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March 20, 2006

AAD Document Control
U.S. Department of Energy
National Energy Technology Laboratory
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Dear AAD Document Control:

Subject: Plains CO_2 Reduction (PCOR) Partnership Phase I Final Report;
DOE Cooperative Agreement No. DE-PS26-03NT41982
EERC Fund Nos. 4251, 4334, 4406, and 9039

As requested, enclosed are hard copies of the PCOR Partnership Phase I Final Report and Request for Patent Clearance form for the PCOR Partnership Program that was originally sent on January 4, 2006. The document has been changed; we have excluded the Quarterly Technical Progress Report and the PowerPoint presentation for the Period July 1 – September 30, 2005.

If you have any questions, please call me at (701) 777-5279 or e-mail at esteadman@undeerc.org.

Sincerely,

Edward N. Steadman
PCOR Partnership Manager
EERC Senior Research Advisor

ENS/slw

Enclosures

c/enc: John Litynski, NETL
Sheryl Landis, EERC (patent clearance form)

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U.S. DEPARTMENT OF ENERGY

REQUEST FOR PATENT CLEARANCE FOR RELEASE OF CONTRACTED RESEARCH DOCUMENTS

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♦ Award No.
DE-PS26-03NT41982

Name & Phone No. of DOE COR
John Litynski (304) 285-1339

A. AWARDEE ACTION (AWARDEE COMPLETES PART A. 1-5)

1. Document Title: Plains CO_2 Reduction Partnership (Phase I) Final Report

2. Type of Document: ☐ Technical Progress Report ☐ Topical Report ■ Final Technical Report

☐ Abstract ☐ Technical Paper ☐ Journal Article ☐ Conference Presentation
Other (please specify) _____

3. Date Clearance Needed: _____

♦4. Results of Review for Possible Inventive Subject Matter:

a. ■ No Subject Invention is believed to be disclosed therein.

b. ☐ Describes a possible Subject Invention relating to _____

i. Awardee Docket No.: _____

ii. A disclosure of the invention was submitted on _____

iii. A disclosure of the invention will be submitted by the following date: _____

iv. A waiver of DOE's patent rights to the awardee: ☐ has been granted, ☐ has been applied for, or ☐ will be applied for by the following date: _____

♦5. Signed Sheryl E Landis (Awardee) Date 3-21-06

Name & Phone No. Sheryl E. Landis (701) 777-5124

Address Energy & Environmental Research Center, PO Box 9018, Grand Forks, ND 58202-9018

B. DOE PATENT COUNSEL ACTION

☐ Patent clearance for release of the above-identified document is granted.

☐ Other: _____

Signed _____ Date _____
(Patent Attorney)

Plains CO_2 Reduction (PCOR) Partnership
Practical, Environmentally Sound CO_2 Sequestration

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP (PHASE I) FINAL REPORT

Final Report

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
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Agreement No. DE-PS26-03NT41982
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January 2006

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Plains CO_2 Reduction (PCOR) Partnership
Practical, Environmentally Sound CO_2 Sequestration

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP (PHASE I) FINAL REPORT

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January 2006

ABSTRACT

During the period of October 1, 2003, through September 30, 2005, the Plains CO_2 Reduction (PCOR) Partnership, identified geologic and terrestrial candidates for near-term practical and environmentally sound carbon dioxide (CO_2) sequestration demonstrations in the heartland of North America. The PCOR Partnership region covered nine states and three Canadian provinces. The validation test candidates were further vetted to ensure that they represented projects with 1) commercial potential and 2) a mix that would support future projects both dependent and independent of CO_2 monetization.

This report uses the findings contained in the PCOR Partnership's two dozen topical reports and half-dozen fact sheets as well as the capabilities of its geographic information system-based Decision Support System to provide a concise picture of the sequestration potential for both terrestrial and geologic sequestration in the PCOR Partnership region based on assessments of sources, sinks, regulations, deployment issues, transportation, and capture and separation. The report also includes concise action plans for deployment and public education and outreach as well as a brief overview of the structure, development, and capabilities of the PCOR Partnership.

The PCOR Partnership is one of seven regional partnerships under Phase I of the U.S. Department of Energy National Energy Technology Laboratory's Regional Carbon Sequestration Partnership program. The PCOR Partnership, comprising 49 public and private sector members, is led by the Energy & Environmental Research Center at the University of North Dakota. The international PCOR Partnership region includes the Canadian provinces of Alberta, Saskatchewan, and Manitoba and the states of Montana (part), Wyoming (part), North Dakota, South Dakota, Nebraska, Missouri, Iowa, Minnesota, and Wisconsin.

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PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP (PHASE I) FINAL REPORT

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January 2006

EXECUTIVE SUMMARY

During Phase I (October 1 2003, through September 30, 2005) of U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnership (RCSP) Program, the Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC) at the University of North Dakota, provided significant value to its more than 40 private and public sector partners by developing a suite of practical and environmentally sound strategies for carbon management in the heartland of North America – an area of 1.36 million square miles (352 million hectares) covering nine states and three Canadian provinces. The sequestration strategies were further vetted to ensure that they represented projects with 1) commercial potential and 2) a mix that would support future projects both dependent and independent of carbon dioxide (CO_2) monetization.

The sequestration strategies are derived from the PCOR Partnership's reconnaissance assessments of the region's sources, sinks, regulations, deployment issues, transportation, and capture and separation technologies as well as input from its partners. These findings are contained in twenty-one topical reports and a regional atlas, and the underlying data are housed in the PCOR Partnership's Web-based, georeferenced Decision Support System.

The PCOR Partnership identified, quantified, and characterized over 1000 stationary sources within its defined region during Phase I. These sources have a combined annual output of nearly 502 million tonnes (553 million tons) of anthropogenic CO_2 from stationary sources for which data were readily available. About two-thirds of the CO_2 is emitted during electricity generation, followed by industrial sources, petroleum refining and natural gas processing, ethanol production, and agricultural processing.

Federal and provincial greenhouse gas inventories report that 219 million tonnes (241 million tons) of CO_2 emissions from fossil fuel combustion in the PCOR Partnership region (including the entire states of Montana and Wyoming) in 2000 are products of the nonstationary transportation sector. This is approximately 10% of the combined U.S.

and Canadian total for transportation emissions.

The theoretical maximum terrestrial sink potential is 1.4 billion tonnes (1.5 billion tons) per year for the near term. The Phase I assessment of terrestrial sequestration indicated that this potential is divided between croplands, forestlands, grasslands, and wetlands, with about 10% of the region unsuitable for any type of terrestrial sequestration. The overall geologic sink capacity is estimated at over 219 billion tonnes (242 billion tons), with significant capability for unminable coals (7 billion tonnes [8 billion tons]), oil fields either with an enhanced oil recovery (EOR) component or simply as sequestration that gets in depleted reservoirs (12 billion tonnes [13 billion tons]), and deep saline reservoirs (200 billion tonnes [221 billion tons]). These geologic sinks occur primarily in the substantial geologic basins of the region.

The PCOR Partnership region has the potential to offset its source emissions in the long term. The near-term theoretical idealized maximum 1.4 billion tonnes (1.5-billion ton)-per-year capacity of the terrestrial sinks has the potential to offset the 219 million tonnes (241 million tons) from the transportation sector. The geologic capacity characterized to date could offset 100% of the region's annual emissions from identified stationary sources (502 million tonnes [553 million tons]) for 437 years.

With respect to terrestrial sequestration strategies, modeling determined that although wetlands offer more modest carbon sequestration opportunities than forestlands and agricultural lands overall, wetland restoration offered significant short-term gains in capacity with a reasonable payoff and, therefore, merited field validation testing in Phase II.

With respect to geological sequestration strategies, three source–geologic sink combinations were identified in the Williston and Alberta Basins that have the promise to become market-driven, full-scale sequestration project opportunities and merited field validation testing in Phase II:

- CO_2 (potentially from the Dakota Gasification Company gasification plant) used for simultaneous sequestration and EOR in oil fields proximal to the existing Dakota Gasification Company CO_2 pipeline in the Williston Basin.

- Acid gas (65% CO_2, 35% H_2S) from sour gas plants in Alberta injected into a nearby oil field for simultaneous sequestration and EOR.

- CO_2 injected into economically unminable lignite seams for both CO_2 sequestration and coalbed methane production.

The results from the validation tests of these promising strategies would provide detailed information needed for more robust economic analysis of CO_2 transportation, injection, and monitoring activities that can support the development of similar projects both within the region and elsewhere. In addition, the Phase I assessment for geologic sequestration projects indicates that:

- Amine scrubbing is probably the nearest to being commercially applied to the majority of the large stationary sources (i.e., coal-fired power plants, cement kilns) in the PCOR Partnership region, but development of emerging techniques that show promise should continue to increase the potential for choice and lower costs.

- The CO_2 produced from sources in the eastern portions of the PCOR Partnership region are more likely to be sequestered in geologic sinks in adjacent RCSP Program regions in order to take advantage of the shorter transportation distances.

- Sequestration that is performed concurrently with EOR or enhanced coalbed methane will likely be the primary sequestration performed in the region in the very near term because these options allow for commercial application without a robust carbon offset market in place.

The outreach toolkit developed during Phase I consists of fact sheets, background pieces, newspaper articles, a public Web site, and a 30-minute television production on Prairie Public Television (also available on DVD). This toolkit forms the basis for the ability to provide general information to the public regarding sequestration as well to support the outreach efforts of specific field validation tests.

ACKNOWLEDGMENTS

The PCOR Partnership is a collaborative effort of public and private sector stakeholders working toward a better understanding of the technical and economic feasibility of capturing and storing (sequestering) anthropogenic CO_2 emissions from stationary sources in the central interior of North America. It is one of seven regional partnerships funded by the DOE National Energy Technology Laboratory RCSP Program. The EERC would like to thank the following partners who provided funding, data, guidance, and/or experience to support the PCOR Partnership:

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- Encore Acquisition Company
- Environment Canada
- Excelsior Energy Inc.
- Fischer Oil and Gas, Inc.
- Great Northern Power Development, LP
- Great River Energy
- Interstate Oil and Gas Compact Commission
- Kiewit Mining Group Inc.
- Lignite Energy Council
- Manitoba Hydro
- Minnesota Pollution Control Agency
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Montana–Dakota Utilities Co.
- Montana Department of Environmental Quality
- Montana Public Service Commission
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- Nexant, Inc.
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Industrial Commission Lignite Research, Development and Marketing Program
- North Dakota Industrial Commission Oil and Gas Division
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- North Dakota State University
- Otter Tail Power Company
- Petroleum Technology Research Centre
- Petroleum Technology Transfer Council
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INTRODUCTION

The U.S. currently accounts for a quarter of the 22 billion tonnes (24 billion tons) of anthropogenic carbon dioxide (CO_2) emitted to the earth's atmosphere. However, by 2050 worldwide anthropogenic CO_2 emissions will grow to nearly 45 billion tonnes (50 billion tons), with China and India each accounting for one of every four units released to the atmosphere. During that period, the U.S. CO_2 emissions will grow modestly and account for only one in eight units by 2050.

Pacala and Socolow (2004) state that stabilizing the atmospheric level of CO_2 at 500 ppmv by 2050, twice the recent historic base level, would require concerted, worldwide action to control anthropogenic CO_2 emissions. These authors suggest that the long-term storage of CO_2 in soils or in the subsurface (CO_2 sequestration) would be a major step in reducing and stabilizing the amount of anthropogenic CO_2 released to the atmosphere.

To date, terrestrial sequestration (carbon storage in plants and soils) has played a modest role in the carbon-trading activities of the Kyoto nations. Geologic sequestration, storing CO_2 in the subsurface, shows great promise as indicated by the results from the Sleipner Site in Norway and the Weyburn Site in Canada. Geologic sequestration is a key component of FutureGen, the U.S. Department of Energy (DOE) concept for a highly efficient coal-based zero emission system for producing electricity and hydrogen transportation fuel.

In the spring of 2003, the President's Global Climate Change Initiative called for a reduction in greenhouse intensity of 18%. As part of the response to this initiative, seven regional partnerships were designated in the fall of 2003 under the DOE Regional Carbon Sequestration Partnership (RCSP) Program, led by the National Energy Technology Laboratory (NETL). Under Phase I of this program, these partnerships have worked by region to chart the scientific and regulatory groundwork needed to facilitate the implementation of practical and environmentally sound CO_2 sequestration.

The Phase I activities of the Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC) at the University of North Dakota, took place during the period of October 1, 2003, through September 30, 2005, and were focused in a 1.36-million-square-mile (352 million hectares) area in the heartland of North America (Figure 1). Phase I had a twofold mission:

1) To identify opportunities for terrestrial and geologic sequestration based on an assessment of sources and sinks as well as transportation systems and capture and separation technologies.

2) To develop capabilities for data management, public education, and outreach and to develop plans to facilitate the implementation of validation projects for sequestration in the region.

In order to accomplish this twofold mission, the program was organized around three technical task areas – characterization of sources, sinks, and infrastructure. These activities fed into a modeling and synthesis task and were supported by outreach and information and data management activities. These tasks are illustrated in Figure 2.

Table 1 gives a list of the PCOR Partnership's Phase I products, and the topical reports and fact sheets are

Figure 1. PCOR Partnership region.

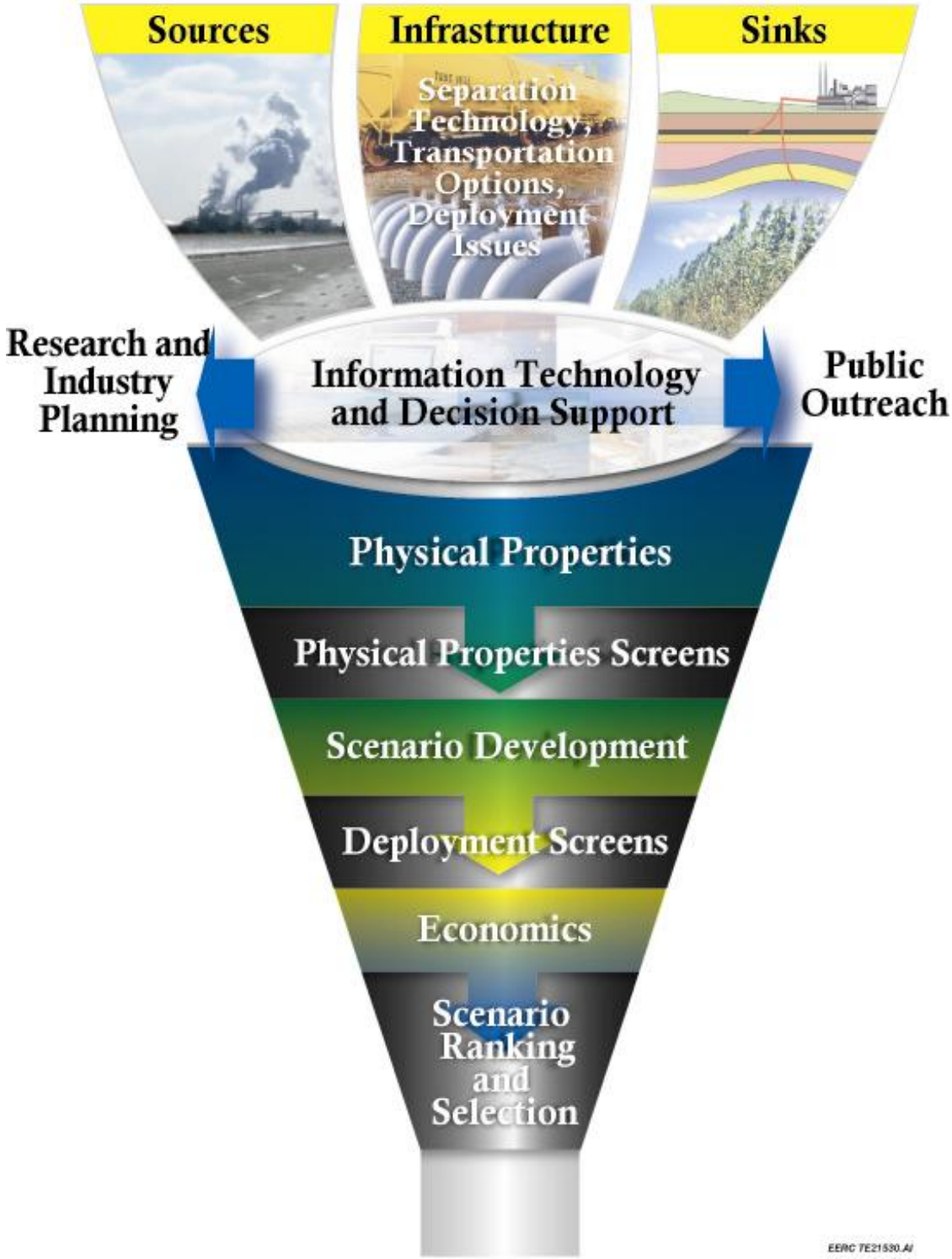

Figure 2. The PCOR Partnership program structure (upper portion) and conceptual model for screening sequestration opportunities (lower portion).

Table 1. Summary of Products from Phase I of the PCOR Partnership Program

Product Name	Citation	Type	Subject Area
1. Fact Sheet 1 – What Is CO_2 Sequestration?	EERC PCOR Partnership (2005a)	Fact sheet	Outreach
2. Fact Sheet 2 – CO_2 Sequestration – Controlling CO_2 Emissions to the Atmosphere Through Capture and Long-Term Storage	EERC PCOR Partnership (2005b)	Fact sheet	Outreach
3. Fact Sheet 3 – The Weyburn Oil Field – A Model for Value-Added Direct CO_2 Sequestration	EERC PCOR Partnership (2005c)	Fact sheet	Outreach
4. Nature in the Balance – CO_2 Sequestration	EERC and PPTV	Television production/DVD	Outreach
5. Carbon Sequestration – A Community Focus Group Study of Attitudes in Williston, North Dakota	Hanson et al. (2005)	Topical report	Outreach
6. Fact Sheet 4 – Wetland Carbon Sinks in the Glaciated North American Prairie	EERC PCOR Partnership (2005d)	Fact sheet	Outreach
7. Regional Atlas	Appendix D	GIS thematic atlas	Characterization, modeling, outreach
8. Newspaper Articles Regarding Carbon Sequestration: Article 1 – Controlling Carbon Dioxide Emissions and Still Providing Affordable Energy, Article 2 – An Introduction to Storage of Carbon Dioxide, Article 3 – The Capture and Long-Term Storage of Carbon Dioxide	Daly et al. (2005a–c)	Newspaper articles	Outreach
9. PCOR Partnership Public Web Site: [www.undeerc.org/pcor]	EERC Staff	Web site	Outreach
10. CO_2 Source Characterization of the PCOR Partnership Region	Jensen et al. (2005a)	Topical report	Source characterization
11. Carbon Separation and Capture	Jensen et al. (2005b)	Topical report	Technology and infrastructure
12. Geologic CO_2 Sequestration Potential of the Wyodak–Anderson Coal Zone in the Powder River Basin	Nelson et al. (2005a)	Topical report	Geologic sink characterization
13. Mission Canyon Formation Outline	Fischer et al. (2005a)	Topical report	Geologic sink characterization
14. Sequestration Potential of the Madison of the Northern Great Plains Aquifer System (Madison Geological Sequestration Unit)	Fischer et al. (2005b)	Topical report	Geologic sink characterization
15. The Influence of Tectonics on the Potential Leakage of CO_2 from Deep Geological Sequestration Units in the Williston Basin	Fischer et al. (2005c)	Topical report	Deployment
16. Overview of Williston Basin Geology as It Relates to CO_2 Sequestration	Fischer et al. (2005d)	Topical report	Geologic sink characterization
17. Factors Affecting the Potential for CO_2 Leakage from Geologic Sinks	Nelson et al. (2005b)	Topical report	Deployment
18. Sequestration Potential of Petroleum Reservoirs in the Williston Basin	Smith et al. (2005)	Topical report	Geologic sink characterization
19. Additional Formation Outlines for the Williston Basin: Newcastle Formation Outline, Skull Creek Formation Outline, Inyan Kara Formation Outline	Fischer et al. (2005e–g)	Topical report	Geologic sink characterization
20. Potential CO_2 Storage Capacity of the Lower Cretaceous Aquifer System in the PCOR Partnership Region	Fisher et al. (2005h)	Topical report	Geologic sink characterization
21. Geological Sequestration Potential of the PCOR Partnership Region	Sorensen et al. (2005)	Topical report	Geologic sink characterization

Continued . . .

Table 1. Summary of Products from Phase I of the PCOR Partnership Program (continued)

Product Name	Citation	Type	Subject Area
22. Geologic CO_2 Sequestration Potential of Lignite Coal in the U.S. Portion of the Williston Basin	Nelson et al. (2005c)	Topical report	Geologic sink characterization
23. The Contribution of Soils to Carbon Sequestration	de Silva et al. (2005)	Topical report	Terrestrial sink characterization
24. Terrestrial Carbon Sequestration Potential in Southwest North Dakota	Bangsund et al. (2005a)	Topical report	Terrestrial sink characterization
25. Economics and Policy of Carbon Sequestration in Agricultural Soils: A Review of Recent Literature	Bangsund et al. (2005b)	Topical report	Terrestrial sink characterization
26. Potential of Restored Prairie Wetlands in the Glaciated North American Prairie to Sequester Atmospheric Carbon	Gleason et al. (2005)	Topical report	Terrestrial sink characterization
27. Deployment Issues Related to Geological and Terrestrial CO_2 Sequestration in the PCOR Partnership Region	Reilkoff et al. (2005)	Topical report	Deployment
28. The PCOR Partnership Decision Support System	O'Leary et al. (2005)	Topical report	Modeling and decision support
29. Fact Sheet 5 – Identifying CO_2 Sequestration Opportunities	EERC (2005e)	Fact sheet	Modeling and decision support
30. Identification of CO_2 Sequestration Strategies for the PCOR Partnership Region	Jensen et al. (2005c)	Topical report	Modeling and decision support
31. The PCOR Partnership Decision Support System	O'Leary et al. (2005)	Software/ Web site	Modeling and decision support

contained on Disk 1 in Appendix A. Table 2 shows how the products in Table 1, including topical reports, data management capabilities, and capabilities for outreach and communication, fit together to achieve DOE's vision for Phase I RCSP activities in the PCOR Partnership region.

METHODOLOGY

As shown in Table 1, the Phase I activities under the PCOR Partnership program consisted in large part of gathering data on the region's major stationary CO_2 sources and potential sinks. Tools that provided for the efficient storage and manipulation of these data were also developed. More than 40 public and private sector stakeholders provided support and direction to the activities. The input of our partners was invaluable with respect to shaping the vision for the Partnership. Our efforts were focused on a market-based approach to carbon sequestration, providing our partners with the information they need for the development of both short- and long-term carbon management strategies. In addition, a public outreach campaign was conducted to inform the general public regarding CO_2 sequestration and attendant issues. The methodologies for select activities are summarized in Appendix B.

RESULTS AND DISCUSSION

The Results and Discussion Section is divided into three parts:

- Part I discusses program development, the relationship to the overall RCSP program, data management, and outreach.
- Part II characterizes the CO_2 sources and CO_2 sequestration opportunities for the PCOR Partnership region.
- Part III discusses select deployment issues including capture and

Table 2. PCOR Partnership Phase I Program Attributes Matched to RCSP Requirements[1]

No.	RCSP Requirement	PCOR Partnership Phase I Attribute
1	Work within a defined geographic area	Area grew from five states and two Canadian provinces (fall 2003) to nine states and three Canadian provinces (fall 2005)
2	Minimum of 20% cost share	Cost share grew from 22.5% (fall of 2003) to 25.6% (fall 2005) concomitant with DOE funding increase of $868,550
3	Develop and maintain a strong and diverse partnership	Partnership grew from 23 members (original proposal) to 49 members (fall 2005) and includes government, business, and nongovernmental organizations; held annual partnership meetings and maintained communication
4	Data management	Developed geographic information system (GIS)-based Decision Support System (DSS) that houses information gathered during characterization tasks and supports modeling and assessments (28, 31); maintained members-only DSS interface through public Web site depleted oil and gas reservoir and enhanced oil recovery (EOR)
5	Source characterization	Identified and characterized 1300 major sources in the region responsible for 13.1% combined total U.S.—Canadian CO_2 emissions (10)
6	Terrestrial sink characterization	Investigators include Ducks Unlimited Canada, North Dakota State University, and the U.S. Geological Survey; delineated five regional terrestrial sink categories and determined storage capacity (23), characterized upland grassland and cropland capacity (24) and economics (25), and inventoried pothole wetland capacity (26)
7	Geologic sink characterization	Delineated overall sink capacity (21), unminable coal capacity (12, 22), depleted oil and gas reservoir EOR capacity (13, 18), and deep saline capacity (14, 19, 20); provided geologic background on region (16); incorporated published information on Canadian sequestration capacity including Bachu and Shaw (2004)
8	Identify deployment issues	Reviewed potential impacts, monitoring, mitigation, and verification (MMV) options, and regulatory structure and defined needs for PCOR Partnership region activities (27), reviewed leakage for geologic storage projects in the region and in general (15, 17), and reviewed the status and options for separation and capture at stationary sources (11)
9	"Best fit" for regional sequestration activities	Ranked potential CO_2 sequestration projects in the region and determined four optimal candidates for near-term CO_2 sequestration projects based on a conceptual model (30).
10	Inform the public regarding sequestration and its regional potential; develop and maintain a public Web site	Developed a public Web site (9), six fact sheets (1, 2, 3, 6, 29), a set of newspaper articles (8), and a 30-minute television program broadcast regionally on public television stations (4); conducted focus groups (5); gave presentations at public meetings
11	Regional atlas	Full-color regional atlas (PCOR Partnership Atlas) that is available as a booklet as well as on the public Web site (7)
12	Support RCSP program	Regular conference calls with other partnerships, attendance at national and regional meetings; facilitated local Programmatic Environmental Impact Statement (PEIS) activities, support to RCSP working groups, poster for RCSP display at 2004 Governor's Energy Summit, active participation in the Regulatory Working Group of the Interstate Oil and Gas Compact Commission, and participation in the development of the national sequestration data base being prepared under DOE's NATCARB initiative.
13	Reporting	Provided regular quarterly reports and a final report to DOE NETL; regular communication with Contracting Officer's Representative (COR)

[1] Numbers in parentheses refer to the number given to products in Column 1 in Table 1.

separation, leakage potential, and regulatory implications.

Part I – Program Attributes, Data Management, and Outreach

Part I discusses accomplishments with respect to the expansion of the region, growth and consolidation of the partnership, growth in funding including matching funds, interaction with the RCSP Program, development of a data management system, and outreach.

PCOR Partnership Region

During Phase I, the PCOR Partnership region grew from five states (Montana, North Dakota, South Dakota, Minnesota, and Wyoming) and two Canadian provinces (Manitoba and Saskatchewan) in the fall of 2003 to nine states (Montana [part], Wyoming [part], North Dakota, South Dakota, Nebraska, Missouri, Iowa, Minnesota, and Wisconsin) and three Canadian provinces (Alberta, Saskatchewan, and Manitoba), shown in Figure 1, by the fall of 2005.

This international region encompasses 17% of the combined land area of the United States and Canada as well as 9% of the combined population and 9% of the combined gross domestic product.

PCOR Partnership Members

The PCOR Partnership represents public and private sector partners from the United States and Canada. As shown in Appendix C, the number of partners grew from 23 in the fall of 2003 to 49 by the fall of 2005.

PCOR Partnership Funding

As noted in Table 2, the funding for the PCOR Partnership grew significantly during Phase I. Phase I started with a total project budget of $2,048,139, with DOE funding of $1,586,614 (77.5%) and matching dollars of $461,525 (22.5%). By the fall of 2005, the total Phase I budget had grown to $3,298,227, consisting of $2,455,164 (74.4%) in DOE funding and $843,063 (25.6%) in matching dollars.

Partnership Building

The PCOR Partnership was strengthened through a number of activities, including the sharing of data and information, the pooling of expertise, collaboration in planning and assessing prospective projects, and partner involvement in the preparation and review of deliverables. As shown on Table 3, the PCOR Partnership held several major meetings. In addition, the EERC, as PCOR Partnership lead, attended numerous meetings with partners over the course of the Phase I effort.

Interaction with the National RCSP Program

The PCOR Partnership kept in contact with other RCSP partnerships through RCSP working group activities, including attendance at national meetings and participation in regularly scheduled conference calls. Examples of significant interaction include the following:

- The PCOR Partnership collaborated on the development of an RCSP display, including a poster for the PCOR Partnership activities, for the Governors' Energy Summit held in Albuquerque, New Mexico, in April 2004.

- Active role in the Regulatory Working Group of the Interstate Oil and Gas Compact Commission.

- The PCOR Partnership provided materials, presentations, and information to the RCSP PEIS hearings held for the PCOR Partnership region in East Grand Forks, Minnesota, on June 12, 2004.

- Attendance at the program kickoff meeting in Pittsburgh in fall 2003 and attendance at the annual

Table 3. PCOR Partnership Meetings

Date	Location	Meeting
October 2003	Beulah, ND	Data needs meeting at Dakota Gasification Company
December 2003	EERC	PCOR Partnership Phase I Kickoff
June 2004	EERC	65th Quarterly Meeting of the Petroleum Environmental Research Forum (PERF)
October 2004	Billings, MT	PCOR Partnership Phase I Midterm
November 2005	Minneapolis, MN (Xcel Energy Corporate Headquarters)	PCOR Partnership Phase I Wrap-Up/ Phase II Kickoff

program meetings in Alexandria, Virginia, in spring 2004 and 2005.

Outreach to Decision Makers

Information on sequestration was given to decision makers through presentations and fact sheets. Presentations were given to the following groups:

- Oil and gas industry
- Legislators
- Utility industry
- Nongovernmental organizations (NGOs) and trade groups

Notably, the PCOR Partnership fact sheets were made available to lawmakers in February of 2005 during North Dakota committee hearings on legislation regarding CO_2 injection incentives.

Data Management

As detailed in the PCOR Partnership topical report entitled "The PCOR Partnership Decision Support System" (O'Leary et al., 2005), the PCOR Partnership developed a Web-based DSS as a central repository for the characterization information collected during the Phase I sink and source assessments and to assist its research team and partners in developing and assessing the wide range of sequestration opportunities identified during the Phase I activities.

The DSS provides a single point of access to a wide variety of tools for 1) evaluating sequestration-related data, 2) assessing potential CO_2 storage capacity, and 3) identifying potential matches of sources with storage opportunities in the region.

Developing the DSS involved 1) determining the purpose of the DSS; 2) dividing the DSS into logical sections; 3) obtaining feedback from the stakeholders on data requirements, features, and capabilities; 4) creating and populating the database; 5) developing the DSS navigation system; and 6) creating, testing, and deploying the DSS.

Partners and stakeholders were involved in each major development step, from identifying the types of data that are key parameters for evaluation of sequestration options to providing direct contacts for collection of data and offering input into the design and functionality of the Web site interface. The DSS is password-protected at various levels to protect partners' confidential information while making available the large majority of the data to the public.

The DSS is divided into two sections – publicly available Web pages and a partnership-only GIS. The publicly available Web pages contain relatively static data, such as links to partnership products, terrestrial maps, snapshots of regional data, current regulatory

framework for the region, and CO_2-related Web sites.

The GIS interface contains several themes of georeferenced data that were considered crucial for the initial phase of the PCOR Partnership project. These data include detailed source and sink characterization information that has been collected or generated by the research team. The detailed attribute data associated with the features in these layers are managed in a relational database. The GIS server contains the majority of the base layers and associated characteristics, including political boundaries, cities, regional geology, road and rail transportation, shaded relief, and land use.

The DSS was put into production in February 2004. As new features and data sets were added, the partnership members were notified via e-mail. The DSS was used by the PCOR Partnership research team to develop knowledge of the character and spatial relationships of sources, sinks, and infrastructure. This knowledge assisted the researchers in the identification of major CO_2 sequestration opportunities in the region and the development of action plans.

The DSS was used to generate reports on the general reservoir characteristics of selected oil fields that may come under consideration for CO_2 flood EOR and to develop detailed information on potential sources that may provide CO_2 for such operations. In addition, the DSS has been used to identify areas that may present challenges with regard to deployment, such as national wildlife refuges, national parks, and national forests and grasslands. The DSS was demonstrated at the project meetings and at several conferences. The major GIS layers – sinks and sources – have been made available to the NATCARB Web site.

The characterization data from the DSS were used in preparing the PCOR Partnership Regional Atlas in Appendix D. The atlas is designed to be an outreach tool for the PCOR Partnership partners dealing with CO_2 sequestration issues.

Public Education and Outreach

Information on sequestration was made available to the general public through a public Web site, a television documentary, fact sheets, news releases, and newspaper articles.

Web Site

The public Web site (www.undeerc.org/pcor/default.asp) went online in June 2004 and is maintained on the EERC server. The Web site is also the point of entry for the DSS (accessible only to PCOR Partnership members during Phase I).

Television Documentary

The 30-minute television documentary, *Nature in the Balance – CO_2 Sequestration*, was aired on Prairie Public Television (PPTV) May 12, 2005, with a second showing a week later. The documentary, written and produced by the EERC and PPTV, provided a general introduction to CO_2, the greenhouse effect, and climate change; provided information on terrestrial and geologic sequestration including regional activities; introduced the RCSP Program and the PCOR Partnership; and touched on evolving strategies, including FutureGen, intended to reduce anthropogenic CO_2 emissions. The documentary is included as Disk 3 in Appendix A. Nearly 325 of the 1000 DVDs printed in May 2005 have been distributed to partners, interviewees, and other interested parties. The remaining DVDs will be distributed to teachers and citizens through activities that will continue through Phase II.

Focus Groups

Nature in the Balance was shown to two focus groups in April of 2005 in Williston,

North Dakota. The Williston area was chosen for the focus groups because it has the potential to have both terrestrial and geologic sequestration activities. As detailed in the PCOR Partnership Topical Report entitled "Carbon Sequestration – A Community Focus Group Study of Attitudes in Williston, North Dakota" (Hanson et al., 2005), the focus groups found the documentary informative and voiced interest in learning more about what they as citizens could do to reduce CO_2 emissions from their own activities.

Education

A number of educational resources including the sequestration curriculum developed by Keystone were identified and will be listed on the public Web site.

Fact Sheets

Fact Sheets (found in Appendix A) included "What Is CO_2 Sequestration?" (Energy & Environmental Research Center Plains CO_2 Reduction Partnership, 2005a), "Carbon Dioxide Sequestration – Controlling CO_2 Emissions to the Atmosphere Through Capture and Long-Term Storage" (Energy & Environmental Research Center Plains CO_2 Reduction Partnership, 2005b), the Weyburn Sequestration Project "The Weyburn Oil Field – A Model for Value-Added Direct CO_2 Sequestration" (Energy & Environmental Research Center Plains CO_2 Reduction Partnership, 2005c), "Identifying CO_2 Sequestration Opportunities" (Energy & Environmental Research Center Plains CO_2 Reduction Partnership, 2005e), and "Wetland Carbon Sinks in the Glaciated North American Prairie (Terrestrial)" (Energy & Environmental Research Center Plains CO_2 Reduction Partnership, 2005d).

Part II – PCOR Partnership Region Characterization

The primary mission of the PCOR Partnership is to facilitate the implementation of geologic sequestration strategies. To that end, the Phase I activities included reconnaissance-level determination of the stationary CO_2 sources in the region and the potential sequestration capacity of the terrestrial and geologic sinks in the region.

Sources and Emissions

Federal and provincial greenhouse gas inventories contain summarized data on CO_2 emissions from fossil fuel combustion (U.S. Environmental Protection Agency, 2005; Environment Canada, 2005). Figure 3 shows the percentage of these emissions in various sectors for the year 2000 for the states and provinces of the PCOR Partnership region, including the entire states of Montana and Wyoming. The PCOR Partnership source characterization data, housed in the DSS,

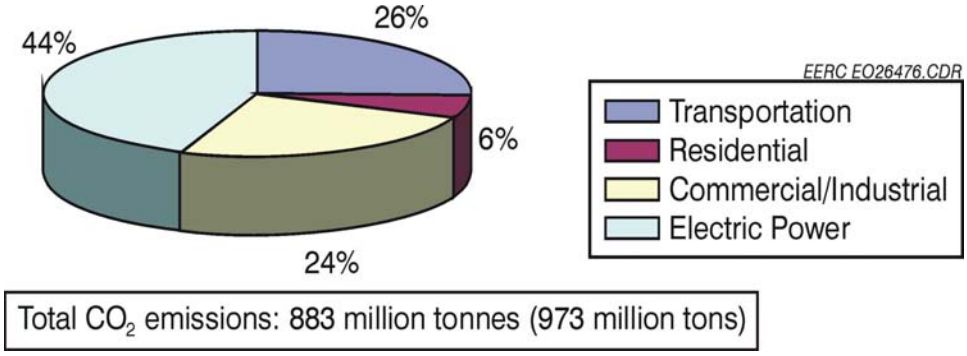

Figure 3. Year 2000 CO_2 emissions from fossil fuel combustion by sector for entire states and provinces within the PCOR Partnership region.

include only the portion of Montana and Wyoming that are within the region's boundaries.

Figure 4 displays these same sectors as compared to the entire CO_2 emissions for the United States and Canada combined. The Phase I assessment provided by O'Leary et al. (2005) identified, quantified, and characterized over 1000 stationary sources within the PCOR Partnership region (Figure 5). The emissions from these stationary sources totaled nearly 502 million tonnes (553 million tons) of CO_2 annually. CO_2 is emitted from electricity generation; energy exploration and production activities; agricultural activities; fuel, chemicals, and ethanol production; and various manufacturing and industrial activities. Table 4 shows that the majority of the region's CO_2 emissions come from just a few source types. About two-thirds of the CO_2 is emitted during electricity generation, followed by industrial sources, petroleum refining and natural gas processing, ethanol production, and agricultural processing. Figure 6 shows the CO_2 emissions profile by state and province.

The emissions profile (i.e., the percentage of CO_2 emissions from various source types) for the Canadian portion of the PCOR Partnership is virtually identical to that of Canada as a whole. However, when compared to the total U.S. CO_2 emissions, the states in the PCOR Partnership region emit relatively more CO_2 from electric utilities and less from industries and transportation. For the most part, the distribution of the sources with the largest relative CO_2 output is coincident with the availability of fossil fuel resources, namely coal, natural gas, and oil. This relationship is significant with respect to geologic sequestration opportunities. Many of the smaller sources are concentrated around more heavily industrialized metropolitan regions in southeastern Minnesota and the southeastern portion of the region.

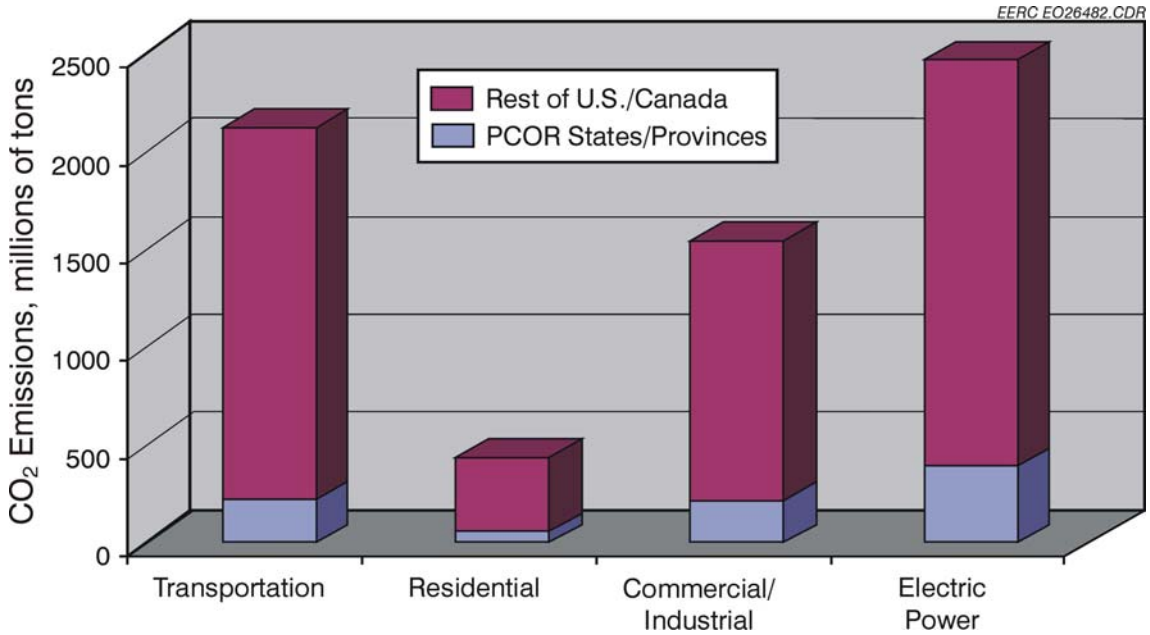

Figure 4. Year 2000 CO_2 emissions from fossil fuel combustion by sector for states and provinces of the PCOR Partnership region relative to the emissions of the rest of the United States and Canada.

Table 4. Summary of CO_2 Point Sources Identified in the PCOR Partnership Region (O'Leary et al., 2005)

Source Type	Quantity	% of All Sources	CO_2 Emissions, short tons/yr[a]	% of CO_2 Emissions
Agricultural Processing	115	10.6	3,647,014	0.7
Ammonia Production	4	0.4	1,780,350	0.3
Animal and Animal By-Product Processing	1	0.1	6,203	0.0
Asphalt Production	23	2.1	1,485,825	0.3
Cement/Clinker Production	13	1.2	12,473,725	2.3
Chemical Production	38	3.5	17,888,288	3.2
Cogeneration	2	0.2	588,559	0.1
Electric Generating	156	14.4	368,397,831	66.6
Ethanol Manufacturing	62	5.7	16,404,839	3.0
Fertilizer Production	2	0.2	38,749	0.0
Foundries/Manufacturing	4	0.4	2,063,867	0.4
Fuels/Chemicals	1	0.1	5,550,057	1.0
Industrial/Institutional Heat and Power	98	9.1	3,070,173	0.6
Iron Ore Processing	6	0.6	2,930,200	0.5
Lime Production	11	1.0	3,974,866	0.7
Manufacturing	205	18.9	10,478,547	1.9
Metals Processing	23	2.1	788,309	0.1
Minerals Processing	9	0.8	509,360	0.1
Mining	9	0.8	122,037	0.0
Miscellaneous	10	0.9	102,966	0.0
Municipal Heat and Power	8	0.7	680,882	0.1
Natural Gas Processing	31	2.9	9,023,148	1.6
Natural Gas Transmission	71	6.6	3,542,082	0.6
Paper and Wood Products	124	11.5	33,937,872	6.1
Petroleum and Natural Gas Processing	14	1.3	28,897,723	5.2
Petroleum Refining	16	1.5	17,717,687	3.2
Sugar Production	10	0.9	4,348,914	0.8
Waste Processing	17	1.6	2,336,808	0.4
TOTAL	1083	100	552,786,881	100

[a] To convert the short tons in the table to metric tons, multiply by 0.9072.

Sinks and Sequestration Potential

The PCOR Partnership region contains sinks in two major categories – terrestrial and geologic. Terrestrial sinks are largely located near the earth's surface, while geologic sinks are in the subsurface. The preliminary Phase I idealized assessments indicated over 219 billion tonnes (242 billion tons) of total capacity for geologic sinks and a total terrestrial capacity of 1.4 billion tones (1.5 billion tons) per year for the near term.

