Midwest Regional Carbon Sequestration Partnership

PHASE II FINAL REPORT

DOE-NETL Cooperative Agreement DE-FC26-05NT42589

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EXECUTIVE SUMMARY

The Midwest Regional Carbon Sequestration Partnership (MRCSP) was formed to assess the technical potential, economic viability, and public acceptability of carbon sequestration within its region. The MRCSP is one of seven regional partnerships established in October 2003, which, together, make up the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnership (RCSP) program. The RCSP program is led by DOE's National Energy Technology Laboratory (NETL).

The MRCSP region consists of nine neighboring states: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. The MRCSP partnership is led by Battelle Memorial Institute and includes nearly 40 organizations from the research community, energy industry, universities, non-government, and government organizations. The region has a diverse range of carbon dioxide (CO_2) sources and many opportunities for geologic and terrestrial sequestration. Additional information about the MRCSP is provided in Tables ES-1 and ES-2.

Table ES-1. A Snapshot of the MRCSP Region

Subject	Fact
Geographic region	Nine States: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia
Population	80.4 million (25% of US population)
Gross Regional Product	$3,114 billion (27% of the US economy)
Electricity generation	26.3% of all electricity generated in the US
CO_2 emissions	Approximately 699 million metric tons of CO_2 per year are emitted from large point sources. 85% of those emissions are related to electricity generation.

Table ES-2. The MRCSP Program is Divided into Three Phases in Concert with DOE's RCSP Program

Phase	Timeframe	Objective
Phase I	October 1, 2003 through September 30, 2005	Analytically characterize the large point sources of CO_2 and potential geological and terrestrial CO_2 storage options for the region.
Phase II	October 1, 2005 through February 4, 2011	Translate the theoretical knowledge gained in Phase I into practical, real world knowledge through the conduct of a series of small scale field validation tests.
Phase III	May 6, 2008 for approximately 10 years (currently in progress)	Demonstrate the potential for geologic CO_2 storage in the region by conducting an injection test of at least one million metric tons of CO_2 into a regionally significant reservoir.

This final report summarizes the research conducted and results obtained during Phase II of the MRCSP's overall program.

Phase II Financial Summary

The total value of the MRCSP Phase II project was $28,801,838, including all cost share received. The primary source of funding for Phase II was the NETL under cooperative Agreement No. DE-FC26-05NT42589. DOE funding provided to the project was $22,304,933 or 77.44% of the total. The second largest contributor to the project was the Ohio Coal Development Office (OCDO) within the Ohio Air Quality Development Authority under OCDO Grant/Agreement No. D-05-13 in the amount of $750,000 or 2.6% of the total. The remaining funding was provided by the MRCSP partners.

MRCSP Partners

The various entities supporting the MRCSP as partners during Phase II are shown in Table ES-3.

Table ES-3. MRCSP Phase II Partners

Industry Partner Team	Research Partner Team
- American Electric Power - AMP Ohio - Babcock and Wilcox - British Petroleum - American Coalition for Clean Coal Energy - Chicago Climate Exchange (CCX) - CONSOL Energy - Constellation Energy - Consumer Energy - Dominion - DTE Energy - Duke Energy - Electric Power Research Institute - FirstEnergy - Indiana Office of the Consumer Counselor - National Rural Electric Cooperative Association - New York State Energy Research and Development Authority - Ohio Coal Development Office within the Ohio Air Quality Development Authority - Ohio Consumers' Counsel - Praxair - RWE	- AJW Inc. - Core Energy LLC - ESG - Indiana Geological Survey - Kentucky Geological Survey, University of Kentucky - Maryland Geological Survey - New Jersey Department of Environmental Protection - New York State Museum - Ohio Division of Geological Survey - Ohio Environmental Council - Pennsylvania Geological Survey - The Keystone Center - The Ohio State University (OSU) - Stanford University - University of Maryland - West Virginia Geological Survey - West Virginia University (WVU) - Western Michigan University

Phase II Accomplishments

The goal for Phase II was to build upon the successes of Phase I to create regional solutions that address climate change while fostering a strong, healthy regional economy by validating the most promising sequestration technologies in two to four selected field tests. A variety of monitoring techniques, including micro seismic, wireline, cross-well seismic, tracer gas, pressure sensing, and fluid sampling, were used to image and track CO_2 behavior. This experience and additional techniques will be used in Phase III to further evaluate and monitor CO_2 storage and containment. In addition, experience gained in building and validating models, as well as correlating injection data with log, core and other site characterization data at a small scale will be used for the larger scale Phase III project to improve the accuracy of these techniques for commercial sites.

In all, seven small-scale field validation tests were conducted in Phase II (Figure ES-1):

- Three geologic injection tests, one in each of the three major geologic provinces of the region: the Michigan Basin, Appalachian Basin, and Cincinnati Arch.
- Four terrestrial field tests in land types characteristic of the heterogeneity of the region: croplands, reclaimed minelands, reclaimed marshlands, and forested wetlands.

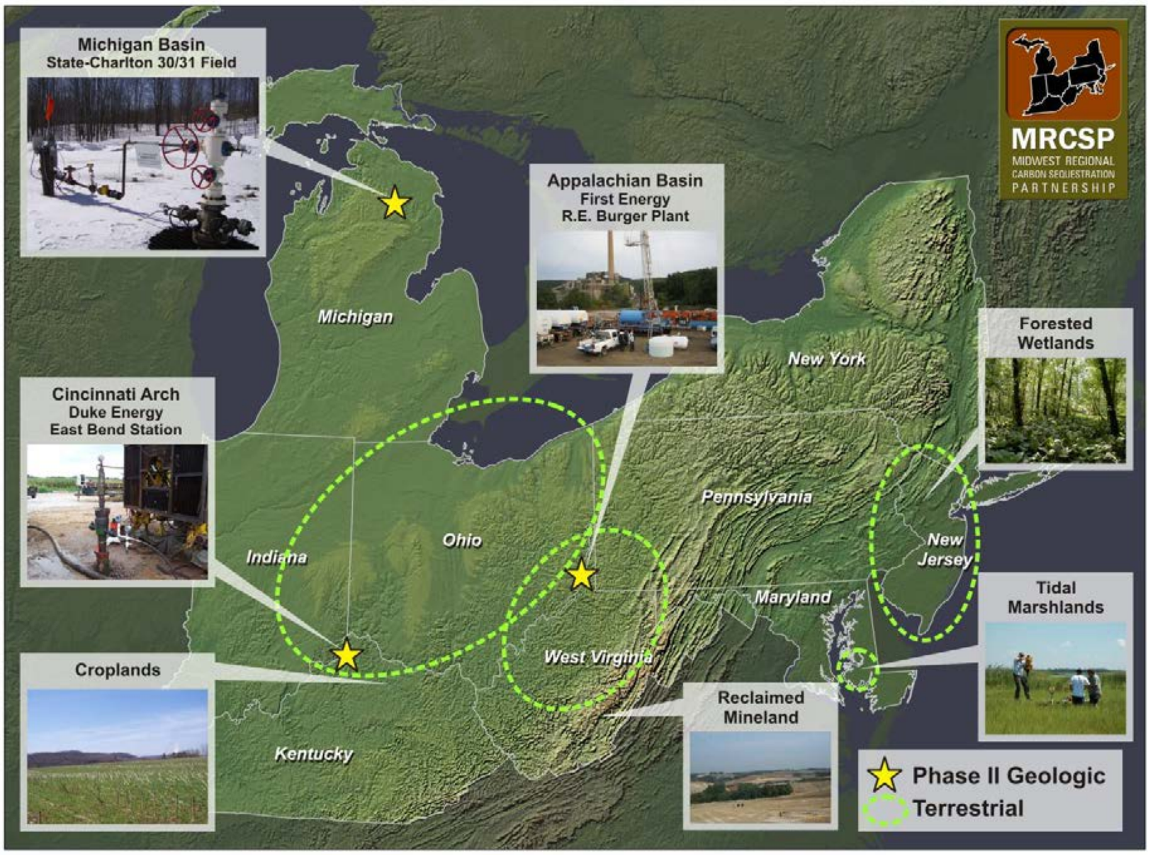


Figure ES-1. Locations of the Various Field Tests Conducted in Phase II

The field tests and the other activities conducted in Phase II are summarized below and described in more detail in the body of this report as well as a number of topical reports completed by MRCSP on specific subjects.

Geologic Field Tests. The majority of the Phase II effort was spent completing the three validation scale field tests of geologic sequestration. These tests involved the injection of CO_2 into selected deep saline reservoirs, a class of reservoirs that represents the most significant geologic storage potential for the region and the US. In addition to drilling the test well and injecting CO_2, these tests involved:

- Obtaining the cooperation and support of a host site willing to allow use of land and facilities and to lend staff support for the conduct of the test
- Obtaining all legally required permits through state and federal agencies having jurisdiction (different states and permitting agencies for each test)

- Extensive outreach including: holding public meetings, one-on-one meetings with elected officials and special interest groups, interacting with the press, and featuring each site on the MRCSP Web page.

Terrestrial Field Tests. Recognizing the importance of terrestrial sequestration to the region, four field tests were conducted in regionally significant terrestrial strata. These tests were conducted through subcontracts to MRCSP partners including:

- The OSU School of Environment and Natural Resources, Carbon Research Center (Croplands),
- WVU (Reclaimed Minelands),
- Rutgers University through the New Jersey Department of Environmental Protection (NJDEP) (forested wetlands)
- University of Maryland (reclaimed marshlands).

These tests involved gaining access to over 30 field sites through cooperation with various MRCSP partners and the acquisition and analysis of thousands of soil samples.

Geologic Regional Exploration. Another major effort under Phase II was to refine and extend the MRCSP‘s pioneering characterization of the region‘s sequestration opportunities. These efforts built upon the initial mapping performed in MRCSP Phase I. The tasks included a program to ‗piggyback‘ on oil and gas drilling to collect additional geophysical logs and rock core from CO_2 storage zones. Five areas of interest include the Upper Cambrian Mount Simon, Middle-Devonian-Middle Silurian formations, Devonian black shales, unmineable coalbeds, and depleted oil and gas formations. In addition, characterization of CO_2 storage formations in New Jersey, which joined the MRCSP during the course of Phase II, was assessed to bring the state of New Jersey up to date with the rest of the MRCSP region.

The MRCSP research team includes the entity in each of the nine states recognized by each state as being responsible for acquiring and retaining knowledge of local geology. The team includes the state geological surveys from Indiana, Kentucky, Maryland, New Jersey, Ohio, Pennsylvania, and West Virginia, along with the New York State Museum and Western Michigan University. Together these organizations comprise the MRCSP geologic mapping team with efforts being coordinated by the Ohio Geological Survey. In Phase II this team extended and refined the regional geologic analysis begun in Phase I, significantly increasing the level of detail in the understanding of sequestration options in deep saline reservoirs, depleted oil and gas fields, coal seams and organic rich shale.

Piggyback Opportunities. Sometimes deep wells are dug in the region by oil and gas operators, state entities or others for reasons outside MRCSP. Piggybacking involves collaborating with those entities to drill deeper and/or take additional log and core data than would otherwise be taken. The result is acquisition of valuable downhole data of interest to sequestration at a fraction of the cost of wells drilled specifically for that purpose.

Three wells were explored in the MRCSP Phase II piggyback program. The wells were drilled in Ohio, Kentucky, and Michigan.

- The Ohio Well, Ohio Geological Survey #1 CO_2 (Ohio #1), was drilled in Salem Township, Tuscarawas County, to a depth of 8,695 feet (ft) in the spring of 2007. This effort was funded almost entirely by the state of Ohio, Ohio Coal Development Office within the Ohio Air Quality Development Authority in a collaborative and cost shared effort with MRCSP.

- The Kentucky well, Batten & Baird K-2605, which was located in southeastern Pike County approximately 5 miles north of the Virginia state line, was drilled to a depth of 5,036 ft in the summer of 2008. This effort was funded almost entirely by the state of Kentucky with MRCSP cooperating on logging and coring of the well.
- The Michigan well, State Charlton & Boeve 2-6, was drilled in the Charlton Field in Otsego County to a depth of 6,202 ft in the summer of 2008. The drilling of this well was funded by Core Energy as part of its exploration activities with MRCSP cooperating on logging and coring in intervals of interest to sequestration.

As part of the MRCSP regional characterization piggyback efforts, drilling and testing were also conducted to assess the sequestration potential of coalbeds. The core acquisition was done in conjunction with CONSOL's ongoing coal seam exploration efforts. A single core was drilled for exploration purposes into the Fallowfield Coal Reserve in Washington County, Pennsylvania in July of 2009. Coal samples were collected from seven unmineable coal seams for analyses of methane desorption and CO_2 sorption. Based on laboratory test results, potential coal seams that could be used for coalbed methane extraction coupled with injection and storage of CO_2 were identified.

Regulatory Analysis. Each test was permitted through appropriate state and federal oversight agencies having jurisdiction over drilling and Underground Injection Control (UIC) activities, including, U.S. Environmental Protection Agency (U.S. EPA) Region 4, U.S. EPA Region 5, and Ohio Environmental Protection Agency (EPA). Table ES-4 provides a chronology of the permitting steps for each of the three field tests.

Table ES-4. Summary of MRCSP Phase II Geologic Test Sites Permitting Process

	Appalachian Basin R.E. Burger Plant	**Cincinnati Arch East Bend Station**	**Michigan Basin State-Charlton 30/31**
Location	Shadyside, OH	Rabbit Hash, KY	Otsego Co., MI
State Agency	Ohio Dept. of Natural Resources Division of Mineral Resources Management, Oil & Gas	Kentucky Dept. of Natural Resources Division of Oil and Gas Conservation	Michigan Dept. Natural Resources Oil and Gas Minerals
UIC Agency	Ohio EPA UIC Program	U.S. EPA Region 4 UIC Program	U.S. EPA Region 5 UIC Program
UIC Application Submittal Date	January 17, 2008	May 1, 2008	April 18, 2007
Public Notice Date	June 21-July 21, 2008	Nov 18-Dec 18, 2008	July 23-Aug 23, 2007
Permit Issued Date	September 3, 2008	February 26, 2009	December 19, 2007
Permit to Inject Date	September 23, 2008	September 10, 2009	February 18, 2008
Injection Start Date	September 24, 2008	September 20, 2009	February 19, 2008*
Injection Stop Date	November 22, 2008	September 25, 2009	March 8, 2008*
Site Closeout	February 24, 2011	April 12, 2010 (final Sept. 2011)	March 2010 (converted to Class II well)

*Note: Michigan Basin extended injection completed February 25 - July 9, 2009.

Stakeholder Outreach and Education. Stakeholder outreach and educational efforts sought to provide information and gain feedback from the public to enable the project team to understand and address public perspectives and issues that could affect progress at the field demonstration sites, as well as the long-term viability of carbon sequestration technologies. Activities encompassed: (1) local, site-specific activities, which focused outreach near the sites where geologic and terrestrial sequestration projects are being conducted; (2) regional communication, with continued use of the MRCSP's interactive Web site (www.mrcsp.org) supplemented with other activities as needed; and (3) broader research to identify factors that shape public acceptability and the long-term viability of sequestration technologies.

In addition, DOE/NETL facilitated information transfer related to all partnership activities, both technical and outreach. MRCSP participated in multiple working groups on topics including the MMV Working Group, Risk Assessment and Simulation Working Group, Capacity Assessment Working Group, Water Working Group, and Outreach Working Group. These working groups contributed to best practice manuals, the Carbon Sequestration Atlas, and other resources of information. The DOE Web site and reference shelf provides links to videos and an extensive list of documents and ongoing updates on all aspects of carbon sequestration.

Phase II Topical Reports. In addition to this final report, the topical documents shown in Table ES-5 have been produced as part of Phase II.

Table ES-5. Description of the MRCSP Phase II Topical Reports

Report Title	Description
Appalachian Basin - R.E. Burger Plant Geologic CO2 Sequestration Field Test	Detailed report on the geologic injection test conducted at FirstEnergy's RE Burger power plant
Mt Simon Formation - Duke Energy East Bend Generating Station Geologic CO_2 Sequestration Field Test	Detailed report on the geologic injection test conducted at Duke's East Bend generating station near Rabbit Hash, Kentucky
Michigan Basin Geologic CO_2 Sequestration Field Test	Detailed report on the geologic injection test conducted in Otsego County Michigan.
Best Practice Manual for Midwest Regional Carbon Sequestration Partnership Phase II Geologic Sequestration Field Validation Tests	Summary of best practices for geologic sequestration based on MRCSP geologic field tests
Midwest Regional Carbon Sequestration Partnership 2005 - 2010 Phase II Final Report on Carbon Sequestration in Croplands	Detailed report on a terrestrial field test conducted on selected cropland sites in Ohio, Indiana, Michigan, and Pennsylvania under subcontract to The OSU.
Midwest Regional Carbon Sequestration Partnership Phase II Report Carbon Storage on Mineland Reclamation Sites	Detailed report on a terrestrial field test conducted on selected reclaimed mineland sites in West Virginia under subcontract to WVU.
Midwest Regional Carbon Sequestration Partnership Assessment of Terrestrial Sequestration Potential in New Jersey	Prepared by NJDEP, this report identifies and delineates the dominant land use types in New Jersey which offer feasible opportunities for terrestrial sequestration opportunities and includes a detailed report on a terrestrial field test conducted on forested wetlands in New Jersey by Rutgers through the NJDEP.
Preliminary Characterization of CO_2 Sequestration Potential in New Jersey and the Offshore Coastal Region	Prepared by New Jersey Geological Survey, in conjunction with Rutgers University, this report provides the preliminary characterization of geological sequestration potential in the state of New Jersey and adjacent offshore region including the continental shelf and slope.

Table ES-5. Description of the MRCSP Phase II Topical Reports (Continued)

Report Title	Description
Geologic Assessment of the Ohio Geological Survey CO2 No. 1 Well in Tuscarawas County, Ohio and Surrounding Vicinity	Report on the stratigraphic test well drilled to the pre Cambrian basement in northeastern Ohio.
Understanding Deep Coal Seams for Sequestration Potential - MRCSP Phase II Topical Report.	Report of a field test conducted under subcontract to CONSOL on a selected coal seam in Pennsylvania as a candidate for CO_2 storage combined with coalbed methane recovery
• **Executive Summary of the Overall Phase II regional characterization Effort** • **A Regional Geologic Characterization and Assessment of Geologic Carbon Sequestration Opportunities in the Upper Cambrian Mount Simon Sandstone in the Midwest Region** • **Characterization Of Geologic Sequestration Opportunities In The MRCSP Region: Middle Devonian-Middle Silurian Formations** • **Evaluation of CO2-Enhanced Oil Recovery and Sequestration Opportunities in Oil and Gas Fields in the MRCSP Region** • **MRCSP Phase II–Reassessment of CO_2 Sequestration Capacity and Enhanced Gas Recovery Potential of Middle and Upper Devonian Black Shales in the Appalachian Basin** • **Storing and Using CO_2 for Enhanced Coalbed Methane Recovery in Unmineable Coalbeds of the Northern Appalachian Basin and Parts of the Central Appalachian Basin**	Various reports updating the regional geologic characterization and mapping conducted by the MRCSP Geological Survey Research Team

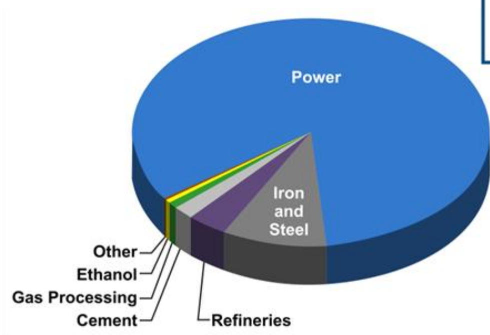
Phase II Findings

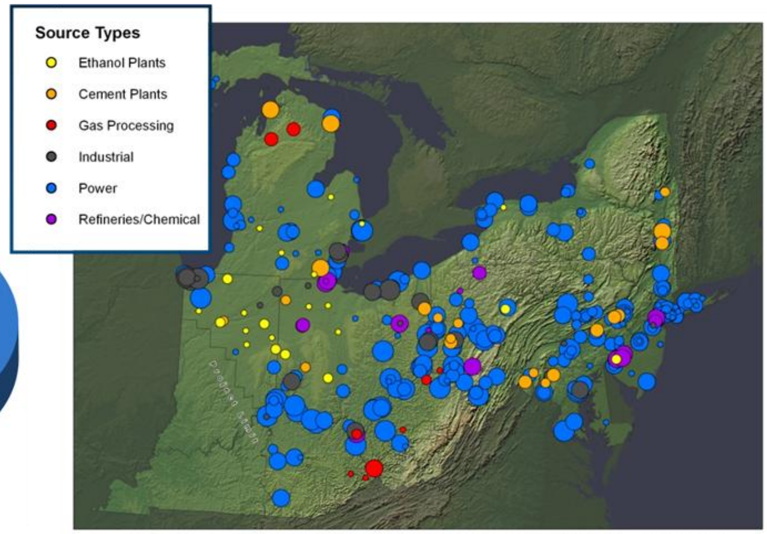
The following section summarizes the research and results of the Phase II effort. Additional details are provided in the body of this report. More information on the MRCSP, including copies of this report and the other Phase II reports listed above can be found at the MRCSP Web site (www.mrcsp.org).

CO_2 Sources in the MRCSP Region

Due to its large and diverse economy, the MRCSP region includes a large variety of sources of greenhouse gases (GHGs). While distributed sources such as agriculture, transportation, and home heating account for a large portion of CO_2 emissions in the MRCSP region, over half of CO_2 emissions are linked to stationary point sources (Figure ES-2). In total, 699 million metric tons of CO_2 is emitted each year from these large, fixed point sources. Emissions are highest along the Ohio River Valley and coastlines where many power plants and industries are located. Power plants in the MRCSP region account for approximately 85% of the region's CO_2 point source emissions.

Pie chart showing relative emissions from the large point sources in the MRCSP





Locations of large stationary point sources within the MRCSP.

Figure ES-2. Large Point Sources within the MRCSP Region

Geologic Storage Opportunities in the MRCSP Region

Potential locations for geologic sequestration in the MRCSP states extend from the deep rock formations in the broad sedimentary basins and arches in the western portion of the region to the offshore continental shelf in the east. Research and testing have established many promising geologic units for CO_2 sequestration, including deep saline rock formations, depleted oil and gas reservoirs, organic shale layers, and coalbeds. Geological surveys from the nine MRCSP states completed an assessment of the potential for geologic sequestration that indicates there is capacity to permanently contain hundreds of years of CO_2 emissions from the region. Reports, data, and maps generated by the research were integrated into a geographic information system available for use on the MRCSP Web site (**www.mrcsp.org**).

Deep saline rock formations are, by far, the MRCSP region's largest resource for long-term geologic CO_2 sequestration. Research indicates that the region's well-defined deep saline formations could potentially sequester 234,800 million metric tons of CO_2. A breakdown by reservoir is shown in Table ES-7. The estimated CO_2 storage resource for the region is very large compared to the present-day emissions, enough to accommodate CO_2 emissions from large point sources for hundreds of years. Saline formations in the MRCSP region are widespread, close to many large CO_2 sources, and are thought to be suitable for future storage needs. As shown in Tables ES-6 and ES-7, storage capacity is not evenly distributed across the region.

Thick sequences of sedimentary rocks are present throughout most of the western MRCSP states in the form of broad basins and arches. In the eastern states, coastal plain deposits along the continental shelf are potential storage zones. The rocks are saturated with dense brine fluids. In addition, the region is considered a fairly stable geologic setting. The rock formations have been correlated and mapped in the region in stratigraphic charts based primarily on rocks encountered in oil and gas wells. These data were used to characterize geologic sequestration opportunities in deep saline formations in the MRCSP region.

Table ES-6. Storage Capacities for Phase II Sequestration by Reservoir Type and by State in the MRCSP Region(1)

Formation	State									
	IN	KY	MD	MI	NY	OH	PA	WV	NJ	Total
Deep Saline(2)	73,800	6,800	2,700	77,700	6,900	19,500	30,100	16,700	600	**234,800**
EOR	61	87		457	272	3,405	2,806	1,423		**8,500**
Coal		17				31	66	92		**200**
Shale		91				463	726	744		**2,000**
Total	**73,900**	**7,000**	**2,700**	**78,200**	**7,200**	**23,400**	**33,700**	**19,000**	**600**	**245,500**

(1) Some numbers presented here differ from the NETL Carbon Sequestration Atlas due to variations in methodology required to harmonize storage capacity estimates amongst the seven regional partnerships.
(2) During Phase I, the calculations for storage capacity were determined using a 10-percent efficiency factor. Phase II assessment calculated storage capacities using more conservative efficiency factors (e.g., 1 percent and 4 percent) to develop estimates with higher confidence. —Medium” values (e.g., those calculated using at least 4 percent efficiency value) are presented here.

Table ES-7. Storage Capacities for Phase II Sequestration by Saline Formation and by State in the MRCSP Region(1)

Formation	State									
	IN	KY	MD	MI	NY	OH	PA	WV	NJ*	Total
Off Shore									450	**400**
Potomac									148	**100**
Waste Gate			1,753							**1,700**
Sylvania(2)				6,044						**6,000**
Bass Islands Gr(2)				2,731						**2,700**
Bass Islands Gr(3)							3,500			**3,500**
Dundee				1,762						**1,700**
Oriskany		5.7	120		21	123	1,170	1,460		**2,900**
Lockport		520	250		990	3,900	4,650	7,830		**18,100**
Medina/Tuscarora		7.5	600		756	1,480	7,980	5,210		**16,000**
St. Peter	41			35,200		26				**35,200**
Rose Run Unit		2,177		305	4,690	3,240	11,900	2,086		**24,400**
Potsdam					423		682			**1,100**
Conasauga		0.593		65.7		1,387	184	64.5		**1,700**
Rome Trough		400				2.35		88.5		**400**
Mount Simon	73,787	3,687		31,627		9,317				**118,400**

(1) Some numbers presented here differ from the NETL Carbon Sequestration Atlas due to variations in methodology required to harmonize storage capacity estimates amongst the seven regional partnerships.
(2) Michigan Basin
(3) Appalachian Basin

The storage resource 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 deep saline rock formation with the largest resource in the region is the Mount Simon Sandstone, followed by the St. Peter Sandstone and the Medina/Tuscarora Sandstone. Other notable storage formations include the Rose Run Sandstone, the Oriskany Sandstone, and the Sylvania Sandstone.

Because of the lack of exploratory wells in various areas, such as in the deepest portion of the Appalachian basin in Pennsylvania, some areas of the MRCSP region may have additional storage options such as porosity zones in the Knox Dolomite. Offshore areas along the East Coast and Great Lakes also contain significant storage capacity not included in the assessment. While Michigan has the highest storage potential, all of the MRCSP states have capacity to store large amounts of CO_2 in deep saline formations.

Oil and gas reservoirs cover large portions of the Appalachian basin and offer the potential for sequestration through enhanced oil and gas recovery. A breakdown of the potential by state is shown in Table ES-6. Significant fields exist in eastern Ohio, western Pennsylvania, western West Virginia, and eastern Kentucky.

Commercial exploration for oil was pioneered in the region when, in 1859, oil was discovered in a shallow well drilled by ―Colonel” Edwin Drake in Titusville, Pennsylvania. Since then, the MRCSP region has produced over 5 billion barrels of oil and more than 50 trillion cubic ft of natural gas. In addition, the MRCSP region includes four of the top seven natural-gas storage states in the nation. Such large volumes of gas storage capacity (both natural and engineered) strongly suggest that CO_2 gas can be successfully managed in subsurface reservoirs within the region. Key oil and gas formations in the Appalachian basin include Devonian Shales, ―Clinton”/Medina/Tuscarora sandstones, the Oriskany Sandstone, and the Rose Run Sandstone.

Within the Michigan Basin, oil and natural gas reservoirs are concentrated along the Niagaran reef trend and Devonian Antrim Shales in the northwestern margin of the basin and the southern margin of the basin. Enhanced oil recovery has only been applied at a few fields in the region.

Studies have suggested that a large amount of oil and gas remains in place in many reservoirs. Thus, there is high potential for enhanced oil and gas production associated with CO_2 sequestration in the MRCSP region. MRCSP research suggests that oil-and-gas fields have a potential storage resource of 8,500 million metric tons of CO_2. Much of this capacity is intermixed with deep saline formations. In fact, it may be difficult to differentiate the two in many areas.

Using CO_2 for enhanced coalbed methane recovery also has potential for sequestering CO_2 in the Appalachian basin. The MRCSP region contains the second (West Virginia), third (Kentucky), fourth (Pennsylvania) and fourteenth (Ohio) leading coal-producing states in the nation. Bituminous coal seams are located in the Appalachian and Michigan basins and anthracite coal seams are located in the state of Pennsylvania. Deep, unmineable coal seams in the Appalachian basin with the highest capacity for CO_2 sequestration are located along the Ohio River Valley in Kentucky, Ohio, Pennsylvania, and West Virginia.

In the last decade, significant coalbed methane (CBM) production has occurred in some of these historic ‗gassy‘ coals, particularly in southern West Virginia. CBM is locally produced from at least 24 pools in Pennsylvania, and historic and modern CBM fields occur also in the northern portion of West Virginia. Furthermore, CBM production has been reported in eastern Kentucky, and in Ohio, historic CBM production occurred as early as 1924. Interest in CBM production and exploration is growing in the basin as well as CO_2 sequestration potential. As part of the MRCSP Phase II program, coal samples were tested from a well in Pennsylvania at depths over 1000 ft to better define CO_2 storage potential for the region.

Thick deposits of organic shales are widespread in the MRCSP region. 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 unconventional gas reservoirs themselves. Analogous to sequestration in coalbeds, CO_2 injection into unconventional carbonaceous shale reservoirs could be used to enhance existing gas production. As an added feature, it is believed the carbonaceous shales would adsorb the CO_2, permitting long-term CO_2 storage, even at relatively shallow depths.

Organic shales are thickest in Kentucky, Ohio, West Virginia and portions of Pennsylvania. In addition, shales are present throughout the Michigan basin. Analysis of these rock formations indicates that they may have the CO_2 storage resource of approximately 2,000 million metric tons (Table ES-X). While laboratory research based on adsorption data from organic-rich gas shales suggests CO_2 storage is possible and may provide a mechanism for enhanced gas recovery, these processes have not been demonstrated with field projects in the MRCSP region.

Geologic Field Tests Conducted in Phase II

Phase II geologic field tests took place along distinct, regional geologic features representing the three major geological provinces within the MRCSP region:

Regional Geologic Feature	Host Site Location
Michigan Basin	Core Energy‘s State-Charlton 30/31 Field, Otsego Co., MI
Cincinnati Arch	Duke Energy‘s East Bend Generating Station, Rabbit Hash, KY
Appalachian Basin	FirstEnergy‘s R.E. Burger Power Plant, Shadyside, OH

In each of these tests, members of the MRCSP research team injected CO_2 into deep saline formations located thousands of ft below the surface. Each geologic field test involved a network of monitoring devices and techniques to monitor the injection, delineate the movement of CO_2 in the formation, and confirm that the injection proceeded as planned.

Figure ES-3. Phase II Injection Well, State-Charlton 30/31 Field

The Michigan Basin test demonstrated industrial-scale CO_2 sequestration potential in the Bass Islands Dolomite at a depth of about 3,500 ft. Injection rates of 600 metric tons per day were sustained into this carbonate formation over a period of several months in two test campaigns, the first in 2008 and second in 2009. Approximately 60,000 metric tons of CO_2 was injected in total with 10,000 metric tons injected in 2008 and an additional 50,000 metric tons in 2009.

This site utilized a monitoring well located about 500 ft laterally from the point of injection. As a result, monitoring at this site was extensive including down hole pressure and temperature, cross well seismic, micro seismic, pulse neutron capture, behind casing sampling of fluids, and surface monitoring with tracer gas injection into the CO_2. The CO_2 plume itself did not reach the monitoring well during the testing, but the pressure front was sensed at the monitoring well and the results were correlated with the STOMP CO2 modeling code used to simulate and evaluate the injection.

The availability of relatively low cost CO_2 along with pre-existing compression and pipeline infrastructure owned by MRCSP partners DTE Energy and Core Energy in conjunction with a natural gas processing plant near the test site made this scale of injection feasible at this site. At the time, this was the largest injection of CO_2 into a deep saline formation in the US. The test results should be applicable to other parts of the Michigan Basin, which is an attractive target in the region.

Permitting of this site was done through the Michigan Department of Environmental Quality -- now part of the Michigan Department of Natural Resources and Environment (drilling) and U.S. EPA Region 5 (UIC Class V injection permit). Drilling of the injection well and monitoring well at the site was completed in December 2006.

In the Cincinnati Arch field test, 910 metric tons of CO_2 were injected at a depth of about 3500 ft at the Duke Energy East Bend Generating Station near Rabbit Hash, Kentucky. The primary research objective was to demonstrate CO_2 sequestration in the Mount Simon sandstone, the largest potential CO_2 sequestration storage reservoir for the region (and the US). The thickness of the Mount Simon at this site is about 300 ft and injection took place over a 100-ft interval at the bottom of the Mount Simon unit.

Figure ES-4. Phase II Injection Well, East Bend Generating Station

The test was aimed at better understanding regional trends (i.e., permeability, porosity, geochemistry, mineralogy) and CO_2 injection testing in the Mount Simon sandstone. The source of CO_2 in this case was liquid food grade CO_2 from a commercial industrial gas supplier. Although the test volume was relatively small due to the high cost of CO_2, injection rates up to about 1,200 metric tons per day were sustained over several hours indicating good permeability and injectivity at this site.

Permitting for this site was done through the Kentucky Department for Natural Resources (drilling) and U.S. EPA Region 4 (UIC Class V injection permit). Drilling of the 3500-ft deep injection well was completed in July 2009 and injection testing was completed in October 2009. The Class V permit for this site also required installation of a sampling well into the groundwater aquifer. Quarterly sampling of that well and several pre-existing groundwater wells in the area is required by the permit for two years following completion of injection operations.

Figure ES-5. Phase II Injection Test, R.E. Burger Plant

For the Appalachian Basin test, FirstEnergy's R.E. Burger Power Plant was chosen as a test site because of its central location to one of the nation's major power generation corridors, the Ohio River Valley, and because it was expected to provide access to geologic formations having significant expected storage capacity across the region.

Specific geologic formations that were assessed include the Oriskany Sandstone, the Salina Formation, and the Clinton Formation, which are located between 5,900 and 8,300 ft below the surface. All three formations were found to be very tight, i.e. have very low injectivity, at this site. Although less than 50 metric tons of CO_2 was injected, the test results will help develop best practices and to better understand the regional geology for its sequestration potential.

Permitting of this site was through Ohio Department of Natural Resources, Division of Mineral Resource Management (well drilling) and Ohio EPA (UIC Class V injection permit). Drilling of an approximately 8,300-ft deep well at the site was completed in January 2007 and injection testing took place in October 2008.

Terrestrial Opportunities in the MRCSP and Field Tests Conducted in Phase II

Terrestrial ecosystems in the MRCSP states offer a viable opportunity for carbon sequestration because of the extensive farmlands, wetlands, minelands, and forests in the region. There are over 22 million hectares (or 88,000 square miles) of land in the MRCSP region that could be utilized for enhanced carbon sequestration. Phase I studies on the region (which did not include New Jersey or New York) indicated that there is potential to sequester 144 million metric tons of CO_2 per year in these areas. A breakdown of that resource by land type is shown in Table ES-8.

Table ES-8. Terrestrial Sequestration Potential from Phase I Effort

Category	Area (Mha)	Sequestration Potential (million metric tons CO_2/year)							
		IN	KY	MD	MI	OH	PA	WV	*Total*
Cropland	10.7	4.4	1.1	0	3.7	4	0.4	0	*14*
Eroded Cropland	1.6	6.6	0	0	0.7	4	0	0	*11*
Marginal Land (Forest)	6.5	19.5	16.9	3.7	16.2	17.7	17.7	7.7	*99*
Mineland	0.6	0	0.7	0.4	0.7	0.7	1.1	1.8	*6*
Wetland	3.4	2.9	0	1.8	8.8	0.7	0	0	*14*
Total	*22.8*	*33.5*	*18.8*	*5.9*	*30.2*	*27.2*	*19.1*	*9.6*	*144*

The assessment of terrestrial opportunities in New Jersey which was performed during Phase II included the following results:

- The dominant land use types in New Jersey that are of most relevance to terrestrial sequestration are: agricultural land (particularly non-eroded cropland), forest land, and wetland (especially forested wetlands and tidal marshes). These are 16%, 28%, and 20%, respectively, of the total land area of the state.
- A total of 288,823 hectares provide opportunities for enhancing sequestration capacities of these land uses potentially sequestering at least 5.5 million metric tons of CO_2 over a 20-year period. This would involve shifting non-eroded prime croplands to carbon conserving practices (106,463 hectares) or conversion to non-cultivated crops (114,614 hectares);

converting or reconverting marginal farm lands to forests (89,638 hectares); and improving stocking of forest lands (92,722 hectares).

- Land uses with carbon storage capacities such as forested wetlands and tidal marshes need to be protected and maintained not only to continually sequester carbon but to keep emissions of methane (another potent GHG) under control. Forested wetlands potentially sequester 5.1 metric tons CO_2 per hectare per year while saline marshes capture approximately 1.5 metric tons CO_2 per hectare per year.

Terrestrial field tests were conducted as part of Phase II on four different land types:

<u>Land Type and Location</u>	<u>Entity Conducting the Research (Host)</u>
Croplands (Michigan, Ohio, Pennsylvania, Indiana)	The OSU School of Environment and Natural Resources, Carbon Research Center
Reclaimed Minelands (West Virginia)	WVU
Forested Wetlands (New Jersey)	Rutgers University
Reclaimed Marshlands (Maryland, Chesapeake Bay)	University of Maryland

Work on croplands at approximately 30 different test sites in several MRCSP states conducted under MRCSP subcontract to The OSU demonstrated agriculture management practices to enhance carbon sequestration, including no-till and conservation tillage; cover cropping; perennial crops; intensive-grazing pasture management; and restoration of marginal farmland back to prairie. Studies consistently showed that large improvements were made with regard to carbon sequestration when crop residues are used with no-till and conservation tillage practices. An additional benefit observed was the improvement in soil quality and agronomic productivity. Soil carbon sequestration rates ranged from 0.25 to 1.0 metric ton carbon per hectare per year, depending on soil properties and best management practices implemented.

Work on reclaimed minelands on several test sites in West Virginia conducted under MRCSP subcontract to WVU determined that the rate of soil carbon sequestration in the near surface for mine lands reclaimed to pasture or grassland ranged between 0 to 3 metric ton carbon per hectare per year. Furthermore, reclaiming mined land to forest increases the amount of carbon stored significantly due to carbon accumulation in aboveground biomass, litter layer, and soils.

Work on forested wetlands conducted under subcontract to Rutgers University through the New Jersey Department of Environmental Protection evaluated five different aged forested wetlands in southern New Jersey. The annual carbon sequestration rates in the wetland soil, litter and tree biomass were estimated to be 8.35 metric ton carbon per hectare per year for the forested wetland ecosystem. The results suggest that the restoration of forested wetlands from agricultural lands could have great potential in sequestering the atmospheric carbon into the biomass and soil.

