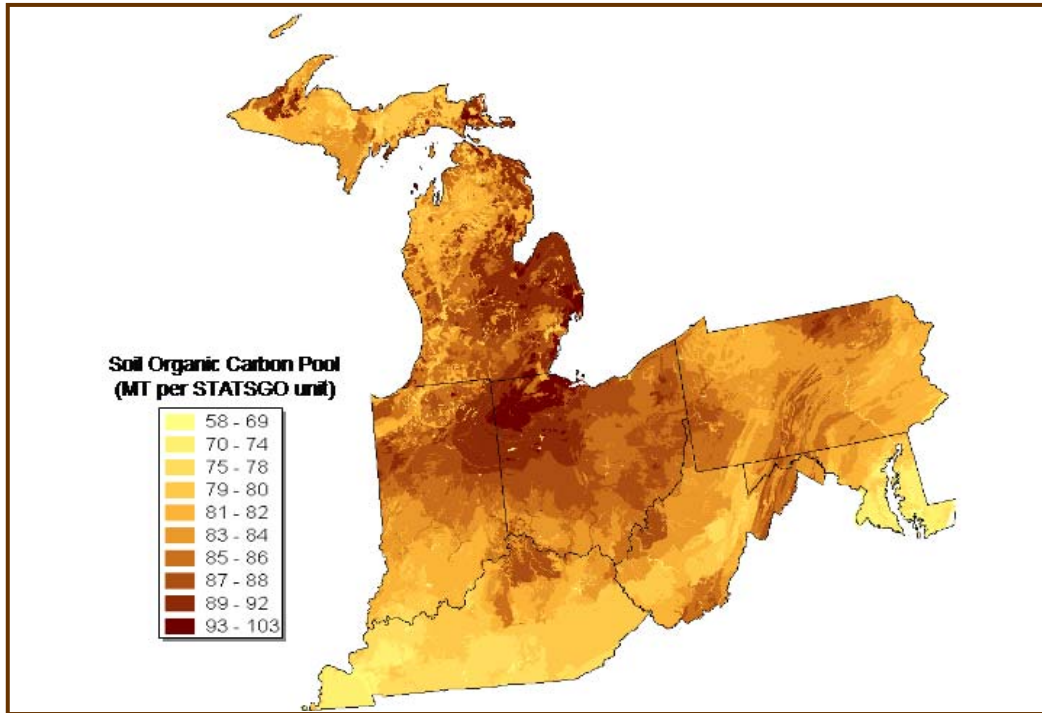
**Figure 5.32.   Pre-settlement soil organic carbon map (0-30 cm) for the MRSCP region as
simulated by the SOCRATES soil organic carbon and ecosystems productivity
model.**
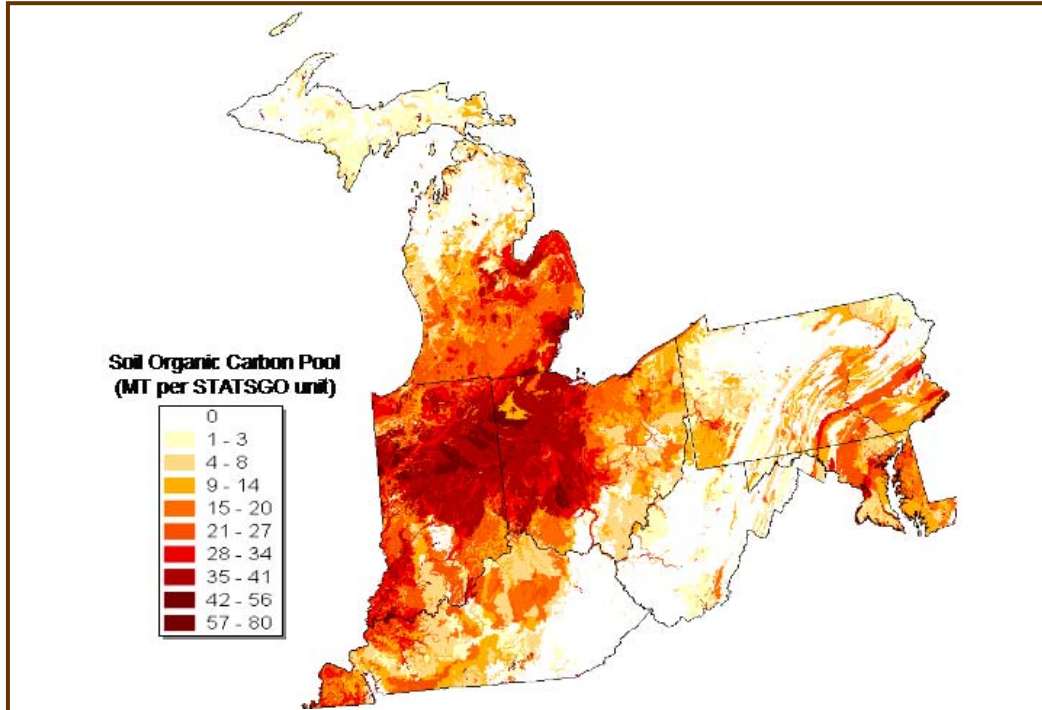
**Figure 5.33.   The amount of soil organic carbon (0-30 cm) lost from MRCSP region soils since
pre-settlement (1840) as simulated by the SOCRATES soil organic carbon and
ecosystems productivity model.**

Table 5.36. Comparison of current state of soil organic carbon pools (0-30 cm) in the MRCSP Region as computed by desktop analysis (STATSGO and NLCD) with the SOCRATES soil carbon simulation model.

Category			SOC Pool (Tg C) in MRCSP States							
			IN	KY	MD	MI	OH	PA	WV	Total
Mineland		Data	0.60	1.50	1.21	4.13	1.02	3.47	1.65	13.58
		Model	0.60	1.21	0.73	2.91	0.85	4.25	2.19	12.74
Forest		Data	73.71	184.53	38.46	511.69	137.38	206.17	124.53	1276.47
		Model	159.57	543.60	91.00	551.43	313.78	690.67	470.42	2820.47
Shrub		Data	2.81	0.00	0.00	20.38	0.02	0.00	0.00	23.21
		Model	3.29	0.00	0.00	27.56	0.03	0.00	0.00	3.88
Pasture[1]		Data	89.57	76.58	20.25	102.08	101.02	85.41	19.70	494.61
		Model	137.10	127.66	36.80	155.85	163.64	148.76	27.18	796.99
Cropland[2]	Non-eroded	Data	245.58	40.93	11.15	156.83	217.14	14.67	1.84	688.14
		Model	137.06	31.43	9.10	124.20	132.74	14.99	1.79	451.31
	Eroded	Data	36.11	1.08	0.00	3.18	21.37	0.00	0.00	61.74
		Model	14.57	1.72	0.00	1.38	6.69	0.00	0.00	24.36
	S. eroded	Data	0.67	0.00	0.00	0.05	0.04	0.00	0.00	0.76
		Model	0.49	0.00	0.00	0.02	0.04	0.00	0.00	0.55
Marginal[3]	Non-eroded	Data	53.15	9.64	2.76	86.22	19.19	6.05	1.82	178.83
		Model	15.74	24.55	7.73	17.89	29.20	42.37	16.30	153.78
	Eroded	Data	8.75	1.38	0.00	0.00	3.63	0.00	0.00	13.76
		Model	33.55	0.92	0.00	3.20	19.38	0.00	0.00	57.05
	S. eroded	Data	0.70	0.51	0.04	0.00	0.03	0.00	0.00	1.28
		Model	0.76	0.00	0.00	0.05	0.07	0.00	0.00	0.88
Wetlands		Data	22.3	5.8	26.80	589.0	7.4	4.0	4.7	660
		Model	13.75	13.87	16.00	211.77	12.90	8.05	1.23	277.57
Urban		Data	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Model	11.78	5.83	5.25	20.67	20.76	15.75	2.43	82.47
Total (excl. Urban)		**Data**	**533.95**	**321.95**	**100.73**	**1473.61**	**508.19**	**319.79**	**150.26**	**3408.48**
		Model	**516.48**	**744.96**	**161.35**	**1096.25**	**679.32**	**909.09**	**519.12**	**4626.57[4]**

[1]Includes all pastures (prime and marginal, and all states of erosion)
[2]Prime cropland
[3]Non-prime cropland
[4]4709 Tg of carbon if Urban soils are included in the Model derived Total.

Future Soil Organic Carbon and Forestry Biomass Stocks

It is evident from the SOCRATES simulations and examination of the outcomes from the management strategies over 20 years, the maximum increases in soil organic carbon (alone) can be obtained through the use of no or reduced tillage on prime non-eroded croplands. These will provide the best returns in terms of carbon sequestered by unit area of soil (Figures 5.34 and 5.35). The regions providing the greatest returns with these technologies are throughout Kentucky and some relatively small areas in the north-western extents of Ohio and West Virginia. There are also extensive prime eroded croplands in southern Indiana which respond favorably to no and reduced tillage (Figures 5.36 and 5.37). The introduction of pastures on these soils provides carbon returns much the same as reduced tillage. The general lack of prime eroded and severely eroded croplands in other states suggests some degree of subjectivity may exist in the classification of these erosion classes across the region (Figure 5.38 and 5.39). In terms of soil organic carbon, forests offer slightly greater returns compared to pastures on prime severely eroded croplands, with forestry providing a conservative return of up to 60 Mg/ha in aboveground biomass over 20 years (Figures 5.40 and 5.41).
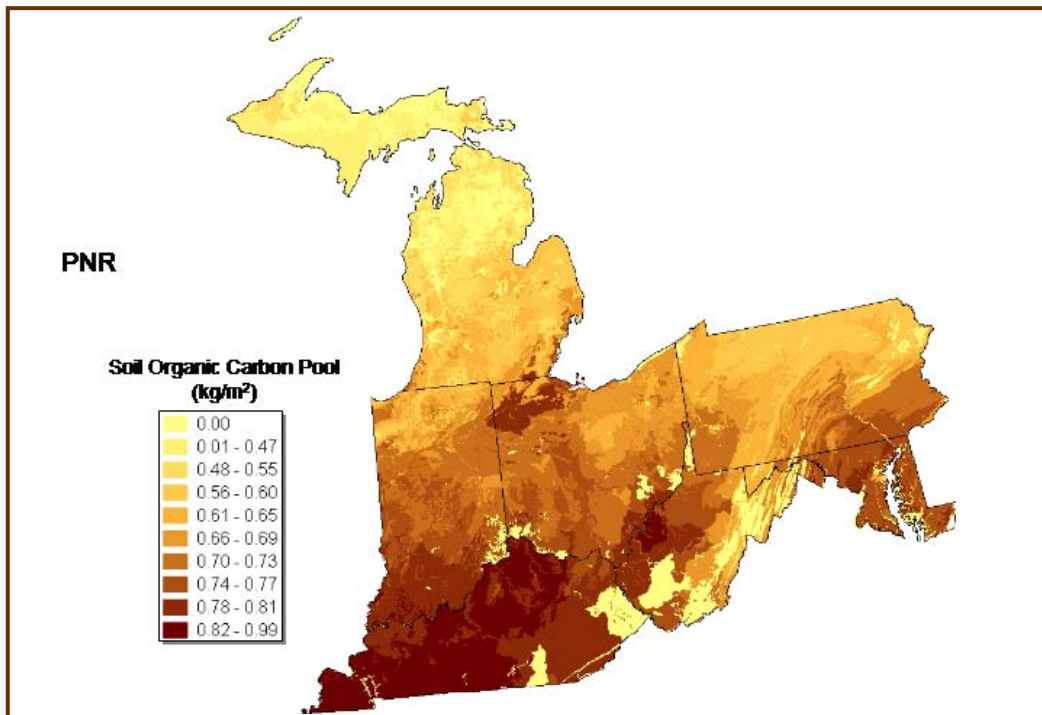
Figure 5.34.   **Soil organic carbon sequestration potential of reduced tillage (0-30 cm) on prime non-eroded cropland in the MRSCP region as simulated by SOCRATES.**
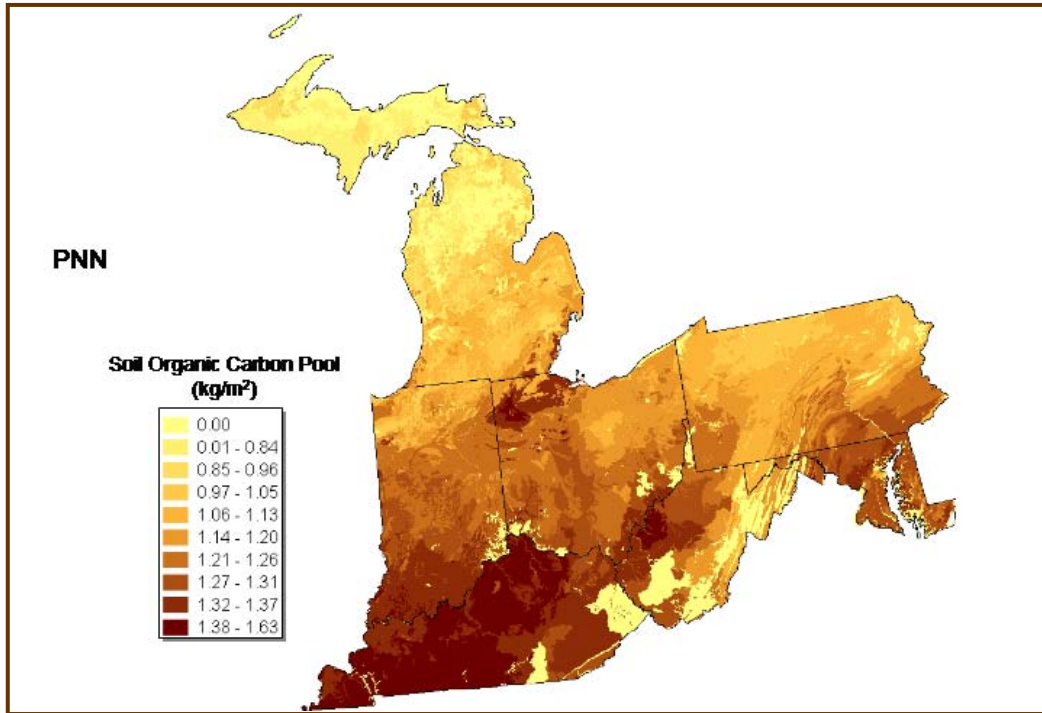
Figure 5.35. Soil organic carbon sequestration potential of no tillage (0-30 cm) on prime non-eroded cropland in the MRSCP region as simulated by SOCRATES.
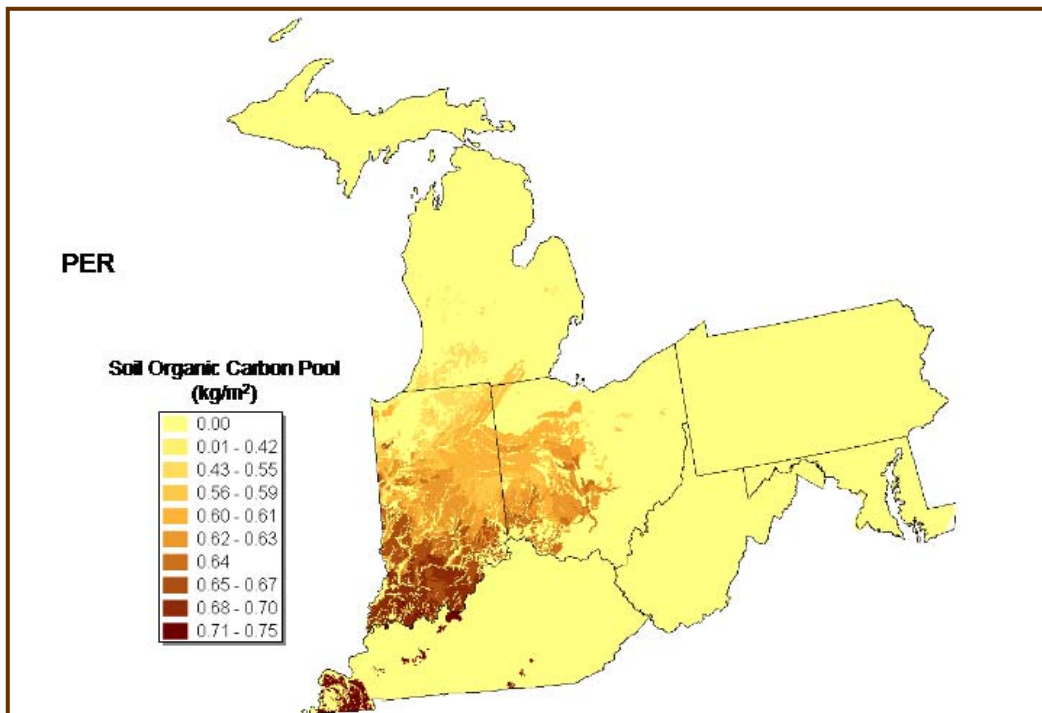
Figure 5.36. Soil organic arbon sequestration potential of reduced tillage (0-30 cm) on prime eroded cropland in the MRSCP region as simulated by SOCRATES.
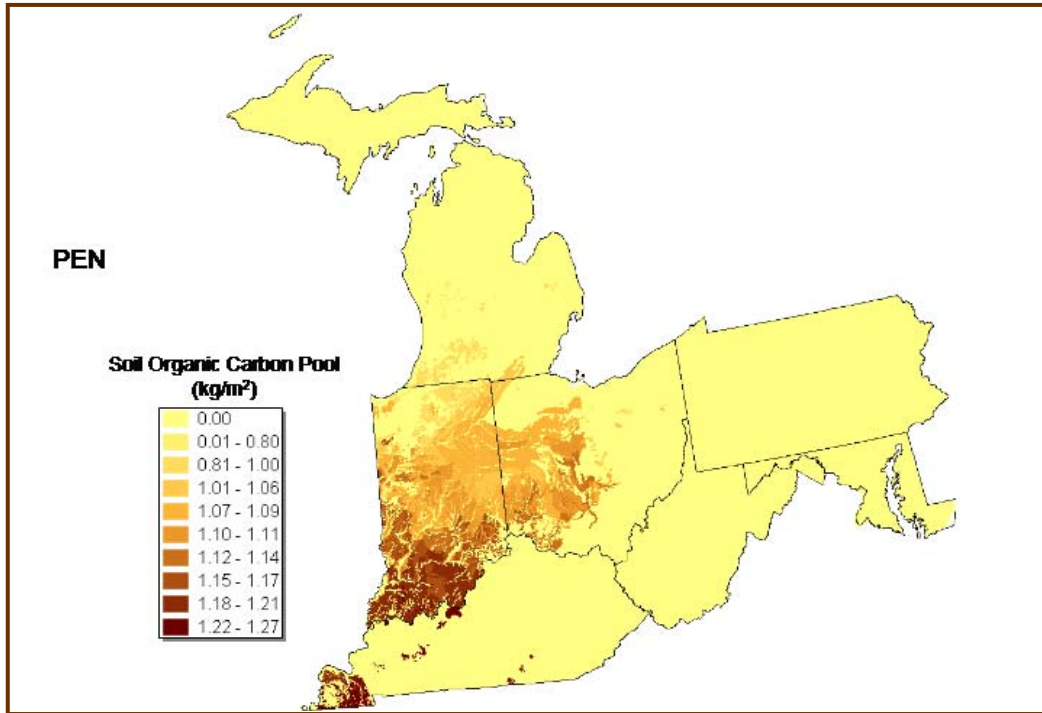
Figure 5.37.   Soil organic carbon sequestration potential of no tillage (0-30 cm) on prime eroded cropland in the MRSCP region as simulated by SOCRATES.
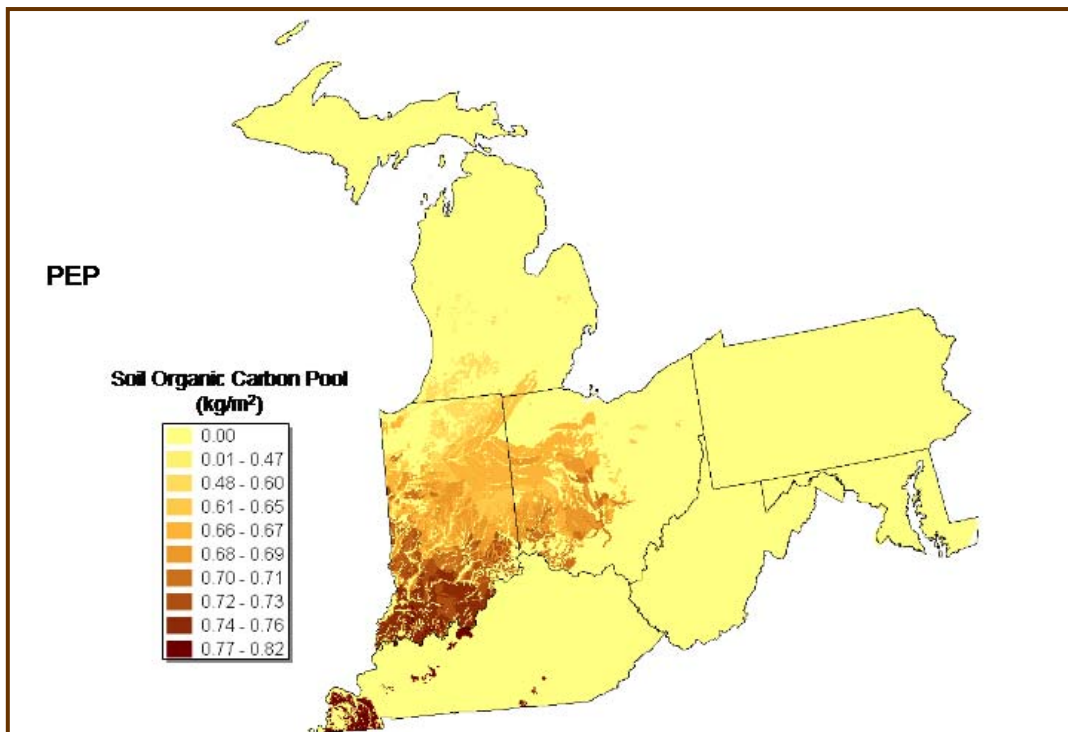
Figure 5.38.   Soil organic carbon sequestration potential of pastures (0-30 cm) on prime eroded cropland in the MRSCP region as simulated by SOCRATES.
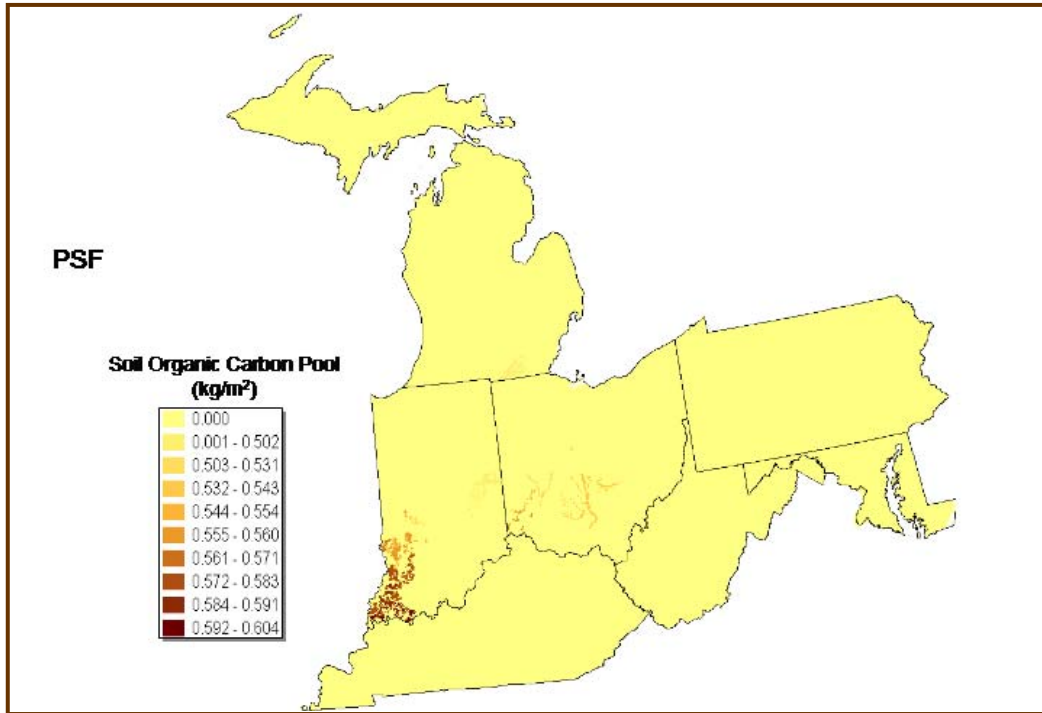
Figure 5.39.   Soil carbon sequestration potential of forestry (0-30 cm) on prime severely eroded cropland in the MRSCP region as simulated by SOCRATES.
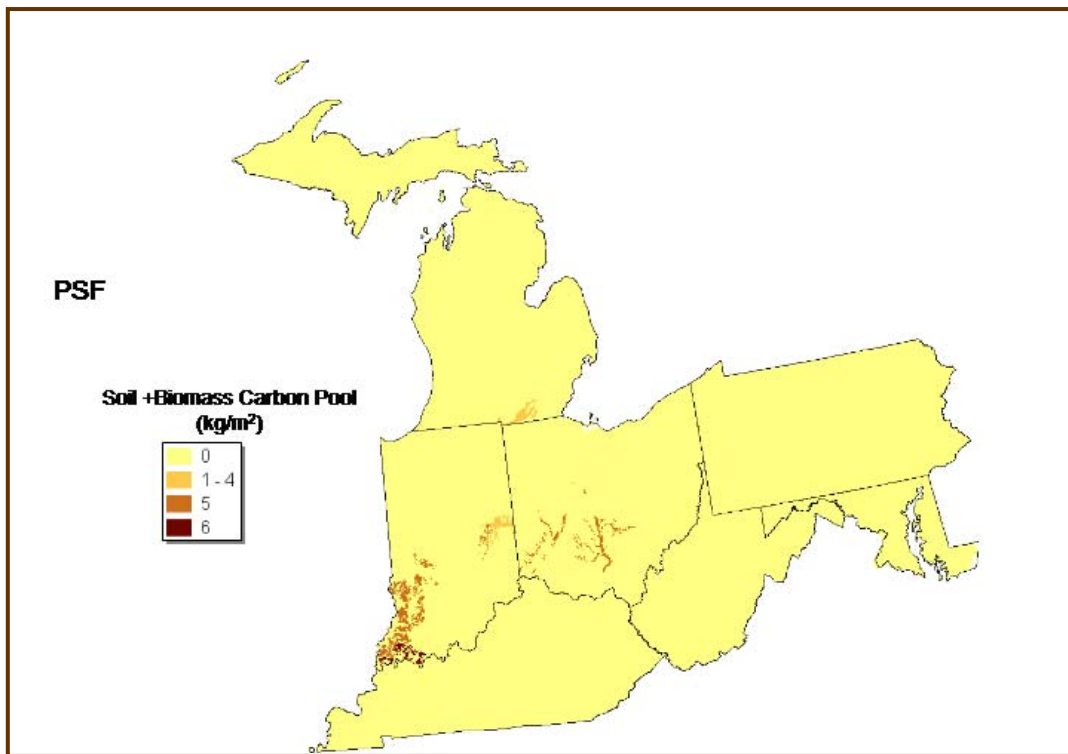
Figure 5.40.   Soil and biomass carbon sequestration potential of forestry on prime severely eroded cropland in the MRSCP region as simulated by SOCRATES.
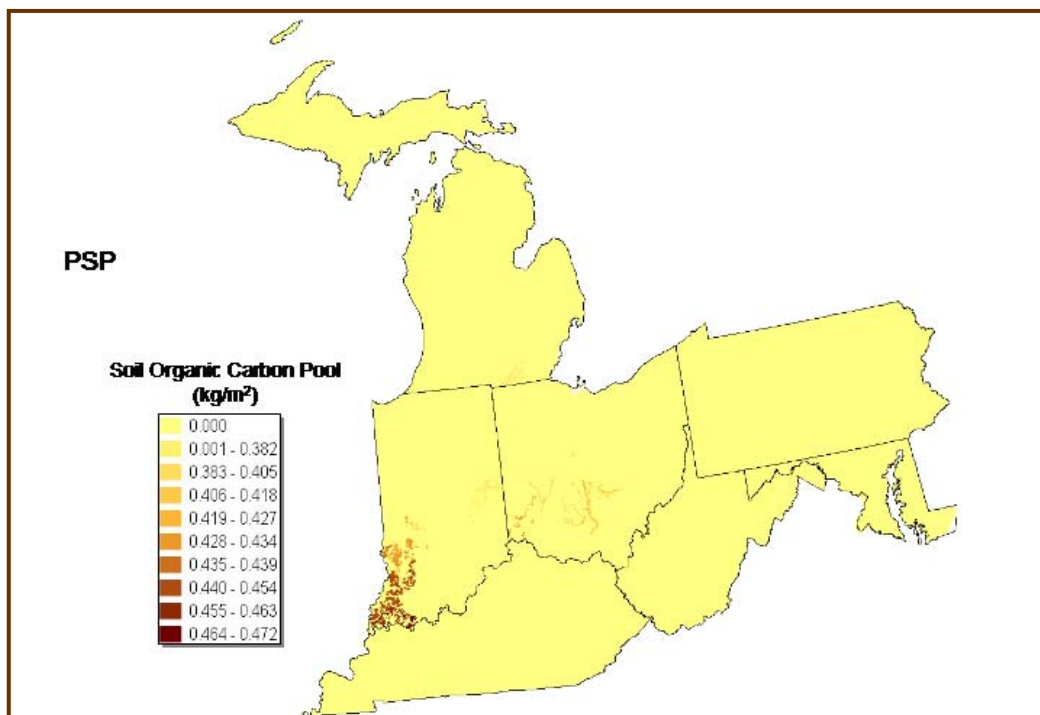
Figure 5.41.   Soil carbon sequestration potential of pastures (0-30 cm) on prime severely eroded cropland in the MRSCP region as simulated by SOCRATES.