Terrestrial Sequestration

The earth's land surface, including wetlands but excluding lakes and rivers,

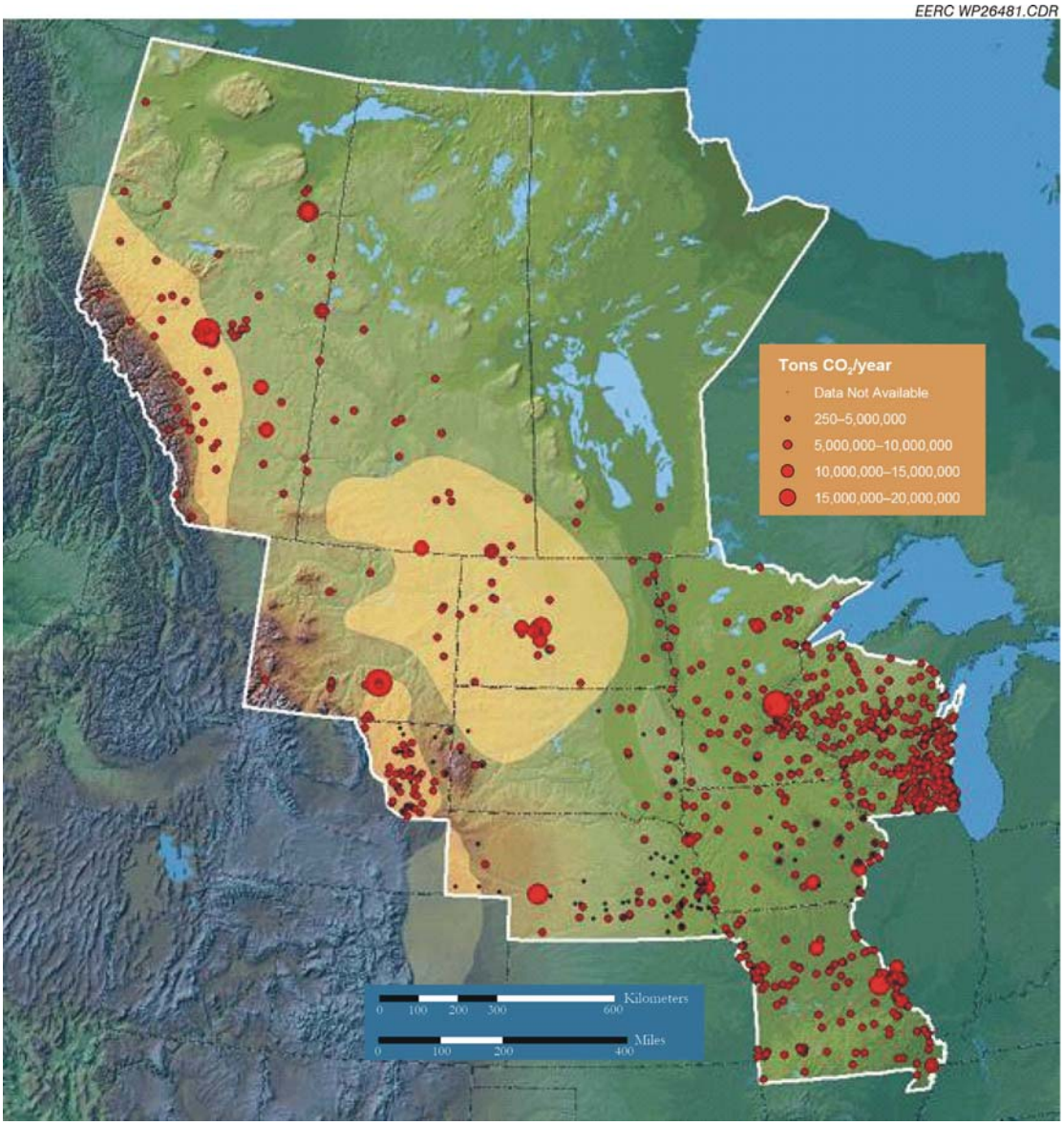

Figure 5. The PCOR Partnership geographic region showing major sinks and stationary sources.

constitutes the overall terrestrial sink resource. Within this overall resource, the land's surface can be divided into areas that broadly reflect potential for carbon storage – grasslands, forestlands, croplands, and wetlands as well as areas with little or no potential for CO_2 uptake.

The landscape represents an active natural system that is already interacting with CO_2 in the atmosphere. The natural systems may have a net intake of CO_2, a net output, or be neutral. Those areas with the capacity for a net intake of CO_2 have a finite uptake capacity and will reach equilibrium with respect to CO_2 flux over a period of time.

The PCOR Partnership ranked the areas of the landscape with respect to potential to

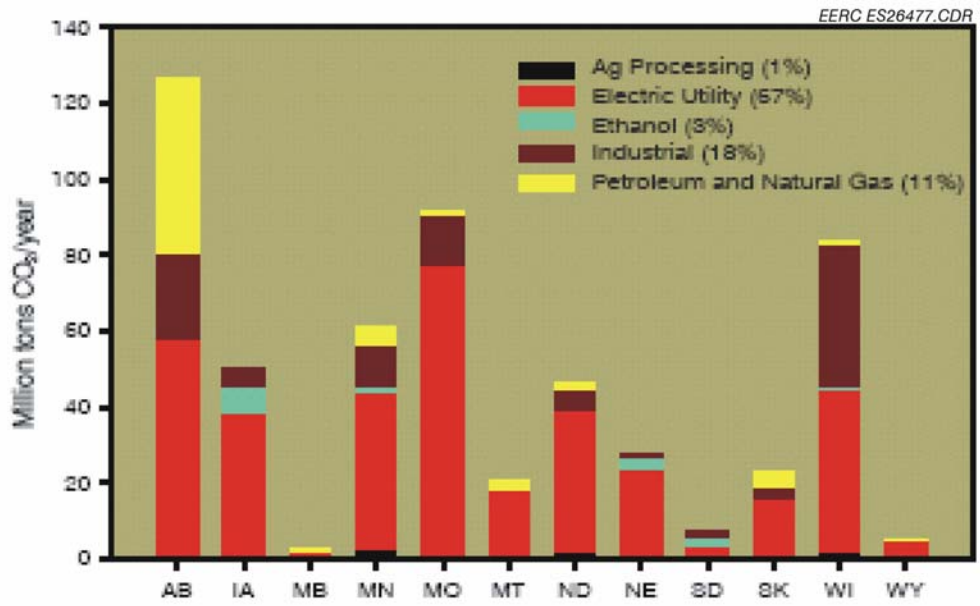

Figure 6. Emissions profile of the PCOR Partnership region.

accept additional CO_2, including those areas that can be managed to improve CO_2 uptake. During Phase I, the region was assessed in order to determine priority areas and project types for terrestrial sequestration.

General survey activities were supplemented by 1) an inventory and characterization of the extensive Prairie Pothole wetland region and 2) specific cropland and grassland studies in upland settings in southwest North Dakota.

Land, Climate, and Vegetation

The elevation within the PCOR Partnership region varies from 150 meters (500 feet) in the east to 3700 meters (12,130 feet) in the west. The northern two-thirds of the region was glaciated, which affected the character of the soil and the landscape. For example, there are a greater number of lakes, wetlands, and closed drainages in the glaciated areas. Prior to agriculture and lumbering, the region was characterized by steppe and prairie grassland, with deciduous forest restricted to the eastern and northern flanks (and in river valleys) grading into needle leaf forest in the far north.

Soils are among the largest pools of carbon and hold great promise for mitigating the increasing atmospheric concentrations of carbon through expanding soil carbon capture (Marland et al., 2001). Lal (2002) suggests that the present carbon storage of U.S. soils can be increased by 30%–50% in the next 50 years and may prove to be a cost-effective measure while technologies are developed to lessen emissions.

Previous investigators have estimated that midwestern U.S. cultivated soils have been depleted of organic carbon by 10–16 metric tons (MT) of carbon per acre and that the conversion from natural to cultivated lands has resulted in soil organic carbon (SOC) reductions of 3×10^9 MT to 5×10^9 MT (Lal, 2002; Dumanski et al., 1998). In Canada, where nearly 80% of the land farmed is in the prairie provinces of Manitoba, Saskatchewan, and Alberta (Dumanski et al., 1998), similar trends are evident, with organic carbon reduced by 15% to 35% following cultivation.

The temperate to subarctic winter climates of the PCOR Partnership region are ideal for organic carbon soil accumulation because of reduced microbial activity and minimal carbon decomposition (Collins and Kuehl, 2001).

A significant proportion of land in the PCOR Partnership region is dominated by black, fertile mollisols that have a significant potential for accumulating SOC. The high concentrations of organic carbon in the near-surface zones of mollisols are attributed to the fibrous root systems of native grasses (Collins and Kuehl, 2001).

Terrestrial Sink Types in the Region
As shown in Figure 4, the terrestrial sink resource of the PCOR Partnership encompasses approximately 90% of the 352 million ha (1.36 million square miles) of the PCOR Partnership region. As detailed in Table 5 and in de Silva et al. (2005), the region contains five basic categories of terrestrial sinks defined on the basis of vegetation, land use, and landscape. These are croplands, grasslands, forestlands, wetlands (pothole and peat types), and nonsink.

Cropland
As shown in Figure 7, approximately 30% of the land cover that makes up the PCOR Partnership region is agricultural lands. This represents over 220 million acres. With much of the PCOR Partnership region already in the agricultural land base, expansion of agricultural activities is unlikely (Paustian and Cole, 1998).

For croplands in general, there will be a peak in the rate of carbon accumulation within the 5–20-year time frame, followed by a decrease in the rate of carbon accumulation. For Nebraska, modeled cropland carbon sequestration rates for 2000 showed estimated yields of 0.06 mTC ac-1 yr-1 across the state, with a range of 0.01–0.25 mTC ac-1 yr-1. This range was influenced primarily by water management and tillage practices (Brenner et al., 2001a).

Tillage is key for carbon uptake. For example, on average, when converting from conventional farming to no-till for all crop systems in North Dakota, the carbon storage rate is 0.23 ± 0.06 mTC ac-1 yr-1 (N.D. Farmers Union and U.S. Geological Survey, 2003a). However, summer fallow does not increase organic soil carbon; only a change to no-till practices achieves that result (N.D. Farmers Union and U.S. Geological Survey, 2003a).

The Phase I Hettinger Study by North Dakota State University (NDSU) (Cihacek et al., 2005) focused on refining the understanding of the effect of tillage management on carbon uptake, specifically to evaluate the economic potential for carbon sequestration on cropland in Adams, Bowman, Hettinger, and Slope Counties in southwest North Dakota, which is dominated by dry land small grain production and livestock grazing.

Grassland
As shown in Figure 7, approximately 19% of the PCOR Partnership region is made up of grasslands, while 9% is shrublands (European Commission Joint Research Centre, 2003), representing over 208 million acres (84 million hectares) in aggregate (National Association of State Foresters, 2005; European Commission Joint Research Centre, 2003). Major amounts of grasslands and shrublands can be found in Saskatchewan, Manitoba, and Alberta, with over 60 million acres (24 million hectares) combined, and Montana (50 million acres), (20 million hectares), Nebraska (20 million acres) (8 million hectares), North Dakota (12 million acres) (5 million hectares), Missouri (14 million acres) (6 million hectares), South Dakota (24 million acres) (10 million hectares), and Wyoming (28 million) (11 million hectares) (National Association of State Foresters, 2005;

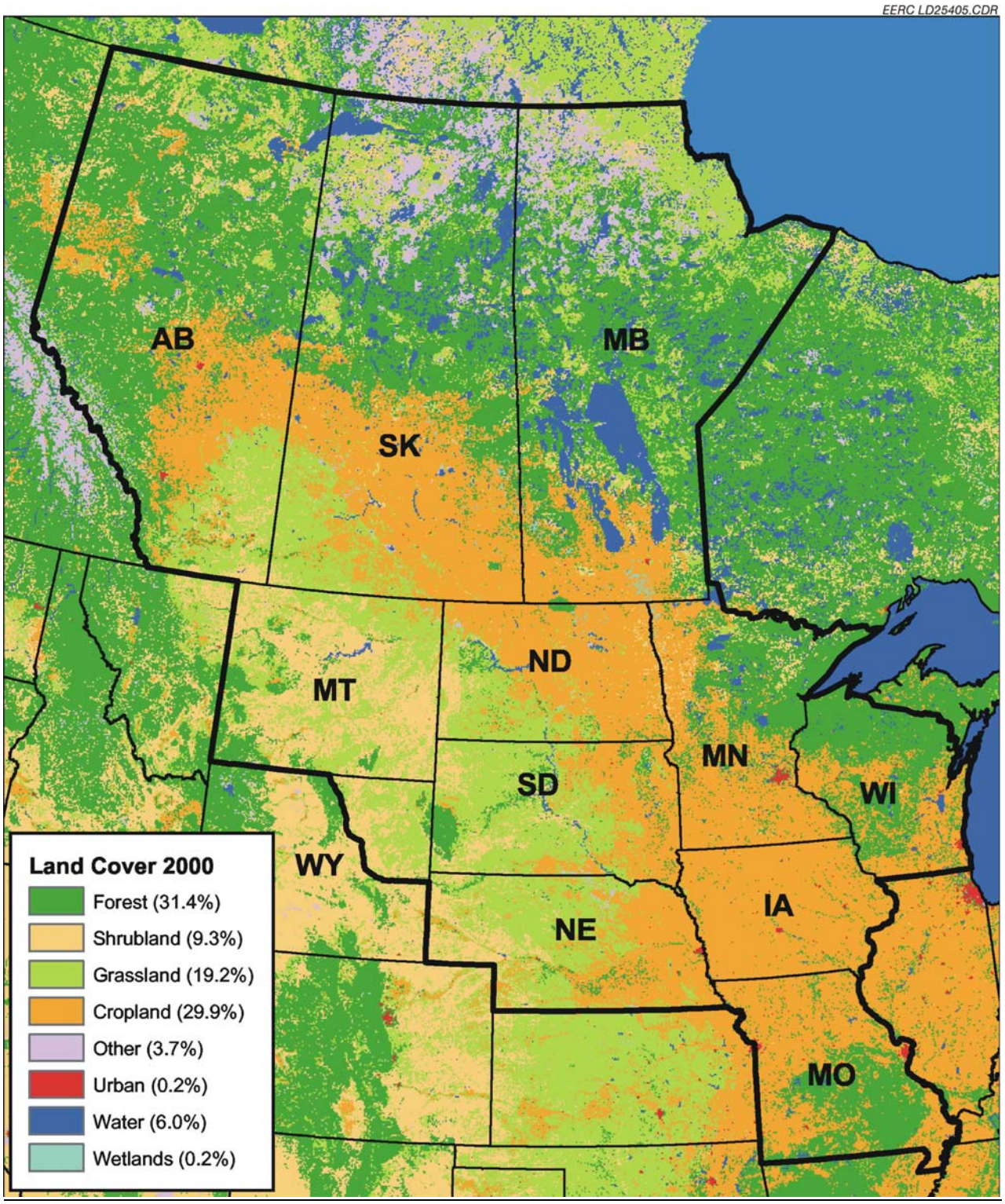

Figure 7. Land cover for the PCOR Partnership region (European Commission Joint Research Centre, 2003).

Table 5. Semiquantitative Assessment of Terrestrial Sinks in the PCOR Partnership Region[1]

Terrestrial Sink[2]	Sink Area, millons of hectares[1,3]	Relative CO_2 Uptake Rate	Time to Reach CO_2 Equilibrium	Estimated Potential of CO_2 that Can Be Sequestered per Year Over the Next 50 years, millions of tons[3]	PCOR Phase I Focus and Products
Cropland	89[5]	Low	20 yr	68[6]	Southwestern North Dakota and adjacent areas; Cihacek et al. (2005); Cihacek (2005a, b)
Grassland	84	Medium	50+ yr	193[7]	
Forestland	131	High	20+ yr	1044[8]	Reconnaissance assessment only
Wetlands (Prairie Potholes)[1]	16[9]	High	50+ yr	153[10]	Inventory Prairie Pothole wetlands in United States and Canada; Gleason et al. (2005)
Wetlands [1] Peatlands[2]	41	Low	50+ yr	49[11]	Reconnaissance assessment only
Total Sink Area	361				
Total Nonsink Area	2				
Total Surface Area	363				

1 Hectares do not correspond directly to percentages from remote sensing in Figure 7.
2 Landscape dominated by this type of sink.
3 Values rounded to nearest million.
4 Total annual uptake approximately 1.5 billion tons.
5 Northern third of the region contains significant Prairie Pothole wetlands.
6 Calculated using National Association of State Foresters (2005); Statistics Canada (2001); N.D. Farmers Union and U.S. Geological Survey (2003b); and Bangsund et al. (2005a).
7 Calculated using National Association of State Foresters (2005); European Commission Joint Research Centre, (2003); and Brenner et al. (2001a).
8 Calculated using McDougall (1986); Manitoba Geography (2005); Saskatchewan (2001); and IEA Greenhouse Gas R&D Programme (2005).
9 Actual extent of wetlands; Prairie Pothole wetlands occur within and overlap several ecosystem/sink types; restorable wetlands, the most useful for sequestration, comprise 5 million ha of the 16 million ha in this sink type.
10 Based on Euliss et al. (2005).
11 Calculated using N.D. Farmers Union and U.S. Geological Survey (2003b); Iowa State University (2005); and U.S. Fish & Wildlife Service (2005).

European Commission Joint Research Centre, 2003).

On average, dry, temperate rangelands in North Dakota have the potential of sequestering carbon for approximately 12–56 years before equilibrium is established, with an average storage rate of 0.04 mTC ac-1 yr-1 (N.D. Farmers Union and U.S. Geological Survey, 2003a). The conversion of marginal cropland to grasslands may prove to be a feasible option to promote carbon buildup in biomass and soils. Sequestration rates modeled on 1998 data for Iowa estimated carbon yields at a rate of 0.53 mTC ac-1 yr-1 for conversion from cropland to the Conservation Reserve Program (CRP) (Brenner et al., 2001b). Even the conversion of continuously cropped land to

a managed grazing system increases efficiency of soil carbon sequestration because there is less soil surface disruption, increased root biomass production, and the return of organic matter in the form of animal dung and urine to the soil (Faller, personal communication, 2004; Schuman et al., 2001; Schnabel et al., 2001).

Forestland

As shown in Figure 7, the region contains over 249 million acres of forestlands not including other wooded land of 75 million acres (Canadian Forest Service, 2001; National Association of State Foresters, 2005). With forests representing 31% of the land cover of this region (Figure 1) and with temperate forests contributing a substantial quantity of organic carbon in aboveground materials and surface soil to a depth of 30 cm in comparison to other ecosystems, reforestation and afforestation provide some of the best options to sequester additional carbon (de Silva et al., 2005).

The afforestation rate of carbon accumulation for white spruce, green ash, and hybrid poplar in the Canadian PCOR Partnership provinces at ages 5 and 10 ranged from 0.113 to 2.12 mTC ac-1yr-1 (Peterson et al., 1999). Since afforestation can store more carbon than other ecosystems such as agriculture lands, afforestation programs have great potential for mitigating carbon in the atmosphere (Plantinga et al., 1999).

Wetlands

As shown in Table 5, frequent wetland occurrence covers more than 21 million hectares of the PCOR Partnership region (Natural Resources Canada, 1993; N.D. Farmers Union and U.S. Geological Survey, 2003b; Iowa State University, 2005; U.S. Fish & Wildlife Service, 2005) and includes primarily peatlands and prairie potholes. However, as shown in Figure 7, wetlands occupy only a fraction of the land in this area. With European settlement, wetlands were cultivated; today these same areas overlap several ecosystems, incorporating drained and/or altered wetlands.

The glaciated Prairie Pothole Region (PPR) is characterized by croplands and grasslands interspersed with shallow palustrine [marshy] wetlands (Figure 8) and is estimated to include 17 million acres of wetlands (Euliss et al., 2005; U.S. Fish & Wildlife Service, 2005) within Alberta, Saskatchewan, Manitoba, North Dakota, South Dakota, Minnesota, Iowa, and Montana. But the PPR acreage may be substantially larger (43 million acres) if one includes drained or altered wetlands (Euliss et al., 2005). Recent research indicates that farmed PPR wetlands, if restored, could sequester as much as 378 million metric tons of organic carbon over the next decade, if contributions from the soil, sediment buildup, and plant ecosystem are accounted for (Euliss et al., 2005).

Phase I PCOR Partnership work by U.S. Geological Survey (USGS) and Ducks Unlimited Canada (DUC) scientists demonstrates that restoration of previously farmed wetlands results in the rapid replenishment of SOC lost to cultivation at an average rate of 3 Mg ha-1 yr-1 (1.2 MT acre-1 yr-1). They estimate that over the next 10 years, by using a more conservative quantification than Euliss et al. (2005), approximately 5 ha of potentially restorable wetlands existing in the PPR could account for as much as 111 metric tons of SOC, with an additional 25 metric tons associated with vegetative standing crop. The carbon sequestration potential by county and rural municipality in the PPR based on wetland restoration is shown in Figure 8. Restoration of wetlands will probably result in added benefits, such as the reduction of emissions of methane and nitrous oxide (Gleason et al., 2005).

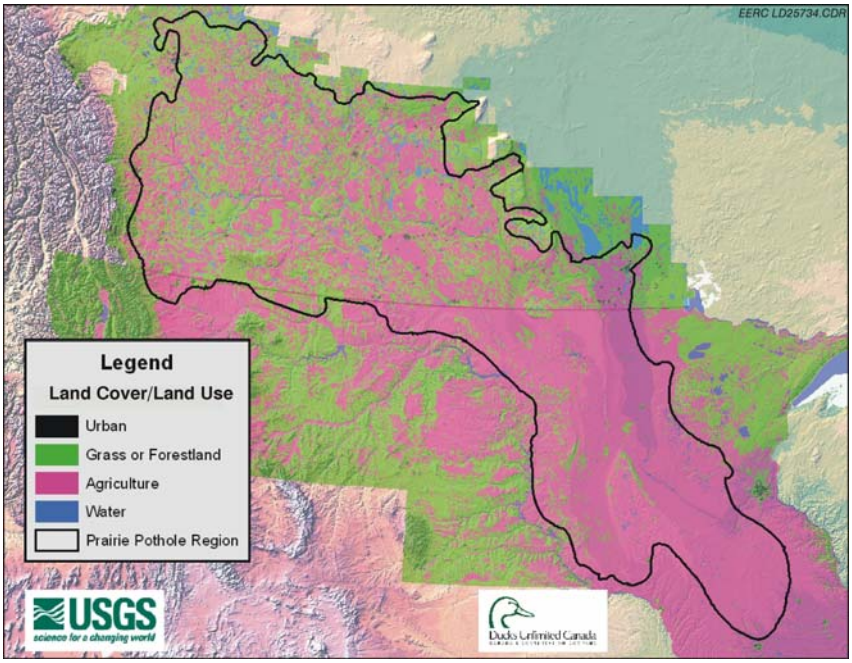

Figure 8. Extent of croplands and grasslands in the PCOR Partnership's PPR (United States and Canada).

The peat region covers well over 100 million acres (160,000 square miles, 40 million ha) within the PCOR Partnership region. This area was not a focus during Phase I. It should be noted that the vast expanse of land that comprises the peatlands does make a substantial contribution to the naturally occurring accumulation of carbon. Relative to the PPR, peatlands have high methane emissions (Gleason et al., 2005) and tend to accumulate carbon at rates tenfold slower than the PPR.

Nonsink

As shown in Figure 7, about 10% of the area of the region is not suitable for carbon uptake. This area is evenly divided between natural features like lakes, rivers, and bare rock outcrops and anthropogenic features like roads and buildings. The natural features in this preliminary analysis correspond to major bodies of water including Lake Winnipeg (24,387 km^2, or 9416 mi^2), the major reservoirs on the Missouri River (Fort Peck Lake [1658 mi^2], Lake Oahe [1164 mi^2], Lake Sacagawea [1403 mi^2]), and the numerous lakes in Minnesota (4854 mi^2) and Wisconsin (1727 mi^2).

Terrestrial Sequestration Capacity and the Place of Incentives

As shown in Table 5 and Figure 7, the idealized terrestrial sink capacity of the PCOR Partnership region is 1.5 billion tons per year for the near term. These idealized capacity estimates indicate that the terrestrial capacity alone in the region would be more than adequate in the near term to take in the 502 million tonnes (553 million tons) of CO_2 put out each year from the characterized sources in the region.

Although not quantified during the work for Phase I, conservation practices like no-till are already being used to some degree in the PCOR Partnership region. Phase I did address the overall question of

conservation practices and incentives for southwestern North Dakota. A baseline analysis indicated that in the absence of external carbon incentives, by 2024, the 1.1 million acres (1718.75 million hectares) of planted croplands in the southwestern North Dakota region would sequester about 130,000 MT of carbon annually. Cumulatively, from 2005 to 2024, the region was estimated to sequester about 2.4 million metric tons (MMT) of soil carbon on cropland (Figure 9; Bangsund et al., 2005a).

Two specific findings are very noteworthy. First, the economic attractiveness of various carbon-sequestering activities varies by farm profitability. For example, with carbon priced at $25 per MT, the most economically advantageous option for low-profitability producers was to convert croplands to permanent grass, average profitability producers would switch tillage systems, and high-profitability producers would find no economic incentive to switch either land management or land use (Table 6; Bangsund et al., 2005a, b).

Second, contrary to many economic studies suggesting that conversion of cropland to perennial grass in the upper Great Plains is not economically competitive with other carbon sequestration activities, results from this analysis suggest that, by including modest revenues from coproducts, perennial grass is an economically viable alternative to crop production (Bangsund et al., 2005a, b). The study indicated that the theoretical maximum rates of sequestration would not occur until a carbon offset price of $125 per MT was reached (see Figure 10).

Despite the rather narrow focus of this study, it demonstrates that gains in carbon sequestration would not likely occur without significant increases in carbon prices in the upper Great Plains. Some changes in agricultural land management and use will occur with relatively modest gains in carbon prices, although the amount of carbon sequestration stimulated with low carbon payments is likely to be less than levels previously estimated in some economic assessments because of

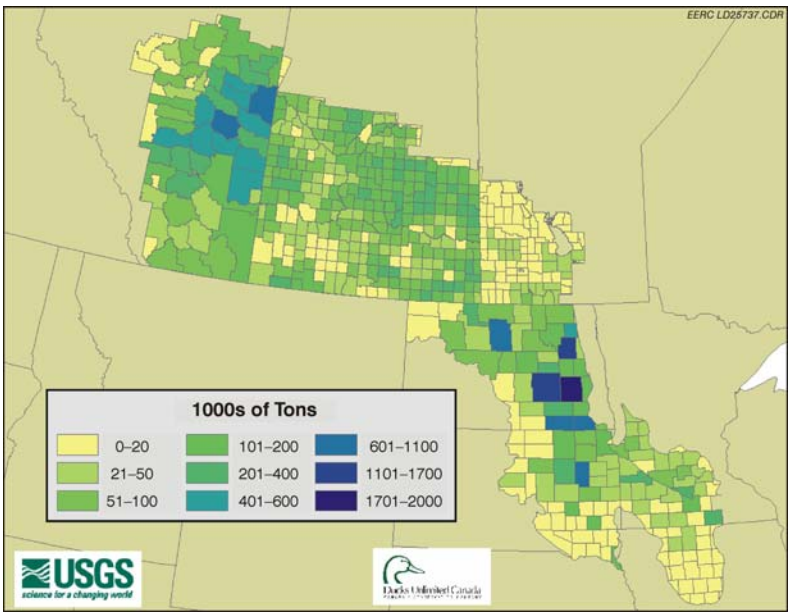

Figure 9. Carbon sequestration potential for counties and rural municipalities in the PCOR Partnership's PPR based on wetland restoration (U.S. Department of Agriculture, 2000).

Table 6. Tillage and Land Use Changes Associated with Various Carbon Incentives, by Profitability and Tillage Group, Southwestern North Dakota, 2005–2024 (Bangsund et al., 2005b)

	Carbon Price, $/MT					
Current Practice	10	25	50	75	100	125
			Low-Profitability Producers			
Summer Fallow	Grass	Grass	Grass	Grass	Grass	Grass
Conventional Tillage	Grass	Grass	Grass	Grass	Grass	Grass
Conservation Tillage	No change	Grass	Grass	Grass	Grass	Grass
No-Till	No change	No change	Grass	Grass	Grass	Grass
			Average-Profitability Producers			
Summer Fallow	Cons. till.	Cons. till.	Grass	Grass	Grass	Grass
Conventional Tillage	No change	Cons. till.	Grass	Grass	Grass	Grass
Conservation Tillage	No change	No change	Grass	Grass	Grass	Grass
No-Till	No change	No change	No change	Grass	Grass	Grass
			High-Profitability Producers			
Conventional Tillage	No change	Cons. till.	Cons. till	Grass	Grass	Grass
Conservation Tillage	No change	No change	No-till	No-till	Grass	Grass
No-Till	No change	No change	No change	No change	No change	Grass

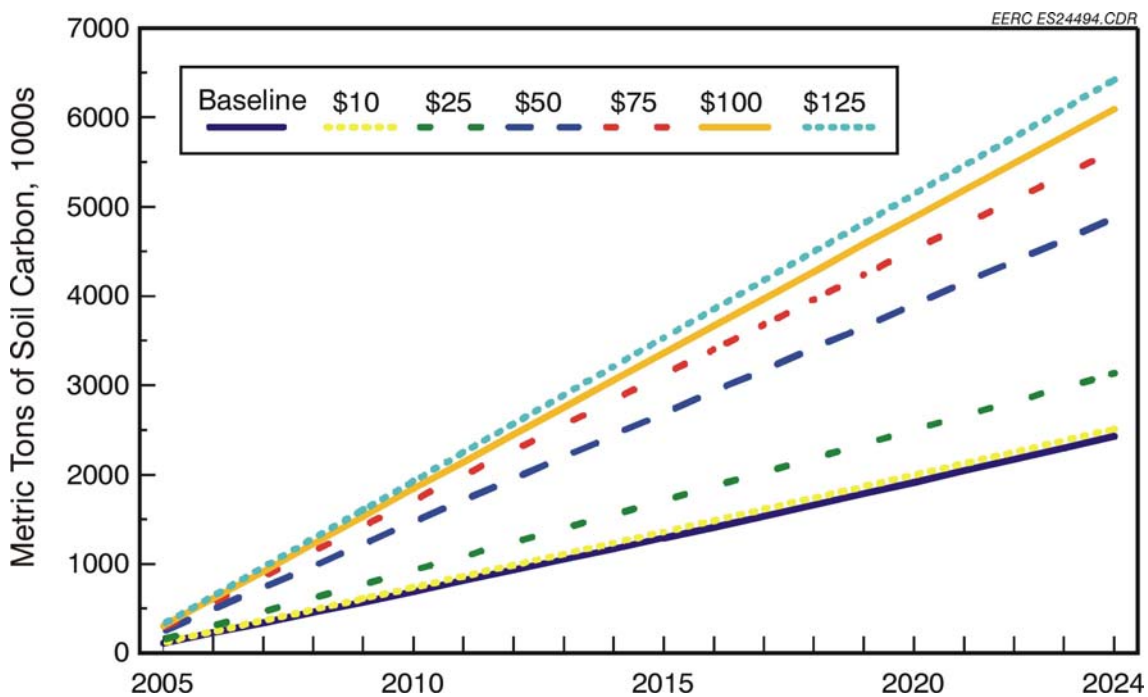

Figure 10. Cumulative soil carbon sequestration, southwestern North Dakota, 2005–2024 (Bangsund et al., 2005a).

ongoing abandonment of summer fallow and adoption of conservation tillage practices. Thus agricultural soils may still serve as a relatively low-cost option for carbon sequestration, albeit at levels substantially less than what have been suggested by technical assessments of soil carbon sequestration.

Geologic Sequestration

During Phase I, nearly 5000 oil pools and other geologic units were characterized for sequestration potential using available literature and data sets. These data were the basis for reconnaissance-level estimates of CO_2 storage capacity for select unminable coal deposits, oil fields, and brine formations. As discussed in Sorensen et al. (2005) the assessment confirmed that the northwestern portion of the PCOR Partnership region, centered on the Williston Basin, contains significant geologic sinks in the form of unminable coals, oil fields, and deep saline reservoirs suitable for geologic CO_2 sequestration.

Phase I assessments indicate that the total potential for geologic sequestration in the PCOR Partnership region is over 219 billion tonnes (242 billion tons) of CO_2. Table 7 summarizes the sequestration potential by sink type, and Appendix B gives the methodology for sink capacity calculations. The Williston Basin and adjacent basins accounted for nearly all of this potential.

As was previously shown in Table 4, the region's emissions from characterized sources are approximately 502 million tonnes (553 million tons) annually. As shown in Table 7, the region's geologic sinks that have been characterized to date could sequester this level of annual production for approximately 437 years. Of course, under a scenario where many geologic storage sites would be in commercial operation across the United States, it is likely that CO_2 from sources on the periphery of the PCOR Partnership region might be shipped to available geologic sequestration facilities in adjacent regions.

Unminable Coal

Laboratory- and field-based studies have shown that coal can physically adsorb many gases and has a higher affinity for CO_2 than for methane (Nelson, 2005b). Gaseous CO_2 injected into a coal seam will flow through the cleat system and become adsorbed onto the coal surface, effectively replacing and releasing gases with lower affinity for coal (i.e., methane). Through

Table 7. Total of Geologic CO_2 Storage Potential for the PCOR Partnership Region by Sink Type, billion tons of CO_2

Geologic Sink Type	Sequestration Potential[1, 2] billion tonnes (billion tons)	Capacity, Total Major Stationary Source Emissions[3]
Unminable Coals	7 (8)	14 years
Oil and Gas Fields	12 (13)	24 years
Deep Saline Aquifers	200 (221)	400 years
Geologic Sink Total	219 (242)	437 years

[1] Rounded to the nearest billion.
[2] Sequestration potential from Jensen et al. (2005c).
[3] Sequestration capacity in billions of tons of CO_2 divided by 502 million tonnes (553 million tons) of CO_2 per year, rounded to nearest whole number.

this phenomenon, the injection of gaseous CO_2 into a coal seam can result in simultaneous sequestration of CO_2 and enhanced coalbed methane (ECBM) production.

Phase I of the PCOR Partnership examined the potential to sequester CO_2 in coal seams in three basins of the region; coal occurrences are shown in Figure 11. The coals, and their respective basins, for which reconnaissance-level evaluations were performed, include 1) the Wyodak–Anderson coal zone of the Powder River Basin; 2) the Harmon–Hansen coal seams of the Williston Basin; and 3) the Ardley coals of the Alberta Basin. Data on coal fields in Iowa, Missouri, and Saskatchewan were also collected, but the coal seams in those fields are too shallow and/or too thin to be considered as viable targets for geologic CO_2 sequestration.

Phase I analyses indicate that these resources represent a likely sequestration capacity of approximately 8 billion tons—345 million tonnes (380 million tons) in Williston Basin lignite and nearly 6 billion tonnes (7 billion tons) in Powder River Basin subbituminous coal, and a minimum of 758 million tonnes (836 million tons) for the Ardley coal in Alberta. The sequestration potential is summarized in Table 8.

Although the coals represent only 3% of the overall estimate for geologic storage capacity in the region, they represent geologically sound sinks adjacent to major stationary sources, are capable of accepting more than a decade of the total output from these major sources and, in the case of the Powder River Basin, could result in substantial monumental coalbed methane (CBM) production.

Powder River Basin coal sink – The Powder River Basin is the No. 1 coal-producing area and ranks second for coalbed natural gas production in the United States. The CO_2 storage potential of the Powder River Basin, as detailed in Nelson et al. (2005b) and in Table 8 is nearly 6 billion tonnes (7 billion tons). The Phase I assessment also indicates that sequestration projects could result in the production of an additional 16 trillion cubic feet of CBM.

Ardley coal zone sink – The Ardley coal zone is the uppermost coal zone in Alberta. The Ardley coal zone includes as many as 34 individual coal seams that vary in thickness from 0.5 to 11.0 m. As part of the Phase I assessment, a portion of the Ardley coal zone (overburden thickness greater than 300 m) was evaluated with respect to CO_2 sequestration, as described in detail in Bachu et al. (2005).

The theoretical CO_2 sequestration capacity of unminable coal seams in the study area was estimated on the basis of CO_2 adsorption isotherms measured on coal samples from eight locations. As shown in Table 8, the results of the evaluation indicate that the Ardley coals within the defined region have a maximum effective sequestration capacity of nearly 3 billion tonnes (3 billion tons) of CO_2. However, assuming that sequestration will be economical only in areas with an effective sequestration capacity greater than 200 kilotons of CO_2/km^2, then the capacity is reduced by over 70% to 758 million tonnes (836 million tons) of CO_2.

Williston Basin coal sink – The Williston Basin contains the second largest deposit of coal resources of any basin in the continental United States. The sequestration potential for the coal is discussed in detail in Nelson et al. (2005c). The sequestration potential for unminable portions of the Harmon lignite (overburden thickness greater than 150 meters [500 ft]), the major coal in the basin, was estimated at 345 million tonnes (380 million tons), as summarized in Table 8. This capacity would be adequate for about 10 years for the total output for local North Dakota power plants.

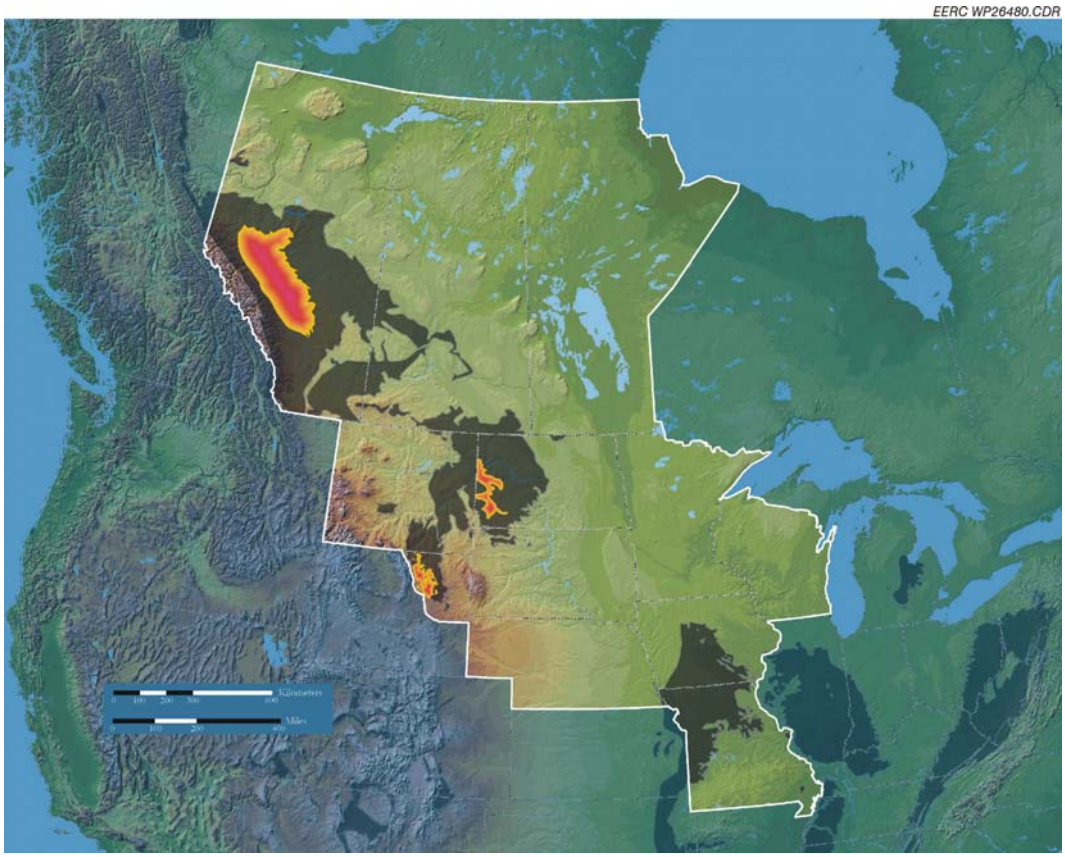

Figure 11. Map from Peck et al. (2005) showing the extent of major coal resources in the region.

Table 8. Reconnaissance-Level Estimates of CO_2 Sequestration Potential in Selected Coal Intervals of the PCOR Partnership Region

Coal Interval (location)	CO_2 Capacity Range, million tonnes (million tons) CO_2	Estimated Potential Recoverable CBM, TCF
Wyodak–Anderson (Wyoming)	6240–7238 (6880–7980)	16.1
Ardley (Alberta)	758–2630 (836–2900)	Not determined
Harmon–Hansen (North Dakota)	345 (380)	1.1

Oil Fields

Oil fields have many characteristics that make them excellent target locations for geologic storage of CO_2. They are well studied, have proven fluid retention competency, and can provide economic incentive for CO_2 sequestration. The oil-producing basins are shown in Figure 12. As detailed in Sorensen et al. (2005) and summarized in Appendix B, the Phase I assessment of oil field sequestration capacity in the U.S. portion of the region used two methods to evaluate more than 1900 oil pools throughout the Williston

Basin, Powder River Basin, and part of the Denver–Julesberg Basin. These methods are referred to as EOR and volumetric:

- The EOR method was used on select reservoirs where additional hydrocarbons could be produced as a result of the CO_2 injection and assumed that 100% of the CO_2 utilized would remain in the reservoir.

- The volumetric method was used to determine capacity in areas not suitable for CO_2 EOR.

Information on the oil-rich province of Alberta came from published reports that addressed CO_2 sequestration and EOR. For example, Bachu and Shaw (2004) evaluated over 4000 pools in Alberta suitable for CO_2 flood EOR and addressed the potential sequestration from such activities.

Information from the assessment of sinks in the U.S. portion of the PCOR Partnership region and the information available on the Canadian portion of the region indicate a total sequestration potential of approximately 1 billion tons of anthropogenic CO_2 through EOR and over 10 billion tons as determined by the volumetric method. This accounts for 4% of the total potential of the region and approximately 1.43 billion barrels of recovered oil with a value of approximately $100 billion at $50 oil. The sequestration capacity is summarized in Table 9.

Saline Reservoirs

Deep saline or brine formations represent a significant portion by volume of the sedimentary basins in the PCOR Partnership region. These formations can sequester or store CO_2 by three primary mechanisms: 1) solubility trapping through dissolution in the formation water, 2) mineral trapping through geochemical reactions with formation water and rocks, and 3) hydrodynamic trapping of a CO_2 plume.

In view of the primary storage mechanisms, the capacity of a brine formation may be considered in terms of free-phase CO_2 in the rock pore space, dissolved-phase CO_2 in the formation water, and CO_2 converted to solid minerals that become part of the rock matrix.

The degree to which each mechanism will affect sequestration under the range of geologic, hydrodynamic, and geochemical conditions that can occur in any given setting is currently not well understood (mineral trapping is least understood) and difficult to predict. It is possible, and perhaps even likely, that all three mechanisms may occur at any given location.

Since the focus of Phase I was to conduct reconnaissance-level evaluations of geologic sinks in the region, capacity estimates for brine formations only considered characteristics that control solubility and hydrodynamic trapping mechanisms. Mineral trapping was not considered, and the effects that it may have on the sequestration of CO_2 in the studied formations, whether they be positive or negative, are unknown.

Using published information, two saline reservoirs have been evaluated for their regional continuity, hydrodynamic characteristics, fluid properties, and ultimate storage capacities: the Mississippian Madison Formation (Figure 13) and the Lower Cretaceous Aquifer System.

The unique lateral extent of these systems, the current understanding of their storage potential gained through produced fluid disposal, and the geographic proximity to major CO_2 sources suggest they may be suitable sinks for future storage needs.