Work on a restored tidal marshland conducted by the University of Maryland in the Blackwater Wildlife Refuge in the Chesapeake Bay concluded that the restored and natural marsh at the Refuge are sequestering carbon on the surface at the rate of 3.4 metric ton carbon per hectare per year, which is a conservative estimate because subsurface carbon storage is not included. The primary funding source for this work was the Maryland Department of Natural Resources Power Plant Research Program under separate contract with the University of Maryland. MRCSP collaborated with the University of Maryland and provided some funding for coordination efforts on this separately funded project.

Regulatory Assessment

Initially, there was little precedent for CO_2 injection in the MRCSP region, aside from a few enhanced oil recovery fields. MRCSP Phase II geologic test sites were spread throughout the region with different agencies at each site (Table ES-4). Completing the permit process at three separate field sites provided direct benefits for the MRCSP region by helping to establish CO_2 storage knowledge and experience with various EPA and state regulatory agencies in the region.

Over the span of MRCSP Phase II, there were significant developments regarding regulating CO_2 storage projects. The U.S. EPA prepared a guidance document using Class V experimental technology well classification for pilot geologic sequestration projects. Toward the end of Phase II, the U.S. EPA started work on new ―Class VI" well guidelines for commercial-scale CO_2 injection. The MRCSP consulted with U.S. EPA during the preparation of these Class VI regulations to ensure that Phase II experiences were considered with the goal of finding better ways to streamline the permitting process and to develop regulation that supports sequestration. The Class VI regulations were finalized on January 10, 2011.

Stakeholder Outreach and Education

The MRCSP outreach program was designed to build a foundation of public awareness for carbon sequestration. The MRCSP approach relied on insight from social science literature involving the role of values and perceptions in developing opinions about a new technology, as well as principles of good science communication. Surveys in the United States and abroad provided empirical data about factors affecting public acceptance of carbon sequestration.

A stakeholder outreach effort to communicate project progress to the local community, general public, and scientific community was undertaken with each of the three geologic field tests in Ohio, Kentucky and Michigan. This effort involved identification of stakeholders followed by proactive engagement with these stakeholders well in advance of any public announcement or press coverage of the planned test. The support and close involvement of field test host and local project participants (with ties to the test site community) were key in communications with local stakeholders. Engagement included public meetings at all three sites, meetings with targeted community groups, open houses at host plants, and support to regulators when public hearings were needed. Informational materials including fact sheets, videos, and hands on displays and models were developed and used very effectively in the communication process.

An outreach team that included members from each host site was established to develop a site-specific strategy and outreach plan for key stages of the project. The team members provided diverse perspectives upon which the project could draw — technical understanding of planned activities, invaluable knowledge about local culture and politics, and experience for effectively communicating with local residents.

The outreach team provided contact points in the local area and project-related information on the MRCSP Web site. The host sites held informational meetings for nearby residents, including a series of exhibits and take-home materials, as well as opportunities for one-on-one discussions with technical staff. Other activities included facility tours for partnership members and media interactions. All three of the Phase II geologic sequestration field tests were completed successfully in terms of relations with the industrial hosts, outreach to the local communities, permitting, and test logistics.

The hands-on involvement of many entities in the region to carry out the field tests including MRCSP partners, regulators, and hundreds of vendors was considered very effective in fostering learning about sequestration technologies at a level that will be needed for commercial implementation.

Regional Implementation Strategic Considerations

During the course of the Phase II project, various conversations took place with MRCSP partners and others regarding the likely course of how and when sequestration technologies would be implemented across the MRCSP region and what features of the region would drive that process. In January 2011, a working group of MRCSP partners, including most of the electric utilities in the MRCSP, was convened to specifically discuss the issues affecting implementation in the region. The following is a summary of the conclusions from those discussions:

(1) The region's CO_2 sources are predominantly coal-fired power plants, especially along the Ohio River Valley. These sources are, for the most part, in reasonable proximity to large potential CO_2 storage reservoirs in the region such as the Mount Simon. As a result, the cost of sequestering CO_2 from the majority of the region's sources is driven mostly by the cost of capturing CO_2 from coal-fired plants. The supply curve shown below, which was developed in Phase I, shows this characteristic of the region.

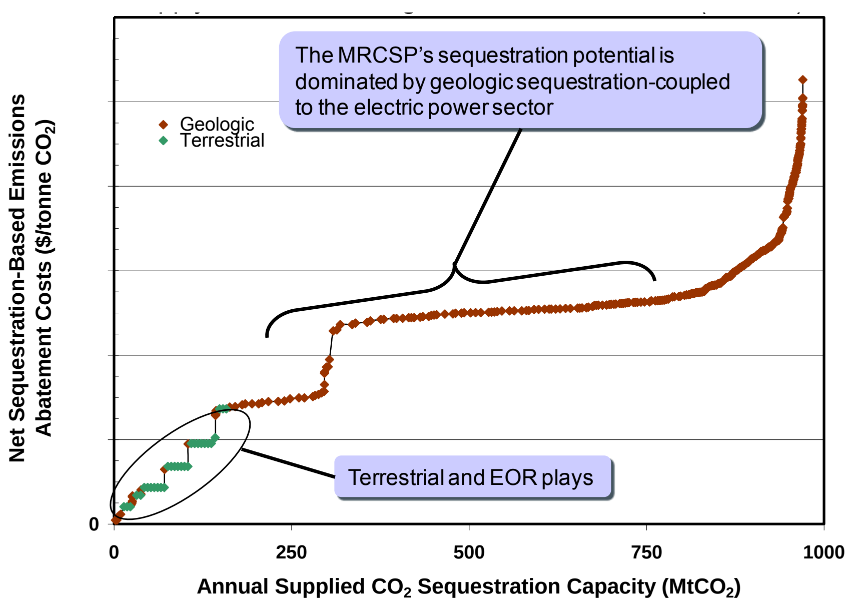


Figure ES-6. Regional Supply Curve from Phase I Effort (c. 2004)

(2) Newly promulgated U.S. EPA rules for controlling air toxics from coal-fired power plants will undoubtedly result in shutting down a number of older, lower capacity factor coal-fired power plants in the region. However, the newer, higher capacity factor plants will probably remain and may increase in capacity factor to make up the difference albeit at reduced peaking reserve margin. An increase in gas-fired generation for the region may also be a side effect, which would tend to reduce the amount of CO_2 produced.

(3) The lack of proven and cost effective capture technology for coal-fired power plants is a deterrent to implementation of geologic sequestration technology in the region given the role coal-fired power generation plays in the region's CO_2 emissions.

(4) A number of proposals for pipeline networks connecting the region's large sources to sinks have been put forward by various groups, both government and private. Some private proposals would pipe CO_2 to the Gulf Coast, presumably to take advantage of enhanced oil

recovery markets and possible future sequestration markets in the Gulf. While interesting and thought provoking, the schemes reviewed to date are highly speculative and some have flawed assumptions regarding the location of likely geologic sinks and which sources would access those sinks.

(5) Enhanced oil recovery (EOR) will likely be a value-added stepping stone to implementation of sequestration technologies in the region given the presence of a number of depleted oil fields in the region in close proximity to major coal-fired power plants. Small-scale tests are needed to further define the EOR potential in the region, particularly in the northeastern Ohio area given its proximity to the Ohio River Valley power generation corridor.

(6) More small-scale tests are also needed to define the sequestration potential in many of the region‘s deep saline formations given the differences in injectivity found in the MRCSP small-scale tests between results based on core and log data versus those found with reservoir testing and actual CO_2 injection.

(7) The northern Appalachian Basin, particularly the Upper Ohio River Valley power generation corridor, is geologically complexity with thick but variable sedimentary deposits. It is also in close proximity to many major coal-fired power plants (approximately 52,000 megawatts of coal fired capacity). In addition, there is potential for nearby EOR, which could be a value-added stepping stone to implementation of a carbon capture and storage (CCS) infrastructure. More research in the form of seismic data and deep well data are needed to characterize the potential for this key part of the MRCSP region to support sequestration.

(8) Before commercial deployment of sequestration can occur in the region it will be important to confirm and assure the safety of geologic sequestration through testing such as that carried out in Phase II and planned in Phase III and other tests.

(9) Outreach and education will be critical precursors to broad implementation of geologic sequestration to communicate the importance and safety of geologic sequestration to elected officials and the public.

(10) Issues such as subsurface property rights and long-term liability were not directly addressed by the small-scale validation tests. A more systematic legal and regulatory approach as well as a comprehensive liability system that properly allocates risks and costs are considered to be key elements towards developing geologic carbon sequestration as an established commercially available technology.

(11) An overarching issue affecting the pace of planning for implementation of sequestration in the region is the fact that carbon legislation at state, regional or federal levels does not appear to be imminent at this point in time.

Overall Conclusions

The MRCSP Phase II program made significant progress towards validating sequestration technologies in the region through various small-scale field validation tests and other activities. No barriers to the technology were encountered as all seven field tests were implemented as planned. Some significant overarching conclusions are as follows:

- Small-scale validation tests helped establish familiarity with CO_2 sequestration technologies amongst many stakeholders and provided deep well data points in strategic locations within the MRCSP region.
- Safety is a well known key public acceptance issue. These tests provided additional confidence in the safety (over 61,000 metric tons of CO_2 was injected and more than 20,000

ft of drilling and other related activities was accomplished safely with no lost time injuries during approximately 35,000 man-hours).

- These tests highlighted the variability of geologic environments, especially in the geologically deep and complex Appalachian Basin. Initial characterization methods (e.g., rock core tests and wireline logging) may only provide indicators of injectivity. True injection potential needs to be proven with field injection tests:
  - Good injectivity was confirmed in the Cincinnati Arch area of the Mount Simon formation as predicted. At the time, the MRCSP test was the only CO_2 injection test into the Mount Simon
  - Better than expected injectivity was found in the Bass Islands Dolomite, a carbonate formation. Prior to the MRCSP Michigan test, carbonates were not considered a significant potential sequestration resource for the region
  - The poor injectivity found in the three formations tested in the Appalachian Basin points out the variability and uncertainty in the geology of this strategically important part of the region, thus the need for more research in this area.
- Monitoring techniques were useful in tracking the CO_2 migration behavior and confirming the effectiveness of the confining zone. While the current validation phase of work is complete, significant additional work is still possible to process, analyze, and model the wealth of operational and monitoring data from the MRCSP injection tests. Further analysis of cross-well seismic, microseismic, geochemical, and modeling results can provide more insights into the CO_2 plume migration and effectiveness of monitoring technologies for large-scale storage.
- Simple models provide the basis for designing injection tests. As more information is obtained, the models can be refined and calibrated to yield more accurate solutions. This experience highlights the potential for the monitoring phase of geologic storage projects to continuously improve the modeling framework used to simulate a geologic sequestration system.
- The value of no-till agriculture was confirmed as a valuable sequestration and sustainable agricultural strategy on various land plots across the farmlands of the region.
- Terrestrial sequestration in general was confirmed as a valuable sequestration resource for the MRCSP region with the biophysical potential to sequester approximately 15% of the region‘s annual CO_2 emissions from large point sources.
- The region‘s deep geologic reservoirs were confirmed to have the theoretical potential to sequester all of the region‘s CO_2 emissions from large point sources for at least 100 years into the future.
- The outreach methodology and execution at all three geologic sites were effective in identifying public concerns and communicating with local stakeholders about the benefits and risks associated with sequestration technologies. Developing clear communications about the safety and benefits of developing CCS technologies will be critical towards increasing public acceptance.
- Issues such as subsurface property rights and long-term liability were not directly addressed by the small-scale validation tests. A more systematic legal and regulatory approach, as well as a comprehensive liability system that properly allocates risks and costs, is considered to be a key element towards developing geologic carbon sequestration as an established commercially available technology.

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ACRONYMS AND ABBREVIATIONS

2-D	two-dimensional
ARRI	Appalachian Regional Reforestation Initiative
BD	bulk density
bpm	barrels per minute
C	carbon
C/N	carbon to nitrogen ratio
CBM	coalbed methane
CCS	Carbon Capture and Storage
CCX	Chicago Climate Exchange
CMASC	Carbon management and sequestration center
CO_2	carbon dioxide
CT	conventional tillage
DBH	diameter at breast height
DIX	Dix Wildlife Manage Area
DOE	U.S. Department of Energy
ECBM	enhanced coalbed methane
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EU-ETS	Union Emission Trading Scheme
ft	foot
g	gram
GHG	greenhouse gas
GIS	geographical information system
GWR	geographically weighted regression
Ha	hectare
IPCC	Intergovernmental Panel on Climate Change
m	meter
mD	millidarcies
MDMS	Middle Devonian–Middle Silurian
Mg	megagrams (10^6 grams)
Mha	million hectares
MLRA	major land resource area
MRCSP	Midwest Regional Carbon Sequestration Partnership
NATCARB	National Carbon Sequestration Database and Geographic Information System
NJDEP	New Jersey Department of Environmental Protection

OCDO	Ohio Coal Development Office
ODNR	Ohio Department of Natural Resources
OSU	The Ohio State University
PFT	perfluorocarbon tracer
PNC	pulsed neutron capture
RCSP	Regional Carbon Sequestration Partnership
RD&D	Research development and demonstration
RGGI	Regional Greenhouse Gas Initiative
scf	standard cubic feet
SETs	surface elevation tables
SMCRA	Surface Mining Control and Reclamation Act
SOC	soil organic carbon
STOMP	Subsurface Transport Over Multiple Phases
SWP	Southwest Regional Partnership on Carbon Sequestration
TOC	total organic content
UIC	Underground Injection Control
USDW	underground source of drinking water
U.S. EPA	U.S. Environmental Protection Agency
WSCE	water, CO_2, salt, energy
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WVU	West Virginia University
yr	year

Section 1.0: INTRODUCTION

1.1 About the MRCSP

The Midwest Regional Carbon Sequestration Partnership (MRCSP) was formed to assess the technical potential, economic viability, and public acceptability of carbon sequestration within its region. The MRCSP is one of seven regional partnerships established in October 2003, which, together, make up the U.S. Department of Energy‘s (DOE‘s) Regional Carbon Sequestration Partnership (RCSP) program. The RCSP program is led by DOE‘s National Energy Technology Laboratory (NETL). An overview of the MRCSP program is provided in Table 1-1. This final report summarizes the research conducted and results obtained during Phase II of the MRCSP‘s overall program.

Table 1-1. The MRCSP Program is Divided into Three Phases in Concert with DOE’s RCSP Program

Phase	Timeframe	Objective
Phase I	October 1, 2003 through September 30, 2005	Analytically characterize the large point sources of CO_2 and potential geological and terrestrial CO_2 storage options for the region.
Phase II	October 1, 2005 through February 4, 2011	Translate the theoretical knowledge gained in Phase I into practical, real world knowledge through the conduct of a series of small scale field validation tests.
Phase III	May 6, 2008 for approximately 10 years (currently in progress)	Demonstrate the potential for geologic CO_2 storage in the region by conducting an injection test of at least one million metric tons of CO_2 into a regionally significant reservoir.

The MRCSP region consists of nine neighboring states: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. The MRCSP partnership is led by Battelle Memorial Institute and includes nearly 40 organizations from the research community, energy industry, universities, non-government, and government organizations. The various entities supporting the MRCSP as partners during Phase II are shown in Table 1-2.

Table 1-2. MRCSP Phase II Partners

Industry Partner Team	Research Partner Team
- American Electric Power - AMP Ohio - Babcock and Wilcox - British Petroleum - American Coalition for Clean Coal Energy - Chicago Climate Exchange (CCX) - CONSOL Energy - Constellation Energy - Consumer Energy - Dominion - DTE Energy - Duke Energy - Electric Power Research Institute - FirstEnergy	- AJW Inc. - Core Energy LLC - ESG - Indiana Geological Survey - Kentucky Geological Survey, University of Kentucky - Maryland Geological Survey - New Jersey Department of Environmental Protection - New York State Museum - Ohio Division of Geological Survey - Ohio Environmental Council - Pennsylvania Geological Survey - The Keystone Center

Table 1-2. MRCSP Phase II Partners (Continued)

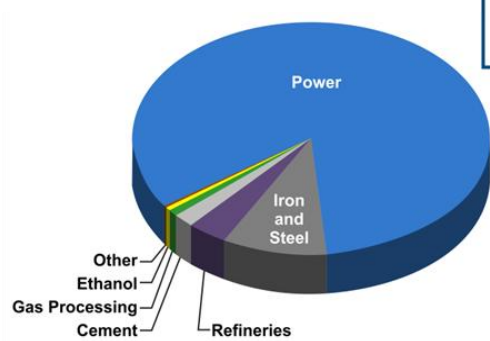
Industry Partner Team	Research Partner Team
- Indiana Office of the Consumer Counselor - National Rural Electric Cooperative Association - New York State Energy Research and Development Authority - Ohio Coal Development Office within the Ohio Air Quality Development Authority - Ohio Consumers' Counsel - Praxair - RWE	- The Ohio State University (OSU) - Stanford University - University of Maryland - West Virginia Geological Survey - West Virginia University (WVU) - Western Michigan University

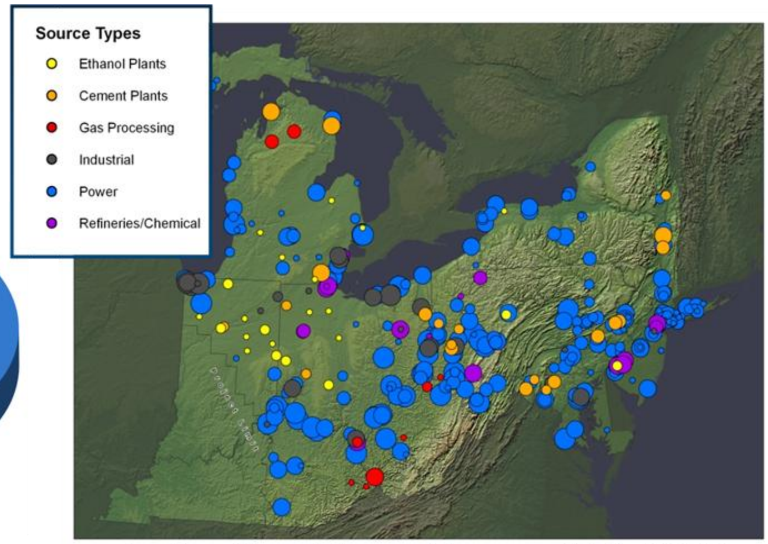
A snaphot of the region is presented in Table 1-3. Due to its large and diverse economy, the MRCSP region includes a large variety of sources of greenhouse gases (GHGs). While distributed sources such as agriculture, transportation, and home heating account for a large portion of CO_2 emissions in the MRCSP region, over half of CO_2 emissions are linked to stationary point sources (Figure 1-1). In total, 699 million metric tons of CO_2 is emitted each year from these large, fixed point sources. Emissions are highest along the Ohio River Valley and coastlines where many power plants and industries are located. Power plants in the MRCSP region account for approximately 85% of the region‘s CO_2 point source emissions.

Table 1-3. A Snapshot of the MRCSP Region

Subject	Fact
Geographic region	Nine States: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia
Population	80.4 million (26% of US population)
Gross Regional Product	$3,114 billion (27% of the US economy)
Electricity generation	26.3% of all electricity generated in the US
CO_2 emissions	Approximately 699 million metric tons of CO_2 per year are emitted from large point sources. 85% of those emissions are related to electricity generation.

Pie chart showing relative emissions from the large point sources in the MRCSP





Locations of large stationary point sources within the MRCSP.

Figure 1-1. Large Point Sources within the MRCSP Region

1.2 Financial Summary

The total value of the MRCSP Phase II project was $28,801,838, including all cost share received. The primary source of funding for Phase II was the NETL under cooperative Agreement No. DE-FC26-05NT42589. DOE funding provided to the project was $22,304,933 or 77.44% of the total. The second largest contributor to the project was the Ohio Coal Development Office (OCDO) within the Ohio Air Quality Development Authority under OCDO Grant/Agreement No. D-05-13 in the amount of $750,000 or 2.6% of the total. The remaining funding was provided by the MRCSP partners.

1.3 Validation Tests

Phase I results indicated that the region has many opportunities for geologic and terrestrial sequestration. The objective of Phase II was to translate the theoretical knowledge gained in Phase I into practical, real world knowledge through the conduct of a series of small-scale field validation tests. In all, seven small-scale field validation tests were conducted in Phase II (Figure 1-2):

- Three geologic injection tests, one in each of the three major geologic provinces of the region: the Michigan Basin, Appalachian Basin, and Cincinnati Arch.
- Four terrestrial field tests in land types characteristic of the heterogeneity of the region: croplands, reclaimed minelands, reclaimed marshlands, and forested wetlands.

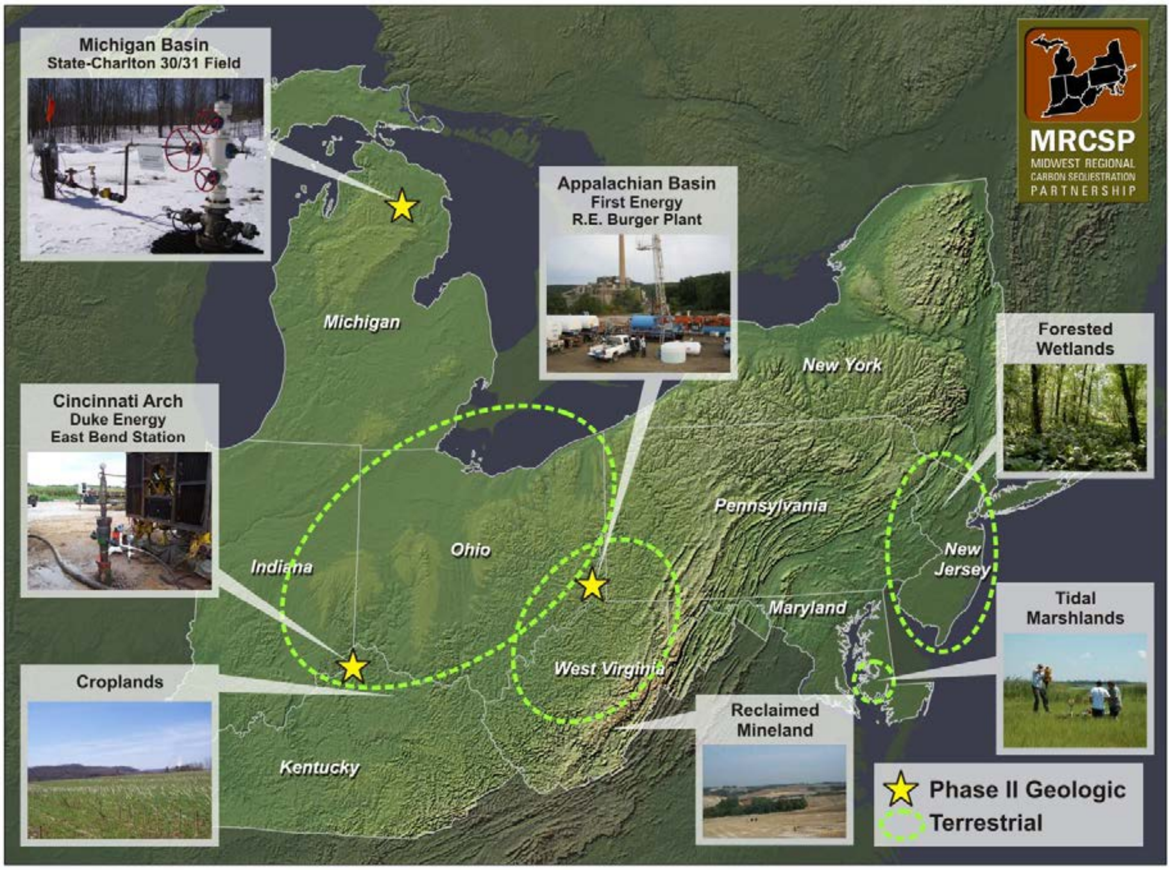


Figure 1-2. Locations of the Various Field Tests Conducted in Phase II

1.4 Report Organization

The MRCSP Phase II program made significant progress towards validating sequestration technologies in the region through various small-scale field validation tests and other activities. This report is divided into sections summarizing the results and major findings of the major activities conducted in Phase II, including:

- Field validation of geologic sequestration
- Field validation of terrestrial sequestration
- Geologic regional exploration, including piggyback opportunities
- Regulatory Analysis
- Stakeholder outreach and education
- Regional implementation strategic considerations.

Section 2.0: FIELD VALIDATION OF GEOLOGIC SEQUESTRATION

Completing successful field validation projects for geologic sequestration was a major emphasis for Phase II. The ultimate goal of these tests was to demonstrate the feasibility of CO_2 storage in order to advance this technology towards commercial deployment. The experience gained during these projects was used to develop best practices to build confidence in this technology; the results of these projects were presented in reports, manuals, and other means of communications to transfer knowledge to potential end users for this technology and to other stakeholders. Through these important small-scale validation tests, information was gained in three major issues facing commercial scale deployment:

(1) *Engineering/scientific issues*: Together these efforts involved the injection of over 61,000 metric tons of CO_2 and nearly 20,000 feet (ft) of drilling. These projects employed a full program of wireline logging, rock coring, seismic acquisition, and brine analysis. These projects provided real experience for assessing storage potential; confirming computer simulations of how CO_2 behaves in a saline formation; verifying surface and subsurface monitoring techniques to detect injected CO_2; and advancing understanding of handling and injecting CO_2.

(2) *Regulatory issues*: The project team and the project regulators (i.e., United States Environmental Protection Agency (U.S. EPA) Region 4, U.S. EPA Region 5, and the Ohio Environmental Protection Agency (EPA)) gained direct experience permitting a CO_2 injection well, which is critical for developing a scientifically sound regulatory framework for possible commercial-scale projects in the future.

(3) *Public acceptance issues*: The tests provided opportunities for MRCSP members to effectively engage the public to develop a better understanding of important public issues and how to resolve them if this technology is to move forward. Outreach efforts conducted at all sites included featuring each project on the MRCSP Web site, preparation of factsheets and other descriptive materials, hands-on displays and interactive models, holding public meetings, and supporting public hearings as required by the regulators.

An overview of the geologic field validation process is presented in Figure 2-1.

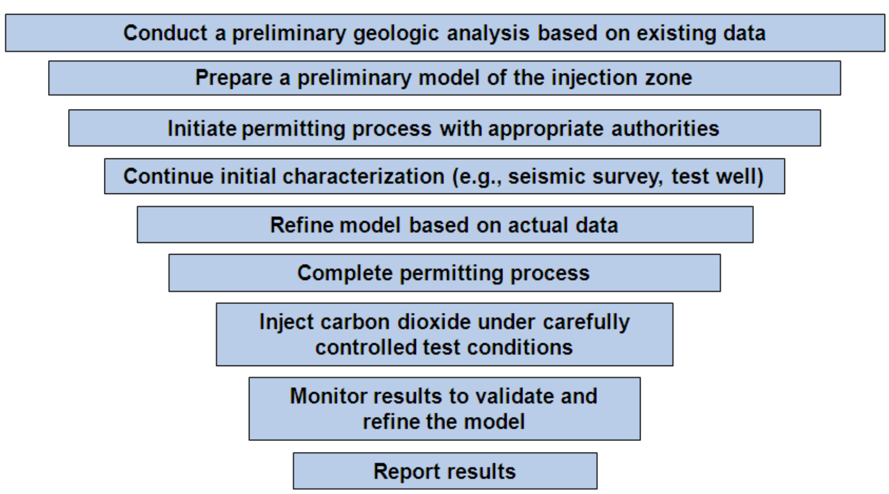


Figure 2-1. Key Steps in Geologic Field Validation Tests

This section summarizes the results of three geologic validation projects conducted during Phase II, one of each in the major geological provinces of the region. The three Phase II geologic injection projects are in the Appalachian Basin at FirstEnergy's R.E. Burger Power Plant near Shadyside, Ohio; in the Michigan Basin at DTE Energy's gas processing operations in the Antrim Gas Fields of Northern Michigan; and near the Cincinnati Arch at the East Bend Station of Duke Energy south of Cincinnati on the Ohio River. More detailed information can be found in the technical reports that have been prepared for each project (Battelle, 2010, 2011a, and 2011b).

2.1 Overview of CCS

Carbon capture and storage (CCS) systems are specifically designed to remove CO_2 from the flue gases and various process streams of large power plants and industrial facilities and safely deposit the CO_2 in secure storage sites deep underground, thus keeping it out of the atmosphere. At present, there are more than 8,100 large CO_2 point sources around the world comprising primarily large fossil fired power plants and large industrial facilities. These facilities collectively emit approximately 15 billion metric tons CO_2 annually (>60% of all global anthropogenic CO_2 emissions). Many of these power plants and industrial facilities are believed to be near suitable candidate CO_2 storage reservoirs (Dooley et al., 2006).

CO_2 can be separated and captured as a byproduct of fossil fuel, used for energy generation and numerous industrial processes. Some industrial processes produce a relatively pure CO_2 stream, resulting in low capture costs and, therefore, these sources are high priority targets of CCS. CO_2 is too dilute in flue gas of coal fired power plants to economically transport it and inject it underground. Therefore, to implement CCS at coal fired power plants, technology is needed to capture the CO_2 from the power generation process in a relatively concentrated and pure form in order to cost effectively transport and store it underground. Current commercial processes for capturing CO_2 were developed for and are used in applications like natural gas processing. Many in the power generation industry do not consider these technologies cost effective for application on the large scale of major coal fired power plants. Research is underway to develop improved means for capturing CO_2 from coal fired power generation. That research is being conducted outside the scope of the regional partnerships and is not addressed in this report.

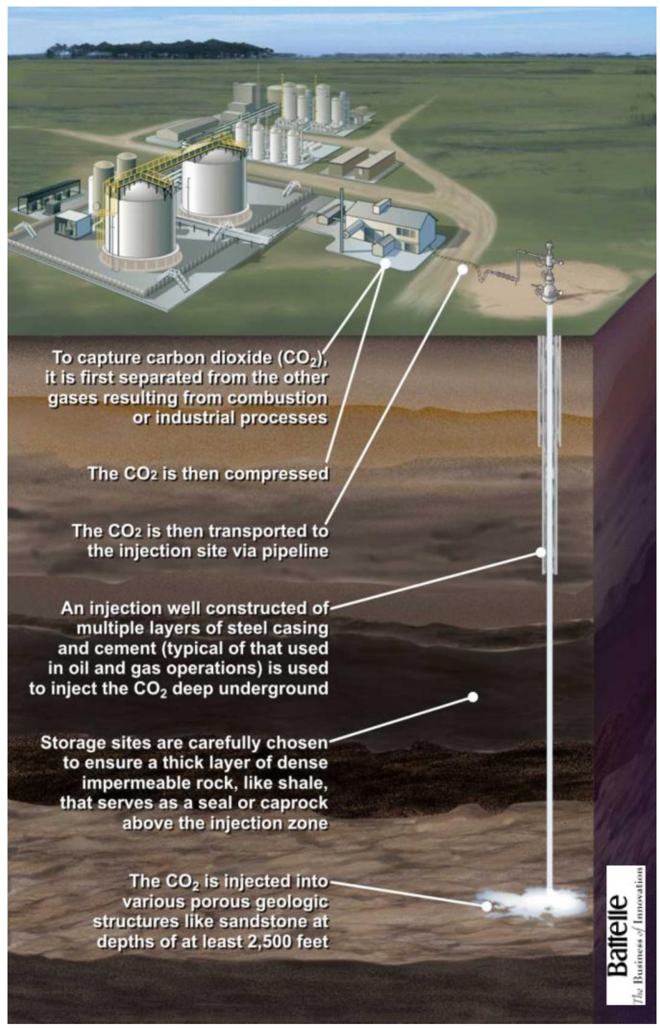


Figure 2-2. Conceptual Illustration of CCS in a Deep Saline Formation

A conceptual illustration of geologic storage within a deep brine reservoir is presented in Figure 2-2. The challenges for geologic sequestration lies in characterizing the geologic system with confidence; maximizing safety/eliminating any potential leaks; and maximizing pore space and optimizing efficiency. The basic procedures for storing CO_2 underground are:

(1) **Site Characterization:** Before any work is begun at a potential storage site, the rock formations and possible injection zones are carefully evaluated to ensure the presence of rocks that are suitable for storing and containing CO_2. Typically, this stage includes a seismic survey of the area and drilling and conducting tests in the well through which the CO_2 will be injected.

(2) **Carbon Capture and Transport:** When a fossil fuel such as coal is burned it produces heat and gases, which include CO_2. The CO_2 is separated from the flue gas rather than released to the air; this is called “carbon capture.” The captured CO_2 is compressed into a supercritical state and transported via pipelines to injection well locations.

(3) **Carbon Dioxide Injection:** If the area is shown to be suitable for storage and the necessary injection well permits are obtained, the captured CO_2 is compressed to a supercritical state and injected into rock formations that are infused with salty water, via an injection well.

(4) **Permanent Storage:** The confining zone, sometimes also called cap rock, is an impenetrable barrier that traps CO_2 in the storage reservoir. The injected CO_2 can undergo several changes over time. It can remain in a liquid-like state, get trapped permanently within the pore spaces of the rock, dissolve into the brine, bond to the organic matter in coal and shale, and over the longer-term, react with minerals in the rock to form stable mineral compounds.

(5) **Monitoring, verification, and accounting:** During and after injection, appropriate monitoring equipment is used both above and below ground to track the composition, pressure, and amount of injected fluids and monitor for CO_2 movement in the deep formations.

2.2 Mount Simon Sandstone, Cincinnati Arch Province, East Bend Generating Station

The Duke Energy East Bend Generating Station, located in Boone County, Kentucky, was the host site for the small-scale validation test into the Mount Simon Sandstone in the Cincinnati Arch Province (Figure 2-3). The Mount Simon and this part of the MRCSP region along the Ohio River Valley is important from the standpoint of the significant potential for storing CO_2 and because of the concentration of large, modern coal-fired power plants, such as the East Bend Generating Station, in close proximity. The primary objective of the East Bend Project was to test CO_2 sequestration in the Mount Simon. In addition to this main objective, the test is aimed at providing information to help better understand regional trends (i.e., permeability, porosity, geochemistry, mineralogy) in the Mount Simon Sandstone. The Mount Simon Sandstone is present across much of the Midwest as a deep saline reservoir and has been historically used for injection of industrial and hazardous liquid waste. The geology of the Mount Simon at the project site is representative of a large part of the MRCSP region; therefore, this test should be useful for current or potential future power plant operators in the MRCSP region that are looking to develop CO_2 sequestration facilities within the Mount Simon.

Figure 2-3. Photograph of the Drilling Site and Drilling Equipment for the East Bend Well

The project helped establish familiarity with carbon sequestration among stakeholders in the area. A proactive public outreach program was implemented throughout the duration of the project to educate and inform stakeholders and facilitate implementation of the project.

The East Bend Project took approximately 3 years to complete. The project began in 2006 with a preliminary geologic assessment of potential injection and confining zones at the proposed site, led by the geological surveys of Ohio, Indiana, and Kentucky. The preliminary assessment indicated that the Mount Simon has depth, good porosity and permeability, and is overlain by low permeability confining layers to trap the CO_2. The Mount Simon is saturated with dense brines having total dissolved solids greater than 100,000 milligrams per liter. These brines have no known economic value. There is a small amount of oil and gas production in the area, but this is limited to shallower rock layers, well above the test zone. In this area, the confining zone includes a layer of caprock approximately 500 ft thick (known as the Eau Claire shale) lying above the injection zone (Figure 2-4).

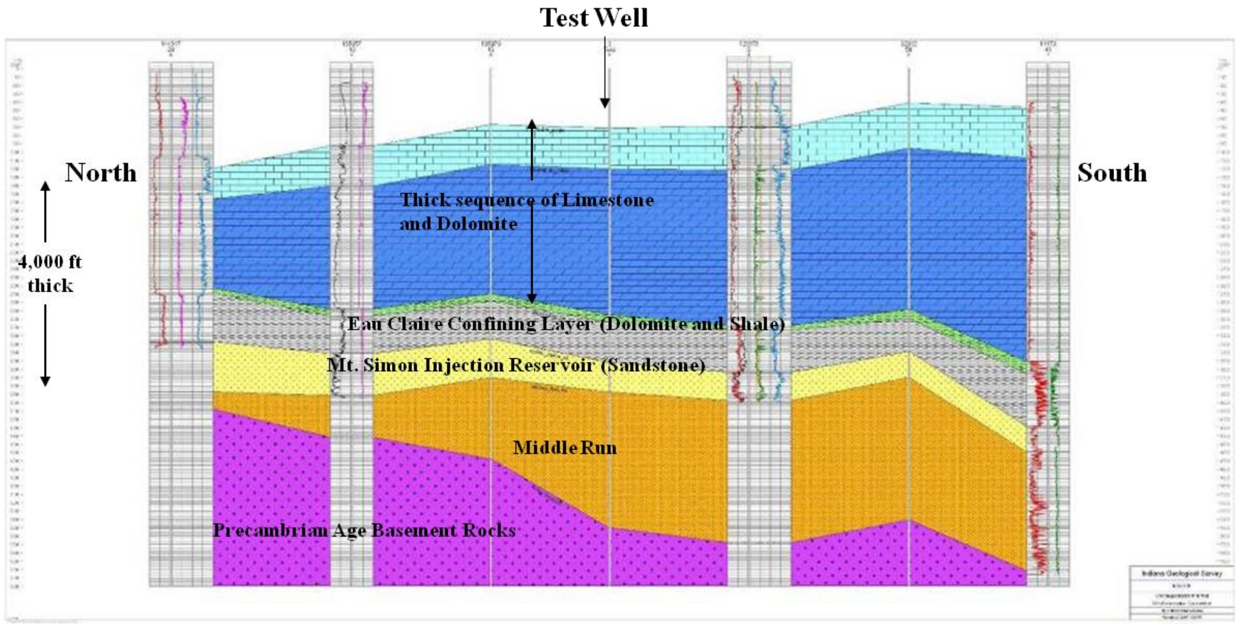


Figure 2-4. Geologic Cross Section of the Area Prepared by the Indiana Geological Survey

The preliminary assessment also documented that the region surrounding the project has low seismic probability. A two-dimensional (2D) seismic survey was completed in November 2006 to evaluate and confirm the suitability of the site for hosting a sequestration test. Much of the work took place on Duke Energy's property and along roads within a 5 mile radius of the East Bend Generating Station and took about two weeks to complete. The seismic survey results confirmed that no deep faulting is present that could provide a natural pathway for CO_2 to escape and provided a basis for proceeding with drilling a well (Figure 2-5).