The conversion of marginal croplands to forest will return up to 6 Mg/ha over 20 years in soil organic carbon, with overall gains in this ecosystem in excess of 65 Mg/ha (Figures 5.42 and 5.43). These management returns are greatest in Kentucky, south-east Ohio and north-west West Virginia. Marginal pastures converted to forest offer little returns in terms of soil organic carbon but will yield as much as 114 Mg/ha in biomass over 20 years, with Kentucky providing good returns (Figures 5.44 and 5.45). If we consider marginal agriculture in general (Figures 5.46 and 5.47), based on a weighted average of crop and pasture systems, terrestrial carbon gains of up to 116 Mg/ha can be made when converting to forestry in the north-west extents of Indiana and Ohio, with some relatively large areas scattered throughout the Lower Peninsula of Michigan providing relatively high biomass carbon returns (Figures 5.48 and 5.49). The conversion of mine sites to pastures or forests returns in excess of 15 Mg/ha in soil carbon throughout Kentucky and north-west Ohio, with Kentucky providing some of the highest estimations of terrestrial carbon return of all management strategies, in excess of 154 Mg/ha (Figure 5.50).

Table 5.37 outlines the potential return in organic carbon if select management options were implemented across the entire MRCSP region on the available land areas as specified in our analysis. The conversion of marginal croplands and pasture to forest would yield an additional 510 Tg of terrestrial carbon, of which 5.4% would be attributed to increases in the soil carbon pool over 20 years. Indiana, Kentucky and Pennsylvania would be the states with the greatest overall returns in carbon. The imposition of no and reduced tillage on prime non-eroded croplands would provide 160 Tg and 104 Tg respectively, with the largest net gains in both Indiana and Ohio. Reduced and no tillage management options on prime eroded croplands would provide soil organic carbon returns for the region of 5.9 - 9 Tg over 20 years.
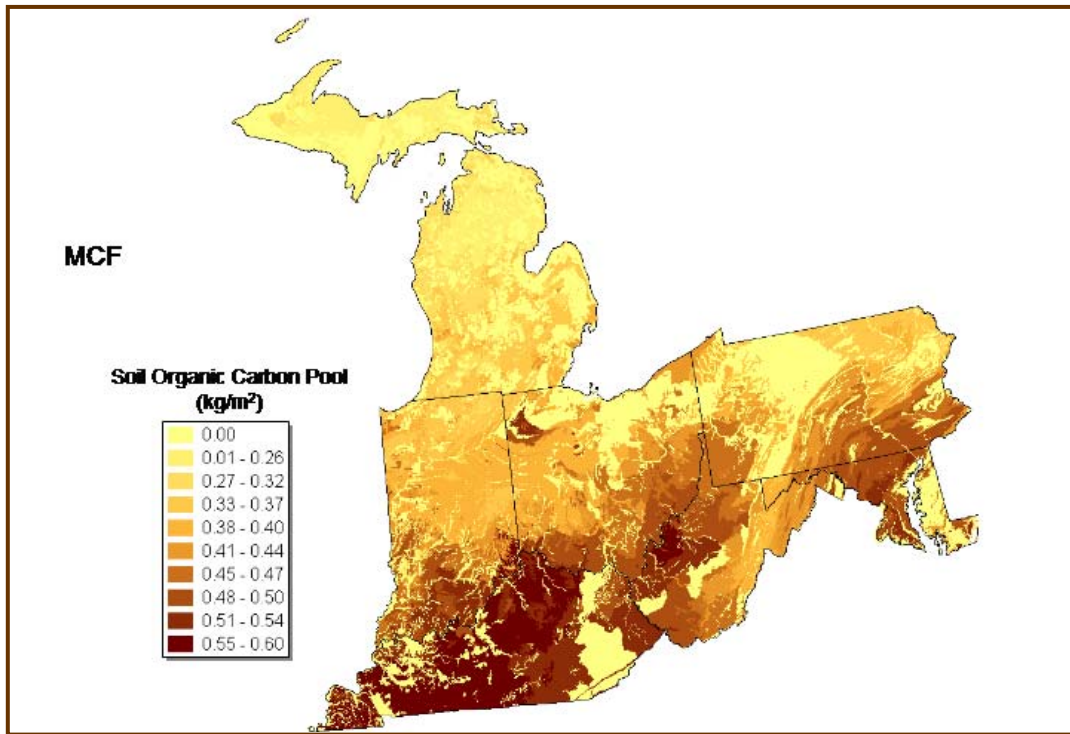
Figure 5.42. Soil carbon sequestration potential of forestry (0-30 cm) on marginal cropland (all erosion classes) in the MRSCP region as simulated by SOCRATES.
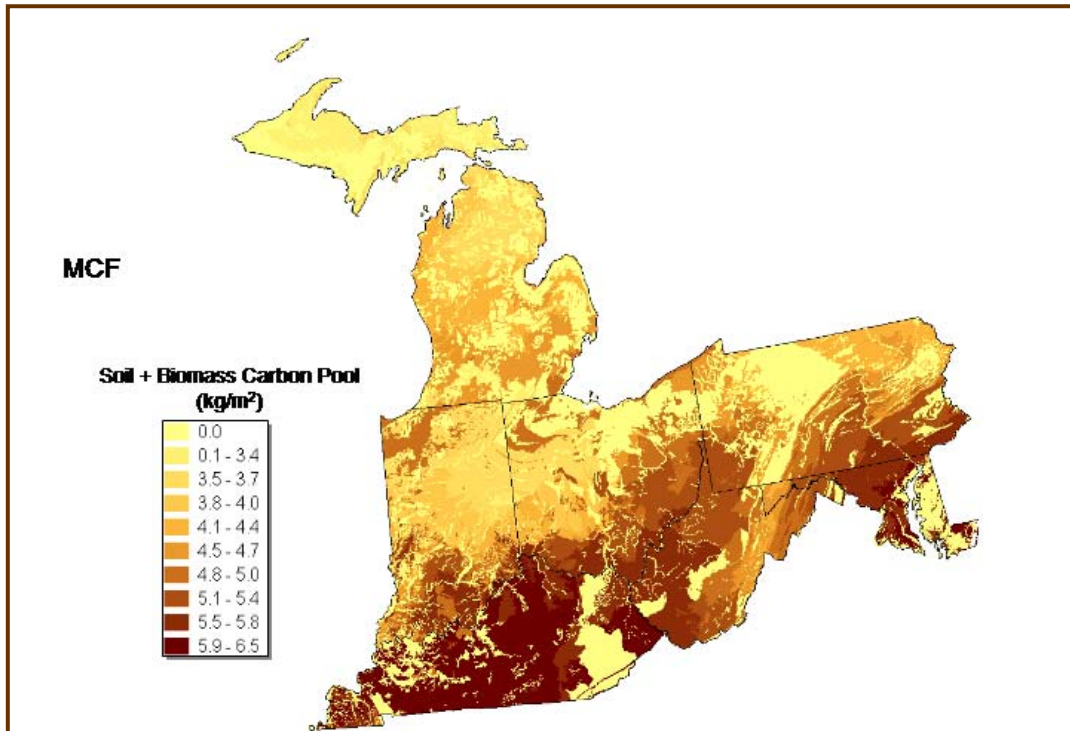
Figure 5.43. Soil and biomass carbon sequestration potential of forestry on marginal cropland (all erosion classes) in the MRSCP region as simulated by SOCRATES.
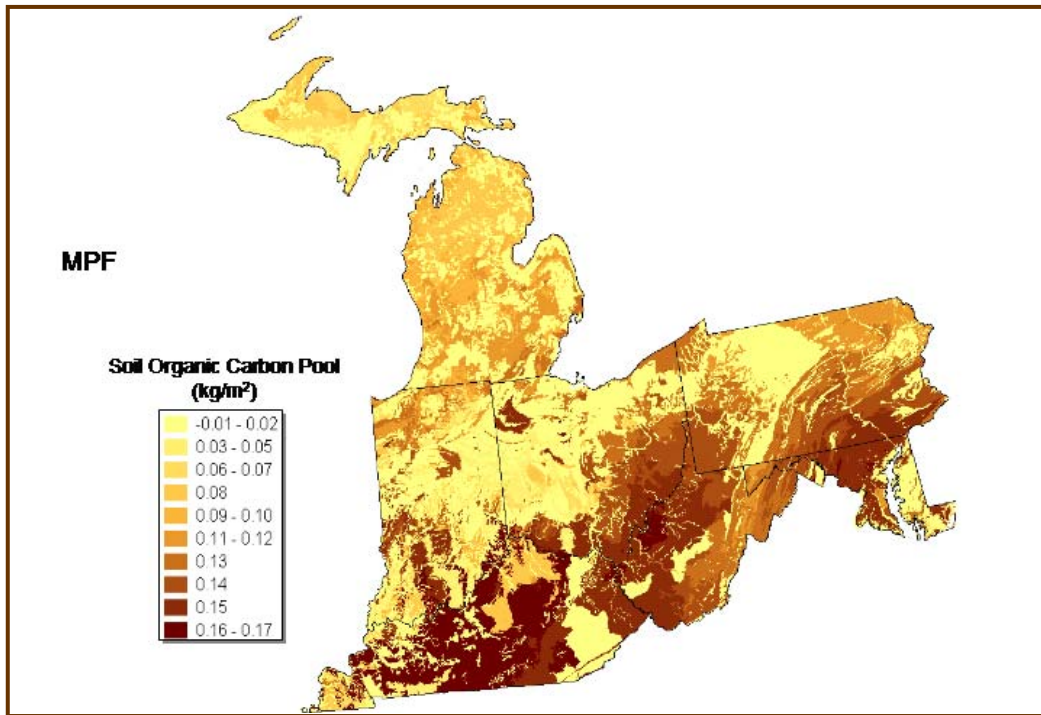
Figure 5.44. **Soil carbon sequestration potential of forestry (0-30 cm) on marginal pastures (all erosion classes) in the MRSCP region as simulated by SOCRATES.**
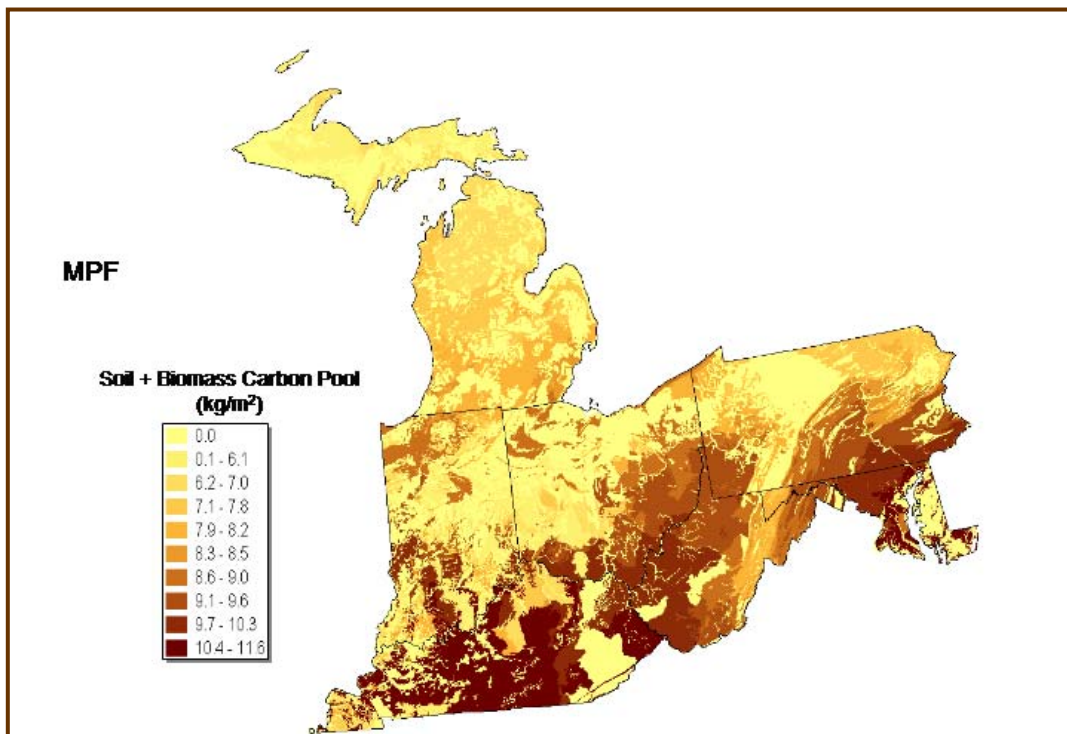
Figure 5.45. **Soil and biomass carbon sequestration potential of forestry on marginal pastures (all erosion classes) in the MRSCP region as simulated by SOCRATES.**
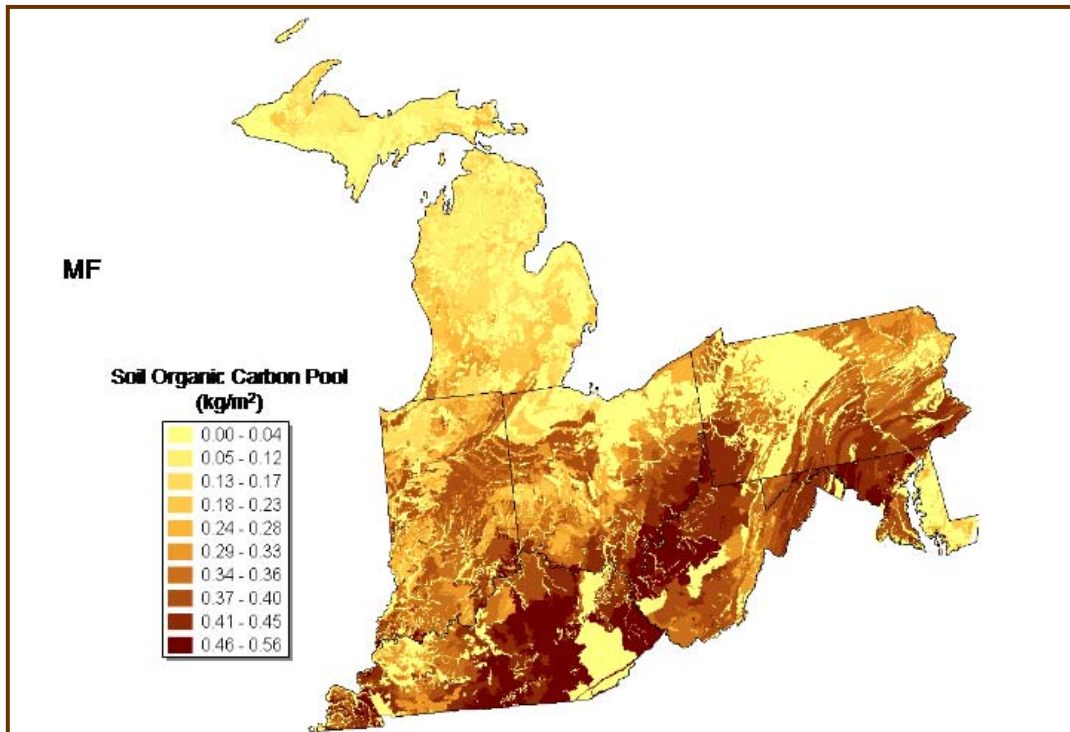
Figure 5.46. Soil carbon sequestration potential of forestry (0-30 cm) on marginal agriculture (crops and pastures in all erosion classes) in the MRSCP region as simulated by SOCRATES.
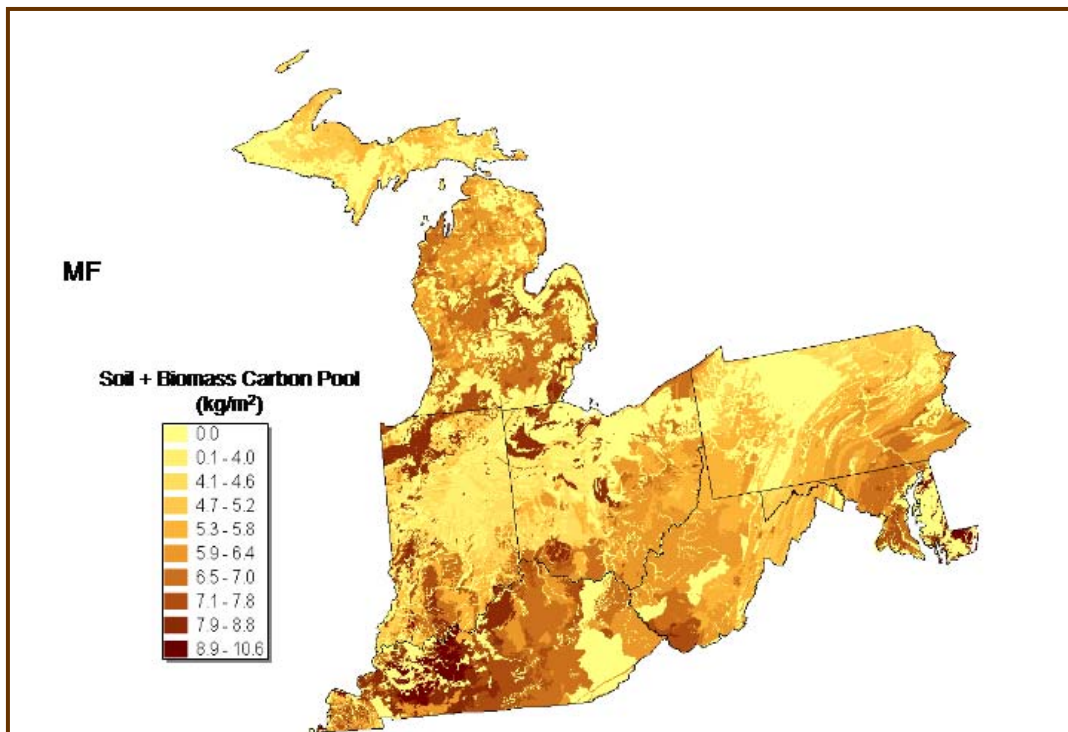
Figure 5.47. Soil and biomass carbon sequestration potential of forestry on marginal agriculture lands (all erosion classes) in the MRSCP region as simulated by SOCRATES.
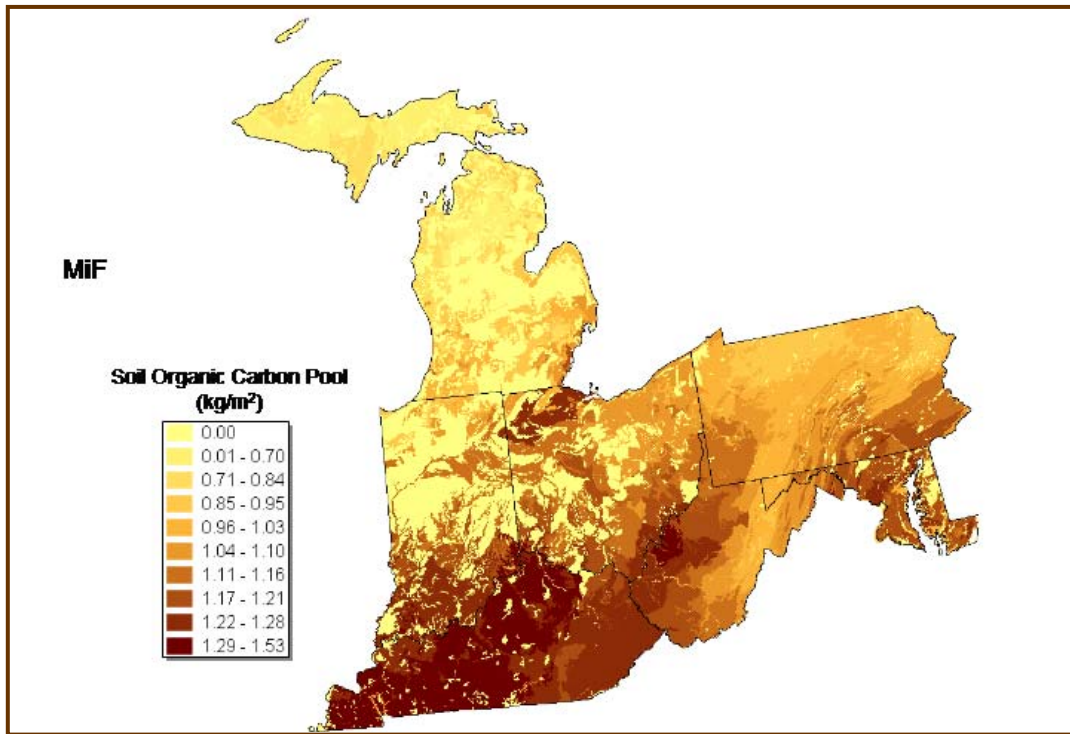
Figure 5.48. Soil carbon sequestration potential of forestry (0-30 cm) on minesites in the MRSCP region as simulated by SOCRATES.
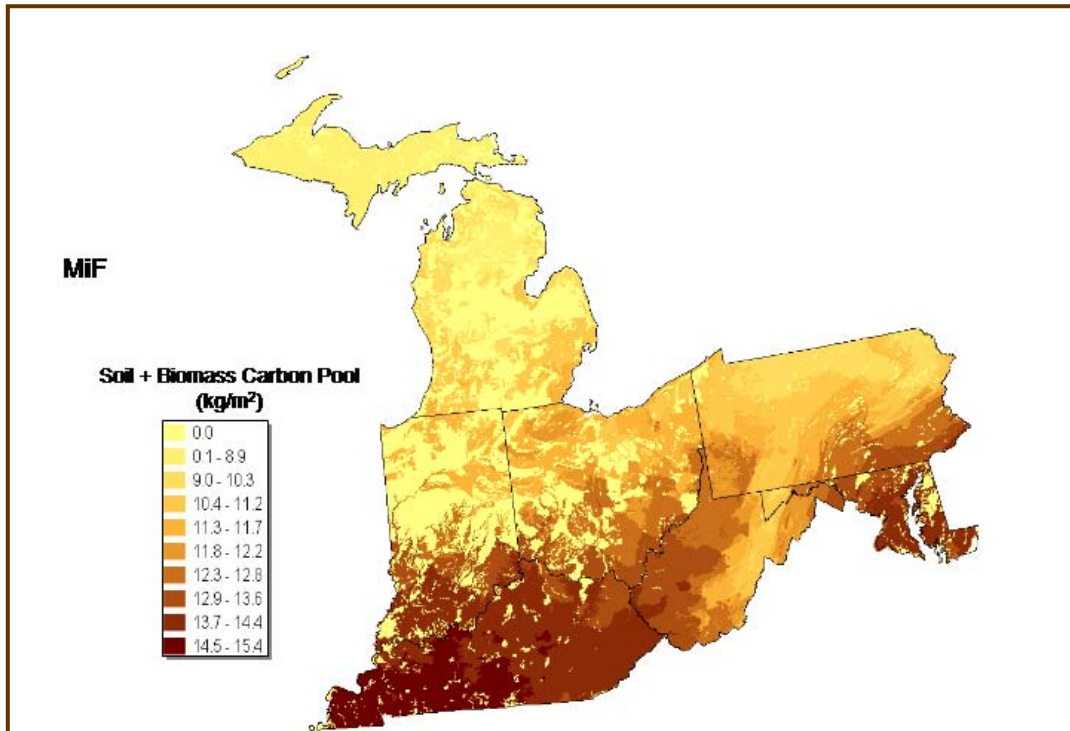
Figure 5.49. Soil and biomass carbon sequestration potential of forestry on mine sites in the MRSCP region as simulated by SOCRATES.
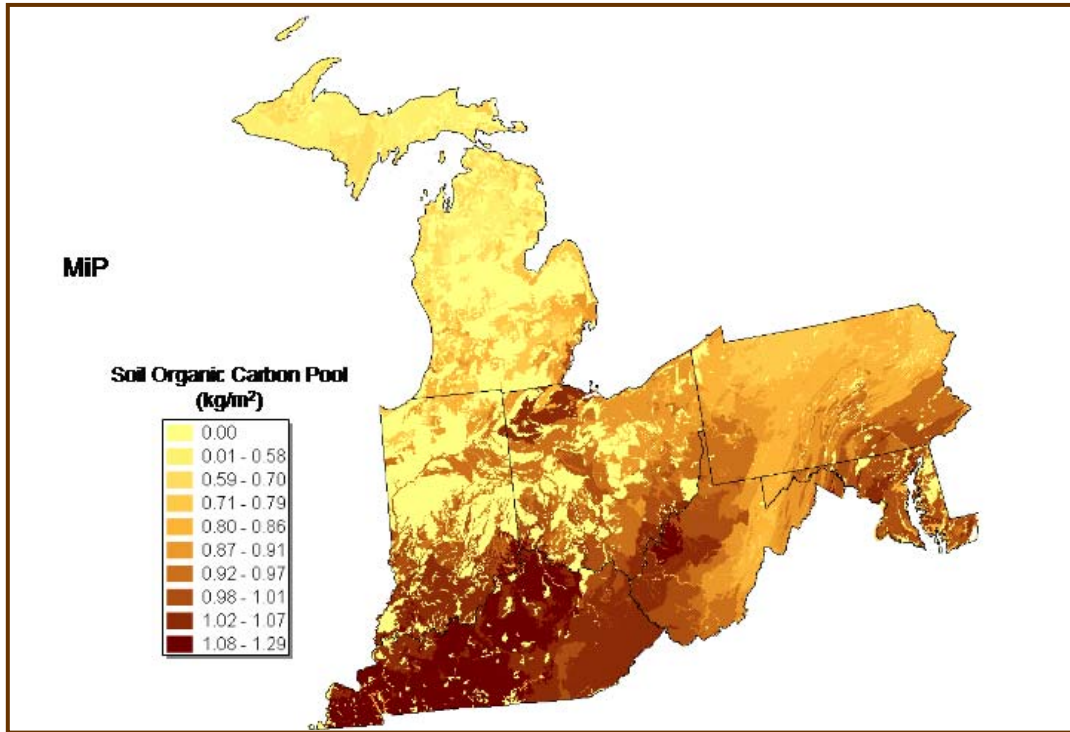
Figure 5.50. **Soil carbon sequestration potential of pastures (0-30 cm) on mine sites in the MRSCP region as simulated by SOCRATES.**