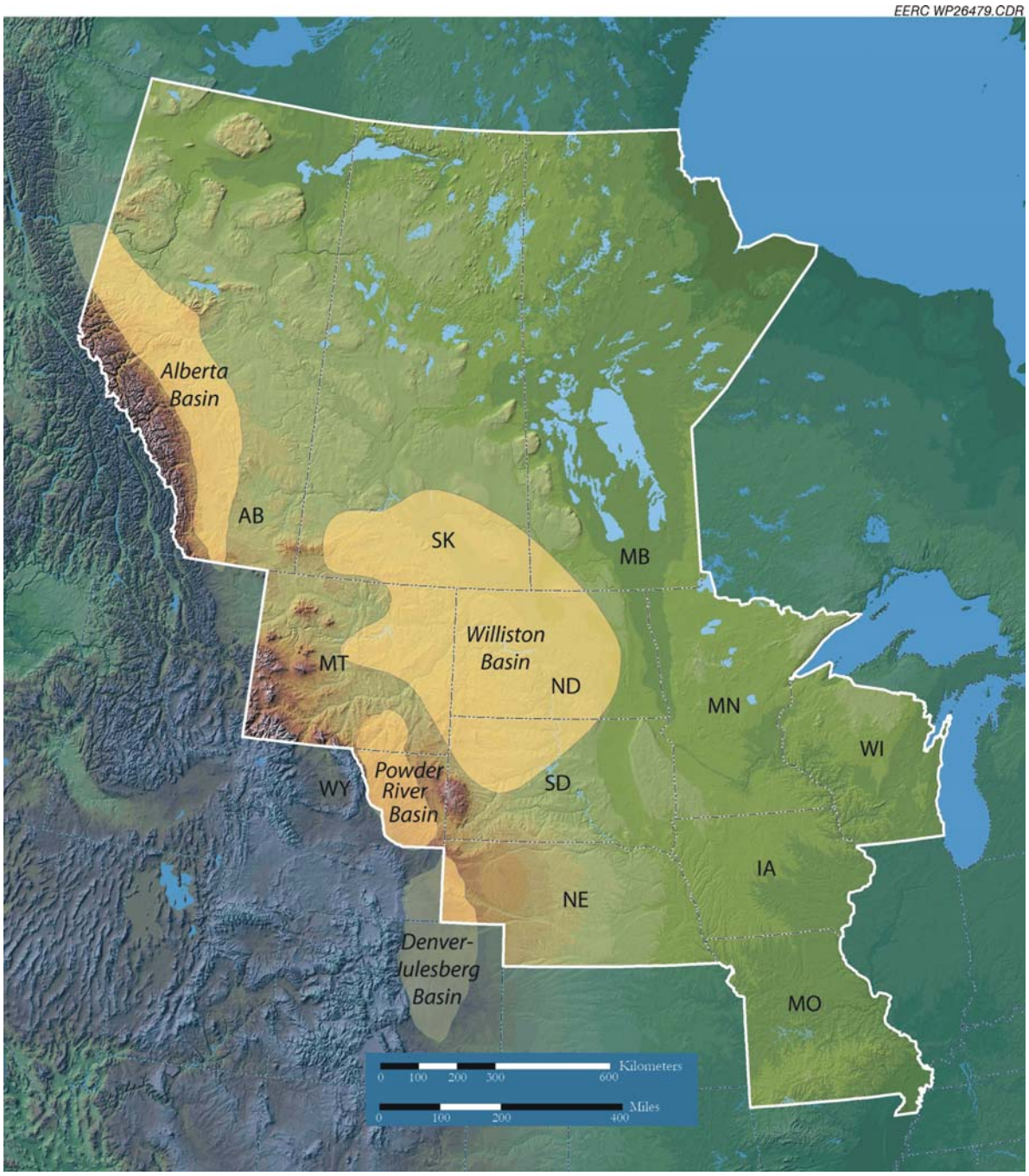

Figure 12. Map from Peck et al. (2005) showing major oil-producing geologic basins and oil fields in the PCOR Partnership region.

Table 9. Potential CO_2 Sequestration Capacities and Incremental Oil Production for Selected Oil Fields in the PCOR Partnership Region

Basin	Number of Pools Evaluated	Sequestration Capacity – Volume Method, million tonnes (million tons) CO_2	Sequestration Capacity – EOR Method, million tonnes (million tons) CO_2	Potential Incremental Oil Recovery, million stock tank barrels
Williston	845	>8200 (>9000)	455 (502)	1023
Powder River	225	>900 (>1000)	170 (187)	381
Denver–Julesberg	21	13 (14)	11 (12)	25
Alberta	4371	NC[1]	494 (545[2])	>2000[2]

[1] Value not calculated for the Alberta Basin.
[2] Values for the Alberta Basin were determined using a different methodology than the other basins and, therefore, may not be directly comparable to the other estimates. They are included in the table to provide insight regarding the general magnitude of CO_2 flood-related sequestration capacity and potential incremental oil production in Alberta.

Specific areas included in the calculations include the Williston and Powder River Basins for the Mississippian Madison Formation and the Alberta, Williston, Powder River, and Denver–Julesberg Basins for the Lower Cretaceous Aquifer System.

The methodology used to calculate storage potentials for the evaluated aquifer systems, as detailed in Jensen et al. (2005c), is included in Appendix B.

As shown in Table 7, the Mississippian Madison Formation and the Lower Cretaceous Aquifer System have a combined total of 200 billion tonnes (221 billion tons) of capacity in the PCOR Partnership region.

- The Lower Cretaceous Aquifer System in the Alberta, Williston, Powder River, and Denver–Julesberg Basins was calculated to have a maximum capacity of 145 billion tones (160 billion tons). This is treated in detail in Fisher et al. (2005e–h).
- The Mississippian Madison Formation in the U.S. portions of the Williston and Powder River Basins was calculated to have a maximum capacity of 54 billion tonnes (60 billion tons). This is treated in detail in Fisher et al. (2005b).

These estimates are reconnaissance level only; are based on a maximum, best-case scenario approach to the evaluation of saline formation storage; and are meant to illustrate the potential value of these formations with respect to their ultimate storage. The inherent heterogeneity found in nearly all geologic formations means that detailed subsurface mapping and characterization must be conducted in any area prior to the initiation of large-scale injection of CO_2.

A summary of the aquifer system storage capacity is shown in Table 10.

Part III – Select Infrastructure and Deployment Issues

Infrastructure and deployment issues for the PCOR Partnership region, discussed in depth in Reilkoff et al. (2005), include technology issues including capture and

separation and MMV capabilities, as well as issues concerning infrastructure, regulations, permitting, and risk. Four issues for geologic sequestration—capture and separation, infrastructure, geologic sequestration units, and leakage potential—are briefly discussed in this section, and other issues for geologic sequestration are summarized in Reilkoff et al. (2005) and the IOGCC Report entitled "Carbon Capture and Storage: A Regulatory Framework for States" (see Appendix E).

Capture and Separation

Geologic sequestration requires high-purity CO_2 to meet pipeline specifications and reduce reservoir interactions. Providing this product from the flue gases found today at anthropogenic stationary sources will require specialized separation and capture technology.

The PCOR Partnership region is home to a commercial-scale EOR operation that utilizes anthropogenic CO_2 from the Dakota Gasification Company in Beulah, North Dakota and pipes it over 200 miles to Weyburn, Saskatchewan. Other potential opportunity sources in the region include ethanol production facilities, acid gas plants, and cement kilns. Although these facilities make up only a small part of the regional CO_2 emissions, they offer relatively inexpensive capture opportunities when compared to the fossil fuel-fired electric generating plants.

The separation of CO_2 from other species in mixed-gas streams has been practiced on the commercial scale for over 50 years. Most of these applications have been for natural gas-sweetening operations, purification of reformer synthesis gas (syngas) to produce H_2 in refinery operations, and ammonia production. Phase I produced a qualitative assessment of existing commercial and emerging processes that could be used to separate CO_2 from combustion gases for the purpose of controlling carbon emissions, particularly from fossil fuel-fired electric generating plants, which contribute one-third of CO_2 emissions in the United States and the PCOR Partnership region. This assessment is detailed in Jensen et al. (2005a) and summarized below.

With respect to existing plants:

- Applying commercial gas separation processes to existing pulverized coal (pc)-fired plants (7% of the sources in the PCOR Partnership region responsible for half of the CO_2 emissions) will result in very high cost and performance penalties, approaching 30% as a result of the large parasitic steam loads.

- Natural gas-fired combined-cycle plants (48 plants in the PCOR Partnership region, or 3% of the sources) are also severely impacted because of the sensitivity to reduced efficiency associated with high fuel cost.

With respect to capture and separation options for future plants, coal-fired integrated gasification combined-cycle (IGCC) plants showed the lowest-cost penalty because the CO_2 capture system is integral to the technology. CO_2 capture and separation can be grouped into five categories: absorption, cryogenic cooling, gas separation membranes, gas absorption membranes, and adsorption. These are the basis for all commercial and developing technologies. These five technologies can be applied in three basic ways: fuel-to-heat/power processes, including postcombustion (stack gas cleaning); precombustion (e.g., gasification or reforming); and oxygen combustion (in some CO_2 sequestration literature, this process is called oxyfuel combustion; using oxygen rather than air for combustion eliminates the large quantity of N_2 diluent).

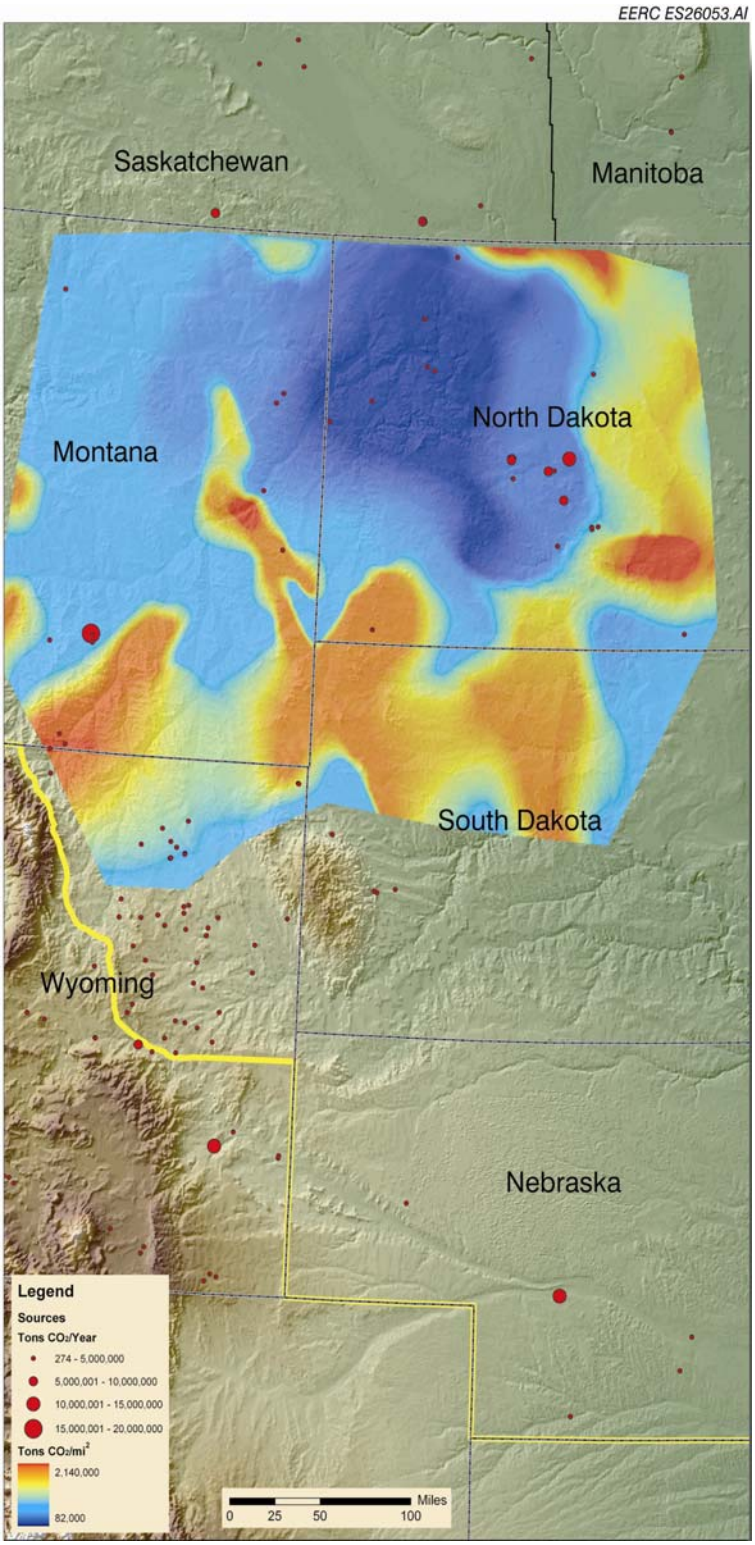

Figure 13. Map from Fischer et al. (2005b) showing the Mississippian Madison saline aquifer system and major CO_2 point sources in the PCOR Partnership region.

Table 10. Summary of Storage Capacity in Deep Saline Aquifers (from Fisher et al., 2005b, h)

Aquifer System	Basin	Estimated CO_2 Capacity, billion tonnes (billion tons)
Lower Cretaceous		
Newcastle Formation	Williston and Powder River	38 (42)
Viking Formation	Alberta	91 (100)
Maha Formation	Denver–Julesberg	17 (19)
Mississippian		
Madison Formation	Williston and Powder River	54 (60)
Total		200 (221)

Although most of the development efforts in CO_2 capture have focused on power production, capture and separation processes could be applied to industrial boilers and turbines, process heaters, kilns, cupolas, and other sources.

The near-term options for separating CO_2 are based on either amine-scrubbing solutions for postcombustion flue gas capture or physical solvents such as Selexol for precombustion IGCC systems. In addition, oxygen combustion is under development at the pilot scale.

All current commercial approaches to CO_2 capture result in significant energy and cost penalties. Emerging gasification combined-cycle systems would provide inherent efficiency and cost advantages to CO_2 capture through higher operating pressure and CO_2 concentrations. Some studies indicate that oxygen combustion may also be cost-effective.

Performance and cost of CO_2 capture from lignite-fired power plants, cement production, and petroleum refining were estimated using the PCOR Partnership's spreadsheet estimation tool. The costs ranged from \$22/ton CO_2 for a coal-fired power plant retrofitted with an amine scrubber to \$51/ton for a petroleum refinery.

All estimates from the Phase I analysis are substantially higher than the DOE goal of \$10/ton, but costs will drop as technologies improve and industry recognizes the potential for profit from the use of CO_2 in enhanced resource recovery operations.

Geologic Sequestration Infrastructure

Current sequestration infrastructure such as injection wells, MMV equipment, and pipelines for CO_2 delivery is available to varying degrees in the PCOR Partnership region. The oil and gas fields in the Williston Basin contain approximately 1100 pools that could be utilized for CO_2 sequestration (Smith et al., 2005), especially as part of EOR activities. A 12-inch-diameter CO_2 pipeline stretches for 204 miles from the Dakota Gasification Company (DGC) plant in Beulah, North Dakota, to the CO_2 sequestration demonstration at Weyburn, Saskatchewan. The pipeline passes through some of the region's best geologic sinks (e.g., North Dakota and Saskatchewan oil and coal fields, the Madison Saline Aquifer, and other potentially suitable saline aquifers) and could transport CO_2 for sequestration into these formations.

Potential for Geologic Sequestration Units as Part of Regulatory and Operations Framework

The development of markets for carbon credits associated with geologic

sequestration will require action from several diverse communities. As with many disciplines and technologies, a broadly recognized, practical framework is needed to facilitate effective communication between the scientific, engineering, regulatory, and legal communities. With this in mind, the PCOR Partnership is developing a monetization framework based on the establishment of geologic sequestration units (GSUs).

The GSU concept is based on the recognition that implementation of geologic sequestration in different types of settings would be facilitated by a common framework. In other words, although the three types of geologic targets generally utilize different mechanisms for sequestration (for example, dissolution into oil vs. dissolution into saline water vs. adsorption onto coal), there are commonalities that can serve as a basis to simplify operational and regulatory approaches and conduct.

For instance, all three types of targets must have competent seals and other trapping mechanisms. From a legal standpoint, each may have privately held mineral rights associated with them. All three will also require a framework for accounting that is based on detailed characterization data, sound engineering design, and an equitable legal and regulatory process.

In addition, the development of carbon credit markets for CO_2 sequestered in geological formations will require proper accounting of injected CO_2, which will be well served by a streamlined process that takes these conditions and issues into account.

The unitization system used in the oil and gas industry has evolved over time to meet similar needs for that activity.

The term "geological sequestration unit" was chosen to acknowledge the legal and regulatory process that will be necessary to inject large volumes of CO_2 that may encompass numerous mineral ownership tracts; it was not chosen to represent entire geologic units or formations. The concept is to apply a similar process by which petroleum fields become unitized to the governing of geological sequestration projects. In modern hydrocarbon production field practices, prior to initiation of subsurface activities that will affect the fluid distribution and production within an area, mineral ownership tracts may be legally combined to form a larger working area. The process of combining individual tracts is referred to as "unitization," and the working area created by this process is referred to as a "unit."

The effective result of unitization is the protection of correlative rights of all mineral owners within the designated area and coordinated injection and reservoir management practices that improve the efficiency of petroleum extraction. It is anticipated that a similar unitization process will need to be developed prior to injection of CO_2 for sequestration in geological formations. Unitization will facilitate monetization by establishing a technical and legal framework by which CO_2 injection can be implemented. The value of these credits will be largely based on the ability to quantify and verify the amount of CO_2 in a given geological target. The physical and legal boundaries of the target must be established as part of the monetization process.

GSUs may be established in petroleum reservoirs, saline aquifers, and coal seams. Unit boundaries have already been established for countless oil fields as part of the field operational and regulatory processes. The establishment of a GSU within a geologic setting that does not produce hydrocarbons, such as a saline aquifer, will likely require the same

detailed documentation that demonstrates to the appropriate regulatory agency that the operator of the project 1) adequately understands the geology and hydrodynamics of the proposed GSU and 2) has an appropriate MMV plan in place to keep track of the injected CO_2. Areas established as GSUs will likely be those that have been proven to provide effective storage and have known fluid migration properties. The first candidates for GSUs will be those geologic features that have already been thoroughly characterized. Since most detailed characterization of the deep subsurface has been conducted as part of hydrocarbon exploration and production activities, it is likely the first GSUs will be oil and gas fields that are currently in production, depleted oil and gas fields, and other characterized structures or stratigraphic sequences that are known to have effective trapping mechanisms (e.g., previously explored anticlines, pinnacle reefs, and other structures that do not have economical reserves of petroleum).

Using unitized oil fields as a model, GSUs could vary in size from as small as a few acres to as large as hundreds of square miles. The size of a GSU is directly dependent on the geologic and hydrodynamic characteristics of the area being considered as a target for CO_2 injection. Like oil field units, a GSU would be established across an area where those characteristics have been demonstrated to be thoroughly documented and well understood. With this in mind, it will not likely be possible to declare entire regional formations or aquifer systems (e.g., the Mississippian Madison Formation or the Lower Cretaceous Aquifer System) to be single GSUs. Geologic formations and aquifer systems are typically too heterogeneous and lacking in characterization data to adequately model large regions to the precision required for unitization. Rather, it will be necessary to identify localized areas within a formation or aquifer system that have specific characteristics, particularly with respect to competent seals, that allow for the secure long-term storage of CO_2.

CO_2 Leakage Potential

Leakage of CO_2 out of a geological storage site is a major concern associated with sequestration of CO_2 in the subsurface, as, clearly, any release to the atmosphere would limit the effectiveness of the sequestration effort. Thus it is important to ensure that long-term sequestration is not only feasible, but that the CO_2 remains in the geological units into which it is injected. Nelson et al. (2005a) provides a more complete overview of CO_2 leakage potential than is included below.

The success of geologic CO_2 sequestration as a large-scale carbon management strategy is critically dependent on the ability of the geologic sinks and trapping mechanisms to confine the injected CO_2 for hundreds to thousands of years. Leakage of CO_2 from geologic sinks could result in significant release of the CO_2 back to the atmosphere, potentially reducing, if not negating altogether, the benefits of geologic CO_2 sequestration.

Injected CO_2 can be trapped in geologic sinks by four types of mechanisms. Different types of geologic sinks in combination with their site-specific properties would trap CO_2 by different mechanisms. More than one type of trapping mechanism would typically be present in a single geologic sink. Most trapping mechanisms do not permanently immobilize CO_2. Thus leakage of CO_2 to the surface can potentially occur from all types of geologic sinks.

In the right types of geologic settings, a large, concentrated amount of CO_2 could be stored for a geologically long time period without the risk of significant CO_2 leakage to the surface. The dominant, but by no means sole, barrier to CO_2 leakage to the

surface from geologic sinks is not the trapping mechanism(s) but rather the permeability characteristics of the rock layers overlying or adjacent to the geologic sink. The hydrologic properties of the formations containing the geologic sinks would also affect the potential for CO_2 leakage. Geologic settings with relatively static hydrology, i.e., low-formation water velocity, would be preferable.

Three basic types of mechanisms could result in CO_2 leakage from geologic sinks. The first mechanism is fast-flow path leakage which would primarily involve CO_2 movement up poorly sealed or failed injection well casings and improperly abandoned wellbores and through transmissive faults or fractures in the cap rock above the geologic sink. The second mechanism is slow leakage, which would primarily involve gas transport by diffusion and loss of dissolved CO_2 because of the hydrodynamic flow of formation water out of the geologic sink. The third mechanism is leakage due to desorption of adsorbed-phase CO_2.

With respect to potential leakage issues that are specifically associated with the PCOR Partnership region, Phase I included a literature-based examination of geologic features of the Williston Basin that may have a bearing on leakage. As discussed in Fisher et al. (2005c), subtle but significant tectonic features have been identified in the Williston Basin, including basement lineaments. Lineaments are zones of tectonic weakness that have been active through time and have exerted influence on the development of the structure and distribution of certain depositional facies. Most of the lineaments in the Williston Basin appear to be closed and are not likely to be points where leakage of sequestered CO_2 can occur. However, evidence suggests that at least one major lineament may have associated open fractures and thereby provide pathways of leakage.

It is clear from examinations of the technical literature, and from concerns expressed by both the regulatory and NGO communities that the process by which sites are selected for large-scale CO_2 sequestration will have to include the identification and evaluation of potential leakage pathways. Such investigations will need to consider geologic characteristics such as hydrogeologic properties and the possibility of open and leaking lineaments. Determining the locations and characteristics of preexisting wellbores, particularly those that have been plugged and abandoned, is also a critical component of evaluating the potential for leakage at sites being considered for CO_2 sequestration. Finally, once potential pathways for leakage have been identified, strategies and techniques for leak mitigation must be developed.

CONCLUSIONS

The Phase I assessments revealed a significant terrestrial and geologic sequestration potential in the PCOR Partnership region. Using the methodology described in Appendix B, the PCOR Partnership fulfilled the major mission of the Phase I program by identifying opportunities for terrestrial and geologic sequestration based on assessments of sources, sinks, and deployment issues including transportation systems and capture and separation technologies. The sequestration strategies were further vetted to ensure that they represented projects with 1) commercial potential and 2) a mix that would support future projects both dependent and independent of CO_2 monetization.

This assessment resulted in the definition of four source–sink candidate combinations or sequestration strategies for the PCOR Partnership region. These candidate projects are described below, and their locations are shown on Figure 14. The action plans developed for

sequestration demonstrations as well as for outreach and select deployment issues in support of the candidate sequestration projects are included in Appendix F.

Terrestrial Sequestration Candidates

As discussed in Jensen et al. (2005a), the Phase I assessment of terrestrial sequestration indicated a significant potential divided between croplands, forestlands, and grasslands, with about 10% of the region unsuitable for any type of terrestrial sequestration. Further analysis indicated that restored wetlands would offer significant potential for carbon uptake even though they account for a relatively small portion of the actual landscape. Further, wetlands terrestrial sequestration has been less investigated relative to other terrestrial sequestration opportunities in the region. As shown in Figure 14, a wetland suitable for restoration, termed T1, was identified as a suitable Phase II validation test candidate.

Geologic Sequestration Candidates

As shown in Figure 5 and listed in Table 4, more than 1000 stationary sources have been characterized in the region. There are also numerous major geologic sinks in the region. As discussed in Jensen et al. (2005) and in Part II of Appendix B, source–sink combinations were rated on a number of factors including 1) the regional significance of the opportunities (i.e., number and availability of source types, number and capacity of sink types); 2) the diversity, capacity, and permanence of sinks investigated; 3) the applicability of the research findings to other regions; 4) socioeconomic factors such as risk, public acceptance, and potential full-scale deployment economics; and 5) societal cobenefits. Results revealed that the best near-term opportunities are in the Montana, Wyoming, North Dakota, Saskatchewan, and Alberta portions of the PCOR Partnership based on the following observations:

- Predominance of carbonate rock formations in the oil and saline geologic sinks, including the prevalence of carbonate pinnacle reefs (steep-sided, moundlike carbonate structures that are stratigraphically and structurally isolated and have adequate porosity and permeability for CO_2 sequestration) that occur in Alberta and in the Saskatchewan and North Dakota portions of the Williston Basin.

- Significant additional CO_2 storage capacity in relatively shallow coal seams in the Williston Basin and Powder River Basin that are in close proximity to two dozen major coal-fired power plants and other major sources. These coal seams have a high affinity for CO_2 and could be used in some cases for CBM EOR.

Three geologic candidate projects (Figure 14) were “best fits” for the criteria and hold the greatest promise to become market-driven, full-scale geologic sequestration projects in the short term. These are as follows:

- G1 – CO_2 injected into economically unminable lignite seams to determine the suitability of these strata for both CO_2 sequestration and CBM production.

- G2 – Acid gas (65% CO_2, 35% H_2S) from sour gas plants injected into a nearby oil field for simultaneous sequestration and EOR.

- G3 – CO_2 used for simultaneous sequestration and EOR in oil fields proximal to the existing DGC CO_2 pipeline in northwestern North Dakota.

These geologic sequestration candidates make use of readily available CO_2 and/or

transportation networks. In turn, these demonstrations will provide detailed information needed for more robust economic analysis of CO_2 transportation, injection, and monitoring activities for a number of similar direct sequestration projects of this type in the region.

Further, the Phase I assessment for geologic sequestration indicates that:

- Amine scrubbing is probably the nearest to being commercially applied to the majority of the large stationary sources (i.e., coal-fired power plants, cement kilns) in the PCOR Partnership region, but development of emerging techniques that show promise should continue to increase the potential for choice and lower costs.

- Because of the lack of local geologic options and the distances involved to transport the CO_2 to Williston Basin sinks, the CO_2 produced from sources in the eastern portions of the PCOR Partnership region will probably be sequestered in geologic

Figure 14. PCOR Partnership Phase II field validation sites (G1 – Lignite coal in North Dakota – CO_2 injected into an unminable lignite coal seam for CO_2 sequestration and possible ECBM production; G2 – Zama, Alberta – Injection site of acid gas for CO_2 sequestration and EOR; G3 – Beaver Lodge, North Dakota – CO_2 injection site for CO_2 sequestration and EOR; and T1 – Wetland sites monitored to establish sequestration potential and MMV technologies).

sinks in adjacent regions. As a national program, it will be important that all options be investigated and infrastructure developed to enable the most cost-effective sequestration to be performed.

- Because of the overall cost reductions possible through the sale of oil or methane, sequestration that is performed concurrently with EOR or ECBM will likely be the only sequestration performed in the near term.

Additional Phase I lessons learned include:

- CO_2 sequestration can be readily integrated into the current regulatory framework.

- The cost of MMV must be market driven to provide for economical solutions.

- The PCOR Partnership DSS system proved to be a flexible, reliable tool for regional characterization of CO_2 sources and sinks.

- Broad-based stakeholder involvement is critical to the development of CO_2 sequestration at every stage.

- A market-based approach is helpful for developing a broad base of stakeholder involvement.

- Public outreach and education are very important.

- Enhanced resource recovery associated with CO_2 sequestration is a very big opportunity for the PCOR Partnership region.

- The heterogeneity of geologic formation is great, and detailed knowledge of geologic and hydrodynamic characteristics is required on a local scale before injection can move forward. Therefore, there is likely no such thing as a "regional" CO_2 sink.

- A common accounting framework is needed to monetize carbon credits for geological sequestration of CO_2. This framework must be based on detailed characterization data, sound engineering design, and equitable legal and regulatory processes. The unitization process for oil fields may be a suitable model for such a framework. We propose to use the term GSU to provide the needed framework.

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APPENDIX A

DVD AND CDs OF SELECT PRODUCTS

Appendix A consists of the following CDs and DVDs:

Disk 1 – Phase I products (listed in Table 1 on page 8 of report).

Disk 2 – DVD of the television production *Nature in the Balance – CO_2 Sequestration*

APPENDIX B

METHODOLOGY

METHODOLOGY

INTRODUCTION

This document contains information on the methodologies concerned with two major Plains CO_2 Reduction (PCOR) Partnership efforts in Phase I: characterizing the sequestration capacity of geological sinks and determining appropriate candidates for demonstration projects for both terrestrial and geologic sequestration.

Methodologies for assessment of sources, infrastructure, and other deployment issues, as well as data management, can be found in the methodology sections of the appropriate topical reports produced during Phase I activities.

METHODOLOGY FOR CALCULATING GEOLOGIC SEQUESTRATION POTENTIAL

This section, based on the PCOR Partnership Phase II Prospectus (Energy & Environmental Research Center Plains CO_2 Reduction Partnership, 2005), summarizes the methodologies used to estimate the sequestration potential for geologic sinks, including unminable coals, oil pools, and saline aquifers.

Lignite in the U.S. Portion of the Williston Basin

The Williston Basin contains the second largest deposit of coal resources of any basin in the continental United States. The resources are lignite and, based on readily available information, the Harmon lignite was deemed the coal having suitable thickness and continuity for consideration for sequestration. Carbon dioxide (CO_2) sequestration potential for these areas was calculated using the procedure described in detail in the report "Geologic CO_2 Sequestration Potential of Lignite Coal in the U.S. Portion of the Williston Basin" (Nelson et al., 2005a).

A geologic model was constructed and used to evaluate the CO_2 sequestration potential of the areas underlain by lignite deposits that are not surface-minable. Areas were determined to be suitable for CO_2 storage if the overburden was at least 500 ft thick and CO_2 sequestration potential was calculated according to the following equation:

$$CO_2 \text{ Sequestration Potential} = A * h * \rho * SC_{CO2}$$

where A = deposit area, h = net coal thickness, ρ = in situ lignite density, and SC_{CO2} = CO_2 storage capacity = (1220 ∗ [P/{P + 548}]).

The gas storage capacity calculations were made using the Langmuir isotherm model, a numerical model that describes the relationship between the gas storage capacity and pressure. It is the most commonly used isotherm model for coal (Mavor and Nelson, 1997). The Langmuir volume and pressure values that appear in the equation (1220 scf/ton and 548 psia, respectively) were experimentally determined for lignite from the Williston Basin. The reservoir hydrostatic pressure, P, was estimated based on the midpoint reservoir depth and assumed a normal hydrostatic pressure gradient of 0.433 psi/ft.

Wyodak–Anderson Coal Zone in the Powder River Basin

The Powder River Basin is the No. 1 coal-producing area in the United States and the second most prolific coalbed natural gas-producing area. The Wyodak–Anderson subbituminous coal is the major coal in the Powder River Basin and was the focus of assessment efforts.

As detailed in Nelson et al. (2005b), the CO_2 storage potential of the Powder River

Basin was calculated using a method similar to that used for the storage potential of the lignite in the Williston Basin. The Powder River Basin calculation took into account the impact of sorbed-phase natural gas and its composition on the total CO_2 storage capacity as follows:

$$\text{Effective } CO_2 \text{ Sequestration Potential} = CO_2 \text{ Sequestration Potential} - [A * h * \rho * GC]$$

where A = deposit area, h = net coal thickness, ρ = density, and GC = sorbed-phase gas content.

CO_2 STORAGE CAPACITY OF OIL FIELDS

As detailed in Sorensen et al. (2005), information on the Canadian portion of the region is available from Bachu and Shaw (2004), but the Phase I assessment of oil field sequestration capacity in the U.S. portion of the region was derived using two methods. These methods were applied to nearly 2000 pools in the Williston Basin, Powder River Basin, and part of the Denver–Julesberg Basin. These methods are referred to as enhanced oil recovery (EOR) and volumetric:

- The EOR method was used on select reservoirs where additional hydrocarbons could be produced as a result of CO_2 injection and assumed that 100% of CO_2 injected would remain in the reservoir.

- The volumetric method was used to determine capacity in areas not suitable for CO_2 EOR.

The amount of oil that could be recovered from CO_2 EOR was also calculated.

Volumetric Methodology

Capacity estimates comprised the sum of each producing interval within a field. This calculation yielded the maximum storage capacity of an oil-bearing reservoir in pounds of CO_2 which was converted to tons. The field area considered represented the entire boundary of the oil field. It was expected that this figure might be larger than the actual productive areal extent used in detailed reservoir analyses. The thickness, porosity, and water saturation figures used represent the reported reservoir thickness as collected from hearing files, reservoir annuals, and published oil field data. CO_2 density was estimated based on reported temperature and pressure values. Where temperature and pressure were not available, depth was used to estimate their value. Where no data exist, the water saturation was estimated to be 50%.

Oil Reservoir Storage Capacity Calculation

Fields were also studied as potential storage areas for non-EOR-related CO_2 sequestration. The calculation was based largely on the pore volume of the reservoir that could be filled with CO_2. This approach gave a maximum storage potential for each field in the study area. Oil pools in selected fields of North Dakota, Montana, and South Dakota were examined with the thought that the method could be applied to any reservoir with a competent top and bottom seal to provide a rough estimate of storage capacity. The equation used to calculate the storage capacity of each oil reservoir was:

$$Q = A * T * \phi * \rho_{CO2} * (1 - S_w)$$

where Q = storage capacity of the oil reservoir (lb CO_2), A = field area (ft^2), T = producing interval thickness (ft), ϕ = average reservoir porosity (%), ρ_{CO2} = density of CO_2 (lb/ft^3), and $(1 - S_w)$ = saturation of oil, where S_w is the initial reservoir water saturation (%).

Methodology for Determining the Amount of Oil Recovery Possible

In trying to determine the sequestration capacity of the unitized pools, assumptions were made. The first major assumption was to simplify the oil recovery potential from injection of CO_2. Shaw and Bachu (2002) noted that oil production could be increased from 7% to 23% of the original oil in place (OOIP) through successful miscible flooding techniques, while Nelms and Burke (2004) suggested a value of 7% to 11%. For these calculations, an average value of 12% recovery of the OOIP was used to estimate the incremental oil recovered. Where OOIP was not available, 25% of the cumulative production was used to estimate recovery. Next, the quantity of CO_2 necessary to recover incremental oil was estimated. Based on the findings of Nelms and Burke (2004), this evaluation assumed 8000 standard cubic feet of CO_2 was required for every incremental barrel of oil recovered.

CO_2 STORAGE CAPACITY IN SALINE AQUIFERS OF THE PCOR PARTNERSHIP REGION

The Mississippian Madison and the Lower Cretaceous are major saline aquifer systems within the PCOR Partnership region. Published data were used to evaluate their regional continuity, hydrodynamic characteristics, fluid properties, and ultimate storage capacities. A regional evaluation of the Mississippian Madison Formation was completed for the Williston and Powder River Basins. The regional evaluation of the Lower Cretaceous aquifer system used existing data sets and included the Newcastle, Viking, and Maha Formations.

Saline Aquifer Storage Methodology

As detailed in Sorensen et al. (2005), a model was developed to produce a continuous gridded surface representing the volume of CO_2 that could be sequestered per square mile for saline systems. The model is based on existing data relating to hydrological studies of regional aquifer systems, oil, gas, water well data, and existing geographic information system (GIS) map data.

The calculation used was a straightforward estimate relating the pore volume in the reservoir (area × thickness × porosity) and the solubility of NaCl in the reservoir water at spatially varying pressures and temperatures. Solubility factors for temperatures and concentrations in excess of 200°F and 200,000 ppm NaCl, respectively, were not readily available at the time of this study (temperatures and concentration values are routinely above these values in the Powder River and Williston Basins). As such, data were extrapolated to above 500°F and 300,000 ppm from tables provided through personal communication with the Indiana Geological Survey in April 2004 in order to attain the necessary solubility correction factors.

Saline Aquifer Storage Calculation

The equation used to calculate the CO_2 storage possible in the saline aquifers was:

$$Q = 7758 * A * T * \phi * CO_2s$$

where Q = CO_2 remaining in the aquifer after injection (ft^3)

$7758 = (43{,}560\ ft^2/acre) \times (0.178\ bbl/ft^3)$

and A = area (acres), T = producing interval thickness (ft), ϕ = average reservoir porosity (%), and CO_2s = solubility of CO_2 (ft^3/bbl).

METHODOLOGY FOR IDENTIFYING CO_2 SEQUESTRATION OPPORTUNITIES

Phase I activities involved identifying optimal sequestration demonstration candidates. As detailed in the Phase II Prospectus (Energy & Environmental

Research Center Plains CO_2 Reduction Partnership, 2005), an objective method for matching CO_2 point sources with sinks was used to identify the most promising geologic CO_2 sequestration opportunities in the PCOR Partnership region. A series of Excel™ spreadsheets containing the CO_2 source data, geologic sink types and capacities, CO_2 capture and separation technologies (both those currently in use as well as those still under development) and the source types to which they could be applied, transportation options, and deployment issues (including permitting and monitoring, measurement, and verification [MM&V]), were generated using data from the PCOR Partnership Decision Support System (DSS). The largest CO_2 sources were screened according to their source type (e.g., electrical utility, ethanol production, metals processing) to group sources that produce similar gas streams. These source subgroups were sorted by quantity of CO_2 produced, the percentage of the exit stream comprising CO_2, and the presence of SO_2 and/or NO_x or other compounds to better define the CO_2 streams' compositions and potential ease of capture.

The data from the DSS were used to identify the most promising sequestration scenarios in two categories: short-term, commercially viable (or nearly so) scenarios that can sequester regionally significant amounts of CO_2 within the 2012 time frame outlined in the *Carbon Sequestration Technology Road Map and Program Plan* and long-term opportunities that can sequester globally significant amounts of CO_2 but require the technological advances and infrastructural improvements provided by meeting the 2012 Road Map goals. The sequestration strategies were further vetted to ensure that they represented projects with 1) commercial potential as well as 2) a mix that would support future projects both dependent and independent of CO_2 monetization.

The various scenarios were compared, and groups of similar scenarios, called sequestration strategies, were formed. Ultimately, the number of possible strategies was reduced to three that were the most likely to be employed in the region in both the near- and long-term. They are:

- CO_2 from coal-fired electricity generation facilities used for EOR, injected into a saline aquifer, or injected into a coal seam for enhanced coalbed methane (ECBM) production.

- CO_2 produced during ethanol production used for EOR, injected into a saline aquifer, or injected into another appropriate sequestration target.

- CO_2 from cement/clinker production used for EOR, injected into a saline aquifer, or injected into a coal seam.

Preliminary economic estimates were made to provide a way to rank these strategies. The economic ranking found that sequestration of CO_2 from power plants during EOR or ECBM activities was probably the most cost-effective.

These results were used to select the following three specific geological sequestration scenarios for demonstration during Phase II activities:

- CO_2 used for simultaneous sequestration and EOR in an Amerada Hess oil field in western North Dakota.

- Acid gas (65% CO_2, 35% H_2S) from an Apache Canada Ltd. sour gas plant injected into a field in northwestern Alberta for simultaneous sequestration and EOR.

- CO_2 injected into economically unminable lignite seams to determine the suitability of these strata for both CO_2 sequestration and coalbed methane production.

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APPENDIX C

PCOR PARTNERSHIP PHASE I PARTNERS

PCOR PARTNERSHIP PHASE I PARTNERS

PCOR PARTNERSHIP PHASE I PARTNERS (*DENOTES ORIGINAL PARTNER FROM U.S. DEPARTMENT OF ENERGY PROPOSAL, 2003):

- Alberta Department of Environment
- Alberta Energy and Utilities Board
- Alberta Energy Research Institute
- Amerada Hess Corporation*
- Basin Electric Power Cooperative*
- Bechtel Corporation*
- Center for Energy and Economic Development (CEED)
- Chicago Climate Exchange
- Dakota Gasification Company*
- Ducks Unlimited Canada
- Eagle Operating, Inc.
- Encore Acquisition Company
- Environment Canada*
- Excelsior Energy Inc.
- Fischer Oil and Gas, Inc.*
- Great Northern Power Development, LP
- Great River Energy*
- Interstate Oil and Gas Compact Commission*
- Kiewit Mining Group Inc.
- Lignite Energy Council
- Manitoba Hydro
- Minnesota Pollution Control Agency*
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Montana–Dakota Utilities Co.*
- Montana Department of Environmental Quality*
- Montana Public Service Commission
- Murex Petroleum Corporation
- Nexant, Inc.*
- North Dakota Department of Health*
- North Dakota Geological Survey*
- North Dakota Industrial Commission Lignite Research, Development and Marketing Program*
- North Dakota Industrial Commission Oil and Gas Division*
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- North Dakota State University*
- Otter Tail Power Company*
- Petroleum Technology Research Centre
- Petroleum Technology Transfer Council*
- Prairie Public Television*
- Saskatchewan Industry and Resources
- SaskPower
- Tesoro Refinery (Mandan)
- University of Regina
- U.S. Department of Energy*
- U.S. Geological Survey Northern Prairie Wildlife Research Center
- Western Governors' Association*
- Xcel Energy

APPENDIX D

PCOR PARTNERSHIP REGIONAL ATLAS

PCOR Partnership

ATLAS

PCO2R Partnership

EERC Energy & Environmental Research Center®

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

PCOR Partnership Atlas

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National Energy Technology Laboratory
and the PCOR Partnership

Published by the

Energy & Environmental Research Center
2005

The Plains CO_2 Reduction (PCOR) Partnership is a group of public and private stakeholders working together to better understand the technical and economic feasibility of sequestering CO_2 emissions from stationary sources in the central interior of North America. The PCOR Partnership is managed by the Energy & Environmental Research Center (EERC) at the University of North Dakota and is one of seven regional partnerships under the U.S. Department of Energy's Regional Carbon Sequestration Partnership Program.

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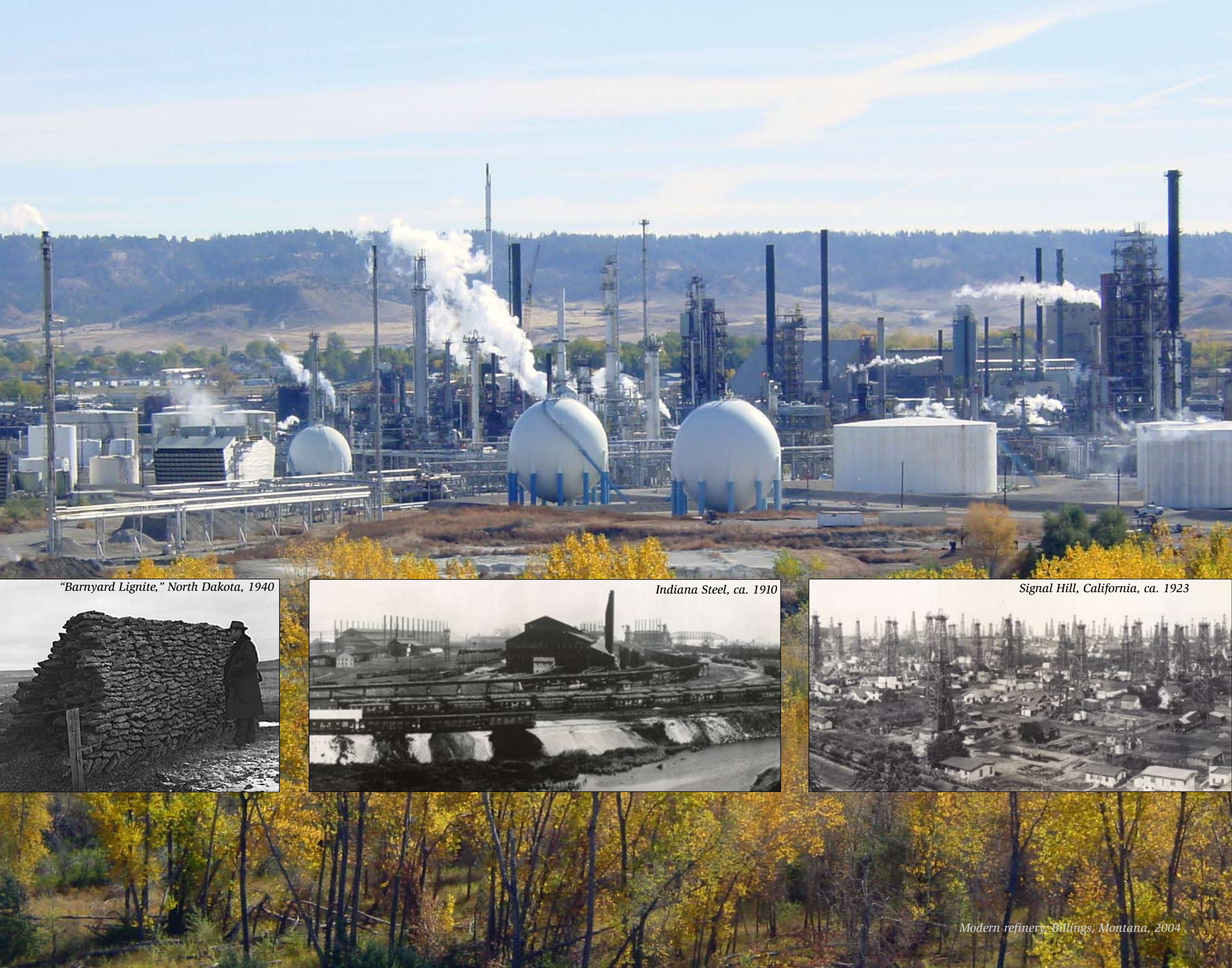
Introduction

Global climate change is considered to be one of the most pressing environmental concerns of our time. This is due in part to the potential magnitude of the changes it could cause and also to the immense economic, technological, and lifestyle changes that may be necessary in order to respond to it. Although uncertainty still clouds the science of climate change, there is strong indication that we may have to significantly reduce anthropogenic emissions of greenhouse gas (GHG) emissions. Carbon sequestration offers a promising set of technologies through which carbon dioxide (CO_2) and potentially other GHGs are stored for long periods of time in sinks represented by biologic materials, geologic formations and, possibly, other places such as oceans. Within central North America, the Plains CO_2 Reduction (PCOR) Partnership is investigating various aspects of sequestration technologies in order to provide a safe, effective, and efficient means of managing the carbon dioxide emissions across the center of the continent.