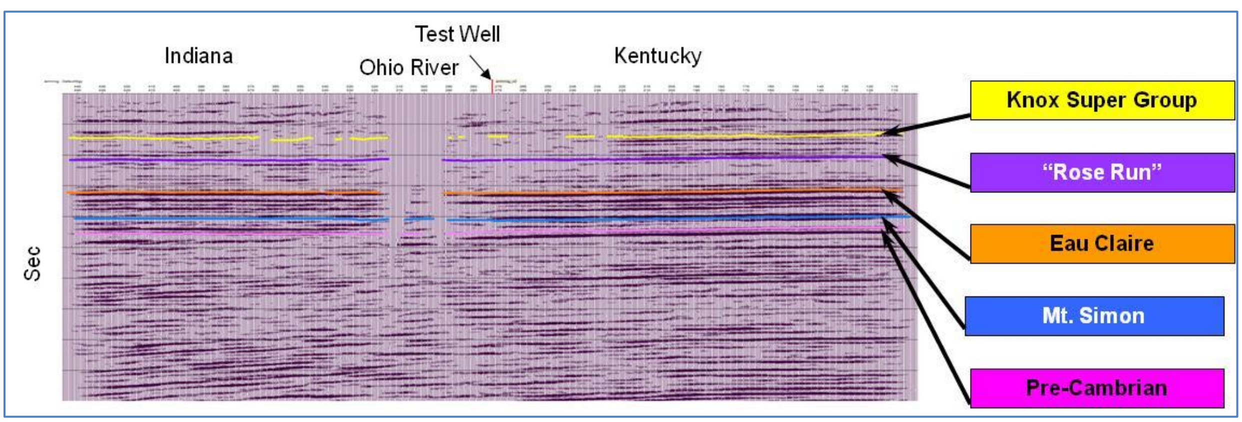


Figure 2-5. Results of the 10-mile Seismic Survey Confirmed the Presence of Continuous Rock Layers with No Deep Faulting

After these initial characterization steps, permits were obtained to conduct a deep-well injection test, including a Class V (Experimental) Underground Injection Control (UIC) permit from the U.S. EPA Region 4 and a drilling permit from the Kentucky Division of Oil and Gas. The test well was regulated as a Class V Experimental well since it was for research and would operate for only a short time. (Because of the small amount injected and site geology, the CO_2 would not move more than 500 ft from the point of injection and would remain within the East Bend property.) The UIC permit issued in March 2009 required Duke Energy, the designated well owner, to submit detailed information on the site, construction and operation of the well, plans to monitor the well integrity and the CO_2 injection, and plans for plugging the well when injection was completed.

The project team began drilling the test well after obtaining the drilling permit from the Kentucky Division of Oil and Gas in June 2009. The boring was completed to a depth of approximately 3,700 ft. The sampling and characterization activities performed during the installation of the well focused on determining the geologic, hydrogeologic, and geochemical conditions of the formations encountered during the drilling activities. The project provided characterization data for the Mount Simon that will be useful in better understanding the regional variability and trends in properties relevant to CO_2 sequestration, including porosity, permeability, and geochemistry. Characterization data that were collected include the following: (1) 60 ft of Mount Simon core and 30 ft of Eau Claire core were collected to support characterization analyses of these formations, including detailed petrology studies that are being performed at the Indiana State Geological Survey (Figure 2-6); (2) a comprehensive suite of geophysical logs was collected to characterize the geologic strata at the project site, including a number of specialized logs that were run on the Mount Simon, Eau Claire, and Knox Group; (3) a fluid sample of the Mount Simon brine was collected and analyzed for geochemical parameters; and (4) a brine step-rate injection test was conducted to determine the fracture pressure of the Mount Simon prior to injecting CO_2.

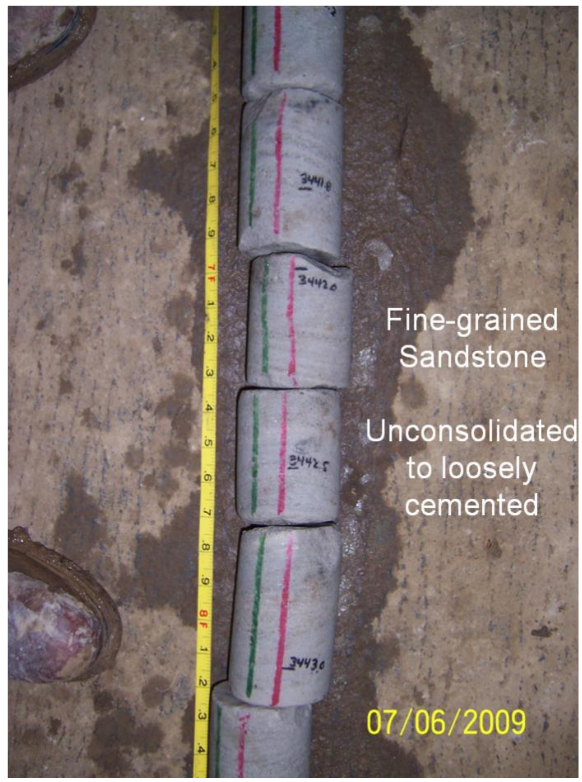


Figure 2-6. Photograph of the Mount Simon Rock Core (A single 30-ft-long core of caprock [Eau Claire] and two 30-ft-long cores of sandstone [Mount Simon] were collected using conventional coring tools. The cores were marked with depth information, cut into 3-ft long sections, placed in core bags, and placed in core boxes for shipment to the laboratory.)

The site-specific characterization data showed that the Mount Simon occurs between depths of 3,230 and 3,532 ft below ground (thickness of 302 ft) and is overlain by approximately 450 ft of the Eau Claire Formation. The porosity of the Mount Simon determined from wireline logs is primarily 5 to 15%, but intervals with <5% and >15% porosity were also encountered. Permeability based on wireline data calibrated to core data indicates that one-third of the formation is between 0 and 10 millidarcies (mD); one-third is between 10 and 100 mD and one-third is 100 mD or greater. The Eau Claire Formation exhibits excellent properties for a caprock, including substantial thickness, permeability generally less than 1 mD, and an absence of fractures and faulting that could compromise its sealing ability.

Conducting a brine injection test prior to injecting CO_2 was found to be a useful indicator of the ability of the formation to accept CO_2. In this test, injecting CO_2 resulted in much lower bottom-hole pressures than injecting a similar amount of brine; this suggests that brine injection tests provide a conservative estimate of the formation's CO_2 injectivity. CO_2 injection rates higher than those achieved during the field test are possible without fracturing the formation. Furthermore, conducting a brine injection test and a CO_2 injection test in the same well provided corroborative data sets that were useful for characterizing key hydraulic parameters of the reservoir (e.g., permeability, transmissivity) and for calibrating numerical models for evaluating CO_2 injection scenarios (Figure 2-7).

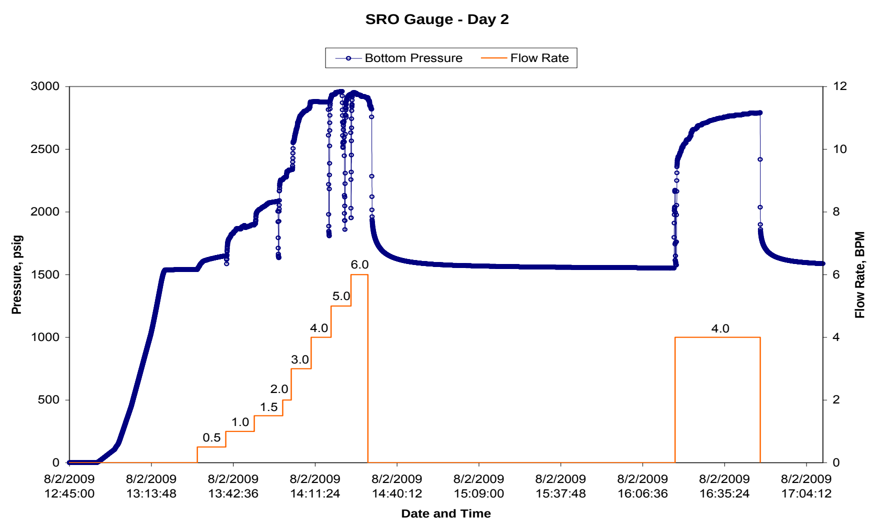


Figure 2-7. Graph Showing Changes in Bottom-hole Pressure in Response to Changes in Brine Injection Rates (Depth 3,410 to 3,510 ft)

After the well logging and testing were completed, a mechanical integrity test, which was observed by an inspector delegated by U.S. EPA Region 4, was successfully completed on the well casing. A report on the test was submitted to U.S. EPA Region 4 for their approval before commencing the CO_2 injection test.

A total of approximately 910 metric tons of liquid CO_2 (approximately 229,000 gallons) was injected into the Mount Simon during a one week period in September 2009 (Figures 2-8 and 2-9). The injection rate, pressure and temperature were continuously measured throughout the test. A CO_2 injection rate on the order of 5 barrels per minute (bpm) was achieved during the injection test. This rate was limited by the pumping equipment used in the test, not the injectivity of the formation. This rate is approximately equivalent to 1,200 metric tons/day or approximately 0.4 million metric tons per year.

Figure 2-8. A Temporary Supply of CO_2 was Stored Onsite in Storage Tanks (The CO_2 that was used for this test was the same in composition as that routinely used in the food industry. It was transported as a liquid by standard delivery trucks.)

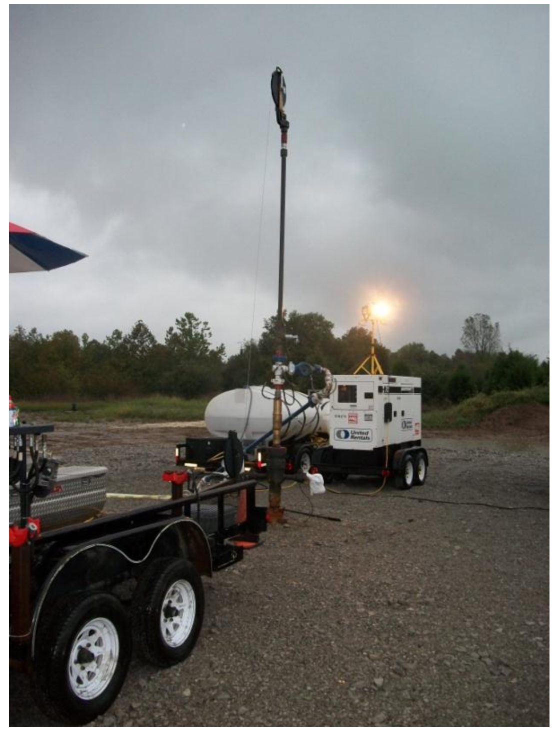


Figure 2-9. The Actual Injection of CO_2 Was Not Visible Because Injection Takes Place at the Bottom of the Well More Than a Half Mile Below Ground (The injection well is shown in the center of the picture.)

A 2D numerical model of the Mount Simon Sandstone was constructed based on geologic characterization data collected during the project and used to simulate the brine injection test and the CO_2 injection test. The model was calibrated to the brine injection test data by adjusting intrinsic permeability determined from wireline logs until the modeled well pressures matched bottom-hole pressures observed during the brine injection test (Figure 2-10). An excellent prediction of the well pressure during the CO_2 injection test was obtained by using geostatistical realizations of porosity and permeability from wireline log data collected in the injection well once the intrinsic permeabilities were adjusted slightly by calibrating to a short brine injection test. Capillary pressure vs. saturation data and brine relative permeability vs. saturation data measured using core samples from the injection well were used.

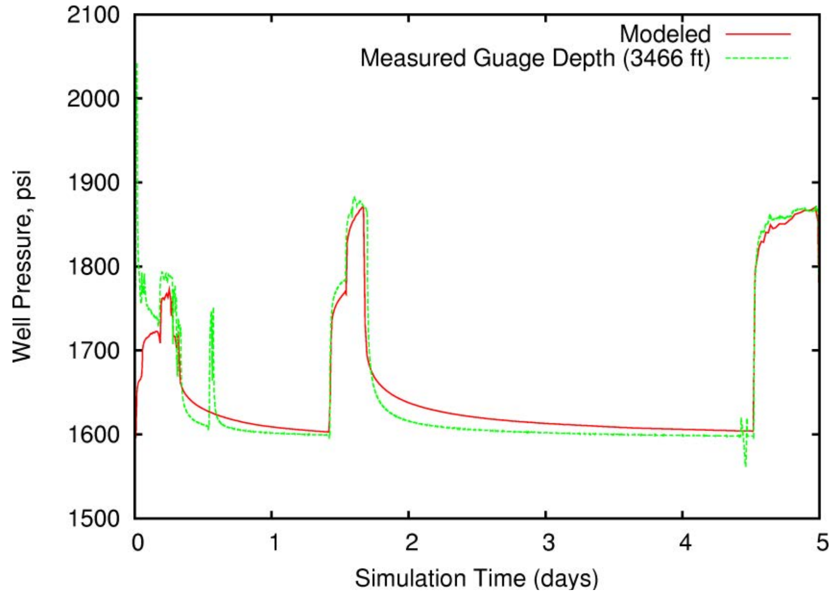


Figure 2-10. Results of Simulation Predicting Well Pressure Using the Same Rate and Temperature Measured during the CO_2 Injection Test Along with the Observed Bottom-hole Pressure

The well was plugged and abandoned and the site was restored to its original condition in April 2010. The UIC permit required a two+ year program to monitor a network of shallow groundwater wells to detect potential adverse impacts to the underground source of drinking water (USDW) aquifer at the site caused by injection of the CO_2. Therefore, monitoring was conducted for chemical parameters that are indicators of CO_2 or brine invasion into the shallow aquifer. Before injection, groundwater samples were collected from 10 monitoring wells in the vicinity of the demonstration site, including a new groundwater monitoring well that was installed 400 ft from the injection well, to obtain baseline data from the relatively shallow drinking water zone. Beginning with the injection test, groundwater samples are being collected on a quarterly basis to comply with the requirements of the UIC permit. The last groundwater sampling event will occur in September 2011. The UIC permit will be terminated upon fulfilling these monitoring obligations. Thus far, levels of all parameters remain similar to pre-injection values and CO_2 and brine invasion is not likely.

2.3 Bass Island Dolomite and Bois Blanc Formation, Michigan Basin, Otsego County Michigan

CO_2 sequestration potential was investigated in the Bass Islands Dolomite and adjacent Bois Blanc deep saline formations within the northern Michigan Basin. The sequestration site was located in State-Charlton 30/31 field, Otsego County, Michigan, in the vicinity of an enhanced oil recovery (EOR) field operated by Core Energy LLC, one of the industry hosts for this test. The CO_2 was supplied from natural processing plants located in the Chester 10 area, including the Turtle Lake facility owned by DTE Energy at the time of the injection test. The Chester 10 area is located approximately 10 miles to the south of the injection well at Charlton 30/31 (Figure 2-11).

A total of approximately 60,000 metric tons of CO_2 was successfully injected into the Bass Islands Dolomite in two campaigns, the first from February-March 2008 (~10,000 metric ton) and the second from January-July 2009 (~50,000 metric tons). The overall injection test benefited from utilizing existing infrastructure and experience related to EOR operations in the area.

Figure 2-11. CO_2 Used in This Test was a Byproduct of Natural Gas Processing; CO_2 was Transported via Pipeline Approximately 10 miles from the Compression Facility to the Injection Well

Field demonstration activities were spread over a period of approximately three years. An outreach plan was developed to link outreach activities to technical activities as the research project progressed. The purpose of the plan was to ensure that the participants involved in the test were coordinated with each other in conducting outreach activities. The outreach effort was ultimately aimed at building a solid foundation of public awareness of this test and for the longer-term implementation of geologic sequestration in the region. Major outreach tasks included production of informational materials, informal public informational meetings, site tours, and press releases. In general, the project was well received, probably due to the prevalence of oil and gas, EOR and natural gas processing in the region and their importance to the local economy.

Initial characterization efforts included a preliminary geological assessment, drilling a test well which was later permitted as the injection well, full rock coring through the test interval, core testing, and wireline logging. The initial geologic assessment was based on available well logs in the area. It suggested that the Sylvania Sandstone would be the best potential storage zone within the depth range of interest. However, after drilling the test well, the stratigraphy was reevaluated, and, based upon that, it was concluded that the Bass Islands Dolomite provided the best storage target within the depth range of interest. The Sylvania Sandstone was found to pinch out to the south of the project location. The stratigraphic understanding for this part of the Michigan Basin was altered as a result of new information gained from drilling of the test well (Figure 2-12).

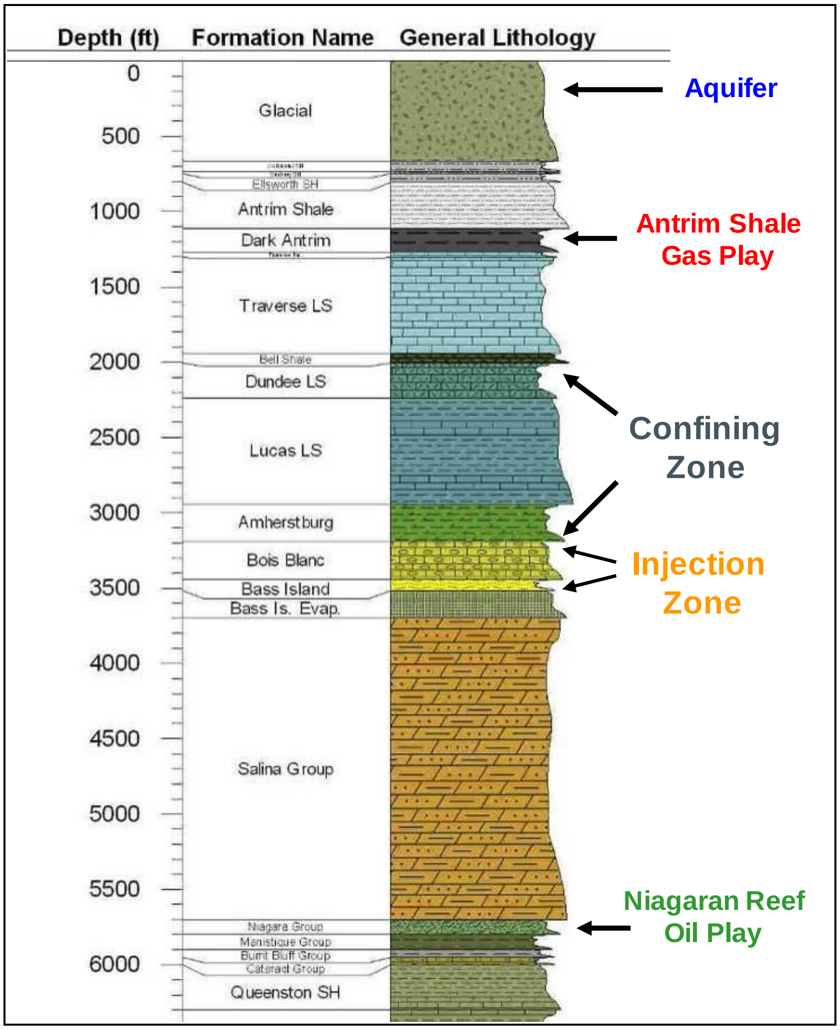


Figure 2-12. Preliminary Geologic Assessment of the Phase II Project in Otsego County, Michigan

The rock core for the Bass Islands provided tangible evidence of injection potential showing average porosity of 13% and average permeability of 22 mD across the 73 ft thick target injection interval (Figure 2-13). The immediately overlying Bois Blanc Formation was not fully understood, but appeared to show features intermediately between an injection zone and a caprock. Therefore, the Bois Blanc was included in the injection zone, although not targeted directly. Wireline logging and rock cores also characterized and confirmed properties of the overlying caprock, which showed porosity of less than 5% and permeability less than the detection limits of the instrument. Amherstburg and Lucas Formations were identified as the primary caprock within the confining zone.

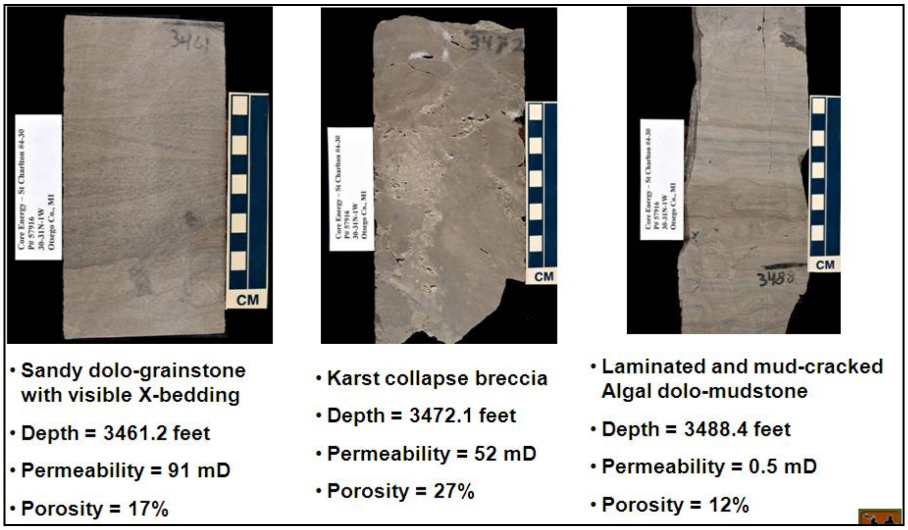


Figure 2-13. Core Sample from Bass Islands Dolomite Showing Vertical Heterogeneity

The well used for the characterization test (labeled Test Well 4-30 in Figure 2-14) was subsequently completed and permitted as a Class V experimental CO_2 injection well through U.S. EPA Region 5. An existing but closed EOR well (labeled C3-30) was reopened and completed as a monitoring well for the MRCSP test. The lateral distance between the two wells at the depth of the Bass Islands was about 490 ft. In addition, an existing oil and gas well (C2-30) was used for microseismic and crosswell seismic testing. Both monitoring wells were permitted only by the State of Michigan. U.S. EPA Region 5 and the State of Michigan were helpful and flexible in regulating the injection test while ensuring that the necessary monitoring, reporting, and public review requirements were enforced.

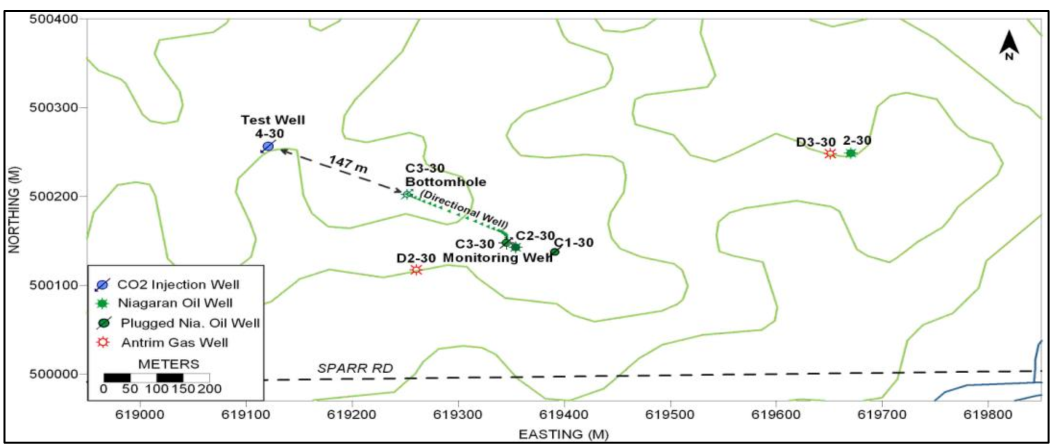


Figure 2-14. Map Showing 4-30 Injection Well and C3-30 and 2-30 Monitoring Wells

During the public comment period required by the UIC process, one appeal came from an individual owning land near the injection site. That appeal delayed the permitting process approximately three months while the appeal was considered by the U.S. EPA Environmental Appeals Board. The U.S. EPA Board subsequently rejected the appeal because it was focused on property rights considerations, which are not in the scope of the UIC process. Overall, public reaction to the injection test expressed during voluntary information meetings held near the injection site was limited and appeared generally favorable.

Mechanical integrity testing was required by the UIC permit prior to the start of injection. The UIC permit also required monitoring of injectate composition and continuous monitoring of injection operations. In general, the monitoring associated with the MRCSP injection test was more extensive than what would be required for a typical Class II CO_2 injection well.

Approximately 10,000 metric tons of CO_2 were injected into a 73 ft thick perforated zone extending from 3442 to 3515 ft depth across the Bass Islands Dolomite from February 7 to March 8, 2008. An extended injection test took place about one year later from February 25 to July 8, 2009, and involved the injection of approximately 50,000 additional metric tons of CO_2. Throughout both periods, injection parameters including volumetric flow (injection) rate, pressure, and temperature were continuously monitored as were other pertinent parameters including bottom-hole pressure and temperature and annulus pressure.

Based on the injection conditions at the wellhead and point of injection, the CO_2 was in a liquid phase when it was injected into the Bass Islands. Although the CO_2 was compressed from gas to a supercritical condition at the Chester 10 compression facility, during the winter months surface temperatures in this part of Michigan are sufficiently low that the CO_2 cools during pipeline transport and becomes a liquid by the time it reaches the wellhead. This is also true for EOR operations in this area and may be the case for future sequestration operations in this area as well.

During injection testing, CO_2 was injected at a rate of approximately 400 to 600 metric tons per day (Figure 2-15). The injection zone was capable of accepting CO_2 at the maximum flow rate possible with the compression system available, while retaining the CO_2 within the injection zone and confining system. The maximum rate was limited by compressor capacity at the site and not by reservoir conditions. Wellhead pressures monitored during the injection suggest that higher injection rates may be possible in this formation using a single injection well, at least initially, without exceeding the maximum injection pressure allowed by the UIC permit. Towards the end of the extended injection period, the bottom-hole pressure in the injection well was still rising at an injection rate of about 600 metric tons per day. However, the corresponding wellhead pressure appeared to be leveling off at a value below about 1000 psi, or about 200 psi below the limit in the UIC permit. It is not possible based on the limited testing done here and the analysis of the data done to date to determine what injection rate could be sustained indefinitely in a single well like that used here.

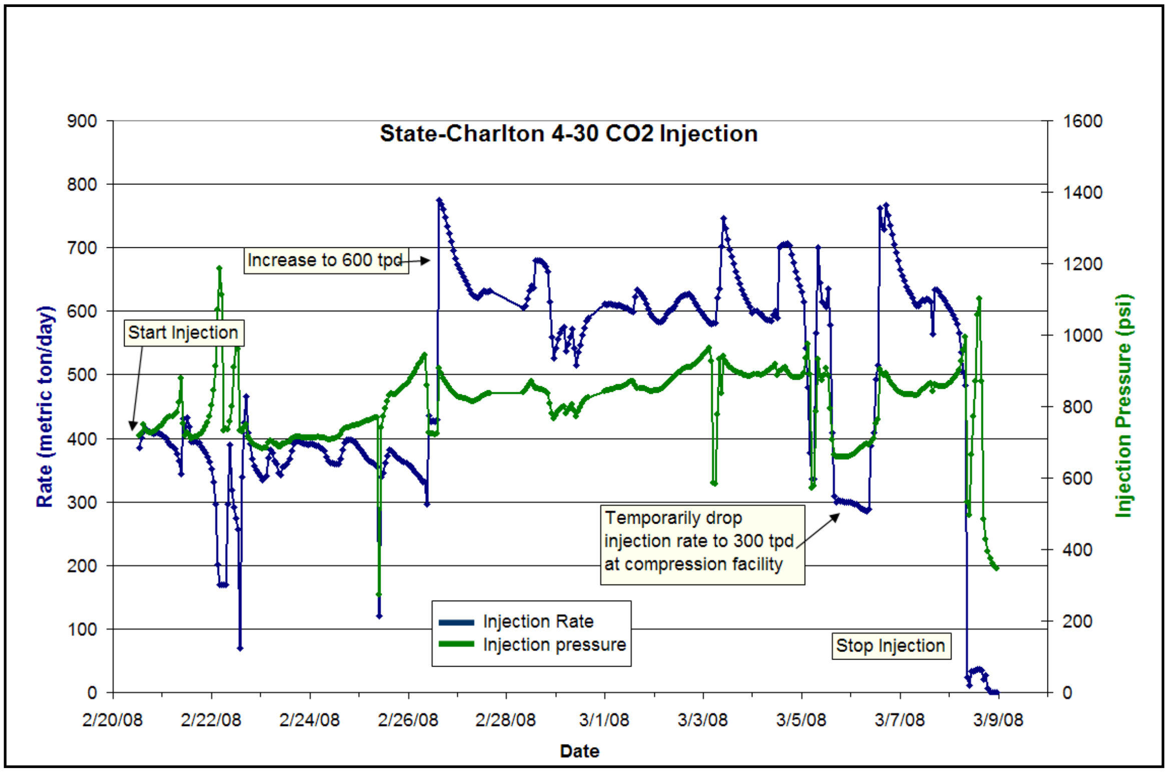


Figure 2-15. Injection Rates and Injection Pressure Measured during the First Injection Period

The monitoring program included wellhead flowmeters, annular pressure monitoring, perfluorocarbon tracer (PFT) surveys, CO_2 surface gas detectors, an array of microseismic sensors, downhole pressure/temperature loggers, crosswell seismic data (processed as both reflection and waveform tomographic images [Figure 2-16]), wireline saturation logging, geochemical analysis of brine samples, formation gas sampling using wireline methods, and cement sampling and evaluation. Pressure/temperature data from injection were useful in evaluating hydraulic parameters and developing a site model. Time-lapse data from cross-well seismic imaging operations were useful in identifying CO_2 migration mechanisms in a complex dolomite reservoir. Data from wireline pulsed neutron capture (PNC) logs, cement evaluation, and fluid sampling were consistent with crosswell seismic observations.

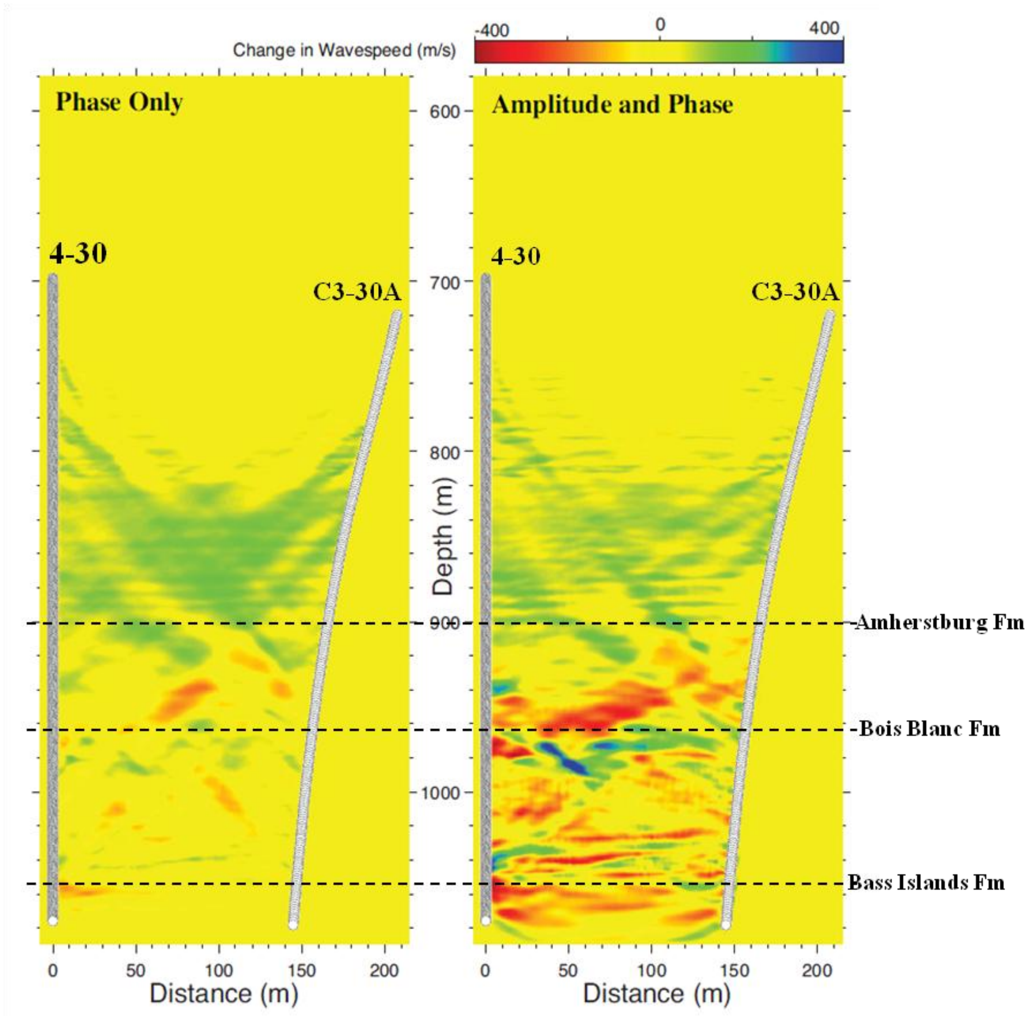


Figure 2-16. Crosswell Seismic Data Processed as Waveform Tomographic Images were Useful for Identifying CO_2 Migration Mechanisms in a Complex Dolomite Reservoir

Monitoring techniques confirmed that the CO_2 was contained by the confining zone. No indication of CO_2 migration to the near surface was detected by the PFT tracers, by various measurements taken in the injection well (Figure 2-17), or by surface sensors around the wellhead. Both vertical and lateral migration of CO_2 was imaged within the storage zone using various techniques including crosswell seismic and PNC. Repeat crosswell seismic and PNC surveys indicated that CO_2 was present within the Bois Blanc (injection zone) and trapped by the Amherstburg Formation (overlying caprock).

Figure 2-17. Temperature Monitoring is Often Required by Regulators for any Underground Injection
(Shown here, temperature was monitored from the surface to the injection reservoir using wireline tools, which are lowered into the well.)

A series of reservoir simulations was completed with STOMP-WSCE (Subsurface Transport Over Multiple Phases - water, salt, CO_2, energy), a multiphase CO_2 sequestration simulator. A preliminary model was first developed based on the regional geologic framework and general hydraulic parameters. It was assumed that the storage zone was 100 ft thick with homogeneous permeability distribution. Once the test well was drilled and test data received, the model was revised to site-specific conditions. While it was not practical to map all of the local-scale geologic heterogeneities at the site, the pre-injection site characterization efforts aided in designing the injection test. Reservoir simulations conducted before and after testing were useful in predicting and explaining the behavior of the CO_2 in the target formation (Figure 2-18). These model results were used to develop the monitoring and injection plans.

Monitoring Point	Maximum Bottomhole Pressure (psi)	
	STOMPCO2 Simulated	Observed
C4-30 Injection Well	2,100	2,020
C3-30 Monitoring Well	1,555*	1,535

*corrected for observed in-situ pressure

Figure 2-18. Preliminary Modeled versus Observed Pressures

After the initial injection period, the model was calibrated to transient pressure and temperature readings measured in the 4-30 injection well and 3-30 monitoring well although the initial simulations, done prior to injection, agreed fairly well with the monitoring data (Figure 2-19). Following the extended injection period, the model was validated with the additional monitoring and injection information. This validation process required additional modifications to the model to match observed CO_2 distribution. For instance, monitoring data suggested that the CO_2 moved farther upward in the storage zone than the model initially suggested. As a result, adjustments to some of the hydraulic parameters used in modeling the CO_2 storage zone, such as vertical permeability, were made.

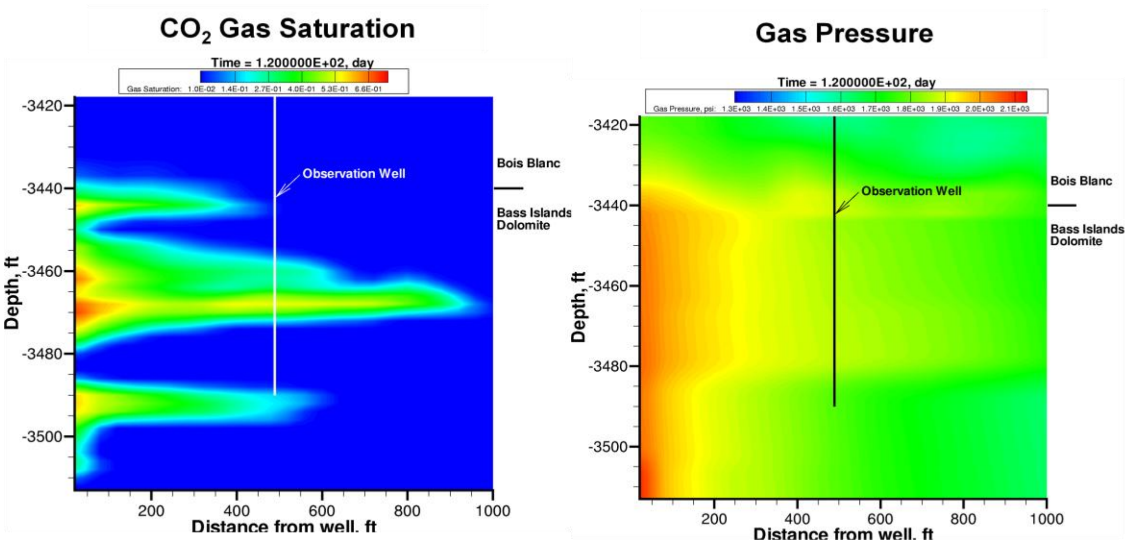


Figure 2-19. Simulated CO_2 Saturation and Pressure for 50,000 metric tons

The Bass Islands and Bois Blanc storage formations are carbonate rocks, which present a complex reservoir from a modeling perspective. As more information about the Bass Islands was obtained, the model was updated to yield a more accurate solution. In fact, significant changes were made to the base conceptual model as additional injection was completed and more detailed monitoring results became available. This experience highlights the potential for the monitoring phase of geologic storage projects to continuously improve the modeling framework used to simulate a geologic sequestration system.

While the current validation phase of work at this site is complete, significant additional work is still possible to process, analyze, and model the wealth of operational and monitoring data from the MRCSP injection test at this site. Further analysis of cross-well seismic, microseismic, geochemical, and modeling results can provide more insights into the CO_2 plume migration and effectiveness of monitoring technologies for large-scale storage.

2.4 Clinton, Salina, and Oriskany Formations, Appalachian Basin, FirstEnergy's R.E. Burger Power Plant

The objective of the test was to explore geologic storage targets in this area of the Appalachian Basin geologic province and develop CO_2 sequestration technology through drilling of a deep test well and conducting CO_2 injection tests. The Appalachian Basin is a regional structure in which sedimentary rocks form an elongated basin stretching across West Virginia, Pennsylvania, Ohio, New York, Kentucky, and Maryland. CO_2 sequestration potential was investigated at FirstEnergy's R.E. Burger power plant located near the town of Shadyside, in Belmont County, Ohio. The R.E. Burger Plant was selected as an exploratory CO_2 storage site for several key reasons:

(1) It is central to the Appalachian Basin and, in particular, the Upper Ohio River Valley Power Corridor (Gallipolis to East Liverpool, Ohio). Nearly 20,000 megawatts of coal-fired capacity exists in this region, including some of the largest and most modern coal-fired power plants in the world.

(2) The original target formations for this site, the Oriskany and Clinton sandstones, are pervasive throughout the Appalachian Basin and were, thus, of keen geological interest.

(3) The Burger plant was also the site for a demonstration of Powerspan‘s ECO® multi-pollutant control technology, which was to include the addition of the ECO_2 capture technology being developed by Powerspan at the time. Thus, this site offered the possibility of integrating the ECO2 capture process with MRCSP subsurface injection, which would have been a world first for a coal-fired power plant.