Table 5.37. Potential changes (Tg C) in total soil organic carbon (0-30 cm) and where applicable additional forest biomass as calculated by the SOCRATES soil carbon and ecosystem productivity simulation model for the MRCSP Region after 20 years of management.

Category			Soil Organic Carbon Change (Tg C) in MRCSP States							
			IN	KY	MD	MI	OH	PA	WV	Total
Mineland	Pasture		0.23	0.56	0.28	0.40	0.24	1.06	0.68	3.45
	Forest Soil		0.27	0.66	0.33	0.48	0.29	1.28	0.81	4.13
	Forest (Soil + Biomass)		2.98	7.45	3.88	5.84	3.16	13.95	8.94	46.20
Cropland[1]	**Non-eroded**	No tillage	41.53	13.99	3.69	27.52	37.88	4.36	0.58	129.55
		No tillage (Net)[2]	50.96	16.40	4.38	35.05	46.76	5.37	0.71	159.64
		Reduced tillage	23.87	8.30	2.17	15.36	21.69	2.49	0.34	74.22
		Reduced tillage (Net)	33.30	10.72	2.86	22.89	30.57	3.51	0.46	104.32
		Conventional tillage	-9.43	-2.42	-0.69	-7.54	-8.88	-1.02	-0.13	-30.10
	Eroded	No tillage	4.35	0.77	0.00	0.31	1.81	0.00	0.00	7.24
		No tillage (Net)[2]	5.44	0.92	0.00	0.40	2.29	0.00	0.00	9.04
		Reduced tillage	2.46	0.45	0.00	0.17	1.01	0.00	0.00	4.09
		Reduced tillage (Net)	3.55	0.60	0.00	0.26	1.50	0.00	0.00	5.90
		Conventional tillage	-1.09	-0.14	0.00	-0.09	-0.48	0.00	0.00	-1.81
	S. Eroded	Pasture	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.07
		Forest Soil	0.08	0.00	0.00	0.00	0.01	0.00	0.00	0.09
		Forest (Soil + Biomass)	0.85	0.00	0.00	0.02	0.06	0.00	0.00	0.93
		Conventional tillage	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Marginal[3]	**Cropland[4]**	Forest Soil	5.78	4.48	1.06	1.47	5.31	4.52	1.98	24.60
		Forest (Soil + Biomass)	59.67	48.43	12.17	18.84	56.46	52.12	22.17	269.85
		Conventional tillage	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Pasture[4]	Forest Soil	0.70	0.48	0.09	0.87	0.55	0.27	0.10	3.05
		Forest (Soil + Biomass)	63.56	35.09	6.48	68.28	41.65	18.48	6.49	240.02
		Conventional tillage	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

[1]Prime cropland
[2]Net sequestration after correcting for conventional tillage losses over 20 years
[3]Non-prime farming land
[4]Includes all erosion classes.

Conclusions for Analytical Modeling

The results of analytical modeling to estimate the terrestrial sequestration potential of the region show that there is currently 4709 Tg of organic carbon in the upper 30 cm of soils across the MRCSP region. This is estimated to be 15% less than the pre-settlement stock of soil organic carbon for this region. Complete adoption of no-tillage on prime cropping lands would potentially yield an additional 137 Tg of soil organic carbon over the next 20 years. The conversion of marginal agricultural lands to forests would yield an additional 28 Tg in soil organic carbon and 492 Tg of carbon in woody biomass. The rehabilitation of minesites would yield an additional 4 Tg in soil organic carbon and 46 Tg in woody biomass. We consider the woody biomass estimates to be a conservative (under)estimate due to the relative simplicity of the NPP model employed in these simulations.

6.0 ANALYSIS OF FEDERAL AND STATE REGULATIONS

This section focuses primarily on federal and state laws within the United States. Ultimately, however, the international legal context must be considered because any international agreements will affect federal and state policies.[1]

The fundamental objective for regulators must be to create a comprehensive and effective regime. Agencies with possible overlapping jurisdiction, both federal and state, should seek to cooperate to develop an appropriate regulatory framework before CO_2 sequestration becomes widespread. This will not only help to ensure the protection of human health and ecosystems, but will also provide regulatory certainty for the companies concerned. For example, American Electric Power's Position Paper on Global Climate Change states: "While AEP has championed voluntary efforts, we also recognize that a committed policy response will be needed to address climate change effectively and provide more certainty for business planning."[2]

Geologic Sequestration

To facilitate geological sequestration at the scale necessary to either stabilize or make significant cuts in greenhouse gas emissions with current fossil fuel usage, reasonable regulations must be in place. If the regulatory scheme is uncertain or onerous, the commercial adoption of geological sequestration technologies will be impeded. Conversely, overly lenient regulations would likewise not be optimal. The National Energy Technology Laboratory and members of the Midwest Regional Carbon Sequestration Partnership are developing the scientific and technical knowledge that will guide future regulation of sequestration. The present report considers the current regulatory scheme and potential directions for the future.

Risks Associated with Geologic Carbon Sequestration

The two main risks involved with geologic carbon sequestration in the Midwest region are release of stored CO_2 into the atmosphere and contamination of underground sources of drinking water. Carbon dioxide could be released into the atmosphere either via a sudden release or by a gradual leak from its underground storage place.[3] Each of these risks can be addressed through a

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[1] Future federal legislation may also affect sequestration, e.g. the Clear Skies Act or McCain-Lieberman "Climate Stewardship Act of 2003" S. 139. Climate change was addressed in the Energy Policy Act of 2005.

[2] See AEP's website at http://www.aep.com. Other companies maintain similar positions. British Petroleum, for example, states that "BP was the first major oil company to state publicly that the risks of climate change were serious and that precautionary action was justified. While uncertainties remain, we believe business planning and long-term strategy should be based on the need to stabilize atmospheric concentrations of greenhouse gases (GHGs)." (from the BP 2003 annual report, available at http://www.bp.com).

[3] Research on the release of carbon dioxide from geologic storage sites is still in a preliminary phase. No existing studies thoroughly investigate the probability and magnitude of release across a sample of credible geological storage systems. For a summary of the research conducted so far, see the IPCC Special Report on Carbon Dioxide Capture and Storage (2005) (the report can be accessed at the IPCC website http://www.ipcc.ch).

single regulatory system with properly tailored rules that require proper characterization of reservoirs, call for continuing monitoring and verification, and address long term responsibility and financial issues. Local risks may be involved for well or pipeline workers. Carbon dioxide can cause asphyxiation. The maximum average exposure for a work day is set by the Occupational Safety and Health Administration (OSHA) at 5000 ppm.[4] Concentrations of 10% or more can be fatal. Lower concentrations may produce shortness of breath, dizziness, or headaches. In occupational settings, the health risks of CO_2 are well known and manageable. These and other risks will become better defined as we gain more experience with deployed geologic sequestration systems.

Analogues for Geologic Sequestration

Several industries already capture, transport, and store various substances underground. Although there are important differences, these current practices can serve as analogues for designing a regulatory regime for geologic sequestration.[5] These analogous industrial practices demonstrate that geological sequestration is feasible. Moreover, since most of the analogues are more hazardous to human health in an immediate sense than CO_2, it appears that CO_2 can be safely sequestered in geologic formations. The only distinguishing feature of geologic sequestration is its long term nature, and possibly its scale if it becomes widespread in the future.

Natural Reservoirs

Natural reservoirs have held CO_2 for long time periods. These can serve as models for the characterization of suitable geologic conditions for sequestration. Although the largest and best known natural CO2 reservoirs are in the Western United States, there are a few smaller natural CO2 reservoris in the MRCSP region. By studying current reservoirs, a better understanding of the conditions for effective containment of injected CO_2 can by gained. Natural CO_2 reservoirs can also be used to study the dynamic interactions between the biological, hydrological, chemical, mechanical, and physical processes within the reservoirs. Moreover, natural reservoirs provide an opportunity to study migration and leakage over long time periods.[6] In the Midwest region, saline aquifers are thought to have the greatest potential for sequestration. Such aquifers are not fully analogous to known natural reservoirs. The issues of characterization and brine displacement require further research with saline aquifers.

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[4] See the OSHA website at http://www.osha.gov/dts/hib/hib_data/hib19960605.html. OSHA's Cincinnati area office reported a case of a delivery person who succumbed to asphyxiation while dispensing carbon dioxide from his vehicle to a restaurant's bulk system. The accident apparently happened because of a leak caused by an incomplete seal on the delivery mechanism. The carbon dioxide was able to accumulate because the delivery person was located in a stairwell below ground level. No other instances of asphyxiation by CO_2 have been cited by OSHA.

[5] See Anhar Karimjee and Bruce Kobelski, *An Overview of Technical and Regulatory Considerations for Geologic CO$_2$ Sequestration* (2004); and Sally Benson *et al.* (Lawrence Berkeley National Laboratory #51170), *Lessons Learned from Natural Analogues of Carbon Dioxide in Deep Geologic Formations* (2002).

[6] Benson, note 9 at p. 4.

Enhanced Hydrocarbon Recovery

Enhanced oil recovery (EOR) and enhanced coal bed methane (ECBM) recovery are often carried out using CO_2. Carbon dioxide, usually from the natural reservoirs discussed above, is flooded into an oil field or coal bed to extract oil or methane that would otherwise be unrecoverable. Oil field brine is also disposed of underground and used in EOR. Enhanced recovery and its relationship with geologic sequestration are discussed in greater detail below. Although regulators have thirty years experience with enhanced hydrocarbon recovery, no regulations have been developed to expressly deal with enhanced recovery in conjunction with long-term sequestration.

Natural Gas Storage

Natural gas is stored underground, usually in depleted oil and gas fields, but also in saline aquifers and salt caverns. States regulate natural gas storage, often with general oil and gas regulations. The gas is normally stored for a short period of time in order to balance capacity with seasonal variations in demand. Natural gas storage is further discussed below.

Acid Gas Injection

Acid gas injection has been used in the Alberta Basin in Canada. In response to caps on H_2S emissions, oil and gas producers have been capturing H_2S and CO_2 and disposing of it in deep geologic formations.

Underground Injection of Waste

Both hazardous and nonhazardous wastes are injected underground. While the physical properties of some of these wastes do not resemble CO_2, the wastes are injected for permanent disposal. Thus, waste injection might serve as a temporal analogue.

These analogues demonstrate that geological sequestration is clearly feasible. Moreover, since most of the analogues are more hazardous to human health in an immediate sense than CO_2, it appears that CO_2 can be safely sequestered in geologic formations. The only distinguishing feature of geologic sequestration is its long term nature, and possibly its scale if it becomes widespread in the future.

Underground Injection Control Program

The Underground Injection Control Program, administered by the federal Environmental Protection Agency (EPA), regulates underground injection of wastes and other fluids. The UIC regulations were enacted pursuant to the Safe Drinking Water Act (SDWA).[7] The UIC Program has several decades experience regulating underground injection wells.

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[7] Safe Drinking Water Act, 42 U.S.C. 300f *et seq.*; 40 CFR §§144-148.

As noted above, the use of CO_2 for EOR is somewhat analogous to geologic sequestration. EOR operations inject CO_2 to extract oil that would not otherwise be produced.[8] EOR projects are licensed under the joint federal-state UIC programs. The most important difference between many existing EOR operations and some of the proposed geologic sequestration projects is that the EOR operations are not meant for the long term disposal of CO_2. Current EOR regulations do not address this issue.

At present, CO_2 used in EOR is treated as a commodity, and state public utility commissions or gas and oil commissions have jurisdiction. The Interstate Oil and Gas Compact Commission (OIGCC) has proposed that all sequestered carbon dioxide should be treated as a commodity.[9] Geologic CO_2 sequestration can be distinguished from EOR however. The geologic sequestration plans for the future do not contemplate further use of the CO_2. Therefore, it may be argued that it is appropriate to treat CO_2 as a disposed waste, rather than a stored commodity. If this occurs, regulatory jurisdiction over sequestration might be more contentious. There are no existing regulations covering long-term storage of CO_2. If in the future sequestered CO_2 is treated as a waste, then state natural resource departments or environmental agencies might have regulatory authority. Given the status quo, the only regulatory scheme that clearly currently has jurisdiction over geologic sequestration is the UIC program. Nonetheless, the UIC program focuses on protecting underground sources of drinking water, while the major concern with geologic sequestration is surface leakage.

A crucial question under this scheme is how CO_2 and storage wells would be classified. Under the UIC system, there are five classes of wells based primarily on the type and depth of injection. These are defined in 40 CFR 144.6. The UIC regulations establish specific criteria for the construction, operation, and monitoring of injection wells. The permitting process for UIC wells consists of providing the information listed in 40 CFR 146 or applicable state regulations[10] to the UIC director with jurisdiction over the well site. The information required relates to geological considerations, structure of the well, operational considerations, status of other wells in the area, and the proposed monitoring of the operation. After submission of the application, a draft permit

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[8] Both EOR and ECBM are encouraged by federal tax incentives. The Federal Windfalls Profits Act of 1980 provides tax credits for those employing EOR. 26 U.S.C. §29 (1996).

[9] IOGCC CO2 Geological Sequestration Task Force, *A Regulatory Framework for Carbon Capture and Storage* 44 (draft report 2004). All of the states in the Midwest Regional Carbon Sequestration Partnership are members of the IOGCC.

[10] The Kentucky Department for Environmental Protection is involved in the UIC program, though the USEPA Region 4 has primacy, see 401 KAR 5:037 *et seq.* The UIC rules for the Indiana Department of Environmental Management are authorized by IC 14-37-3 and found at 312 IAC 16-1-1 *et seq*. Oil and gas rules are promulgated by the Natural Resources Commission. The Maryland UIC program is managed by the Department of Environment; the Code of Maryland Regulations §26.08.07.00 *et seq*, incorporates the federal regulations with only a minor exception. US EPA Region 5 is in charge of Michigan's UIC program. In Ohio, the UIC program is established by ORC §1509.01 *et seq.* and UIC regulations are set out in OAC §3745-34-01 *et seq.*; oil and gas issues are regulated by the Ohio Department of Natural Resources, Division of Minerals Resources Management. US EPA Region 3 handles UIC issues in Pennsylvania. The West Virginia Department of Natural Resources UIC rules are found in 47 CSR 01 *et seq*., pursuant to the authority of 22 W.V.C. §11-10 (Groundwater Protection Act).

decision will be prepared and publish for notice and comment. Any person may request a public hearing for further comment.[11]

> Class I wells are those used for deep injection of hazardous and nonhazardous industrial or municipal liquid wastes below the lowest sources of potable groundwater within one quarter mile of the well bore. When not administered directly by the federal EPA, Class I wells are normally regulated by state agencies of environmental protection or natural resources.

> Class II wells inject fluids for disposal that are associated with oil, natural gas, and methane gas dehydration. Class II also covers wells used for enhanced recovery of oil and gas. This category includes wells used to dispose of fluids employed in EOR and fluid hydrocarbons. The most common Class II wells are those disposing of brine water brought to the surface with hydrocarbons, enhanced hydrocarbon recovery wells, and liquid hydrocarbon storage. Offsite waste fluids are not defined as oil field fluids and cannot be disposed of in a Class II well.

> Class III wells are used for injecting associated with in situ mineral extraction, mostly uranium or salt.

> Class IV wells are those used for hazardous or radioactive waste injection. These are generally prohibited.