The regional characterization activities conducted under Phase I of the PCOR Partnership confirmed that while there are numerous large stationary CO_2 sources, the region also has tremendous capacity for CO_2 sequestration. The varying natures of the sources and sinks reflect the geographic and socioeconomic diversity of the region. In the upper Mississippi River Valley and along the shores of the Great Lakes Michigan and Superior, large coal-fired electrical generators power the manufacturing plants and breweries of St. Louis, Minneapolis, and Milwaukee. To the west, the prairies and badlands of the north-central United States and central Canada are home to coal-fired power plants, natural gas processing plants, ethanol plants, and refineries that further fuel the industrial and domestic needs of cities throughout North America. The PCOR Partnership region is also rich in agricultural lands that hold tremendous potential for terrestrial sequestration. The Prairie Pothole Region that stretches from northwestern Iowa, across the Dakotas, and into Saskatchewan and Alberta holds promise as an area that can be transformed into a significant terrestrial CO_2 sink.

Deep beneath the surface of the region lay geological formations that hold tremendous potential to store CO_2. Oil fields already considered to be capable of sequestering CO_2 can be found in roughly half the region, while formations of limestone, sandstone, and coal suitable for CO_2 storage exist in basins that, in some cases, extend over thousands of square miles. In many cases, large sources in the region are proximally located to large-capacity sinks, and in some cases, key infrastructure is already in place.

This atlas provides an introduction into the concept of global climate change and a regional profile of CO_2 sources and potential sinks across nearly 1.4 million square miles of central North America.



"Barnyard Lignite," North Dakota, 1940

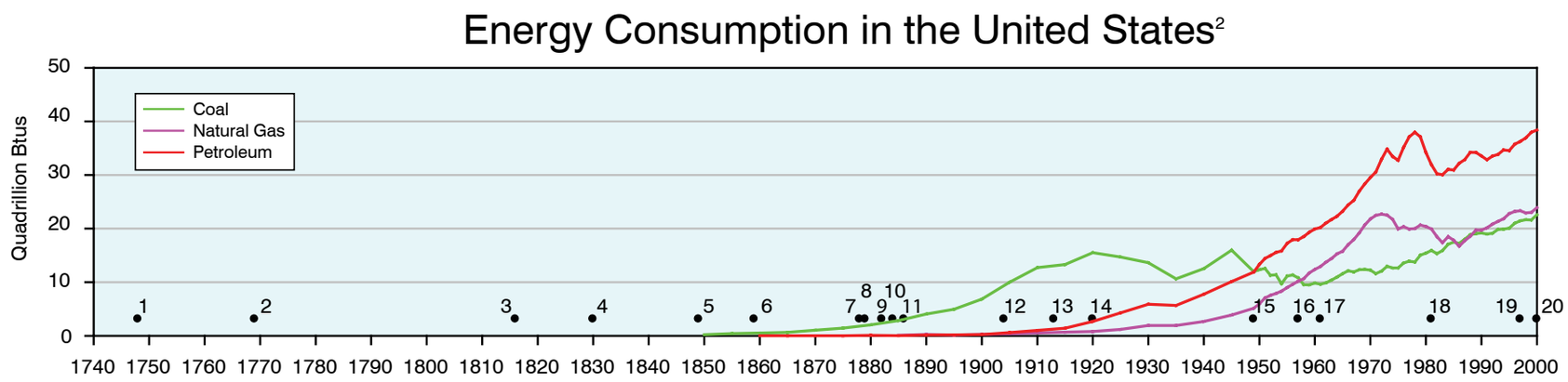
Indiana Steel, ca. 1910

Signal Hill, California, ca. 1923

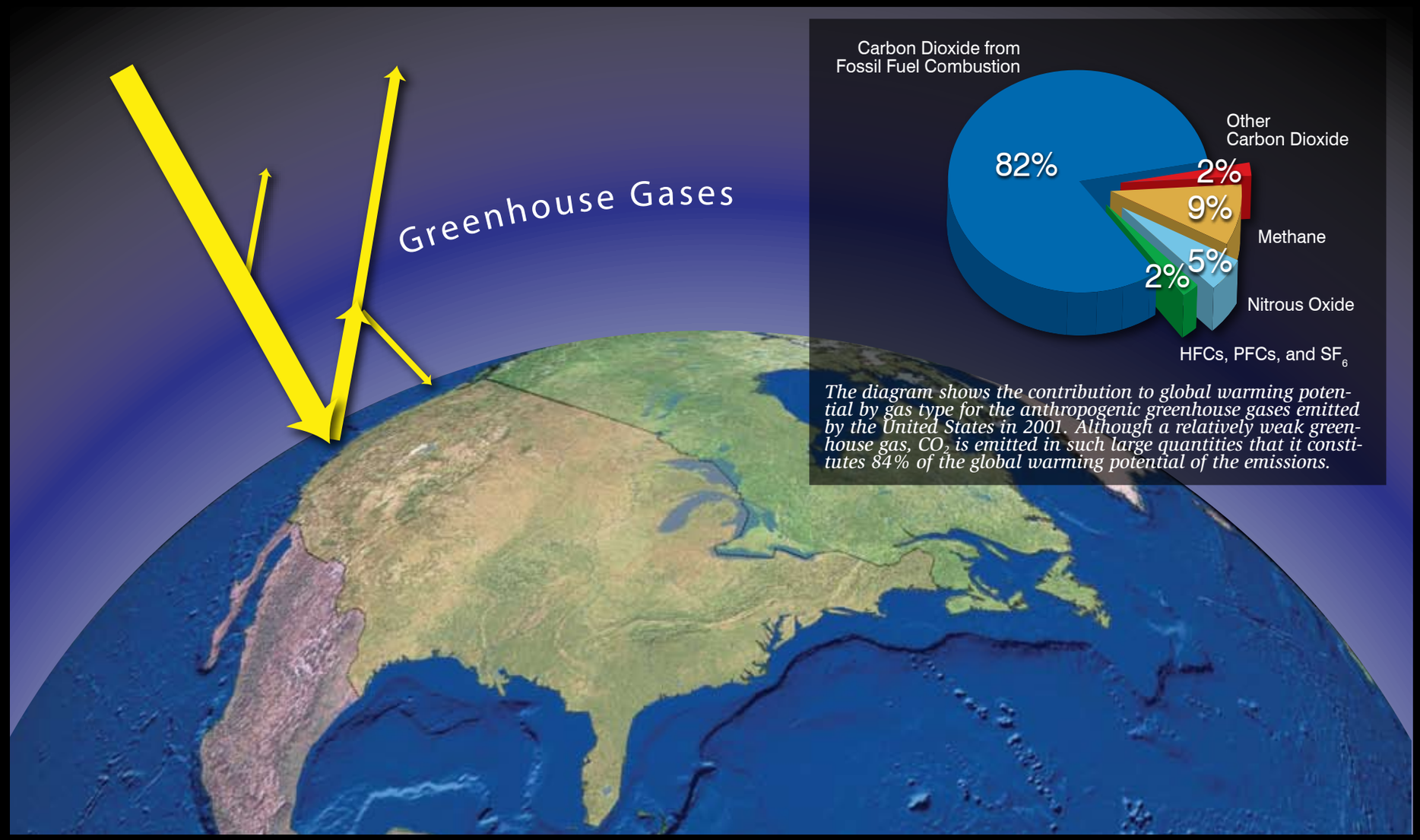
Modern refinery, Billings, Montana, 2004

A Change Is in the Air

Before the onset of the Industrial Revolution in Europe during the late 18th century, the dominant energy sources in the world were wood and animal by-products, such as whale oil and dung. But as the Industrial Revolution moved forward, largely on the shoulders of the steam engine, better energy sources were needed to fuel factories and transportation and provide energy to generate electricity. Humans quickly turned from energy-poor fuels—wood and animal droppings—to energy-rich fossil fuels, including coal, oil, and natural gas. Fossil fuel use has continued to increase dramatically in the industrialized world in the last 150 years.[1]



1. First commercial U.S. coal production begins near Richmond, Virginia[3]
2. James Watt patents modifications to steam engine[3]
3. Baltimore, Maryland, becomes first city to light streets with gas from coal[3]
4. First steamship to cross Atlantic[3]
5. Distillation of kerosene replaces whale oil[4]
6. First oil well in United States[4]
7. Edison invents electric lighting[5]
8. First commercial electric power station opens in San Francisco[5]
9. First practical coal-fired electric generating station goes into operation to supply household lights in New York.[5]
10. Steam turbine invented[5]
11. Gasoline-powered internal combustion engine developed[3]
12. Svante Arrhenius is first to investigate the effect that doubling atmospheric carbon dioxide would have on global climate.[6]
13. Electric refrigerator invented[5]
14. 9 million autos in the United States[5]
15. U.S. population at 148.7 million[7]
16. First commercial nuclear power plant[5]
17. 61.6 million autos registered in the United States[8]
18. Beginning of the modern global warming debate[6]
19. 129.7 million autos registered in the United States[8] and an estimated 600 million motor vehicles in the world[9]
20. U.S. population at 281.4 million[7]



The diagram shows the contribution to global warming potential by gas type for the anthropogenic greenhouse gases emitted by the United States in 2001. Although a relatively weak greenhouse gas, CO_2 is emitted in such large quantities that it constitutes 84% of the global warming potential of the emissions.

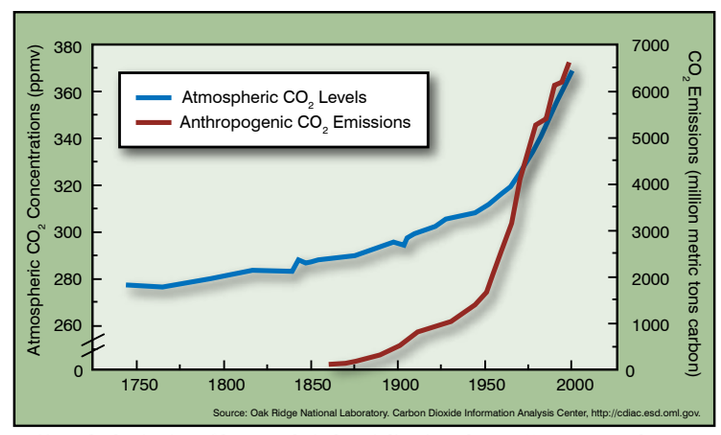
Greenhouse Effect

Energy from the sun drives the earth's weather and climate and heats the earth's surface; in turn, the earth radiates energy back into space. Certain atmospheric gases (water vapor, carbon dioxide, and other gases) trap some of the outgoing energy, retaining heat somewhat like the glass panels of a greenhouse.

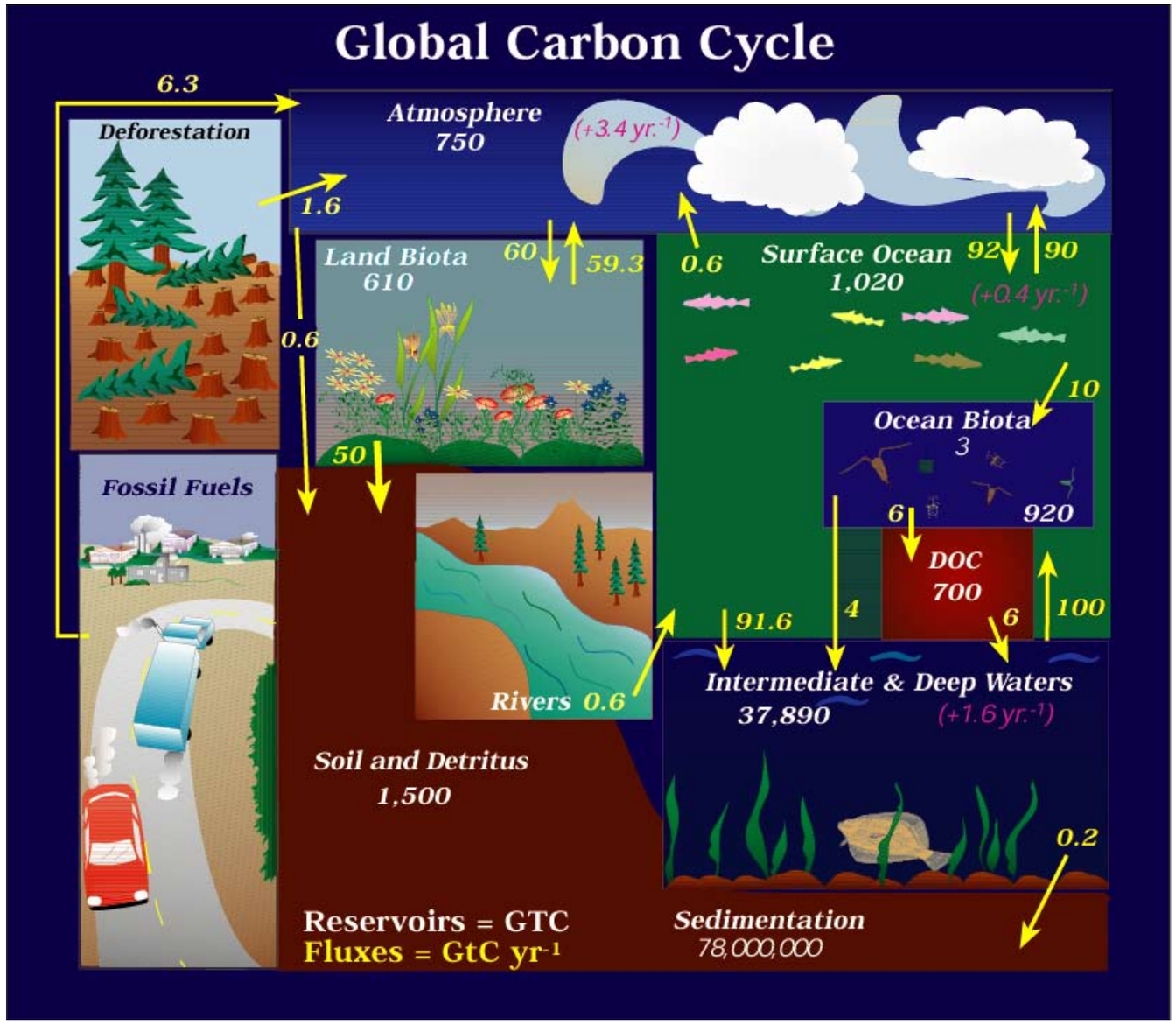
Without this natural "greenhouse effect," global temperatures would be considerably lower than they are now, and life as it is known would not be possible. However, problems may arise when the atmospheric concentration of greenhouse gases increases.[10]

Nearly 100 years ago, Swedish scientist and Nobel Prize winner Svante Arrhenius postulated that anthropogenic increases in atmospheric CO_2 as the result of fossil fuel combustion would have a profound effect on the heat budget of the earth. In 1904, Arrhenius became concerned with rapid increases in anthropogenic carbon emissions and recognized that "the slight percentage of carbonic acid in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries."[11]

Human (anthropogenic) activity, including the use of fossil fuel, generates a significant volume of greenhouse gases like CO_2. Since the beginning of the Industrial Revolution, atmospheric concentrations of carbon dioxide have increased nearly 30%, methane concentrations have more than doubled, and nitrous oxide concentrations have risen by about 15%.[10] These increases have enhanced the heat-trapping capability of the earth's atmosphere. There is concern that the anthropogenic greenhouse gases entering the atmosphere are causing increased warming and that this warming will affect climate on a global scale.



Since the beginning of large-scale industrialization about 150 years ago, the level of CO_2 in the atmosphere has increased by about 30%.



The cycle of carbon movement between the biosphere, atmosphere, hydrosphere, and geosphere is a complex and important global cycle. In the atmosphere, carbon occurs primarily as carbon dioxide. Across the landscape, carbon occurs mainly in living organisms and decaying organic matter in soils.

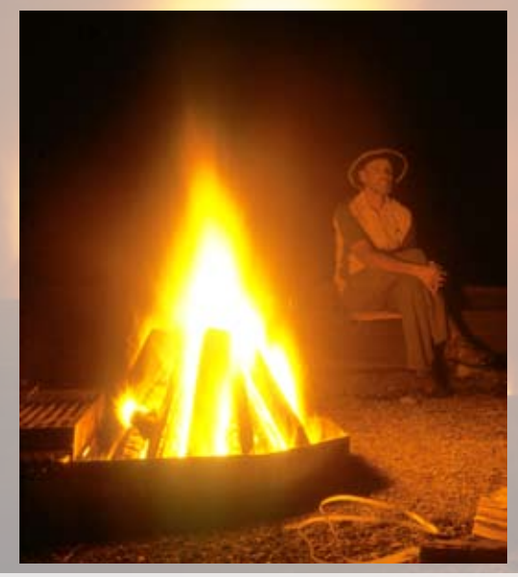
Carbon is continuously circulated between reservoirs in the ocean, land, and atmosphere, where it occurs primarily as carbon dioxide. On land, carbon occurs primarily in living biota and decaying organic matter. In the ocean, the main form of carbon is dissolved carbon dioxide and small creatures, such as plankton. The largest reservoir is the deep ocean, which contains close to 40,000 GtC, compared to around 2000 GtC on land, 750 GtC in the atmosphere, and 1000 GtC in the upper ocean. Although natural transfers of carbon dioxide are approximately 20 times greater than those due to human activity, they are in near balance, with the magnitude of carbon sources closely matching those of the sinks. The additional carbon resulting from human activity is the cause of atmospheric carbon dioxide increases over the last 150 years.[12]

What Is CO_2?

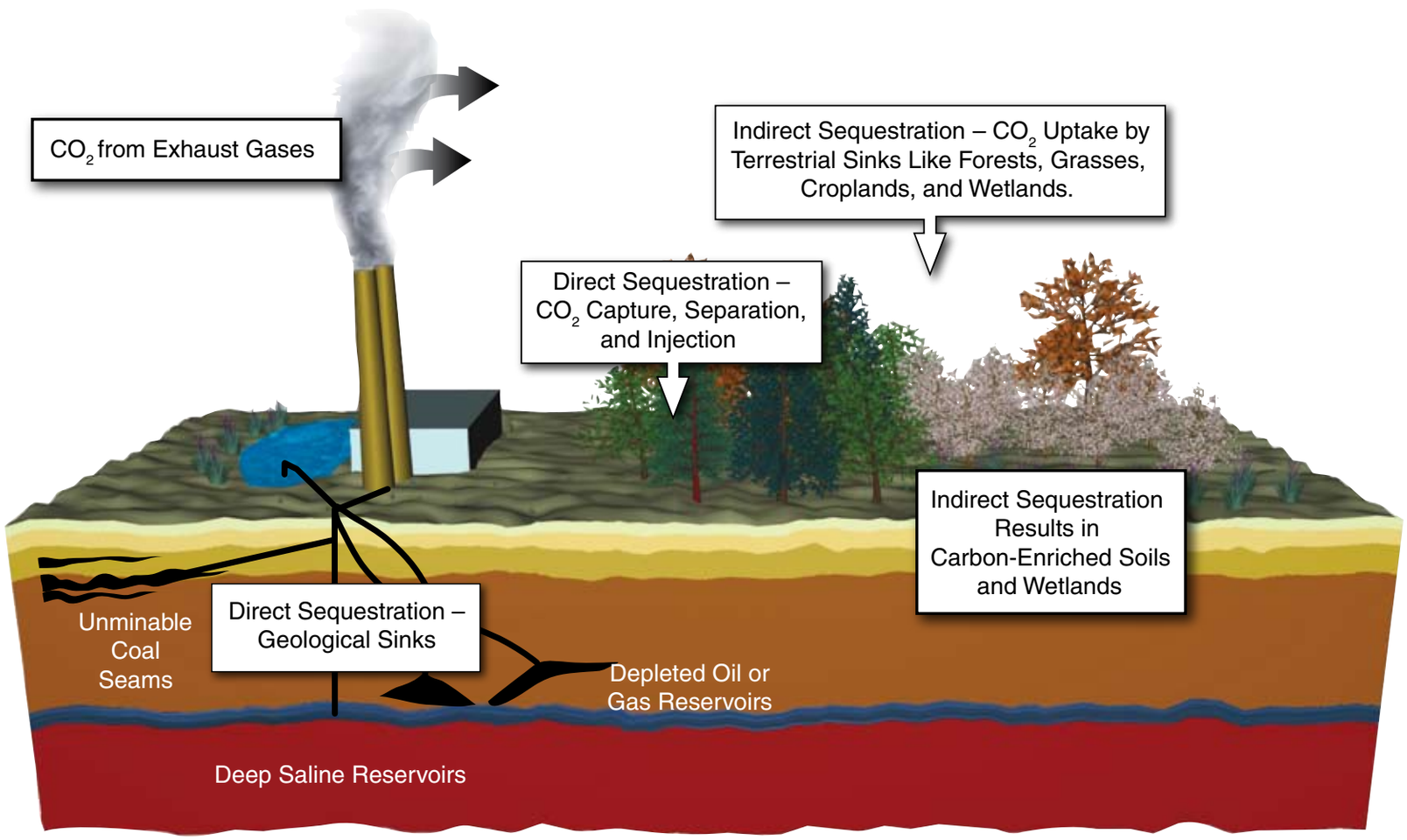
Carbon dioxide is a clear, naturally occurring gas composed of one atom of carbon and two atoms of oxygen. At temperatures below -78°C, carbon dioxide condenses into a white solid called dry ice. Liquid carbon dioxide forms at pressures above 5.1 atmospheres; at atmospheric pressure, it can pass directly from the solid to gaseous phase in a process called sublimation.

Under high temperature and pressure conditions, such as those encountered in deep geological formations (greater than 2600 feet), CO_2 will exist in a dense phase that is referred to as "supercritical." When injected into a geological formation, a portion of the supercritical CO_2 may be dissolved in any fluids, such as water or oil, that are present in the formation, while another portion will be available to react with rock minerals. When CO_2 dissolves in oil, it acts as a solvent, reducing oil viscosity and increasing mobility. The sequestration of CO_2 in a supercritical form is beneficial for two reasons: 1) the supercritical state maximizes the number of CO_2 molecules that can be injected into a given volume and 2) if injected into in an oil reservoir, supercritical CO_2 can increase oil production, which in turn can be used to pay for the capture and transportation of the CO_2 from the original source.

Carbon dioxide is essential to plant life and, as a greenhouse gas, helps create the greenhouse effect that keeps our planet livable. CO_2 is exhaled by birds and animals and is used to put the bubbles in soft drinks, as a coolant (dry ice), and in fire extinguishers. It is also a major by-product produced in the generation of energy through the burning of carbon-based fuels such as wood, coal, and oil. Without sufficient natural uptake of the CO_2, the immense volume of fuel burned in the United States and the world over the past 1.5 centuries may have perturbed the global carbon balance.



Fuel + Oxygen ⇒ Heat + Water + CO_2


CO_2 from Exhaust Gases
Indirect Sequestration – CO_2 Uptake by Terrestrial Sinks Like Forests, Grasses, Croplands, and Wetlands.
Direct Sequestration – CO_2 Capture, Separation, and Injection
Indirect Sequestration Results in Carbon-Enriched Soils and Wetlands
Unminable Coal Seams
Direct Sequestration – Geological Sinks
Depleted Oil or Gas Reservoirs
Deep Saline Reservoirs

What Is CO_2 Sequestration?

Carbon sequestration is the capture and storage of CO_2 and other greenhouse gases that would otherwise be emitted to the atmosphere and potentially contribute to global climate change. The greenhouse gases can be captured at the point of emission, or they can be removed from the air. Captured gases can be used; stored in underground reservoirs or, possibly, the deep oceans; absorbed by trees, grasses, soils, and algae; or converted to rocklike mineral carbonates or other products. Carbon sequestration holds the potential to provide substantial reductions in greenhouse gas emissions.

There are two types of sequestration: *direct* and *indirect*.

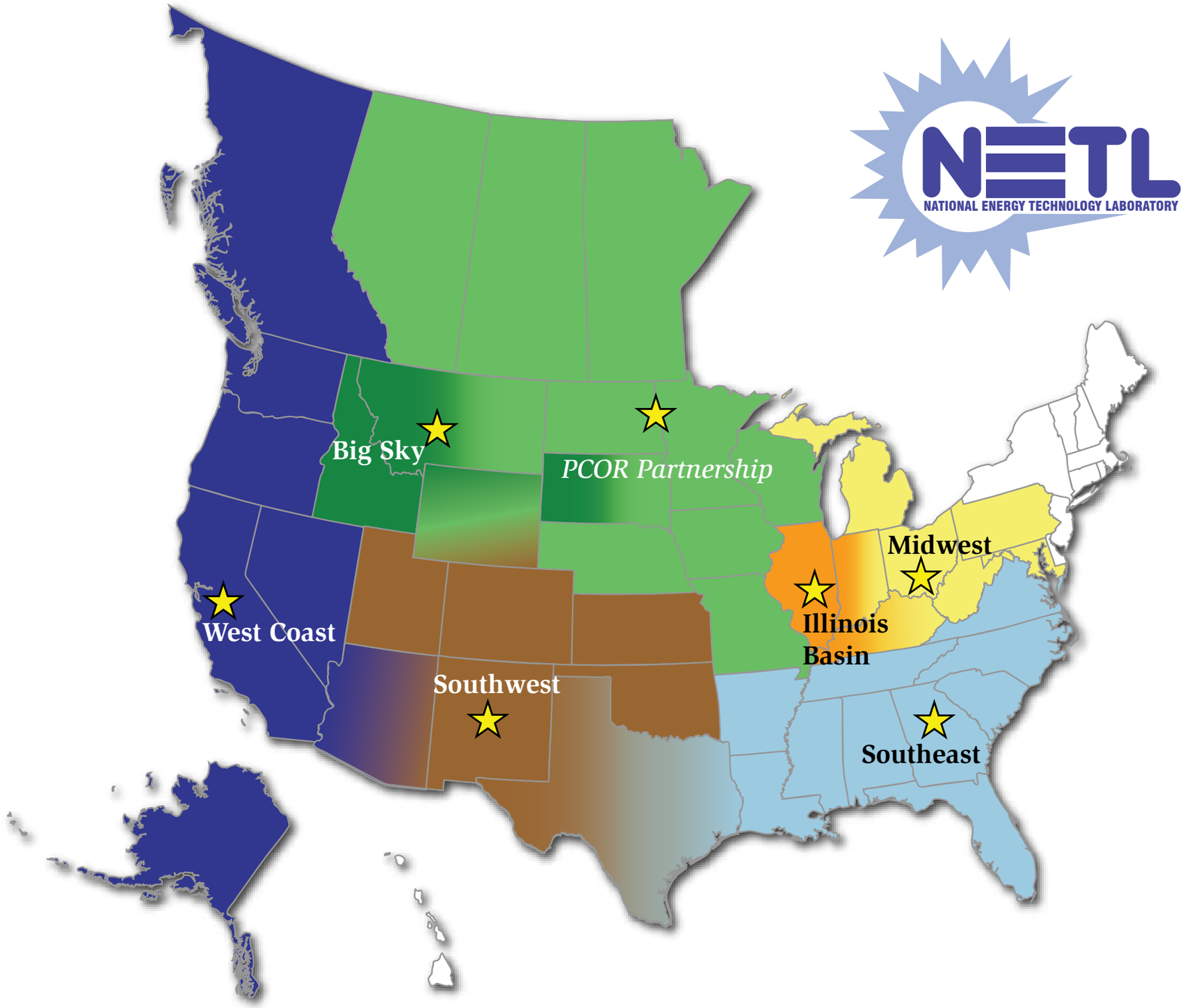
Direct CO_2 Sequestration

Direct, or geologic, sequestration involves capturing CO_2 at a source before it can be emitted to the atmosphere. The most efficient concept would use specialized equipment to capture CO_2 at large stationary sources like factories or power plants and then inject the CO_2 into secure storage zones deep underground (geologic sequestration) or into the deep ocean.

Indirect CO_2 Sequestration

Indirect or terrestrial sequestration involves removing CO_2 from the atmosphere. Indirect sequestration employs land management practices that boost the ability of natural CO_2 sinks like plants and soils to remove carbon as CO_2 from the atmosphere, regardless of its source. Opportunities for indirect sequestration can be found in forests, grasslands, wetlands, and croplands.

Affordable and environmentally safe sequestration approaches could offer a way to stabilize atmospheric levels of carbon dioxide without requiring the United States and other countries to make large-scale and potentially costly changes to our energy infrastructure.

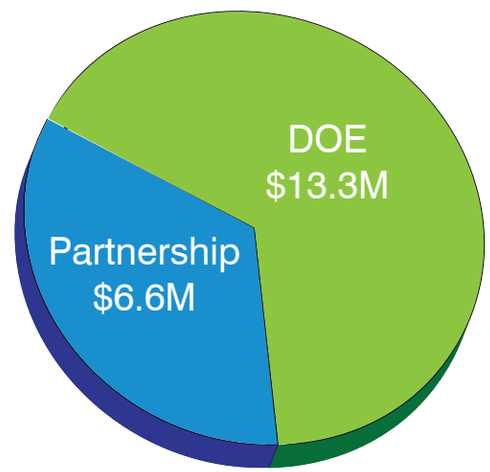

NETL
NATIONAL ENERGY TECHNOLOGY LABORATORY
Big Sky
PCOR Partnership
Midwest
Illinois Basin
West Coast
Southwest
Southeast

DOE's Phase I Carbon Sequestration Regional Partnerships

If science indicates that carbon sequestration must be implemented in the United States on a broad scale and in a relatively short time frame (meaning over several years), it will take a concerted effort of federal and state agencies, working in cooperation with technology developers, regulators, and others, to put into place both the concepts and the necessary infrastructure to achieve meaningful carbon reductions.

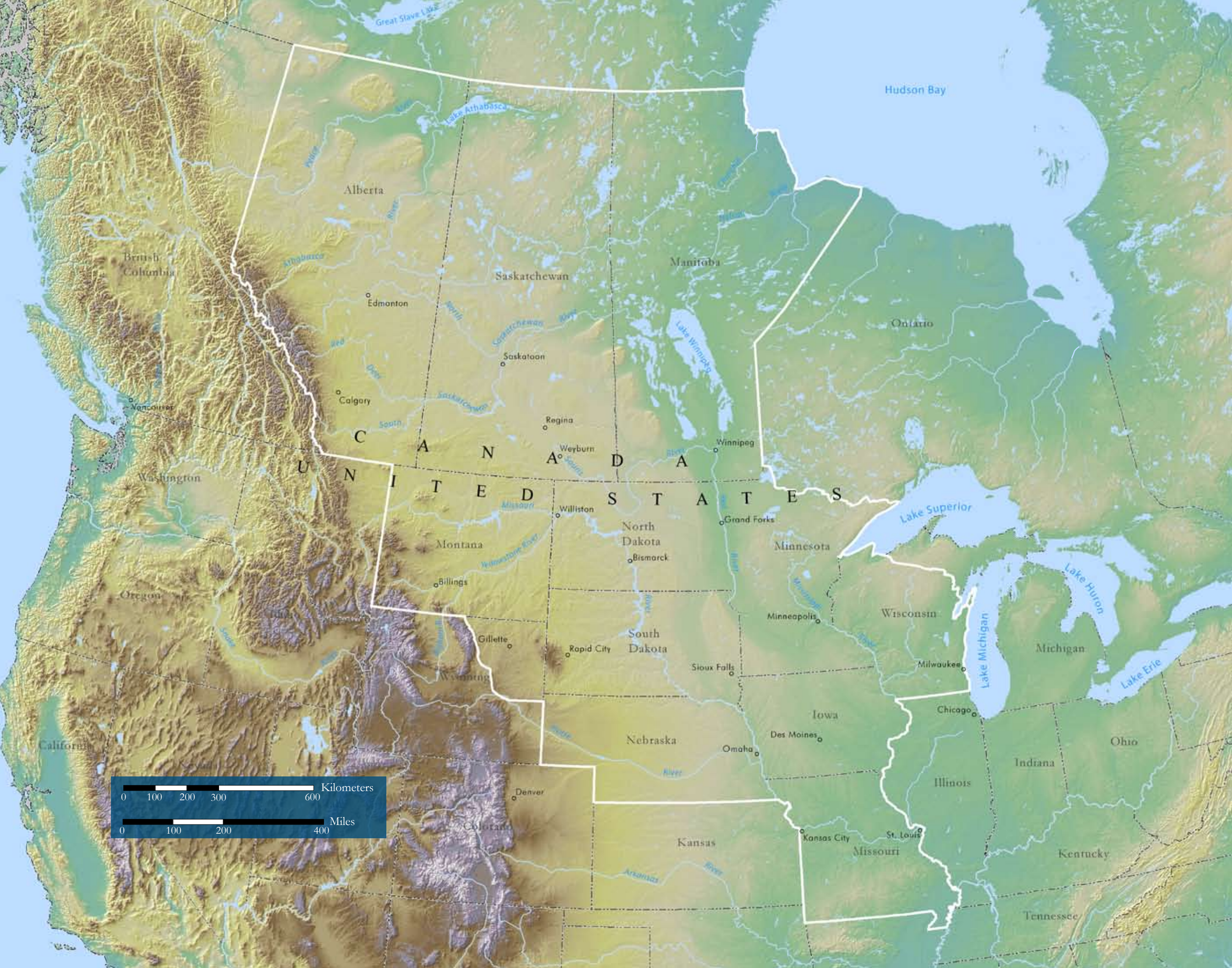
To ensure that America is fully prepared to implement this climate change mitigation option, then-Secretary of Energy Spencer Abraham on November 21, 2002, announced plans to create a national network of public–private sector partnerships that would determine the most suitable technologies, regulations, and infrastructure needs for carbon capture, storage, and sequestration in different areas of the country. The Secretary called the partnership initiative "the centerpiece of our sequestration program." The partnerships are a key part of President Bush's Global Climate Change Initiative (GCCI).

On August 16, 2003, following a competitive evaluation, Energy Secretary Spencer Abraham named seven teams, called Regional Carbon Sequestration Partnerships, to evaluate and promote the carbon sequestration technologies and infrastructure best suited to their unique regions. The original partnerships included leaders from more than 140 organizations spanning 33 states, three American Indian nations, and two Canadian provinces. By February 2005, the partnerships had expanded to include 216 organizations spanning 40 states, three Indian nations, and four Canadian provinces.[13]



Representing:

- 216 Organizations
- 40 States
- 4 Canadian Provinces
- 3 Indian Nations
- 34% Cost Share


Great Slave Lake
Hudson Bay
Lake Athabasca
Alberta
Saskatchewan
Manitoba
Ontario
British Columbia
Edmonton
Saskatoon
Calgary
Regina
Weyburn
Winnipeg
Vancouver
Lake Winnipeg
C A N A D A
U N I T E D S T A T E S
Washington
Williston
Grand Forks
North Dakota
Bismarck
Montana
Billings
Minnesota
Lake Superior
Lake Huron
Lake Michigan
Lake Erie
Oregon
Idaho
Minneapolis
Wisconsin
Michigan
Gillette
Rapid City
South Dakota
Sioux Falls
Milwaukee
Wyoming
Chicago
Iowa
Des Moines
Nebraska
Omaha
Ohio
Indiana
California
Illinois
Denver
Colorado
Kansas
Kansas City
St. Louis
Missouri
Kentucky
Tennessee
Kilometers
0 100 200 300 600
Miles
0 100 200 400

The PCOR Partnership

The Plains CO_2 Reduction (PCOR) Partnership is a diverse group of public and private sector stakeholders working together to better understand the technical and economic feasibility of capturing and storing CO_2 emissions from stationary sources of CO_2 in the cental interior of North America. The PCOR Partnership is managed by the Energy & Environmental Research Center (EERC) at the University of North Dakota and is one of seven regional partnerships funded by the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnership Program and a broad range of project sponsors.

The PCOR Partnership assessed and prioritized the opportunities for sequestration in the region and identified and worked to resolve the technical, regulatory, and environmental barriers to the most promising sequestration opportunities. At the same time, the PCOR Partnership has informed policy makers and the public regarding CO_2 sources, sequestration strategies, and sequestration opportunities.

- In 2000, the states and provinces within the PCOR Partnership region contributed approximately 13% (911* million tons) of the total CO_2 emissions from the United States and Canada.[14]
- CO_2 emissions in the U.S. portion of the PCOR Partnership region are split between mobile (27%) and stationary (73%) sources.[14]
- Croplands, wetlands, and forests in the PCOR Partnership region represent opportunities for indirect (terrestrial) sequestration projects.
- The PCOR Partnership region is currently home to several indirect sequestration research projects involving wetlands, cultivated land, prairie, and forest.
- Unminable coals, depleted oil and gas zones, and deep saline reservoirs in the PCOR Partnership region represent opportunities for direct (geologic) sequestration projects.
- The PCOR Partnership region is currently home to the Weyburn direct sequestration demonstration project (an example of enhanced oil recovery [EOR]).

*This value includes sources in Wyoming and Montana outside of the PCOR Partnership region.

ptrc
Petroleum Technology Research Centre

MUREX PETROLEUM CORPORATION

minnesota power
AN ALLETE COMPANY
YOUR POWERFUL PARTNER

NDSU
NORTH DAKOTA STATE UNIVERSITY

EXCELSIOR ENERGY

AERI
Alberta Energy Research Institute

Manitoba Hydro

LIGNITE Energy COUNCIL

Ducks Unlimited Canada
CANADA'S CONSERVATION COMPANY

HESS

GREAT NORTHERN

North Dakota Department of Health

GREAT RIVER ENERGY
A Touchstone Energy Cooperative

Great Plains SYNFUELS
Dakota Gasification Company

SaskPower

MONTANA-DAKOTA UTILITIES CO.
A Division of MDU Resources Group, Inc.

NORTH DAKOTA NATURAL RESOURCES TRUST

N. D. I. C.
Oil & Gas Div.

Encore
Acquisition Company

Prairie Public Television

OTTER TAIL POWER COMPANY

TESORO

USGS
science for a changing world

EERC
Energy & Environmental Research Center®

UND University of North Ducota
Grand Forks, North Dakota

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

NETL
NATIONAL ENERGY TECHNOLOGY LABORATORY

KIEWIT PKS SINCE 1884
Kiewit

Eagle Operating Inc.

UNIVERSITY OF REGINA
AS ONE WHO SERVES

CEED®
Center for Energy and Economic Development

North Dakota Petroleum Council

INTERSTATE OIL AND GAS COMPACT COMMISSION
DEDICATED TO THE CONSERVATION OF OIL AND GAS
1935

Minnesota Pollution Control Agency

PTTC
TECHNOLOGY CONNECTIONS

BASIN ELECTRIC POWER COOPERATIVE
A Touchstone Energy® Cooperative

Nexant

Alberta Environment

CCX
Chicago Climate Exchange

Fischer Oil and Gas, Inc.

NORTH DAKOTA GEOLOGICAL SURVEY 1895

Environment Canada

PUBLIC SERVICE COMMISSION
MONTANA

Minnkota Power
MPC COOPERATIVE, INC.
Your Touchstone Energy® Partner

Montana Department of ENVIRONMENTAL QUALITY

Saskatchewan Industry and Resources

WESTERN GOVERNORS' ASSOCIATION

BECHTEL

EUB
Alberta Energy and Utilities Board

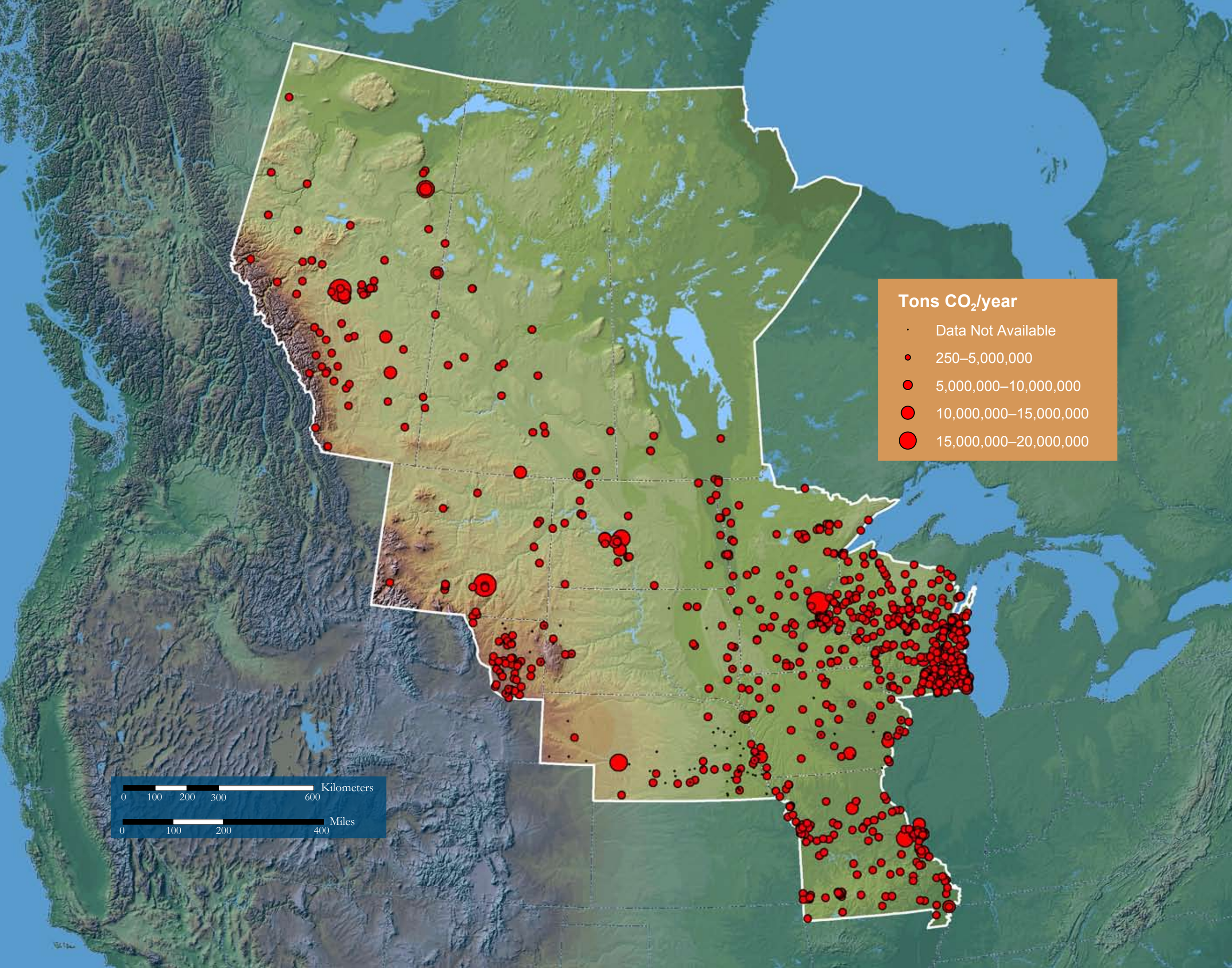
Xcel Energy™

PCOR Partnership Phase I Partners

The PCOR Partnership is a collaboration of more than 40 public and private sector stakeholders from the central interior of North America that have expertise in power generation, energy exploration and production, geology, engineering, the environment, agriculture, forestry, and economics. Our partners are the backbone of the PCOR Partnership and provide data, guidance, and practical experience with direct and indirect sequestration, including value-added projects.