(4) The willingness of the host company, FirstEnergy, to provide site access, technical support, and co-sponsorship (Figure 2-20).

Figure 2-20. Battelle Coordinated with FirstEnergy to Host Site Visits and Presentations

An outreach plan was developed to ensure that the partners involved in the test were coordinating with each other in conducting outreach activities aimed at building a solid foundation of public support for this test and for the longer-term concept of geologic sequestration. Major outreach tasks included production of informational materials, informal public-employee meetings, an Ohio EPA UIC program public hearing, site tours, and press releases. In general, the project was well received with little opposition, probably due to the importance of the plant for the local economy and familiarity with oil and gas operations in the area.

Prior to any field work, a preliminary geological assessment of the general area was completed by the Ohio, Pennsylvania, and West Virginia Geological Surveys. This study reviewed the regional geologic setting, stratigraphy, oil and gas horizons, coal seams, seismic setting, groundwater resources, artificial penetrations, and surface features in the area based on existing data. Several deep saline rock formations were identified as potential injection targets, but there was little information on the nature of these formations since few deep wells were located near the site.

In August 2006, a 2D seismic survey was completed at the R.E. Burger Power Plant site to help delineate rock formation depths in the area as well as to gain insight into the structure of geological rock layers. The survey included two 5-mile long transects through the test site and one additional parallel trace approximately 1 mile in length to simulate a ―quasi-three-dimensional” trace (Figure 2-21). This additional survey line provided greater geologic coverage in the vicinity of the proposed well. The information provided by this shorter trace helped to better delineate the Oriskany Sandstone and Clinton-Medina Sandstone, which have a somewhat variable distribution in the general area. Survey results indicated that the site is located in a structural setting with flat to mildly undulating Precambrian surface overlain by essentially flat strata, the whole having a slight southeast dip into the heart of the Appalachian Basin. No faults or fracture zones were detected that may have affected the testing.

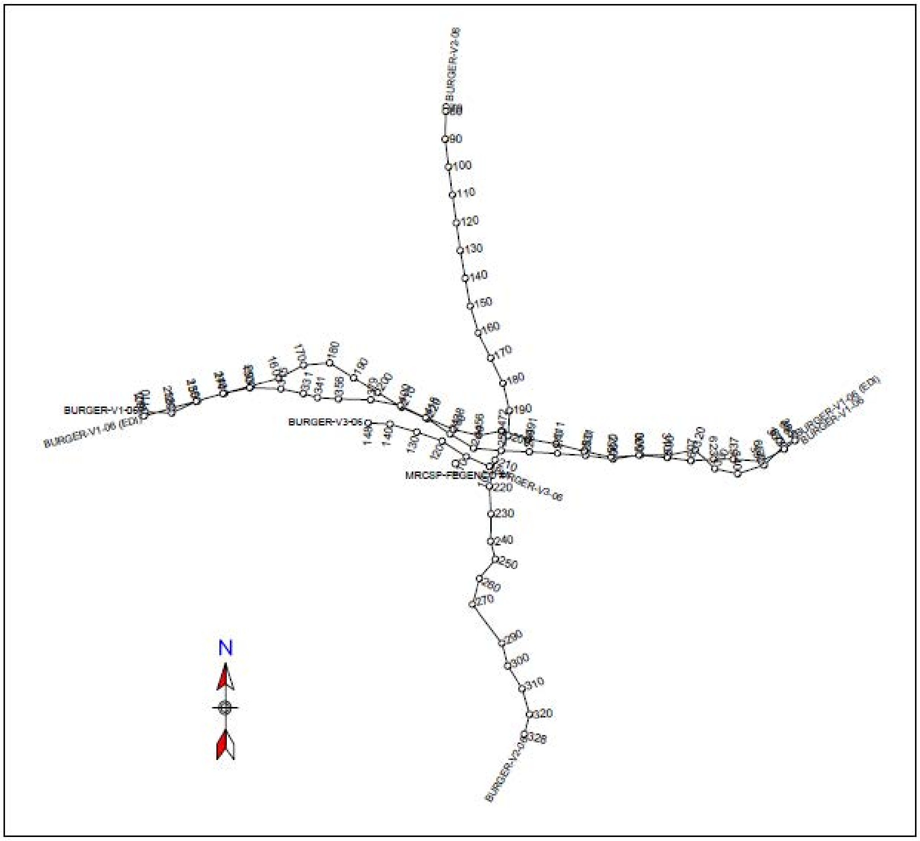


Figure 2-21. Seismic Lines and Well Location Map for R.E. Burger Site

The main permits required for the injection tests included well drilling permits and the UIC permit. The FEGENCO #1 test well was first permitted as a stratigraphic test well with the Ohio Department of Natural Resources (ODNR) Division of Mineral Resource Management. The permit form required standard information on well location, construction specifications, and site restoration that any oil and gas well would necessitate. The deep test well was drilled at the R.E. Burger site to a total depth of 8,384 ft in February 2007 including completion of associated logging and characterization tests (Figure 2-22). The test well was completed with injection casing in February 2008, which included several casing runs cemented to surface to isolate the well from the shallow groundwater zones. The injection zones were perforated in September 2008.

Figure 2-22. Drilling the Test Well (left); Test Well Completed (Right)

A full program of mud logging, wireline logging, sidewall coring, core testing, and petrophysical analysis was completed to characterize the geologic units. This information was used to identify injection targets, define confining layers, and plan injection testing. A full suite of wireline logs was completed in the well in three runs. Wireline logs showed zones of porosity between 2% and 10% within the key injection targets. A total of 48 rotary sidewall rock cores were collected in the test well from key injection targets and caprocks based on wireline logs. Core samples were tested for porosity, permeability, mineralogy, and density with standard procedures. Results generally showed porosity less than 5% and permeability less than 1 mD for most of the cores. Based on characterization efforts, three targets were selected for injection testing: the Oriskany Sandstone, Middle Salina Carbonate, and Clinton/Medina Sandstone.

Hydraulic analysis of injection potential suggested that high injection pressures would likely be encountered due to the relatively low permeability and thickness of the injection targets at the test well location. Based on these results, a flexible testing plan was developed to vary injection rates and readily move from one testing zone to another.

CO_2 injection was regulated by the Ohio EPA UIC program. A UIC Class V permit application was submitted to the Ohio EPA UIC program on January 17, 2008, and the permit was issued on September 3, 2008. During injection, Ohio EPA was notified of daily activities. Monthly reports were submitted to Ohio EPA summarizing maximum injection pressure, annular pressure, injection rates, and total injection volumes. While the test was small in scale, the permit process established familiarity with CO_2 sequestration with regulators and the public.

A commercial source of liquid food grade CO_2 was used for the injection testing at this site. Initially, it was hoped that the injection test could be integrated with a pilot CO_2 capture plant being developed by Powerspan and to be tested at the Burger site in a separate project. Because the Powerspan capture pilot plant was not available at the time needed for testing, a decision was made in early 2008 to utilize commercial CO_2 as the backup source. Nevertheless, this test site offered a chance to evaluate various technologies needed to monitor, verify, and account for the CO_2 sequestration at an operating coal-fired power plant.

Photographs of the test site are shown in Figures 2-23 and 2-24. Tanker trucks carrying about 20 metric tons of CO_2 each from the Praxair Marmet, West Virginia facility delivered the liquid CO_2 at approximately -10ºF and 250 psig to the R.E. Burger injection site. Three 50 metric ton mobile storage tanks were set up on the R.E. Burger site to provide an interim holding system before injecting into the well. The tanks were connected to a trailer-mounted injection system which included a triplex pump, a propane fired heater, and a programmable logic controller. At the wellhead, the system included flow meters, automated annulus pressure system, wellhead and downhole pressure gauges. Because this was a limited injection test with a single injection well, much of the monitoring was focused on assessing hydraulic response in the reservoir, vertical distribution of CO_2 in the injection targets, and health and safety.

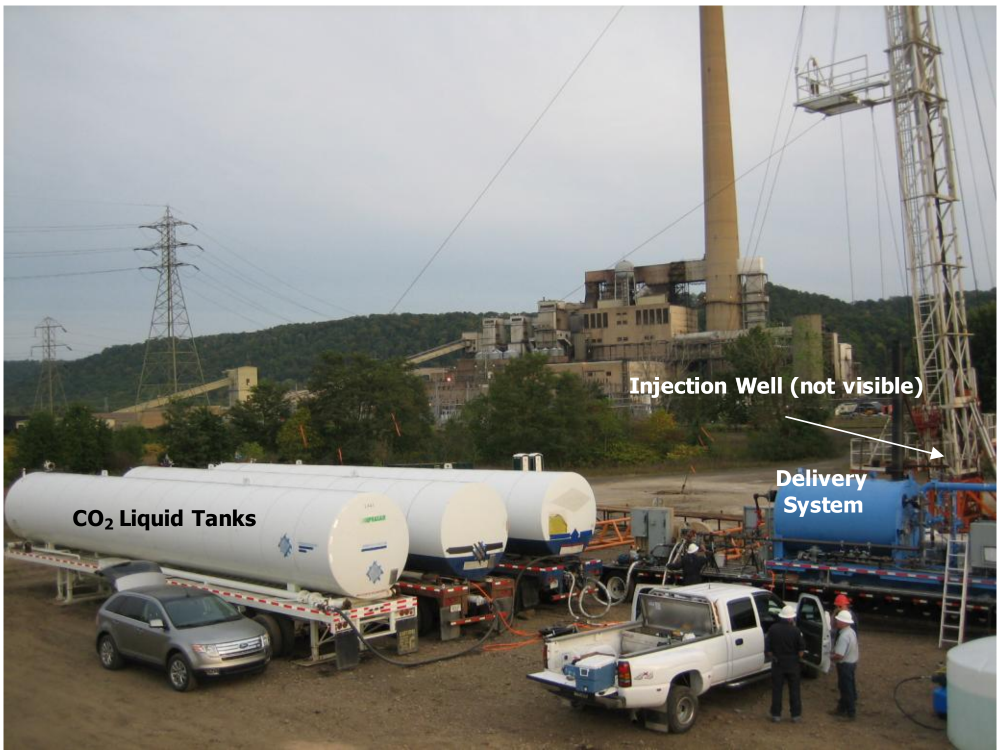


Figure 2-23. Setting Up for the CO_2 Injection Test at the R.E. Burger Plant

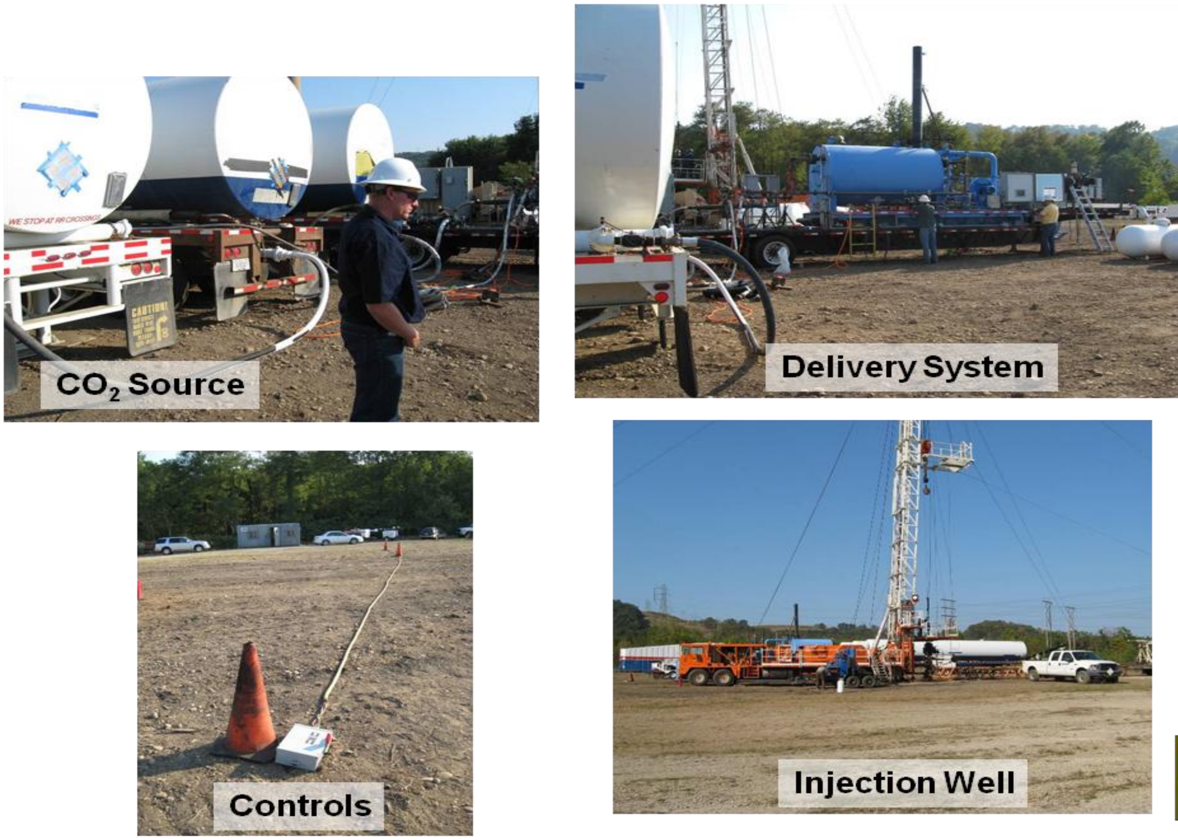


Figure 2-24. Photographs of Various Components of the Injection Test

A series of injection tests was completed in the Clinton, Salina, and Oriskany Formations in the fall of 2008. The testing started in the deepest formation (Clinton) and moved upward to the shallower formations.

- Testing of the Clinton Formation was conducted in three events. In addition to the attempts at CO_2 injection, the well was stimulated with acid on two separate occasions. During each attempt of injection, injection and formation pressures quickly increased even with relatively low injection rates of about 8 metric tons per day of CO_2 and water/acid (<2 bpm).
- Several acid treatments were completed in the Salina to remove any cement from the test zone. Overall, high injection pressures and low flow rates were observed in the Salina Formation (Figure 2-25). Hydraulic analysis predicted injection rates approaching 50 metric tons per day for the Salina at pressures less than 2000 psi; in actuality, injection rates of less than 20 metric tons per day were not sustainable at twice that pressure.
- Finally, the Oriskany was also treated with acid before injection and then CO_2 injection testing was completed. Initial injection rates were relatively low at approximately 0.25 bpm until the desired pressure limit was approached. The flow rates were then reduced to maintain pressures below the limit until they were less than 20 metric tons per day. Analysis of pressure response curves suggest that mainly borehole storage was encountered during the pressure falloff tests. It did not appear that radial flow was observed during the pressure falloff after injection.

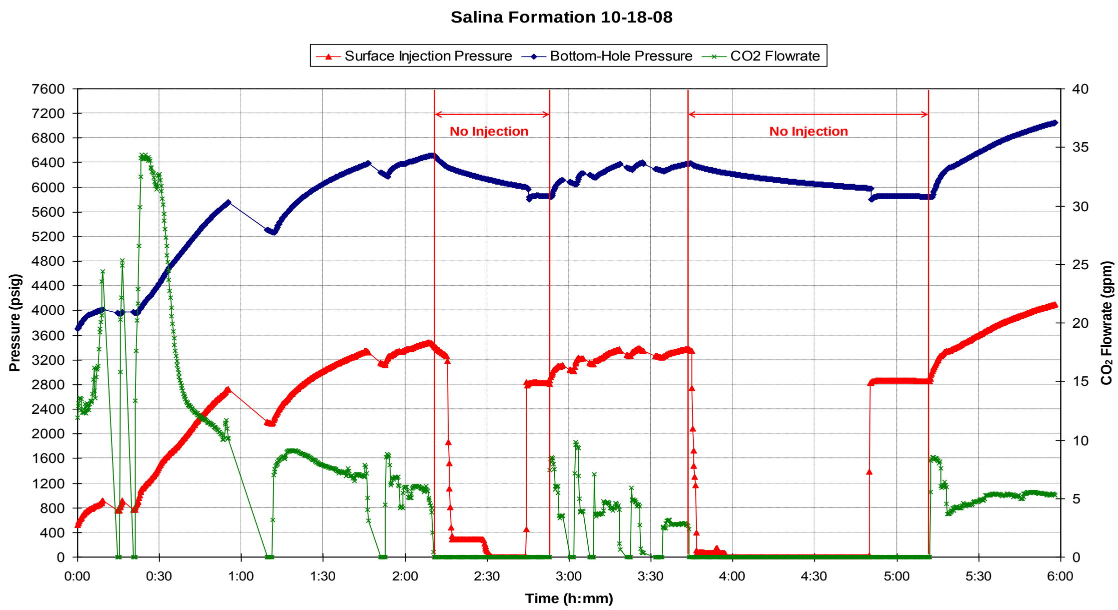


Figure 2-25. Injection Pressures and Flow Rates Measured during the Injection Test in the Salina Formation

A well stimulation/hydraulic fracture operation was not completed in the well per Ohio EPA UIC permit restrictions. The formations that were tested are commonly fractured for oil and gas production in the Appalachian Basin, although fracturing for injection purposes would be looked at differently by regulators than for production operations. It may have been possible to obtain better injection results after hydraulically fracturing the well. Given the relatively low injection volume of 3,000 metric tons initially planned for this test, well stimulation was not considered during the test design and would have added complexity, time and cost to the permitting process. However, the flexibility to complete a hydraulic fracture operation in the near well bore may be an important consideration for future CO_2 sequestration testing and permitting in the Appalachian Basin.

After the injection tests, the well was temporarily abandoned with bridge plugs above the injection intervals. Wellhead pressure readings were completed and monthly reports were submitted to the Ohio EPA UIC program. In the fall of 2009, an oil and gas company inquired about leasing the well for gas production from shallow formations. The possibility was considered, but using the well for gas production was found infeasible in April 2010 due to pipeline siting issues. As a result, the well was closed out according to the Ohio EPA approved plugging and abandonment plan.

Although injectivity at this site was less than expected, the test did help establish familiarity with CO_2 sequestration technologies in the region and provided an important deep well data point in a strategically valuable portion of the MRCSP region. The test also highlights the variability of geologic environments, especially in the geologically deep and complex Appalachian Basin. The Burger test described here, as well as the other two MRCSP Phase II tests, showed that characterization methods (rock core tests, wireline logging, and geologic logging) may only provide indicators of injectivity. True injection potential needs to be proven with field injection tests. This Burger site highlights the value of these smaller, research-oriented tests, which allow valuable experience to be gained in site characterization, permitting, infrastructure implementation, and injection testing with significantly less capital investment compared to full-scale application.

2.5 Key Findings

Small-scale validation projects play an important role in paving the way for commercial-scale projects. These tests allow valuable experience to be gained in site characterization, permitting, infrastructure implementation, and injection testing with significantly less capital investment compared to full-scale application. Although small-scale validation tests do not address the full scope of issues, considerations, and decisions processes involved in commercial-scale operations, validation tests help to address various technical, regulatory, and public acceptance issues. The key findings derived from these tests include:

- The tests helped establish familiarity with CO_2 sequestration technologies amongst many stakeholders and provided deep well data points in strategic locations within the MRCSP region.
- Safety is a well known key public acceptance issue. These tests provided additional confidence in the safety (over 61,000 metric tons of CO_2 was injected and nearly 20,000 ft of drilling was accomplished safely, with no time lost injuries during approximately 35,000 man hours). However, as discussed in the regional implementation planning section, developing clear communications about the safety and benefits of CCS will be critical towards increasing public acceptance.
- The tests highlighted the variability of geologic environments, especially in the geologically deep and complex Appalachian Basin. Initial characterization methods (e.g., rock core tests and wireline logging) may only provide indicators of injectivity. True injection potential needs to be proven with field injection tests.
- Monitoring techniques can be used to track the CO_2 migration behavior. While the current validation phase of work is complete, significant additional work is still possible to process, analyze, and model the wealth of operational and monitoring data from the MRCSP injection tests. Further analysis of cross-well seismic, microseismic, geochemical, and modeling results can provide more insights into the CO_2 plume migration and effectiveness of monitoring technologies for large-scale storage.
- Simple models provide the basis for designing injection tests. As more information is obtained, the models can be refined and calibrated to yield more accurate solutions. This experience highlights the potential for the monitoring phase of geologic storage projects to continuously improve the modeling framework used to simulate a geologic sequestration system.
- The outreach methodology and execution at all three geologic sites were effective in identifying public concerns and communicating with local stakeholders about the benefits and risks associated with sequestration technologies. Developing clear communications about the safety and benefits of developing CCS technologies will be critical towards increasing public acceptance.

Section 3.0: FIELD VALIDATION OF TERRESTRIAL SEQUESTRATION

Terrestrial sequestration involves carbon storage in soils, including degraded soils (soils that have declined in quality), and in forests and agricultural land. Terrestrial ecosystems in the MRCSP states offer a viable opportunity for carbon sequestration because of the extensive farmlands, wetlands, minelands, and forests in the region. There are over 22 million hectares (or 88,000 square miles) of land in the MRCSP region that could be utilized for enhanced carbon sequestration. Phase I studies on the region (which did not include New Jersey or New York) indicated that there is potential to sequester 144 million metric tons (159 million tons) of CO_2 per year in these areas. A breakdown of that resource by land type is shown in Table 3-1.

Table 3-1. Terrestrial Sequestration Potential (from Phase I Effort)

Category	Area (Mha)	Sequestration Potential (million metric tons CO_2/year)							
		IN	KY	MD	MI	OH	PA	WV	*Total*
Cropland	10.7	4.4	1.1	0	3.7	4	0.4	0	*14*
Eroded Cropland	1.6	6.6	0	0	0.7	4	0	0	*11*
Marginal Land (Forest)	6.5	19.5	16.9	3.7	16.2	17.7	17.7	7.7	*99*
Mineland	0.6	0	0.7	0.4	0.7	0.7	1.1	1.8	*6*
Wetland	3.4	2.9	0	1.8	8.8	0.7	0	0	*14*
Total	*22.8*	*33.5*	*18.8*	*5.9*	*30.2*	*27.2*	*19.1*	*9.6*	*144*

The assessment of terrestrial opportunities in New Jersey which was performed during Phase II included the following results:

- The dominant land use types in New Jersey that are of most relevance to terrestrial sequestration are: agricultural land (particularly non-eroded cropland), forest land, and wetland (especially forested wetlands and tidal marshes). These are 16%, 28%, and 20%, respectively, of the total land area of the state.
- A total of 288,823 hectares provide opportunities for enhancing sequestration capacities of these land uses potentially sequestering at least 5.5 million metric tons of CO_2 over a 20-year period. This would involve shifting non-eroded prime croplands to carbon conserving practices (106,463 hectares) or conversion to non-cultivated crops (114,614 hectares); converting or reconverting marginal farm lands to forests (89,638 hectares); and improving stocking of forest lands (92,722 hectares).
- Land uses with carbon storage capacities such as forested wetlands and tidal marshes need to be protected and maintained not only to continually sequester carbon but to keep emissions of methane (another potent GHG) under control. Forested wetlands potentially sequester 5.1 metric tons CO_2 per hectare per year while saline marshes capture approximately 1.5 metric tons CO_2 per hectare per year.

Phase I terrestrial studies indicated significant sequestration potential in marginal cropland areas, reclaimed mineland areas, and wetlands across the MRCSP region. The MRCSP Phase II effort focuses on conducting field tests at multiple locations to investigate CO_2 sequestration feasibility for the region. These field tests are part of a national effort sponsored by DOE/NETL to develop robust strategies for mitigating CO_2 emissions that contribute to GHGs. Terrestrial field tests were conducted to validate potential carbon sequestration through agriculture management practices, mineland reclamation, and wetland preservation, with the objective to continue to develop best approaches for terrestrial CO_2.

Terrestrial tests have been carried out in three land types identified in Phase I as important to achieving significant new sequestration in the region in the future:

- **Croplands-** these tests were conducted by The OSU on farmland in Indiana, Kentucky, Michigan, Ohio, and Pennsylvania.
- **Reclaimed Minelands-** these tests were conducted by WVU on reclaimed mineland plots in West Virginia.
- **Wetlands (Reclaimed Marshlands)-** these tests were conducted by the University of Maryland in the Blackwater Wildlife Refuge area of the Chesapeake Bay.
- **Wetlands (Forested Wetlands) -** these tests were conducted by Rutgers University through the New Jersey Department of Environmental Projection (NJDEP) in Cumberland and Cape May counties in Southern New Jersey where a significant acreage of forested wetlands are located.

3.1 Carbon Storage on Croplands

The validation tests were conducted by the Carbon Management and Sequestration Research Center at OSU at multiple sites across the MRCSP; for more detailed information, please refer to the Phase II Final Report on Carbon Storage on Croplands (Lal et al., 2011).

3.1.1 Introduction. This unique study involved the most extensive soil sampling to date covering an entire region for assessing land use and management effects on soil organic carbon and soil quality. Multiple test sites located within the MRCSP region were selected to evaluate the rates and magnitude of soil carbon sequestration in relation to principal management systems widely adopted by the farmers in the MRCSP region. Test sites consisted of paired conventional tillage (CT) and no-till fields, as well as an adjacent woodlot (Figure 3-1).

Figure 3-1. Conventional Tillage (left) and No-Till (right) Land Management Practices

The soil, land use and climate of the region are spatially variable. Soil samples were collected from regions with similar soil, climate, and physiography, known as Major Land Resource Areas (MLRAs). Soils were sampled in each MLRA in order to study the land use effect on different soil properties including soil carbon. Critical factors for site selection were soil type, slope, and past management practices (e.g., cropping and fertilization histories).

Soil samples were collected from five different depths (i.e., 0-5 cm, 5-10 cm, 10-30 cm, 30-50 cm, and >50 cm) in four replications 100 meters (m) apart. These samples were analyzed for total soil organic carbon (SOC) and total nitrogen (N) concentrations and various soil physical quality parameters, including soil moisture content, soil BD, aggregate size distribution and stability, plant available water, texture, shrinkage, soil compaction, and soil hydraulic properties. A complete range of field and laboratory studies have been conducted to assess the impact of soil carbon pool on soil quality and the attendant co-benefits (Figure 3-2).

Figure 3-2. Field Tests Comparing Yields and Hydraulic Conductivity of No-till versus Conventional Tillage Plots

3.1.2 Objectives. The objectives of this study included demonstrating carbon sink capacity for predominant land use systems, developing a credible measuring, monitoring, and modeling protocol to evaluate carbon sink capacity in biota and soil at different scales, and assessing the mechanism of carbon sequestration with regards to land use and soil management.

3.1.3 Materials and Methods. Multiple test sites located within the MRCSP region were selected for soil sample collection and analysis to evaluate the rates and magnitude of soil carbon sequestration in relation to principal management systems widely adopted by the farmers in the MRCSP region. Critical factors for site selection were soil type, slope, and past management practices (e.g., cropping and fertilization histories). Ideally, the same land use and soil management practice would be sampled at plots established within each MLRA under controlled experimental conditions (i.e., research plots). Because such research plots were not available within each MLRA, farmers' fields were sampled to obtain comprehensive data for different crop rotation, tillage operations, and soil management practices across the MRCSP region. In contrast to research plots, the plots on farmers' fields are therefore not exactly similar but comparable with respect to land use (e.g., crop rotation) and soil management (e.g., tillage management, fertilization). The information collected from test plots also were used to evaluate various scaling procedures to relate SOC changes for individual field plots to a regional scale via geographical information system (GIS).

Soil samples were also collected from woodlots/forest areas in MLRAs to compare the soil properties under less disturbed land use with those in no-till and CT plots. Woodlots, no-till, and CT plots/fields were often located adjacent to each other and had similar slopes and soil types. The woodlot plots served as a control in comparison to the effects of tillage treatments on soil properties.

The SOC concentrations and physical and other chemical soil properties (e.g., pH, cation exchange capacity, total nitrogen, bulk density (BD), porosity, hydraulic conductivity, and water infiltration) under no-till and CT systems were determined within each MLRA (Figure 3-3). The effect of no-till and CT was extrapolated to larger scales under different soil types. More than 20 MLRAs were sampled for comparing different land use systems.

Figure 3-3. The CN Analyzer for Analyzing Soil Organic Carbon and Total Nitrogen

Soil cores were also taken on no-till sites converted from CT to assess the changes in SOC levels occurring after the change in cropland management. Soil samples were collected from plots under no-till and CT practices that were generally less than 20 years old. The major crop rotations in no-till and CT were corn (*Zea mays* L.), soybean (*Glycine max* L.), and continuous corn. In addition, soil cores were collected to compare the soil properties resulting from different crop residue treatments under both tillage systems. SOC levels under conservation tillage where crop residues are either incorporated or left on the surface depends on the amount, quality, and depth to which the residue is incorporated. Thus, soil cores were also collected at mulch and non-mulch treatments for monitoring the benefits of mulch (residues) on SOC sequestration under different land uses.

Soil sampling at shallower depths may be insufficient to assess land use and soil management effects on the SOC pool. Thus, to evaluate impacts of different tillage systems and to improve estimates for the SOC pool, deeper profile sampling to about 1-m depth for various soil types, management scenarios, and cropping system was completed. The spatial distribution and number of samples required for obtaining valid comparisons among different treatments are very important. Field sampling generally requires three to six replications up to 50 or 60-cm depth in each treatment depending on the soil type. The soil sampling depths at the majority of locations were: 0-10, 10-20, 20-30, 30-40, 40-50, and greater than 50 cm. The most common sampling design used in the research areas was the complete randomized block design. This design has the least mean sum of squares due to higher degree of freedom of error as compared to other designs. However, variations in the soil parameters and landscape required occasional use of a randomized block design.

SOC predictions at the state and regional scale were performed using different spatial interpolation methods, including ordinary kriging, multiple linear regression, regression kriging, and geographically weighted regression (GWR). The soil data served as a basis for validating models. In addition, the SOC data were also extracted from the National Cooperative Soil Survey Characterization Database or from soil characterization database from different US universities.

3.1.4 Key Findings

- **Impacts of land-use and management on soil carbon.** The conversion of CT to no-till practices does not necessarily result in higher SOC concentrations and pools in soil profiles. Specifically, while SOC generally increased in surface soil horizons for no-tillage (NT) because of less disturbance resulting in lower residue and SOC decomposition, the SOC dynamics in deeper horizons after conversion of CT to NT were variable and depended on soil type and landscape position. Thus, soil samples need to be taken up to 0.5 to 1.0 m depth or ideally the entire rooted soil profile to assess the effects of tillage treatments on profile SOC. However, well-drained soils on sloping landscape positions generally had higher profile SOC after conversion of CT to NT. Most importantly, the effects of tillage on SOC and soil quality cannot be generalized for the entire MRCSP region as effects are soil type specific.
- **Crop residue management influences on soil properties.** Residue retention as surface mulch is essential for soil carbon sequestration and soil quality improvement in a NT system. Results of the validation test indicated that retention of wheat straw in NT practices increased aggregate tensile strength, and SOC, and retained higher moisture levels. The annual rate of carbon sequestration was 1.2 metric tons per hectare per year, with the mean of wheat straw converted into SOC being approximately 33%. These data strongly suggest that long-term straw mulching increased SOC concentration, improved near-surface aggregation, and improved crop yields.
- **Crop residue removal for bioenergy.** The MRSCP conducted a study on the effects of corn (*Zea mays* L.) stover removal for bioenergy on soil properties. To minimize detrimental effects on soil quality at the studied sites, the removal rates must be lower than 1.25 metric ton carbon per hectare per year. However, this removal rate is not applicable to the entire MRSCP region as site-specific adjustments are required.
- **Impact of rotational tillage on surface hydrology, soil erodibility and SOC concentration.** Further, combining CT with NT during rotational tillage practices adversely affects the SOC pool and soil physical properties. Thus, NT has to be maintained to sustain any benefits for SOC and soil quality.
- **Effects of grazing in rotation with cropland on soil dynamics.** Field testing was also performed to assess the effects of cattle grazing during the growing season and, in addition, the dormant season on SOC and soil physical properties. It was shown that although dormant season grazing reduced soil quality, a mix of seasonal paddocks reduces the pressures by over-grazing on individual sites.

- **Soil erosion and soil quality in relation to carbon pool.** The results obtained by carbon management and sequestration center (CMASC) as part of this MRCSP-funded project about soil erosion indicated that the loss of highly productive topsoil by erosion causes a strong decrease in SOC and soil physical quality. Thus, land use and management practices causing accelerated soil erosion must be reduced to maintain SOC and agricultural productivity.
- **Carbon sequestration and soil quality improvement potential of restored tallgrass prairie in Ohio.** The restoration of degraded soil by planting to tallgrass prairie and effects on SOC and soil physical properties was also studied by CMASC as part of this MRCSP-funded project. The positive effect of tallgrass on SOC and soil quality enhances its potential as a bioenergy crop for cultivation on degraded soils.
- **Modeling the impacts of carbon sequestration in terrestrial systems and implications for carbon trading.** GIS was used to assess and model the SOC sequestration potential in the MRCSP region. An optimum combination of baseline soil carbon, land use, and management practices can maximize soil carbon sequestration potential. For state level estimation of carbon pool and identifying potential regions for carbon sequestration, less detailed soil maps may be used without compromising data accuracy. Detailed soil maps are useful for sub-county level mapping of SOC. Further, the prediction of SOC and its spatial variability is possible using geostatistical approaches, and the geostatistical methods can be adopted at different scales. Specifically, the (GWR approach can play a vital role in improving the prediction ability of SOC pools across regional scales.

Taken together, the findings from the research showed that the quantity and rate of carbon loss and carbon sequestration depends on soil type, texture and drainage, tillage intensity, and duration of NT management. A rapid decrease in SOC and nutrients occurs when forest soils are cultivated. The NT management practices potentially restore SOC which was otherwise depleted due to the tillage practices. The NT practices improve the SOC and hence the soil hydraulic properties such as water retention, hydraulic conductivity and pore size distribution compared to mold board plow and chisel plow. The crop residue left on top of the soil in NT practices improves the soil hydraulic properties. The GIS studies conducted under the MRCSP project showed that SOC can be estimated at a larger (state and regional) scale. While, the soil sampling at the state and regional scale is expensive and time consuming, the GIS findings showed that surface interpolation methods (e.g., ordinary kriging, multiple linear regression, GWR and regression kriging) can be used to estimate the SOC pool at a larger scale. The SOC pool to 50 cm soil depth for the MRCSP region was calculated to be 6.21 billion metric tons. A higher SOC pool in the region was attributed to the high rainfall, low temperature and the presence of Histosols and Mollisols in this region.

3.1.5 Best Practices. The Validation Phase studies on terrestrial carbon sequestration in cropland have resulted in the following recommended best practices:

- Residue retention as surface mulch is essential for soil carbon sequestration and soil quality improvement in a no-till system.
- The no-till practices are very effective in enhancing SOC, but this effect depends on soil depth and duration of management practice.
- Rates of soil carbon sequestration (0.25 to 1 metric ton carbon per hectare per year) depend on soil properties, crop rotations, residue management, soil fertility management, and the time since conversion from plow tillage to no-till. Residual removal adversely impacts soil quality (Figure 3-4).

- Residence time of carbon sequestered in soil depends on soil properties (more for clayey than sandy soils), depth (longer for sub-soil than surface soil), land use (longer for perennials than annuals), and management. The soil carbon pool is maintained or enhanced as long as no-till systems and other best management practices are used.
- The soil carbon pool stored in deeper layers (greater than 30 cm) is the most important fraction for long-term SOC sequestration as it is stabilized in association with the soil mineral phase resulting in long carbon mean residence time. This must be taken into account when conducting research trials in the MRCSP region.

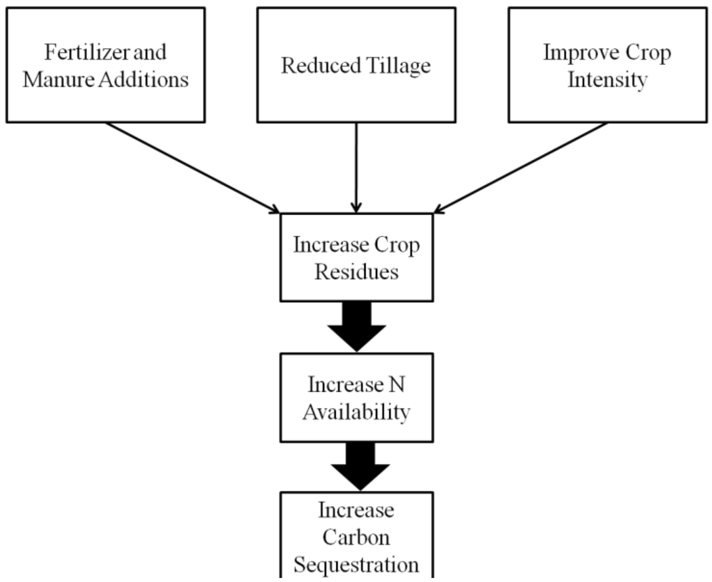


Figure 3-4. Optimum Management Practices that Enhance N Availability and Carbon Sequestration (Christopher and Lal, 2007)

3.1.6 Regional Implementation. The MRCSP Phase II findings reported here show that there is an estimated 10.7 million hectares of prime non-eroded cropland present in the MRCSP region. It is estimated that 22.5% of that land area is already practicing no-till and will likely remain in that mode. The remaining 77.5% or 8.3 million hectares is potentially amenable to adopting no-till or reduced tillage practices, which, if adopted on these lands, would result in an estimated 55 to 74 additional billion metric tons of carbon sequestered over a 20-year period for the MRCSP region. Conversion of cropland to NT and reduced tillage practices also yields benefits of placing land use in a more sustainable agricultural practice, and reduces emission through diesel consumption used for plowing and other farm operations.

Implications for carbon credit trading based on the MRSCP terrestrial field validation test in croplands study are that complete life-cycle analyses (LCA) of production systems (i.e., no-till, plow tillage, manuring) must be conducted to assess management-induced changes in the ecosystem carbon pool. The data on changes in the ecosystem carbon pool are essential to developing an effective mechanism for monitoring and verifying SOC on regional scales, which could be utilized by possible offset programs in the future. In particular, up-scaling of the SOC pool can be performed by using GIS and terrain characteristics. This modeling approach is extremely useful in assessing carbon credits for trading purposes.

3.1.7 Assessment of Storage Opportunities and Benefits. The potential benefit of adopting no-till or reduced tillage practices over a 20-year period could result in an estimated 200 to 270 million metric tons of additional CO_2 sequestered. The stored carbon may be sold as CO_2 offset credits, which would provide additional profits to landowners in the region. Converting cropland to no-till and reducing tillage practices also yields benefits of placing land use into a more sustainable agricultural practice, while reducing emissions from fossil fuel consumption used for plowing and other farm operations.

3.2 Carbon Storage on Mineland Reclamation Sites

The validation tests were conducted by WVU on reclaimed mineland plots in West Virginia; refer to the Phase II Final Report on Carbon Storage on Mineland Reclamation Sites (Sperow et al., 2011) for more detailed information.