> Class V includes wells that do not fit into the first four categories. These are predominantly shallow injection wells. Experimental wells are put into Class V as well.

Another issue under the UIC scheme is whether or not CO_2 should be considered as hazardous or non-hazardous.[12] This is important because, among other reasons, in ten states, including Ohio and Michigan, a 10,000 year no-migration demonstration is required for Class I hazardous waste wells. The SDWA definition is the same as that of the Resource Conservation and Recovery Act (RCRA). The EPA's definition of hazardous waste is found in 40 CFR 261. Certain wastes are listed as hazardous in 40 CFR 261(D); others are hazardous because they have one of four hazardous characteristics (ignitable, corrosive, reactive, or toxic). Carbon dioxide is neither listed as a hazardous waste nor is it particularly ignitable, corrosive, reactive, or toxic. Therefore, CO_2 might not be considered hazardous. Moreover, none of the regulators contacted in the Midwest who are working in the UIC program or in the oil and gas field are currently advocating that CO_2 should be considered a hazardous industrial waste.

It might still be argued by some that CO_2 could be considered hazardous under the RCRA. The RCRA defines hazardous waste as a solid waste, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or

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[11] See the USEPA publication *Technical Program Overview: Underground Injection Control Regulations* or their website at http://www.epa.gov/safewater/uic.html for more details.
[12] See *NRDC v. EPA*, 907 F2d 1146 (DC Cir. 1990).

disposed of, or otherwise managed.[13] It goes on to clarify that a solid waste includes solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations.[14] Subtitle C of the RCRA regulates solid wastes that are hazardous. Subtitle D regulates nonhazardous solid wastes and some other wastes that are excluded from Subtitle C.

Geologic carbon sequestration is a new endeavor with unknown consequences. Consequently, more detailed geologic and hydrologic data and modeling must be done before further classifying CO_2 injection wells. For many of the regulators consulted with, UIC Class I or Class V appear to be the most appropriate for injection of CO_2 into brine aquifers based on current knowledge.[15] Requiring a Class I permit is consistent with the goal of storing CO_2 below the deepest underground sources of drinking water. It also provides for storage of CO_2 in a supercritical state, thereby avoiding the adverse effects of separation of CO_2 into liquid and gas phases in the injection zone.[16] Whether a well is considered Class I or Class V depends on the depth of the injection and the proximity of the underground source of drinking water.[17] The area of review for Class I wells varies by state, but is normally between ¼ and 2 ½ miles.

Others make the case that Class II might be more suitable. This argument is based on the fact that the costs and delays that might accompany Class I permitting could discourage some carbon sequestration projects. Because Class I wells face more stringent regulations, the permitting process costs more and takes longer (about 1 year) than Class II wells. Considering the costs of preparing a petition and geologic modeling and testing, a petition could cost more that $2,000,000.[18] Unlike Class II wells, Class I wells are permitted individually. However, many of the requirements are the same for both Class I and Class II wells. Both require pressure tests at least once every five years; and each must monitor pressure, flow rate, and fluid chemistry.

Of course, it is possible that regulation of CO_2 injection will continue in an ad hoc manner, with wells associated with EOR being treated as Class II and other wells such as deep brine injection regulated as either Class I or Class V. This approach might be acceptable in the short term. Class V, in particular, is appropriate for the demonstration CO_2 injection wells envisioned by the MRCSP. Experience gained from such wells will provide data that can provide information needed to develop an appropriate regulatory framework for geologic CO_2 sequestration. However, this approach could lead to some regulatory uncertainty if geologic sequestration

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[13] 42 U.S.C. §6903(5)(B). The RCRA regulates the disposal of several types of waste: solid waste, hazardous waste, underground storage tanks, oil waste, and medical waste. For newly generated solid hazardous waste, RCRA establishes a cradle to grave regulatory scheme.

[14] 42 U.S.C. §6903(27).

[15] The UIC offices that believe Class I or Class V are the most appropriate for saline aquifer sequestration include: EPA Region 1, EPA Region 3, EPA Region 5, and the Ohio EPA. See also Chin-Fu Tsang & Sally M. Benson (Lawrence Berkeley National Laboratory) and Bruce Kobelski & Robert Smith (of the USEPA Office of Drinking Water and Ground Water), *Scientific Considerations Related to Regulations Development for CO2 Sequestration in Brine Aquifers* at 3.

[16] Tsang and Benson, *supra*. The critical point of CO_2 is a pressure of 73.82 bars with a temperature of 31.04° C, which exists at depths below 800m.

[17] Email communication with the Ohio Environmental Protection Agency. See OAC §§3745-34-04 & 07. The rules in the other Midwestern states are similar.

[18] Sally M. Benson *et al.*, *Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geologic Formations* at 103.

becomes a widespread practice, because those wishing to inject might not be clear how a proposed well would be classified, which agency would have regulatory jurisdiction, or the cost of the project.

Despite the debate about classifying geologic sequestration wells, there is a clear consensus among the UIC regulators in the Midwest Region that CO_2 from power plants injected into saline aquifers and not associated with EOR will eventually be regulated as a Class I well. If it is determined that Class I is not a proper classification, then the UIC regulations will need to be amended.

Rather than putting CO_2 injection into one of the existing UIC classes, there is also the possibility of creating a sixth class specifically designed for geologic sequestration. According to state regulators in the Midwest Region, the new regulations could be enacted within five years. Any wells put into operation in the interim could be regulated under the existing UIC program. Whether or not a new class of UIC wells is developed will depend on the expansion of geologic sequestration and concomitant policy considerations.

The IOGCC report also notes that CO_2 can be considered a commodity, which further supports employing state natural gas statutes to regulate sequestration. It proposes that a regulatory framework for sequestration should allow for the potential of future removal of CO_2 for commercial purposes.[19] Finally, the IOGCC report recommends that, if the EPA regulates geologic sequestration not associated with EOR under the UIC program, such wells should be classified as a subclass of Class II or a new class of wells, but that Class I or Class V wells are not appropriate.[20]

The states in the Midwest Regional Carbon Sequestration Partnership all have statutes dealing with underground natural gas storage.

- **Indiana**: The Department of Natural Resources, Division of Oil and Gas has jurisdiction. General oil and gas regulations are applied, see 310 IAC 7 and 312 IAC 16. Indiana has 30 underground natural gas storage sites.

- **Kentucky**: The Department of Mines and Minerals has jurisdiction. There are no specific gas storage statutes; see 805 KAR §1:080. Kentucky has 23 underground natural gas storage sites.

- **Maryland**: The Department of Natural Resources, Water Resources Administration has jurisdiction; see COMAR 8.10 Ch. 1. Maryland has 1 underground natural gas storage site.

- **Michigan**: The Michigan Department of Environmental Quality, Geological and Land Management Division as well as the Public Service Commission have jurisdiction. The Natural Resources and Environmental Protection Act 451, Part 615 is the relevant statute. Michigan has 54 underground natural gas storage sites.

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[19] *Id.* at 49.
[20] *Id.* at 45.

- **Ohio**: The Department of Natural Resources, Division of Mineral Resources Management has jurisdiction; see ORC §1571. Ohio has 22 underground natural gas storage sites.

- **Pennsylvania**: The Department of Environmental Protection, Bureau of Oil and Gas Management has jurisdiction; see PA Act 223 Ch. 3 and 25 Pa. Code §78.401. Pennsylvania has 62 underground natural gas storage sites.

- **West Virginia**: The Department of Environmental Protection, Office of Oil and Gas has jurisdiction; see 22 WV Code §9. West Virginia has 34 underground natural gas storage sites.

Wells injecting CO_2 into coal seams as a part of Enhanced Coalbed Methane Recovery (ECBM) are somewhat analogous to EOR. Carbon dioxide is injected into coal seams and methane (natural gas) is recovered. ECBM could provide financial incentives for carbon sequestration by creating a marketable product. One of the first pilot projects is being conducted in the Midwest Region. Consol Energy, Inc. has a project with five test wells in West Virginia. Injection of CO_2 is still several years away, so the company has not yet applied for a permit. The West Virginia Division of Environmental Protection, Division of Water Resources, Groundwater Program will most likely require a Class V permit for the injection wells. Their assessment is based on the fact that they consider CO_2 to be nonhazardous, that the wells are deeper than Class II wells, and the possibility of seismic activity in the state.[21] West Virginia does not have any Class I wells.

Devonian black shale in Kentucky is being studied as another possible sequestration medium. As with coalbed methane production from unmineable coal seams, the absorption of carbon dioxide in Devonian black shale may enhance desorption of methane. Researchers are still analyzing the potential for such sites, so no drilling has taken place.

The recent Frio pilot project (injection into a brine-bearing interval) in Texas by the University of Texas received a Class V permit. Class V was chosen rather than Class I because: 1) the injection period was brief; 2) the amount of CO_2 was small (3000 tons); 3) the food-grade CO2 injected is considered a benign substance; 4) as an experiment it will be closely monitored; 5) the injection area is not suitable for Class I wells due to faults and heavy drilling for oil wells; and 6) the permitting process is faster for Class V, so information that will benefit future projects can be gathered quickly.[22] Unlike EOR wells, hydrocarbon production is not part of the research project. Therefore, a Class II permit was not applied for.

No permits for geologic carbon sequestration have been granted yet in the Midwest Region, although there have been several inquires. The Ohio EPA has been approached by several entities that are considering injection of CO_2 into abandoned coal mines and into the Mount

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[21] Telephone and personal interviews with staff members of the West Virginia Division of Environmental Protection, both in the Groundwater Program and the Office of Oil and Gas, and with staff of Consol Energy. See the West Virginia Groundwater Protection Act, 22 WVC §11 and 47 CSR 13. N.B., The WVDEP, Office of Oil and Gas grants permits for construction of wells and verifies well integrity.

[22] See Susan D. Hovorka *et al., Report to the Texas Commission on Environmental Quality to Accompany a Class V Application for an Experimental Technology Pilot Injection Well* (2003).

Simon Formation. The Ohio EPA instructed them that they would need to obtain the applicable UIC permits in order to drill and operate an injection well disposing of CO_2.[23] The Groundwater Program of the West Virginia Department of Environmental Protection has also received enquiries regarding geologic sequestration, but no permit applications have been filed.[24]

Drilling of a 2,800 meter (10,000 ft.) deep test well is already underway for the Ohio River Valley CO_2 Storage Project near AEP's Mountaineer Plant in New Haven, West Virginia. No injection of CO_2 is involved at this time. For now it serves as a test site to explore the geologic potential for carbon sequestration along the Ohio River corridor on the border of Ohio and West Virginia. A seismic survey has already been conducted. This site was chosen because of the large number of greenhouse gas emitting electricity generation facilities in the area, as well as the presence of the Mt. Simon Sandstone and other promising deep geologic storage formations present throughout the region.

Despite the comprehensive regulatory scheme developed for the UIC program, a possible gap exists in regard to geologic carbon sequestration. Specifically, there is no federal requirement for monitoring the actual movement of fluids or gas within the injection zone, nor are there requirements for monitoring in overlying layers to detect leakage.[25] Given the long time frame for geologic sequestration, monitoring for migration will likely be required. Also, financial responsibility for long time frames might be necessary. Geologic carbon sequestration projects might be required to obtain a permit calling for an adequate plan for after the well is closed, including continued monitoring and financial responsibility. The specific characteristics, especially the long time frame, of geologic carbon sequestration need to be fully considered before large-scale commercial projects begin.

Siting has not yet been a major issue with geologic carbon sequestration. The Frio project was carried out in a location that already had oil wells and EOR operations. The Ohio River Valley project is located on land associated with American Electric Power's Mountaineer Power Plant. Future geologic carbon sequestration operations in the Midwest Region may well encounter more difficulties with site selection. State agencies that might assert jurisdiction over site selection are public utility commissions, siting boards, and gas and oil commissions. Public opposition may become a possibility if geologic carbon sequestration becomes more common. Like other infrastructure projects in the energy industry, even those at existing well sites, injection facilities and pipelines might suffer from the NIMBY (not in my backyard) syndrome.

The current UIC regulatory scheme will likely be extended to cover CO_2 sequestration, unless other regulations are developed. EPA Regional Offices and state offices are regulating the injection at current demonstration projects as Class V experimental wells. The EPA Office of Ground Water and Drinking Water would issue any national guidance or initiate new regulations

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[23] Email correspondence with the Ohio EPA.
[24] Telephone interview with staff members of the West Virginia Division of Environmental Protection, Groundwater Program.
[25] Elizabeth J. Wilson, Timothy L. Johnson, and David W. Keith, Regulating the Ultimate Sink: Managing the Risks of Geologic CO2 Storage, *Environmental Science & Technology*, 2003, 37, 3476-3483 at 3479. Monitoring may be ordered for specific classes of Class I hazardous wells, but this rarely happens. The minimum federal requirements for either Class I nonhazardous or Class II wells focus primarily on the mechanical integrity of the well.

for commercial sequestration projects.[26] EPA Regional Offices and Primacy States would likely participate, and input from others such as the DOE would be included. The federal EPA can authorize states to implement the UIC program. States may apply for primary responsibility, or primacy, for the UIC program for all classes of wells; only oil and gas related wells (Class II wells); or all wells except oil and gas related wells (Classes I, III, IV and V). If a state does not obtain primacy for all well classes, then EPA implements the program directly through one of its Regional offices.

In the Midwest Region, the UIC program is administered by the regional divisions of the US EPA in Michigan, Pennsylvania, and Kentucky; by state agencies in Primacy States: in Ohio by the state EPA and by the Ohio Department of Natural Resources, in Maryland by the Department of the Environment (administers all classes of wells), in West Virginia by the Department of Natural Resources; and by a joint federal/state program in Indiana where the EPA directly implements the UIC while the Indiana Department of Natural Resources has enforcement authority.

- **Indiana**: Region 5 of the federal EPA regulates all classes of well except Class II. The Indiana Department of Natural Resources, Division of Oil and Gas is responsible for Class II wells.

- **Kentucky**: EPA Region 4 regulates all classes of wells.

- **Maryland**: The Maryland Department of the Environment has primacy over all classes of wells.

- **Michigan**: EPA Region 5 oversees all classes of wells.

- **Ohio**: The Ohio EPA Division of Ground and Drinking Water regulates Class I, III, and V wells. The Ohio Department of Natural Resources Division of Mineral Resources Management Office of Oil and Gas handles Class II wells.

- **Pennsylvania**: EPA Region 3 regulates all classes of wells.

- **West Virginia**: The West Virginia Department of Environmental Protection regulates all wells. Its Division of Water Resources Groundwater UIC oversees Class V wells (there are not Class I wells); the Office of Oil and Gas handles Class II wells.

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[26] This issue was discussed in email and a telephone conversation with Ahnar Karimjee of the USEPA Climate Protection Partnership division, and via email correspondence with Bruce Kobelski of the USEPA Underground Control Program, Office of Ground Water and Drinking Water. Both of these federal officials agree that is it too early to say how full-scale projects will be regulated.

Property Rights Issues

Property rights issues will arise if geologic sequestration becomes widespread. Property interests consist of rights that the state will protect against infringement and concomitant obligations that the state can enforce. Law is the instrument by which property interests are defined and enforced. In a legal sense, property is considered to be a bundle of rights. The common term "ownership" might include many different legal rights, for example: possession, use, exclusion, transfer, and bequest.

As with oil and natural gas, surface and subsurface property rights will affect the regulation of geologic sequestration, the cost of transportation and storage of CO_2, and will be central in determining liability. Property rights issues that might affect geologic carbon sequestration operations include, among other things: surface rights and easements, subsurface mineral rights, ownership of the injected CO_2, neighboring mineral leases, and water rights. Property rights also affect issues of liability. Because property rights are governed by state law and often develop through state court precedent, it is difficult to predict precisely how property issues will affect geologic carbon sequestration.[27] Nonetheless, the basic issues that might arise can be anticipated.

Surface property rights include rights to the land at the injection site, rights to land above the sequestration reservoir, and easements for pipelines to transport CO_2. The key question for transportation will be whether a company has the power of eminent domain. These issues are addressed in the report for Task 3.1. In regard to owners of injected CO_2, potential conflicts could arise with surface estate owners. If injected CO_2 migrates laterally beyond the reservoir where property rights have already been secured, the adjacent surface estate owners may have legal causes of action such as trespass[28], nuisance[29], negligence, strict liability, or unjust enrichment. Ownership of subsurface CO_2 would most likely remain with the injecting party, so liability as well as monitoring and verification responsibilities will follow ownership.

Under the surface, similar concerns must be addressed with owners of mineral estates and water rights. Most issues involving water resources will be taken care of by the permitting process if the UIC program governs geologic sequestration. Subsurface mineral rights will be determined by state laws. The rules for mineral rights developed primarily from oil and gas law. Some of these rules might not apply, or might require some modification to apply to geologic sequestration.

The classic maxim defining property rights is: *cujus est solum, ejus est usque ad coelum et ad infernos* (to whomsoever the soil belongs, also goes ownership to the sky and to the depths). This "from heaven to hell" concept of ownership has been limited over time. The ability of human flight opened up new possibilities for airspace. Courts responded by allowing access to airspace

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[27] Elizabeth Wilson in the Department of Engineering and Public Policy at Carnegie Mellon University researched these issues for her Ph.D. thesis in the Department of Engineering and Public Policy at the Carnegie Mellon University. She was kind enough to share an unpublished paper, *Subsurface Property Rights: Implications for Geologic CO2 Sequestration* with the authors. Her paper and her thesis, *Managing the Risks of Geologic Carbon Sequestration: A Regulatory and Legal Analysis* (October 2004), informed much of the following discussion on property interests.

[28] Trespass is an interference with the plaintiff's right to possess a property interest.

[29] Nuisance is an interference with the plaintiff's right to use and enjoy a property interest.

and restricting the right of land owners to sue for trespass.[30] Although surface estate owners generally own the pore space below the surface, modern cases have likewise narrowed the *ad coelum* doctrine in regard to subsurface ownership (discussed further below).

There are two main legal concepts of ownership of subsurface substances. A majority of states hold that a landowner has ownership rights to substances under the land. In the Midwest Region, Michigan, Ohio, and West Virginia law provide for ownership of subsurface minerals by the surface estate. A minority of states do not grant ownership of subsurface minerals to a surface landowner, but rather an exclusive right to capture such minerals by operations on the land. The law in Kentucky, Indiana, Maryland, and Pennsylvania is based on a non-ownership theory where minerals are not directly owned by the surface estate.

This concept developed in response to early oil and gas exploration. In the early stages of fossil fuel use, the common law contained no provisions for mobile subsurface minerals. Courts in some states reasoned that oil and gas were not analogous to coal or other solid minerals because they could migrate. Instead, some courts looked to the law relating to the capture of wild animals. The common law rule of capture provides that a landowner does not have a property right to wild animals, but has a right incident to their title in land to capture animals located on their land. Likewise, a landowner may drill for oil and gas below their property, but may not claim an ownership interest until they actually take possession of it.[31] Oil and gas are considered fugitive resources, *ferae naturae*, and the surface estate has constructive possession of the oil and gas *ratione soli*. Once the owner of the surface estate establishes volition over the resource, it is considered captured and therefore owned by the surface estate. As long as a mineral owner conducts operations without trespassing or interfering with the rights of adjacent landowners, there will be no liability for capturing a substance that drains from under another's land.

A corollary to the rule of capture is the principle that injecting a liquid or gas into subsurface strata releases it back into a wild state, and therefore is no longer owned by the surface estate. Early oil and gas cases upheld this principle.[32] The analogy to wild animals has largely been abandoned both because of the inappropriateness of the analogy for injected minerals and because of the hindrance to underground storage.[33] Note that once oil or gas has been produced it is considered personal property rather than real property. As long as control is maintained, the oil or gas remains personal property.

The rule of capture is in turn limited by the correlative rights doctrine, which dictates that surface owners should have a fair share of subterranean minerals in a common reservoir. Thus, while the rule of capture allows any surface owner to drill for oil and gas, the correlative rights doctrine

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[30] See *United States v. Causby*, 328 U.S. 256 (1946).

[31] For example, in *Ohio Oil Co. v. Indiana*, 177 U.S. 190 (1900) the U.S. Supreme Court agreed with the Indiana Supreme Court that an Indiana oil and gas regulation did not amount to a taking of private property because the surface owners did not own the subsurface oil and gas under Indiana law.

[32] For instance, a case in Kentucky held that the defendant was not liable for migration of injected gas under the plaintiff's land because the gas had been released into its wild habitat. *Hammonds v. Central Kentucky Natural Gas Co.,* 255 Ky. 685, 75 S.W.2d 204 (1934).

[33] The Kentucky Supreme Court later overruled the *Hammonds* case, holding that injected minerals do not really leave the control of the injector and are not in a truly wild state. *Texas American Energy Corp. v. Citizens Fidelity Bank & Trust Co.*, 736 S.W.2d 25 (Ky. 1987).

holds that capture must not unreasonable interfere with others' use of the same resource. Furthermore, capture should not be done in a negligent or wasteful manner. In addition to these common law rules, state oil and gas agencies also limit drilling through well spacing and density regulations. All of these rules are consistent with a policy of encouraging mineral exploitation.

The rule of capture and the correlative rights doctrine both apply to the removal of substances from underground. However, a related rule developed in Texas in response to the growth of injection for enhanced oil recovery. The negative rule of capture allows a landowner to inject below the surface even if the substance migrates below another's land.[34] The negative rule of capture might be applied to geologic sequestration in the Southwestern states where the rule developed. As discussed below however, it will most likely not be used in the Midwest, at least not in Ohio.

One method of limiting liability to adjacent landowners for migrating minerals is to unify an entire oil or gas field. Field unitization is common in the oil and gas industry. Unitization is the creation of a drilling unit that supersedes individual property rights to establish a common interest in the reservoir of natural resources beneath adjacent tracts of land.[35] Mineral leases are combined into a single field and managed as one unit with production costs and profits shared by all unit members. This limits liability by concentrating operations to areas where most mineral estate owners are involved. The unit is not immune from trespass or nuisance or trespass claims by adjacent estates, but the likelihood of liability is reduced. For oil and gas, many states have compulsory unitization statutes. Because unifying a field usually requires years of negotiations, these statutes mandate that once a specified number of mineral leases agree to unitize, all the mineral leases must join the common field. Indiana, Kentucky, Michigan, Ohio, Pennsylvania, and West Virginia have compulsory unitization statutes. Maryland does not. Given the large scale geologic sequestration of carbon dioxide will have to take in order to make significant cuts in emissions, some sort of field unitization will be necessary. Compulsory unitization statutes and regulations will probably have to be drafted for carbon dioxide sequestration.

The doctrines mentioned above apply in the absence of explicit divisions of property interests. The most unrestricted form of property in common law is the fee simple. A fee simple estate is only restricted by legal doctrines such as the right to use airspace for flight, and by government regulation. A fee simple estate can be divided. Mineral interests can be severed from a fee simple estate. Mineral interests include the right to search for, develop, and produce minerals such as oil and gas. The cases outlined below look at how courts have sought to balance the interests of surface owners, those seeking to use the subsurface for economic purposes, and mineral owners.

Chance et al. v. BP Chemicals, Inc. The Supreme Court of Ohio declared in the case Chance v. BP Chemicals, Inc. that: "Just as a property owner must accept some limitations on the ownership rights extending above the surface of the property, we find that there are also limitations on property owners' subsurface rights."[36] The Chance case merits further discussion not only because it rejected the argument that a surface estate owns everything below the surface

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[34] See *Railroad Commission of Texas v. Manziel*, 361 S.W.2d 560 (1962 Tex.).
[35] *Mongrue v. Monsanto*, 249 F. 3d 422, 432 (5th Cir. 2001).
[36] *Chance v. BP Chemicals, Inc.*, 77 Ohio St. 3d 17, 23; 670 N.E. 2d 985 (1996).

even in the absence of an express severance of mineral rights, but also because it dealt with the lateral migration of material injected into deep brine formations.