PCOR Partnership Phase I List of Partners

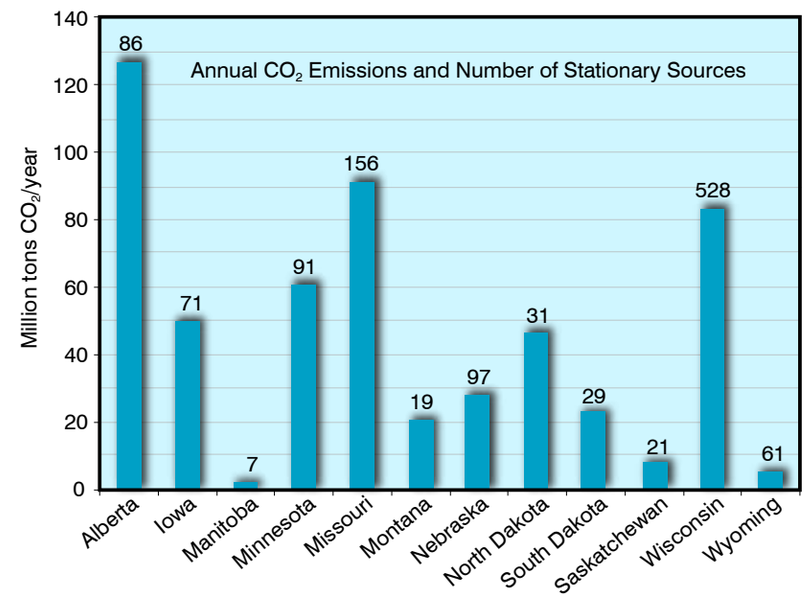
- U.S. Department of Energy
- University of North Dakota Energy & Environmental Research Center
- Alberta Department of Environment
- Alberta Energy and Utilities Board
- Alberta Energy Research Institute
- Amerada Hess Corporation
- Basin Electric Power Cooperative
- Bechtel Corporation
- Center for Energy and Economic Development (CEED)
- Chicago Climate Exchange
- Dakota Gasification Company
- Ducks Unlimited Canada
- Eagle Operating, Inc.
- Encore Acquisition Company
- Environment Canada
- Excelsior Energy Inc.
- Fischer Oil and Gas, Inc.
- Great Northern Power Development, LP
- Great River Energy
- Interstate Oil and Gas Compact Commission
- Kiewit Mining Group Inc.
- Lignite Energy Council
- Manitoba Hydro
- Minnesota Pollution Control Agency
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Montana–Dakota Utilities Co.
- Montana Department of Environmental Quality
- Montana Public Service Commission
- Murex Petroleum Corporation
- Nexant, Inc.
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Industrial Commission Lignite Research, Development and Marketing Program
- North Dakota Industrial Commission Oil and Gas Division
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- North Dakota State University
- Otter Tail Power Company
- Petroleum Technology Research Centre
- Petroleum Technology Transfer Council
- Prairie Public Television
- SaskPower
- Saskatchewan Industry and Resources
- Tesoro Refinery (Mandan)
- University of Regina
- U.S. Geological Survey Northern Prairie Wildlife Research Center
- Western Governors' Association
- Xcel Energy


Tons CO_2/year
Data Not Available
250–5,000,000
5,000,000–10,000,000
10,000,000–15,000,000
15,000,000–20,000,000
Kilometers
0 100 200 300 600
Miles
0 100 200 400

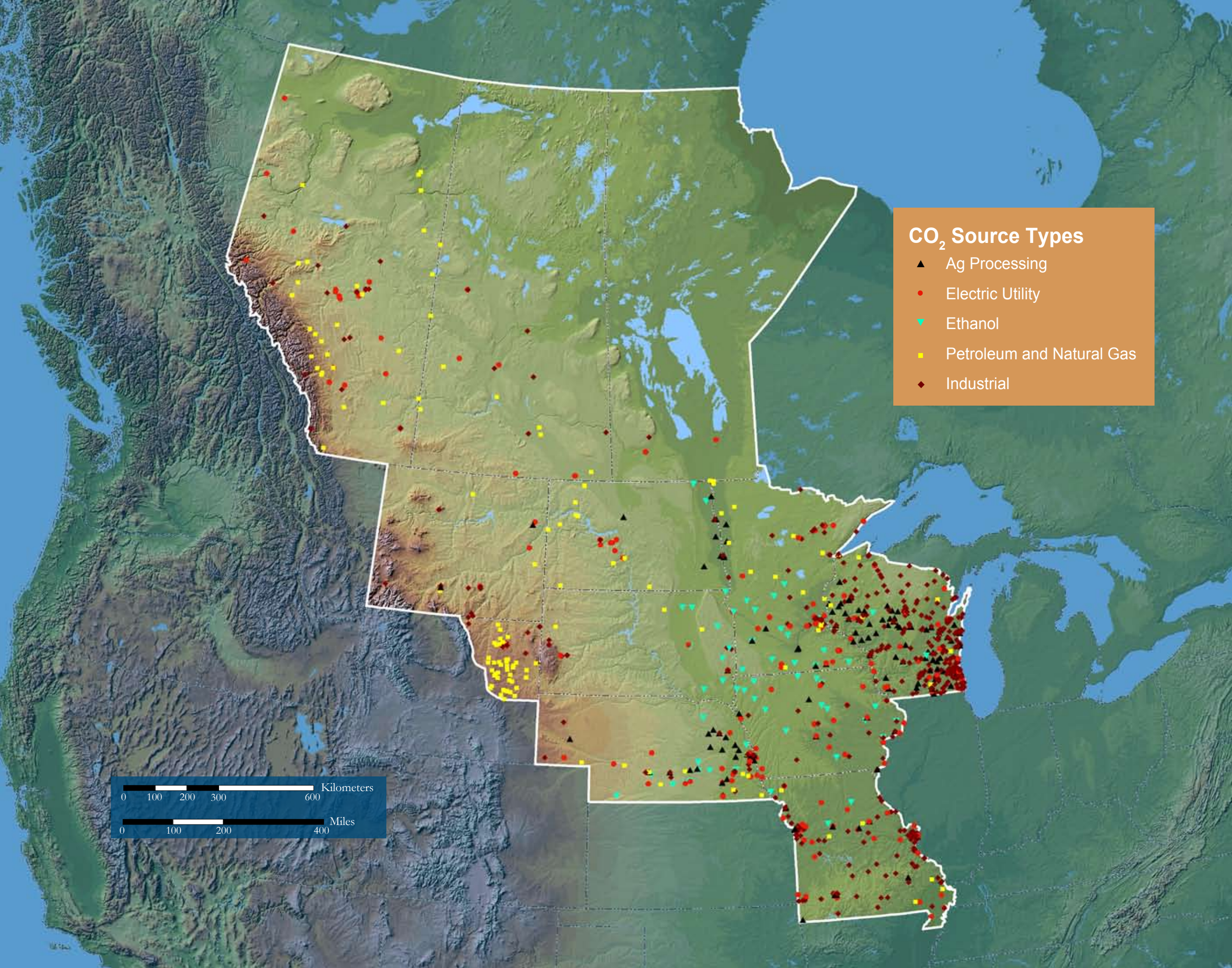
CO_2 Sources

The PCOR Partnership project has identified, quantified, and categorized nearly 1360 stationary CO_2 sources in the region. These stationary sources have a combined annual CO_2 output of nearly 553* million tons or 8.88 trillion cubic feet. And, although not a target source of CO_2 for direct sequestration, the transportation sector contributes nearly 223 million additional tons of CO_2 to the atmosphere every year.[14]

The annual output from the various stationary sources ranges from 10 million to 18 million tons for the larger coal-fired electric generation facilities, to under 5000 tons for industrial and agricultural processing facilities. For the most part, the distribution of the sources with the largest CO_2 output is coincident with the availability of fossil fuel resources, namely, coal, natural gas, and oil. This relationship is significant with respect to geologic sequestration opportunities. Many of the smaller sources are concentrated around more heavily industrialized metropolitan regions such as southeastern Minnesota and southeastern Wisconsin.



*This value includes only the sources with emissions greater than 1000 tons/year located *inside* the PCOR Partnership region.

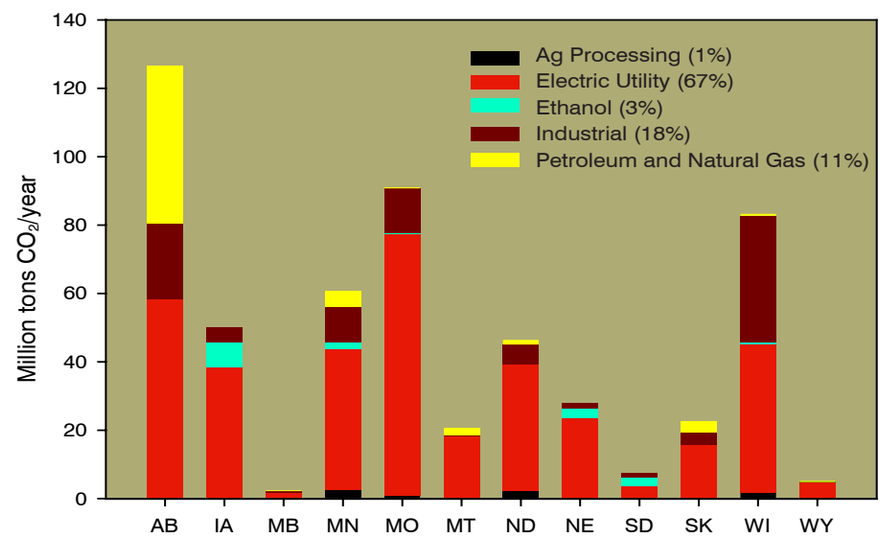

CO_2 Source Types
Ag Processing
Electric Utility
Ethanol
Petroleum and Natural Gas
Industrial
Kilometers
0 100 200 300 600
Miles
0 100 200 400

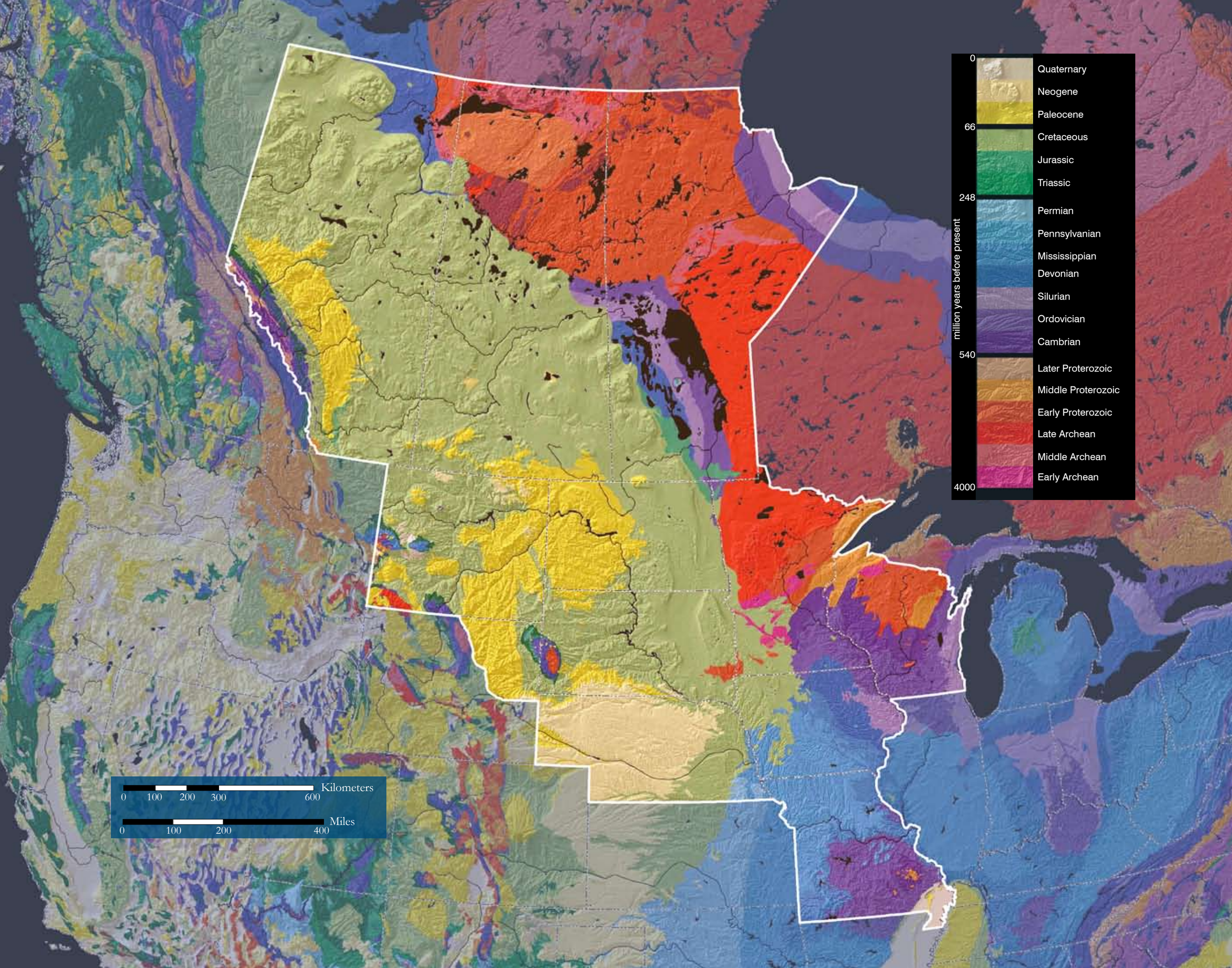
CO_2 Source Types

The geographic and socioeconomic diversity of the region is reflected in the variable nature of the carbon dioxide sources found there. CO_2 is emitted from electricity generation; energy exploration and production activities; agricultural; fuel, chemicals, and ethanol production; and various manufacturing and industrial activities. The majority of the region's emissions come from just a few source types. About two-thirds of the CO_2 is emitted during electricity generation, followed by industrial sources, petroleum refining and natural gas processing, ethanol production, and agricultural processing.

The emissions profile (i.e., the percentage of CO_2 emissions from various source types) for the Canadian portion of the PCOR Partnership is virtually identical to that of Canada as a whole. On the other hand, when compared to the total U.S. CO_2 emissions, the states in the PCOR Partnership region emit relatively more CO_2 from electric utilities and less from industries and transportation.[14]

While the CO_2 emissions from the individual PCOR Partnership point sources are no different from similar sources located around the United States, the wide range of source types within the PCOR Partnership region offers the opportunity to evaluate the capture, separation, and transportation of CO_2 in many different scenarios. The fact that the PCOR Partnership region's emission trends are similar to those of the United States means that the region's sources are representative of the entire United States, and the work performed during Phase II of the PCOR Partnership will be transferable to the rest of the country.




0
Quaternary
Neogene
Paleocene
66
Cretaceous
Jurassic
Triassic
248
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
540
Later Proterozoic
Middle Proterozoic
Early Proterozoic
Late Archean
Middle Archean
Early Archean
4000
million years before present
Kilometers
0 100 200 300 600
Miles
0 100 200 400

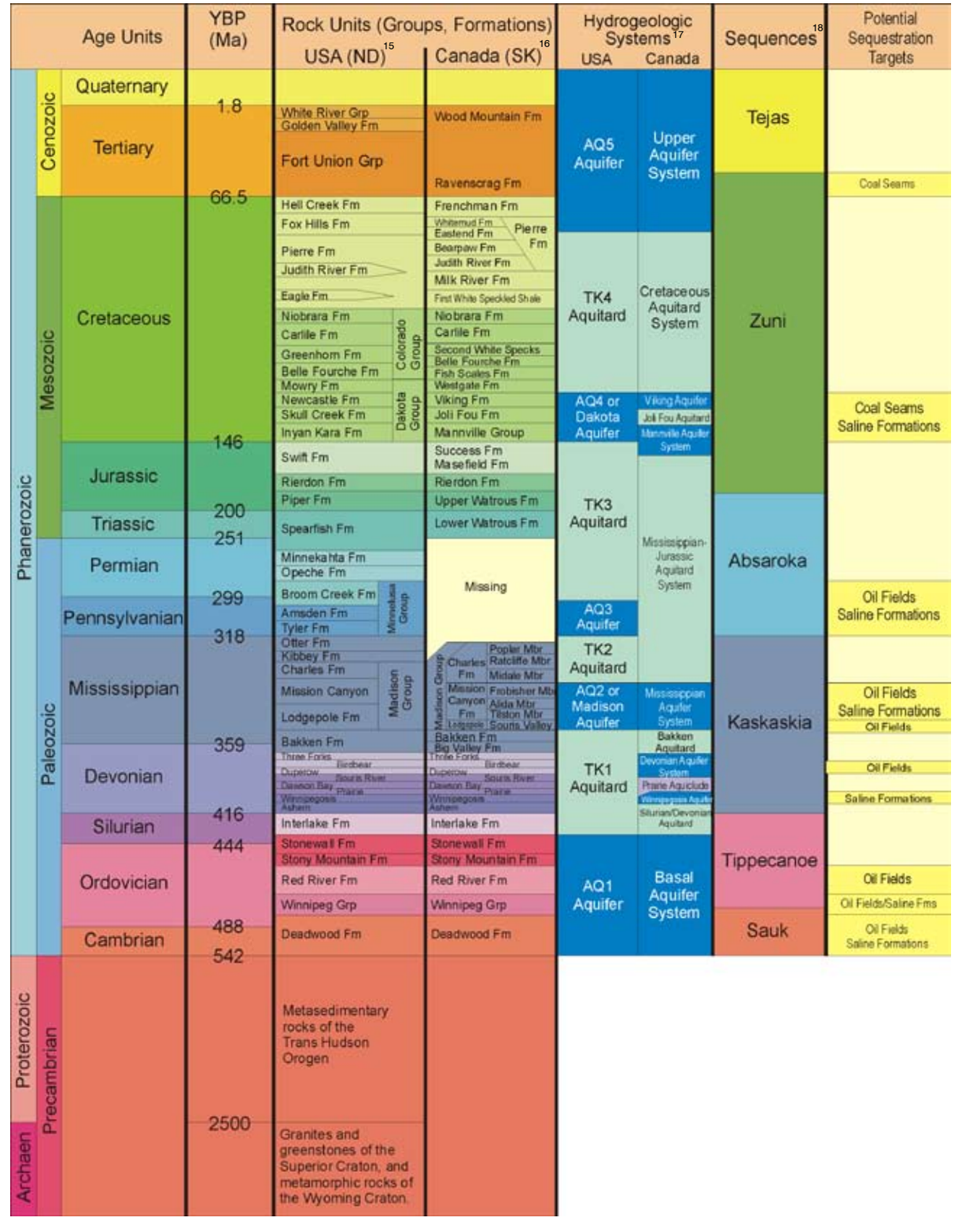
Geologic Framework

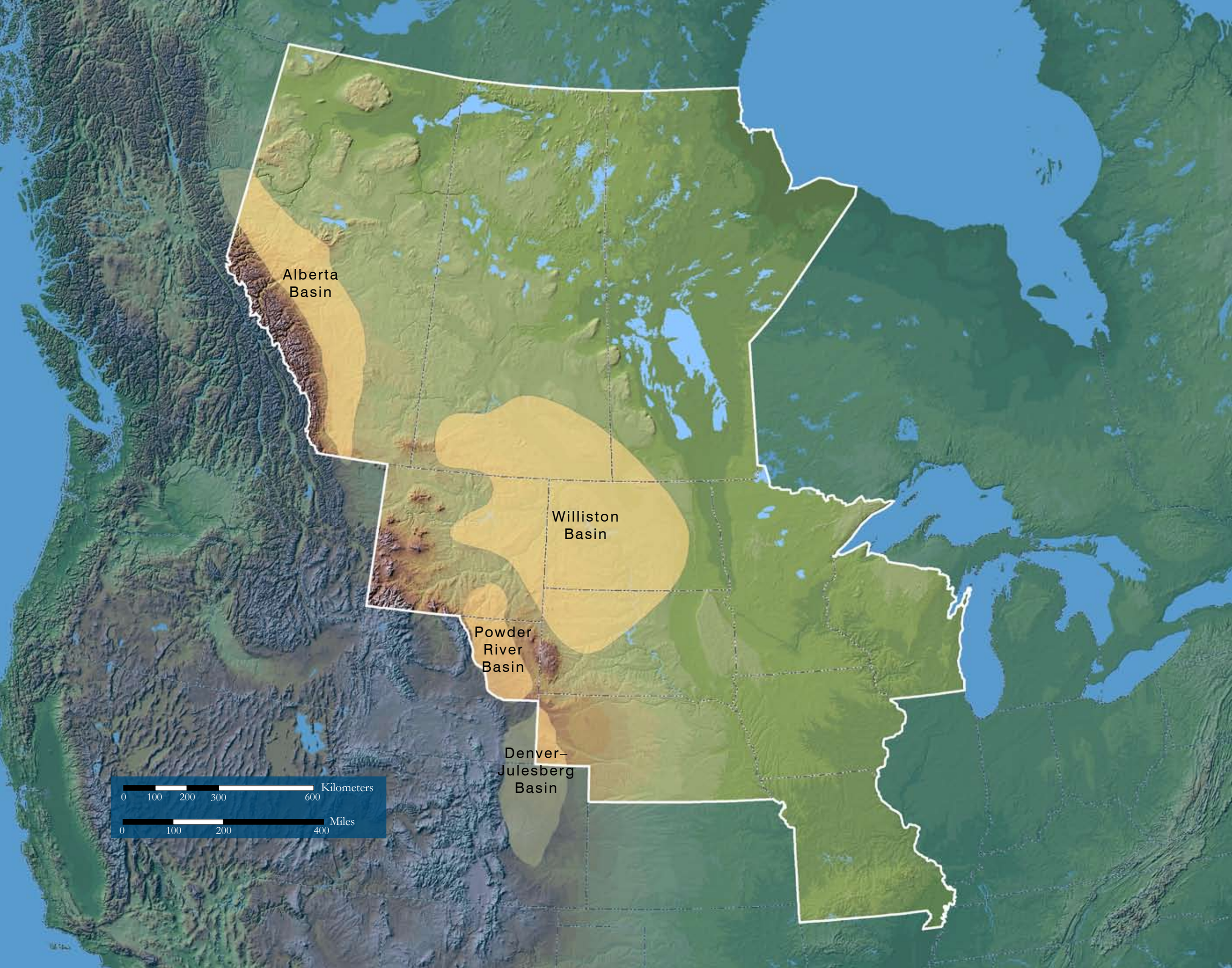
The same geological framework that makes a large percentage of the PCOR Partnership region a significant producer of fossil fuels also creates prime opportunities for CO_2 sequestration. The western two-thirds of the region is underlain by great thicknesses of sedimentary rocks that span the entire stratigraphic record. The remainder of the region is underlain by Precambrian igneous and metamorphic rocks of the Canadian Shield.

The most extensive sequence of rocks in central North America is represented by the Cretaceous-aged marine sediments that were deposited in the former western interior seaway. This intracratonic sea extended from the Gulf of Mexico, across the center of North America, to the Arctic Ocean. The deeper portions of these strata offer tremendous capacity for sequestration.

As the sea retreated from the continent, deltaic and marginal marine environments were established. The remains of these ecosystems are evident in the vast subbituminous and lignite coal reserves of Alberta, Wyoming, Montana, and North Dakota. The unminable portions of these deposits also provide opportunities for CO_2 sequestration.

In the millions of years since the seaway retreated, the central portion of the North American continent has been relatively stable. This tectonic stability is of prime importance with respect to safe and secure sequestration in deep geologic formations.




Alberta Basin
Williston Basin
Powder River Basin
Denver–Julesberg Basin
Kilometers
0 100 200 300 600
Miles
0 100 200 400

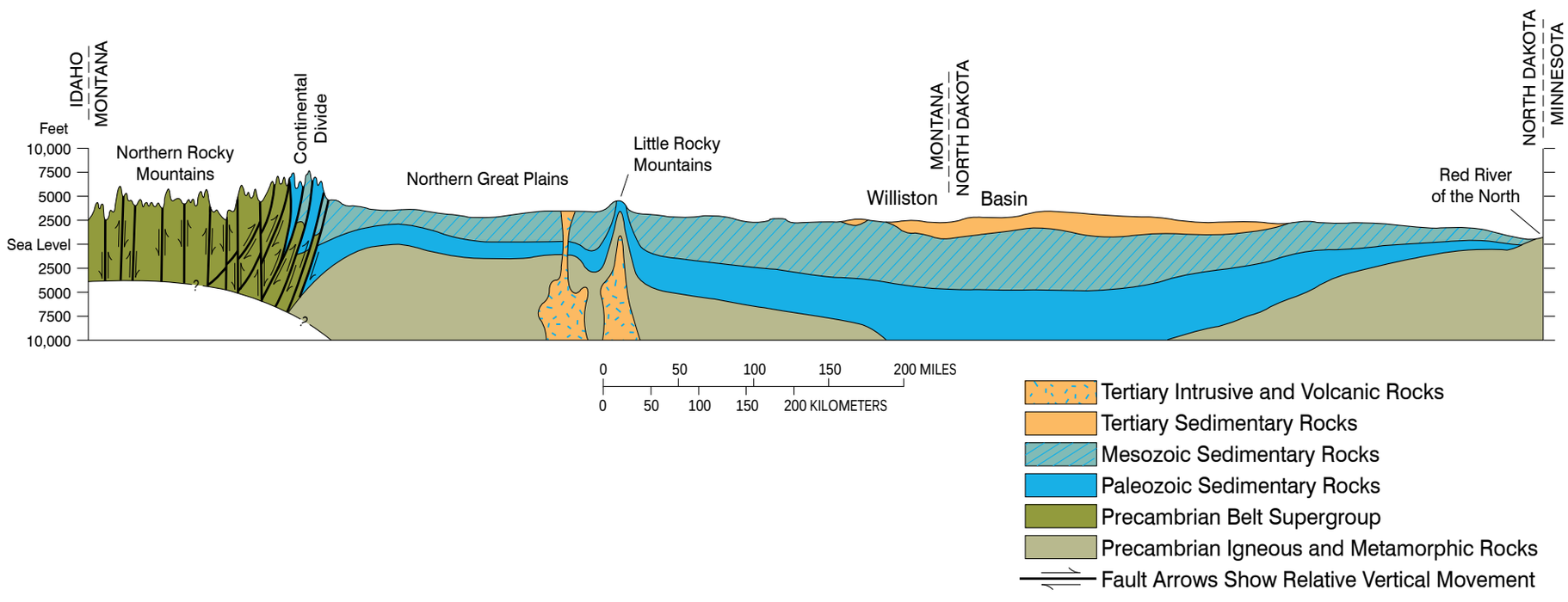
Sedimentary Basins

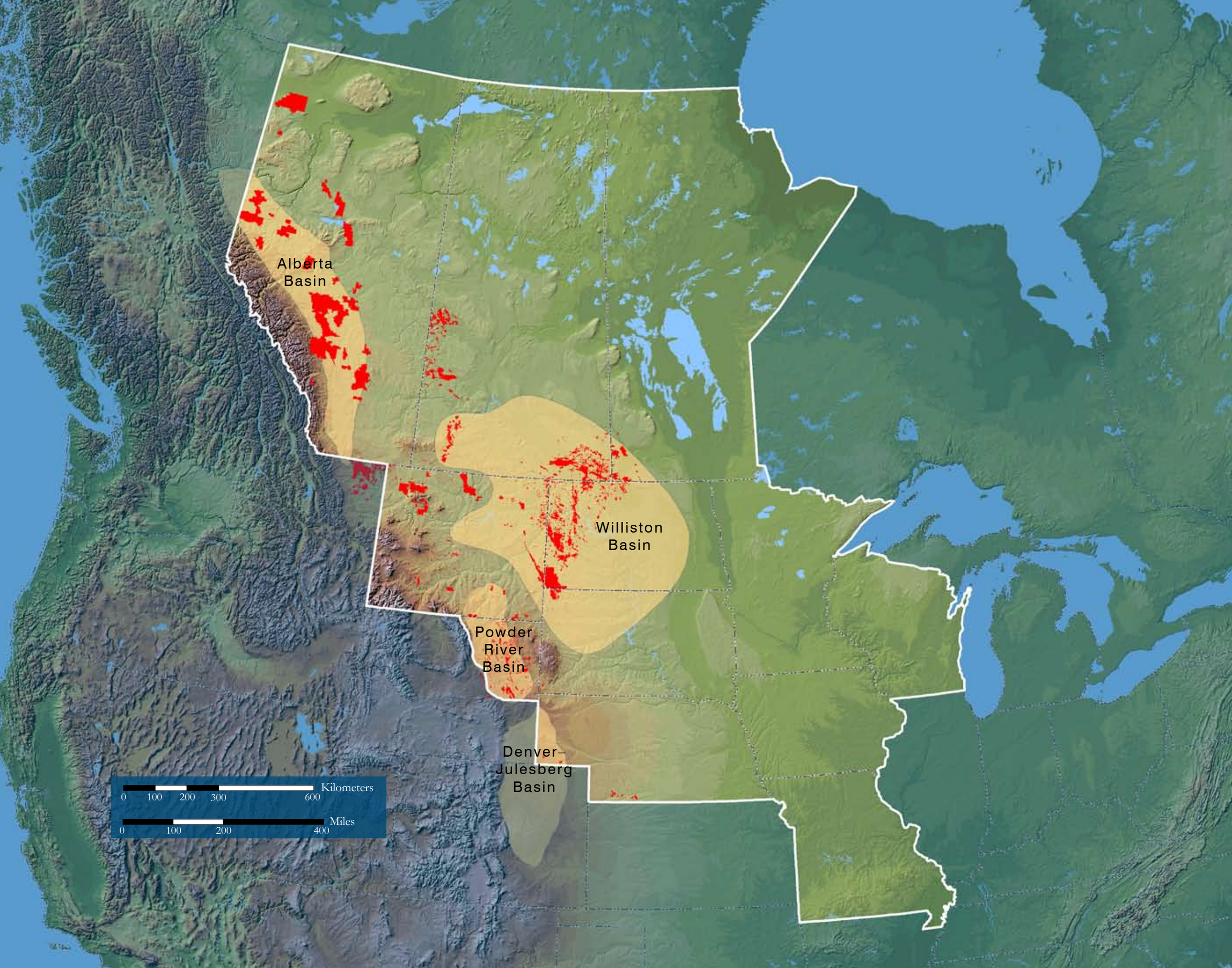
There are four relatively large and deep, intracratonic oil-producing basins intersecting the PCOR Partnership region, each with a sedimentary cover thousands of feet thick. The basins in the PCOR Partnership region have significant potential as geological sinks for sequestering CO_2. Geological sinks that may be suitable for long-term sequestration of CO_2 include both active and depleted petroleum reservoirs, deep saline formations, and coal seams, all of which are common in these basins.

While general information on the structural geology, lithostratigraphy, hydrostratigraphy, and petroleum geology of these basins is available, additional characterization data for specific geological sinks will be necessary. Rocks that have been explored or developed for hydrocarbon recovery have been geologically characterized to a great extent, while non-hydrocarbon-bearing zones (such as saline formations) will require much more geologic investigation prior to large-scale sequestration.

As with many disciplines and technologies, a precise and descriptive vocabulary is needed to adequately describe and discuss the sequestration of CO_2 in geological formations. In the petroleum industry, a rock layer that contains fluid or gas is referred to as a ***reservoir***. A rock layer that oil or gas cannot flow through is referred to as a ***trap*** or a ***cap***. In hydrogeology, a rock layer that contains water is referred to as an ***aquifer***. A rock layer that contains water with dissolved solids (salt) concentrations that are above drinking water standards is commonly known as a ***saline aquifer*** or ***brine formation***. A rock layer that water cannot flow through is referred to as an ***aquitard*** or a ***confining bed***.

Carbon dioxide can be geologically sequestered in sedimentary basins by the following mechanisms: 1) stratigraphic and structural trapping in depleted oil and gas reservoirs, 2) solubility trapping in reservoir oil and formation waters, 3) adsorption trapping in unminable coal seams, 4) cavern trapping in salt structures, and 5) mineral immobilization. Phase I of the PCOR Partnership focused on the sequestration of CO_2 in coal seams, petroleum reservoirs, and brine formations.




Alberta Basin
Williston Basin
Powder River Basin
Denver–Julesberg Basin
Kilometers
0 100 200 300 600
Miles
0 100 200 400

Oil and Gas Fields

The geology of carbon dioxide sequestration is analogous to the geology of petroleum exploration; the search for oil is the search for sequestered hydrocarbons. Oil fields have many characteristics that make them excellent target locations for geologic storage of CO_2. Therefore, the geological conditions that are conducive to hydrocarbon sequestration are also the conditions that are conducive to CO_2 sequestration. The three requirements for sequestering hydrocarbons are a hydrocarbon source, a suitable reservoir, and an impermeable trap. These requirements are the same as for sequestering CO_2, except that the source is artificial and the reservoir is referred to as a sink.

A single oil field can have multiple zones of accumulation which are commonly referred to as pools, although specific legal definitions of fields, pools, and reservoirs vary for each state or province. Once injected into an oil field, CO_2 may be sequestered in a pool through dissolution into the formation fluids (oil and/or water), as a buoyant supercritical-phase CO_2 plume at the top of the reservoir (depending on the location of the injection zone within the reservoir), and/or mineralized through geochemical reactions between the CO_2, formation waters, and formation rock matrix.

Oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from 2500 to 4000 feet for the shallower pools, to 12,000 to 16,000 feet for the deepest pools.

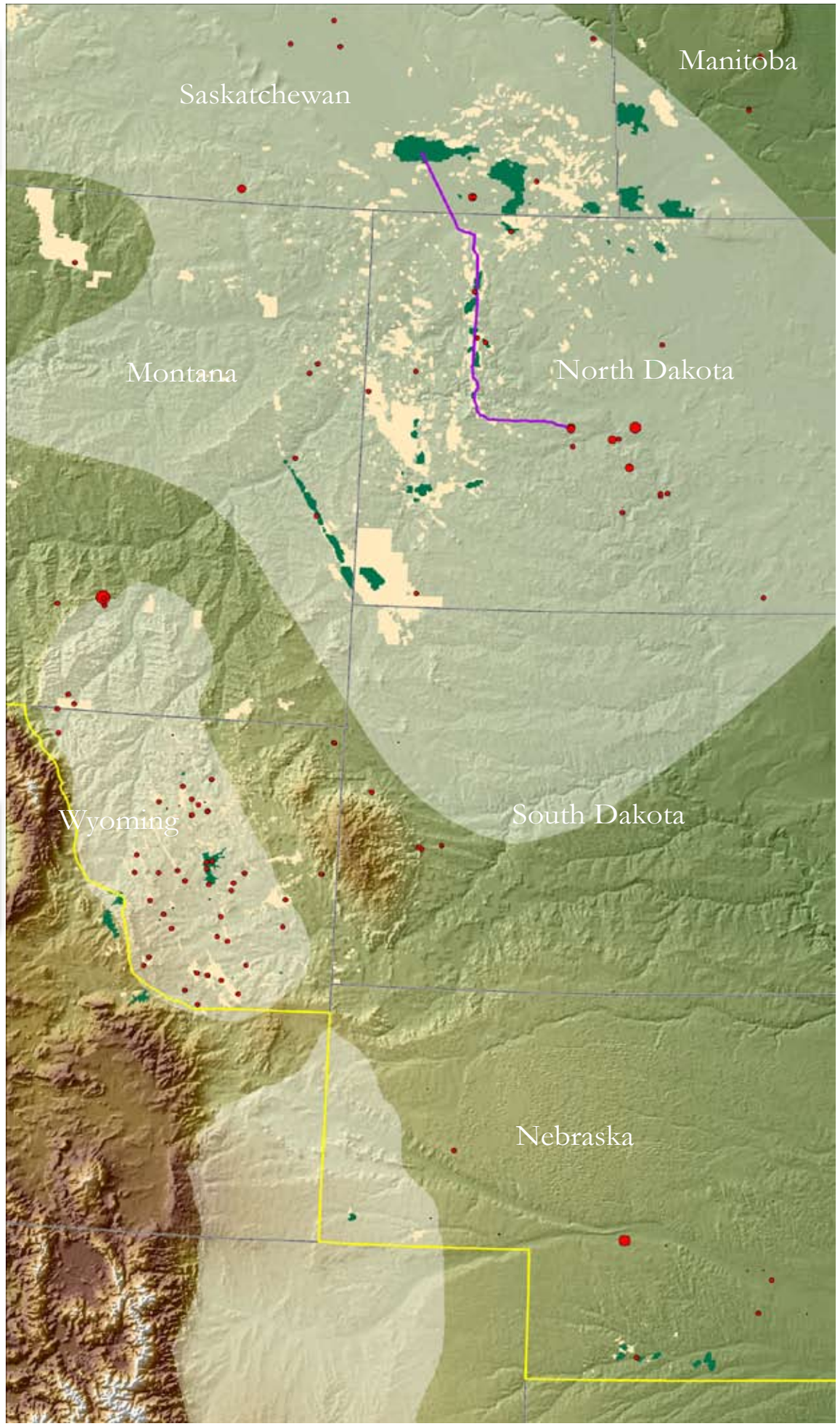
Although oil was discovered in this region in the late 1800s, significant development and exploration did not begin until the late 1940s and early 1950s. The body of knowledge gained in the past 60 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure sequestration of significant amounts of CO_2.

Selected Saskatchewan Oil Fields
- 11 unitized fields
- Total OOIP = 2762 million bbl
- Potential incremental oil = 331 million bbl
- Total CO_2 needed for EOR = 2652 Bcf

Selected Montana Oil Fields
- Ten unitized fields
- Total OOIP = 3250 million bbl
- Potential incremental oil = 390 million bbl
- Total CO_2 needed for EOR = 3120 Bcf

Selected Wyoming Oil Fields
- 17 fields
- Total cumulative production = 1524 million bbl
- Potential incremental oil = 381 million bbl
- Total CO_2 needed for EOR = 3049 Bcf

CO_2 Source Output tons/year
- 250–5,000,000
- 5,000,000–10,000,000
- 10,000,000–15,000,000
- 15,000,000–20,000,000
- Dakota Gasification Pipeline
- Select EOR Fields
- Oil Fields



Selected Manitoba Oil Fields
- Three unitized fields
- Total OOIP = 332 million bbl
- Potential incremental oil = 39 million bbl
- Total CO_2 needed for EOR = 319 Bcf

Selected North Dakota Oil Fields
- 28 unitized fields
- Total OOIP = 2183 million bbl
- Potential incremental oil = 262 million bbl
- Total CO_2 needed for EOR = 2095 Bcf

Buffalo Field, South Dakota
- Portions of this field are currently undergoing tertiary recovery operations using air injection.
- CO_2-based EOR may be technically feasible.

Selected Nebrasks Oil Fields
- Ten fields
- Total cumulative production = 100 million bbl
- Potential incremental oil = 25 million bbl
- Total CO_2 needed for EOR = 199 Bcf

Enhanced Oil Recovery

Most oil is extracted from the ground in three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. Natural pressures within the reservoir drive oil into the well during primary recovery, and pumps bring the oil to the surface. Primary recovery produces roughly 12%–15% of a reservoir's original oil. An additional 15%–20% of the original oil can be extracted through secondary recovery processes which involve injecting water to displace the oil.[19]

Conventional primary and secondary recovery operations often leave two-thirds of the oil in the reservoir. In the United States, EOR methods have the potential to recover much of that remaining oil, which is estimated to be 200 billion barrels.[19] However, oil recovery is challenging because the remaining oil is often located in regions of the reservoir that are difficult to access, and the oil is held in the pores by capillary pressure.

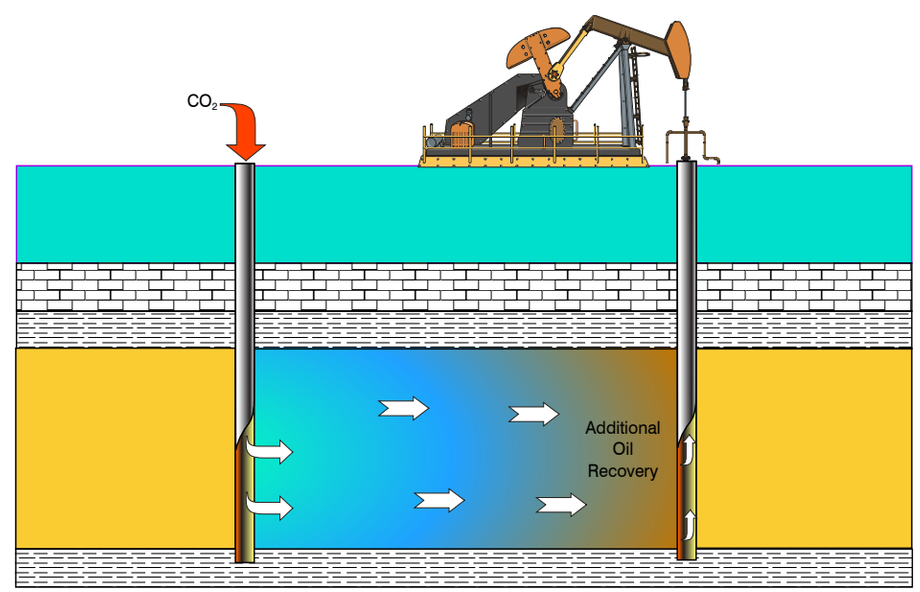
Reconnaissance-level CO_2 sequestration capacities were estimated for selected oil fields in the Williston Basin, Powder River Basin, and Denver–Julesberg Basins. Two calculation methods were used, depending on the nature of the available reservoir characterization data for each field. The estimates were developed using reservoir characterization data that were obtained from the petroleum regulatory agencies and/or geological surveys from the oil-producing states and provinces of the PCOR Partnership region. Results of the estimates for the evaluated fields (using a volumetric method) in the three basins indicate a storage capacity of over 10 billion tons of CO_2.

Aside from non-market-based incentives, CO_2 sequestration in many geologic sinks is not generally economically viable under current market conditions. However, EOR miscible flooding is a proven, economically viable technology for CO_2 sequestration that can provide a bridge to future non-EOR-based geologic sequestration. For example, a portion of the revenue generated by CO_2 EOR activities can pay for the infrastructure necessary for future geologic sequestration in brine formations. It is expected that unitized oil fields subjected to this type of recovery process would retain a significant portion of the injected CO_2 (including the amount recycled during production) as a long-term storage solution.