Surface mining operations alter existing landscape patterns (Figure 3-5). The change from naturally-formed landscapes to highly graded, reconstructed landscapes adversely affects soil quality. The original upper-soil horizons are destroyed by pre-mining removal and mixing and post-mining replacement, leading to soil erosion, enhanced SOC mineralization and nutrient leaching. However, with proper reclamation and sufficient time, these degraded soils have the potential to return to functioning soils, primarily by increasing the SOC content. Thus, reclaimed mine sites planted to trees, grasses, or legumes provide opportunities for removing CO_2 from the atmosphere through carbon accumulation in soils and aboveground biomass (Figure 3-6).

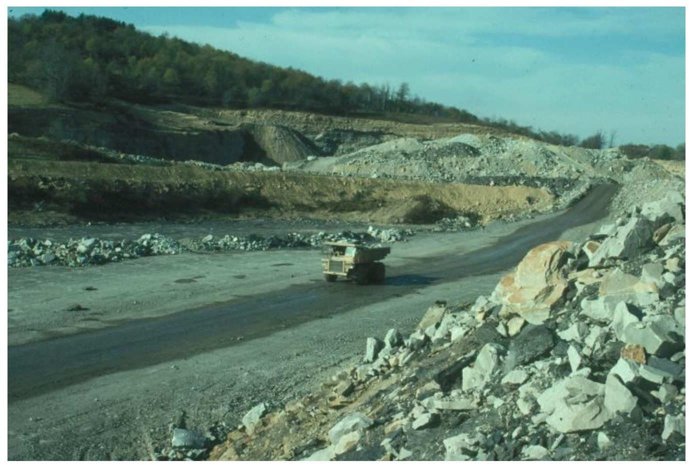


Figure 3-5. Active Mine (Mylan Park, West Virginia)

Figure 3-6. Reclaimed Mineland (Mylan Park, West Virginia)

3.2.1 Objective. The overall objective of this project was to estimate the amount of soil carbon that may be stored in mine sites reclaimed to grass and/or legumes. Soil samples from multiple mine sites where mining activities ended at different times were collected to assess the change in soil carbon over time (Table 3-2). Mine sites were selected that had known pre-mining land use, coal seam, overburden geology and mining and reclamation practices, and where the mine operator or landowner was known and permitted access to the sites. These characteristics of site selection account for the predominant characteristics that influence changes in SOC accumulation that occur under different conditions. This information, combined with soil samples collected from the same site over time, enhanced estimates of the amount of CO_2 emissions that may be offset through mineland reclamation to grass/legumes.

Table 3-2. Site Characteristics of the Reclamation Sites Identified in 2006

Site Name	Mylan Park	WVSK	Dent's Run[1]	New Hill	WV01
Mining Begins	1982	1996	1999	2003	2004
Mining Ends	1985	1998[2]	2000	2005	2006
Mine Soil Age in 2006	21	8[2]	6	1	0[3]
Latitude	80 2 0.168	83 3 43.263		80 1 29.338	80 3 16.287
Longitude	39 38 32.628	39 37 31.821		39 38 52.859	39 40 30.141
Slope (Degree)	~10-20	~0-10		0-5; 10-15	0
Aspect	N	N		N	0
Area (hectares)	0.6	0.8		1.0	0.6
Pre Mine Land use	-------------------- Mixed Pasture and Forest --------------------				
Coal Seam	---------------------------- Waynesburg ----------------------------				
Method of Mining	---------------- Contour Mining, Front end loaders ---------------				
Overburden Type	------------------ 70-80% Sandstone, rest is shale -----------------				
Reclamation Method	--------- Backfilled, 7.6 cm" topsoil, grass and legumes ---------				

(1) After soil sampling in 2006, the property owner stopped allowing access to the site.
(2) After soil sampling in 2006, it was discovered that this site had been re-contoured in 2003 and thus was actually only three years old.
(3) Could not be sampled in 2006.

A secondary objective of the project was to assess the tradeoffs between existing land management activities and those that enhance carbon sequestration. The economic analysis entailed estimating the difference in soil carbon accumulation rates in soils on sites reclaimed to grass/legumes compared to reclaimed forest sites. Reclaiming mined land to forest increases the amount of stored carbon because not only SOC sequestration, but also above- and belowground biomass carbon accumulation are considered in the assessment of the total amount of stored carbon. Reclamation costs depend upon the specific costs to re-contour, vegetate, fertilize, etc., which varies by region and planting density. Data for the costs of reclamation activities to grass/pasture and to forest were collected or estimated and used to derive the market value of the stored carbon.

3.2.2 Methods/Recommended Best Practices to Quantify Carbon Sequestration. To quantify this increased SOC content, the spatial and temporal variability in SOC must be accounted for. Soil sample collection required an initial assessment of the number of samples required to generate statistically significant results. Therefore, the first year of sampling was more intensive than later years to establish the minimum number of soil samples required to capture the heterogeneity of mine site characteristics. For initial site assessment, the nested transect approach offers maximum information while minimizing sample collection and analysis (Figures 3-7 and 3-8). An optimized grid sampling strategy can then be

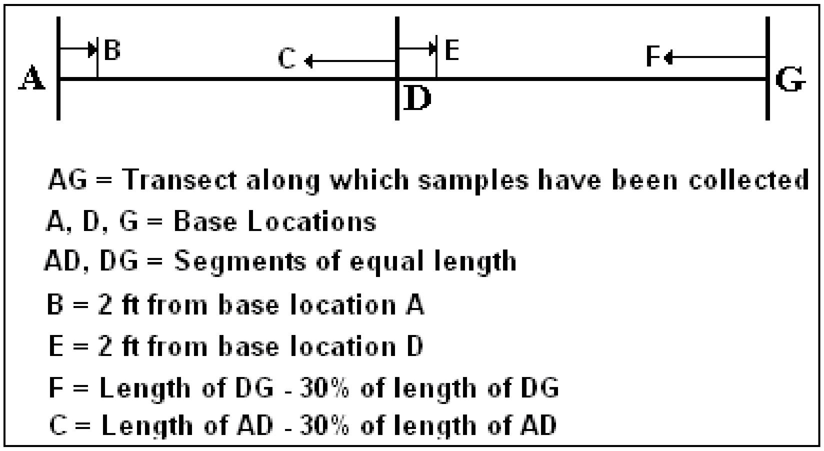


Figure 3-7. Schematic Representation of the Nested Transect Sampling Strategy Adapted in 2006 at All Five Reclaimed Mine Sites

Figure 3-8. White Circles show Sampling Locations at a Reclaimed Mine Site

used in subsequent years. Because the spatial variability in SOC changes with time, it may be necessary to repeat the nested transect analysis periodically. The use of a hand-held global positioning system should be used to identify sampling points so that the same locations can be sampled each year. This is especially important when coal and/or wood ash is expected to occur in the sampled horizons.

The heterogeneity of reclaimed mine soils increases the number of soil samples required for verification. To attain a minimum of 10% deviation in the carbon sequestration rate would require approximately 20 to 60 soil samples from the mine sites addressed in this analysis. Mine soils are not easy to collect soil samples from due to the presence of rock fragments and depth is limited due to the shallow top-soil replacement requirement. Soil sampling this extensively increases the cost of soil carbon sequestration on reclaimed mine sites because the cost of soil sample analysis may range from $16 to $25 per soil sample.

Alternative non-intrusive methods for measuring soil carbon content that do not require physically removing soil samples are under development by various corporations and government agencies, but these are not on the market yet. These new techniques promise to lower the cost of verifying carbon accumulation in soils.

3.2.3 Best Practices to Enhance Sequestration. Mine operators are required to reclaim surface mining sites by restoring the original contours of the landscape and planting a vegetative cover according to requirements established by the Surface Mining Control and Reclamation Act (SMCRA) of 1977 (SMRCA; Public Law 95-87). Carbon accumulation rates on reclaimed minelands are predominantly dependent upon the vegetative cover, planted for the reclamation activity, and the climatic region. Three potential carbon sequestration pools (soil, litter layer, and aboveground biomass) were analyzed to provide a thorough assessment of the potential for reclaimed mine sites to mitigate GHG emissions. To qualify for carbon credits, any terrestrial carbon sequestration project must sequester more carbon than what would occur in the absence of carbon-uptake incentives. The SMCRA requires mined lands to be reclaimed, so even without a carbon market the vegetation grown on mined lands would sequester some carbon. Therefore, if a land owner chooses a post-mining land use that sequesters more carbon than the pasture/hayland baseline levels, which is the predominant reclamation activity, the difference then should qualify for carbon credits.

The results of the soil sample analyses verify that the SOC accumulation on reclaimed mine soils are dependent upon adequate top-soil replacement prior to planting the vegetative cover. Mine sites with thin top soils tend to have higher rock content, and accumulate SOC at a rate slower than mine sites with deeper topsoil. In the mine soils sampled in this study, rock fragment content was low and did not influence the results. This will likely not be true in other mine soils that have not been top-soiled, including those in the southern West Virginia coalfields. Mine soils with significant quantities of rock fragments are expected to be significantly more spatially variable. Thus, sampling and analytical costs will be higher.

Reclaiming mined land to forest increases the amount of stored carbon because not only SOC sequestration, but also above- and belowground biomass carbon accumulation are considered in the assessment of the total amount of stored carbon. Existing methods for estimating carbon accumulation in forest are based on simple estimates of above and below ground biomass. Forest establishment and growth on reclaimed mineland may be enhanced by leaving the soil less compacted following re-contouring and leveling activities required to satisfy government policies that control mine reclamation. The 1.7 to 5.5 million metric tons CO_2 per year accumulation on mine land reclaimed to forest in the MRCSP region may be achieved by implementing reclamation activities that reduce soil compaction during re-contouring and leveling processes (Figure 3-9).

Compacted soils　　　　　　　　　　　　Non-compacted soils

Figure 3-9. Photographs Demonstrating Compacted and Non-compacted Soils on a Reclaimed Mine Site
(Site is Catenary Mine, WV; Photos courtesy of Paul Crosby Emerson, WVU [2008].)

Research has demonstrated that reclaimed mine lands can be as productive as native sites under the proper conditions. The Forest Reclamation Approach (FRA) outlined by the Appalachian Regional Reforestation Initiative (ARRI) provides a good model for estimating how the decrease in soil compaction enhances forest establishment and productivity. The FRA recommends loosely graded soil and rocks and debris left on the site. Therefore, the final grading step for forest requires less bulldozer work than the heavy compacting of the soil required for pasture. According to ARRI, the FRA reclamation technique complies with SMCRA and would require 4 hours per acre less than reclaiming to pasture, and could potentially save \$500 ha^{-1} in re-contouring costs. The ARRI approach has been demonstrated to enhance carbon accumulation over normal re-contouring and leveling activities used for pasture as the reclamation activity.

3.2.4 Summary of Key Findings

- The predominant mined land reclamation activity is currently to plant grass/pasture. This activity is perceived as the most efficient way for controlling soil erosion, one of the primary concerns of reclamation activities, and the quickest way to achieve bond release.
- The results of the SOC analyses indicate that carbon does accumulate in mined land reclaimed to pasture/grass, but the variability of SOC accumulation across sites is significant. The results of the soil sample analyses verify that the SOC accumulation on reclaimed mine soils are dependent upon adequate top-soil replacement prior to planting the vegetative cover. Mine sites with thin top soils tend to have higher rock content, and accumulate SOC at a rate slower than mine sites with deeper topsoil. (In the mine soils sampled in this study, rock fragment content was low and did not influence the results.)
- One key finding of the analysis is that the number of soil samples required to adequately characterize SOC accumulation in the heterogenic soils found on reclaimed mine land is high. This heterogeneity of soil characteristics increases the cost of soil sampling, and would make verification under a carbon trading scheme more costly.

- Depending upon the market mechanisms, the SOC accumulating under pasture systems may or may not count towards CO_2 emission reduction requirements. If the business-as-usual carbon accumulation is considered a CO_2 offset, as the current Chicago Climate Exchange (CCX) market does, then planting pasture could offer additional income streams to the mine operator/landowner.
- Reclaimed mineland planted to forest could store 2.6 to 5.5 million metric tons CO_2 per year over the CO_2 accumulation in pasture soils when the carbon accumulation in aboveground biomass, litter layer, and soils are included. This represents the marketable CO_2 that could occur under the European Union Emission Trading Scheme (EU-ETS) CO_2 market system. The CCX carbon trading scheme would count the 5.4 to 9.9 million metric tons CO_2 per year that accumulates in forest, increasing the offset potential of forest on reclaimed mine sites.
- The costs to landowners to achieve these carbon sequestration rates depends upon the specific costs to re-contour, vegetate, fertilize, etc., which varies by region and planting density. This analysis demonstrated that the reclamation costs in some regions for forest are lower than for pasture, so landowners should already be planting forest. The marginal cost of storing 1.7 to 3.2 million metric tons CO_2 per year, from reclaimed mineland with a poor site index assuming average and maximum potential CO_2 storage, respectively, is less than the July 2008 CCX market price of $7.35 per metric ton CO_2. When the EU-ETS carbon trading scheme is considered and FRA reclamation activities are practiced, potential storage is 0.7 to 1.9 million metric tons CO_2 per year assuming average and maximum storage potential, which could be achieved with prices up to $25 per metric ton CO_2. Relative to the July 2008 EU-ETS carbon price, nearly 3.7 million metric tons CO_2 per year could be stored assuming maximum storage rates and market prices at least $50 per metric ton CO_2.
- The potential carbon sequestration on mined land reclaimed to forestry in the MRCSP region represents a small portion of the total CO_2 emission reduction that may be required for the region. While the CO_2 emission offset offered by reclaimed mineland is small, it may represent one of the lower cost options for offsetting emissions.
- In addition to the environmental benefit of offsetting CO_2 emissions, reclaiming mined land to forests enhances wildlife habitat, provides recreational opportunities, controls soil erosion, and could provide timber revenue in the future.

3.2.5 Regional Implementation. The predominant mined land reclamation activity is currently to plant grass/pasture. This activity is perceived as the most efficient way for controlling soil erosion, one of the primary concerns of reclamation activities, and the quickest way to achieve bond release. Depending upon the market mechanisms, the SOC accumulating under pasture systems may or may not count towards CO_2 emission reduction requirements. If the business-as-usual carbon accumulation is considered a CO_2 offset, as the current CCX market does, then planting pasture could offer additional income streams to the mine operator/landowner.

Since carbon accumulation, and therefore ability to offset CO_2 emissions, is higher in forest systems than in pasture systems, an incentive is required to encourage mine operators/landowners to adopt the reclamation activity that sequesters more carbon.

Enhancing carbon sequestration on reclaimed mine land provides societal benefits that are not included in this analysis. As soil carbon accumulates, water holding capacity, nutrient availability, and microbial activity is enhanced, providing improved biomass production and soil health. Mine land reclaimed to forest enhances wildlife benefits, decreases soil erosion, and provides societal benefits not directly captured by the value of the carbon credits that may be created. These non-market benefits of carbon sequestration on reclaimed mine land increase the value of stored carbon. Communities near reclaimed mine sites benefit from the changes in biomass production, wildlife habitat, and erosion control. Outreach activities need to highlight the win-win outcome for mine operator/landowner and neighboring communities when activities to enhance carbon sequestration on reclaimed mine land are implemented.

3.2.6 Assessment of the Potential for Deployment. Carbon accumulation in terrestrial systems and reclaimed mine sites in particular is dependent upon the climate, vegetative cover used for reclamation, top-soil replacement, and management activities. In addition, when forestry is the reclamation activity, carbon accumulation depends upon the degree of soil compaction caused by re-contouring and the tree species used for vegetative cover. Since there are 1.8 million hectares of permitted mine land in the U.S., there is opportunity for substantial carbon sequestration to offset CO_2 emissions. The potential for enhanced carbon storage on reclaimed mine sites is site specific. Some reclaimed mine sites in other regions have the potential to store more SOC or have higher biomass production from forests, and some less.

The average rate of SOC accumulation in the MRCSP study sites in the 0 to 12 cm depth is 1.8 metric ton carbon per hectare per year (6.6 metric ton CO_2 per hectare per year) with a range of 0.0 to 3 metric ton carbon per hectare per year (0 to 11.1 metric ton CO_2 per hectare per year). Assuming average rates of SOC accumulation attained in the study sites of this study are achieved in all reclaimed mine sites in the U.S. provides potential SOC storage of 3.2 billion metric ton carbon per year (11.8 billion metric ton CO_2 per year). If the highest SOC sequestration rate is applied, reclaimed mine land may store up to 5.4 billion metric ton carbon per year (19.9 billion metric ton CO_2 per year).

Forest growth on reclaimed mine sites will vary by tree species that are appropriate for different climatic regions, soil types, and re-contouring and leveling activities. The potential for carbon accumulation from forest on reclaimed mine sites may be estimated from the data used for this analysis, however, as with SOC accumulation, results in different parts of the U.S. may be higher or lower than these rates. Carbon accumulation on all reclaimed mine land in the U.S., based on average carbon sequestration rates from forest biomass including the litter layer, belowground biomass, and soil, is 4.6 billion metric ton carbon per year (16.9 billion metric ton CO_2 per year). The potential for accumulating carbon in forest on reclaimed mine land ranges from 2.5 to 9.7 billion metric ton carbon per year (9.2 to 35.6 billion metric ton CO_2 per year) if all reclaimed mine land in the U.S. used forestry as a post-mining reclamation activity.

3.3 Carbon Storage in Restored Tidal Marshes at Blackwater National Wildlife Refuge

The work reported here is being carried out by Professor Brian Needelman, Martin C. Rabenhorst, and Raymond R. Weil at the University of Maryland under a grant from the Maryland Department of Natural Resources, Power Plant Research Program. Because of the relevance of this work to terrestrial sequestration in the MRCSP region, MRCSP provided a modest amount of funding for coordination and integration with other MRCSP activities. The interim results of this ongoing study are presented in this section.

3.3.1 Introduction. Concerns over the mitigation of global warming and the impacts of rising sea levels caused by global warming have focused attention on tidal wetlands. The restoration and management of tidal wetlands may allow such areas to sequester carbon, helping to mitigate global warming, while the accumulation of organic materials will keep tidal marshes from being inundated by rising sea levels.

The rate of organic matter and sediment accumulation must be studied over numerous years to determine if the rates will match or exceed sea level rise, subsidence, and glacial rebound. The rate of carbon sequestration, effectively the net amount of carbon dioxide deposited in the marshes, must also be studied over a number of years to accurately determine the rate.

Two separate tidal marshland sites at the Blackwater National Wildlife Refuge in Maryland are being studied to allow comparison between natural and restored tidal marshes (Figures 3-10 and 3-11). The natural site, Barbados Island, is located on the historic main river channel. The restored site, Wildlife Drive Island, was restored in 2003 using locally dredged material and is easily visible to the public from Wildlife Drive. Studying these two sites offers insight into how the two areas differ in the rates of carbon sequestration and organic matter accumulation and to evaluate the full benefits of future tidal marsh restorations using dredged materials. A total of 85 soil sampling locations have been established, as well as locations to monitor groundwater levels, salinity, subsurface temperature, and methane emissions.

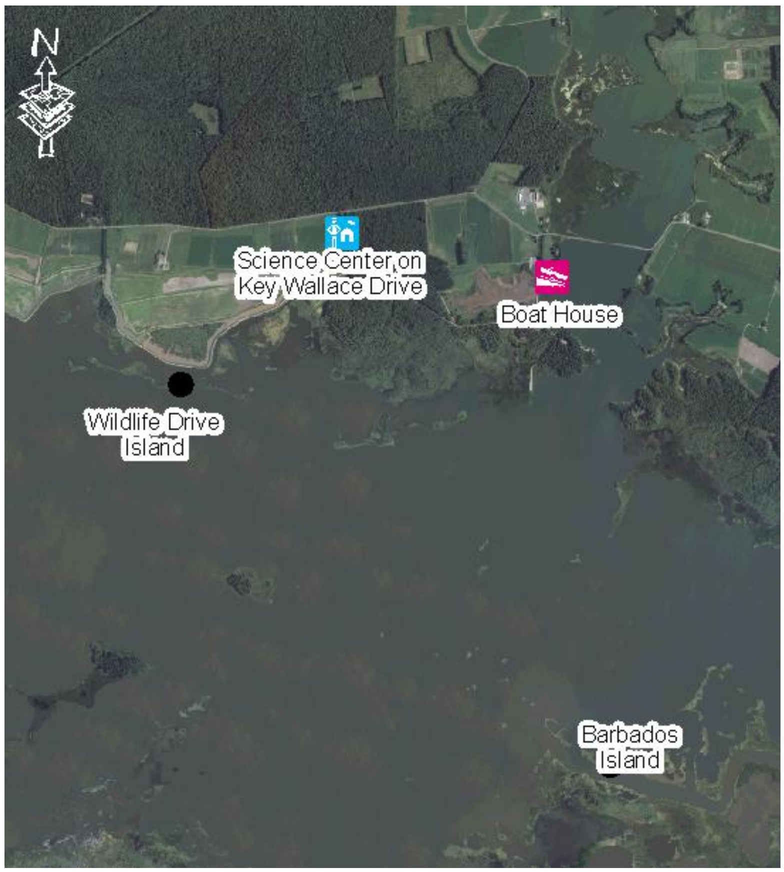


Figure 3-10. Location of Barbados and Wildlife Drive Study Areas, Blackwater Wildlife Refuge

Figure 3-11. Blackwater National Wildlife Refuge (Eastern Maryland)

3.3.2 Project Background and Objective. In Phase I, 3,388 kilohectares of wetlands were estimated in the MRCSP region with a total soil carbon pool in the upper 30 cm of 656 million metric tons (Battelle, 2005). 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. High net primary productivity and low decomposition rates in wetlands can lead to high carbon concentrations. Carbon sequestration rates are particularly high in tidal marshes that are accreting due to sea-level rise and in wetlands remediated following drainage for agricultural use. Carbon sequestration in wetland environments may be partially offset through methane and other GHG emissions.

Tidal marshes are important for the ecosystem of the Chesapeake Bay, serving as critical habitats for wildlife and as a buffer to large storm events. Sediment deposition directly builds marsh soils to assist in accretion rates. However, as sea level rises, some tidal marshes are susceptible to submersion. The balance of sea-level rise and sediment deposition rates affect the long-term viability of tidal marshes and their ability to store carbon (Slocum et al., 2005). The U.S. Fish and Wildlife Service and the U.S. Army Corps of Engineers are investigating the use of clean dredged sediments from the shipping channels in the Chesapeake Bay to restore and rebuild tidal marshes within the Blackwater National Wildlife Refuge (Benson et al., 2007). The success of these plans depends upon the ability of the restored marshes to maintain accretion rates that outpace sea-level rise.

The objective of this project is to demonstrate the terrestrial carbon sink capacity of a restored tidal marsh at the Blackwater National Wildlife Refuge by evaluating the vertical and lateral distribution of carbon in a marsh restored in 2003 (i.e., Wildlife Drive Island) and a natural reference marsh (i.e., Barbados Island). The data are being used to assess the potential for carbon sequestration accounting in restored marsh systems without time zero sampling, with an emphasis on variability and carbon density to soil density relationships.

3.3.3 Materials and Methods

3.3.3.1 Field Study Design. The study was conducted at the Blackwater National Wildlife Refuge, a part of the Chesapeake Marshlands National Wildlife Refuge Complex in Maryland. The refuge is located near the Chesapeake Bay in Dorchester Country, Maryland, at 38^o latitude, 76^o longitude. Data were collected from two 5-acre marsh cells: Barbados – a reference wetland site in the Barbados section, and Wildlife Drive – a marsh restored in 2003, along Wildlife Drive (Figure 3-10). The Wildlife Drive marsh was restored with locally derived coarse-textured mineral and organic sediments.

Each marsh cell has three surface elevation tables (SETs). These mechanical leveling devices are used to determine relative elevation above or below a benchmark in wetland sediments (Cahoon et al., 2002). At each SET, three transects were created beginning 3 to 4 m from the SET and running to the edge of the marsh (Figure 3-12). Along each transect, four to six marker plots (60 by 40 cm) were laid out depending on the length of the transect and the variability of the terrain and vegetation (44 plots in the restored marsh and 41 in the reference marsh). Finely ground feldspar was applied at each plot to a depth of approximately 5 cm in May-June 2006. The feldspar forms a bright white layer on the soil surface that is being tracked over time as the marsh accretes. The design allows for future sample collection within the feldspar marker plots. In addition, each cell has a datalogged well and a datalogged temperature probe to monitor groundwater levels, salinity and subsurface temperatures; values are measured hourly to a depth of 1 m.

At each plot, a soil core was collected annually using a McCauley peat auger to a depth of 50 cm. This auger removes an intact core and minimizes compaction and vertical distortions. Samples are divided by horizon (if apparent), by the presence of the feldspar marker horizon, or by 25-cm increments (if horizons were not apparent) and bagged in the field. Color and horizon designation are recorded according to standard soil description procedures (Schoenberger et al., 2002). Samples were collected in 2006, 2007, and 2008. These samples were processed and analyzed to determine the total amount of carbon contained in the soils. These values were then compared to the data from soil samples taken in the same locations in 2006.

In a separate project, monthly measurements of methane emissions were collected at the two marsh islands. Data were collected from May through October 2008 from three locations per island.

3.3.3.2 Laboratory Analyses. BD and total carbon content were calculated on each horizon. Each sample was weighed moist and homogenized. Then 5 gram subsamples were oven dried at 105^{o}C for calculation of water content. BD was then calculated as the estimated dry sample mass divided by core volume. Organic carbon and total nitrogen were measured using high temperature combustion with a Leco CHN2000 (Leco Corp., St. Joseph, MI).

3.3.4 Results

3.3.4.1 Soils. Soils at the reference marsh are characterized by fibric and hemic horizons. These soils are Typic Sulfihemists according to Soil Taxonomy (Soil Survey Staff, 2006). They have 100 cm of mostly hemic (moderately decomposed) organic-sulfidic materials within 100 cm of the soil surface. The reference marsh is at a river levy with varying amounts of mineral material at depth. The restored marsh soils have multiple classifications. There are remnants that have not received additional mineral deposition and would be classified as Typic Sulfihemists. The majority of the cell has more than 10 cm of mineral deposition and thus classified as Aquic Udorthents.

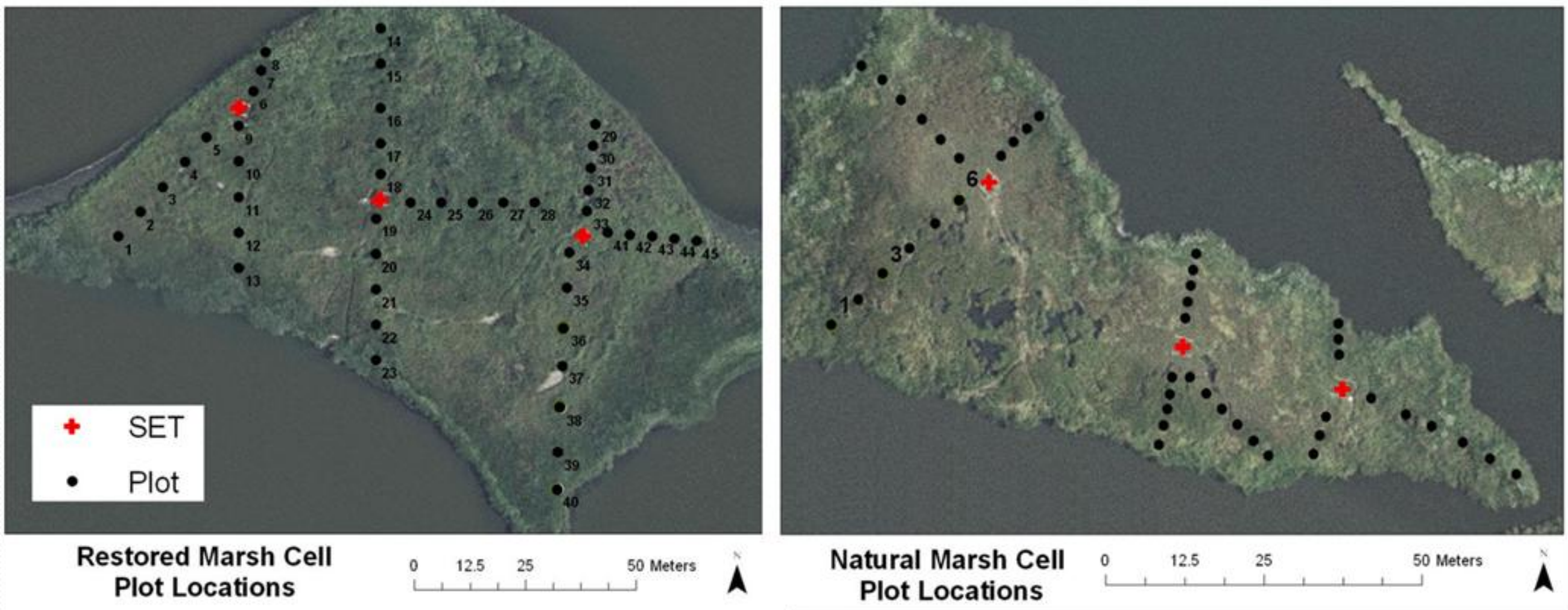


Figure 3-12. Surface Elevation Table and Plot Locations for the Restored and Natural (Reference) Marshes at Blackwater National Wildlife Refuge

3.3.4.2 Surface Carbon Sequestration. The analytical results for BD and total carbon content by horizon type are presented in Wills et al. (2008). Reconstructing the pre-restoration marsh surface has been difficult because of the extreme variability in both the old marsh surface and the new dredge and organic material distributions. Using the information available, it was assumed that organic material above dredge material represents new accretion. Based on the differences in surficial carbon sampled between 2006 and 2008, the rates of surficial carbon sequestration were estimated at the restored site of 3.4 metric ton carbon per hectare per year with a range of 0.8 to 5.9 metric ton carbon per hectare per year from individual plots. At the natural site, the estimated rate was 4.4 metric ton carbon per hectare per year with a range of 3.4 to 5.7 metric ton carbon per hectare per year. This rate at the restored site is greater than the rate of 1.8 metric ton carbon per hectare per year estimated from the same marsh for the period between 2003 and 2006 (first year of project data collection), indicating that the rate of carbon sequestration in this marsh may be increasing over time as the marsh establishes itself (Wills et al., 2008).

Variability of surficial carbon sequestration was significantly greater at the restored site than at the natural site, with a standard deviation of 2.3 metric ton carbon per hectare per year versus 1.3 metric ton carbon per hectare per year. This indicates that a greater number of samples may be required for precise estimation in restored sites than in natural sites. This variability was primarily due to variation in the organic matter accumulation rates (Figures 3-13 and 3-14).

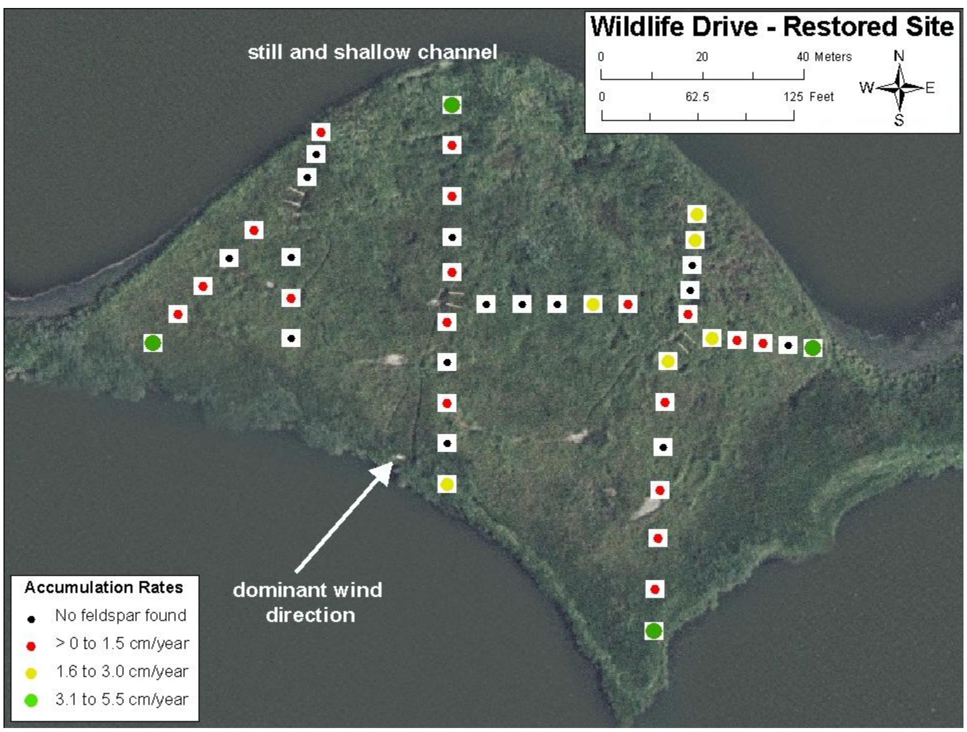


Figure 3-13. Surface Peat Accumulation Rates at the Restored Marsh Cell from 2006 to 2008

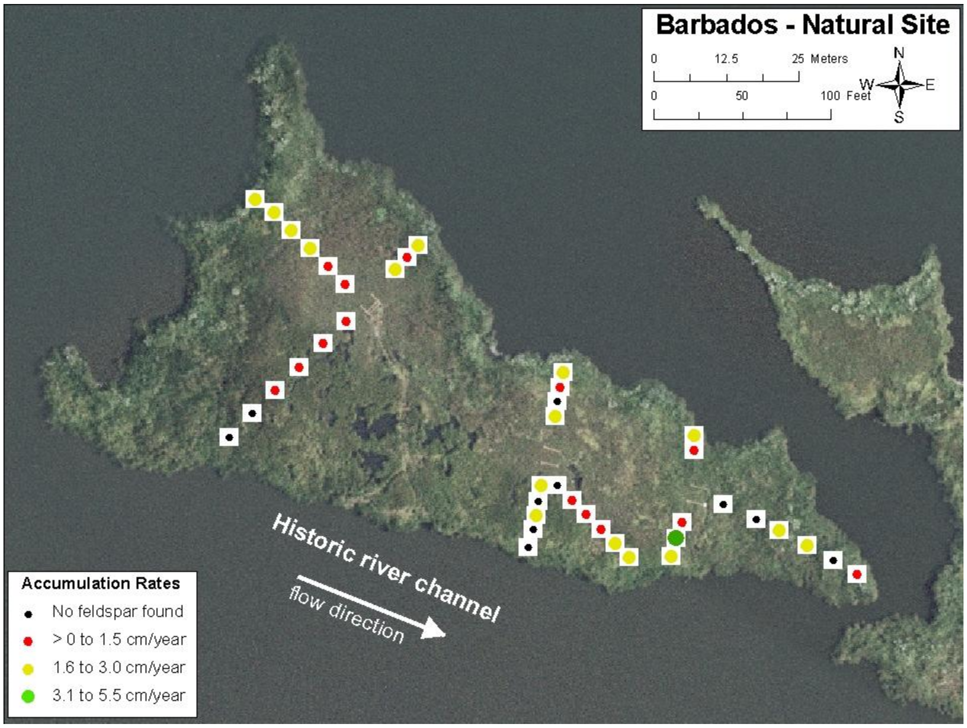


Figure 3-14. Surface Peat Accumulation Rates at the Natural Marsh Cell from 2006 to 2008

3.3.4.3 Subsurface Carbon Changes. This methodology was not successful for the quantification in changes in subsurface carbon contents in tidal marsh soils; however, an alternative methodology was developed. The challenge with marsh soils is that they are highly dynamic in their volume plus they are continually accumulating material near the surface. Therefore, the samples taken to a depth of 50 cm may have represented different soil layers across years such that the difference in carbon contents did not necessarily reflect net carbon gains or losses. It was originally planned to address this complication through the use of marker horizons in the soil profiles; however, these horizons proved to be inconsistent and were therefore not reliable. The equivalent mass method is not applicable to these soils because their mass is changing significantly due to their low mineral content and dynamic organic content (Ellert and Bettany, 1995).

The proposed solution was to install an earth anchor, which is a metal rod with a horizontal plan at its base (similar to a screw). This would then serve as a reference plane for future sampling. If the soil layers became denser above this reference plane, then the samples would be collected to a shallower depth; if they loosen, then sampling will be deeper.

3.3.4.4 Methane Emissions. Based on monthly methane flux measurements from May to October 2009, it was estimated that the annual daily average methane flux from these marshes was: 94 and 90 mg CH_4 m^2 day^{-1} for the natural and restored marsh cells, respectively (Poffenbarger et al., in review). At a 100-year global warming potential time horizon, this converts to a CO_2-equivalent flux of 7.2 and 6.9 metric ton CO_2 per hectare per year. Based on the surface accumulation rates presented above, these marshes are sequestering carbon at rates of 16.1 and 12.5 metric ton CO_2 per hectare per year. Based on these rates, the methane emissions are offsetting 44 and 55% of the surface carbon sequestration benefit at the two marsh islands.

3.3.5 Summary of Key Findings. The objective of this project is to demonstrate the terrestrial carbon sink capacity of a restored tidal marsh at the Blackwater National Wildlife Refuge. The presence of new organic material indicates that at least some areas of the restored marsh are accreting and building the marsh surface. Based on the results of the study, the following conclusions were made:

- The restored and natural marshes at the Blackwater National Wildlife Refuge are sequestering carbon at an above-average rate versus the national average based solely on surficial accumulation, which is probably an underestimate. At the rate of 3.4 metric ton carbon per hectare per year of surficial carbon sequestration, the proposed 8,000 ha restoration would sequester about 27,000 metric ton carbon per hectare per year (or 110,000 metric ton CO_2 per hectare per year). The rate of carbon sequestration would likely vary across wetland types within the proposed restoration, but this estimate is within the range typically found in this region and is conservative because it is only accounting for surficial carbon deposits.
- Thus far, it has not been possible to quantify subsurface carbon changes. Difficulties in finding the original and post-restoration surfaces highlight the problems associated with evaluating carbon sequestration in restored systems without knowledge of conditions prior to restoration. Future monitoring of SETs will allow better tracking of accretion and subsidence in both surface and subsurface materials, but there will be difficulty tracing the distribution of carbon within the profile prior to the initiation of monitoring.
- The use of feldspar markers was not a successful method to establish a reference plane for future sampling. The earth anchor method appears to be a viable method to perform carbon accounting deeper into the soil profile.
- Methane emissions were expected to be insignificant because this is a brackish marsh; however, monthly measurements of methane emissions indicated that a significant portion of the carbon sequestration benefit accounted by the surficial carbon deposits in these marshes is offset through methane emissions. Restoring marshes with higher salinity or other conditions that reduce methane generation would be preferable to improve the net GHG balance.