In the Chance case, the defendants argued that the Chemicals injected by BP violated their rights as property owners when they migrated below their property. The plaintiffs brought claims of trespass, nuisance, negligence, strict liability, fraudulent concealment, and unjust enrichment. The latter claim was based on the argument that BP had been unjustly enriched by disposing of the chemicals under the plaintiffs' property rather than in a more costly manner. The trial court limited the claims to trespass, so it was the only cause of action discussed in the appeals. The Supreme Court of Ohio held that the plaintiffs did not prove by a preponderance of the evidence that they had been harmed by the subsurface lateral migration of injected substances. Nonetheless, the justices took pains to point out that their decision was based on the fact that the plaintiffs had not met the evidential standard. They stated that, under Ohio law, surface land owners have a property interest (though a potentially limited one) in the subsurface pore space below their land.[37] If injecting a substance into the pore space interferes with the landowner's reasonable and foreseeable use of the land, the injector could be liable regardless of the way the injected material mixes with the native brine.[38]

The circumstances of the Chance case are analogous to those that might arise with geological sequestration, so it will likely serve as a precedent in the absence of any specific legislation. BP injected chemicals into deep brine formations. The wells were operated pursuant to UIC Class I permits. The plaintiffs argued that lateral migration of the injected chemicals damaged the substrata of their lands by lowering property values and by causing them to be unsuitable for other purposes, such as oil and gas extraction. Although the defendant BP prevailed in the case, it was not because a trespass claim was invalid. The issue of the extent of lateral migration was hotly contested by the parties, with experts testifying for both sides. In the end, it was due only to the difficulty of proving subsurface damages by a preponderance of the evidence that the plaintiffs' claims were not successful. The justices determined that, as a factual matter, the claims were too speculative.

The justices' analysis of the case, however, notes situations where claims for damages caused by underground injection might prevail. Despite repeatedly pointing out that the plaintiffs had failed to sufficiently demonstrate lateral migration below their land, the justices went on to state that merely proving migration would not be enough. They felt that the trespass was indirect, and therefore set out the rule that, in this type of case, physical damage or actual interference with the reasonable and foreseeable use of the properties must be demonstrated.[39] After setting this higher legal standard, the justices then went on to give an example of a case where damages would be much easier to prove. Where there are mineral rights or where mineral extraction is possible, deep well injection would lead to clear economic losses, since other wells could not be drilled. The lesson for geological sequestration is clear—injecting where mineral rights are held will leave the injector vulnerable to lawsuits.

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[37] *Id.* at 22.
[38] *Id.*
[39] *Id.* at 28.

The justices also commented on several potential issues for geologic sequestration. First, they stated that operating wells pursuant to permits does not insulate the operators from liability.[40] Second, the justices explicitly rejected the negative rule of capture for injection cases, declaring that: "We find the situation before us is not analogous to those present in the oil and gas cases, around which a special body of law has arisen based on special circumstances not present here."[41] They went on to say that oil and gas extraction is "fundamentally dissimilar to the unique situation before us, which involves the injection of waste byproducts from the production of industrial chemicals."[42] Moreover, they rejected arguments based on a natural gas storage case for the same reason. Later courts might conclude that geologic sequestration of CO_2 is unlike the injection of other chemicals, yet it seems possible and perhaps likely that courts (at least in Ohio) will follow this precedent and not oil and gas law.

Several principles can be taken from the Chance case in regard to geological sequestration.
- The subsurface rights of surface land owners are limited. Thus, geologic sequestration will not violate surface owners' rights in the abstract.
- Surface owners do, however, have the right to exclude invasions of the subsurface that actually interfere with their reasonable and foreseeable use of the subsurface. The easiest case of such a violation to prove would be the case where geological sequestration interfered with existing mineral rights. Plaintiffs probably will not be successful bringing a case based solely on an environmental stigma associated with injection below their properties.[43]
- And finally, at least in Ohio,[44] oil and gas law, including enhanced oil recovery and natural gas storage rules, might not apply to geological sequestration.

Mongrue et al. v. Monsanto Co.[45] The facts of the Mongrue case resemble the Chance case. Mongrue and the other plaintiffs argued that the wastewater injected by Monsanto into deep sandstone formations migrated into their subsurface property. Like the plaintiffs in the Chance case, Mongrue brought claims of unjust enrichment and trespass. Mongrue, however, also claimed that Monsanto had unconstitutionally taken his property without just compensation.[46] The United States Court of Appeals for the Fifth Circuit upheld the district court's ruling that there was no unconstitutional taking.

Although Monsanto's underground injection was permitted by the Office of Conservation of the State of Louisiana, the court determined that there had been no express delegation of eminent domain power to Monsanto by the legislature. Moreover, the permits granted to Monsanto made

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[40] *Id.* at 16. This rule is based in part on the Ohio Revised Code §6111.08.

[41] *Id.* at 19.

[42] *Id.*

[43] *Id.* at 27.

[44] The Chance case is binding precedent on all courts under the Supreme Court of Ohio, but other state courts are not obliged to follow it.

[45] *Mongrue v. Monsanto*, 249 F. 3d 422, 432 (5th Cir. 2001) (hereinafter Mongrue).

[46] Though the government's power of eminent domain is beyond dispute, a clause in the Fifth Amendment of the U.S. Constitution limits the power of eminent domain by stating that private property shall not be taken for public use without just compensation. The Fifth Amendment applies to the states because of the due process clause of the Fourteenth Amendment. Furthermore, most state constitutions have an identical provision.

no reference to any right to place wastewater in the plaintiffs' subsurface property. Therefore, Monsanto was deemed to be acting as a private party, not as a state actor.

Since Monsanto was not authorized by the state government to take private property, the issue of trespass raised in the Chance case is implicated. The judges noted that the plaintiffs could still bring actions for trespass. They concurred with the Chance court, stating that, upon a proper showing of damages, plaintiffs may recover under a state unlawful trespass claim regardless of a permit allowing for injection.[47]

In addition to the primary discussions of takings and trespass, the Mongrue case mentioned a couple of issues that will be important for geological sequestration. The judges mentioned that unitization authorized by the Office of Conservation might insulate defendants from some trespass claims.[48] In its arguments, the Office of Conservation pointed out the importance of eminent domain for underground injection. It stated that, because of the fragmented nature of land ownership, it would be a quite unusual situation where an injection well would be located on a site that would assure that all injected material would remain under the tract where injection occurs.[49] The requirement of obtaining the consent of each adjacent land owner would dramatically increase the cost of injection, possibly to the point of foreclosing the option of underground injection altogether. This underscores the importance of the power of eminent domain and unitization laws.[50]

Possible Sources of Liability

Potential leakage from geologic sequestration into the atmosphere would nullify the purpose of storing CO_2 as a means of addressing climate change and could potentially cause injury to persons or property. In the absence of specific statutory provisions concerning liability for damages, the default standard of tort law is the negligence standard.[51] The negligence standard has been applied to natural gas storage.

If CO_2 storage were considered an abnormally dangerous activity (it has not), then a strict liability standard would apply. A strict liability standard is imposed on hazardous wastes. Hazardous wastes are governed by the Comprehensive Environmental Response, Compensation and Liability Act (CERLA or Superfund) 42 U.S.C. §9601 *et seq.* CERLA employs the principle of joint and several liability. Thus, intermediaries such as contractors, shippers, or insurers could be held liable. CO_2 has not thus far been classified as a hazardous waste.

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[47] Mongrue at note 17.
[48] *Id.*
[49] *Id.* at footnote 13.
[50] Louisiana expressly grants the power of eminent domain to companies performing select functions related to carbon dioxide. Nevertheless, this grant is limited to enhanced hydrocarbon recovery projects. La. Rev. Stat. §19:2(10). This calls attention to the fact that, even where states have considered CO_2 transportation and injection, laws and regulations might need to be changed to facilitate geological sequestration.
[51] R2d Torts §§282-284

Accidents involving CO_2 might also lead to liability based on commercial law principles. For example, breach of implied warranty could apply if courts determine CO_2 is a good rather than a service under UCC Art. 2.

7.0 PUBLIC OUTREACH AND EDUCATION

Public perception and support for new technologies is critical for effective deployment. As illustrated generally by studies of nuclear facility siting and hazardous waste storage and disposal, and more specifically by public reaction to the Ocean Field Experiment in Hawaii (de Figueiredo, 2002),[1] negative public perceptions and active opposition can effectively delay, increase costs to a prohibitive level, and/or prevent deployment of projects. Therefore, understanding and addressing public issues at an early stage of project development, has and will continue to be the cornerstone of the MRCSP's approach to public outreach.

A small number of studies conducted to date regarding public views and support for carbon sequestration, including research conducted by Battelle, point to consistent findings. A finding of particular significance is the limited public awareness of carbon capture and storage (CCS). Reiner, for example, presenting work conducted with the Alliance for Global Security, reported that only a small proportion of the public is attentive, i.e., pays attention to, science and technology issues in general; that only 3.9% of survey respondents said that they had heard about CCS and only 2.6% reported having heard about carbon sequestration;[2] and that, in addition, responses to several survey questions suggest that even when respondents have some familiarity with the words, they do not usually have a substantive understanding of them.

In a recent survey of 212 randomly selected individuals in the U.K., Shackley et al.[3] concluded that:

- In the absence of any information about its purpose, the majority of people do not have an opinion at all or have a somewhat negative perspective about CCS
- When even limited information is provided on the role of CCS in mitigating the effects of CO_2 emissions, opinion shifts toward expressing slight support
- Support depends on concern about climate change, recognition of the need for reductions in CO_2 emissions, and on CCS being viewed as one part of a wider strategy for achieving those reductions
- Uncertainties about the potential risks of CCS, in particular the risks of accidents and leakage, needed to be addressed and reduced (including associated potential environmental, ecosystem and human health impacts).

Battelle's experience and research conducted earlier in relation to the Mountaineer project produced similar findings.[4] In their analysis of the media's portrayal of geological sequestration, Battelle found that:

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[1] B. DeFigueredo, D.M. Reiner, and H.J. Herzog, "Ocean Carbon Sequestration: A Case Study in Public and Institutional Perceptions." *Proceedings of the 6th International Conference on Green House Gas Control Technologies (GHGT-6)*, Kyoto, Japan. October 1-4 2002.

[2] Presentation to the NETL Outreach Working Group by David Reiner, Judge Institute of Management, University of Cambridge & Laboratory for Energy and Environment, March 2005.

[3] Shackley, Simon, Carly McLachlan, and Clair Gough. *The Public Perception of Carbon Dioxide Capture and Storage in the U.K.: Results from Focus Groups and a Survey*, Tyndall Center for Climate Change Research, Manchester Business School, University of Manchester, 2004.

[4] Bradbury, Judith A. and Dooley, James J. "Who's Talking? What are the Issues? The Media's Portrayal of Carbon Dioxide Capture and Sequestration in the U.S," PNWD-SA-6019. *Proceedings of the 7th International Conference on Green House Gas Technology (GHGT-7)*, Vancouver, BC Canada, September 5-9, 2004.

- Views reported in the media —either pro or con—were linked to the larger energy and climate change debate, in which CCS was seen as one aspect of a broader set of activities
- Discussion of CCS was occurring at the national and conceptual level only, with no comment by local publics
- Representatives of national environmental organizations expressed differing, and relatively measured views, and appeared to be serving as a proxy for the public voice in articulating environmental and safety issues issues about the technology.

In addition, Battelle found that similar concerns about the need to address containment issues were expressed in informal discussions with stakeholders—in particular with Mountaineer employees and environmental organizations. As in Shackley's study, these concerns were primarily about leakage and the potential environmental and human health impacts. Concerns about leakage were also expressed by MRCSP stakeholders in public meetings such as those held in Columbus, Ohio on February 25, 2005 and in Cincinnati, Ohio on July 19, 2005 under the auspices of the Ohio Coal Development Office. At those meetings, a few attendees asked specifically about the potential for leakage from geologic reservoirs and what could be done to minimize their potential and detect and mitigate their effects should they occur.

The limited public awareness of carbon capture and storage (CCS) offers both opportunities and challenges to the partnership program. On the one hand, an opportunity exists for introducing and presenting the issues related to CCS in a constructive, problem-solving mode. On the other hand, the task of increasing awareness and knowledge among multiple "publics" in a seven-state region who have different degrees of interest, concerns, levels of awareness, and desired levels of involvement presents a challenge. An additional challenge is that of engaging the public in the topic of CCS when the issues are generic and abstract—yet, as the history of facility siting has shown, this situation is likely to change when the issues become immediate and close to home as field testing proceeds in Phase II and subsequent phases. Therefore, the outreach effort needs to plan for addressing issues related to containment, as well as other issues shown to affect the acceptability of sequestration technologies, such as involvement in decision making, accountability and trust. [5]

Objectives of Outreach

The overall objectives of the Phase I outreach program were three-fold:

1. Provide a platform for informed discussion.
2. Identify key stakeholder groups in the region, building awareness among those segments of the public likely to be attentive and interested[6] (recognizing that other members of the public may become more engaged as an issue moves closer to their community during Phase II).
3. Build a base for future deployment in Phase II.

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[5] Bradbury, Judith A, Kristi M. Branch, Judith H. Heerwagen and Edward B. Liebow. *Community Viewpoints of the Chemical Stockpile Disposal Program.* Summary report and eight community reports prepared for the U.S. Army and Science Applications International Corporation, November 1994.

[6] As reported by Reiner, the attentive public consists of those who express a high level of interest: typically, these persons are informed and regularly read newspapers, magazines or access internet sources relevant to an issue. The interested public consists of those who have a high level of interest but do not feel well informed.

MRCSP Outreach Approach

Throughout Phase I, approximately sixty presentations and papers were prepared and 16 meetings were held with partners, local and state officials, including regulators, and other stakeholders. On one end of the spectrum, these meetings targeted stakeholders who knew little or nothing about climate change, CCS and the MRCSP. In these cases, the presentations covered a broad range of general information on the partnership's activities. In addition, members of the MRCSP research team also prepared technical papers for presentation at technical conferences and with professional organizations. As Phase I progressed, the meetings targeting regulators and policy-makers focused on both the findings in Phase I and the potential implications for Phase II. Appendix A lists meetings and workshops and Appendix B lists presentations and papers.

Early in the Phase I project a website (www.mrcsp.com) was created for use by the public and the MRCSP members. A series of fact sheets were developed, reviewed by the MRCSP research team and DOE, and placed on the web site to educate visitors to the site about climate change and the technologies and issues associated with carbon sequestration.

Beyond the meetings, the web site, and other efforts described above, Phase 1 outreach activities were conducted in three primary steps.

1. An initial, foundation-building step focused on working with the partners to develop information materials and stakeholder contacts throughout the region.
2. A second step consolidated and expanded information and contacts via an interactive web site, which was designed to provide basic awareness information to as large an audience as possible, in a cost-effective way.
3. A final step focused on initiating more direct interaction with key state officials and beginning Phase II planning with candidate sites.

Each of these steps is described in greater detail in the following sections.

Step One: Building an Initial Foundation of Information and Contacts

The focus during this outreach step was to work with the our MRCSP partners to develop and distribute basic informational materials and to identify and open lines of communication with key stakeholders in the region. Initially, the MRCSP included partners in five states (Indiana, Kentucky, Ohio, Pennsylvania and West Virginia), but was expanded to include Maryland and Michigan by the summer of 2004.

During Step One, lasting approximately nine months, outreach activities were conducted as follows:

- Each partner was asked to designate an outreach contact with whom the outreach team could coordinate activities as needed. The discussions with each contact served to open lines of communication, provide an opportunity to discuss our overall approach to outreach, solicit members' feedback and ideas, and begin gathering contacts across the region for compiling a stakeholder database.
- A set of basic informational materials was developed, with review and comment by the project team and partners. These materials included a briefing on the MRCSP and six fact sheets explaining the need for and information about carbon sequestration. The topics discussed were: climate change, carbon sequestration, geologic sequestration, terrestrial sequestration, the U.S.

Department of Energy, National Energy Technology Laboratory (DOE/NETL) regional partnership program, and the MRCSP. Following approval by DOE, these materials were prepared in hard copy and also posted on an interim web site which was established in April, 2004.

- An initial stakeholder data base of nearly 130 contacts in diverse organizations was developed based on significant input from the MRCSP partners. These stakeholders included government, trade associations, industry, and environmental and other non-government organizations. During April 2004, the MRCSP Project Manager mailed each stakeholder organization a letter introducing them to the MRCSP and inviting them to participate in the scoping meeting for the Programmatic Environmental Impact Statement, which was scheduled to take place in Columbus the following month.

Step Two: Consolidating and Expanding Information and Contacts via an Interactive Web Site

The key activity during this step was the conversion of the initial web site into an interactive site that could share information, provide a vehicle for public feedback to the partnership, and promote the expansion of a stakeholder database. The site was conceived following a stakeholder's suggestion that such a tool would allow the MRCSP to share information more broadly with people who might not have the time to attend a meeting and who would prefer to gather information according to their own schedule. Such a tool was felt to be of particular value in reaching the attentive and interested segments of the public when the issues are generic and abstract, rather than site-specific. (In Phase II, the intent is to conduct more targeted outreach and direct interaction as field implementation begins at specific field sites).

The design of the interactive version of the web site began in late 2004. It went on line in early January, 2005 accompanied by a mass emailing to over 300 stakeholders representing different organizations across the seven-state MRCSP region. That original stakeholder mailing list, which was provided earlier in the Phase I project by MRCSP industry and research partners, has been subsequently expanded in conjunction with the revisions to the website and now numbers 620 stakeholders. Those stakeholders come from a variety of organizations: 321 from state and local government; 25 from industry (not including the industry members in the partnership); and 150 from non-governmental organizations, including 105 environmental groups. Website visitation increased significantly as a result of increased outreach efforts in the form of phone calls and emails to stakeholders. The experience gained in using the site has been valuable and provides a basis for further developing and using the tool effectively in Phase II. The progress to date and plans to use the website during Phase II are discussed below.

Website Design

The website was conceived based on discussions with stakeholders and designed to provide:

- A cost-effective means of providing basic information on the project and related issues to a broad range of stakeholders
- An information source that stakeholders can use at their convenience
- A database of informed stakeholder groups in the region as the project moves into Phase II and beyond
- A vehicle for obtaining feedback from as broad a group as possible.

The text of the website is based primarily on the program presentation and fact sheets that were developed and approved during the previous outreach step. While each fact sheet is written at the layman's level, links are provided to resources that provide more detailed, scientific information for those who wish to pursue a particular topic (for example, to sites operated by the DOE/National Energy Technology Laboratory (NETL), the International Energy Agency (IEA), and the Intergovernmental Panel on Climate Change (IGCC)). The site has two main sections. The first section describes the science of climate change and the concepts of sequestration. The second section describes the partnership program and the MRCSP specifically. As visitors go through each screen they learn more about the topics and are given the opportunity to offer feedback to open-ended questions about the topics.

Site Use

Visitation to the site increased dramatically after the interactive feature was launched and continued to remain relatively high following that launch. The slight drop in traffic over the past summer may be attributable both to the onset of the summer vacation season and also to a slowing down in the number of follow-up telephone calls made by the outreach team and the limited new information being posted on the site. This slow down is expected to be reversed, once the telephone calls resume and new, Phase II information is posted in October.

Table 7.1 shows the number of stakeholders seeking information about the MRCSP each month. As the table shows, the total number of visitors and also the number of unique visitors (i.e., visitors who were not repeat visitors during that month) increased noticeably after the launch and remained high.

In addition to total numbers, the outreach team tracked visitation by day. The graph in Figure 7.1, below, which is representative of one month of data, shows that the average number of visits per day varied significantly. The team believes that much of the variation correlated with outreach calls and informational meetings during which the website address was publicized, both verbally and with the aid of a brightly colored flyer. The noticeable increase in the visitation rate at those times appeared to indicate the value of the website in reinforcing messages and providing a long-term point of connection for stakeholders.

Some planned changes to the site are being designed to draw attention more effectively to newly posted information. An increased number of site visits is expected in response to these notices and we believe that the website can continue to be a cost-effective way of sharing information broadly as the project moves into Phase II.

Table 7.1.   Website visitation.

| Month/Statistic	Total Visitors	Average number of Visitors per Day	Unique Visitors
August 2004	270	8	134
September 2004	365	12	178
October 2004	560	18	219
November 2004	659	21	301
December 2004	635	20	315
10-31 January 2005[7]	982	42	549
February, 2005	762	27	477
March, 2005	916	29	570
April, 2005	959	30	503
May, 2005	984	32	496
June, 2005	630	21	355
July, 2005	805	25	409
August, 2005	703	21	310
September, 2005	(To be added)		
Monthly averages since launching of the interactive site			
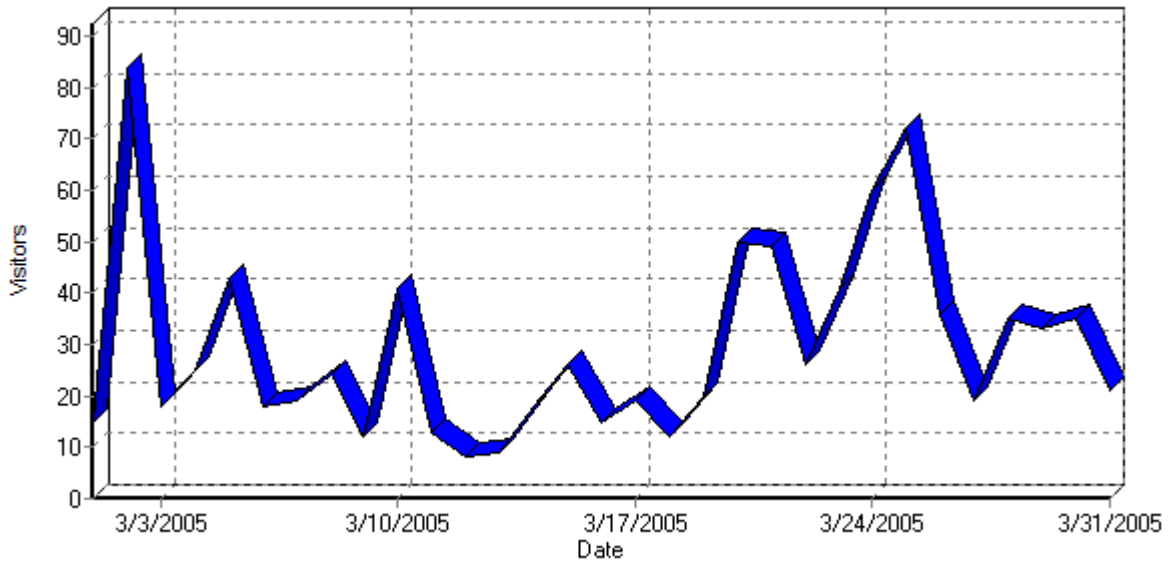
Figure 7.1. Website daily visitor counts, March 1 – March 31, 2005.

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[7] The interactive site was launched on January 10. These data are for a 21-day period only.

Lessons Learned During Phase I

"Co-Benefits" Perhaps more important than the visitation metrics as an indication of success was the impact of follow-up phone calls conducted by the outreach team. Within a few weeks of launching the interactive version of the website, the team followed up with telephone calls to approximately 100 "key" stakeholders, including government officials, industry, and non-governmental and environmental organizations. These calls provided some very useful information:

- First, although there was a significant increase in site visits after the mass e-mail was launched, responses indicated that a large number of the key stakeholders had not seen or received the e-mail. This is attributed to so-called "spam blocking" software and to the fact that a number of key stakeholders view blanket emails like junk mail – it gets tossed immediately. This knowledge will help the outreach team to tailor future email notifications.
- Second, responses confirmed that people do view the web as a reasonable approach to disseminating information. We recognize that the site will need to move to more targeted communication as specific sites are considered; however, these responses were positive in showing the value of the site for general outreach because people could take their time to review materials at their convenience.
- Third, the calls provided an opportunity to engage stakeholders in very productive and cordial discussions about the MRCSP.
- Finally, the personal contact enabled the outreach team to expand their network of persons and groups who may be willing to assist in reaching out and networking to other members of the public and to help in recruiting and scheduling focus groups and other meetings with different public groups.