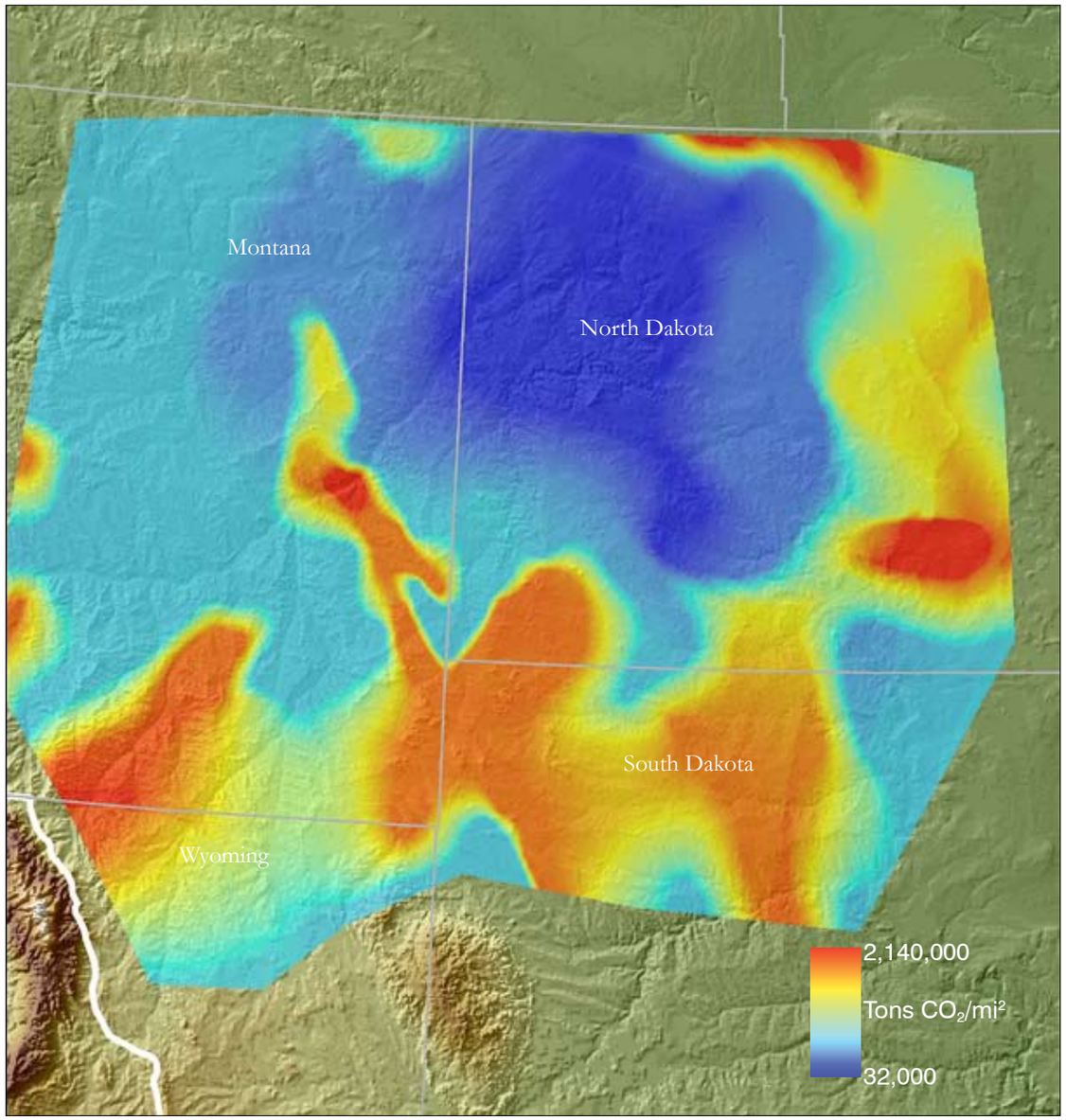
Storage and Incremental Recovery Through EOR in Selected Fields

Basin	Cumulative Incremental Recovery (million stb)	CO_2 Required* (Bcf)	CO_2 Sequestration Potential (Bcf)	CO_2 Sequestration Potential (tons)
Williston	**1023**	**8186**	**8186**	**501,900,647**
Powder River	**381**	**3049**	**3049**	**186,949,845**
Denver–Julesberg	**25**	**199**	**199**	**12,211,839**

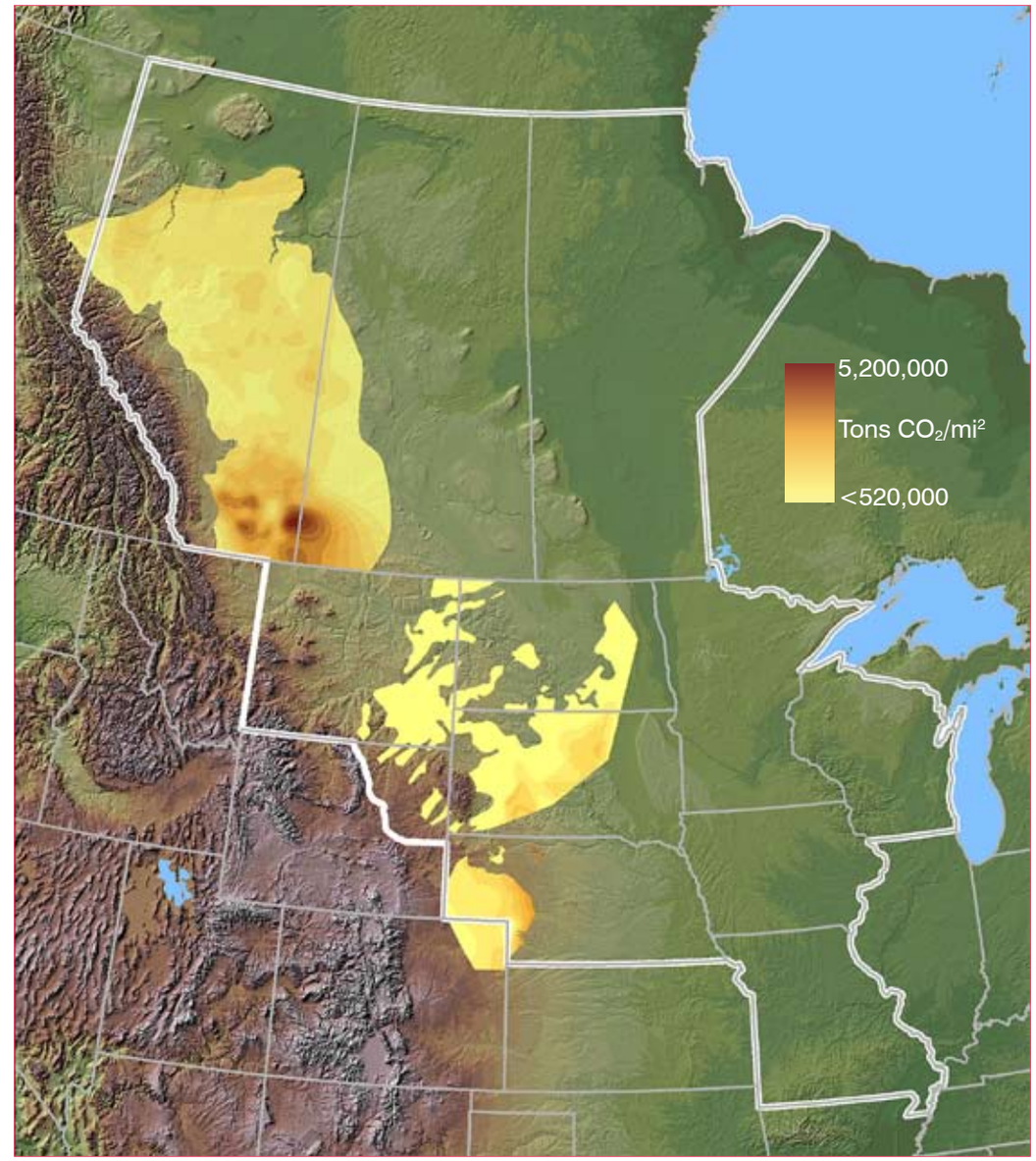
**CO_2 quantity required is the total purchase amount and does consider recycling of CO_2 from the tertiary recovery operation.*



Mississippian Madison System



Lower Cretaceous System

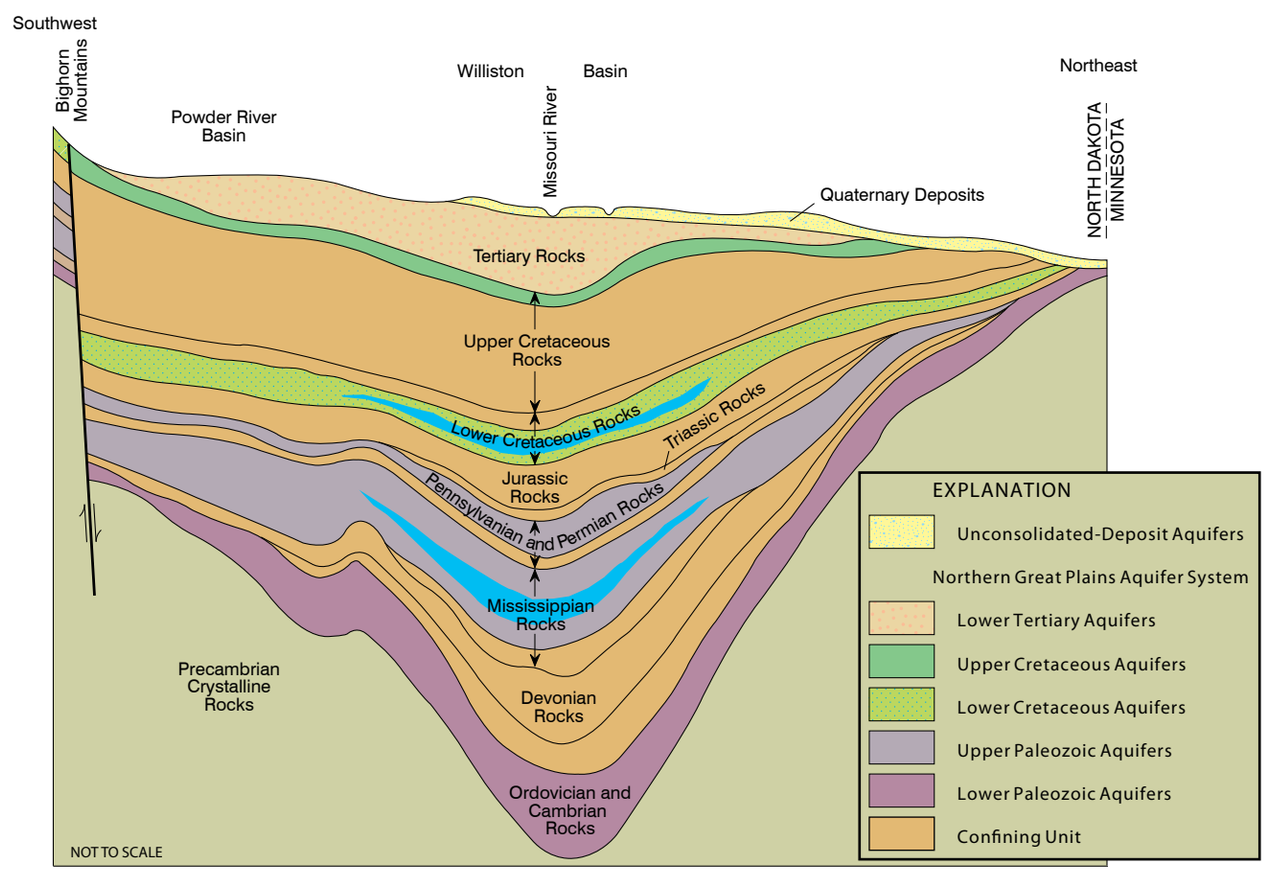


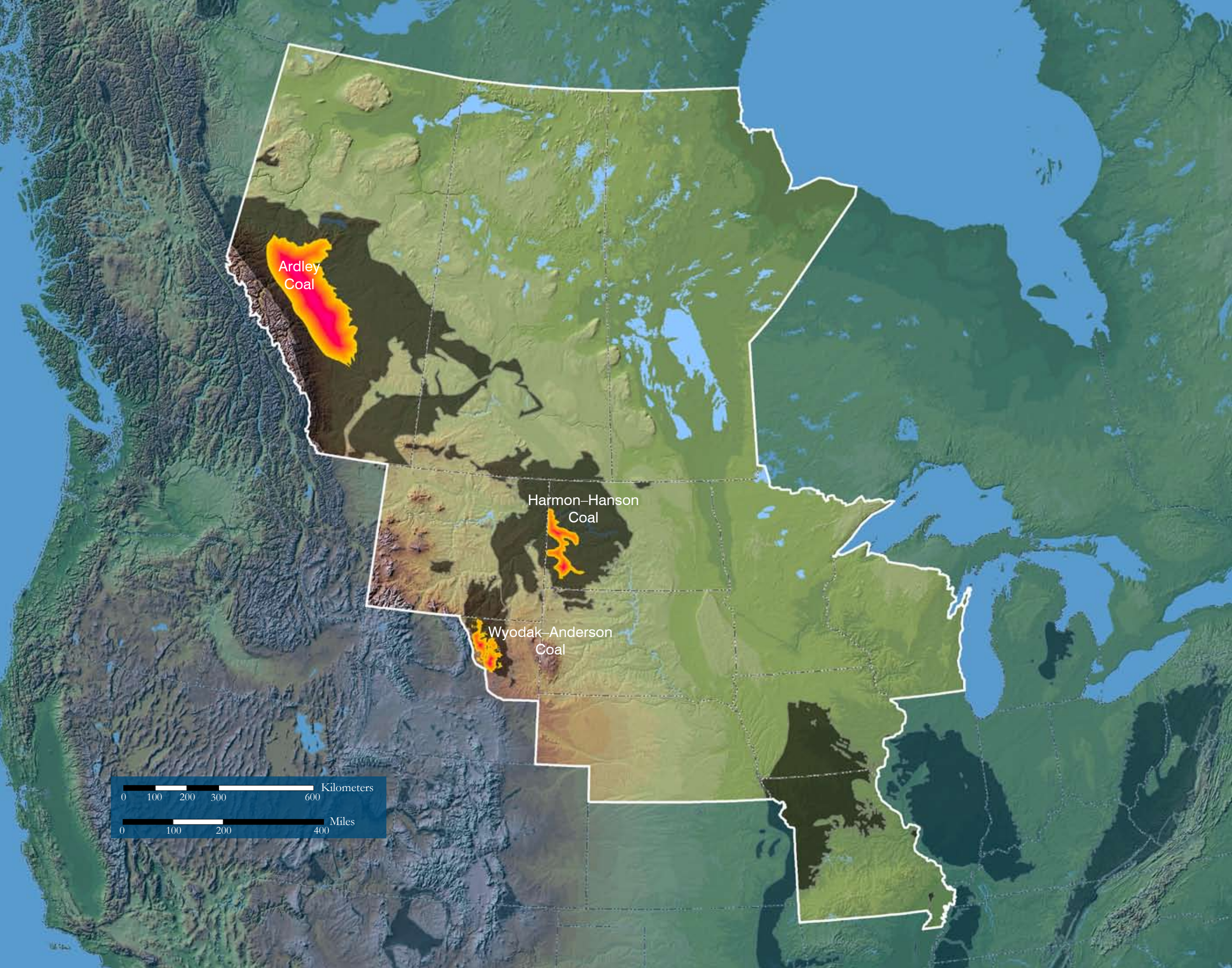
Saline Formations

Saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic carbon dioxide. Two saline aquifer systems, the Mississippian Madison and the Lower Cretaceous, have been evaluated for their regional continuity, hydrodynamic characteristics, fluid properties, and ultimate storage capacities using published data.

The lateral extent of these aquifers, the current understanding of their storage potential gained through injection well performance, and the geographic proximity to major CO_2 sources suggest they may be suitable sinks for future storage needs. For example, reconnaissance-level calculations on the Mississippian System in the Williston Basin and Powder River Basin suggest the potential to store upwards of 60 billion tons of CO_2 over the evaluated region, while the Cretaceous System has the potential to store over 160 billion tons.[20,21]

Formation	Basin	Estimated CO_2 Capacity (billion tons)
Lower Cretaceous System		
Newcastle Formation	Williston and Powder River	42
Viking Formation	Alberta	100
Maha Formation	Denver–Julesberg	19
Mississippian System		
Madison Formation	Williston and Powder River	60




Ardley Coal
Harmon–Hanson Coal
Wyodak–Anderson Coal
Kilometers
0 100 200 300 600
Miles
0 100 200 400

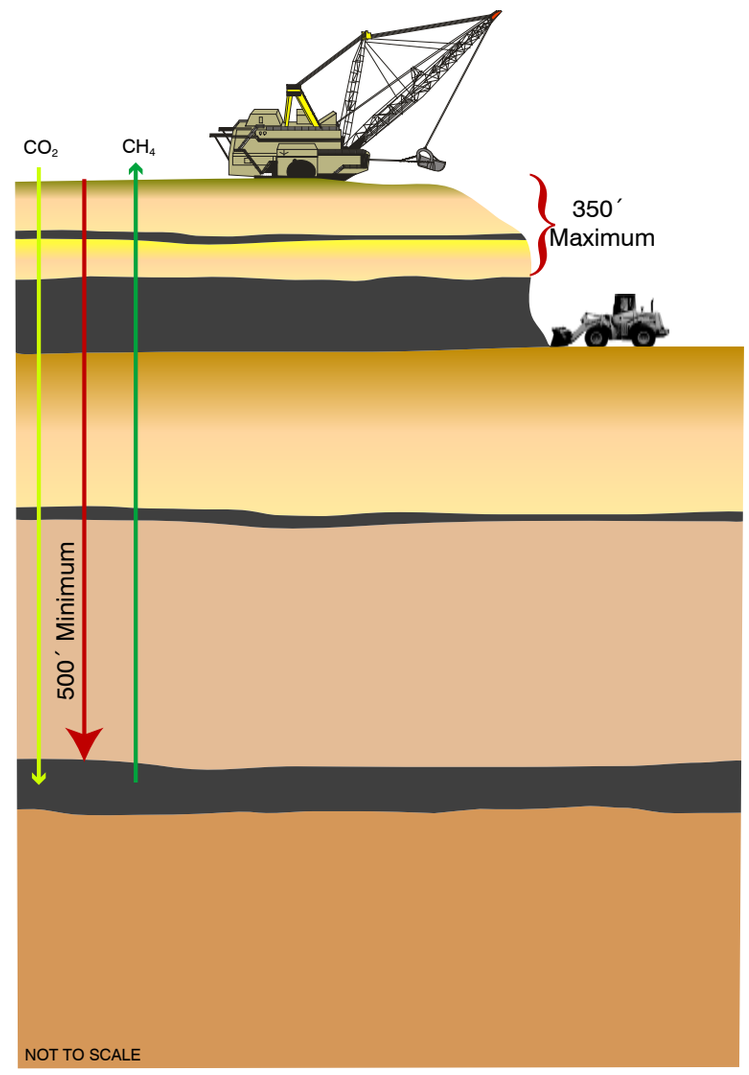
Sequestration in Coal

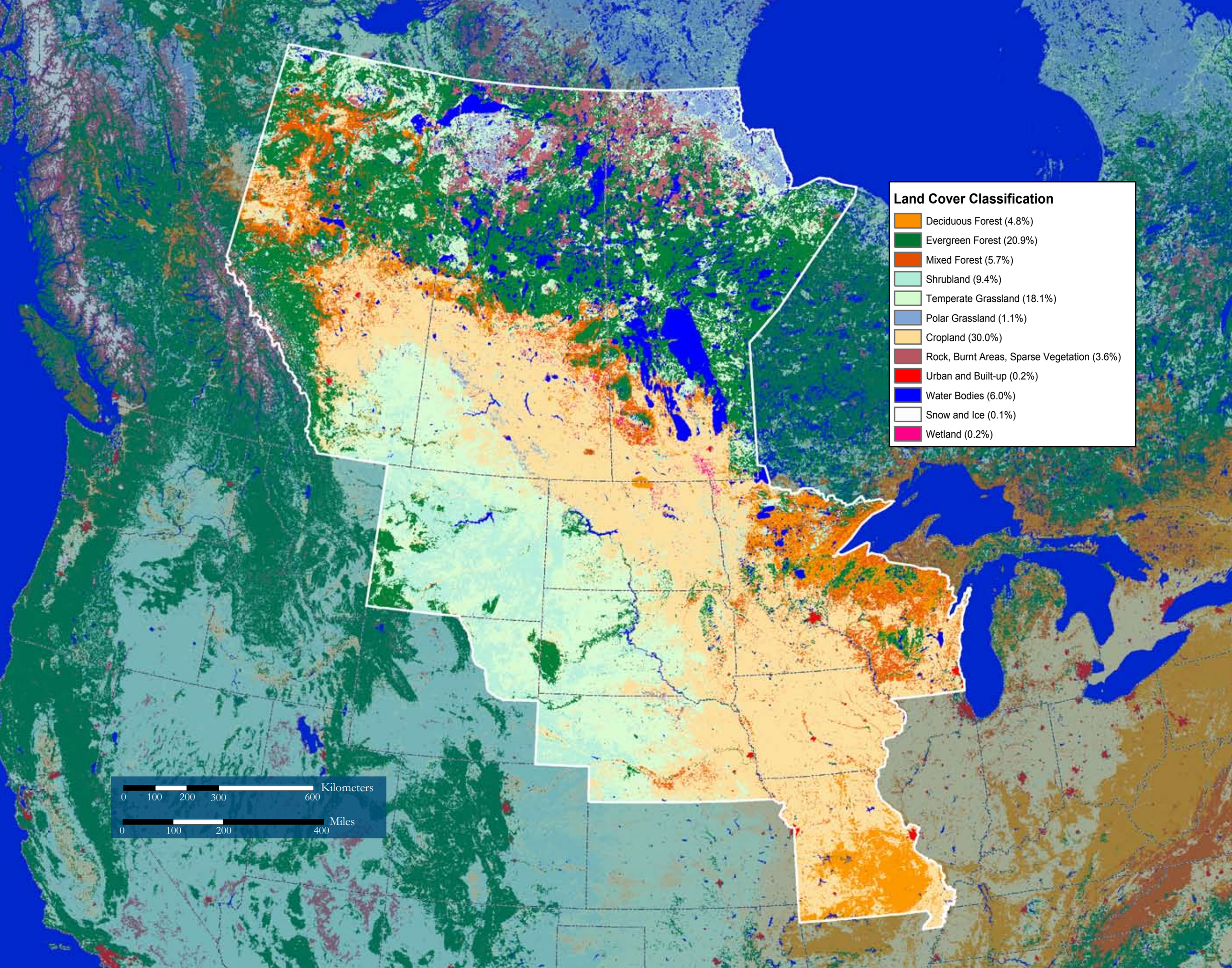
Many coal seams throughout central North America are too deep or too thin to be mined economically. However, many of these coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into the coal beds to recover this "coalbed methane" (CBM). In fact, CBM is the fastest growing source of natural gas in the United States and accounted for 7.2% of domestic production in 2003.[22]

As with oil reservoirs, the initial CBM recovery methods, dewatering and depressurization, can leave methane in the coal seam. Additional CBM recovery can be achieved by sweeping the coal bed with CO_2, which preferentially adsorbs onto the surface of the coal, releasing the methane. For the coals in the PCOR Partnership region, up to thirteen molecules of carbon dioxide can be adsorbed for each molecule of methane released, thereby providing an excellent storage sink for CO_2.[23] Just as with depleting oil reservoirs, unminable coal beds are a good opportunity for CO_2 storage.

Three major coal horizons in the PCOR Partnership region have been identified for further study: the Wyodak–Anderson bed in the Powder River Basin, the Harmon–Hanson interval in the Williston Basin, and the Ardley coal zone in the Alberta Basin. The total maximum CO_2 sequestration potential for all three coal horizons is approximately 8 billion tons.[24–26]

In northeastern Wyoming, the CO_2 sequestration potential for the areas where the coal overburden thickness is > 1000 ft (305 m) is 6.8 billion tons (6.2×10^{12} kg). The coal resources that underlie these deep areas could sequester all of the current annual CO_2 emissions from nearby power plants for the next 156 years.[26]

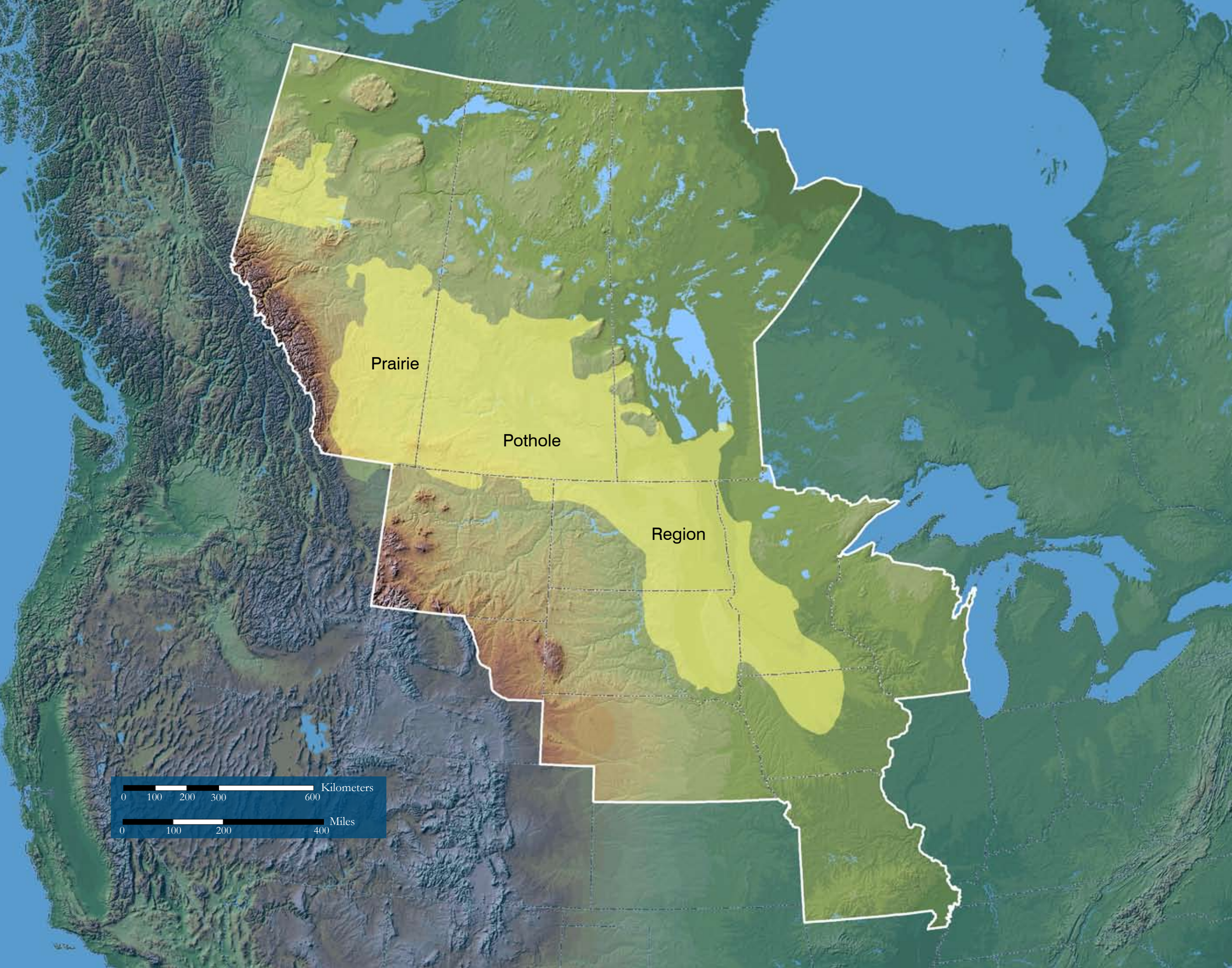



Land Cover Classification
Deciduous Forest (4.8%)
Evergreen Forest (20.9%)
Mixed Forest (5.7%)
Shrubland (9.4%)
Temperate Grassland (18.1%)
Polar Grassland (1.1%)
Cropland (30.0%)
Rock, Burnt Areas, Sparse Vegetation (3.6%)
Urban and Built-up (0.2%)
Water Bodies (6.0%)
Snow and Ice (0.1%)
Wetland (0.2%)
Kilometers
0 100 200 300 600
Miles
0 100 200 400

Land Use and Sequestration Potential

In contrast to direct sequestration deep within the earth, the concept of terrestrial sequestration focuses on a more passive mechanism of CO_2 storage in vegetation and soils within a few feet of the surface. From the Central Lowlands forests and cropland in the southeastern portion of the region, through the expansive grasslands and croplands of the northern Great Plains, to the northern boreal forests of Canada, the PCOR Partnership region has a rich agrarian history founded on fertile soils. However, as central North America developed into the pattern of land use seen today, much of the original soil carbon has been lost to the atmosphere. In this setting, the most promising potential to sequester carbon would be to convert marginal agricultural lands and degraded lands to grasslands, wetlands, and forests when favorable conditions exist.[27]

Some of the most promising terrestrial sequestration methods would promote and implement water and land management practices that enhance carbon buildup in biomass and soils, including adopting conservation tillage, reducing soil erosion, and minimizing soil disturbance; using buffer strips along waterways; enrolling land in conservation programs; restoring and better managing wetlands; eliminating summer fallow, using perennial grasses and winter cover crops; and fostering an increase in forests.[27,28] Managing soils for increased carbon uptake will pull CO_2 from the atmosphere for a 50–100-year time frame after which the soils will have reached a new equilibrium, a point at which the total amount of carbon in the soil does not change over time.[29] Once a steady state has been reached, the carbon will remain sequestered until the land management practices change or some other event occurs. The manipulation of soils and biomass for carbon sequestration has the advantage that it can be implemented immediately without the need for new technologies.


Prairie
Pothole
Region
Kilometers
0 100 200 300 600
Miles
0 100 200 400

Prairie Pothole Region

The PCOR Partnership region includes the Prairie Pothole Region, a major biogeographical region that encompasses approximately 347,000 mi^2 (222.4 million acres) and includes portions of Iowa, Minnesota, Montana, North Dakota, and South Dakota in the United States and Alberta, Saskatchewan, and Manitoba in Canada.[30] Formed by glacial events, this region historically was dominated by grasslands interspersed with shallow palustrine wetlands. Prior to European settlement, this region may have supported more than 48 million acres of wetlands, making it the largest wetland complex in North America.[31] However, fertile soils in this region resulted in the extensive loss of native wetlands as cultivated agriculture became the dominant land use. Because of oxidation of organic matter by cultivation, agriculture has resulted in the depletion of soil organic carbon (SOC) in wetlands.

Recent work by U.S. Geological Survey and Ducks Unlimited scientists for the PCOR Partnership conducted at wetlands study sites demonstrated that restoration of previously farmed wetlands results in the rapid replenishment of SOC lost to cultivation at an average rate of 1.1 tons $acre^{-1}$ yr^{-1}.[31] The finding that restored prairie wetlands are important carbon sinks provides a unique and previously overlooked opportunity to store atmospheric carbon in the PCOR Partnership region.

Decision Support System

PCORP GIS

Indirect Carbon Sequestration

Regulating CO2 Sequestration

Partner Contacts

Presentations

Reports

List of Products

DOE: Global Climate Change Initiative Links

Other Carbon Related Links

- Sources/Sinks/ Infrastructure Data
- General/Background Information
- CO2 Related Projects

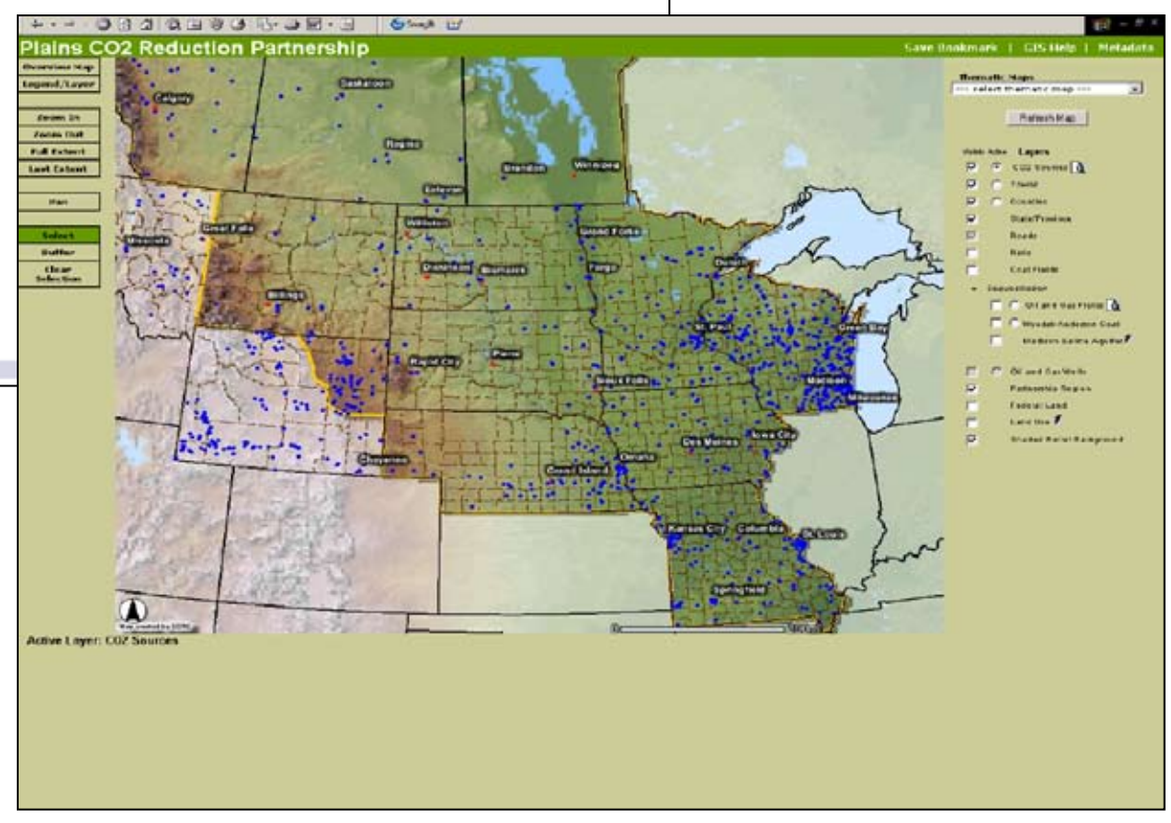
Contact Us

PCORP Home

Sponsored in Part by the U.S. Department of Energy

The PCOR Partnership Decision Support System (DSS) is a web-based database, GIS, and scenario modeling system. The DSS will allow our research partners to browse, query, analyze, and download data regarding CO2 sequestration in the PCOR region. The focus of this system is to compile an interactive data analysis and modeling interface that will provide for the definition and inspection of a wide range of transport and sequestration scenarios.

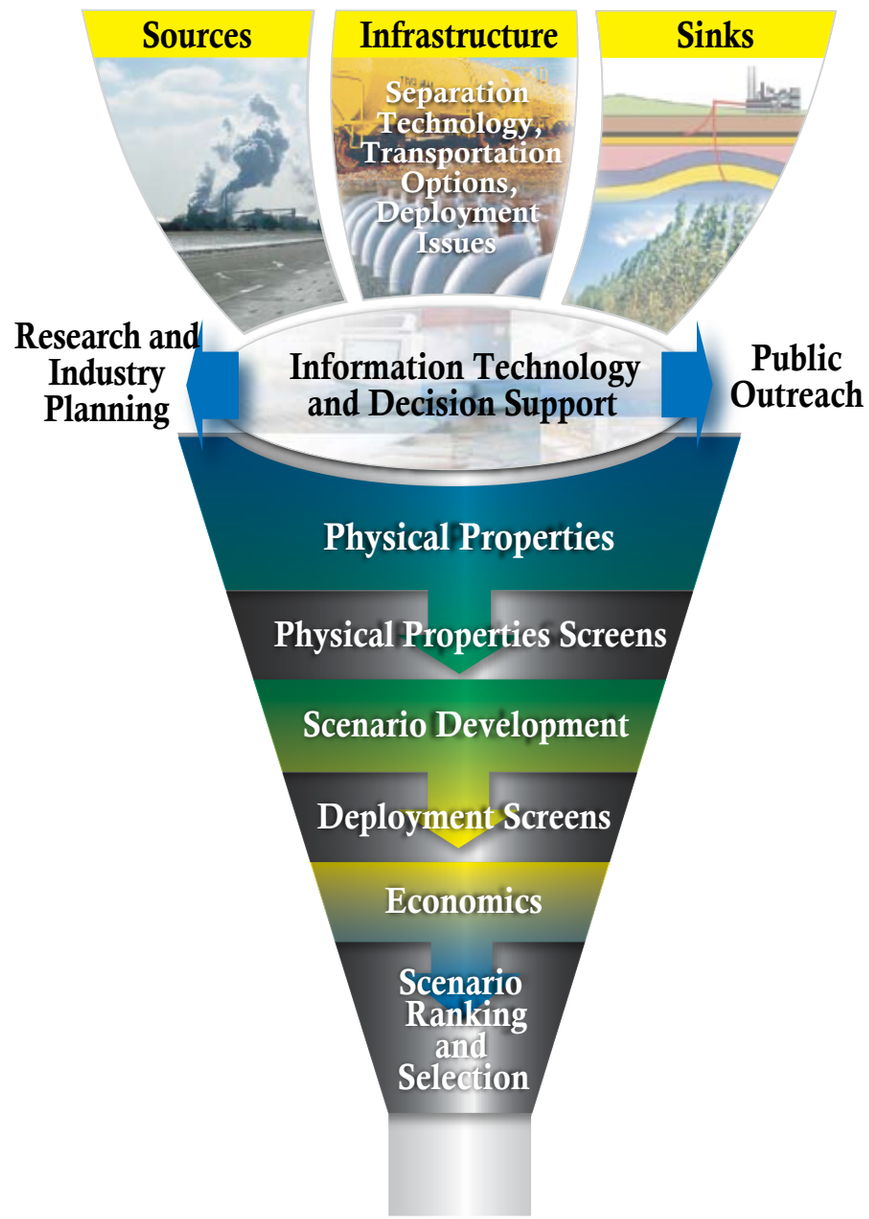
Datasets and models will be updated as new information becomes available and provided to team members performing engineering and scientific calculations. In turn, engineering and scientific results will be used to modify the DSS as they become available. This iterative process will result in the most effective and up-to-date database and modeling system possible. The DSS will leverage and integrate the developing knowledge of the character and spatial relationships of sources, sinks and the transportation links between them into an overall scenario assessment methodology. The scenario assessment methodology will include all of the critical elements to the demonstration or commercial implementation of any scenario including environmental risk, technical feasibility and availability, cost and economics, life cycle assessment impacts, and social and political factors.

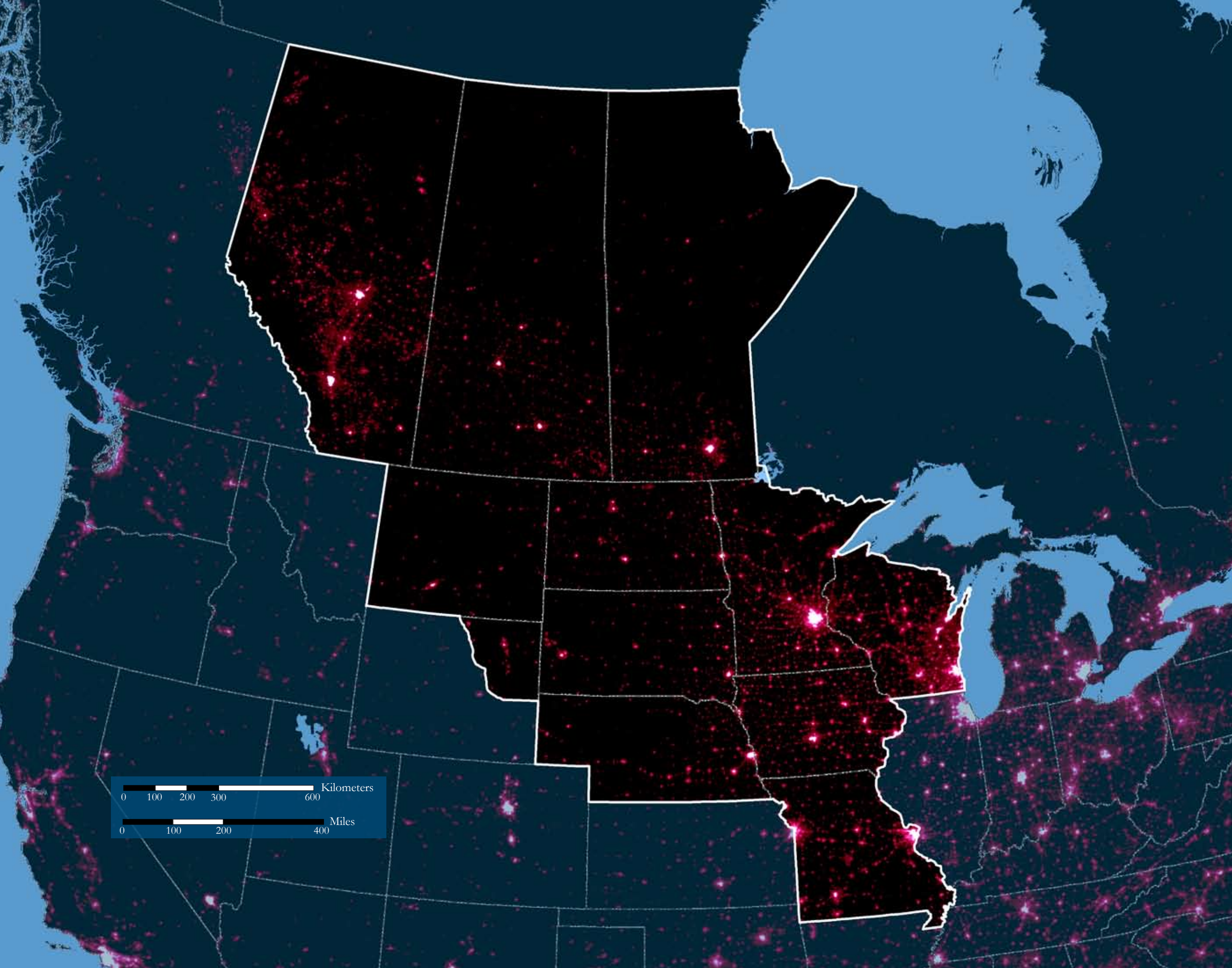


Web Site (DSS)

The PCOR Partnership has accumulated a wealth of data in characterizing the partnership region with respect to CO_2 sequestration opportunities. These data are compiled, stored, and managed in the computer systems underlying a Web-based decision support system (DSS) that was put into place to assist the partnership research team in developing and assessing a wide range of sequestration opportunities for the PCOR Partnership region. The DSS allows members of the PCOR Partnership to browse, query, analyze, and download data regarding CO_2 sequestration in the PCOR Partnership region. Outputs from the DSS are used in the PCOR Partnership model to facilitate the identification of CO_2 sequestration opportunities.

To date, the DSS has been used to generate reports on the general reservoir characteristics of selected oil fields that may come under consideration for CO_2 flood enhanced oil recovery and to develop detailed information on potential sources that may provide CO_2 for such operations. The DSS has also been used to identify the location of areas that may present challenges with regard to deployment, such as Indian reservations, national wildlife refuges, national parks, national forests, or grasslands. The research team responsible for the development of geologic sequestration scenarios has used the DSS to download source information to a spreadsheet for use in a model that will identify potential source–sink matches.



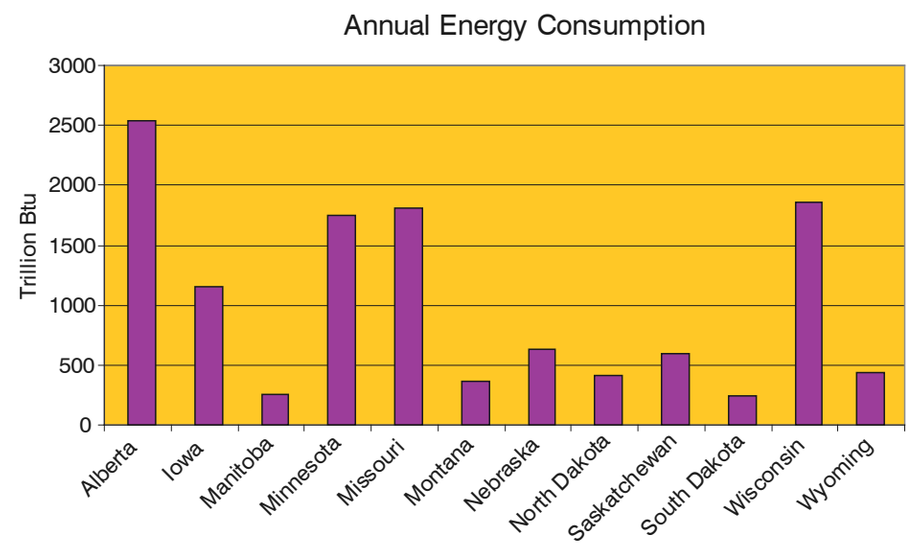

Kilometers
0
100
200
300
600
Miles
0
100
200
400

Keeping the Lights On

Affordable energy not only fuels our vehicles and electrical plants, it also fuels our economy and our quality of life. Collectively, the states and provinces of the PCOR Partnership region use approximately 1200 trillion Btu of energy a year.[32,33] At the most basic level, energy is essential, but to use our resources in a sensible way without damaging our planet requires a balance between energy and the environment.