3.4 Carbon Storage on Forested Wetlands

The validation tests were conducted by Rutgers University through the NJDEP; more detailed information can be found in the project's technical report (Yan and Ehrenfeld, 2011)

3.4.1 Introduction. Forested wetlands constitute the majority of New Jersey's freshwater wetland resource. These wetlands currently occupy 240,195 ha, or about 10% of New Jersey's land area. They currently store a significant, although not well characterized or quantified, amount of carbon, in both the mature tree community and in their soils. However, large areas of wetlands have been drained worldwide for agriculture (Armentano and Menges, 1986) and forestry (Paavilainen and Paivanen, 1995). In New Jersey, wetlands are losing about 700 hectares per year from 2002 to 2007 (Hasse and Lathrop, 2010). Much of the agricultural land in New Jersey is drained wetland area. These are lands in which farmers installed tile drains and dug ditches to permit farming to occur on land that would otherwise be too wet for crop growth. Drained wetland soils decompose and subside at the rate of approximately 1 to 2 cm per year primarily due to oxidation (Rojstaczer and Deverel, 1995; Wosten et al., 1997). The New Jersey Land-Use Regulation Program favors wetland restoration as a mechanism for restoration, as the re-creation of wetlands on land that naturally has the hydrologic characteristics essential for wetland existence provides a more reliable form of mitigation than de-novo creation of wetlands on upland areas.

This present study quantified the carbon sequestration both in biomass and soil of a series of forested wetlands with different restoration ages that were exclusively restored from the drained agricultural lands, which could provide the greatest potential to sequestrate carbon. By illustrating the ability of forested wetland to sequestrate carbon, this study could provide useful information in the development of carbon management and wetland mitigation policy.

3.4.2 Material and Methods

3.4.2.1 Site Selection. This study investigated the potential for carbon sequestration through the restoration of agricultural land into forested wetlands. Successful site selection met the following criteria: 1) historical record of agricultural land use; 2) currently hardwood forested wetlands; 3) presence of drained hydric soil; 4) documentation of mitigation or restoration actions (time of planting or restoring, planted densities and species composition, and actions taken to re-establish wetland hydrology, etc.); 5) availability of existing nearby agricultural fields on similar soil type that have not been restored; and 6) the tree community is established enough to be considered as forest (>10 years old).

Taking all of the site specifications and statistical validity into account, the Dix Wildlife Manage Area (DIX) was chosen as the main study site. DIX is located in Bridgeton, Cumberland County, and is owned by the state. It is surrounded by vast marshlands and bounded by the Delaware Bay to the west. The fields, small woodlots, and forested wetlands create a mosaic of critical resting, feeding and nesting habitat attractive to a variety of wildlife. As shown in Table 3-3 and Figure 3-15 (modified from NJDEP‘s environmental mapping tools ―i-MapNJ DEP”) five forested wetland sites that were 20, 30, 35, 40, 40+ years old, respectively, were selected. Since all of these sites are very close to each other, only one active agricultural land was chosen as the control site.

Table 3-3. DIX Study Site Specifics*

Site Ages (yrs.)	Soil Survey Map Units Within Site	Coordinates
ag. Land	HboA	39.377634,-75.322738
20	FamA+HboA	39.37309,-75.321279
30	FamA+HboA	39.357496,-75.316129
35	FamA+HboA	39.374317,-75.323424
40	FamA+HboA	39.353414,-75.306687
40+	FamA+HboA	39.356003,-75.315528

*All sites above have the same soil type (sandy loam).
*All sites above are rated as ―partially hydric”. According to the ―Hydric Soil” report in Web Soil Survey, the specific hydric soil percentage is as follows: within ―FamA” map unit, 95% is hydric; within ―HboA” map unit, 15% is hydric. During the actual sampling, the area containing 100% hydric soil was focused on.

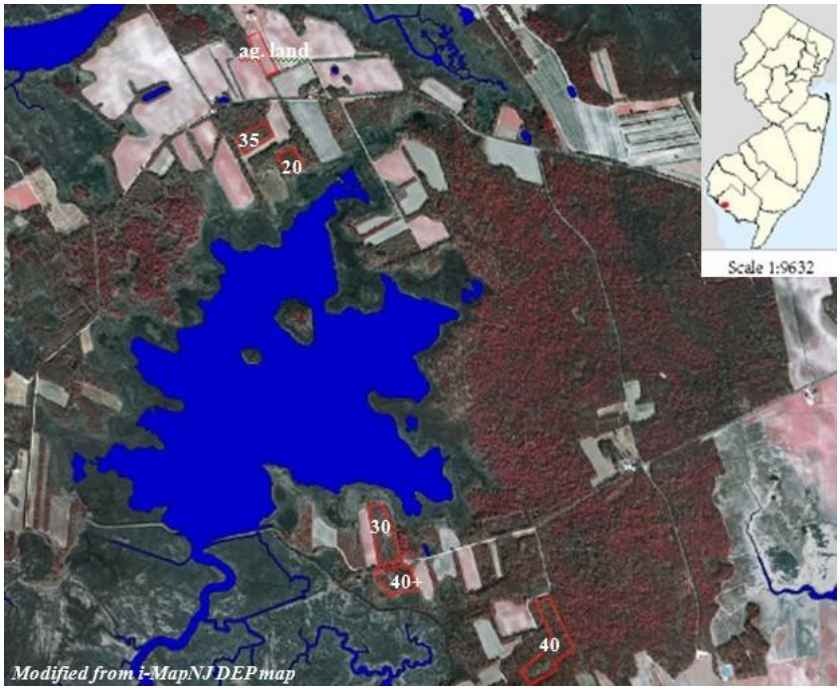


Figure 3-15. Aerial Photo of the Study Sites at DIX (2002)

3.4.2.2 ***Plot Design.*** At each study site, five plots were designed: a, b c, d, and e (Figure 3-16) (10 m×10 m or 20 m×20 m depending on the actual site size and tree density) within the largest soil map unit according to the Natural Resource Conservation Service/ US Department of Agriculture ―Web Soil Survey". In order to ensure that the replicate samples were independent of each other and covered the site as extensively as possible, soils along and between transects greater than 60 m apart were sampled. Generally, the plot design followed the pattern as indicated in Figure 3-17. The distance from the center (60 m, 80 m, 100 m and 120 m) to the plots was subjected to change depending on the actual site size. The samples were taken between September and November 2010.

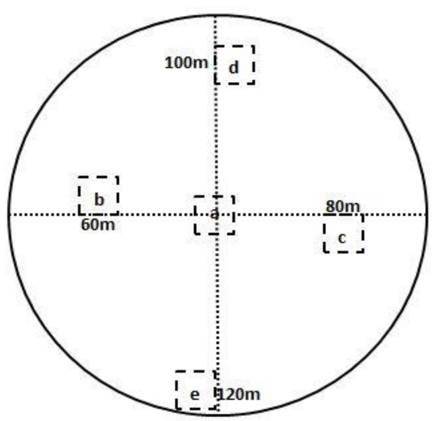


Figure 3-16. Plot Design Pattern within a Given Site

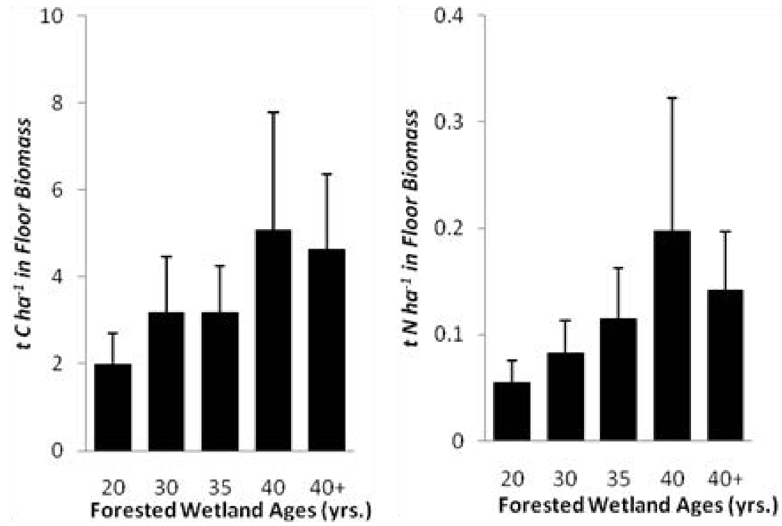


Figure 3-17. Areal Carbon (C) and Nitrogen (N) Content in Floor Biomass

3.4.2.3 Forest Floor Biomass Sampling. In forested sites, litter samples were also taken using a 400 cm^2 plot frame. Within each frame-covered sample area, all living vegetation was removed carefully with a pair of clippers. Living mosses were clipped at the base of the green, photosynthetic material. The forest floor along the inner surface of the frame was cut through to separate it from the frame and surrounding soil. The entire volume of the forest floor from within the confines of the sampling frame down to the top of the mineral soil layer were removed carefully and placed into a pre-labeled paper bag, which was then stapled shut. It yielded $5 \times 3 = 15$ forest floor samples per site which were used to determine oven-dry to wet mass ratios to convert the total wet mass to oven-dry mass. Their oven-dry portion was ground for carbon and nitrogen concentration (CN) analysis (Figure 3-17).

3.4.2.4 Soil Sampling. MacDonald (1999) found there was no significant increase of carbon content below 40 to 50 cm of soil in hardwood forest and even shallower in other types of forests. Therefore, samples were only collected from the top 30 cm of soil at three depths: 0 to 10 cm, 10 to 20 cm and 20 to 30 cm, respectively, based on the soil horizon structure and Munsell colors, which yielded $5 \times 3 \times 3 = 45$ soil samples for both BD and CN measurements. For the samplers, a rigid stainless steel ring with 3.75 cm of diameter and 10 cm of length, or 110cm^3 in volume, was used along with a series of smaller wear-resistant copper rings with a range of diameters (1.5 to 3 cm) and lengths (2 to 5 cm), which were used in case the soil was extremely hard to dig in (i.e., rocky, deep soil). These samplers have a very thin wall and sharp edge so as to minimize the effects of soil compactness on BD.

In the field, a big pit was first dug to check the soil structure and colors. For sampling at each depth, the ring was carefully driven through the soil profile in a top-down direction or along the horizontal direction, depending on the actual texture of the soil. In order to minimize disturbance to the sample, digging was conducted around and underneath the ring with the knife, carefully lifting it out to prevent any loss of soil and removing any excess soil from the sampler with a flat bladed knife. For the 10 cm length sampler, only one sample was collected at each depth because it is enough for analysis; when using small samplers, at least three small subsamples were collected from each depth to compose one sample. All soil samples were wrapped with foil and placed into pre-labeled zip-lock bags.

For sampling in the comparative agricultural land, 10 locations were randomly chosen and sampled at three depths: 0 to 10 cm, 10 to 20 cm and 20 to 30 cm, respectively, which yielded $10 \times 3 = 30$ total samples. The same procedures as those used for sampling in forested wetlands were used.

For BD measurements in the lab, each sample was weighed and then one weighed subsample was oven dried at 105°C for 24 hours, then weighed again to determine its water content (Figure 3-18). The oven-dried subsample was ground, sieved with a 2 mm sieve and the coarse fraction was weighed. For CN analysis, another subsample that was air dried was separated and then ground, sieved with a 2 mm sieve and packed into a small vial to be sent out to Ecosystem Analysis Laboratory at the University of Nebraska-Lincoln for CN analysis using dry combustion GC.

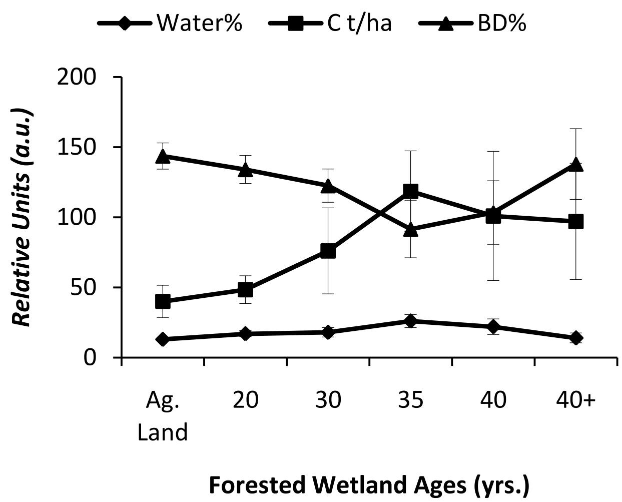


Figure 3-18. Relationships between metric ton per hectare (C t/ha), BD and Water%

3.4.2.5 Tree Biomass Survey. A standard census of tree density and diameter at breast height (DBH) were completed at the five forested wetland sites, according to the procedure recommend by Pearson et al. (2007). For the aboveground biomass estimation, the living biomass, the standing dead wood biomass and the down dead wood biomass were surveyed. The present work focused only on the big hardwood (DBH ≥5 cm), while ignoring the small trees (DBH<5 cm) and the understory herbaceous vegetation since their contribution to carbon sequestration is trivial (Pearson et al., 2007).

3.4.3 Key Findings. Carbon sequestration was investigated in the soil and biomass of five different aged forested wetlands that were restored from farmland and one comparative agricultural field located at DIX, Bridgeton, New Jersey, from September through November 2010. In addition to the biomass survey including both aboveground and belowground biomass, the water content, CN, and carbon:nitrogen ratio for the top soil from three depths (0 to 10 cm, 10 to 20 cm and 20 to 30 cm) are quantified in the present work. This study showed that forested wetland sequestered approximately 124 to 382 metric ton carbon per hectare, depending on age, in contrast to approximately 40 metric ton carbon per hectare in agricultural land (Figure 3-19). The annual carbon sequestration rates in the wetland soil, litter and tree biomass were estimated to be 8.35 metric ton carbon per hectare per year for the forested wetland ecosystem.

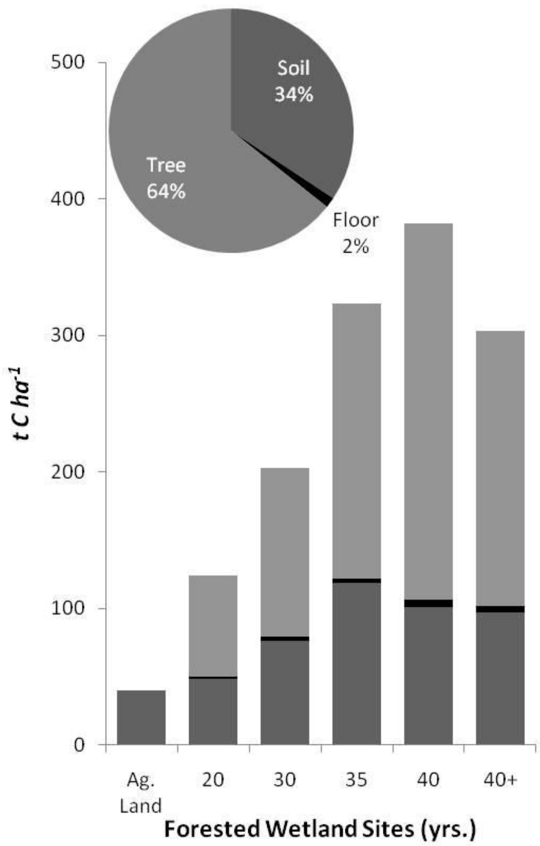


Figure 3-19. Comparison of Carbon Sequestration Rates in Soil, Litter and Tree Biomass

The carbon sequestration potential of wetlands is quite substantial, more specifically in the case of forested wetlands and tidal marshes. The superior potential for forested wetlands over farmland and even upland forests in sequestrating carbon may partially be credited to its abundant water supply, balanced organic matter mineralization and nutrient immobilization processes (indicated by carbon:nitrogen ratio) and anoxic wetland soil condition. The results suggest that the restoration of forested wetlands from agricultural lands could have great potential in sequestering the atmospheric carbon into the biomass and soil, which should be considered while developing carbon management policy as well as wetland mitigation policy.

3.4.4 Assessment of Storage Opportunities and Benefits. Land uses with carbon storage capacities such as forested wetlands and tidal marshes need to be protected and maintained not only to continually sequester carbon but to keep emissions of methane (another potent GHG) under control. Forested wetlands potentially sequester 5.1 metric tons CO_2 per hectare per year while saline marshes capture approximately 1.5 metric tons CO_2 per hectare per year (Reyes, 2011).

Section 4.0: REFINEMENT AND EXTENSION OF THE MRCSP'S PIONEERING CHARACTERIZATION OF THE REGION'S SEQUESTRATION OPPORTUNITIES

The MRCSP research team includes the entity in each of the nine states having the most knowledge of local geology including the state geological surveys from Indiana, Kentucky, Maryland, New Jersey, Ohio, Pennsylvania, and West Virginia along with the New York State Museum and Western Michigan University. Together these organizations comprise the MRCSP geologic mapping team with efforts being coordinated by the Ohio Geological Survey. In Phase II this team extended and refined the regional geologic analysis begun in Phase I, significantly increasing the level of detail in the understanding of sequestration options in deep saline reservoirs, depleted oil and gas fields, unmineable coal seams and organic rich shale.

These efforts built upon the initial mapping performed in MRCSP Phase I to better define CO_2 sequestration potential in the region. The efforts included a program to ‗piggyback' on oil and gas drilling to collect additional geophysical logs and rock core from CO_2 storage zones. The MRCSP research team also defined the regional geologic framework for CO_2 storage in the Upper Cambrian Mount Simon, Middle-Devonian-Middle Silurian formations, Devonian black shales, unmineable coalbeds, and depleted oil and gas formations. In addition, characterization of CO_2 storage formations in New Jersey was assessed to bring the state up to date with the rest of the MRCSP region. Reports, data, and maps generated by the research were integrated into a geographic information system available for use on the MRCSP Web site (**www.mrcsp.org**).

4.1 Filling Critical Data Gaps in Regional Geologic Framework through Piggy Back Drilling

The MRCSP Piggyback drilling program was completed to develop an improved understanding of CO_2 storage feasibility in the region by leveraging existing regional oil and gas drilling activities. During the Phase II project, oil and gas activities in the region were monitored for new drilling projects in areas where more information on deep rock formations would help in characterizing CO_2 storage potential. Opportunities were pursued to complete additional drilling, logging, and/or rock coring in these wells. The piggyback work better characterized formations of interest for CO_2 storage and the geologic patterns in their regional distribution. Both seals and potential reservoirs were evaluated.

Three wells were explored in the MRCSP Phase II piggyback program. The wells were drilled in Ohio, Kentucky, and Michigan (Figure 4- 1).

- The Ohio Well, Ohio Geological Survey #1 CO_2 (Ohio #1), was drilled in Salem Township, Tuscarawas County, to a depth of 8,695 ft in the spring of 2007.
- The Kentucky well, Batten & Baird K-2605, which was located in southeastern Pike County approximately 5 miles north of the Virginia State Line, was drilled to a depth of 5,036 ft in the summer of 2008.
- The Michigan well, State Charlton & Boeve 2-6, was drilled in the Charlton Field in Otsego County to a depth of 6,202 ft in the summer of 2008.

The three MRCSP Phase II piggyback wells provided valuable insight into several CO_2 storage reservoirs at a relatively low cost.

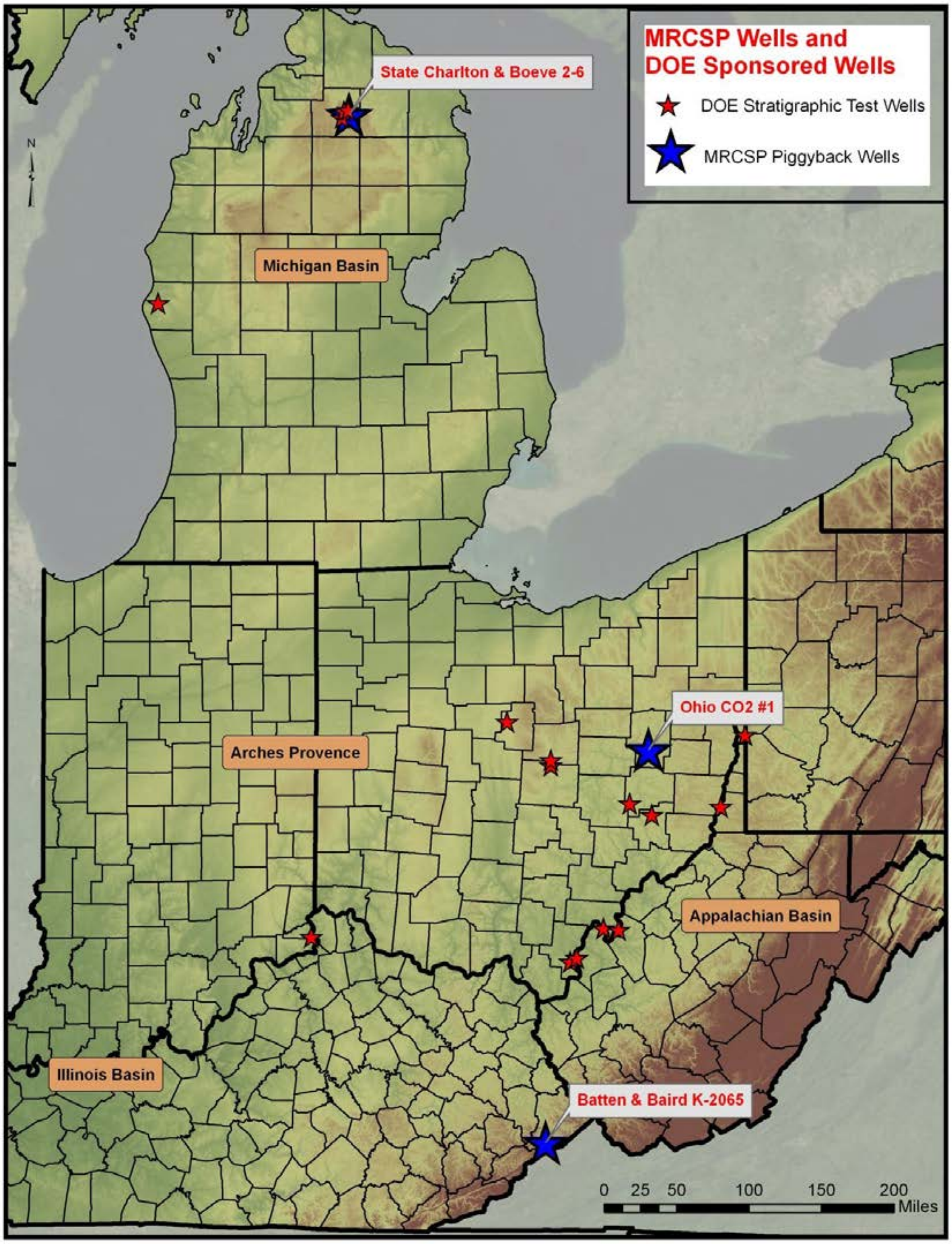


Figure 4-1. Map Showing the MRCSP Piggyback Well Locations Relative to Other DOE Sponsored Wells

These wells also added valuable data to that obtained in the separately funded NETL project titled ―Regional Characterization of the Midwestern United States Geologic Carbon Sequestration Potential" (DOE Contract DE-FC26-05NT42434), which included the characterization of a number of locations in the midwestern US between 2005 and 2009. Detailed results of that separately funded effort are presented in the final technical report ―Leveraging Regional Exploration to Develop Geologic Framework for CO_2 Storage in Deep Formations in Midwestern United States" (Battelle, 2009). Key conclusions for the piggyback wells funded in MRCSP Phase II and described here are as follows:

- The Ohio #1 well geophysical logs indicate the Cambrian basal sands in the area have high porosity and are very fitting for injection and storage. The Cambrian basal sands have multiple overlying confining and sealing formations. The Ohio #1 well is the deepest well in the area and significantly added to the relatively little known Ordovician and Cambrian formations in east central Ohio.
- The Batten and Baird K-2065 in Kentucky provided data for the Upper Devonian Ohio Shale as a potential CO_2 storage formation. The Ohio Shale in this area could act as the reservoir, confining unit and seal for the injected CO_2. Sidewall cores obtained in the well provided valuable laboratory data.
- The State Charlton and Boeve 2-6 in Michigan provided data strengthening the belief that the Bass Islands Dolomite is an excellent candidate for CO_2 storage. The high porosity of the Bass Islands Dolomite and its overlying buffer unit, the Bois Blanc Formation, and subsequently its overlying confining unit, the Amherstberg Formation, make up an excellent model for injection and storage. The State Charlton and Boeve 2-6 is in close proximity to the Phase II Field Validation Test well. Geophysical logs in the well aided in understanding the extent of the Bass Island Dolomite-Bios Blanc formations targeted for CO_2 storage in the MRCSP Phase II State-Charlton 4-30 injection well.

In general, the stratigraphic tests within the piggyback wells focused on specific formations of interest in order to evaluate their potential for CO_2 storage. The collaboration with oil and gas industry is critical for successful execution and meeting site-specific objectives. This depends on both the technical evaluation of the drilling prospects and understanding risk sharing and contractual aspects. A full understanding of the objectives of each party and a clear upfront agreement of cost sharing and drilling responsibilities are important for avoiding disagreements in the field. Obviously, the host companies are most interested in exploring for oil and gas and ensuring that the producing zones are not adversely impacted due to additional drilling, logging, or testing in the wells. In this regard, it may not always be possible to achieve the objective of evaluating formations of interest for geologic storage, if the operators deem the risk to producing zones to be unacceptable.

As part of the MRCSP regional characterization piggyback efforts, drilling and testing were also conducted to assess the sequestration potential of coalbeds (*Understanding Deep Coal Seams for Sequestration Potential*). The core acquisition was done in conjunction with CONSOL's ongoing coal seam exploration efforts.

A single core was drilled for exploration purposes into the Fallowfield Coal Reserve in Washington County, Pennsylvania in July of 2009. Coal samples were collected from seven unmineable coal seams for analyses of methane desorption and CO_2 sorption (Figure 4- 2). Based on laboratory test results, potential coal seams that could be used for coalbed methane extraction coupled with injection and storage of CO_2 were identified.

The methane desorption for the coals ranged from 60 standard cubic feet (scf) per ton of coal to 194 scf/ton on an as-received basis. The CO_2 adsorption for the coals ranged from 354 scf/ton to 717 scf/ton on an in-situ basis at the estimated pressure of the coal seam. The three coal seams that adsorbed the most CO_2 were Middle Kittanning at 717 scf/ton, Brookville at 667 scf/ton, and Upper Kittanning at 665 scf/ton. Sorption capacity of the coals was related to various chemical parameters of the coal as ash content, volatile matter, and maceral composition.

Figure 4-2. Drilling Rig Used at the Fallowfield Site Showing Drilling Bit and Core Section Being Removed

Comparison of the relationship between the CO_2 sorption and methane sorption on a dry, ash-free basis showed that the coals were capable of storing from 2.9 to 5.6 times as much CO_2 as methane on a scf/ton basis. These ratios suggest enhanced coalbed methane recovery and CO_2 sequestration may be feasible in coalbeds in the MRCSP region, although more testing would be necessary to ensure CO_2 can be effectively injected into coalbeds.

4.2 Building and Refining a Geologic Sequestration Framework for the Region

Potential locations for geologic sequestration in the MRCSP states extend from the deep rock formations in the broad sedimentary basins and arches in the western portion of the region to the offshore continental shelf in the east. Research and testing have established many promising geologic units for CO_2 sequestration including deep saline rock formations, depleted oil and gas reservoirs, organic shale layers, and coalbeds. Geological surveys from the nine MRCSP states completed an assessment of the potential for geologic sequestration that indicates there is capacity to permanently contain at least one hundred years of CO_2 emissions from the region. Reports, data, and maps generated by the research were integrated into a geographic information system available for use on the MRCSP Web site (www.mrcsp.org).

The MRCSP geologic sequestration framework effort for Phase II consisted of five topics designed to evaluate and extend knowledge of the region's geologic sequestration potential. These topics were selected by a collective effort led by the MRCSP team of state geological surveys from the nine MRCSP member states and were reviewed with the MRCSP partnership early in the Phase II process. A separate detailed report has been prepared for each topic and is available on the MRCSP Web site (www.mrcsp.org). These reports build upon previous mapping efforts completed in MRCSP Phase I. The Phase II efforts present more exhaustive research on key rock formations for CO_2 storage. As with the previous MRCSP work, these assessments span various states in the MRCSP region and represent a unique assessment of geologic factors affecting CO_2 storage potential in the region. Table 4-1 provides an overview of the region's sequestration resource totals by reservoir type and by state in the MRCSP region, while Table 4-2 provides a more detailed look at sequestration capacities by saline formation and by state in the MRCSP region.

In addition to the five general geologic topics addresses, an assessment of geologic sequestration potential for the state of New Jersey was completed to bring that state in line with progress made for other MRCSP states. The results of this assessment are included in Tables 4-1 and 4-2.

Table 4-1. Storage Capacities for Phase II Sequestration Capacities by Reservoir Type and by State in the MRCSP Region[(1)]

Formation	State									
	IN	**KY**	**MD**	**MI**	**NY**	**OH**	**PA**	**WV**	**NJ**	**Total**
Deep Saline[(2)]	73,800	6,800	2,700	77,700	6,900	19,500	30,100	16,700	600	**234,800**
EOR	61	87		457	272	3,405	2,806	1,423		**8,500**
Coal		17				31	66	92		**200**
Shale		91				463	726	744		**2,000**
Total	**73,900**	**7,000**	**2,700**	**78,200**	**7,200**	**23,400**	**33,700**	**19,000**	**600**	**245,500**

(1) Some numbers presented here differ from the NETL Carbon Sequestration Atlas due to variations in methodology required to harmonize storage capacity estimates amongst the seven regional partnerships.
(2) During Phase I, the calculations for storage capacity were determined using a 10-percent efficiency factor. Phase II assessment calculated storage capacities using more conservative efficiency factors (e.g., 1 percent and 4 percent) to develop estimates with higher confidence. “Medium” values (e.g., those calculated using at least 4 percent efficiency value) are presented here.

Table 4-2. Storage Capacities for Phase II Sequestration Capacities by Saline Formation and by State in the MRCSP Region[(1)]

Formation	State									
	IN	**KY**	**MD**	**MI**	**NY**	**OH**	**PA**	**WV**	**NJ***	**Total**
Off Shore									450	**400**
Potomac									148	**100**
Waste Gate			1,753							**1,700**
Sylvania[(2)]				6,044						**6,000**
Bass Islands Gr[(2)]				2,731						**2,700**
Bass Islands Gr[(3)]							3,500			**3,500**
Dundee				1,762						**1,700**
Oriskany		5.7	120		21	123	1,170	1,460		**2,900**
Lockport		520	250		990	3,900	4,650	7,830		**18,100**
Medina/Tuscarora		7.5	600		756	1,480	7,980	5,210		**16,000**
St. Peter	41			35,200		26				**35,200**
Rose Run Unit		2,177		305	4,690	3,240	11,900	2,086		**24,400**
Potsdam					423		682			**1,100**
Conasauga		0.593		65.7		1,387	184	64.5		**1,700**
Rome Trough		400				2.35		88.5		**400**
Mount Simon	73,787	3,687		31,627		9,317				**118,400**

(1) Some numbers presented here differ from the NETL Carbon Sequestration Atlas due to variations in methodology required to harmonize storage capacity estimates amongst the seven regional partnerships.
(2) Michigan Basin
(3) Appalachian Basin

A Regional Geologic Characterization and Assessment of Geologic Carbon Sequestration Opportunities in the Upper Cambrian Mount Simon Sandstone in the Midwest Region, with Addendum – Cambrian. This topic focused on the Upper Cambrian Mount Simon Sandstone, which is a deep saline reservoir thought to contain the greatest potential for CO_2 storage of all on-shore formations within the MRCSP region. Phase I work and ongoing research have demonstrated that the formal Mount Simon of Indiana, Michigan, and western Ohio does not extend eastward into eastern Ohio and much of the Appalachian Basin. The ―basal sandstone” present in eastern Ohio is stratigraphically higher than the Mount Simon Sandstone and lithologically distinct. Thus, the Phase II characterization work has concentrated on the Mount Simon within Indiana, Michigan, western Kentucky, and western Ohio. Here, studies of core samples collected from the Mount Simon indicate that porosity and permeability values change predictably with depth, generally decreasing with depth. Such a predictive relationship allows a better methodology for predicting the geologic carbon sequestration resource of this unit in the Midwest. This methodology was used to provide a better estimate on CO_2 storage within the Mount Simon (Figure 4-3). While this formation is thought to hold the greatest on-shore potential for CO_2 storage in the MRCSP region, there is limited information available on the reservoir due to its depth and lack of hydrocarbon resources. Therefore, the stratigraphic relationships and resource of the Mount Simon and ―basal sands” will continue to be evaluated within Phase III efforts.

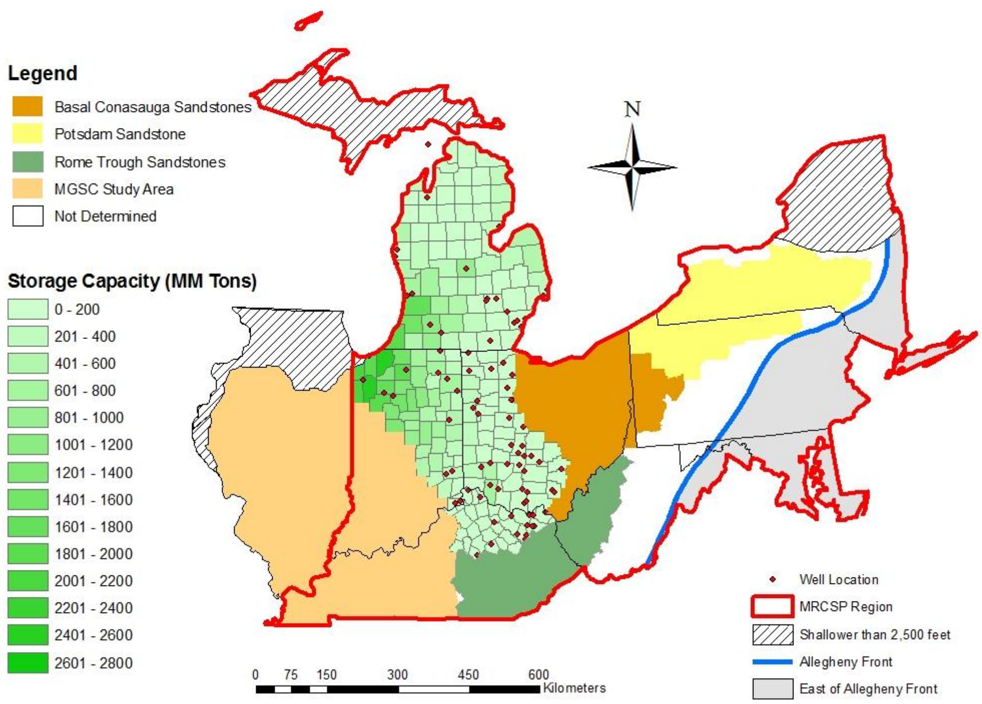


Figure 4-3. Storage Resource Calculated by County Using an Efficiency Factor of 4 Percent (ξ =4%) in the Mount Simon Sandstone

Characterization of Geologic Sequestration Opportunities in the MRSCP Region: Middle Devonian–Middle Silurian (MDMS) Formations. For Phase II, the MDMS group within the MRCSP geological survey team completed a detailed evaluation of several promising rock formations within the MDMS being considered for CO_2 storage. Within this interval, available data indicate the most promising target for geologic sequestration in the Appalachian Basin is the Oriskany Sandstone, specifically in the areas of eastern Ohio, western West Virginia, and western Pennsylvania (Figure 4-4).

In these areas, the Oriskany exhibits an average porosity of 5 percent and permeabilities ranging from 1 mD to as high as 185 mD. In the Michigan Basin, the most promising MDMS targets are the Bass Islands Dolomite and the Dundee Formation (Figure 4-5). These layers exhibit average porosities of 10 and 5 percent, respectively. A successful Phase II validation test has been accomplished in the Bass Islands Dolomite in an existing oil and gas field in Otsego County, Michigan, where approximately 60,000 metric tons of CO_2 has been injected.

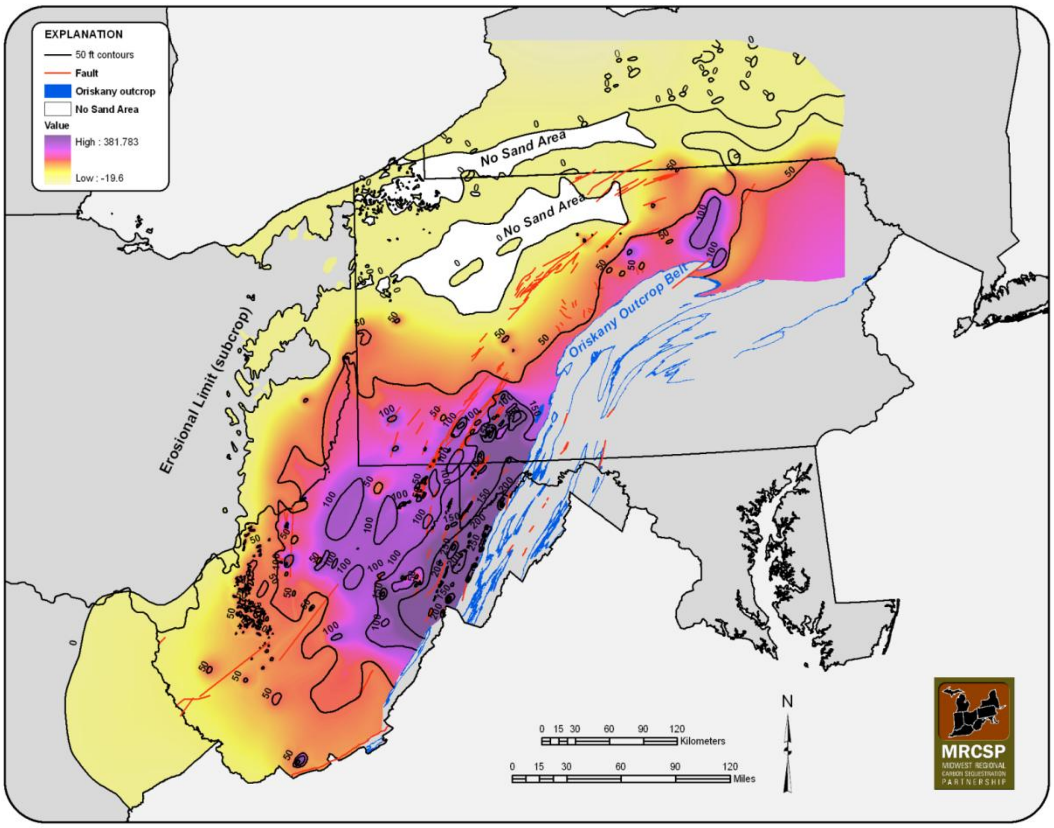


Figure 4-4. Gross Thickness Contour Map of the Oriskany Sandstone in the MRCSP Region

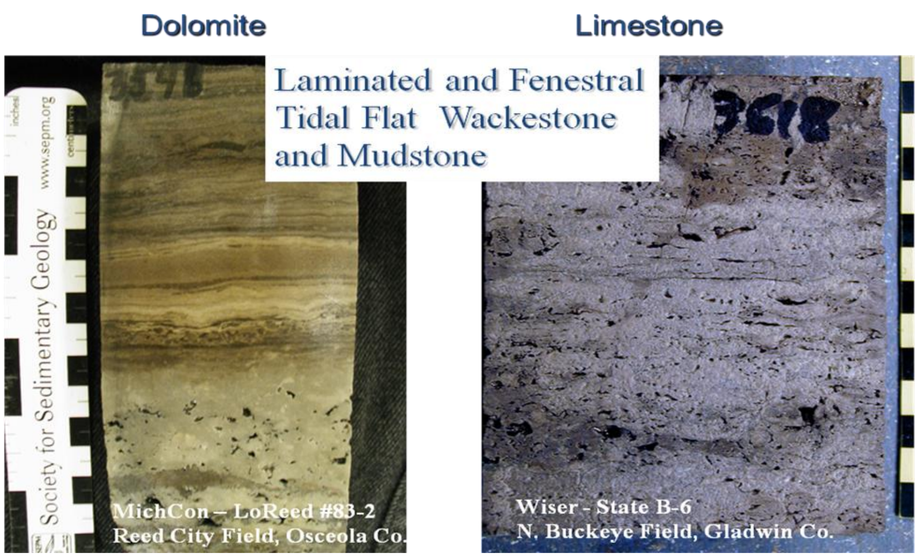


Figure 4-5. Core Slabs of the Laminated-Fenestral Mudstone/Wackestone of the Peritidal Facies in the Dundee Formation

Reassessment of CO_2 Sequestration Capacity and Enhanced Gas Recovery Potential of Middle and Upper Devonian Black Shales in the Appalachian Basin. Research on CO_2 storage potential in Devonian shale formations continued during Phase II. Low-permeability shale units of high lateral extent are expected to be effective regional seals for CO_2 storage in deeper zones. However, in addition to serving as seals, black Devonian shales may also serve as target zones for actual CO_2 storage. CO_2 storage in shale is related to shale density and volume and is also based on a shale's ability to adsorb CO_2 onto molecules containing organic carbon within the shale matrix. Thus, shale storage can be more simply estimated from shale total organic content (TOC). A method to assess the CO_2 sequestration

resource of Devonian shales was developed that takes into account the variability of the organic content of the interval. While displacement and storage efficiency data were not available, calculations suggest a storage capacity of 2.3 billion tons (3 percent efficiency analogous to efficiency estimates in deep brine storage) in the deeper and thicker portions of the Devonian shale in the Appalachian Basin. If efficiencies similar to coal are realized, as much as 29.68 billion tons of CO_2 may be sequestered. The Devonian Shale study also concluded that TOC varies across the Appalachian Basin with lower values toward the basin center possibly because of greater shale thicknesses contributing to a dilution effect (Figure 4-6). Simulated full pattern injection scenarios suggest appreciable incremental recoveries of natural gas. However, continuous full pattern injection of CO_2 suggests both sequestration and incremental recovery of gas are feasible. Due to low permeability and thus injection rates, it isn't likely that these shales will be a primary injection zone. However, their capacity to adsorb CO_2 is expected to increase the effectiveness of these shales as regional seals for deeper sequestration.