The outreach team had not anticipated how well these calls would go and in retrospect think the following applied:

- The nature of the call was courtesy – not a sales call and not a long lecture
- People seemed to appreciate an opportunity to hear and ask questions about the project background and often agreed that the web was a good way to try to build knowledge
- Because the calls were one-on-one and open ended, people did not have to give public speeches or stake out ground. In some cases, people acknowledged that they were skeptical about the role of coal in the region, or about climate change, but the calls did not ask them to make up their mind, merely to visit the site and learn more – this seemed to go over very well with people
- The site was designed to accommodate differing levels of knowledge, time and interest. One contact from the environmental community offered what may be considered to be one of the best compliments the MRCSP could have received. She pointed out that while some of the material was too basic for her, other material was informative. She concluded that it was well designed to serve multiple levels of knowledge and a good first step in building a stakeholder base. Others seemed to offer acknowledgement that this effort responded to many of the constraints that prevent people from getting involved (for example, timing, access, level of information) and so put an onus on people to get informed. These reactions are anecdotal but very encouraging.

"If You Build It…" One of the innovative features of the interactive website is the ability for visitors to offer comments through an email system. The outreach team had hoped that visitors would ask additional questions and provide reactions to the general questions raised in the text of the web pages. In fact, very little feedback was received. There were about 20 comments sent to the MRCSP through the website.

These raised some interesting points but in general were not as helpful in informing the team as had been hoped.

The outreach team is currently considering possible explanations for the relatively limited feedback and exploring ways to increase feedback in the future. Anecdotally, possible explanations are that the materials on the website were at the introductory level and therefore not "meaty" enough, or were at the generic rather than the site-specific level and therefore did not inspire comments and questions. It could also be that people were uncomfortable using the approach. As the MRCSP moves into Phase II, the feedback function will remain, but anonymity will be preserved by eliminating the current requirement for visitors to register in order to make comments. The site will also include additional information and graphics that describe and invite comments on the specific field demonstration projects.

Phase II Modifications and Plans

The website has played an important role during Phase I, when the issues were generic and the goal was to provide basic awareness information to as large an audience as possible in a cost-effective way. The interactive website is viewed as a valuable and important complement but not a replacement for more personal outreach efforts, particularly at the field demonstration sites. The outreach team expects to continue directing stakeholders to the website for follow-up after conducting various outreach activities, ranging from phone calls to one-on-one meetings, and focus group and other group meetings.

Modifications being planned on the basis of Phase I experience, with the goal of enhancing the value of the site as MRCSP moves into Phase II include:

- Making access to the feedback features more anonymous and linked to more frequently updated information
- Simplifying and making more visible the posting of short updates and notices so that visitors can immediately click on to newly-posted information
- Changing content more frequently than in Phase I
- Making the site a more useable database for the MRCSP team members. Currently, documents are shared through email. As the field demonstrations move forward, however, the sponsors will take a more active role in outreach around each field test. Providing sponsors ready access to talking points, presentations and other material to share with neighboring site communities will be important.

The outreach team will continue to monitor the effectiveness of the site in obtaining feedback and the optimum combination of approaches to use in reaching out to the public, both at the field demonstration sites and across the seven-state region.

Step Three: Initiating Direct Interaction with Key State Officials and Candidate Sites

During this final step, which occurred primarily during the final six to eight months of Phase I, outreach activities were expanded to include direct interaction between state officials and the MRCSP project team, and visits and discussions with the sponsors of potential candidate sites for the field demonstrations. As noted previously, these meetings are listed in Appendix A.

Interactions with Regulatory and State Officials

Several types of meeting were held with State officials. Some were scheduled with regulatory officials, some were held in response to state requests, and one large workshop was scheduled by one of the MRCSP sponsors. MRCSP participants included the project manager, outreach coordinator, and in addition, technical and regulatory team leads as appropriate.

As part of the regulatory task, the regulatory task team leader scheduled a series of meetings with officials in the seven-state area to ascertain the status of regulations in each state. Regulators are especially key stakeholders and the meetings were expanded to include background presentations on the MRCSP and outreach activities, as well as regulatory issues. MRCSP participants included, in addition to the regulatory team lead, the MRCSP project manager, geologic field project manager and outreach coordinator. In several states, also, state officials responsible for environmental issues and natural resources participated in addition to the regulators. The number of participants in these meetings ranged from six to over 20. It was apparent that, in many states, officials were interested in, but not very familiar with the topic of carbon sequestration. The meetings provided an opportunity to develop personal contacts within each state and proved to be an educational benefit for all participants. The MRCSP team learned more about the state context and issues that could affect deployment in that state. State officials were able to learn more about carbon sequestration and the MRCSP, as well as being informed directly about the web site and project contacts for future information needs. Much of the specific regulatory information learned in these meetings is summarized in the Regulatory Report which is being prepared as a separate Phase I deliverable.

In addition to meetings with regulators, members of the MRCSP project team also provided briefings at meetings sponsored and attended by state officials in Pennsylvania (two meetings, including a seminar on terrestrial sequestration, with approximately 25 officials) and Maryland (11 officials and MRCSP partners).

Of particular note, was a seminar on carbon sequestration sponsored by the Ohio Coal Development Office of the Ohio Air Quality Development Authority (an MRCSP partner), on February 25, 2005. Two half-day sessions were held and attended by over 150 key stakeholders, including many from local and state government, industry and non-governmental and environmental organizations. MRCSP team leads and a well-known national speaker from the Lawrence Livermore National Laboratory gave presentations on geologic sequestration and on sequestration as it relates to Ohio and the broader MRCSP region. The information was well received and the discussions were very informative. Approximately one third of attendees completed brief feedback forms. Their responses showed that:

- All liked the half-day format
- Almost all reported that they were "more comfortable" with the concept of geological sequestration after attending the seminar
- A few attendees commented that they would like some more information about "worst case" scenarios
- Responses were split between those who had a technical background and those who did not: the former wanted more information and the latter thought there was enough, or too much, information

Interaction with Potential Candidate Site Sponsors

During the late summer of 2005, and following the announcement of the Phase II awards, members of the project team, including outreach staff, visited each of three sites that had been identified as candidates for the geologic field demonstrations. The objectives of the visits were both technical—to learn more about the technical feasibility and options at each candidate site—and outreach-oriented, specifically to build relationships and lay the foundation for planning and conducting site-specific outreach activities, including assessing public support for the field demonstrations under consideration for Phase II.

From the outreach perspective, the objectives of the meetings were four-fold:

1. Establish a collaborative and coordinated process between MRCSP and candidate site outreach teams
2. Conduct fact finding: learn more about the technical issues and site context, including expanding on, and prioritizing the list of stakeholders currently included in the data base
3. Agree on future outreach action items and responsibilities
4. Draw up interim "talking points" to be used, as needed, prior to Phase II.

The outreach team found the meetings very productive. Although much remains to be done in Phase II, the team believed that they had met their objectives and set the stage for a collaborative and constructive outreach process during Phase II.

Lessons Learned and the Potential Impact on Phase II Project Selection and Commercial Deployment

Phase I outreach activities provided an invaluable learning experience and foundation for Phase II and eventual commercial deployment.

Perhaps the key finding from the MRCSP outreach experience during Phase I is the confirmation of recent studies, discussed in Section 2.0, which found limited public awareness of carbon sequestration—of both the terminology and knowledge of the actual mechanics or potential role of carbon sequestration. Although not statistically demonstrated, the team identified a number of indicators that consistently pointed to this same conclusion (other factors, however, could also have contributed). For example:

- In meetings held with officials across the region, state, including regulatory officials, and local officials expressed interest in learning more about the technologies which could prove of benefit in view of the important economic role of coal in their states. Some also expressed interest in learning more about issues and worst case scenarios that could be raised by their constituents. Frequently, however, they acknowledged that carbon sequestration was a relatively new and unknown issue both for them and the general public.
- Leaders of regional environmental groups typically appeared more knowledgeable about the topic and expressed interest in MRCSP activities. However, most acknowledged that their resources were limited, that they had more urgent environmental priorities to address, and that carbon sequestration was currently not high on the public's radar screen—although they noted that this could change as the field demonstrations made the issues more immediate and site-specific. Some emphasized that it was important for the MRCSP to demonstrate openness in its activities and in its provision of information.

- Very minimal public attendance occurred at the PEIS scoping meeting, which was held in Columbus in May 2004, despite the mailing of individual letters to over 130 representatives of stakeholder organizations in the region
- Limited feedback was provided to the questions posed on the web site, despite increased visitation following establishment of the interactive web site during the second year of Phase I.

As noted previously, the finding of limited knowledge of carbon capture and storage offers both opportunities and challenges to the partnership program. Clearly, an opportunity continues to exist for introducing and presenting the issues related to sequestration in a constructive, problem-solving mode. The economic importance of coal in Midwestern states and the recent media attention on energy problems, including increased oil prices and global warming, could play a role in such a presentation. However, public acceptance cannot be guaranteed: although terrestrial sequestration appeared to be considered "green" and acceptable, documented concerns about geologic sequestration, primarily about leakage and the potential environmental and human health impacts, as well as the skepticism of coal expressed by some persons with whom the outreach team spoke, should not be ignored.

In addition, as the project moves into the field demonstrations in Phase II and, eventually, more widespread commercial deployment, members in neighboring communities may become more interested as the issues become more immediate and close to home. Previous studies and the outreach team's experience have documented the importance of a variety of factors in encouraging a positive response and willingness to discuss issues of potential concern: identifying and addressing public issues early, working to build trustworthy relationships with the public, putting in place an open decision-making process and ensuring accountability are likely to play an important role.

Apart from identifying limited public awareness of CCS, a major value of Phase I is the knowledge gained from the activities described in previous sections. This knowledge and experience has helped establish a firm base that can be used to assist the MRCSP in Phase II. The outreach team has developed a database of stakeholders from different organizations on whom the partnership may draw to network to others who are likely to play a more active role as issues become more concrete and site specific. They have developed some initial state contacts, become aware of the differing state contexts and regulatory and other issues that could affect future deployment of carbon sequestration in each of the even states. They have visited and met with representatives from the site candidate sponsors, developed an understanding of the technical options at the various candidate sites, and established a foundation for effective future collaboration between MRCSP and candidate site outreach teams. And finally, as discussed in Section 5, the outreach team has gained valuable experience in designing and maintaining the interactive website, which the project plans to use as a source of information and feedback to complement the more personal outreach efforts being planned for Phase II at the field demonstration sites. Modifications currently being planned on the basis of Phase I experience will serve to simplify and enhance the value of the site as MRCSP moves into Phase II.

MRCSP Meetings with Stakeholders

Meetings with MRCSP Partners, including Sponsors of Candidate Sites for the Field Demonstrations

Team Kickoff Meeting, Columbus Ohio. November 19-20, 2003.

Second Industry Partners' Meeting. Columbus Ohio, July 20, 2004.

Third Partners' Review Meeting. Delaware, Ohio, June 15, 2005.

Visit with DTE. Michigan, August 1-2, 2005.

Visit with FirstEnergy, Ohio, August 4-5, 2005.

Visit with Cinergy, Kentucky and Ohio, August 9-10, 2005

Meetings with Regulators

Arranged meeting with the State of Pennsylvania regulators. Harrisburg, Pennsylvania, September 29, 2005.

Arranged meeting with the State of Kentucky regulators. Frankfort, Kentucky, September 26, 2005.

Arranged meeting with the State of Maryland regulators. Baltimore, Maryland, June 7, 2004.

Arranged meeting with the State of Indiana regulators. Indianapolis, Indiana, April 28, 2005.

Arranged meeting with the State of West Virginia regulators. Charleston, West Virginia, November 29, 2005.

Arranged meeting with the State of Ohio regulators. Columbus, Ohio, November 8, 2004.

Meetings with other Stakeholders

Special meeting sponsored by the Pennsylvania Department of the Environment. Harrisburg, Pennsylvania, January 6, 2005.

Seminar on carbon dioxide sequestration, sponsored by the Ohio Coal Development Office of the Ohio Air Quality Development Authority. Columbus, Ohio, February 25, 2005.

Meeting with State of Maryland officials and industry representatives. Annapolis, Maryland, April 20,2005.

Terrestrial sequestration workshop sponsored by the Pennsylvania Department of Conservation and Natural Resources. Harrisburg, Pennsylvania, May 9, 2005.

MRCSP Papers and Presentations

During Phase I, the MRCSP conducted 58 briefings/presentations for a wide variety of audiences including industry groups, professional associations, government and public sector officials, academic institutions, and other civic groups.

The following table shows a breakdown of the number of presentations provided for each type of audience.

Audience Type	# of Presentations
Industry	8
Professional Associations	19
Government/Public Sector	15
Academic Institutions	6
Other Civic Groups	10

Presentations

Ball, D.A. "How Carbon Sequestration Technologies Can Work in our Region." Presentation to Ohio FutureGen Task Force Regional Meeting, Hamilton and Clermont Counties, based on presentations by Sally Benson, Lawrence Livermore Lab, and James Dooley, PNNL, Cincinnati, Ohio, July 19, 2005.

Ball, D.A. "The Midwest Regional Carbon Sequestration Partnership, Proposed Phase II Project." Presentation to Ohio Air Quality Development Authority Board of Directors, June 14, 2005, Columbus, Ohio

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presentation to MRCSP meeting with Maryland Regulators, Baltimore Maryland, June 7, 2005.

Ball, DA. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." The Global Energy Technology Strategy Project's Annual Steering Group Meeting, Washington, DC, May 25, 2005.

Ball, D.A. and Gupta, Neeraj "Clean Coal Technology, MRCSP and Mountaineer Projects." Presentation to Auditor of State for Ohio Betty D. Montgomery, May 13, 2005, Columbus, Ohio.

Ball, D.A. "The Midwest Regional Carbon Sequestration Partnership, Proposed Phase II Project." Presentation to the Ohio Coal Development Office Technical Advisory Committee, Columbus, Ohio, May 12, 2005.

Ball, D.A. and Duiker, Sjoerd "Managing Climate Change and Securing a Future for the Midwest's Industrial Base, Terrestrial Opportunities in Pennsylvania." Presented at a Terrestrial Sequestration Workshop arranged by Pennsylvania DCNR, Harrisburg, PA May 9, 2005.

Ball, D.A. for Lal, Rattan and Sperow, Mark "Carbon Sequestration in Terrestrial Ecosystems in the MRCSP Region." NETL Fourth Annual Conference on Carbon Sequestration, Alexandria, VA, May 5, 2005.

Ball, DA. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." NETL Fourth Annual Conference on Carbon Sequestration. Alexandria, Virginia. May 2-5, 2005.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presented to the MRCSP meeting with regulatory officials in Indiana, Indianapolis, Indiana, April 28, 2005.

Ball, DA. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Ohio Gas Association, 2005 Technical Seminar. March 31, 2005.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Special meeting of Pennsylvania state government representatives, Pennsylvania Department of Environmental Protection, Harrisburg, PA, January 6, 2005.

Ball, D.A. and Lal, Rattan "Managing Climate Change and Securing a Future for the Midwest's Industrial Base" and "Terrestrial Sequestration Opportunities in Ohio" Presented to the Ohio Corn Growers Association, December 20, 2004.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Ohio Air Quality and Coal Research Symposium, Ohio University, Athens, Ohio, December 2, 2004.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presentation to the Ohio FutureGen Task Force, Columbus, Ohio, October 22, 2004.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presentation to the Ohio Consumers Council, Columbus, Ohio, October 12, 2004.

Ball, DA. The Midwest Regional Carbon Sequestration Partnership. Presented to Board of the Ohio Air Quality Development Authority (OAQDA), October 12, 2004.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presentation to Mark Maddox, U.S. DOE, May 24, 2004.

Ball, D.A. "Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presentation to the Ohio Hydrogen from Coal Conference, Columbus, Ohio, April 2, 2004.

Carter, Kristin and Venteris, Erik. "A Multi-Disciplinary Approach for Mapping Rock Units with Geological Carbon Sequestration Potential." Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Dooley, JJ. "How Sequestration Technologies Can Work in Our Region." *Carbon Dioxide Sequestration, What It Is, What Is Its Status: A National, Regional, and Ohio Review* sponsored by the Ohio Coal Development Office of the Ohio Air Quality Development Authority, Columbus, Ohio, February 25, 2005.

Dooley, JJ and Ball, D. "Midwest Regional Carbon Sequestration Partnership: Managing Climate Change and Securing a Future for the Midwest's Industrial Base." MRCSP Briefing for the Third National Carbon Sequestration Conference, Alexandria, Virginia, May 2004.

Dooley. JJ. Carbon Management and Ohio's Future. Briefing for the Board of the Ohio Air Quality Development Authority, December 9, 2003.

Dooley, JJ and Cudnick, R. "Midwest Regional Carbon Sequestration Partnership: Managing Climate Change and Securing a Future for the Midwest's Industrial Base." Presented at the: The Fourth Annual MIT Carbon Sequestration Forum. Massachusetts Institute of Technology, Boston, November 6, 2003

Dooley, JJ. Carbon Management Briefing for the State of Ohio's Congressional Delegation. Capitol Hill, Washington, DC, August 18, 2003

Drahovazal, JA and Wickstrom, LH. Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Drahovzal, JA, , Harris, David, Nuttall Brandon, Solis, Michael, and Greb, Stephen. "Potential Carbon Sequestration Targets in Saline Reservoirs of Kentucky." Kentucky Geological Survey. Eastern Section

AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Greb, S.F., Nuttall, B.C., Solis, M.P., Parris, T.M., Drahovzal, J.A., Eble, C.F., Harris, D.C., Hickman, J.B, Lake, P.D., Overfield, B., and Takacs, K.G. "Siting coal-fired power plants in a carbon-managed future; the importance of geologic sequestration reservoirs." Kentucky Geological Survey. Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Greb, S.F., Slucher, E., Venteris, E.R., Brezinski, D.K., Marskowki, T, Blake, B.M, Fedorko, Nick. "Assessing the carbon sequestration potential of "unmineable" coal beds in the Appalachian Basin." Geological Survey of America, Annual Meeting, Denver, Colorado, November 7-10, 2004.

Gupta, Neeraj. "Improved Understanding of Regional Geologic CO2 Storage Options through Collaboration with Oil and Gas Industry." Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Gupta, Neeraj. "Overview, Phase II Test Plans." Cinergy Plant Visit, August 9, 2005.

Gupta, Neeraj, and Ball, DA. "Overview, Phase II Test Plans." First Energy Plant Visit, August 4, 2005.

Gupta, Neeraj. Mitsubishi Heavy Industry, Yokohama, Japan, July 25, 2005.

Gupta, Neeraj. Overview presentation at Central Research Institute for the Electric Power Industry (CRIEPI). Abiko, Japan, July 21, 2005.

Gupta, Neeraj. First Indo-US Workshop on Carbon Capture and Sequestration. National Geophysical Research Institute, Hyderabad, India, June 2, 2005.

Gupta, Neeraj and Sass, Bruce. "MRCSP Capture Task Summary." Capture Working Group Meeting, Champaign, Illinois, March 29, 2005.

Gupta, Neeraj. Ohio Geological Society Seminar. Columbus, Ohio, March 23, 2005.

Gupta, Neeraj. Houston (Poster presentation during BP CO2 Open House). February 21-22, 2005.

Gupta, Neeraj. Cincinnati, Ohio (in combination with Phase II planning meeting). February 11, 2005.

Gupta, Neeraj. Groundwater Protection Council Annual UIC meeting. New Orleans, Louisiana, January, 17, 2005.

Gupta, Neeraj. Stanford University Geophysics Department and Global Climate and Energy Program. Stanford, California, May 14, 2004.

Gupta, Neeraj. Battelle Conference on Remediation. Monterey California, May 2004.

Harper, John. "An Overview of Carbon Sequestration in Pennsylvania." Monthly Electric Industry Lunch Seminar, Carnegie Mellon University, Pittsburg, Pennsylvania, April 28, 2005.

Harrison, William. "CO2 Sequestration Assisted Enhanced Recovery Potential in the Midwest Carbon Sequestration Partnership." Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Harrison, William. "An Overview of the MRCSP Project." Pfizer Pharmaceutical Company Environmental Affairs Division, Kalamazoo, Michigan, August 25, 2005.

Nuttall, Brandon, Drahovzal, James, Eble, Cortland, and Bustin, R. Marc. "CO_2 Sequestration in Gas Shales of Kentucky." Kentucky Geological Survey. Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Venteris, Erik. "Characterization of America's "Engine Room" for Geologic CO_2 Sequestration." Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Venteris, E.R., Solis, M.P., Carter, K.M., and McDonald, J. "Uncertainty and Grid-Resolution Analysis for Regional-Scale Geological Maps." Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Venteris, E.R., Solis, M.P., Carter, K.M., and McDonald, J. "Uncertainty and Grid-Resolution Analysis for Regional-Scale Geological Maps." International Association of Mathematical Geologist (IAMG) Meeting, Toronto, Canada, August 22-26, 2005.

Venteris, Erik, Avary, Katharin, Bartley, Jeremy, Barnes, David, Carter, Kristen, Garcia, Catherin, Radhakrishnan, Premkrishan, and Solis, Michael. "A Web-based Decision Support System for Geologic Carbon Sequestration." American Association of Petroleum Geologists, Annual Meeting, Calgary, Canada, June 9-12, 2005.

Venteris, Erik, Wells, J., McDonald, J, Slucher, E and Wickstrom, L. "A Web-Distributed Data Service and Decision-Support System to Facilitate Carbon Sequestration Implementation." 14th Annual Ohio GIS Conference, Ohio, September 29-October 1, 2004.

Venteris, Erik, Wells, J., McDonald, J, and Wickstrom, L. "A decision-support system for the modeling of Geological CO2 Sequestration." Ohio Air Quality Symposium, Athens, GA.

Wickstrom, L.H. "Geologic CO2 Sequestration – An Introduction" Ohio Geological Survey. Eastern Section AAPG Meeting, Carbon Sequestration Meeting. Morgantown, West Virginia, September 19-21, 2005.

Wickstrom, L.H. Baum, G, Greb, S, Gupta, N, Harper, J, Harrison, W, Hohn, M, and Rupp, J. "Geological CO2 Sequestration Characterization of America's 'Engine Room'." American Association of Petroleum Geologists, Annual Meeting, Calgary, Canada, June 9-12, 2005.

Wickstrom, L.H. "Geologic CO2 Sequestration – An Introduction" Ohio Geological Survey. Ohio University, Athens, Ohio, May 13, 2005.

Wickstrom, L.H., Venteris, E.R., Rupp, J. A., Greb, S.F., Baum, G.R., Harrison, W. B., Carter, K.M., and Hohn, M.E. "Mapping and Characterization for Geological Sequestration by the Midwest Regional Carbon Sequestration Partnership (MRCSP). DOE/NETL Fourth Annual Conference on Carbon Capture & Sequestration, Alexandria, Virginia, May 2-5, 2005.

Wickstrom, L.H., Venteris, E.R, Slucher, E, McDonald, J, Wells, J. "A First Look At Regional Geological Maps from Recent CO2 Sequestration Characterization Research." Ohio Geological Society, Monthly Meeting, Columbus, Ohio, April 21, 2005.

Wickstrom, L.H. "Geologic CO2 Sequestration – An Introduction" Ohio Geological Survey. Ohio State University, March, 2005.