The abundant, affordable energy provided by the PCOR Partnership region's fossil fuel resources powers a very productive part of the world. For example, the three Canadian provinces of the PCOR Partnership produce over 90% of Canada's wheat, while the U.S. portion of the Partnership contributes over 30% of U.S. wheat production.[34] Most of the continent's barley crop, which is critical to the breweries of Milwaukee and Saint Louis, comes from North Dakota and Minnesota. Wisconsin, as the top producer of paper in the United States, generates over $12 billion in annual shipments of paper products from the state.[35] The Missouri and Mississippi Rivers, railways, and highways of the region transport industrial output which includes heavy machinery, construction materials, and many other consumer goods.

The PCOR Partnership is working to develop technologies that will allow for CO_2 capture and sequestration. It is critical that technologies to reduce the environmental effects of fossil fuel use continue to be evaluated and developed while we explore and further develop future energy sources. The wise stewardship of our technological, social, and natural resources is essential to the future of our culture. Our challenge is to keep the lights on while simultaneously ensuring that our environment and economy stay strong.



EERC
The Plains CO_2 Reduction Partnership
PCOR
PARTNERS ONLY
Plains CO_2 Reduction (PCOR) Partnership
Practical, Environmentally Sound CO_2 Sequestration
Supporting Materials
Phase I - Vol. I
Nature in the Balance
CO2 Sequestration
NETL

Education and Outreach — CO_2 Sequestration

The PCOR Partnership recognizes that CO_2 sequestration research and development cannot occur in a vacuum, especially when it involves fieldwork. Public support is important to the success of the research efforts. Therefore the PCOR Partnership is working with the public both to explain the research efforts and to address concerns regarding the environment, health, and safety as they arise. The benefits of this outreach effort will accrue to the research teams, by enabling them to improve their research efforts, and to the public, by providing it with more of a role in addressing climate change. Ultimately, the large-scale adoption of CO_2 sequestration necessitates the concurrence of an understanding and accepting public.

Produced for a general audience, "Nature in the Balance: CO_2 Sequestration" provides a 30-minute introduction to CO_2 management with a focus on the North American heartland. The video introduces audiences to NETL's seven Regional Carbon Sequestration Partnerships and describes their role in assessing opportunities for carbon sequestration across North America.

"Nature in the Balance" was produced by Prairie Public Television, Fargo, North Dakota, in collaboration with the PCOR Partnership.

An array of multimedia products was developed during the first phase of the PCOR Partnership project. These products include five fact sheets, 21 topical reports, a public and members-only Web site, a 30-minute video, and several posters.

For more information regarding the content of this atlas and the Plains CO_2 Reduction Partnership, contact:

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More information concerning DOE's NETL Regional Carbon Sequestration Partnerships can be found at www.netl.doe.gov/coal/Carbon%20Sequestration/partnerships.

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Back Alexander MacKenzie, 1801, A map of America between latitudes 40 and 70 north and longitudes 45 and 180 west exhibiting Mackenzie's track from Montreal to Fort Chipewyan & from thence to the north sea in 1789 & to the west Pacific Ocean in 1793, Map Collections: 1500-2004. http://memory.loc.gov/ammem/gmdhtml/gmdhome.html [g3401s ct000692 http://hdl.loc.gov/loc.gmd/g3401s.ct000692] (accessed July 2005)

A much earlier map of the PCOR Partnership Region

A map of America between latitudes 40 and 70 north and longitudes 45 and 180 west exhibiting Mackenzie's track from Montreal to Fort Chipewyan & from thence to the North Sea in 1789 & to the west Pacific Ocean in 1793. Published by Alexander MacKenzie, 1801.

APPENDIX E

INTERSTATE OIL AND GAS COMPACT COMMISSION REPORT

FINAL REPORT

For

DOE Award No. DE-FC26-03NT41994
Admendment No. A000

Report Submitted January 24, 2005

Prepared by Kevin Bliss
Phone No.: (202) 484-1026
FAX No.: (405) 525-3592

Report Submitted
By The
Interstate Oil and Gas Compact Commission
P.O. Box 53127
Oklahoma City, OK 53127-3127

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IOGCC CO2 Geological Sequestration Task Force

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IOGCC CO_2 Geological Sequestration Task Force
A Regulatory Framework for Carbon Capture and Geological Storage

Executive Summary

The prospect of global climate change fueled by the increase of carbon dioxide in the Earth's atmosphere – attributed by many climate scientists to the activities of man – has mobilized governments worldwide, including the United States, to examine ways to decrease the emission of carbon dioxide to our atmosphere from anthropogenic sources. One promising option is through carbon capture and geological storage (CCGS) – capturing carbon dioxide (CO_2) before it is released into the atmosphere and storing it in underground geologic formations.

Given the jurisdiction, experience, and expertise of states and provinces in the regulation of oil and natural gas production and natural gas storage in the United States and Canada, states and provinces will play a critical role in the regulation of CCGS. Regulations already exist in most states and provinces covering many of the same issues that need to be addressed in the regulation of CCGS. For this reason the Interstate Oil and Gas Compact Commission (IOGCC) formed its *Geological CO_2 Sequestration Task Force*, which, for the last year, has been examining the technical, policy, and regulatory issues related to safe and effective storage of CO_2 in the subsurface (depleted oil and natural gas fields, saline formations and coalbeds). Funded by the United States Department of Energy (DOE) and the National Energy Technology Laboratory, the Task Force is comprised of representatives from IOGCC member states and international affiliate provinces, state oil and natural gas agencies, DOE, DOE-sponsored Regional Carbon Sequestration Partnerships, the Association of American State Geologists (AASG), and other interested parties.

This is the Final Report of the IOGCC Geological CO_2 Sequestration Task Force (Task Force). The report that follows contains (1) an assessment of the current regulatory framework applicable to carbon capture and geologic storage and (2)

recommended regulatory guidelines and guidance documents for the states and provinces.

In this report the Task Force has chosen to use the term "carbon capture and geologic storage" over "CO_2 geological sequestration". The former better describes the process and is less ambiguous. The Task Force has not addressed the regulatory issues involving CO_2 emissions trading and accreditation. The Task Force strongly believes that the development of future trading and accreditation regulatory frameworks should utilize the experiences of the states and provinces outlined in this report.

Guiding the work of the Task Force have been four analogues, which, in the opinion of the Task Force, provide the technological and regulatory basis for CCGS:
1) naturally occurring CO_2 contained in geologic reservoirs, including natural gas reservoirs; 2) the large number of projects where CO_2 has been injected into underground formations for enhanced oil recovery (EOR) operations; 3) storage of natural gas in geologic reservoirs; and 4) injection of acid gas (a combination of hydrogen sulfide and CO_2), into underground formations, with its long history of safe operations.

For the purposes of this report, the process of CCGS can be divided into four components labeled by the Task Force as capture, transportation, injection, and post-injection storage. Establishment of a CCGS regulatory scheme in any particular jurisdiction will require an assessment for each component of the technical issues and a review of the existing regulatory framework. Most states and provinces have existing regulatory frameworks covering all of these components with the exception of extremely long-term storage.

Principal recommendations of the Task Force in each of these four areas include:

Capture. There exists a large body of state, provincial, and federal laws and regulations dealing with emissions from industrial and energy production and power generation facilities. The Task Force notes that these regulations do not, for valid reasons, classify CO_2 as a pollutant, waste, or hazardous substance, and with few minor exceptions at the state level, do not regulate CO_2 emissions into the atmosphere. States that already might have defined CO_2 as a waste, air contaminant, or pollutant might be advised to reassess that definition so as to not negatively impact CCGS development. While some nations, in response to concern over global climate change, have adopted regulatory imperatives that limit CO_2 emissions, the United States has taken a different approach built upon voluntary efforts to reduce greenhouse gas intensity. Under the voluntary system present in the United States, the development of CCGS projects likely will be limited in the near future to relatively pure streams of CO_2 that prove to be economic for use in CO_2 EOR projects. The Task Force recognizes, however, that this scenario could change with the introduction of emission caps, economic incentives (tax and otherwise), and/or advances in technology that reduce capture costs.

Transportation. More than 3,500 miles of high-pressure CO_2 pipelines have been constructed in the United States. In addition, numerous parallels exist between CO_2 transport and natural gas transport. Most rules and regulations written for natural gas transport by pipeline include CO_2 and are administered and enforced by the U.S. Department of Transportation's Office of Pipeline Safety (OPS). States also may regulate under partnership agreements with OPS. These rules are designed to protect the public and the environment by assuring safety in pipeline design, construction, testing, operation, and maintenance. Given the large body of experience in pipeline operation, including CO_2, well established regulatory frameworks, and well established materials and construction standards, there is little necessity for additional state and provincial regulations in this area. The Task Force recognized in its deliberations that state eminent domain powers necessary for pipeline

construction and "open access" and the potential need for Federal Energy Regulatory Commission (FERC) jurisdiction might be future issues that need to be addressed at the state and federal level.

Injection. Although distinct, injection and storage are part of the same operation and should be considered together. Given the regulatory experience of the states and provinces in the area of CO_2 EOR, natural gas storage and acid gas injection, future CO_2 regulations for injection and storage should be built upon the regulatory frameworks already tested and in place. However, the Task Force has concluded that for purposes of regulation, a distinction needs to be made between injection for purposes of EOR, which has a project time frame, and injection for non-EOR purposes, which spans a much longer time frame.

The Task Force recommends that CO_2 injection for EOR purposes continue under current state and provincial regulations. Many states regulate EOR under the Underground Injection Control Program (UIC) of the Safe Drinking Water Act as Class II wells.

Concerning CO_2 injection for non-EOR purposes, the Task Force has concluded that, given the commodity status of CO_2 in the market and given the natural gas storage and acid gas injection regulatory analogues, future CCGS projects can and should incorporate existing state and provincial natural gas storage statutes and existing regulatory frameworks. The Task Force recognizes, however, that the U.S. Environmental Protection Agency (EPA) may recommend that the UIC program should also cover non-EOR CO_2 injection wells. The Task Force suggests that EPA, before it makes any recommendation concerning UIC applicability to non-EOR CO_2 injection, work closely with states. Further, should EPA make such a recommendation, the Task Force strongly suggests a new classification for such wells that allows for regulation dealing with economic considerations not contemplated by the UIC program. The Task Force strongly believes that inclusion of non-EOR CCGS wells under Class I or Class V of the UIC program would not be

appropriate or conducive to the growth of CCGS as a viable option in mitigating the potential impact of CO_2 emissions on the global climate.

Post-Injection Storage. There exist a significant number of CO_2 EOR injection projects in the U.S., and, therefore, "storage" of CO_2 is already taking place. Most of this CO_2 is from natural sources, as opposed to anthropogenic or industrial sources (as would be the case with CCGS). CO_2 EOR injection and storage has the economic benefit of increasing the production of oil. It also increases the likelihood that CO_2 EOR projects will be the vehicle that will drive CCGS, at least in its early years. It can be the means to build both injection/storage experience, regulatory and otherwise, and physical infrastructure (pipelines/facilities). Together the EOR, natural gas storage, and acid gas injection models provide a technical, economic, and regulatory pathway for long-term CO_2 storage. However, the sparsity of post-injection CO_2 EOR projects and abandoned natural gas storage fields have not provided adequate guidance for a long-term CO_2 storage regulatory framework. Consequently, a regulatory framework needs to be established to determine long-term liability and to address monitoring and verification of the reservoir and mechanical integrity of wellbores penetrating formations in which CO_2 has been emplaced over storage time frames.

Two final issues considered by the Task Force in the area of post-injection storage are worthy of note. The first concern arises in the ownership of storage rights (reservoir pore space) and payment for use of those storage rights. Jurisdictions must consider the potential need for legislation to address this complex issue. The second concerns liability. During the operational phase of the CO_2 storage project, the responsibility and liability for operational standards, release, and leakage mitigation lies with either the owner of the CO_2 – established through contractual or credit arrangements – and/or the operator of the storage facility. Long-term ownership (post-operational phase) will remain with the same entities. However, given the nonpermanence of responsible parties over long time frames, oversight of CCGS projects will require creation of specific provisions regarding financial

responsibility in the case of insolvency or failure of the licensee. The Task Force believes that this assurance ultimately will reside with federal and state or provincial governments cooperatively through the establishment of specialized surety bonds, innovative government and privately backed insurance funds, government trust funds, and public, private, or semi-private partnerships.

The Task Force offers two important recommendations for states and provinces as they begin their process of amending existing statutes and regulations and promulgating new rules to effectuate CCGS. The first is that the states and provinces actively solicit public involvement in the process as early as possible. The second is that the process from the outset be clear and transparent. As stated previously, although CO_2 is not considered a pollutant and not considered hazardous and has a long and safe history of being transported, handled, and used in a variety of applications, the public must be educated on the facts and included in an open regulatory development process.

The Task Force gratefully acknowledges the support of the U.S. Department of Energy, the National Energy Technology Laboratory, and the Illinois State Geological Survey, as well as the support of the states/provinces and other entities that generously contributed their employees' time to the production of this report.

1. Chapter 1 – Introduction

While the major components of Earth's atmosphere are nitrogen (78%) and oxygen (21%), there are also small concentrations of other gases such as carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), chlorofluorocarbons (CFCs), ozone (O_3), aerosols, and water vapor. In total these other gases comprise only 1% of our atmosphere and are commonly referred to as "greenhouse gases" because of their effect on warming our planet. The "greenhouse" effect results in the capture of radiation from sunlight by preventing radiative heat from reflecting back into space. While this greenhouse effect is critical in making our planet warm and habitable, the fact that concentrations of CO_2 are increasing yearly raises concern that it may be a primary factor in climate change or global warming. Although the science of climate change is evolving and far from certain, there is growing interest both within industry and government in the possible opportunities for mitigating the release of carbon into our atmosphere, particularly through carbon capture and geologic storage (CCGS). The interest in the storage of carbon stems from the fact that every year we, the inhabitants of Earth, release ever-greater amounts of carbon dioxide into our atmosphere – largely the consequence of our burning carbon fuels (oil, natural gas, and coal) for energy.

The conclusion of a key United Nations working group of the Intergovernmental Panel on Climate Change (IPCC) is that emissions of greenhouse gases and aerosols due to human activities are likely to alter the atmosphere in ways that are expected to affect the climate.[1] A major concern relates to increasing concentrations of greenhouse gases, such as CO_2 and methane, that may have a positive radiative forcing, thus tending to warm the Earth's surface. The IPCC notes that the global average surface temperature has increased over the 20th century by 0.6 degrees C[2] and that the 1990s was the warmest decade on record since 1880, with 1998 and 1997 the warmest and second warmest years. All told, six of the warmest years since

[1] Intergovernmental Panel on Climate Change, Third Assessment Report: Climate Change, 2001.
[2] Intergovernmental Panel on Climate Change, Third Assessment Report: Climate Change, Summary for Policy Makers, p. 20, 2001.

1880 were in the 1990s, and each year of the decade of the 1990s was one of the top 15 warmest of the last century.[3] Since 1750, atmospheric concentrations of CO_2 have increased 32 percent, from 280 parts per million (ppm) to 375 ppm concentration in 2003.[4] For purposes of this report, it is assumed that this increase is the result of the activity of mankind.

This increase in CO_2 requires the development and implementation of mitigation strategies aimed at reduction of CO_2 concentrations. It can be argued as to when or to what extent such strategies may need to be implemented. However, there is consensus that these mitigation strategies may need to be deployed and we must have developed a knowledge base to implement these strategies. Consequently, the methodologies of capturing and storing CO_2 emissions prior to release to the atmosphere must be investigated and perfected.

Reducing concentrations of anthropogenic[5] greenhouse gases can be accomplished in four basic ways: 1) through energy conservation and energy efficiency; 2) by using technologies involving renewable energy, nuclear power, hydrogen, or fossil fuels containing lower percentages of carbon, i.e., natural gas; 3) by indirect capture of CO_2 after its release into the atmosphere utilizing the oceans or terrestrial sequestration, i.e., reforestation, agricultural practices, etc.; or 4) by carbon capture and geological storage, whereby CO_2 is captured and stored in geologic formations through underground injection (instead of being released into the atmosphere).[6]

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[3] National Oceanic and Atmospheric Administration, 2000, Climate of 1999-Annual Review, National Climatic Data Center, http://www.ncdc.noaa.gov

[4] Keeling, C.D. and T.P. Whorf. Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, 2004, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[5] Anthropogenic is defined in this context as "involving the impact of man on nature: induced or altered by the presence and activities of man". Webster's Third New International Dictionary, G. & C. Merriam Company, 1981.

[6] The Department of Energy's Office of Fossil Energy, on behalf of the U.S. government, has begun an aggressive research program in this regard through its National Energy Technology Laboratory (NETL).

Four existing analogues provide guidance concerning CCGS. These are: 1) naturally occurring CO_2 contained in geologic reservoirs[7], including natural gas reservoirs;[8] 2) the vast number of projects where CO_2 has been injected into underground formations for enhanced oil recovery (EOR) operations;[9] 3) storage of natural gas in geologic reservoirs; and 4) injection of acid gas[10] into underground formations, which has a long history of safe operations. These well-documented analogues provide the technological and regulatory basis for CCGS.

The interest of the Interstate Oil and Gas Compact Commission (IOGCC)[11] in CCGS stems from the fact that for half a century the states and provinces have been the principal regulators of EOR in the United States and Canada[12], as well as for natural gas and hydrogen sulfide (H_2S) storage. Regulations already exist in petroleum producing states and provinces covering many of the same issues that need to be addressed in the regulation of CCGS.[13] As part of their responsibilities, state and provincial oil and natural gas regulators have focused on environmental issues since

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[7] The best-known examples are the three underground CO_2 source fields for enhanced oil recovery projects that are located in New Mexico and Colorado. Here naturally sourced CO_2 is trapped under pressure within geological structures that have been utilized via drilling as sources of CO_2 for injection into oil reservoirs in West Texas for more than thirty years. Natural storage sites occur in many other locales as well, some effectively permanent and some with evidence of spill or seal leakage.

[8] CO_2 can be found in natural gas reservoirs in concentrations that can reach as high as 70%.

[9] See section 2.5 for a history of CO_2 use in EOR.

[10] Acid gas is a combination of hydrogen sulfide (H_2S) and CO_2.

[11] The IOGCC represents 30 member and 7 affiliate oil and natural gas producing states. There is a map and listing of the IOGCC member states on the inside front cover of this publication. Organized as an interstate compact in 1935 – in essence a treaty among states ratified by Congress – the mission of the IOGCC is to promote the conservation and efficient recovery of domestic natural gas and oil resources, while protecting health, safety, and the environment. It conducts studies for the states, writes model statutes and regulations, fosters dialogue among producing states, and works with the federal government to promote sound energy policy.

[12] According to the Canadian Constitution, natural resources and the environment are under provincial jurisdiction. The federal government exerts jurisdiction over transborder issues (international and interprovincial), the Territories, and territorial waters. In 2002, the Province of Alberta passed legislation that, in effect, stipulates that "...carbon dioxide and methane are not toxic and are inextricably linked with the management of renewable and non-renewable natural resources, including sinks", reaffirming the provincial jurisdiction over reduction of CO_2 emissions. Thus, as long as CO_2 is not stored in geological media under Canadian territorial waters or in the Territories, provinces have full jurisdiction over CO_2 capture and geological storage.

[13] Some states that do not have petroleum production store natural gas and, therefore, have in place natural gas storage regulations. Thus these states, too, have regulations that at least in part cover many of the same issues that need to be addressed in the regulation of CCGS.

the 1800s. As science developed methods for recovering more petroleum through enhanced recovery techniques, like use of CO_2, states and provinces modified their regulations to accommodate these advances in technology. The member states of IOGCC and its international affiliate provinces have considerable experience in regulating the affairs of CO_2 handling. In Texas alone, the Railroad Commission has regulatory oversight of an enhanced oil recovery industry handling more than 50 million metric tons (Mt)[14] per year of CO_2. Handling involves the aspects of transportation, injection, processing, and production of CO_2, much of which is at considerable pressure. Many states and provinces also have experience in regulating CO_2 in combination with toxic gases such as H_2S. As noted above, much of the regulatory experience in natural gas storage has direct application to CCGS.

The IOGCC began exploring a potential role for the states in CCGS in July 2002. With the sponsorship of the United States Department of Energy (DOE), the lead federal department on this issue, the IOGCC convened a meeting of state regulators and state geologists. The purpose of the meeting was to explore the issue of CCGS and assess the interest of the states, through the IOGCC, in undertaking the development of regulatory guidelines and guidance documents for CCGS. As a result of that meeting, the IOGCC in December 2002 unanimously passed Resolution 02.124 calling for establishment of a "Geological CO_2 Sequestration Task Force". The IOGCC Geological CO_2 Sequestration Task Force (Task Force) has been tasked by DOE with two primary objectives:

1. Examination of the technical, policy and regulatory issues related to safe and effective storage of CO_2 in the subsurface (oil and natural gas fields, coalbeds and saline formations[15]), whether for enhanced hydrocarbon recovery or long-term storage; and

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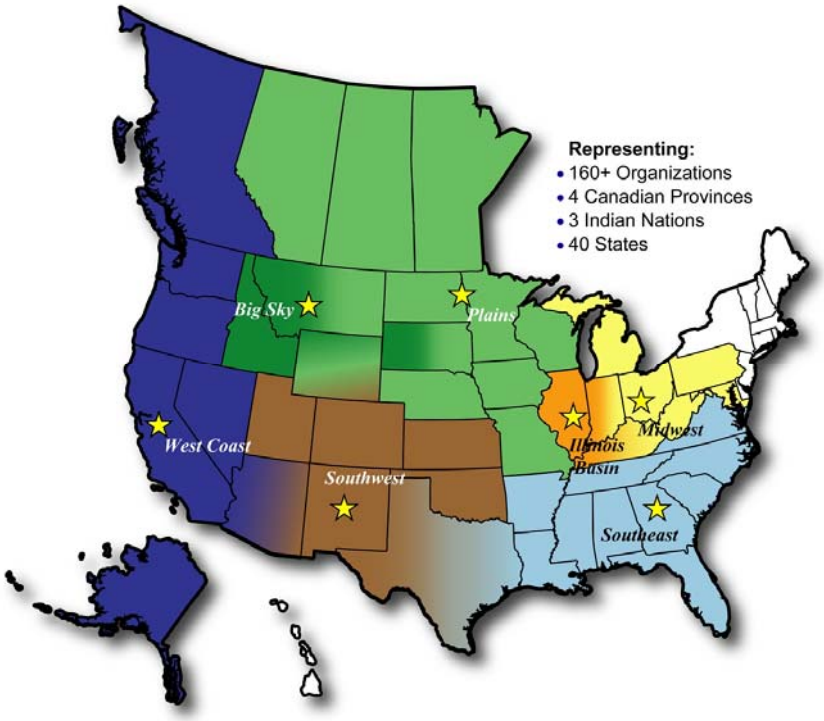
[14] 1 million metric tons = Megaton (Mt). 1 metric ton = 1.1023 short tons = 2,204.62 pounds. 1 metric ton of CO_2 is equal to 18.85 Mcf and 17,200 standard cubic feet (scf) at standard conditions.
[15] Although not part of the tasking from DOE, the Task Force Final Report also addresses the potential use of salt caverns and organic shales for storage of CO_2.

2. Production of a Final Report containing (1) an assessment of the current regulatory framework likely applicable to geologic CO_2 sequestration, and (2) recommended regulatory guidelines and guidance documents. The Final Report and the documents contained therein will lay the essential groundwork for a state-regulated, but nationally consistent, system for the geologic sequestration of CO_2 in conformance with national and international law and protocol.

This is the Final Report of the CO_2 Task Force. The members of the Task Force are listed in Appendix 1. The Task Force is comprised of representatives from IOGCC member states and international affiliates, state oil and natural gas agencies, DOE, DOE-sponsored Regional Carbon Sequestration Partnerships, the Association of American State Geologists (AASG), and other interested parties.

In developing the Final Report, the Task Force has worked closely with DOE and the seven Regional Carbon Sequestration Partnerships established by DOE. The regional partnerships represent a government/industry effort to determine the most suitable technologies, site-specific sinks, regulations, and infrastructure for carbon capture, storage, and sequestration in different areas of the United States. These partnerships are comprised of state agencies, universities, and public companies and include more than 150 organizations spanning 40 states, three Indian nations and four Canadian provinces. The seven regions are listed in Figure 1.0-1.[16]

[16] The partnerships are a key ingredient of the *United States Global Climate Change Initiative*.



Partnership	Partnership Lead	States Represented
Midwest Regional Carbon Sequestration Partnership	Battelle Memorial Institute	IA, KY, MI, MD, OH, PA, WV
An Assessment of Geological Carbon Sequestration Options in the **Illinois Basin**	The Board of Trustees of the University of Illinois, Illinois State Geological Survey	IL, IN, KY
Southeast Regional Carbon Sequestration Partnership	Southern States Energy Board	AL, AR, FL, GA, LA, MS, NC, SC, TN, TX, VA
Southwest Regional Partnership for Carbon Sequestration	New Mexico Institute of Mining and Technology	AZ, CO, KS, NE, NM, OK, TX, UT, WY
West Coast Regional Carbon Sequestration Partnership	State of California, California Energy Commission	AK, AZ, CA, NV, OR, WA
Big Sky Regional Carbon Sequestration Partnership	Montana State University	ID, MT, SD, WY
Plains CO2 Reduction Partnership	University North Dakota - Energy & Environmental Research Center	IA, MO, MN, ND, NE, MT, SD, WI, WY

Figure 1.0-1 Regional Carbon Sequestration Partnerships.[17]

[17] U.S. DOE – NETL Carbon Sequestration Partnership web site: http://www.netl.doe.gov/coal/Carbon%20Sequestration/partnerships/index.html, specifically, http://www.netl.doe.gov/coal/Carbon%20Sequestration/partnerships/index.html.

Worldwide, in response to concern over global climate change, some nations have put into place regulatory imperatives that limit CO_2 emissions. Further, there is an international consensus that CO_2 storage is considered a viable alternative in assisting those nations in achieving their emission goals. While the United States has not yet promulgated any regulations covering CO_2 emissions, under its *Global Climate Change Initiative* the U.S. has set a goal to reduce greenhouse gas intensity by 18% by 2012 through encouraging voluntary efforts by industry.

As was stated above, the purpose of this Task Force Report is to: 1) examine the technical, policy and regulatory issues related to CCGS; 2) assess the current regulatory framework likely applicable to CCGS; and 3) provide regulatory guidelines and guidance documents to the states for adaptation of their current regulatory regimes to accommodate CCGS. Among the specific recommendations of the Task Force contained in Chapter 4 are two general, but very important, recommendations for states as they begin their process of amending existing regulations and promulgating new regulations to effect CCGS. The first is that the states actively solicit public involvement in the process as early as possible. The second is that the process from the outset be clear and transparent. Although CO_2 is neither a waste nor hazardous and has a very long and safe history of being transported, handled and used in a variety of applications, the public must be educated on the facts and included in a clear and open regulatory development process.

It is also useful to note that in this report the Task Force has chosen to use the term "carbon capture and geologic storage" over "CO_2 geological sequestration". The former better describes the process and is less ambiguous in interpretation.

Of relevance also in this Task Force Report is a discussion of the issue of sustainability. The purpose of CCGS is to provide one methodology to help assure a sustainable future. The concept of promoting practices today that assure a sustainable future has been gaining traction nationally and internationally in recent

years, at the same time that the need to develop strategies to address global climate change has become more and more evident. CCGS provides an opportunity for the fossil fuel sector to play a key supportive role on both fronts. Current energy scenarios assume that fossil fuels will continue to be the primary source of energy for the world and the United States well into the 21st century.[18] While there may be some who feel that coal and oil and natural gas interests have no place in sustainability discussions, the very foundation of sustainability theory is the concept that environmental, economic, and social interests are mutually dependent and mutually supportive, and energy derived from fossil fuels is a major factor in the national and global economy. While the day will come when we shift to other energy sources, we have an opportunity now to utilize those same sectors to make a significant contribution to produce cleaner energy and reduce the amount of CO_2 released to the atmosphere.

The Task Force Final Report is comprised of 3 chapters. The next chapter, Chapter 2, entitled "CO_2 Overview" contains general information about CO_2 and its past and potential uses, including more information on its potential role in climate change. The remaining chapter entitled "Regulatory Overview" covers the technical and regulatory aspects (including a discussion of regulatory gaps and recommendations) of the capture, transportation, injection and post-injection storage of CO_2.

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[18] EIA, 2004, Energy Information Administration, Annual Energy Outlook 2004 with Projections to 2025, Report #: DOE/EIA-0383 (2004), January, 2004, 278, http://www.eia.doe.gov/oiaf/aeo/.

IEA, 2002, International Energy Agency, World Energy Outlook 2002, ISBN 92-64-19835-0 (2002), 530p, summary at: http://library.iea.org/textbase/weo/pubs/weo2002/WEO2002_1sum.pdf.

2. Chapter 2 – CO_2 Overview

The natural carbon cycle is an exchange of carbon between the atmosphere, oceans, and terrestrial biosphere. As part of the carbon cycle, CO_2 is removed from the atmosphere by plants in a process called photosynthesis. In this process the carbon and oxygen atoms are separated, with oxygen being returned to the atmosphere and carbon being synthesized into the plant structure using light as the energy source. In certain oceanic settings carbon is often deposited as carbonate sediment, mainly limestone and dolomite, over geologic time. The weight of scientific evidence suggests that human activity has altered the operation of the natural carbon cycle to the extent that CO_2 formed by the combustion of hydrocarbons is not completely absorbed in the exchange process and remains in the atmosphere for a period of 50 to 200 years.[19] Figure 2.0-1 is a graphic of the global carbon cycle.

[19] Greenhouse Gasses and Climate Change, April 2, 2004, IEA Greenhouse Gas R&D Programme.

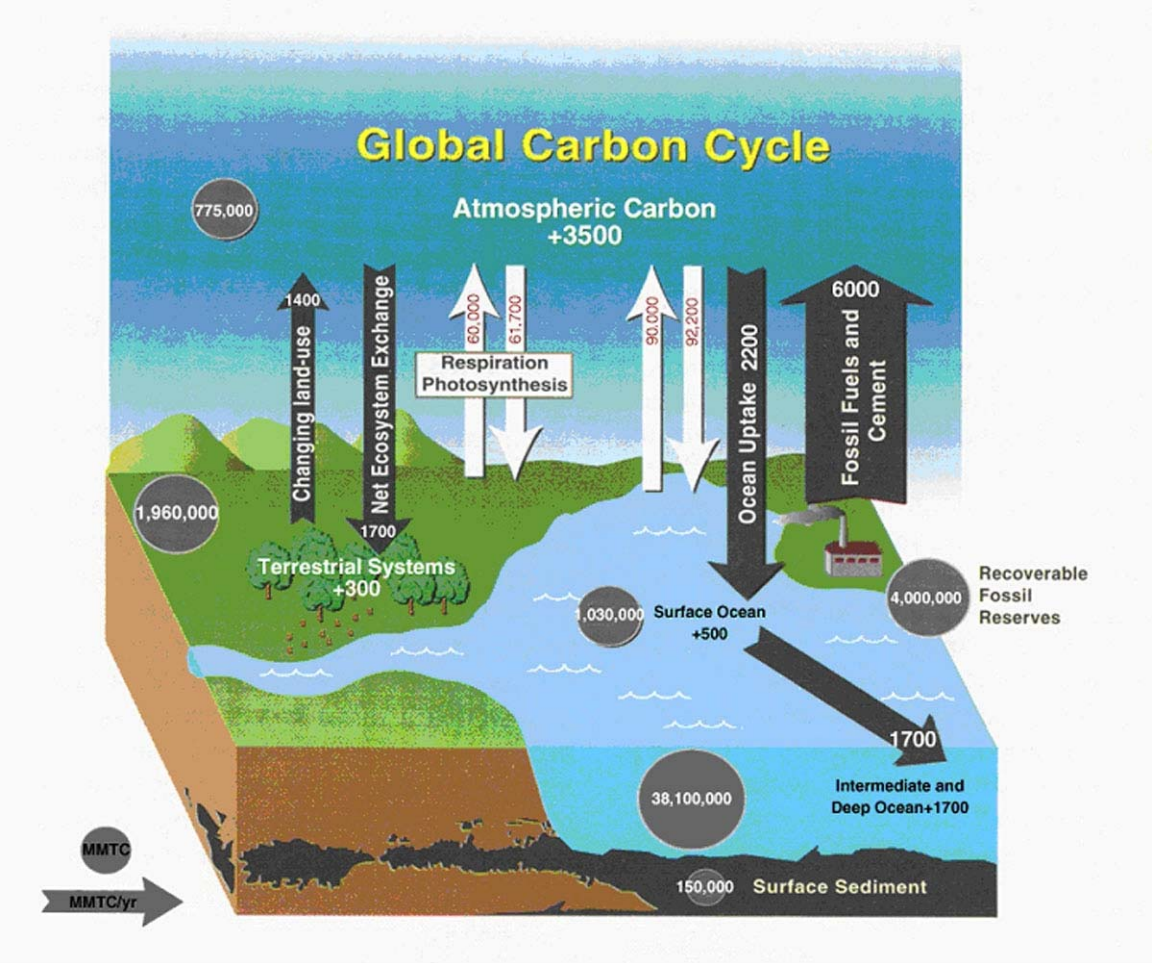

Figure 2.0-1 Global Biogeochemical Carbon Cycle. Includes human influence from fossil fuel combustion and changing land-use patterns. Black arrows indicate net fluxes and white arrows indicate gross fluxes. Annual net additions are shown as + numbers, and pool sizes (circles) are shown in gray. All quantities are in million metric tons (Mt) Carbon, and all fluxes are in million metric tons (Mt) Carbon/yr. [20]

The purpose of CCGS is to provide a means of capturing and storing CO_2 that otherwise would be released to the atmosphere through the combustion of hydrocarbons. As was noted in the Introduction, the concept of the geologic storage of CO_2 has several important analogues. The natural occurrence of CO_2 in geologic reservoirs demonstrates the ability of geologic formations to contain CO_2 over extremely long periods of time, exactly our goal in implementing CCGS.

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[20] S.M. Benson, R. Hepple, J. Apps, C.F. Tsang, and M. Lippman 2002 Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geological Formations, Report No. LBNL-51170, Lawrence Berkeley National Laboratory, Berkeley, California, p.14, modified from U.S. DOE, 1999.

Additionally, EOR operations have demonstrated that CO_2 can be safely transported and injected into geologic formations. Yet another is storage of natural gas in geologic reservoirs, providing an additional useful precedent for underground storage of CO_2. The final analogue is the safe handling and injection of acid gas, which includes H_2S, a byproduct of some natural gas production, that is, unlike CO_2, a substance that poses significant health and safety concerns. The long history of the safe handling of this hazardous gas is well documented. Additionally, thermodynamically, H_2S is very similar to CO_2 and thus physical handling and processes are similar. These well-documented analogues provide the technological and regulatory basis for CCGS.

2.1 Carbon Dioxide (CO_2) Characteristics

At normal atmospheric conditions, CO_2 is a non-hazardous, odorless gas that makes up a small fraction of Earth's atmosphere (0.03%).[21] CO_2 occurs in four forms: 1) as a gas which is 1.5 times denser than air; 2) as a liquid, occurring in the subsurface in regions with low geothermal gradients where the pressure is sufficiently high but the temperature is still below the critical point; 3) as a supercritical fluid that behaves like a gas but has density characteristics of liquids at pressures greater than 1,073 pounds per square inch (psi) and temperatures greater than 87.7 degrees F; and 4) as a solid form most commonly referred to as dry ice (remains solid below temperatures of minus 109 degrees F). Assuming normal geologic pressure and temperature gradients (0.433 psi/ft, 15 degrees F/1000 ft) those reservoirs deeper than approximately 2,500 feet will dictate that CO_2 will exist as a supercritical fluid.

[21] For comparison, exhaled air from humans is approximately 3.5% CO_2.

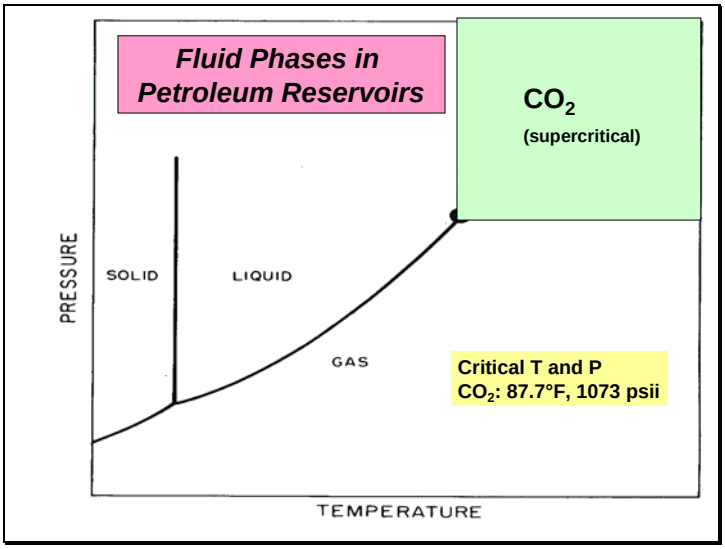

Figure 2.1-1 Fluid Phases in Petroleum Reservoirs.[22]

Consequently, the capture, transportation, injection, and storage of CO_2 will involve only the gaseous, liquid, and supercritical phases of CO_2. Humans cannot detect CO_2 in its gaseous form without detection equipment and, as Figure 2.1-2 shows, increased concentrations of CO_2 do have potential human health and safety consequences. However, the risk associated with CCGS depends much more on effective dispersion than total quantity of CO_2.

[22] Illustration courtesy of the Midwest Geological Sequestration Partnership (Illinois Basin), 2004.

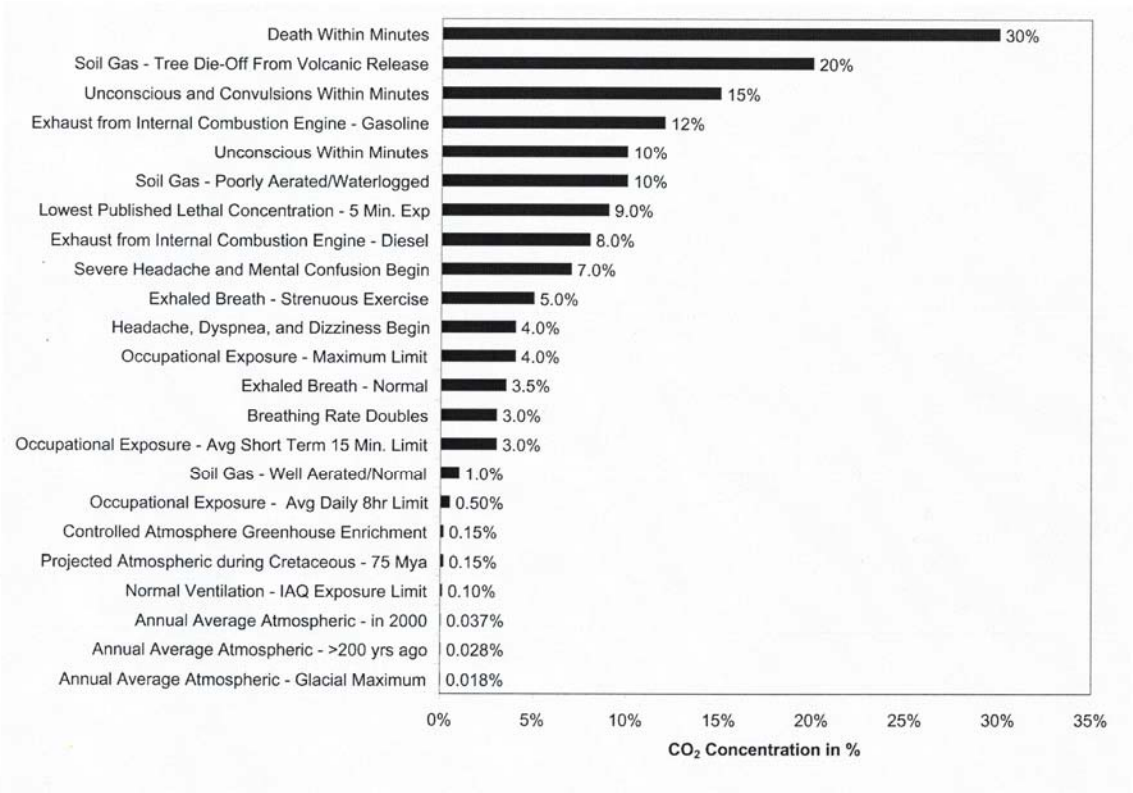

Figure 2.1-2 Comparison of Ambient Concentrations of CO_2 and Risks of Exposure.[23]

2.2 Uses of CO2

As noted above, CO_2 is a naturally occurring gas and is essential to the natural plant life process on Earth. Carbon dioxide is also a valuable commodity with many beneficial uses as shown in Figure 2.2-1. However, all of these uses of CO_2 only utilize a small fraction of the total 2,564 Mt of CO_2 available from anthropogenic sources excluding transportation sources. See Figure 2.2-2. This emphasizes the important role that CCGS must play.

[23] Benson, S.M., Hepple, R., Apps, J., Tsang, C.F. and Lippman M., Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geological Formations, Report No. LBNL-51170, Lawrence Berkeley National Laboratory, Berkeley, California, p.14, 2002, modified from U.S. DOE, 1999, p.23 and Appendix 4 - Data tables with references.

Beneficial Uses of CO_2

1	Refrigeration	Used for cooling
2	Fire Extinguishers	Extinguishes some fires by depriving the fire of oxygen
3	Carbonated beverages	Produces carbonation
4	Decaffeinated coffee	Used in super cooled fluid extraction process
5	Dry ice	Used to make stage fog and other visual effects
6	Feedstock	Can be used as feedstock for chemical manufacturing
7	Biofuels	Aids in the process of algae growth to make biofuels

Figure 2.2-1 Beneficial Uses of CO_2.

CO_2 Emissions in the United States

(2000 & 2002 Data)

Sources	**US Total Metric ton**
Power Generation	2,239,700,000
Coal	1,868,400,000
Natural Gas	299,100,000
Oil	72,200,000
Industries	324.789.000
Refinery	184,918,000
Iron and Steel	54,411,000
Cement	42,898,000
Ammonia	17,652,000
Aluminum	4,223,000
Lime	12,304,000
Ethanol	8,383,000
Total	**2,564,489,000**

Figure 2.2-2 CO_2 Emissions in the United States.[24]

[24] Illustration courtesy of the Midwest Geological Sequestration Partnership (Illinois Basin), 2004.

2.3 Geologic Options for Carbon Dioxide Storage

There are four primary options for the geologic storage of CO_2, discussed in more detail below: 1) storage in depleted oil and natural gas reservoirs; 2) storage in deep saline formations; 3) storage in salt caverns; and 4) adsorption within coalbeds that are unminable because of depth, thickness or other economic factors. In addition, there is the possibility of other storage options such as organic shales, fractured basalts, and hydrates. The four primary geological options involve injection of CO_2 through wells into the receiving formations or coal layers. Figures 2.3-1 and 2.3.3-1 illustrate the geologic options for underground injection of CO_2. There are advantages to injecting into deeper formations, deeper than 2,500 feet, because the CO_2 can be emplaced in a supercritical state under pressures exceeding 1,200 psi. Supercritical CO_2 occupies less pore space for a given quantity of CO_2, thereby maximizing the reservoir capacity for geologic storage.