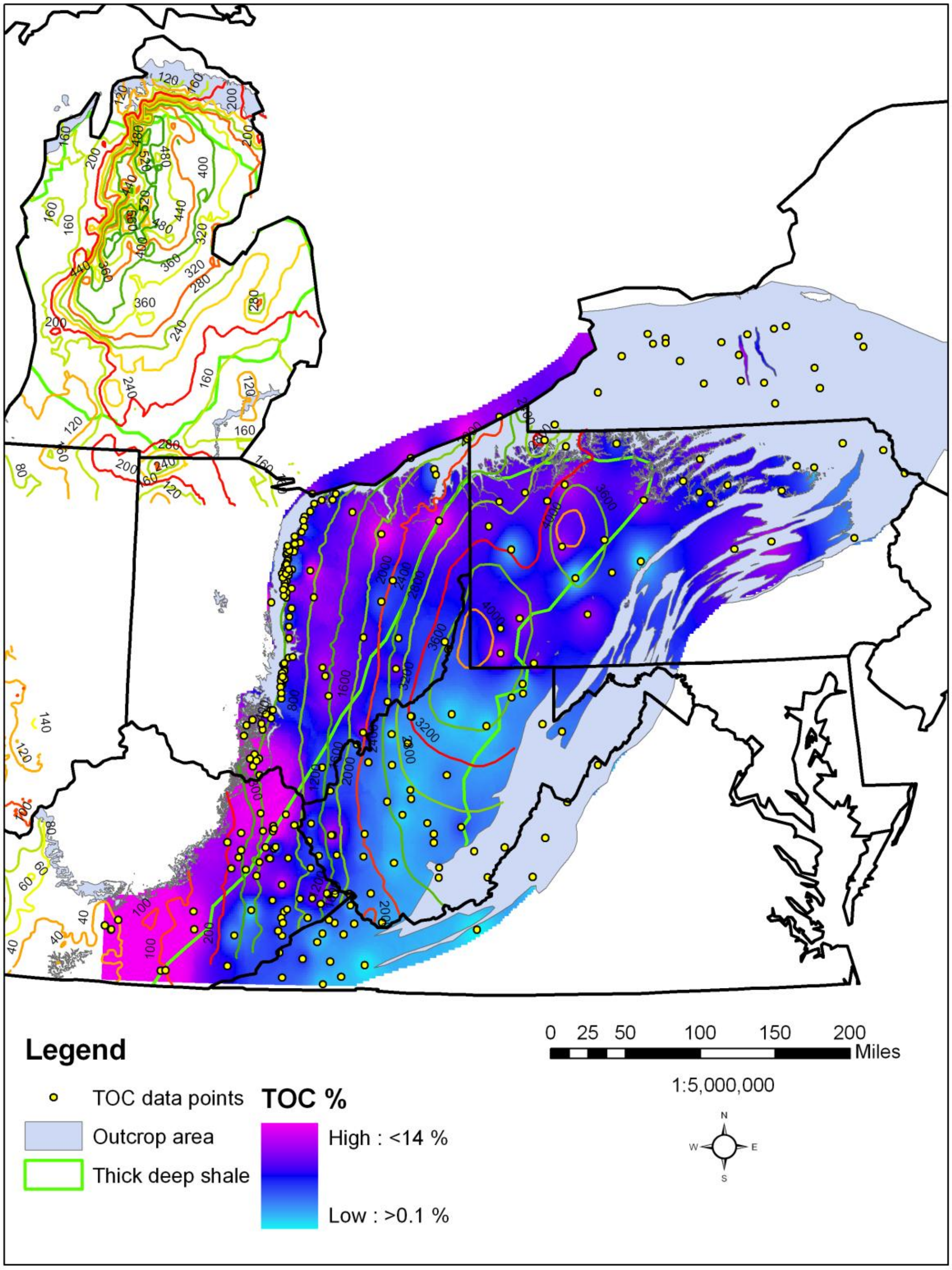


Figure 4-6. Spatial Distribution of Percent TOC Data in Devonian Shales across MRCSP Region Including Isopach of the Total Shale Thickness

Storing and Using CO_2 for Enhanced Coalbed Methane Recovery in Unmineable Coalbeds of the Northern Appalachian Basin and Parts of the Central Appalachian Basin. The objective of the Phase II work on coal was to: (1) evaluate and summarize current research regarding the use of CO_2 for enhanced coalbed methane (ECBM) recovery in the MRCSP region, that is, work not addressed in Phase I, and (2) evaluate and summarize CO_2 tests in coal from non-MRCSP projects in the region. During Phase II, the outlook and emphasis on using coalbeds for carbon storage has shifted to using coals only for producing CBM under ECBM projects. In Phase I the MRCSP mapped all coals greater than 500 ft deep as potential for sequestration. Projected higher prices for coal in the future and reluctance of the coal industry to potentially lose the deeper reserves have resulted in remapping the potential coals to include only those greater than 1,000 ft deep. This shift in thought results in a significant reduction in the size of total potential geologic carbon storage area attributed to coal. Coalbeds are being investigated as CO_2 sequestration reservoirs because CO_2 has a greater affinity for coal than for methane, meaning that it will displace methane, adsorb to the coal matrix, and remain sequestered within the coalbed. The amount of adsorption and subsequent methane displacement varies with coal rank, type, and moisture content, but CO_2:CH_4 displacement ratios generally range from 2:1 for bituminous coals to 10:1 for lignites. In the MRCSP region, the displacement ratio is likely to be similar to that for Illinois Basin coals, ranging from 3.5:1 to 5.3:1.

Evaluation of CO_2-Enhanced Oil Recovery and Sequestration Opportunities in Oil and Gas Fields of the MRCSP Region. The Phase II EOR task conducted a preliminary assessment of 940 oil fields in the MRCSP region to determine potential for CO_2 EOR and sequestration. Producing reservoirs range in age from Cambrian through Pennsylvanian. Detailed reservoir, production, and engineering data were collected on 15 selected fields undergoing secondary or tertiary production. Case histories were constructed for each of these 15 fields that present stratigraphy, structure, trapping mechanisms, production history and secondary recovery efforts, and results. A region-wide inventory assessment of oil and gas reservoirs was conducted showing that original oil in place totaled over 20 billion barrels and that 5 billion of those barrels have been produced (Figure 4-7). Because primary production was only successful at recovering one quarter of the original oil in place, the vast majority of the remaining 15 billion barrels will not be recoverable but will remain stranded unless some type of EOR method is utilized. In many cases, CO_2 EOR is very likely the best means for extracting more reserves from these reservoirs.

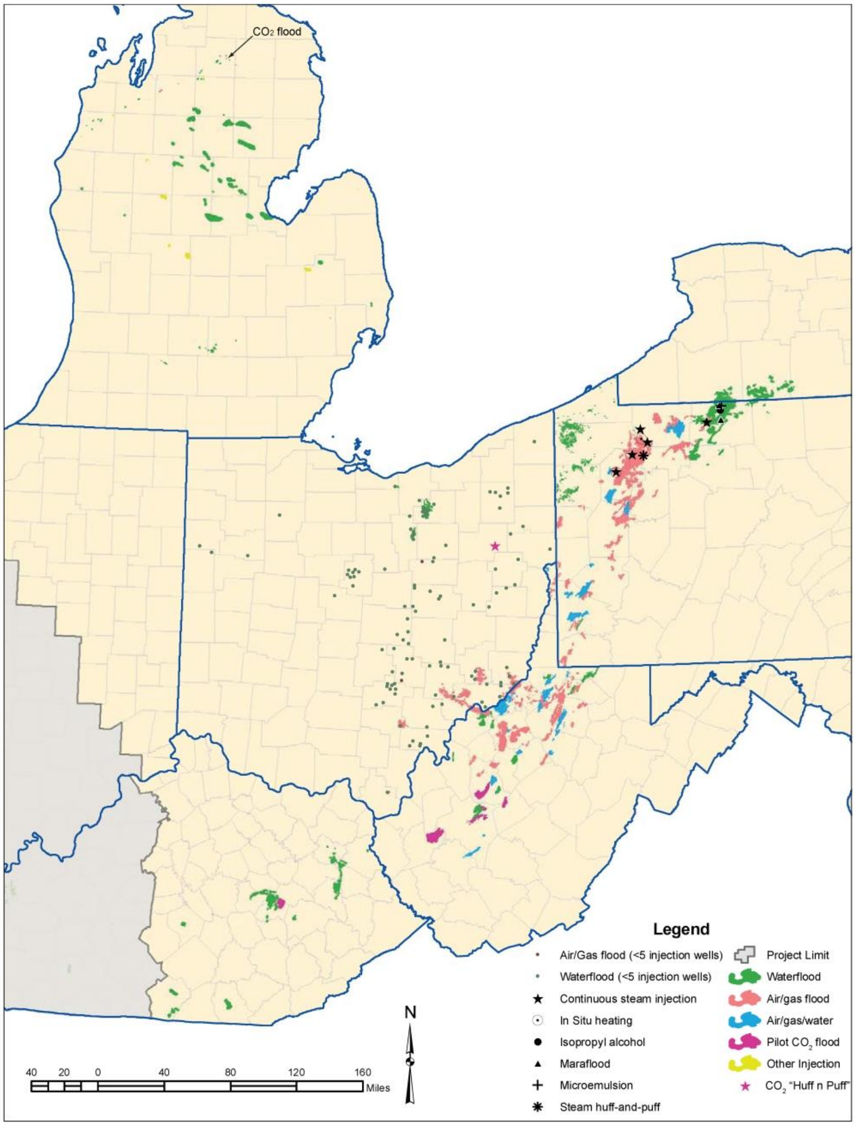


Figure 4-7. Map Showing All Historical Secondary and Tertiary Recovery Projects in the MRCSP Region

Preliminary Characterization of CO_2 Sequestration Potential in New Jersey and the Offshore Coastal Region. In the later stages of MRCSP Phase II, the New Jersey Geological Survey, in conjunction with Rutgers University, completed a preliminary characterization of geological sequestration potential in the state of New Jersey and adjacent offshore region including the continental shelf and slope. The geology of New Jersey and its offshore region encompasses the Coastal Plain, offshore continental shelf and continental slope, Piedmont (Newark basin), and Highlands, Valley and Ridge. Based on the preliminary characterization, the main geologic sequestration options in New Jersey are the numerous deep, saline, sandy formations found in the New Jersey Coastal Plain and adjacent continental shelf and slope. These formations are thick, with burial depths >800 m, a necessary criteria for supercritical storage of CO_2. Additionally, these formations are capped by thick low permeability confining beds required to isolate CO_2 in the sequestration target formation.

The Potomac Formation is the deepest unit in the Coastal Plain with suitable conditions for sequestration of supercritical CO_2: it is saline, attains sufficient depth south of Island Beach, and is in proximity to several large anthropogenic CO_2 point sources. The Potomac Formation is subdivided into three units from youngest to oldest: Potomac unit 3, Potomac unit 2, and Potomac unit 1 (Figure 4-8). The Potomac unit 1 sands present the most likely target for sequestration. This unit is very sandy but discontinuous, is hydrologically isolated from shallow fresh water aquifers, and has the capability to store and absorb significant volumes of CO_2. The range of total CO_2 storage in the three sand units was estimated at 57 to 283 million metric tons.

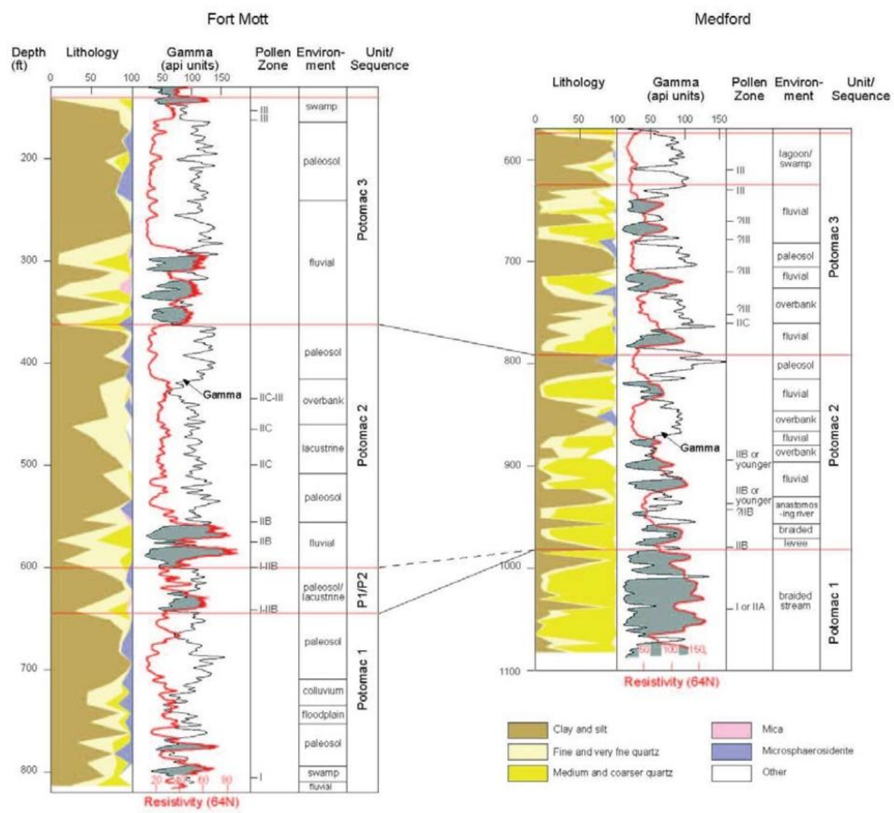


Figure 4-8. Correlation of the Potomac Formation in the Fort Mott and Medford Boreholes Located along the New Jersey Coastal Plain

Initial studies of the offshore New Jersey continental shelf and slope suggest three sand bodies provide the most likely targets for geological sequestration within the Logan Canyon and the Missisauga equivalents. The potential range of CO_2 storage in these three units is 150 to 750 million metric tons. The Stockton Formation, within the Mesozoic Newark basin, has some potential but, due to a lack of deep data, hydrologic parameters and lateral continuity of target lithologies is speculative. To address the continuity and properties of potential sequestration formations in the New Jersey Coastal Plain and adjacent offshore region, New Jersey is collaborating with Rutgers University and New York and Maryland in conducting additional research on the deep rock formations.

4.3 Refine and Update Geographic Information System (GIS)

Reports, data, and maps generated by the Phase I research were integrated into a geographic information system available for use on the MRCSP Web site (www.mrcsp.org). The ongoing use of ESRI's suite of ArcGIS products, along with custom macros and database calculations, has been instrumental in capturing, analyzing, integrating, and depicting all of the data and information utilized in Phase II. Updates to the GIS involved collecting additional data and performing additional interpretation and mapping. The new data combined with the previously collected Phase I data were used to calculate an updated, more refined, second approximation of the region's geologic carbon sequestration storage capacities, including values for: (1) deep saline formations, (2) oil and gas fields, (3) unmineable coalbeds, and (4) organic shales. GIS data were provided to National Carbon Sequestration Database and Geographic Information System (NATCARB). These contributions included data for the 2007, 2008, and 2010 DOE Carbon Sequestration Atlas of the United States and Canada. The MRCSP team participated in the DOE Regional CO_2 Sequestration Partnership GIS working group, including periodic conference calls and meetings to coordinate GIS activities. Overall, the GIS provided a method to investigate and visualize data. The GIS methods were useful for computing CO_2 storage resource estimates.

Section 5.0: REGULATORY ANALYSIS

5.1 Permitting for Phase II Field Research

Each of the three MRCSP Phase II geologic CO_2 sequestration tests required permits to drill the test wells and inject CO_2 underground. Initially, there was little precedent for CO_2 injection in the MRCSP region, aside from a few enhanced oil recovery fields. MRCSP Phase II geologic test sites were spread throughout the region with different agencies at each site (Table 5-1). This resulted in a fair amount of uncertainty regarding how to implement the tests within both the MRCSP team and the EPA regulatory agencies. Completing the permit process at three separate field sites provided direct benefits for the MRCSP region. The permitting process helped establish CO_2 storage knowledge and experience with various EPA and state regulatory agencies in the region by providing a real life test case.

Table 5-1. Summary of MRCSP Phase II Geologic Test Sites Permitting Process

	Appalachian Basin R.E. Burger Plant	Cincinnati Arch East Bend Station	Michigan Basin State-Charlton 30/31
Location	Shadyside, OH	Rabbit Hash, KY	Otsego Co., MI
State Agency	Ohio Dept. of Natural Resources Division of Mineral Resources Management- Oil and Gas	Kentucky Dept. of Natural Resources Division of Oil and Gas Conservation	Michigan Dept. Natural Resources Oil and Gas Minerals
UIC Agency	Ohio EPA UIC Program	U.S. EPA Region 4 UIC Program	U.S. EPA Region 5 UIC Program
UIC Application Submittal Date	January 17, 2008	May 1, 2008	April 18, 2007
Public Notice Date	June 21-July 21, 2008	Nov 18-Dec 18, 2008	July 23-Aug 23, 2007
Permit Issued Date	September 3, 2008	February 26, 2009	December 19, 2007
Permit to Inject Date	September 23, 2008	September 10, 2009	February 18, 2008
Injection Start Date	September 24, 2008	September 20, 2009	February 19, 2008*
Injection Stop Date	November 22, 2008	September 25, 2009	March 8, 2008*
Site Closeout	February 24, 2011	April 12, 2010 (final Sept. 2011)	March 2010 (converted to Class II well)

*Note: Michigan Basin extended injection completed from February 25 through July 9, 2009.

The UIC permit itself provides organization and procedures to the overall injection process, and ensures that the UIC permitting agency is engaged early in the process. The permitting process for each of the three sites, shown pictorially in Figures 5-1 through 5-3, was similar, but with some differences. Typically, drilling permits were obtained from state oil and gas agencies. The permit required for CO_2 injection was a Class V UIC permit in all three cases. At the Michigan Basin and Appalachian Basin sites, test wells were drilled on exploratory drilling permits from state oil and gas divisions. Information from the test wells was then used to obtain the actual UIC permit. At the Cincinnati Arch site in Boone County, Kentucky, a UIC permit was required by U.S. EPA Region 4 before any drilling could take place. From submitting the application to obtaining the permit, it may take 6-12+ months to complete the initial U.S. EPA UIC permit.

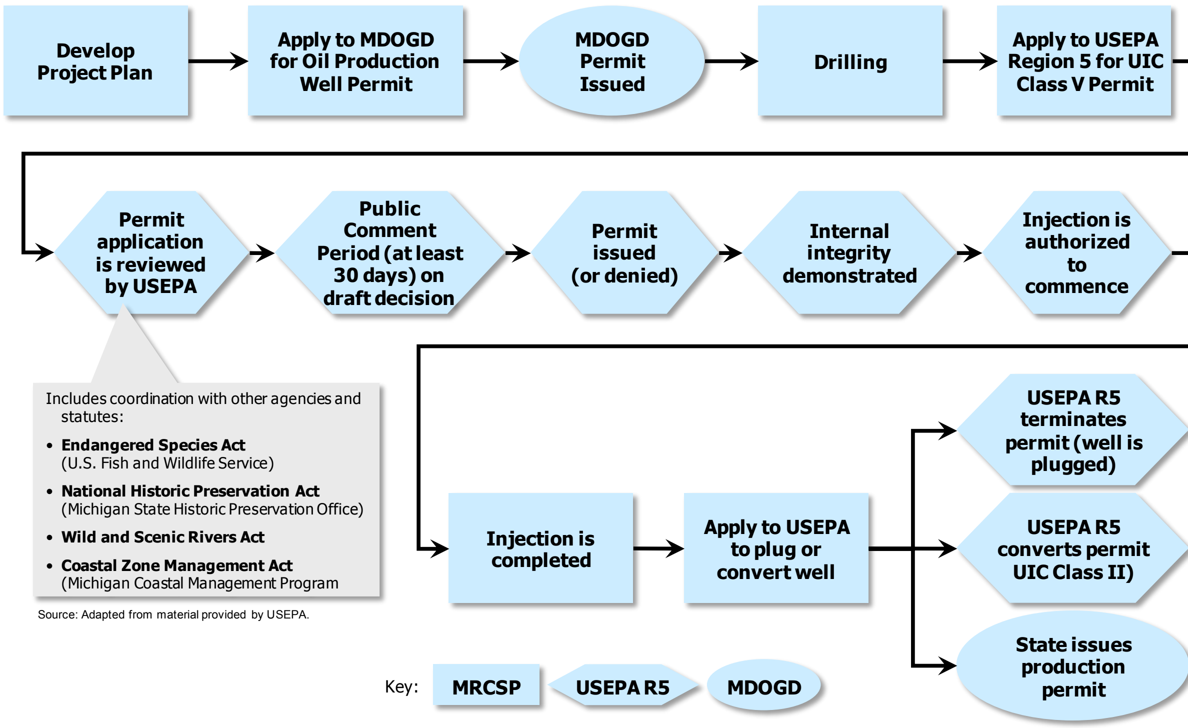


Figure 5-1. U.S. EPA Region 5 Permitting Process for Michigan Basin Test Site, Michigan

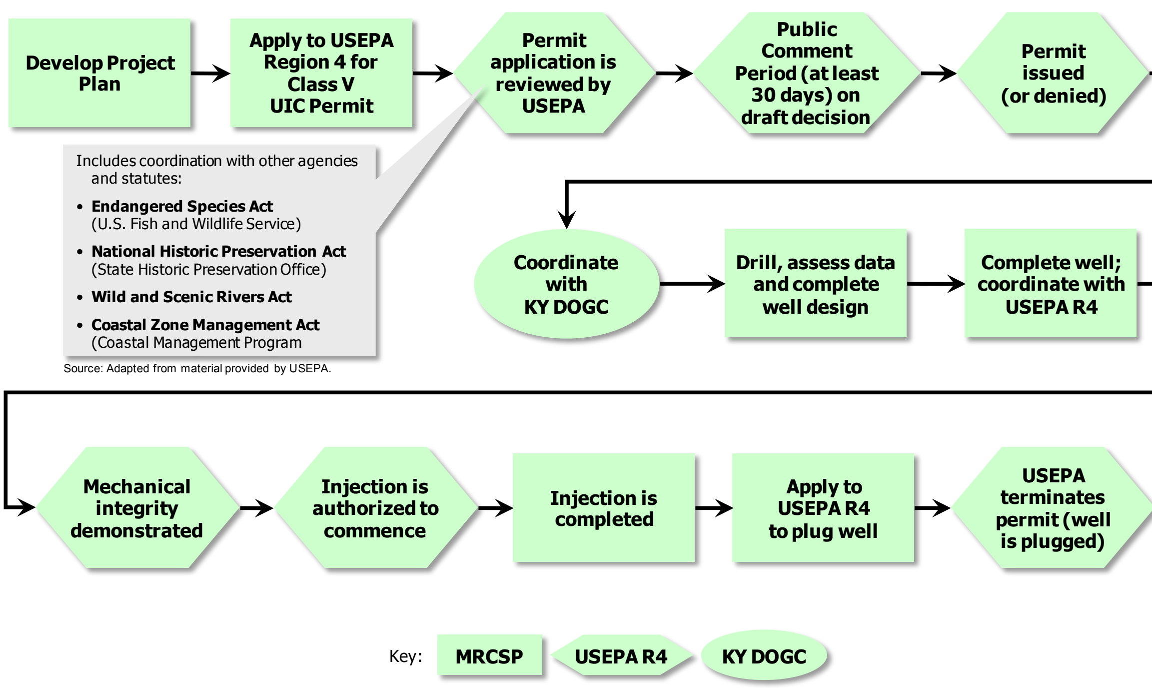


Figure 5-2. U.S. EPA Region 4 Permitting Process for Cincinnati Arch Site, Kentucky

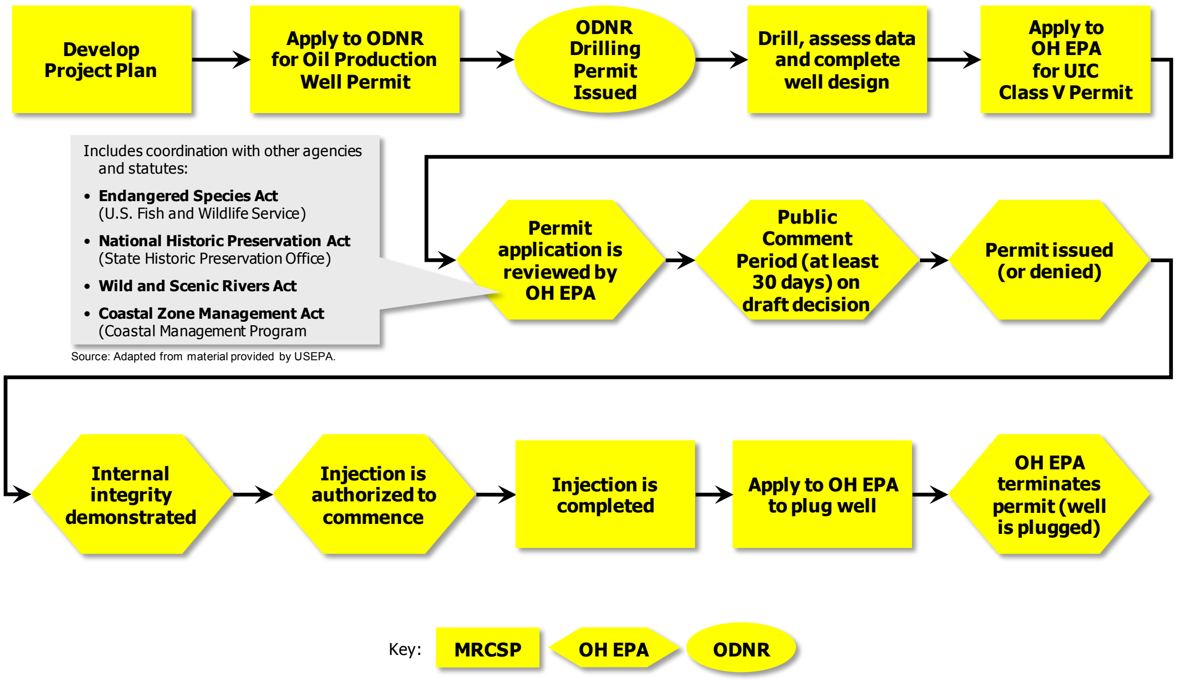


Figure 5-3. U.S. EPA Region 4 Permitting Process for Appalachian Basin Site, Ohio

Experiences at the three geologic test sites revealed several key steps in the regulatory process. All states required a permit to drill a deep exploratory well through the state oil and gas division. This permit required a survey plat of the drill site, well construction diagram, site restoration plan, blow out prevention, application fee, etc. These permits were fairly standard due to historical oil and gas operations in the region.

Preparation of the UIC permit package was much more involved and included a description of the geologic setting, injection targets, containment layers, well design, monitoring, and many other items. The area of review was set at the default minimum ¼ mile for all test sites, based on advanced computer simulations of the CO_2 injection process. Once the permit application was submitted, each EPA agency performed a technical review and provided comments. Most EPA comments were minor technical details. After comments were addressed, the EPA permit writer prepared a draft permit. These permits contained a large amount of standard language from the state or federal code of regulations.

All three draft permits were posted for 30-day public comment. This involved posting the permit in local newspaper(s), sending a copy to the local libraries, posting the notice on the EPA Web site, and sending permit notices to a distribution list (about 100 to 200 parties). At the Michigan Basin site, a comment on subsurface trespassing delayed the permit about 3 months as the permit was sent to the U.S. EPA Environmental Appeals Board. No major comments were received for the other two field sites.

Before injection was allowed to begin, the relevant EPA agency granted a final ―permit to inject” letter. This required field work such as well completion, cement bond log, and mechanical integrity pressure leak-off test to demonstrate mechanical integrity of the well. At each site, injection started within a few days after receiving the permit to inject.

During operations, monthly reports were sent to EPA agencies summarizing injection flow rates, wellhead pressures, and other operational data. Site closure required sending a plugging and abandonment plan for the injection well to the EPA agency for approval.

Each of the three EPA agencies required plugging the well to surface with normal well cement. Region 4 was unique among the three in requiring quarterly groundwater monitoring in 11 water wells around the test site for an additional two years after injection stopped.

5.2 Regulatory Assessment for New Jersey

The state of New Jersey joined the MRCSP about halfway through the Phase II period of performance. As part of the effort to bring the database for New Jersey in line with that already existing for the other MRCSP states, an assessment of the regulatory processes in the state that might affect implementation of sequestration technologies in the state was conducted.

Like New York and Maryland, New Jersey is part of the Regional Greenhouse Gas Initiative (RGGI), an initiative of the Northeast and Mid-Atlantic States of the U.S. (Pennsylvania is an observer of the RGGI process). RGGI includes a regional budget, or cap, for CO_2 emissions from the power sector. The RGGI effort includes a market-based system that allows emission trading through auctions and investment of proceeds in consumer benefits: energy efficiency, renewable energy, and other clean energy technologies.

Underground injection in New Jersey is regulated by the NJDEP Bureau of Nonpoint Pollution Control. NJDEP has authority for Class I and Class V UIC wells. In general, there are many Class V wastewater disposal wells in the state, but not a history of deep well waste injection. One CO_2 storage related project has been proposed in New Jersey, the PurGen One Integrated Gasification Combined Cycle Project in Linden, New Jersey. CO_2 will be sequestered more than 70 miles offshore if the project proceeds.

A number of the CO_2 storage targets being considered for New Jersey are located offshore in the Atlantic Ocean. Consequently, the status of offshore regulations related to drilling and deep well injection was reviewed. No formal regulation for CO_2 storage in offshore geologic formations has been established. Offshore oil and gas drilling is prohibited along the East Coast.

Nationally, the regulation of offshore CCS will likely be managed by the Bureau of Ocean Energy Management, Regulation and Enforcement, also known as the Bureau of Ocean Energy, formerly known as the Minerals Management Service. This agency of the United States Department of the Interior manages the nation's natural gas, oil and other mineral resources on the outer continental shelf. The moratorium on offshore drilling leasing is currently set to expire in 2012, at which point leasing of offshore drilling areas could be banned again given the 2010 Deepwater Horizon oil spill in the Gulf of Mexico.

U.S. EPA released proposed policy on *Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide Sequestration (GS) Wells* for comment on December 10, 2010. The policy established a new ‗Class VI' CO_2 injection well category. The policy became effective on January 10, 2011. The Class VI UIC regulations are designed to mainly protect USDW from contamination via injected fluids. The policy includes requirements for site characterization, testing, monitoring, and operations. The new class also requires an ‗emergency and remedial response plan' and ‗post injection site care and closure' plan. At this time, there are no Class VI CO_2 injection projects in the MRCSP region. However, some of the Class VI proposed well construction and monitoring requirements were required at the Phase II test sites, even though the wells were permitted as Class V experimental CO_2 injection wells.

5.3 Regulatory Analysis of Topical Issues

Initially, there was little precedent for CO_2 injection in the MRCSP region, aside from a few enhanced oil recovery fields. MRCSP Phase II geologic test sites were spread throughout the region with different agencies at each site (Table 5-1). Completing the permit process at three separate field sites provided direct benefits for the MRCSP region by helping to establish CO_2 storage knowledge and experience with various EPA and state regulatory agencies in the region.

Over the span of MRCSP Phase II, there were significant developments regarding regulating CO_2 storage projects. The U.S. EPA prepared a guidance document using class V experimental technology well classification for pilot geologic sequestration projects (U.S. EPA, 2007). Toward the end of Phase II, the U.S. EPA started work on new —Class VI” well guidelines for commercial-scale CO_2 injection. The MRCSP consulted with U.S. EPA during the preparation of these Class VI regulations to ensure that Phase II experiences were considered with the goal of finding better ways to streamline the permitting process and to develop regulation that supports sequestration. The Class VI regulations were finalized on January 10, 2011.

Issues such as subsurface property rights and long term liability were not directly addressed by the small-scale validation tests. A more systematic legal and regulatory approach as well as a comprehensive liability system that properly allocates risks and costs are considered to be key elements towards developing geologic carbon sequestration as an established commercially available technology

Section 6.0: STAKEHOLDER OUTREACH

The MRCSP outreach program was designed to build a foundation of public awareness for carbon sequestration. The MRCSP approach relied on insight from social science literature involving the role of values and perceptions in developing opinions about a new technology, as well as principles of good science communication. Surveys in the U.S. and abroad provided empirical data about factors affecting public acceptance of carbon sequestration.

Outreach performed during Phase II provided information to stakeholders and the general public and sought feedback to enable the project team to understand and address public perspectives and issues that could affect progress at the field demonstration sites, as well as the long-term viability of carbon sequestration technologies. Phase II stakeholder outreach activities encompassed:

- Local, site-specific activities: focused outreach near sites where geologic and terrestrial sequestration projects are being conducted.
- Regional communication and education: regional communication, with continued use of the MRCSP's interactive Web site (www.mrcsp.org) supplemented with other activities as needed.
- Broader research: identification of factors that shape public acceptability and the long-term viability of sequestration technologies.

In addition, a number of meetings were held with the MRCSP Partners, industry, professional associations, government/public sector, academic institutions, and other civic groups. The hands-on involvement of many entities in the region to carry out the field tests including MRCSP partners, regulators, and hundreds of vendors was considered very effective in fostering learning about sequestration technologies at a level that will be needed for commercial implementation.

6.1 Local, Site-Specific Outreach

6.1.1 Terrestrial Field Tests. While the majority of local, site-specific outreach was geared towards the geologic field tests, some outreach was conducted early in the Phase II program for the terrestrial field tests. Outreach activities of particular note include a visit and follow-up interactions at the Blackwater National Wildlife Refuge Center and a workshop for farmers involved in the cropland research.

In November 2006, a visit was made by DOE officials to the Blackwater National Wildlife Refuge Center to view the MRCSP terrestrial field test being conducted by the University of Maryland. Following a presentation by U.S. Fish and Wildlife staff and the University researchers, participants embarked on small boats to visit the actual site. Following the visit, revised fact sheets were prepared and mailed for distribution through the Visitors' Center. A presentation on the MRCSP project by the University of Maryland was made at the Center's Annual Science Meeting in March 2007.

In February 2007, the Outreach Team organized a workshop for farmers involved in the croplands research. The workshop provided a valuable opportunity to exchange lessons learned, including farmers' views on climate change, challenges and research needs.

6.1.2 Geologic Field Tests. A stakeholder outreach effort to communicate project progress to the local community, general public, and scientific community was undertaken with each of the three geologic field tests in Ohio, Kentucky and Michigan. The support and close involvement of field test host and local project participants (with ties to the test site community) were key in communications with local stakeholders. Each project had a unique set of issues in terms of public acceptance; however, typical Phase II outreach activities included:

- Forming an outreach team for each geologic field test site
- Identification of stakeholders
- Development of informational materials, including video and other media development, such as content for the Web site
- Media interviews and press releases
- Briefings for local officials in the host site area
- Informal meetings and discussions with key officials and community opinion leaders
- Presentations and small group meetings with various local businesses, civic and environmental stakeholder groups
- Public meetings associated with permitting

The outreach teams included outreach and technical staff members from the organizational partners involved in the research. The outreach team developed a series of plans linked to technical stages of the project that established specific outreach objectives and the actions to be taken with identified stakeholders. The outreach objective and example outreach activities for key project stages are shown in Table 6-1. The outreach team identified with stakeholders at all levels (local, state and national) to ensure that they were aware of the need and potential benefits of the project, as well as planned field activities at each stage of the project. The outreach team also identified stakeholder concerns that would need to be addressed if this new technology was deployed on a large scale.

Table 6-1. Project Stage, Outreach Objectives, Sample Outreach Activities for the Phase II Field Validation Tests

Project Stage	Outreach Objectives	Sample Outreach Activities
Announcing the field test location and initiating site characterization activities	• Identify and inform key stakeholders about upcoming activities • Seek agreement from property owners for access where needed for seismic survey • Prepare for potential media coverage or public inquiry.	• Development of a short list of ―talking points” and answers to ―frequently asked questions” to ensure consistency in communication among all involved staff with stakeholders and the media. • Preliminary identification of stakeholders and potential issues, drawing on personal experience and background research. • Informal conversations with key state and local leaders/stakeholders.
Submission and review of injection permit to the regulators	• Build public awareness and support, secure injection permit • Coordinate with regulators in preparing for potential requirements for a public hearing • Prepare for media and stakeholder inquiry.	• Ongoing employee information updates. • Make informal telephone calls and face-to-face meetings with key stakeholders to provide an update on site activities and identify potential issues of public concern and need for additional outreach. • Host open house/informal public information meeting to share information about the project and the context/reason for the field test.(1)

Table 6-1. Project Stage, Outreach Objectives, Sample Outreach Activities for the Phase II Field Validation Tests (Continued)

Project Stage	Outreach Objectives	Sample Outreach Activities
Injection operations	• Focus attention on the research • Respond to questions • Further build public awareness and support.	• Providing updates to individual stakeholders who have requested them. • Planning and implementing media event(s). • Developing and posting updated project snapshots on the Web site.
Dissemination of results	• Maintain information flow and relationships with key stakeholders • Share information with broader set of stakeholders.	• Assist with dissemination of results to professional groups through conferences and scientific journals. • Disseminate results to local and regional stakeholders through informal meetings and telephone calls, web updates, briefings, fact sheets, press releases and feature articles.