8.0 COST SUPPLY CURVE FOR THE MRCSP

The MRCSP region is a diverse region with significant geologic and terrestrial sequestration potential. It is also a region with a strong economy, and therefore it is home to a significant number of large CO_2 point sources that could potential employ sequestration technologies as a means for reducing their CO_2 emissions at some point in the future.[1] Within the MRCSP, large CO_2 point sources contribute over 776 million tonnes of CO_2 emissions per year. On the storage capacity side, these states are home to an estimated 500 to 550 gigatonnes (GT) of potential CO_2 storage capacity in geologic formations, and over 140 million tonnes of storage capacity available annually in terrestrial carbon sinks.

Any effort to address one of the major goals of the MRCSP – helping governmental, industrial and public stakeholders understand what it would mean to apply sequestration techniques in this region – requires that we attempt to better understand how the real world variability in CO_2 emissions and geologic and terrestrial sequestration reservoirs (as documented in the first phase of the MRCSP's research) would influence the potential large-scale adoption of sequestration-based technologies within this important region. To accomplish this, an engineering and economic sequestration cost methodology was used to analyze sequestration opportunities and economics within the MRCSP region that explicitly accounted for variations among key attributes of the sources and sinks found within this region.[2] This methodology has been employed to simulate how a market-based, competitive economy would seek to exploit the enormous sequestration potential within the MRCSP given a heterogeneous set of deployment options.

Methodology

While the MRCSP's geologic and terrestrial sequestration options are immense in terms of capacity, these resources also vary in ways that are both subtle and significant. Since the marketplace will be principally interested in the cost effectiveness of various means of reducing emissions, the MRCSP needed to create an engineering and economic model that would allow for an examination of these emissions mitigation options on a common cost-per-tonne basis. Given that terrestrial and geologic sequestration technologies are so fundamentally different, we needed to create two essentially different cost methodologies. A levelized cost was determined for each possible sequestration option, whether it be a source-reservoir pair identified for potential geologic sequestration or a particular terrestrial opportunity. These levelized costs were estimated based on each of the processes involved in each type of project, and are expressed on a dollar per tonne of CO2 sequestered basis.

Overview of Terrestrial Sequestration Cost Methodology -- Costs for Regional terrestrial sequestration opportunities were estimated based on the experience and research of the MRCSP terrestrial team, resulting in costs ranging from $4/tonne for non-eroded cropland to $27/tonne for wetland and peat land restoration with the other options falling in between and marginal land carbon enhancement being split

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[1] This section draws heavily upon the MRCSP report that documents the MRCSP's cost curve methodology and the results obtained by applying this methodology to the source and sink data collected during Phase 1of the MRCSP. Further details can be found by consulting, "Developing CO_2 Sequestration Cost Curves for the MRCSP" by RT Dahowski, JJ Dooley, CL Davidson, which can be found on the MRCSP website.

[2] A detailed description of this cost curve methodology was first published in Dahowski, RT, Dooley, JJ, Davidson, CL, Bachu, S and Gupta, N. *Building the Cost Curves for CO_2 Storage: North America.* Technical Report 2005/3. IEA Greenhouse Gas R&D Programme.

into three separate cost sub-categories representing different classes of marginal lands as found within the MRCSP region.[3]

Overview of Geologic Sequestration Cost Methodology — The crucial component of the geologic sequestration methodology involves calculating pairwise solutions matching each MRCSP source with its lowest cost, globally optimized storage option (i.e., finding the best option taking the entire system into account). Cost curves were computed, by solving for the best option for each stationary source subject to a set of constraints that are discussed below.

- First, due to the close proximity of candidate storage reservoirs to the CO_2 sources of the region, a maximum 100-mile search radius was imposed, such that each source was able to consider selecting any potential storage reservoirs within a distance of 100 miles.[4]

- For candidate geologic sequestration opportunities, net costs were determined by summing individual capital and operating costs for capture, compression, dehydration, pipeline transport, and storage including injection infrastructure and measurement, monitoring, and verification, less any revenue that might be generated by recovery of incremental oil or coalbed methane as a result of CO_2 injection. Summing each of these resulting cost components, and subtracting the value of any recovered oil or gas, arrives at a total net CCS cost, which is then levelized by applying an appropriate fixed charge rate for the project.

- Because each geologic storage formation contains a finite amount of potential lifetime storage capacity, this cost methodology also accounts for reservoir filling and competition for low-cost storage. Within this methodology, the source with the lowest net cost of capture, transport, and storage for a given formation is given first access to that formation's capacity. The source with the next-lowest storage cost is given access next, continuing in this manner until all sources seeking to store their CO_2 in the formation have been satisfied, or until the formation is full, whichever comes first. In the event that all of a formation's storage capacity has already been spoken for, the source's next-best option is pursued. In order to account for the fact that a source will seek to minimize capital costs by selecting a storage formation of sufficient available capacity to accept a reasonable volume of the source's CO_2, this analysis assumes a 20-year minimum capacity requirement. That is, in order for a formation to be considered a valid option for a source, it must have enough uncommitted capacity remaining to accept and store 20 years' worth of emissions from a source in order to grant it access.

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[3] As discussed in the Future Enhancements section of the MRCSP report "Developing CO_2 Sequestration Cost Curves for the MRCSP," we understand that a key improvement to this methodology is to craft a mechanism that will allow for the various terrestrial sequestration options available within the MRCSP to be better treated as the graded resources that they are. It is clear that the cost of implementing any of these terrestrial sequestration options would likely vary from place to place across the MRCSP region; hopefully, the terrestrial sequestration field projects planned for Phase 2 will help to better define the variability in terrestrial sequestration costs likely to be encountered in the real world.

[4] Our previous work has shown that vast majority (in excess of 85%) of large point sources in the United States can reach at least one candidate CO_2 storage reservoir within 100 miles of the facility and therefore we will use this search radius in this analysis. Interested readers can consult: R. T. Dahowski and J. J. Dooley, Carbon management strategies for US electricity generation capacity: A vintage-based approach, Energy, Volume 29, Issues 9-10, July-August 2004, Pages 1589-1598.

Cost Curve and the MRCSP

Figure 8.1 shows the resulting annual CO_2 sequestration capacity supply curve for the MRCSP region. That is, each point on the curve represents the specific cost of exercising a given terrestrial or geologic sequestration option within the MRCSP region. For example, each point represents the cost of capturing CO_2 from a fossil-fired power plant or other large CO_2 source, compressing the CO_2 to pipeline quality conditions, transporting it via pipeline and injecting the CO_2 into a suitable deep geologic storage reservoir. The curve is displayed on an annual basis, meaning that this is the amount of CO_2 that could be sequestered at each cost, during each year of the initial 20-year period being examined.
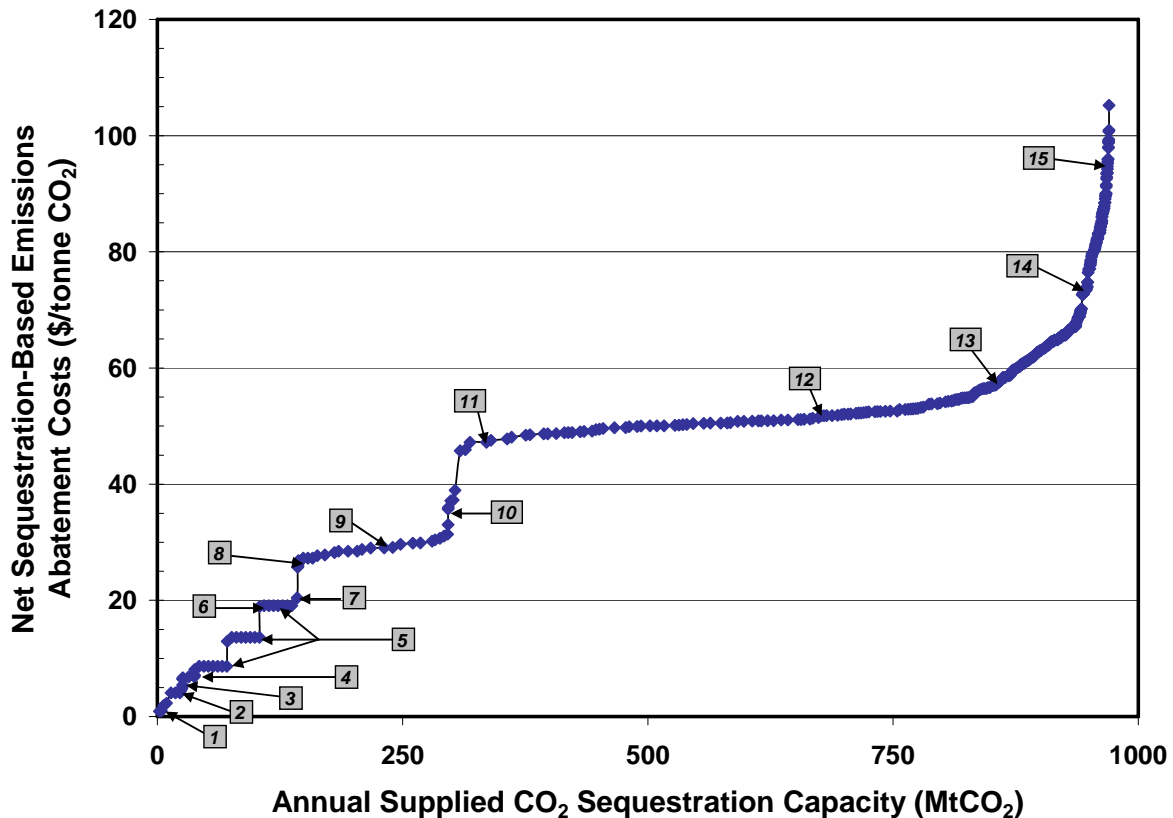
Figure 8.1.   Annual CO2 sequestration capacity supply curve for the MRCSP region.

The annual MRCSP sequestration supply curve presented here offers a richly detailed window to better understand how sequestration technologies might deploy within the MRCSP region. The MRCSP sequestration supply curve has several distinct segments in which different types of sequestration technologies are dominant:

- First, according to the analysis presented here, all terrestrial and geologic sequestration options within the MRCSP are likely to carry a positive cost. Therefore, there will need to be provided some disincentive on the free venting of CO_2 to the atmosphere or some better quantification of ancillary benefits of various terrestrial and geologic sequestration measures before these practices begin their large-scale deployment within the MRCSP. While the revenues associated with regional enhanced oil recovery and enhanced coal bed methane recovery can help to offset the cost of CO_2 capture and transport, these enhanced hydrocarbon recovery-related revenues do not

presently appear significant enough to completely cover the cost of capture, compression, transport, injection and long-term monitoring in this region.

- The lower part of the MRCSP sequestration cost curve, from $0 to $25 per tonne of CO2 stored, is dominated by terrestrial sequestration options and CO2 capture and geologic storage options centering on high-purity sources (ethanol, hydrogen, gas processing facilities, etc.) storing their CO2 in regional coal seams and oil-bearing deep sedimentary formations. The low costs are driven by the low cost of capture from high-purity sources, as well as the offsetting revenues that can be had by selling the additional oil and methane produced from EOR and ECBM formations, respectively, since more oil and gas can be produced from these formations after the introduction of CO2.

- From $25 to about $32 per tonne of CO_2 stored, the curve consists mainly of low-purity sources (power, iron and steel foundries, oil refineries, cement plants, etc) storing their CO_2 in value-added coal formations. While the cost of capture is higher for low-purity sources, the offsetting revenues from sale of the produced coalbed methane keep the net per-tonne cost of storage on the lower end of the curve.

- From $32 to $46/tCO$_2$, a combination of high-purity sources storing their CO_2 in non-value-added formations (deep saline-filled formations and depleted gas basins, neither of which contain saleable oil or gas) and low-purity sources paired with value-added EOR- and ECBM-based storage dominate this part of the curve.

- The long plateau in the middle of the curve (between about $46 and $63/tCO$_2$) is made up almost entirely of low-purity sources (predominantly coal-fired power plants) storing their CO_2 in deep saline-filled formations and gas basins. The increasing per-tonne cost is the result of sources becoming smaller and more distant from their best available sink.

- Finally, in the tail end of the curve (up to $105/tCO$_2$) there is an acceleration of this trend with mostly low purity sources of decreasing size and purity (e.g., small gas-fired power plants), able to access storage reservoirs at increasingly longer distances.

The numbered boxes on Figure 8.1 highlight some of the individual points on this sequestration supply curve. A short description of each point or region is provided on Table 8.1, which includes the type of source, selected sink, and a rough indication of the distance between them that each point represents. The points are representative of their respective segment of the curve, and are therefore by themselves not particularly special or unique. The purpose of calling out such sample points is to help illustrate the nature and development of the curve and the characteristics of the individual sources and sinks that contribute to the final placement and abatement cost for each point.

Table 8.1.   Description of select points on the resulting MRCSP region's sequestration cost curve.

Curve Point	Description
1	Large, high purity natural gas processing facility coupled with CO_2 storage in a nearby (<10 miles) ECBM opportunity
2	Non-eroded cropland terrestrial sequestration opportunities
3	Mid-size high purity natural gas processing facility coupled with CO_2 storage in a nearby (<10 miles) EOR opportunity
4	Eroded cropland terrestrial sequestration opportunities
5	Marginal lands terrestrial sequestration opportunities
6	High purity ethanol plant coupled with a distant (>50 miles) EOR opportunity
7	Small, high purity ethanol plant coupled with a nearby (<10 miles) depleted gas field CO_2 storage opportunity
8	Wetland / peatland terrestrial sequestration opportunities
9	Large, coal-fired power plant coupled with CO_2 storage in a nearby (<10 miles) coal seam
10	Small, high purity hydrogen production facility with a moderately distant (<50 miles) storage opportunity in a depleted gas field
11	Large, coal-fired power plant coupled with CO_2 storage in a nearby (<25 miles) deep saline formation
12	Iron & steel plant coupled with a nearby (<10 miles) deep saline formation
13	Smaller coal-fired power plant coupled with CO_2 storage in a nearby (<25 miles) deep saline formation
14	Cement plant coupled with a distant (>50 miles) deep saline formation
15	Gas-fired power plant coupled with a distant (>50 miles) deep saline formation

Further detail on the selected geologic sequestration points are presented in Figure 8.2. Here, the individual capture, compression, transport and net injection cost components are shown, which combine to result in the final estimated abatement cost for each geologic source-sink pair. This more clearly illustrates the impact of individual source and reservoir characteristics have in defining the total cost per tonne of each point. For instance, note that the capture cost component for these 11 sources ranges from $0/tCO_2$ for the very high purity CO_2 sources up to $57/tCO_2$ for the small and very low purity source (NGCC power plant). Compression cost estimates vary also, depending again on the size of the CO_2 stream and other characteristics, roughly between $6 and $12/tCO_2$. Likewise, transport costs are driven by the mass flow rate of CO_2 to be transported, but also the distance between source and its selected reservoir. Here, they range from about $0.20/tCO_2$ for the very large coal-fired power plant requiring minimal pipeline length, to nearly $15/tCO_2$ for the very small gas-fired power plant that is closer to 100 miles from its target sink. The injection costs shown here represent the cost of injecting the CO_2 into the selected reservoir (including all necessary capital and operating costs for wells and distribution pipeline, as well as monitoring equipment and procedures). Additionally, for value-added CO_2 injection for EOR or ECBM, the value of the anticipated incremental recovered oil or gas is then subtracted, thereby allowing for this net injection cost to be negative (i.e., an added value) in some situations. For these 11 sample points, the net injection costs vary from about $-7 to $12/tCO_2$, based largely on the type and characteristics of the selected reservoir (e.g., depth, injectivity, oil/gas recovery potential).
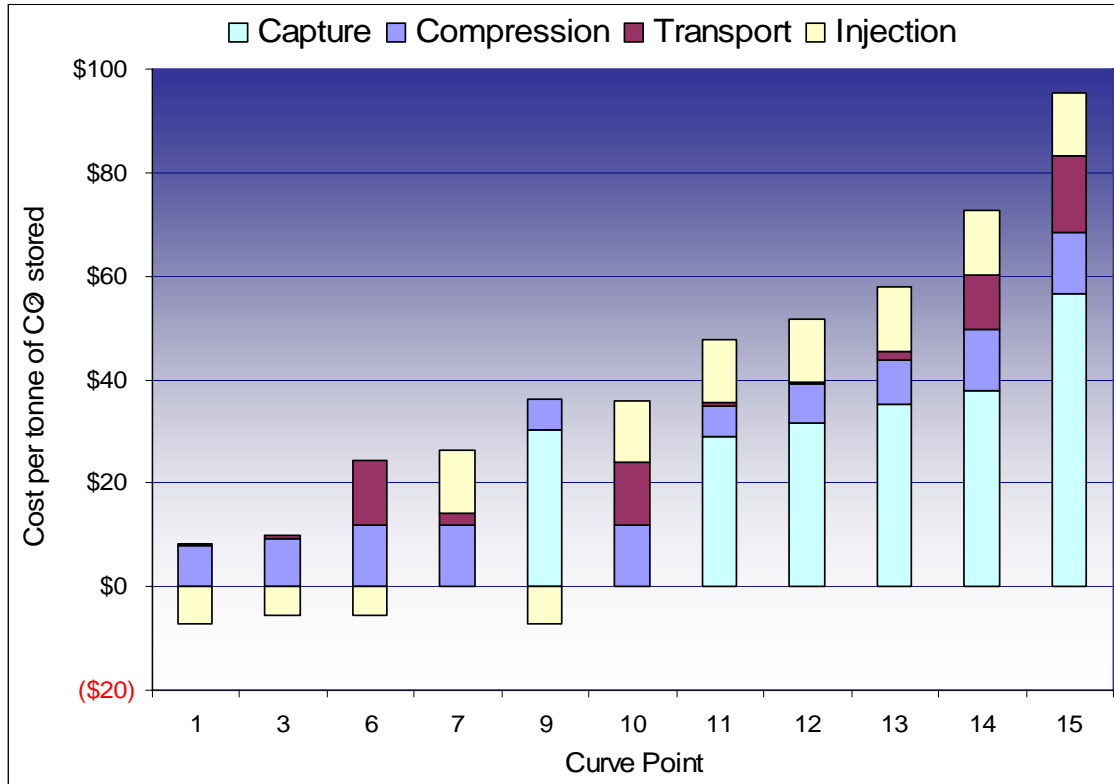
Figure 8.2. Component costs for the noted points on the curve representing geologic sequestration options.

For all but the very high purity sources, it is important to note that the largest cost is related to separation of CO_2 from the flue or process stream. In fact, for the example curve points shown here, the cost of capture represents roughly 60% of the total estimated net sequestration cost, for each point including a low purity source. This is significant, as lowering the cost of CO_2 capture from these low purity sources (and from power plants in particular) would provide a major boost to the economic viability of geologic sequestration within the MRCSP region, as well as elsewhere. For the MRCSP region alone, which relies heavily on coal-fired power production to drive its strong economy, advancing the separation of CO_2 from the flue gas streams of existing and future coal-fired power plants would have a significant and sustained impact on the region's ability to cost effectively reduce CO_2 emissions.

9.0 PHASE II PLAN

The MRCSP Phase II plan is designed to optimize and implement multiple parallel geologic and terrestrial field projects at locations across the MRCSP region representing the best source and storage opportunities for large reductions in regional greenhouse gas emissions. We believe these projects and their locations also will be representative of situations throughout the region to ensure good potential for replication and technology transfer, should wide-scale deployment of sequestration technologies become necessary.

Candidate Geologic Demonstration Projects

Our Phase II plan involves a number of candidate geologic sequestration test sites distributed across the seven-state MRCSP region. These are shown in Figure 9.1
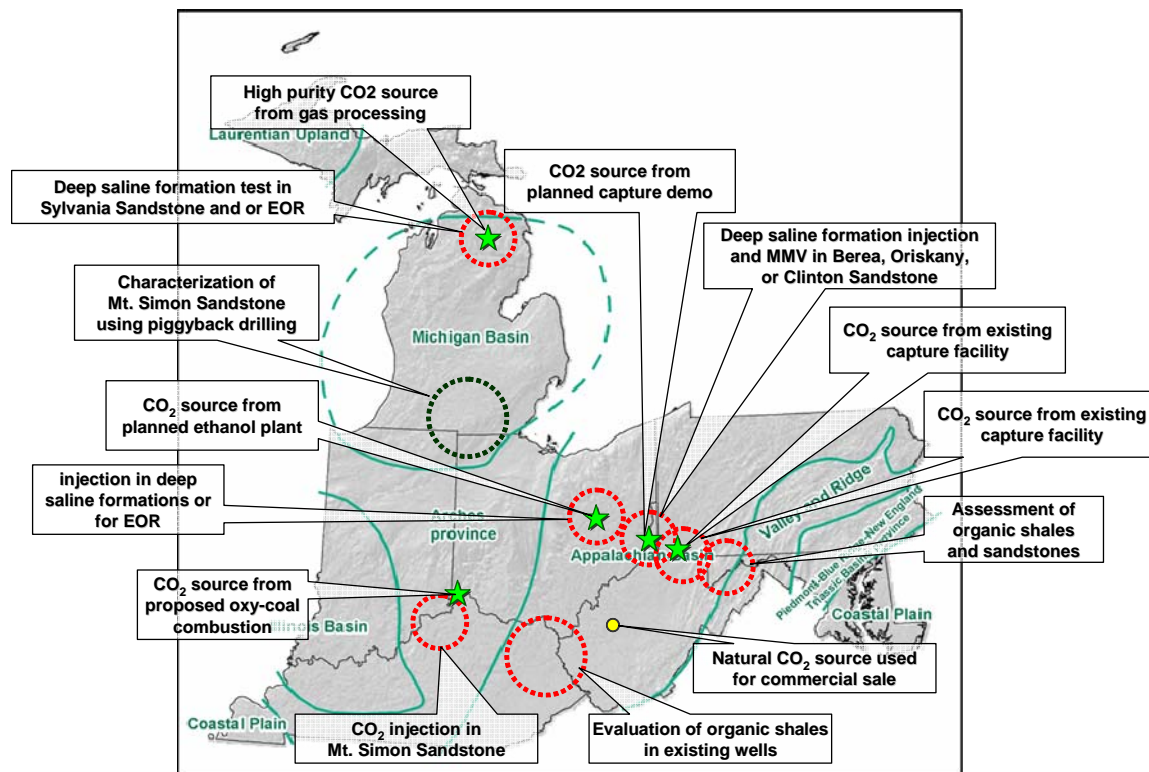
Figure 9.1.   Candidate geologic demonstration project sites for MRCSP Phase II.

The sites are distributed across the seven-state MRCSP Region and have been put forward as candidates because they will allow the MRCSP to validate the most important geologic storage reservoirs within our Region.

Three of these geologic project sites have been offered for testing and would be supported with both cash and in-kind cost share by major industrial sponsors of MRCSP: DTE Energy, FirstEnerg, and Cinergy. Visits were made by the MRCSP project team to all three sites in August 2005 and meetings were held

with site and corporate personnel from all three candidate host companies. These sites and potential injection demonstration projects are discussed below.

Saline Reservoir Test at a DTE Gas Processing Location in Michigan Basin — DTE has offered its gas processing facilities in the northern part of the Michigan Basin as a host site for CO_2 injection and also has offered to provide high purity CO_2 from this site. In addition to being a potential source of high purity CO_2, this general area also offers other infrastructure assets for conducting a CO_2 injection demonstration.

Figure 9.2 shows CO_2 compression and dehydration facilities adjacent to one of the DTE gas processing plants. These facilities currently support EOR operations in the area by taking CO_2 from the nearby DTE natural gas processing plant (Turtle Lake), dehydrating and compressing it to supercritical state, and transporting it via a six inch diameter pipeline about 10 miles to the oil fields.

Figure 9.2. Gas compression and dehydration facilities at the northern Michigan candidate test site.

The operations at the oil fields, including the CO_2 pipeline, are shown in Figure 9.3. Together these facilities offer a potentially unique existing infrastructure to explore injection opportunities in various geologic reservoirs in the area which are of interest specifically to DTE but also have broader value for extrapolation to other areas of the MRCSP region.

Figure 9.3. CO_2 pipeline feeding existing EOR wells at the northern Michigan candidate test site.

In addition to the Mt. Simon Sandstone, this area has shallower injection intervals with high permeability in the Sylvania Sandstone and the Bois Blanc Dolomite at depths greater than 2,500 ft and thickness between 200 to 300 ft, and caprocks consisting of very low permeability anhydrite and salt layers. There is a large amount of geologic data and potential for using existing wells for injection/monitoring in this area.

Saline Reservoir Injection in the Appalachian Basin in Eastern Ohio, Western Pennsylvania, or Northern West Virginia — FirstEnergy plans to test an enhanced version of the Powerspan technology (which is currently optimized to remove SO_x, NO_x, and Hg) that would be capable of capturing CO_2 at their R.E. Burger plant in eastern Ohio during 2007. Figure 9.4 shows the Burger plant and the existing Powerspan multipollutant (NOx, SOx, and Hg) pilot plant.
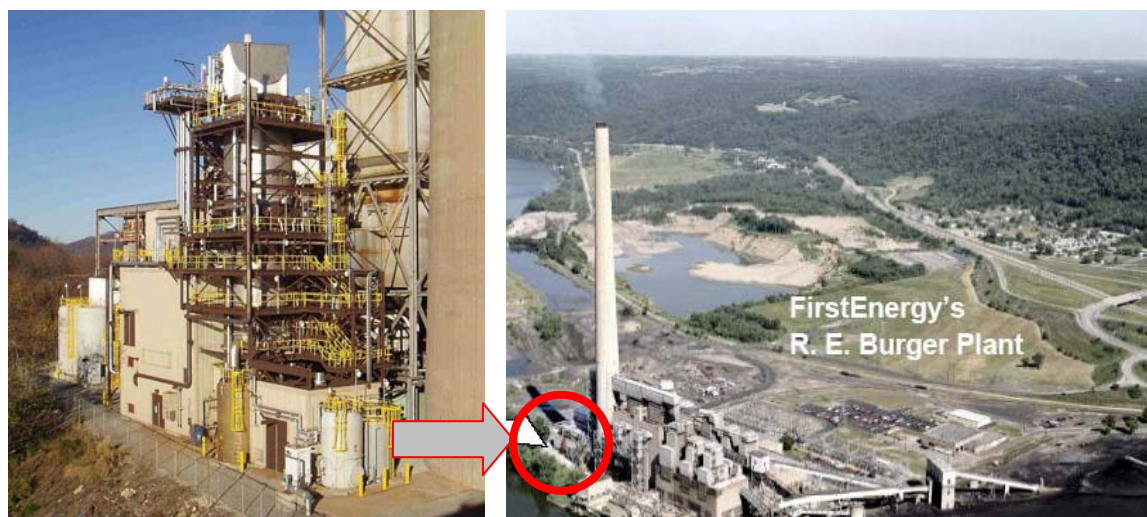
Figure 9.4.   The FirstEnergy R.E. Burger power plant (right) showing the Powerspan pilot plant (left) currently in operation there.

This will provide an ideal opportunity to test an integrated CO_2 capture, handling, and injection system in this tri-state area of the Appalachian Basin. The injection zones in this area are likely to be the Berea Sandstone, the Oriskany Sandstone, the Clinton Sandstone, or the high permeability zones in carbonate layers. There is sufficient containment and the area has a large concentration of power plants, making it critical for future evaluation of CO_2 storage potential.

Saline Reservoir Tests at a Cinergy Site in Southeast Indiana or Northern Kentucky — Two locations, one an operational power plant and one a greenfield site for a potential future power plant, in this area have been offered by Cinergy for an injection test. This area represents the uplifted arches geologic province that separates the Illinois Basin from the Appalachian Basin. The most likely injection zone in this area is the Mt. Simon Sandstone (~300 ft thick and ~4,000 ft deep) although other high permeability zones are likely to be present above (Knox Dolomite) or below (Middle Run Formation) this interval. There is excellent containment in this area and overall injectivity should be very high. The site is representative of a large part of the MRCSP Region and an explicit linkage to current or potential future power plants makes it attractive for deployment at full-scale in the future.

In addition to the three projects listed above, other promising projects for testing storage in different geologic sinks have been put forward. Below is a selection of these other candidate projects, which will be further evaluated for their storage potential, scientific benefits, and importance to MRCSP stakeholders.

Northern Michigan Basin EOR Tests — As mentioned above for the DTE hosted demonstration, there is currently ongoing enhanced oil recovery in the Niagaran Pinnacle Reef Trend (dolomites with high thickness, porosity, and permeability) using very pure (>99 percent) CO_2 from various gas processing plants in northern Michigan including the DTE plants mentioned earlier.

The infrastructure for CO_2 injection (e.g., processing, pipelines, equipment) already exists in this part of the MRCSP region in that there is a very large suite of geological and geophysical data along with an operator willing to discuss cooperation with the MRCSP. There is significant co-benefit to using this site in terms of additional oil recovery, however, it remains to be seen how this opportunity can be tailored to evaluate CO_2 retention in the oil field.

It may be possible to use this site for a case study for EOR sequestration in the region rather than an actual field injection project. Other opportunities in the Michigan Basin include the oil fields in Dundee Formation that may have a significant CO_2 storage and EOR potential due to large areal extent and associated saline reservoir parts of the formation.

Deep Saline Formation and EOR Storage Test Opportunities in Eastern Ohio — Several counties in eastern Ohio (e.g., Coshocton, Tuscarawas, Carroll, Stark) have an active oil and gas industry resulting in availability of a large amount of geologic data. It also may be possible to use existing wells in oil and gas fields to evaluate and potentially conduct field test injection for EOR (e.g., East Canton Field) or deep saline formations (e.g., Copper Ridge Dolomite, Rose Run Sandstone, Clinton Sandstone, Lockport Dolomite, Bass Island Dolomite) and thousands of feet of caprock. This area also has promising potential sources for CO_2, including Baard Energy's soon-to-be-completed ethanol plant and FirstEnergy's plans to test a Powerspan CO_2 capture unit at their R.E. Burger Plant. There is also potential economic co-benefit from potential CO_2 EOR (estimated at 40 million additional barrels for the East Canton field alone).

Injection Tests in Northern Appalachian Basin Sites — Two locations in this Region have been identified for potential injection tests. Greene County in southwestern Pennsylvania has numerous potential injection zones in deep saline formations (e.g., Oriskany and Tuscarora Sandstones, Lockport Dolomite), deep coal seams at depths from 1,500 to 2,000 ft, and coal bed methane production areas. The source for this could be a gas processing plant operated by CONSOL Energy in the area that produces high-purity (~90 percent) CO_2. The second opportunity is in the western panhandle of Maryland, where a coal-fired plant with an existing CO_2 capture unit, owned by MRCSP Phase I member AES Warrior Run, could provide food-grade CO_2.

The storage reservoirs in this area include the Oriskany Sandstone and the organic rich Mandata Shale. The rocks are folded into a series of anticlines and synclines with up to 200 ft of sandstone. If Mandata Shale proves to contain sufficient organic matter for CO_2 storage and methane, there will be a co-benefit in the form of methane production.

Similar injection potential close to sources of CO_2 (e.g., a natural CO_2 source near Charleston, WV or another CONSOL gas processing plant in western West Virginia) is also present in the Appalachian Basin in West Virginia and Kentucky and these options will be further evaluated for feasibility of conducting the field tests.

Organic Shale Injection Potential in the Appalachian Basin – The Kentucky Geological Survey has been conducting research on the potential of organic rich shales, which are extremely widespread in MRCSP Region, to store CO_2 through adsorption in Devonian Shale. The initial results are promising, however, continued research on the implementation aspects is needed.

There are several potential opportunities to conduct limited field tests and/or focused laboratory analysis to make further progress on this option. For example, there is large production from several fields in an area known as the Big Sandy along the Kentucky-West Virginia border and it is highly likely that some of the existing wells could be used for injection and monitoring. At a minimum, an effort will be made to further characterize the shale zones for their organic carbon content, sorption properties, and retention potential.

We also plan to supplement the field validation tests described above with further characterization of other reservoirs through the following mechanisms:

- **Continued refinement of maps prepared during Phase I,** preparation of new maps for horizons that were not mapped separately during Phase I, and compilation of injectivity data to assist in storage capacity calculations

- **Characterization of deep coal seams for CO_2 adsorption potential** in collaboration with CONSOL Energy

- **Characterization of deep saline reservoirs** through collaboration with ongoing commercial oil and gas drilling in the Region (e.g., Mt. Simon Sandstone in Michigan Basin, basal sandstone in Appalachian Basin, and carbonate formations throughout the Region)

- **Assessment of the CO_2 storage potential of two to three representative oil and gas fields in the region**, based on existing geologic, oil composition, and production data and possibly with simplified reservoir simulations.

Finally, another key component of the Phase II geological research will be an innovative "piggyback drilling" program. This type of program, which has been used successfully by Battelle in other DOE sponsored projects, will allow the MRCSP to leverage the ongoing and extensive investments made by the local oil and gas drilling companies to gather "real world" sequestration-related data such as core samples from deep geologic formations.

Reservoir Modeling

Throughout Phase II, the MRCSP will be conducting a rigorous program of reservoir and geochemical modeling. Such modeling is essential for developing a unified geologic and conceptual framework based on site characterization data and forms the basis for regulatory permits. It is also useful in developing the designs for CO_2 injection (e.g., maximum injection pressure, radius of influence, and CO_2 phase behavior) and monitoring program. The modeling will be used with the injection data to upscale the field tests for evaluation of full-scale, long-term injection of CO_2.

The principal tool for reservoir simulation will be the state-of-the-art STOMP- CO_2 multiphase, multi-component model, which previously has been used for modeling the geologic injection for Mountaineer Plant data. Other semi-analytical models, commercial numerical models, and geochemical codes will be used if needed to augment the STOMP-CO_2 results. Calibration runs will be performed to tune the hydrogeologic parameters to conform to data collected from the geologic field tests which will allow for the use of models for predictive simulations of full-scale injection (e.g., 100 percent of CO_2 injection from a hypothetical 1000 MW IGCC plant for several decades) and lay the groundwork for possible future commercial deployment, an overarching goal of Phase II.

Permitting

A detailed implementation plan and roadmap for obtaining all relevant permits will be developed for each of the geologic sequestration field test sites. The plan and roadmap will include a detailed list of steps to obtain project permits. The plan also will address existing regulatory gaps, uncertainties, and an explanation of the associated barriers toward technology deployment. The plan also will identify and address any local, state, or regional requirements for measurement, monitoring, and verification (MMV). The Federal National Environmental Policy Act (NEPA) requirements will be addressed for each site.

We assume an Environmental Assessment (EA) rather than an Environmental Impact Statement (EIS) will be needed for each site. We will also identify and prepare relevant state and regional permits for the drilling and construction of the deep well and any needed monitoring wells as well as obtain Underground Injection Control permits and any state permits needed for the injection phase of the field validation tests. We will work with DOE and EPA geologic sequestration working groups to the extent possible to develop uniform and hopefully simplified permitting process for the Phase II projects.

Construction Requirements

Major construction activities will include drilling and completion of deep wells and, if needed, any monitoring wells (where possible, MRCSP will identify and use existing wells to minimize drilling costs and use resources for monitoring); CO_2 storage facilities and ancillary equipment such as a surge tanks; utilities connected to the field test site and suitable platforms completed for equipment, such as compressors to prepare the CO_2 for injection into the well; and completion and insertion of the injection string and casing before CO_2 injection can commence. The MRCSP will draw extensively on the knowledge gained through the Mountaineer Project and the expertise of our sponsors such as Schlumberger to help plan and guide all of our field work, including construction.

Injection Operations

A critical task for each of the planned geologic field tests will be the safe execution of CO_2 injection into the target storage reservoirs and the measurement, monitoring, and verification of the injected CO_2. Computer modeling will be employed to study various CO_2 injection scenarios and to support the development of the injection system and its associated MMV system. The MRCSP will create a detailed plan for the CO_2 injection phase of the field test which will address how CO_2 will be transported to the site; stored at the site; injected into the proposed CO_2 storage formations; and measured, monitored, verified. This plan will be sent to the site host sponsors and the DOE COR for approval, before CO_2 injection begins. Having obtained all relevant permits and having obtained all needed permissions and clearances from the project sponsors, including the DOE COR, a sufficiently large quantity of CO_2 (up to 10,000 tonnes per site) will be injected through the deep well and into the target formation(s) to allow the MRCSP research team to measure and monitor the injected CO_2.

Monitoring and Verification Equipment and Operations

It is through the practical, transparent and safe demonstration of CO_2 injection into the region's deep geologic formations that the MRCSP will be able to fundamentally advance the geologic sequestration as a viable carbon management solution for our Region. Data will be collected on the injected CO_2 which will help establish and verify its fate and demonstrate the viability of MMV technologies. The specific suite of

MMV technologies that will be employed will be dictated by conditions at the site but will most likely draw from proven common industry methods or emerging MMV options.

At the same time it must be recognized, that within the project budget it will not be possible to incorporate all available options at each site. Thus an attempt will be made to select technologies that are applicable to the geology of individual sites and also help demonstrate the use of different suites of MMV for CO_2 storage across the region (see Figure 9.1).

The MRCSP's MMV work also will seek to leverage research supported in this area through the Core DOE [Carbon Sequestration] Research Program. At a minimum, MRCSP will conduct the monitoring required by regulatory agencies under the permitting process. In addition, the MMV options for above-ground monitoring (e.g., soil flux, 4-D seismic, gravity methods, seismic monitoring) and sub-surface monitoring options (e.g., vertical seismic profiles, cross-hole seismic or EM monitoring, RST saturation monitoring or other wireline tools, borehole seismicity, mechanical wellbore integrity tests) will be considered.

Risk Mitigation Approach.

The primary risk mitigation objective will be a deliberate, thoroughly planned and vetted sequential step-wise program that puts safety above all else. During the course of the field validation tests, the MRCSP will develop site-specific action plans that will outline and satisfy project permitting requirements for each of the major system components of the geologic field tests, including capture, transport, seismic survey, drilling, injection, well closure, site restoration.

During drilling, specific attention will be paid to the potential presence of high pressure zones, natural gas, or hydrogen sulfide pockets, and to prevent any impact on shallow groundwater zones. Sitting above these task-specific plans will be more compressive health, safety, and environmental (HS&E) protection plans for each site. All visitors and workers at the site will be briefed on these HS&E plans before being allowed access to the site. In addition, the MRCSP will carry out a rigorous site-specific risk assessment modeling and analyses which will allow for risks to be assessed and for risk mitigation scenarios to be developed.

A specific goal of this risk assessment work is to document what was learned at each site and how this site-specific knowledge could be extrapolated to larger commercial-scale application of sequestration projects within the MRCSP Region.

CO$_2$ Sources

A number of potential high purity CO_2 sources for up to 10,000 tonnes of CO_2 that will be used for the various geologic storage validation tests have been identified in the region and include:

- A new state-of-the-art ethanol plant is under construction by Baard Energy in Coshocton County in eastern Ohio. This new ethanol plant will be operational in 2006 and can provide CO_2 for injection tests in Appalachian Basin deep saline formations, oil fields, organic shales, or coal seams.
- Several natural gas processing plants operated by DTE in Michigan provide a source of very high purity CO_2, and one of these has been offered as a site for CO_2 injection in deep saline formations and potentially in nearby oil fields for EOR.
- Two operational natural gas processing facilities owned by CONSOL Energy in southwestern Pennsylvania and western West Virginia provide CO_2 with greater than 90 percent purity.

- A test of CO_2 capture using an enhancement of PowerSpan technology is planned at the FirstEnergy's RE Burger Plant at Shadyside, Ohio, and has been offered as a source of CO_2 with potential injection in nearby deep saline formations, coal seams, or organic shales.
- Babcock and Wilcox is proposing a demonstration of an oxy-coal combustion process at a small municipal plant in southeastern Ohio, which will produce up to 15,000 tonnes of CO_2 with more than 80 percent purity on a wet basis in 2008. This CO_2 has been offered for injection tests.
- Several other sources of CO_2 are present in the Region, including refineries, a natural CO_2 field near Charleston, West Virginia, and commercial CO_2 from companies such as Praxair, Air Liquide, and BOC.

During the project definition period of Phase II, we will work with the above-mentioned sources and commercial CO_2 handling companies to evaluate issues related to availability, composition, pressure, handling requirement, and cost. Several of the sources are already matched with the potential geologic storage test sites.

The final selection will be made based on the best available options at the time of the geologic tests. Obviously, the highest benefit to the DOE program and MRCSP sponsors comes from using anthropogenic CO_2, especially from any ongoing capture tests in the region. Therefore, a preference will be given to these sources to permit understanding of full-system deployment.

This desire to use the CO_2 from anthropogenic source also means additional purification or polishing may be needed to remove impurities such any excess nitrogen, methane, and other post-capture impurities that may affect compression, handling, or regulatory requirements. Some of these, such as nitrogen, may also affect the subsurface processes by creating a three-phase flow situation because it remains in a gas phase. These issues will be the subject of site-specific assessment during the final selection stage. It is our intent to use very pure CO_2 to the extent possible to ease permitting and public acceptance aspects.

It is clear that the CO_2 will need to be shipped via a tanker truck. We do not expect the distance between source and the field test will be more than tens of miles at the most, and for some of the sites under consideration, injection may even be on site. The transport of CO_2 via tanker truck over these kinds of distances is a well established practice and we do not foresee any significant issues arising.

The combined result of the portfolio of research projects during Phase II will be a validation and demonstration of the geologic storage potential in the region as well as development of a geologic framework required for systematic implementation of CO_2 storage in the MRCSP Region.

Candidate Terrestrial Sequestration Projects

In Phase II, the MRCSP will conduct a detailed field test of soil carbon sequestration techniques on agricultural soils and reclaimed minelands in collaboration with our partners the Corn and Soybean Growers Association and CONSOL. While there are numerous potential opportunities to address terrestrial sequestration within an area as large as the MRCSP, we have decided to focus, in Phase II, on demonstrating soil carbon sequestration in agricultural soils and reclaimed minelands as there is strong commercial interest in these areas, coupled with the potential for large-scale emissions abatement and an opportunity to advance research in this area. Adoption of recommended management practices (RMPs) on cropland and the restoration of minelands affords a unique opportunity to demonstrate soil carbon sequestration techniques, which can assist us in addressing climate change over the long-term, and to

deliver immediate benefit to the local environment (e.g., reduced runoff and low risks of water pollution) by stabilizing these anthropogenically disturbed lands.

In collaboration with Corn and Soybean Growers Associations and CONSOL, we will demonstrate how a number of promising soil/terrestrial carbon sequestration techniques can offset fossil fuel emissions and reduce the net increase in atmospheric concentration of CO2 while improving quality of soil and water resources. As can be seen from Figure 9.5, there are approximately 10.7 million hectares (Mha) of productive cropland, 1.7 Mha of eroded cropland and 0.6 Mha of minelands within the MRCSP.
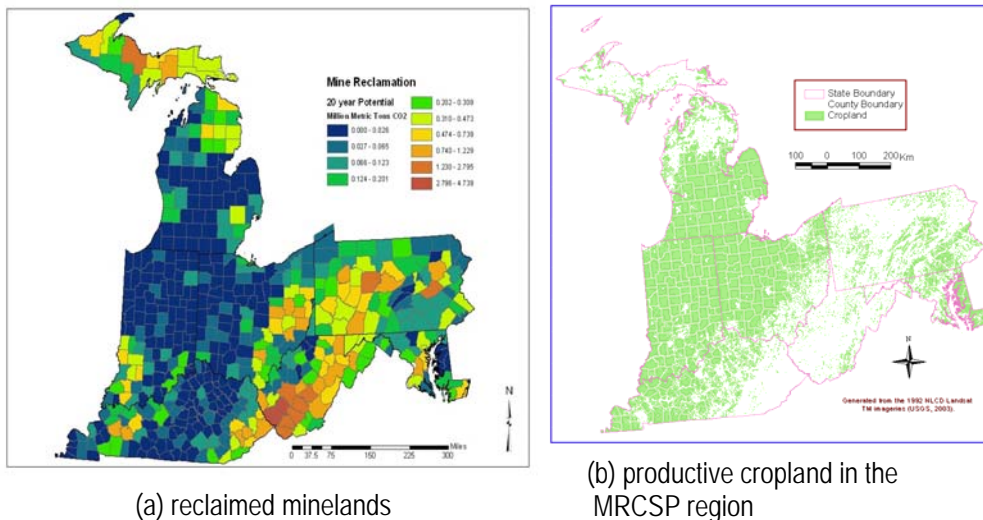

(a) reclaimed minelands

(b) productive cropland in the MRCSP region

Figure 9.5.   Area of Minelands and Croplands in the MRCSP region

These lands are found in each of the seven MRCSP states. Reclaimed minelands are concentrated in Kentucky, Ohio, West Virginia, and Pennsylvania. We estimate that adoption of RMPs would sequester 13.6 million tons (MT) of CO_2 on productive cropland, 11.4 MT CO_2 on eroded cropland, and 5.9 MT CO_2 on reclaimed minelands. If fully implemented, terrestrial C sequestration in these ecosystems would offset more than 500 MT of CO_2 credits over a typical project lifetime of 20 years.

The actual test plots to be used will be chosen in our screening efforts early in Phase II. Final sites will be chosen based on the basis of:

- Similarity of soils, bedrock geology, slope, and aspect
- Known history of land use and management on croplands, and mining dates and reclamation technique
- Known land use history (hay, forest, cropland) and soil/vegetation management (manuring, mulching, fertilizer)
- A range of tree and forage species
- Mineland sites reclaimed prior to 1977 and post-1980.

By choosing sites based on these criteria, we can extrapolate the results from our small field tests to the much wider set of potential circumstances encountered once these practices are commercially deployed.

Practices to be demonstrated for carbon sequestration include:

- Cropland – no-till farming with cover crops and manuring
- Minelands – restoration with and without topsoil, and establishment of trees and pastures as post-reclamation land use.

Before any work is initiated at the field sites, we will establish baseline measurements of soil carbon contents and pools and other key physical parameters (e.g., bulk density, clay content, N concentration). This baseline will allow assessment of the total carbon pool. The geostatistical variability in total carbon pool will be determined for each site using standard methods. Data of other soil parameters (N and clay contents) will be used to quantify differences among management systems.

Bulk and core soil samples will be obtained on a replicated basis to measure carbon concentration, bulk density, and other parameters. Carbon and nitrogen concentrations will be measured by a C:N analyzer using dry combustion method. Bulk density will be measured by the core method, and textural properties by the hydrometer method.

Monitoring and Verification

Soil samples on croplands will be obtained on a rectangular grid, with sampling points chosen: 200 m by 100 m grid on cropland, and 25 m by 50 m grid on mineland. Soil samples will be collected from 0 to 10, 10 to 30, 30 to 60, and 60 to 100 cm depth on cropland; and for 10 cm depth increments to the spoil material or 50 cm depth in reclaimed mineland.

Soil samples from minelands will be obtained for different land uses either for an age chronosequence (5, 10, 20, 30 years since reclamation) for the same land use, or soil samples will be taken over time (once every year) for the same site.

All sites will be geo-referenced, and spatial variability will be assessed using the geostatistical techniques. The data thus obtained will be extrapolated using scaling procedures.

Other Activities

In addition to the demonstration projects described above, the MRCSP Phase II program will continue the crucial work initiated in Phase I to map and define the sequestration potential of the region, seek to understand key regulatory issues and undertake a first-ever systematic approach to engage and inform stakeholders across the entire region about this important class of technologies. This will include continued refinement and updating of the MRCSP website, www.mrcsp.org.

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