(1) U.S. EPA regulations require that members of the public be notified that a draft permit has been issued and have an opportunity to comment before it becomes final. Some regions and states automatically hold a public meeting to record public comments; others do so only if a meeting is requested. The R.E. Burger site was the only site where the regulator required a public hearing; open houses were held at all three sites to provide an opportunity for informal interactions and learning.

This effort involved early identification of stakeholders followed by engagement with these stakeholders well in advance of any public announcement or press coverage of the planned test. The level of outreach increased as the permitting process got underway and preparations were made for a project informational meeting or formal public meeting associated with review and comment on the draft permit submitted. The outreach team provided points of contact and project-related information on the MRCSP Web site. The host sites held informational meetings for nearby residents, including a series of exhibits and take-home materials, as well as opportunities for one-on-one discussions with technical staff.

To the extent possible, a proactive approach was followed in order to address potential issues before they arose. For example, talking informally with key community opinion leaders enabled the outreach team to learn about community dynamics and likely issues of concern to local stakeholders. The team could then better frame the project and plan outreach activities and informational materials that addressed these concerns. For example, project materials for each site addressed what neighbors would be likely to see or hear during the field demonstration to mitigate any concerns that the project would be disruptive. As another example, before seismic testing began, Duke Energy mailed a ―Dear Neighbor” letter explaining the project to over 1,300 stakeholders, conducted a briefing for local officials, and held a public meeting at the site (primarily because the seismic survey extended off of plant property onto properties adjacent to the plant site). The ―Dear Neighbor” letter resulted in a number of questions being raised, which were in turn answered by sending response letters to anyone who submitted questions. Overall, the mixed format of a presentation and informal discussion at the open house was effective in facilitating a level of comfort about the project — people were able to express concerns and team members could respond in an individualized manner. The upfront work conducted by host site staff with key stakeholders and the local media was valuable, as was the active participation of the Kentucky State Geological Survey. As a result of the feedback received, both from neighbor questions and the briefing, seismic testing was delayed until after crop harvest to prevent damage to crops and allow for ease of access through neighboring fields.

Informational materials including fact sheets, videos, and hands-on displays and models were developed and used very effectively in the communication process. For example, a hands-on informational display was developed by Western Michigan University to demonstrate the key geologic concepts at public meetings (Figure 6-1). This display consisted of six posters describing the geology of Michigan and definitions of geologic terms, and rock cores of varying permeability connected to bicycle pumps. The objective of the experiment was to show that permeable rocks can store the CO_2 and impermeable rocks can keep the CO_2 confined. Using the bicycle pump, participants were able to push air through the permeable rocks but not the impermeable one.

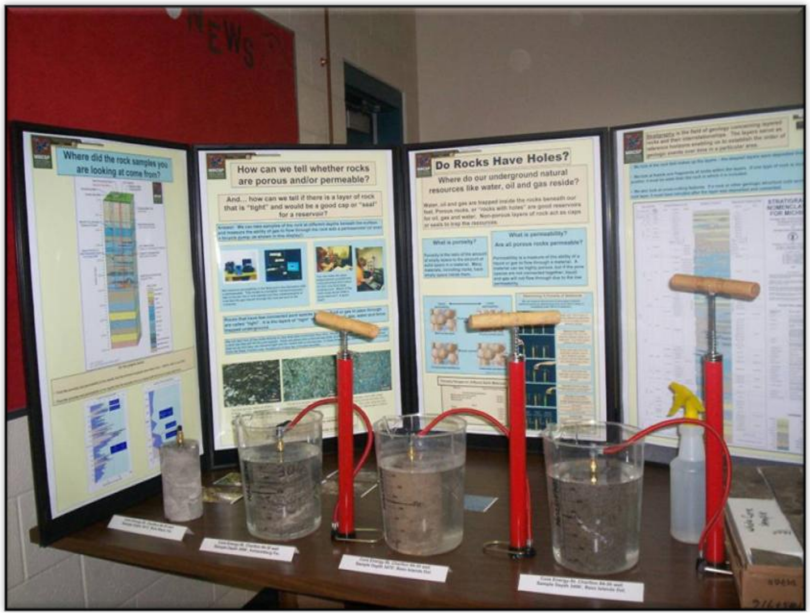
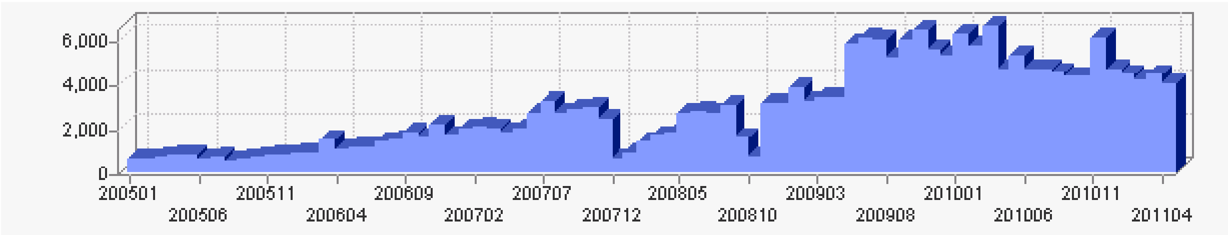


Figure 6-1. Hands-on Display Developed by Western Michigan University Proved to be an Effective Communication Tool of Key Geologic Concepts

6.2 Regional Communication and Education

MRCSP used the MRCSP Web site (www.mrcsp.org) as a primary vehicle for regional communication, as well as a source of information about individual site activities. The goal of the Web site was to increase the prominence of all field validation tests, as well as new events and activities. A key feature of the Web site was the periodic posting of ―snapshots" – a series of photographs, accompanied by a brief summary of site activities to tell the project story graphically and in relatively simple terms. MRCSP project reports, presentations, project specific facts, and more general fact sheets that apply to all MRCSP activities also were made available to the public at the Web site. Other information, such as copies of exhibits shown at the public informational meeting held about the project, also was posted on the Web site. Regular updates were provided as the technical activities progressed. In addition, information about the Ohio Stratigraphic Test well was posted on the Web site, including a fact sheet, press release, and a link to the ODNR, Division of the Geologic Survey Web site, which provided project updates.

Figure 6-2 shows a summary of the monthly site visits and page views generated by the Web site statistical software. A ―visit" happens when someone or something (i.e., Web robot or spider) visits the site. Each visit consists of one or more page views/hits. One visitor can make multiple visits to the site. An overall increasing trend in site visits was observed, with a sharp increase occurring following the announcement of the first Phase III project in the May/June 2009 time frame. As shown in the summary statistics, the site received an average of 2,780 visits per month between January 2005 and April 2011. 85% of the Web site visits were the result of direct traffic (e.g., via a bookmark). By far, the length of time spent on the Web Site during a visit was one minute or less (84% of the visits); 5% was between 1 and 5 minutes; 6% was between 5 and 60 minutes; and 5% percent was more than 60 minutes.



Detail Monthly Activity

	Hits	Page Views	Visits	Bandwidth
Total	555389	311554	211266	0.00 MB
Maximum	14532	8661	6548	0.00 MB
Minimum	1441	912	474	0.00 MB
Average	7308	4099	2780	0.00 MB

Figure 6-2. Monthly Activity on the MRCSP Web Site (note: includes Spiders)

Another Web site statistic that was tabulated is the number of file requests for particular pieces of information. The MRCSP Phase I Final Report and the MRCSP Phase 1 Geologic Characterization Report were the most downloaded files, followed by project-specific fact sheets and presentations for the Phase II geologic tests, which indicates both a broad and local interest in the materials presented in the Web site. A snapshot of the Web site statistical tabulator is shown in Figure 6-3.

Most Downloaded Files

	Filename	File Requests	% of Total File Requests
1	userdata/Phase I Report/MRCSP_Phase_I_Final.pdf	58802	24.29%
2	userdata/mrcsp_report_geo.pdf	20661	8.53%
3	userdata/Fact Sheets/Michigan.pdf	7071	2.92%
4	userdata/Cincinnati Arch/East Bend Briefing.pdf	6140	2.54%
5	userdata/Michigan/Michigan Basin Briefing 3-20-07.pdf	5932	2.45%
6	userdata/Phase I Report/mrcsp_report_geo.pdf	5676	2.34%
7	userdata/Fact Sheets/Geologic Sequestration.pdf	5350	2.21%
8	userdata/appalachain basin/project briefing first energy projec.pdf	4258	1.76%
9	userdata/Fact Sheets/MRCSP.pdf	2995	1.24%
10	userdata/Phase I Report/section 4.pdf	2766	1.14%

Shows the top 10 files most downloaded from the site. Note: due to the large size of the Phase I report and the Phase I Geology Report, the download manager breaks up the file into segments and downloads a few segments at a time, which inflated the number of file requests.

Figure 6-3. Top 10 File Requests on the MRCSP Web Site

Other Regional Outreach Activities. An additional outreach activity that was conducted at the regional level was the training program provided by the Keystone Center for middle and high school teachers. MRCSP took advantage of the DOE/NETL-funded opportunity to provide information and helpful curriculum materials to teachers to use in the classroom to educate and increase awareness among the next generation of stakeholders (www.keystonecurriculum.org). Two educational workshops for middle and high school teachers were held in conjunction with the Keystone Center: an initial one-day workshop was conducted at the 2007 annual conference of the Science Education Council of Ohio in Dayton, Ohio, and a two-day workshop was held at the Columbus Metro School the following summer. In both workshops, teachers conducted several labs and activities that documented the full climate change/sequestration curriculum.

The outreach team also provided assistance to the Science Media Group (part of the Harvard-Smithsonian Center for Astrophysics) in creating a video for high-school teachers on carbon sequestration, using the R.E. Burger plant experience. The Science Media Group filmed the documentary on geological sequestration at the R.E. Burger site on January 24–25, 2007 and followed up with additional interviews at Battelle‘s headquarters and the Ohio Geological Survey Core Lab. The documentary is part of a series on energy being produced by Annenberg Media which is being used for educating teachers about sequestration. The video is accessible via a link on the MRCSP Web site or directly at http://www.learner.org/resources/series209.html.

Outreach experience also was shared as part of the regional activities underway at regularly held meetings, in increased interaction with state regulators and legislative officials, and presentations to professional and other organizations. For example, US EPA Region 5 scheduled a workshop in July 2009 in Angola, Indiana, for both the MRCSP and the Midwest Geological Sequestration Consortium to present information on the broad range of technical, regulatory and outreach ―lessons learned" across both regions.

6.3 Broader Research

Broader research was performed to identify factors that shape public acceptability and long term viability of sequestration technologies via focus groups and other research was another element of the Phase II program. Focus group discussions, for example, provided a valuable tool for understanding stakeholder perspectives and developing communication approaches and materials that were responsive to local needs and preferences. Early in Phase II, the MRCSP collaborated with two other partnerships (West Coast Regional Carbon Sequestration Partnership [WESTCARB] and the Southwest Regional Partnership on Carbon Sequestration [SWP]) in conducting a series of focus groups that used a common discussion protocol. Although the MRCSP focus groups were conducted in Columbus and not at a test site location, the research was very useful in confirming the social factors that affect stakeholders‘ perception of carbon sequestration. MRCSP has presented these results, which drew on the collaborative research conducted with the SWP and WESTCARB partnerships, in several papers (Bradbury et. al., 2008). At all three locations, social factors, such as existing low socioeconomic status, desire for compensation, benefits to the community and past experience with government, were of greater concern than concern about the risks of the technology itself. Three factors seem to influence a community‘s sense of empowerment: history of environmental problems, relationship to the oil and gas industry, and socioeconomic status. In Ohio, issues of trust were central to focus group participants‘ perceptions of CCS in that they doubted the ability of the government or the project developers to ensure their safety.

Monitoring and incorporating lessons learned was conducted on an on-going basis. These included team review and discussions of meetings and activities, recording and following up on issues raised in meetings and discussions with stakeholders, tracking media reports, touching base informally with key stakeholders and noting questions received by the Web site administrator. DOE/NETL formed an outreach working group, composed of Outreach Coordinators from the other DOE partnerships, to conduct regular conference calls and meetings for discussion of activities and issues; to provide updates on events occurring at the national and international level; to provide assistance on particular documents such as developing user friendly products for the media; and to contribute to the development of videos for the general public. The direct site experience provided valuable information that was shared as part of the regional activities underway at regularly held meetings, in increased interaction with state regulators and legislative officials, and presentations to professional and other organizations. Outcome of this research culminated in the NETL manual describing the Best Practices for Public Outreach and Education for Carbon Storage Projects (DOE, 2009).

6.4 Meetings, Presentations, Papers and Reports

A number of meetings were held with the MRCSP Partners, industry, professional associations, government/public sector, academic institutions, and other civic groups to foster learning about sequestration technologies and to share information about the MRCSP validation tests and its Phase II program. The Partner's meetings were held once to twice per year, as well as annual project review meetings with NETL. A detailed description of various stakeholder interactions and a bibliography of publications are included in Attachment 1.

In addition, a number of topical reports were prepared; these are listed in Table 6-2.

Table 6-2. Description of the MRCSP Phase II Topical Reports

Report Title	Description
Appalachian Basin - R.E. Burger Plant Geologic CO_2 Sequestration Field Test	Detailed report on the geologic injection test conducted at FirstEnergy's RE Burger power plant
Mt Simon Formation - Duke Energy East Bend Generating Station Geologic CO_2 Sequestration Field Test	Detailed report on the geologic injection test conducted at Duke's East Bend generating station near Rabbit Hash, Kentucky
Michigan Basin Geologic CO_2 Sequestration Field Test	Detailed report on the geologic injection test conducted in Otsego County Michigan
Best Practice Manual for Midwest Regional Carbon Sequestration Partnership Phase II Geologic Sequestration Field Validation Tests	Summary of best practices for geologic sequestration based on MRCSP geologic field tests
Midwest Regional Carbon Sequestration Partnership 2005 - 2010 Phase II Final Report on Carbon Sequestration in Croplands	Detailed report on a terrestrial field test conducted on selected cropland sites in Ohio, Indiana, Michigan, and Pennsylvania under subcontract to The OSU
Midwest Regional Carbon Sequestration Partnership Phase II Report Carbon Storage on Mineland Reclamation Sites	Detailed report on a terrestrial field test conducted on selected reclaimed mineland sites in West Virginia under subcontract to WVU
Midwest Regional Carbon Sequestration Partnership Phase II Assessment of Terrestrial Sequestration Potential in New Jersey	Prepared by NJDEP, this report identifies and delineates the dominant land use types in New Jersey which offer feasible opportunities for terrestrial sequestration opportunities and includes a detailed report on a terrestrial field test conducted on forested wetlands in New Jersey by Rutgers through the NJDEP.
Preliminary Characterization of CO_2 Sequestration Potential in New Jersey and the Offshore Coastal Region	Prepared by New Jersey Geological Survey, in conjunction with Rutgers University, this report provides the preliminary characterization of geological sequestration potential in the state of New Jersey and adjacent offshore region including the continental shelf and slope.

Table 6-2. Description of the MRCSP Phase II Topical Reports (Continued)

Report Title	Description
Geologic Assessment of the Ohio Geological Survey CO_2 No. 1 Well in Tuscarawas County, Ohio and Surrounding Vicinity.	Report on the stratigraphic test well drilled to the pre Cambrian basement in northeastern Ohio
Understanding Deep Coal Seams for Sequestration Potential - MRCSP Phase II Topical Report.	Report of a field test conducted under subcontract to CONSOL on a selected coal seam in Pennsylvania as a candidate for CO_2 storage combined with coalbed methane recovery
• Executive Summary of the Overall Phase II regional characterization Effort • A Regional Geologic Characterization and Assessment of Geologic Carbon Sequestration Opportunities in the Upper Cambrian Mount Simon Sandstone in the Midwest Region • Characterization Of Geologic Sequestration Opportunities In The MRCSP Region: Middle Devonian-Middle Silurian Formations • Evaluation of CO2-Enhanced Oil Recovery and Sequestration Opportunities in Oil and Gas Fields in the MRCSP Region • MRCSP Phase II–Reassessment of CO_2 Sequestration Capacity and Enhanced Gas Recovery Potential of Middle and Upper Devonian Black Shales in the Appalachian Basin • Storing and Using CO_2 for Enhanced Coalbed Methane Recovery in Unmineable Coalbeds of the Northern Appalachian Basin and Parts of the Central Appalachian Basin	Various reports updating the regional geologic characterization and mapping conducted by the MRCSP Geological Survey Research Team

DOE is also compiling lessons learned from the MRCSPs in a series of six best practices manuals. Three of these manuals (Monitoring Verification and Accounting of CO_2 Stored in Deep Geologic Formations; Public Outreach and Education for Carbon Storage Projects; and Site Screening, Site Selection and Initial Characterization of CO_2 in Deep Geologic Formations) can be downloaded from the NETL Carbon Sequestration Reference Shelf (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/refshelf.html). The remaining three manuals, which include Simulation and Risk Assessment; Well Construction, Operation and Completion; and Terrestrial Sequestration, will be released in the 2011 timeframe.

Section 7.0: CCS DEPLOYMENT WITHIN THE REGION

7.1 Introduction

When the Intergovernmental Panel on Climate Change (IPCC) released its Special Report on Carbon Capture and Storage in 2005, they found no major technical or knowledge barriers to the adoption of geological storage of captured CO_2 (IPCC, 2005). Studies on potential CO_2 storage capacity indicated an enormous potential capacity for storage in deep saline formations and also a large potential capacity in the depleted oil and gas fields. The capacity of these formations is likely more than enough to meet CO_2 storage needs from industry for the next century. However, several key technology gaps were identified. Most significant was that an integrated commercial-scale coal or natural gas power plant with CCS has yet to be built. Hence, data on integrated operation, reliability, and environmental performance from commercial-scale plants are not yet available. Another significant barrier towards wide-scale deployment is cost: more research is needed in new technologies to reduce the capture cost penalty. Other challenges include legal and regulatory barriers: pore space access, storage site access, pipeline access, geologic storage longer term liability/stewardship, financial support, and public acceptance.

As of 2010, there are four commercial CO_2 capture and storage facilities: Sleipner West Field located in Norway, Great Plains Synfuels Plant/Weyburn EOR Project located in Canada, In Salah Natural Gas Production Facility located in Algeria, and Snøhvit LNG Project located in Norway. These commercial CCS projects utilize a broad range of CCS technologies, proving at a high level the technical viability of geologic CO_2 storage technologies. While the components behind geologic storage are technologically mature, significant challenges still remain with regard to developing monitoring technologies and deployment at large scale for use by the power industry.

Research development and demonstration (RD&D) programs sponsored by the DOE focus on advancing the state of technology to facilitate widespread, cost-effective deployment after 2020 (Figure 7-1).

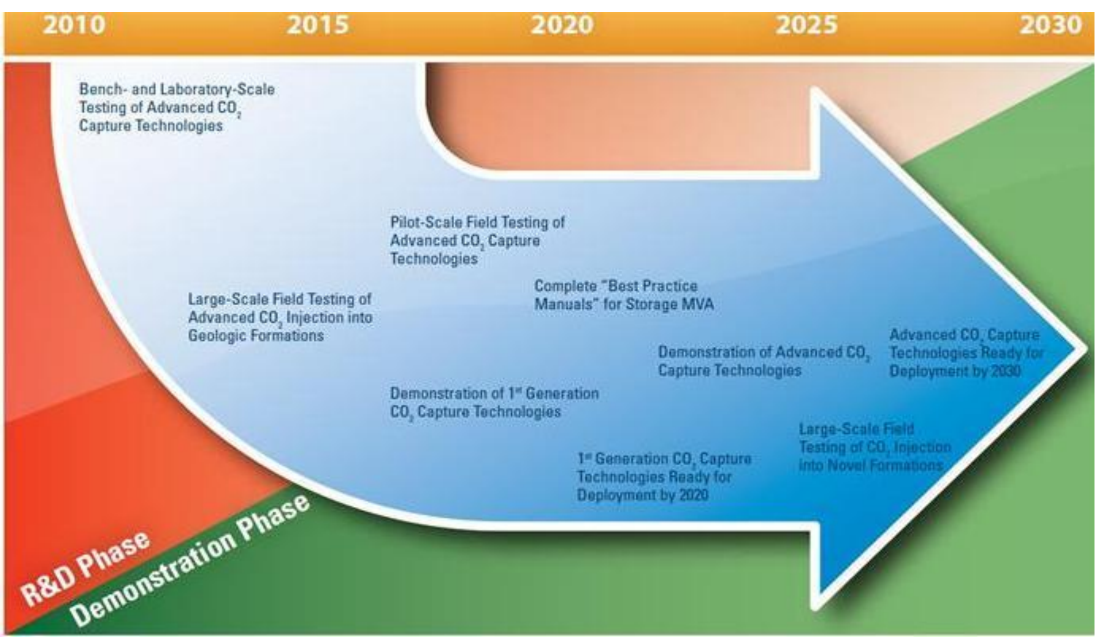


Figure 7-1. DOE/NETL's RD&D Roadmap for CCS Evolution Provides a Suggested Timeline (Source: Capture and Storage RD&D Roadmap, NETL, December 2010)

7.2 Objectives and Scope

MRCSP seeks to be known as a neutral and credible source of scientific information on what is needed to safely and cost effectively implement CCS. Moving forward, the MRCSP will use its diverse membership to achieve the following objectives:

- Facilitate CCS-related education activities
- Engage the public and help industry engage the public
- Perform research and demonstrations
- Develop maps of CO_2 sources and sinks
- Disseminate information: not only MRCSP data but data from other research efforts in the region and as relevant, from other areas of the country and world
- Provide a venue for states to participate in the process.

Phase III (also called the Development Phase) will build on the Phase II (also called the Validation Phase) and includes the goal to demonstrate the potential for geologic CO_2 storage in the region by conducting an injection test of at least one million metric tons of CO_2 into a regionally significant reservoir. The Development Phase will continue integrated efforts by geological surveys from all nine states to map diverse geologic storage potential that will refine the GIS mapping for sources and sinks and help translate the results of field testing into actionable strategies for the stakeholders in the region. Stakeholder outreach and education also will continue in the Development Phase.

7.3 The Challenges Facing CCS Implementation

The known challenges to CCS implementation include the following:

- There is no clear market driver justifying investment in CCS. Legislation widely believed to be needed to enable carbon markets is not felt to be likely to be enacted in the foreseeable future. In the meantime, U.S. EPA is moving forward to regulate CO_2 emissions. This may actually force affected parties to argue against CCS on a Best Available Control Technology basis, which could impede CCS development.
- Public understanding and acceptance of CCS is questionable
    - Public (voter) perception for needing to address climate change is not strong and may be eroding in the wake of a weak economy and controversy over the science. Public apathy or opposition to spending money to address climate change will delay or block attempts by lawmakers to regulate emissions.
    - Public knowledge of CCS as a technology is vague. Concerns about safety include leakage, induced seismic, brine displacement, and mobilization of metals
        - It is also difficult to measure public understanding and acceptance and the roadmap for getting there.
        - Regulatory framework is not well established. There are many unknowns about property rights with respect to pore space. Who owns the pore space and what if any compensation is due to surface owners? Pore space rights may remain vague in the absence of a market for CO_2 to drive commercial value for CO_2 storage.
- Cost of implementation is thought to be high and it is uncertain who would bear the cost: taxpayers, ratepayers, stockholders, or others.

- CCS technology is in a developmental stage. Some would say it is not ready for implementation now or in the next decade, especially for power plants requiring capture.
    - Better subsurface knowledge is needed to select, design, operate and monitor storage projects
        - Many important areas of the MRCSP region lack deep well data, especially Appalachian Basin, but also Michigan Basin and Cincinnati Arch.
        - Beyond the need for more deep well data, reservoir testing is needed to complement seismic, log and core data.
        - Few CO_2 injection tests have been conducted worldwide. More experience is needed, especially in regions of complex geology.
        - Monitoring techniques for CO_2 are largely derived from oil and gas practice. There is limited experience applying and validating them for CO_2 storage.
        - Competing uses for pore space (e.g., brine injection, Class I injection, EOR) need to be evaluated in the context of permanently storing massive amounts of CO_2.
    - Capture technology is still in developmental stages
        - Capital expenditure cost and parasitic load for power plants is perceived to be high for known technologies
        - Field testing of selected capture technologies on a few power plants worldwide has only recently begun and only at a limited scale (~1/100th of commercial scale)
- The risks associated with long-term liability for CO_2 storage are uncertain and could be problematic for many companies.
    - EOR, Class 1, and natural analogues provide some basis for comparison, but there is a lack of field experience directly related to storage and a lack of rigorous monitoring data in general. The result is that there is little precedence for establishing probabilities and consequences for various risk scenarios.
    - Some insurers have expressed interest in the market but products are limited and will be slow to develop without clear market drivers for implementing CCS.
    - Governments in general have been reluctant to deal with issues that would limit liability for private companies (e.g., eminent domain, setting ground rules for law suits, indemnification for long-term storage).

7.4 Elements of an Implementation Plan

Demonstration projects play an important role in paving the way for commercial projects. Validation for the storage potential comes through field assessments of injectivity and containment at three locations: one each in the Appalachian and Michigan Basins and one in the uplifted Cincinnati Arch region. All three field projects were conducted in a series of steps that contribute towards development of best practices for CCS validation that are applicable to the MRCSP region and elsewhere. Although specific practices are highly site dependent, the general steps include initial regional geologic assessment, site characterization through seismic surveys and drilling of test wells, permitting, outreach, development of a CO_2 supply system, injection and monitoring operations, and post-injection monitoring and site closure.

Collectively, the regional mapping and three field demonstrations provide significant insight into geologic storage feasibility over a range of rock types and properties. Two of the tested sites indicate injection and storage rates exceeding 1000 metric tons/day/well. Such rates suggest that commercial-scale applications should be possible. The regional mapping of these zones also indicates that the tested layers are likely to be continuous over a large area, and, therefore, have potential for large-scale, long-term injection operations required for the numerous CO_2 sources in the region. At the R.E. Burger site, all three formations were found to have lower than expected injectivity (although the log and core data indicated low injectivity), highlighting the variability of geologic environments within the complex Appalachian Basin that need to be further explored.

Although the potential storage capacity is significant within the MRCSP, regional implementation is constrained by numerous technical and institutional issues, such as those described above. During the course of the Phase II project, various conversations took place with MRCSP partners and others regarding the likely course of how and when sequestration technologies would be implemented across the MRCSP region and what features of the region would drive that process. In January 2011, a working group of MRCSP partners, including most of the electric utilities in the MRCSP, was convened to specifically discuss the issues affecting implementation in the region. The following is a summary of the conclusions from those discussions:

(1) The region's CO_2 sources are predominantly coal-fired power plants, especially along the Ohio River Valley. These sources are, for the most part, in reasonable proximity to large potential CO_2 storage reservoirs in the region such as the Mount Simon. As a result, the cost of sequestering CO_2 from the majority of the region's sources is driven mostly by the cost of capturing CO_2 from coal-fired plants. Figure 7-2, which was developed in Phase I, shows this characteristic of the region.

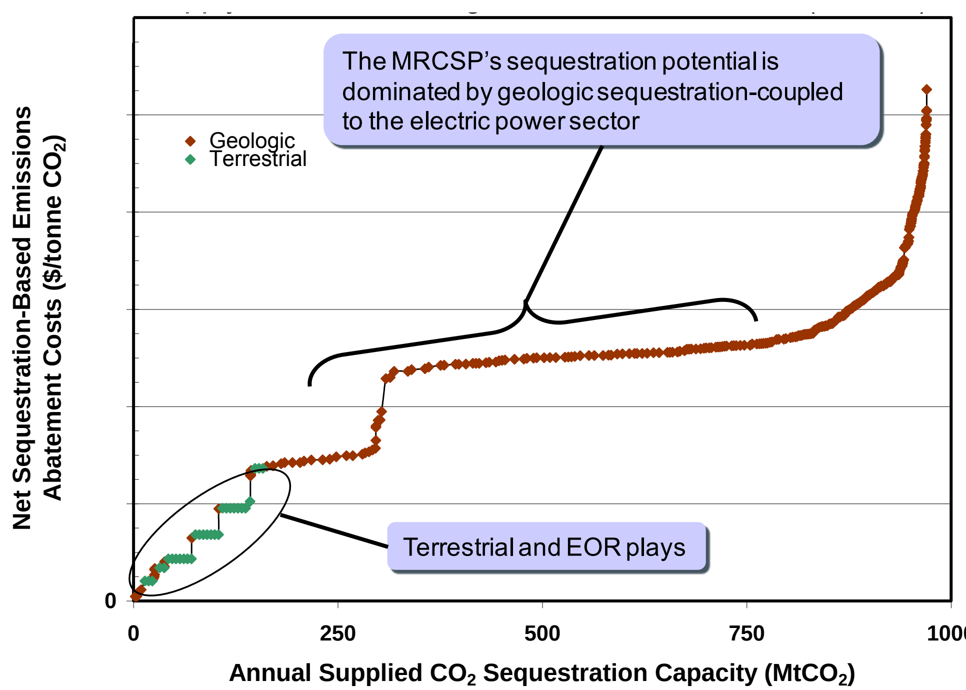


Figure 7-2. Regional Supply Curve from Phase I Effort (c. 2004)

(2) Newly promulgated U.S. EPA rules for controlling air toxics from coal-fired power plants will undoubtedly result in shutting down a number of older, lower capacity factor coal-fired power plants in the region. However, the newer, higher capacity factor plants will probably remain and may increase in capacity factor to make up the difference albeit at reduced peaking reserve margin. An increase in gas-fired generation for the region may also be a side effect, which would tend to reduce the amount of CO_2 produced.

(3) The lack of proven and cost effective capture technology for coal-fired power plants is a deterrent to implementation of geologic sequestration technology in the region given the role coal-fired power generation plays in the region‘s CO_2 emissions.

(4) A number of proposals for pipeline networks connecting the region‘s large sources to sinks have been put forward by various groups, both government and private. Some private proposals would pipe CO_2 to the Gulf Coast, presumably to take advantage of enhanced oil recovery markets and possible future sequestration markets in the Gulf. While interesting and thought provoking, the schemes reviewed to date are highly speculative and some have flawed assumptions regarding the location of likely geologic sinks and which sources would access those sinks.

(5) EOR will likely be a value-added stepping stone to implementation of sequestration technologies in the region given the presence of a number of depleted oil fields in the region in close proximity to major coal-fired power plants. Small-scale tests are needed to further define the EOR potential in the region, particularly in the northeastern Ohio area given its proximity to the Ohio River Valley power generation corridor.

(6) More small-scale tests are also needed to define the sequestration potential in many of the region‘s deep saline formations given the differences in injectivity found in the MRCSP small-scale tests between results based on core and log data versus those found with reservoir testing and actual CO_2 injection.

(7) The northern Appalachian Basin, particularly the Upper Ohio River Valley power generation corridor, is geologically complex with thick but variable sedimentary deposits. It is also in close proximity to many major coal-fired power plants (approximately 52,000 megawatts of coal fired capacity). In addition, there is potential for nearby EOR, which could be a value-added stepping stone to implementation of a CCS infrastructure. More research in the form of seismic data and deep well data are needed to characterize the potential for this key part of the MRCSP region to support sequestration.

(8) Before commercial deployment of sequestration can occur in the region it will be important to confirm and ensure the safety of geologic sequestration through testing such as that carried out in Phase II and planned in Phase III and other tests.

(9) Outreach and education will be critical precursors to broad implementation of geologic sequestration to communicate the importance and safety of geologic sequestration to elected officials and the public.

(10) Issues such as subsurface property rights and long-term liability were not directly addressed by the small-scale validation tests. A more systematic legal and regulatory approach as well as a comprehensive liability system that properly allocates risks and costs is considered to be a key element towards developing geologic carbon sequestration as an established commercially available technology.

(11) An overarching issue affecting the pace of planning for implementation of sequestration in the region is the fact that carbon legislation at state, regional or federal levels does not appear to be imminent at this point in time.

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Workshop/ Symposium/Webinar

Description	Location	Date
Geologic Carbon Sequestration Site Integrity: Characterization and Monitoring Workshop	Columbus, OH	June 7-8, 2010
Symposium and Workshop on Advancing the Science of Geologic Carbon Sequestration	Ohio State University, Columbus, OH	March 9-10, 2009
Conducted a workshop for middle and high school teachers on climate change and carbon sequestration	Columbus, Ohio	Summer 2008
Presented the fundamentals of modeling for geologic storage for the American Water Works Association	Webinar	December 8, 2008
Presentation at New Jersey CCS symposium	Rutgers University	October 28, 2008
Climate Solutions in the Buckeye State and Beyond	Oberlin College, Oberlin, Ohio	April 18, 2008
Conducted a workshop for middle and high school teachers on climate change and carbon sequestration	Dayton, Ohio	Summer 2007
WVU Department of Natural Resource Seminar	Morgantown, WV	September 14, 2007
Presentation on the MRCSP and the geology of the Michigan basin area at a sequestration workshop	Ontario, Canada	February, 2006

Formal Presentations (Conferences, Professional Meetings*)

Description	Location	Date
Geological Society of America North and Central Sections Annual Meeting	Branson, Missouri	April 12, 2010
MRCSP Field Demonstrations overview presentation to the North-Central GSA	Rockford, IL	April 2, 2009
MRCSP Field Demonstrations overview presentation to Northern Ohio Geological Society	Twinsburg, OH	March 4, 2009
AGU Winter Meeting	San Francisco, CA	December 15-16, 2008
Presentation on carbon capture and sequestration (CCS) and MRCSP to environmental stakeholders	Athens, Ohio	October 23, 2008
Presentation and site tour for a group of Electric Power Research Institute (EPRI)/utility stakeholders	Gaylord, Michigan	October 11, 2008
Kentucky Public Service Commission	Frankfort, KY	September 25, 2008
Presented CCS overview and regional partnerships work at an environmental stakeholders briefing arranged by Ohio Environmental Council	Columbus, OH	September 25, 2008
A detailed presentation on the status of Phase II and plans for Phase III was given to a peer review committee organized by IEA	Washington, DC	March 27, 2008
Special Session of the West Virginia Legislature hosted by West Virginia Technology Association	Charleston, WV	January 15, 2008
Presentations and tours were given on all active areas of the project.	Gaylord, Michigan	October 22-23, 2008
American Association of Petroleum Geologists Eastern Section Meeting	Lexington, KY	September 17-18, 2007
Presentation of MRCSP material to Shenhua Group of China	Battelle, Columbus, Ohio	August 31, 2007
Presentation to Fundacion Chile on MRCSP Projects	Battelle, Columbus, Ohio	July 31, 2007
Association of Resource and Environmental Economist Annual Meetings	Portland, OR	July, 30-31, 2007
DOE/NETL Capacity Working Group and National Atlas II Meeting	Pittsburgh, Pennsylvania	June 21, 2007
Region V EPA CO2 Sequestration Meeting	Pokagon, Indiana	March 21-22, 2007
Presentation to Pennsylvania Carbon Management Advisory Group	Harrisburg, KY	March 12, 2007
Presentation to Kentucky Public Utilities Commission and Department of Environment	Frankfort, KY	March 7, 2007
Presentation to the American Society of Biological and Agricultural Engineers	Ohio State University, Columbus, Oh	March 6, 2007
The American Institute of Chemical Engineers-West Virginia University Chapter	Morgantown, WV	March 1, 2007
Presentation of MRCSP seismic analysis overview for University of Houston, Texas	Houston, Texas	February 9, 2007
Presentation for Ohio EPA Division of Water Chief	OEPA Columbus Office	November 6, 2006
Northeastern Agricultural and Resource Economics Association Annual Meeting	Mystic, CT	June 11-14, 2006

*Doesn't include DOE annual review meetings

Stakeholder Interactions, Work Groups, Briefings, Site Tours, Etc.*

Description	Location	Date
Meeting between Ohio Division of Geological Survey (ODGS) and New Jersey Department of Environmental Protection (NJDEP) about Tri Carb project	Rockland, NY	February 9, 2010
Battelle Sponsored Peer Review of MRCSP Geologic Field Tests	Columbus, OH	August 26-27, 2009
Sim-SEQ meeting	Pittsburgh, Pennsylvania	May 7, 2009
North American Energy Working Group (NAEWG) Capacity Estimation Meeting	Pittsburgh, Pennsylvania	May 4, 2009
Meeting with Ohio EPA UIC Program to discuss Phase III TAME seismic survey work plan and overall permit track for Phase III project.	Columbus, OH	May 4, 2009
A site tour for MRCSP partners, community leaders from Greenville Ohio, Ohio EPA, and US EPA Region 5 was held at Test Site in Gaylord Michigan.	Gaylord, Michigan	April 21, 2009
Appalachian Basin test site results meeting	First Energy, Akron, Oh	January 21, 2009
Participated in the CCS collaboration workshop with US, Canada, Mexico as part of North American Energy Working Group	Houston, TX	Dec 2-3, 2008
Test Site Review meeting, NETL	Pittsburgh, PA	October 30, 2008
Participated in a panel discussion on regulatory experiences at the annual meeting of Ground Water Protection Council	Cincinnati, OH	September 24, 2008
MRCSP participated in the Indiana CCS Summit and assisted with breakout session reporting	Indiana	September 3-4, 2008
Meeting at headquarters of the National Rural Electric Cooperative Association to discuss details of the agreement and participation of NRECA in MRCSP	Washington, DC	March 20, 2008
Briefed staff from Ohio State Senators Voinovich (R) and Brown (D) on MRCSP Phase II and Phase II plans	Washington, DC	March 20, 2008
Meeting with Ariel Compression to discuss compressor options for R.E. Burger test	R.E Burger Plant, OH	September 27, 2007
Meeting with Ohio EPA UIC program to discuss schedule for permitting injection tests at R.E. Burger site	Columbus, OH	September 14, 2007
Informal Public Outreach meeting with local community in support of the Michigan Basin CO2 injection tests	Gaylord, Michigan	July 18, 2007
Briefing to Babcock & Wilcox Management	Barberton, OH	April 27, 2007
MRCSP progress review meeting with Pennsylvania Dept. of Conservation and Natural Resources	Pittsburgh, PA	February 22, 2007
Duke Energy site review and seismic discussions for East Bend site	Cincinnati, OH	February 16, 2007
DOE site visit for Burger Project, hosted by First Energy, Battelle and Powerspan	R.E Burger Plant, OH	January 30, 2007

*Doesn't include Partner's Meetings