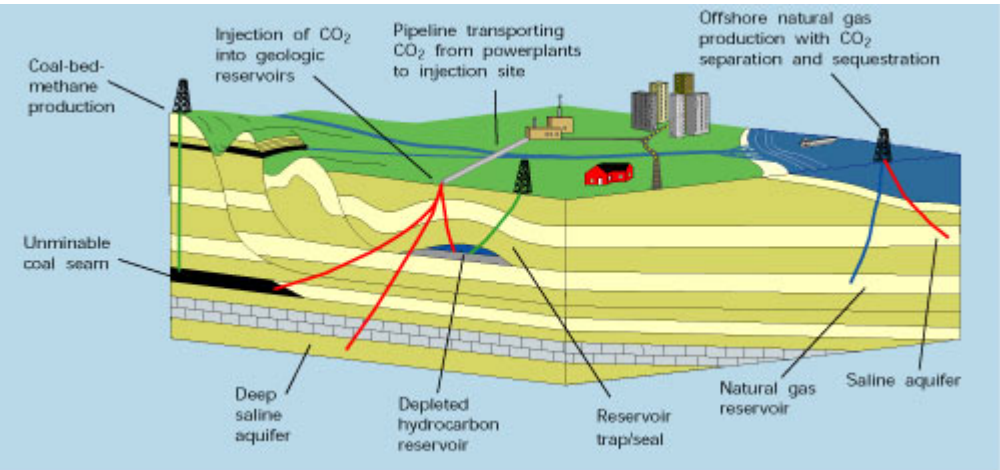

Figure 2.3-1. Potential CO_2 Sequestration Reservoirs and Products. Red lines indicate CO_2 being pumped into the reservoirs for sequestration, green lines indicate enhanced recovery of fossil fuels caused by CO_2 sequestration, and the blue line indicates conventional recovery of fossil fuels. The offshore natural gas production (blue line) and CO_2 sequestration scenario is currently occurring off the coast of Norway at the Sleipner complex operated by Statoil. There, the gas produced is a mixture of CO_2 and methane. The CO_2 is removed and injected into a nearby saline aquifer.[25]

[25] Diagram and explanation from U.S. Geological Survey Fact Sheet 26-03, March 2003 - Online Version 1.0. See: http://pubs.usgs.gov/fs/fs026-03/fs026-03.html

Many regions of the United States offer one or more of these geologic options, the most common of which are discussed below.

2.3.1 Depleted Oil and Gas Fields

Many regions of the U.S. and the world have produced oil and natural gas from geologic traps that represent a substantial reservoir capacity available for storage of CO_2. Where these reservoirs are below 4,000 feet, they offer tremendous pore volume space for supercritical CO_2 injection and storage. These geologic traps by their very nature, having confined accumulations of oil and natural gas over millions of years, have proven their ability to contain fluids and gas. Additionally, if storage pressures of CO_2 stay below original reservoir pressures, fluid containment is assured if leakage from wellbore penetrations can be avoided.

2.3.2 Deep Saline Formations

The CO_2 storage option with the greatest potential among the geologic possibilities nationwide is the injection of CO_2 into saline formations significantly below underground sources of drinking water. Storage of CO_2 in deep saline formations currently may not have demonstrated confining mechanisms, unlike depleted oil and natural gas reservoirs, but has the advantage of providing volumetrically the largest CO_2 storage potential of the three primary geologic options. In addition, access to saline aquifers often occurs close to existing CO_2 emission sources, such as coal-fired power plants. The water in some of these formations, for example in the depth range of 4,000 to 5,000 feet in the Illinois Basin, has many times the salinity of sea water and hence is not usable as a potable resource. Injection of CO_2 into these deeper saline formations could be contained through solubility trapping (CO_2 dissolution in formation waters), structural trapping (formation of a secondary gas cap within formation boundaries), or through mineral trapping (carbonate precipitation).

An example of a full-scale utilization of a saline reservoir for CO_2 storage is occurring off the coast of Norway. In this project, 1 Mt of CO_2 per year is separated from a natural gas production stream and injected into the Utsira saline formation well below the seabed of the North Sea.[26] In the U.S., our knowledge of deep saline reservoirs comes from oil and natural gas exploration, from deep-well waste injection, and from natural gas storage into saline formations. A small pilot project recently injected a total of 1,600 Mt of CO_2 into the Frio formation of east Texas, initiated through funding by DOE. The purpose of the pilot program is to test the containment parameters of injecting CO_2 into a saline aquifer. If saline storage proves successful for CCGS, the storage capacities are potentially significant. An example is the Mt. Simon Sandstone, which is used extensively for natural gas storage in the Midwest, where knowledge of its porosity, permeability, injectability, and water chemistry have been developed though the operation of natural gas storage facilities. The potential storage capacity of the Mt. Simon Sandstone has been estimated to be at least 160 billion metric tons (Gt) of carbon.[27] CO_2 injected into saline reservoirs would be in the form of a supercritical fluid, under pressure and temperature conditions where it would exhibit liquid-like behavior, and could be contained in a structural or stratigraphic trap much like oil and natural gas. Also important is an understanding of the sealing units above the saline reservoirs that must act as vertical permeability barriers to contain injected CO_2 and the degree to which CO_2 dissolves in the saline waters. Where such units have been used for natural gas storage, extensive studies have been undertaken to ensure natural gas containment. Deep saline reservoir storage of CO_2 will incorporate detailed studies of reservoir seals to ensure containment and will build on the experience of natural gas storage facilities.

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[26] Saline Aquifer CO_2 Storage, IEA Greenhouse Gas Programme, http://www.ieagreen.org.uk/

[27] Gupta, N., Wang, P., Sass, P., Bergman, P., and Byrer, C., 2001, Regional and site-specific hydrologic constraints on CO_2 sequestration in the Midwestern United States saline formations: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies, CSIRO Publishing, pp. 385-390.

2.3.3 Salt Cavern Storage

For over 40 years, salt caverns have been used successfully in the storage of oil and natural gas and provide an option for the storage of CO_2. Carbon dioxide can be stored in salt caverns as a gas, liquid, or in supercritical state. Several states currently have in place regulatory frameworks[28] for salt cavern storage of natural gas. These rules and regulations, with appropriate modifications, as well as the experience gained by state oil and natural gas regulatory agencies in this regard, can be applied to the storage of CO_2. Existing regulations address issues such as facility design, construction, and operation; storage cavern mechanical integrity; acceptable operating pressures and conditions; verification of stored volumes; design, drilling, and operation of injection wells, including mechanical integrity; surface facilities; and general safety and environmental concerns, among others.

Salt caverns for natural gas storage are typically developed in thick-bedded salt strata or in salt domes (structures formed from the upwelling and upward piercement of salt from depth) through solution mining. Geologic salt formations have characteristics that render them highly suitable for storage operations. Salt formations (comprised of the mineral halite – NaCl) are generally impermeable at typical storage pressures, have compressive strength comparable to concrete, and are self-sealing, owing to their plastic nature, resulting in a strong, safe, and reliable storage environment. Often, pores in strata adjacent to salt deposits are effectively plugged with crystalline salt, further impeding the movement of gas and fluids out of the storage cavern. Salt is easily and economically mined, using fresh water as a solvent. Figure 2.3.3-1 is a diagram illustrating salt cavern storage, as well as a breakdown of areas of state and federal regulation in natural gas production and storage.

[28] Natural Gas Storage in Salt Caverns, A Guide for State Regulators, Interstate Oil and Gas Compact Commission, Energy Resources Committee 1995.

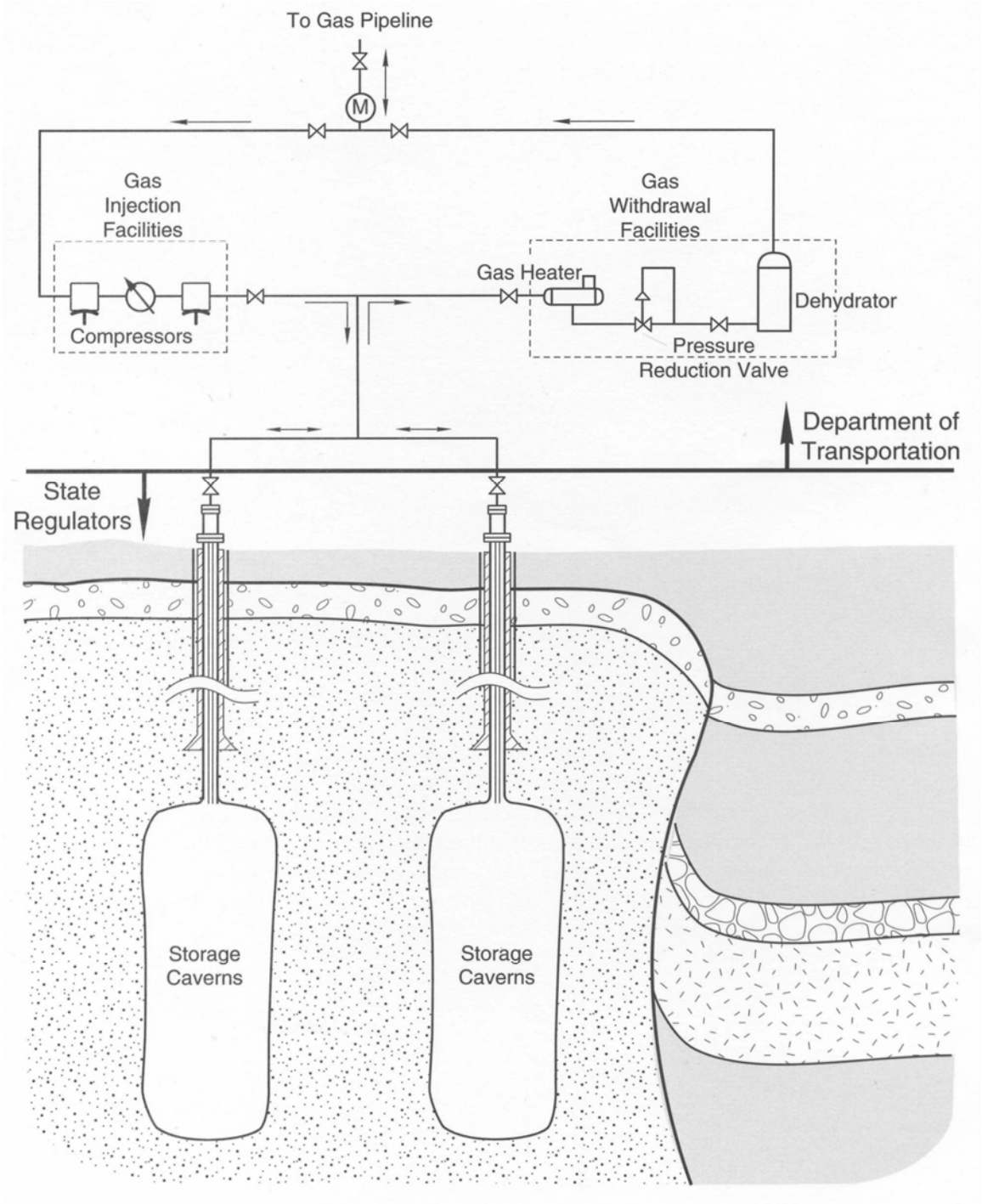

Figure 2.3.3-1 Diagram of Salt Cavern Storage and Breakdown of Areas of State and Federal Regulations.[29]

[29] Energy Resources Committee, Interstate Oil and Gas Compact Commission, Natural Gas Storage in Salt Caverns, A Guide for State Regulators, p. 11, 1998.

Salt cavern storage is based on technologies and industrial practices with a long history of safe, effective, efficient, and environmentally sound operations. These technologies and practices, and the rules and regulations that govern them, are readily adaptable to the storage of CO_2. The cost of salt cavern storage is presently prohibitive relative to other options; consequently relatively little research on salt cavern storage is currently taking place.

2.3.4 Coalbed Storage

Coalbeds also provide a potential geologic storage option for CO_2 through adsorption. Methane is chemically adsorbed on coalbeds to varying extents, depending on coal character (maceral type, ash content, etc.), depth, basin burial history and other factors, and has been produced to an ever greater extent over the last decade to add to the nation's natural gas supply. Coalbed methane (CBM) currently comprises 8% of the total U.S. natural gas production and 10% of the total U.S. natural gas reserves.[30] Major sources of CBM have been the San Juan, Black Warrior, and Powder River basins, with additional resources coming from other Rocky Mountain basins, the Mid-continent, and the Appalachian Basin. Injection of CO_2 has been tested in the San Juan Basin for enhanced CBM production.[31] In one pilot project in West Virginia, DOE currently has undertaken with Consol to test adsorption of CO_2 on coals specifically for storage purposes using a set of horizontal wells. The expectation for this project, among other similar experiments and with the support of laboratory testing, is that the adsorption sites on the coal matrix surface have stronger affinity for the CO_2 than the methane and would retain CO_2 and liberate producible methane. Injection of CO_2 for the purpose of enhanced CBM production would not be defined as storage if the coals will be mined in the future, thereby liberating the adsorbed CO_2. Coals deemed economically unminable due to depth, limited thickness, or other factors would be the only coals potentially suitable for storage. A DOE-supported enhanced CBM production test at the Allison Unit in

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[30] Advance Summary, U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 2004, DOE/EIA-0216(2003), at: http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/advanced_summary_2003/adsum2003.pdf

[31] Allison Project Report by Advanced Resources International.

New Mexico has been completed and is in its post-injection phase. It has demonstrated recovery of 1 scf of methane per 3 scf of injected CO_2.[32]

2.4 Mature Oil and Natural Gas Fields As Pathways to CCGS

An excellent working model for CCGS is the injection of CO_2 into mature oil fields that have evolved through their primary and secondary (waterflooding) phases of production. Injection of CO_2 for EOR has been in practice for the past three decades, most widely in the Permian Basin of west Texas and southeast New Mexico. The technical and economic success of this form of tertiary recovery is widely accepted as "standard oil field practice" and is being studied and expanded in the U.S. and abroad. It is important to note that during EOR operations CO_2 is not released into the atmosphere but is captured, separated and recycled back into the reservoir to recover additional oil.

It should be emphasized that CO_2 used in EOR projects has a clear value to the oil industry and as such has commodity status within the industry infrastructure currently required to handle 2.9 billion cubic feet per day (bcfd) of CO_2 (approximately 155,000 Mt per day or 56.6 Mt per year). The regulatory framework developed for CO_2 EOR will provide a valuable starting block for CCGS regulatory structure. Perhaps most important though, by utilizing CO_2 for EOR in new areas of the U.S. and the world, the CO_2 EOR process can provide the commercial drivers for building much of the necessary infrastructure to transport CO_2 from sources to the sinks.

In 2000, 34 Mt of CO_2 were injected underground as part of EOR operations in the United States. This is roughly equivalent to the CO_2 emissions from 4.7 million cars in one year.[33] For CO_2 EOR, 6,000-10,000 scf of CO_2 are typically injected per

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[32] U.S. Department of Energy, Topical Report: The Allison Unit CO_2-ECMB Pilot Project: A Reservoir Modeling Study, January 1, 2000 – June 30, 2002.
[33] Number derived from Information Card, U.S. Greenhouse Gas Facts, *Global Climate Change Technology Initiative*, NETL Carbon Sequestration Program.

barrel (bbl) oil recovered.[34] Most EOR projects in the U.S. are miscible floods wherein pressure and temperature in the reservoir are such that CO_2 and oil fully mix. At shallower depths, generally less that 2,500 ft, CO_2 and oil are immiscible and the recovery process may not be as efficient, yet may still be economical, depending on the cost of delivering CO_2 to a field and the volume of unrecovered oil remaining in the reservoir.[35] Larger fields that have a significant unrecovered oil resource would most likely justify the costs of surface facilities, of drilling or refurbishing of wells to accommodate CO_2 injection, and of the reservoir studies necessary to develop an efficient CO_2 EOR process.

Additionally, CO_2 could potentially enhance natural gas recovery (EGR) by being used to maintain pressure in depleting natural gas fields and also could potentially provide cushion gas if a reservoir were later to be converted to natural gas storage. Modeling has shown the potential for injection of CO_2 for up to a decade before breakthrough.[36] There are many other reservoir factors that will dictate the success of EGR projects. At the present time there are no active EGR projects. However, as this industry evolves, CO_2 pipelines will be constructed and this infrastructure will lay the foundation for future CCGS.

2.5 The History and Use of CO_2 for Enhanced Oil Recovery

The required components of CO_2 injection have been developed and enhanced for more than 30 years, primarily within the Permian Basin oil and natural gas producing and regulatory communities. This operation is depicted in Figure 2.5-1. Carbon dioxide has been used effectively as an injectant to increase oil production within the Permian Basin region of west Texas and southeast New Mexico since 1972 and many other regions since the early 1980s. With the development of the commercial

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[34] Practical Aspects of CO2 Flooding, SPE Monograph, November 2002.
[35] Mohammed-Singh, L. and Singhal. A. , "Lessons from Trinidad's CO_2 Immiscible Pilot Projects 1973-2003", Paper #89364, presented at the 14th SPE/DOE Conference on Improved Oil Recovery, April 2004.
[36] Oldenburg, Curtis M., "Carbon Sequestration in Natural Gas Reservoirs: Enhanced Gas Recovery and Natural Gas Storage". Paper No. LBNL-52476, Lawrence Berkeley National Laboratory, Berkeley, California, April 8, 2003. http://repositories.cdlib.org/lbnl/LBNL-52476

application of CO_2 to oil recovery, much research and practical experience has been gathered.[37]

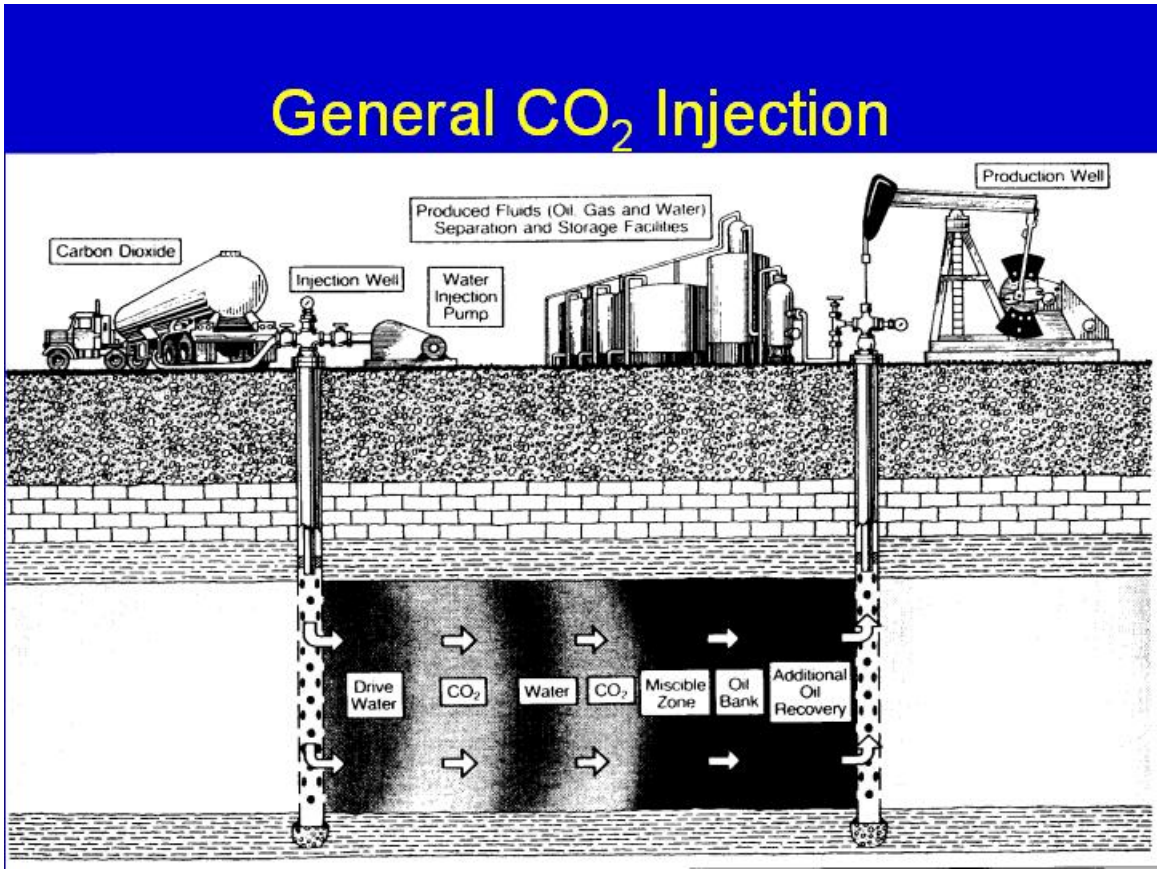

Figure 2.5-1 General CO_2 Injection.[38]

[37] Practical Aspects of CO_2 Flooding, SPE Monograph, November 2002.
[38] Illustration courtesy of the Midwest Geological Sequestration Partnership (Illinois Basin), 2004.

The utilization of CO_2 as an injectant into oil reservoirs for producing incremental oil began as early as the 1950s.[39] Those early experiments went largely unnoticed until the early 1970s when two large-scale floods in the Permian Basin region of west Texas were developed for commercial reasons. Those floods were supplied CO_2 from anthropogenic sources via the first long distance CO_2 pipeline, the Canyon Reef Carriers (CRC) pipeline. The CRC connected several natural gas processing plants in the southern Permian Basin with Shell's North Cross flood in Pecos County and the huge SACROC flood in Scurry County, Texas.

CO_2 floods utilize both new and recycled CO_2 in the EOR process, confirming the commodity value of CO_2. The typical price for new CO_2 ranges from $0.50/mcf to $1.00+/mcf. The components of cost include gathering, drying, purification, compression, and pipeline transportation. Recycling of CO_2 from the return flow of producing wells is economical because, even after treatment, this cost is generally less than one-half the cost of purchasing and transporting new CO_2.

As of 2004, there were 78 CO_2 EOR operations worldwide and 70 in the U.S., primarily in the Permian Basin of west Texas.[40] Within the U.S. during 2003, 1.5 billion cubic feet per day (bcfd) or 28 Mt[41] per year of new CO_2 were injected and an estimated 1.4 bcfd were recycled during EOR operations. Taken together, these new and recycled streams of CO_2 were responsible for recovering more than 55 million barrels of annual crude oil production. Figure 2.5-2 shows the recent project and production history of CO_2 flooding in the Permian Basin, which is responsible

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[39] See: "How Carbon Dioxide Floods Stack up with Conventional Waterfloods", Oil and Gas Journal, July 16, 1962 (Carbonated Waterfloods); "Summary Report of CO_2 Flood Test at Mead-Strawn Field", Union Oil of Calif., Internal Report, Nov, 1968 (Hybrid WAG; Immiscible); "Carbon Dioxide Test at the Mead-Strawn Field", L. W. Holm & L. J. O'Brien, Journal of Petroleum Technology, April, 1971; "Performance of Domes Unit Carbonated Waterflood-First Stage", J. O. Scott & C. E. Forrester, Journal of Petroleum Technology, December, 1965 (Carbonated Waterflood); "Carbonated Waterflooding: Is it a lab success and a field failure?", N.H. de Nevers, World Oil Magazine, September 1966; "Experience with CO_2 EOR Process in Hungary", G. Nemeth, J. Papay & A. Szittar, Presented at 4th European Symposium on EOR, Hamburg, October 1987 and revised in Revue de l'Institut Francais de Petrole, Vol. 43, No. 6, November-December, 1988.
[40] The Oil and Gas Journal Survey of EOR Projects, April 12, 2004.
[41] See footnote 14.

for 71% of the CO_2 floods and 84% of the CO_2 EOR barrels of oil produced in the United States. The chart shows a significant number of projects, the substantial contribution of these projects to energy production, and the growth trend over the last 20 years.

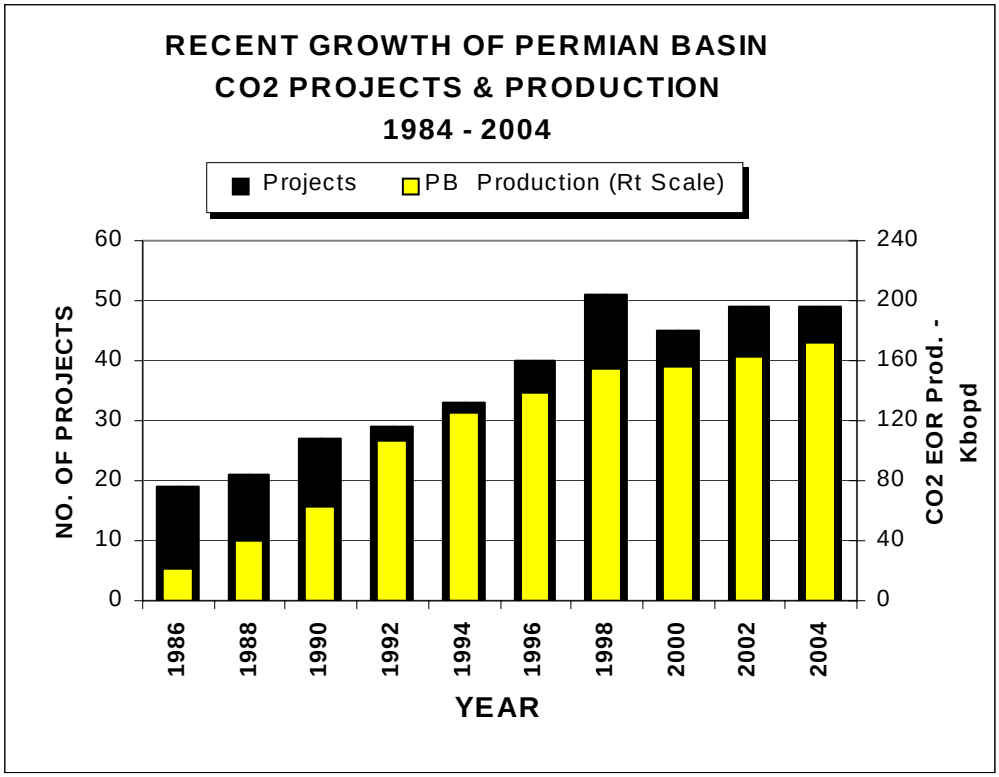

Figure 2.5-2 Recent Growth of Permian Basin CO_2 Projects & Production 1984-2004.[42]

The majority of new CO_2 utilized in the U.S., including Permian Basin CO_2 floods, comes from three naturally occurring CO_2 source fields, Sheep Mountain, Bravo Dome, and McElmo Dome. (See Figure 2.5-3). The underground source fields have the desired properties of day-to-day reliability along with high purity (>95% CO_2) and high pressure CO_2 in large volumes. Similarly, pure anthropogenic sources of CO_2 were available, although in relatively low volumes, and had occasional reliability issues and required substantial compression to reach pipeline operating pressures (1,800-2,200 psi). These industrial (anthropogenic) sources of CO_2 were used (and continue to be used today) in the SACROC, North Cross and other

[42] The Oil and Gas Journal Survey of EOR Projects, April 12, 2004.

projects, but have become relatively minor source contributors as the natural source fields with large and reliable volumes available were able to be connected to new CO_2 floods. Anthropogenic sources of CO_2 have become commercial in areas outside the Permian Basin in Wyoming, North Dakota, Michigan, and Kansas, and are projected to be a major source for future CO_2 floods.

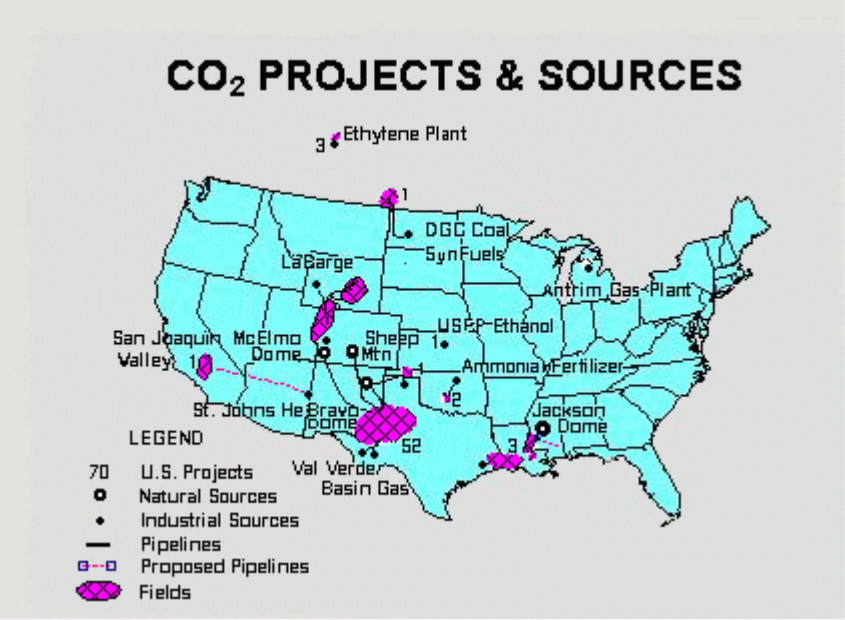

Figure 2.5-3 CO_2 Projects & Sources.[43]

In addition to the large knowledge base which has been developed for CO_2 EOR projects, a similar CO_2 transportation knowledge base has been developed. High-pressure CO_2 pipelines for short and long hauls are widely used in the CO_2 EOR industry. It is estimated that more than 3500 miles of high pressure (>1,300 psi) CO_2 pipelines have been constructed in the U.S. since 1971. In total, approximately 4 bcfd of CO_2 are handled by the nearly 30,000 persons who operate the plants, pipelines, injection, and producing wells associated with existing CO_2 projects.[44] EOR operations have an enviable safety record with no major accidents occurring over their 33-year history.

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[43] Created by Melzer, L.S, 2004.
[44] "Permian Basin Drives CO_2 Technology," Melzer, L.S. and Stiles, L.H., American Oil and Gas Reporter, Permian Basin Oil Show Program Edition, Vol 39, No. 10, October 1996, pp. 149-152.

Carbon dioxide EOR projects will lay the foundation for CCGS by providing expansion of the CO_2 pipeline infrastructure, expansion of the knowledge base, continued development of CCGS technologies, and the necessary economic incentives through increased domestic oil and natural gas production. Consequently, CO_2 EOR is likely to continue to provide new and improved technologies and an expanding infrastructure for CCGS. Today's energy producers can be strong contributors to mitigating the impact of fossil fuel consumption necessary to fuel our modern economy by providing critical pathways to CCGS.

2.6 Acid Gas Injection -- Regulatory Experience in U.S. and Canada

As mentioned previously, another commercial-scale analogue to geological CO_2 storage is the injection of acid gas, a combination of H_2S and CO_2. H_2S is an impurity associated with some oil and natural gas production. The safe removal, transportation, and injection of this impurity demonstrate the ability to safely regulate and handle a gas, which unlike CO_2, is overtly hazardous.

Acid gas is a by-product of processing streams of sour natural gas and oil. Processing to remove acid gas is necessary to meet pipeline and market specifications. Because flaring of acid gas is not permitted by regulatory agencies except for very small quantities of H_2S, and because surface desulfurisation is uneconomical in a depressed sulfur market and the surface storage of the produced sulfur constitutes a liability, increasingly, operators in Canada and the U.S. are turning to acid gas disposal by injection into deep geological formations. Compared to other options, acid gas injection has less environmental consequences than sulfur recovery (where leaching of the sulfur piles can lead to groundwater contamination) or flaring (which essentially substitutes sulfur dioxide (SO_2) for H_2S in the atmosphere, as well as releasing CO_2). Although the purpose of the acid gas injection operations is to dispose of H_2S, significant quantities of CO_2 are being

injected at the same time because it is neither beneficial nor necessary to separate the two gases.

Acid gas is injected into deep saline aquifers and depleted oil or natural gas reservoirs at 44 locations in Alberta and British Columbia in Canada, and at close to 20 sites in Michigan, New Mexico, North Dakota, Oklahoma, Texas, and Wyoming in the United States. In Canada, a total of 2.5 Mt CO_2 and 2 Mt H_2S have been injected by the end of 2003, at rates that vary between 840 and 500,720 cubic meters per day per site, with a cumulative injection rate in 2003 of 0.45 Mt/year CO_2 and 0.55 Mt/year H_2S. Injection depths vary between 3,000 and 11,000 feet.

In the United States, "there have been no known incidents where significant harm has occurred as a result of an acid gas injection operation".[45] In Canada, no safety incidents have been reported since the first acid-gas injection operation began in 1990. These acid-gas injection operations represent a commercial-scale analogue to geological storage of CO_2. The technology and experience developed in the engineering aspects of acid-gas injection operations (i.e., design, materials, leakage prevention, and safety) can be easily adopted for large-scale operations for CO_2 geological storage, since a CO_2 stream with no H_2S is less corrosive and non-hazardous.

[45] Heinrich, J.J., Herzog, H.J., and Reiner, D.M., Environmental Assessment of Geologic Storage of CO_2, Publication No. LFEE 2003-002 Report, Prepared for Clean Air Task Force, December 2003, Revised March 2004. The authors state that this is the case "[d]espite H_2S being much more toxic that CO_2."

3. Chapter 3 – Regulatory Overview

In the United States and Canada, onshore regulation of oil and natural gas production and natural gas storage is under the jurisdiction of the states and provinces.[46] State and provincial oil and natural gas regulatory programs and state and provincial oil and natural gas regulatory storage programs have kept pace with the evolution and technological advancements of the oil and natural gas industry over the last 90 years, which has included the injection of CO_2 for EOR and the underground storage of natural gas. The state/provincial regulatory frameworks, which currently govern the use of CO_2 for EOR and underground natural gas storage, are well established. (For a compendium of current state and provincial regulatory frameworks for CO_2, see Appendix 2).

In the case of EOR, the transportation by pipeline from the source to the project site and the drilling and operation of wells is governed by state and provincial regulations. For example, the Texas Railroad Commission, especially Districts 8 and 8A, have now had 30 years of experience in regulating CO_2 EOR and related transportation facilities. Other states and provinces, including New Mexico, Oklahoma, Wyoming, Michigan, Mississippi, North Dakota, and Alberta also have significant regulatory experience, including monitoring for health, safety, and environmental effects during the processing, transportation, and injection of CO_2.

In the case of underground storage of natural gas, the transportation by pipeline from the source of the natural gas to the storage site, as well as the drilling and operation of wells and the establishment of storage site operational parameters, are currently regulated by federal, state, and provincial regulations. In the U.S. there are currently 450 permitted underground natural gas storage projects in 35 states as shown in Figure 3.0-1, injecting and storing approximately 140 Mt annually. The natural gas

[46] States also have regulatory jurisdiction offshore although the limits of that jurisdiction vary by state.

storage industry has more than 80 years experience with underground storage technology.[47]

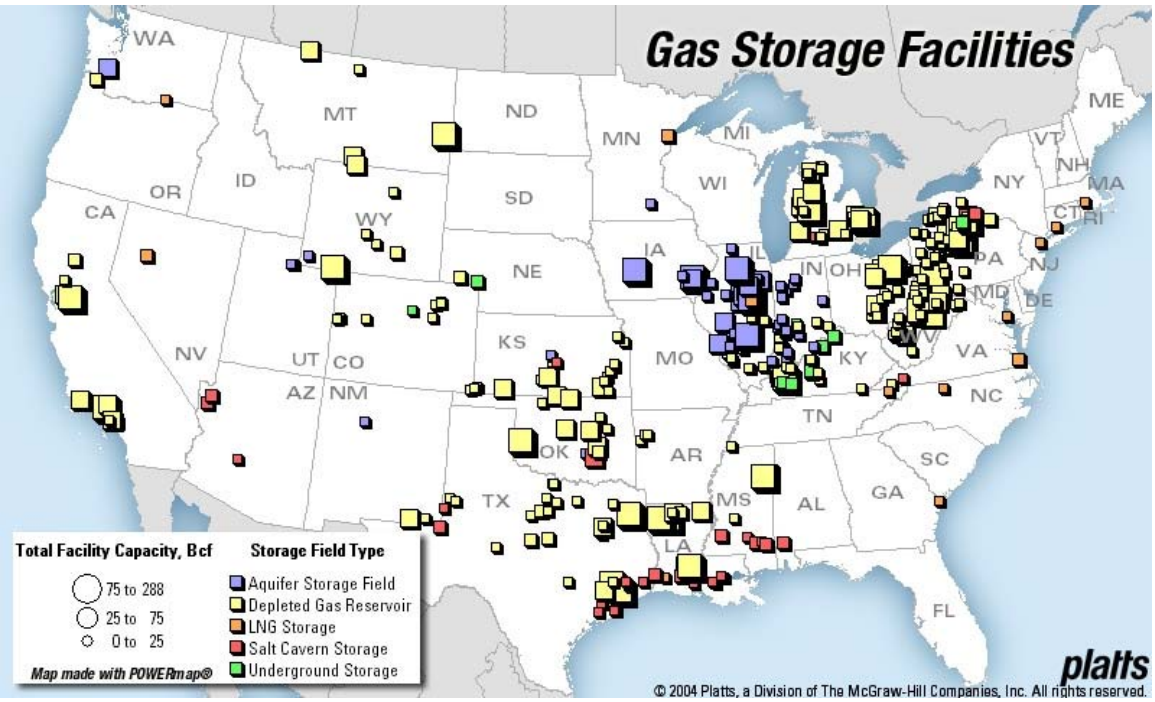

Figure 3.0-1 Gas Storage Facilities.[48]

The process of CCGS consists of 4 components, each of which has technical issues and regulatory frameworks necessary to fully address all the issues that comprise a CCGS regulatory scheme. For the purposes of this report, these components are divided into capture, transportation, injection, and storage. Each state and province has regulatory frameworks in place covering each of these elements with the exception of long-term storage. This report will attempt to analyze in a general way

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[47] "The use of underground gas storage facilities in the natural gas industry is almost as old as the development of long distance [natural gas] transmission lines. The first high pressure [natural gas] transmission lines began operations in 1891 with successful construction of two parallel 120-mile, 8-inch diameter lines from fields in northern Indiana to Chicago. The first successful [natural] gas storage project was completed in 1915 in Welland County, Ontario. The following year, operations began in the Zoar field near Buffalo, New York." From FERC Staff report issued on current state of and issues concerning underground natural gas storage and announcement of technical conference on October 21, 2004, at http://www.ferc.gov/EventCalendar/Files/20040930183109-Final%20GS%20Report.pdf.

[48] The map was prepared by and is used with the permission of Platts.

the regulatory gaps between the present regulatory structure and that needed to implement a CCGS regime in each of the 4 areas identified above.

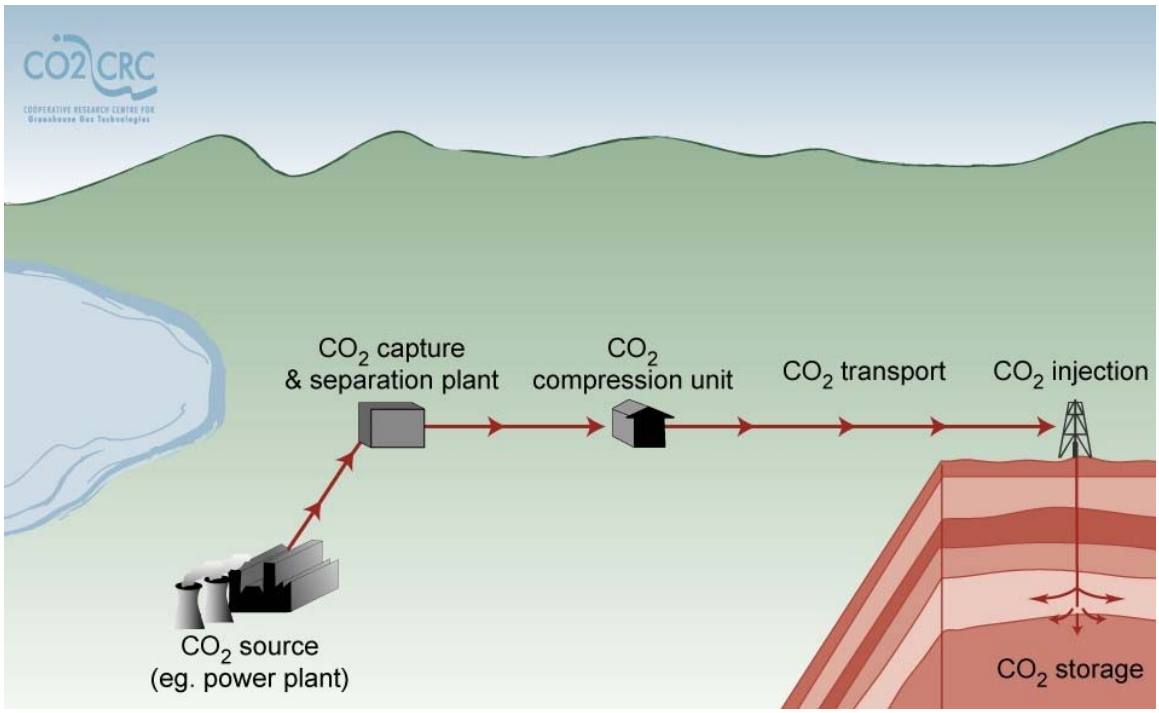

Figure 3.0-2 Carbon Dioxide Capture & Storage Project Life Cycle.[49]

3.1 Capture

The capture of industrial or anthropogenic CO_2 can be defined as the process of gathering, drying, purifying, and compressing the CO_2 stream to allow transportation to a market, EOR operation, or storage site. There are 4 technologies currently available for CO_2 capture from anthropogenic sources, which incorporate the process of gathering, drying, and purifying. These are most often combined in one or more physical or chemical processes such as glycol adsorption, membrane separation or amine adsorption as shown in Figure 3.1-1. Each of these technologies has advantages and disadvantages that impact the relative cost of CO_2 capture. Capture costs are a function of the capture technology employed, CO_2 composition of the

[49] The diagram was prepared by and is used with the permission of the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Australia.

emissions stream, and energy consumed during the capture process. Emission streams with low CO_2 concentrations and low pressure are the most costly to capture.

Capture technologies are currently being employed in the oil and natural gas industry. It is estimated that 27 million Mt per year of CO_2 are captured by approximately 40 natural gas processing plants in the Permian Basin region alone.[50] Given that the largest cost component of CCGS is capture technology, much research is being devoted to improvements in both optimizing current technologies and developing new technologies to reduce capture costs. As history has shown us, CO_2 capture costs are projected to decrease in the future, as they will be applied on a large scale along with technological improvements.

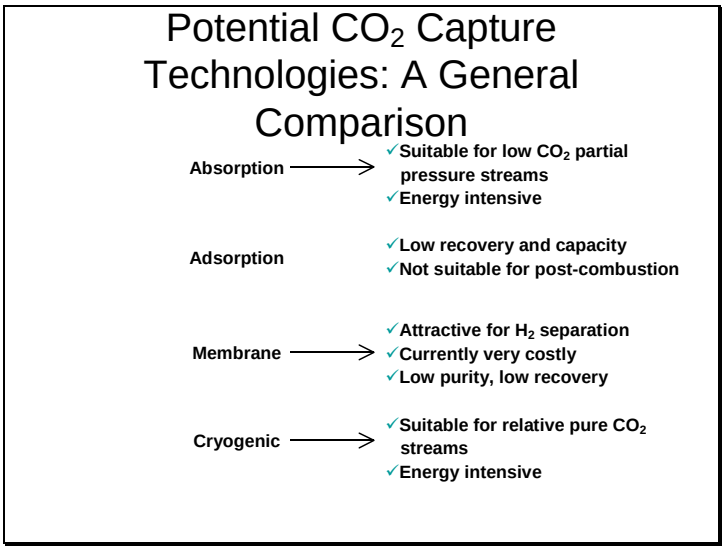

Figure 3.1-1 Potential CO_2 Capture Technologies: A General Comparison.[51]

[50] Compiled by Melzer, L.S. from Personal Data Files 2004.
[51] Illustration courtesy of the Midwest Geological Sequestration Partnership (Illinois Basin), 2004.

3.1.1 Capture Technical Issues

CO_2 is a byproduct of numerous industrial processes and fossil fuel utilization. These various sources result in the generation of varying concentrations of CO_2 in their emission streams. The chart below shows that the largest volume of CO_2 emissions is contained in highly dispersed sources which do not lend themselves to CCGS. The sources at the top of the pyramid, although small in volume, have the advantage of point source generation and high purity concentration – greater than 95% – which is the minimum requirement for pipeline transportation. Consequently those sources are the best economic candidates for CCGS. The sources at the middle of the pyramid – for example electric generation – will require costly capture technologies, but would supply substantial quantities of CO_2.

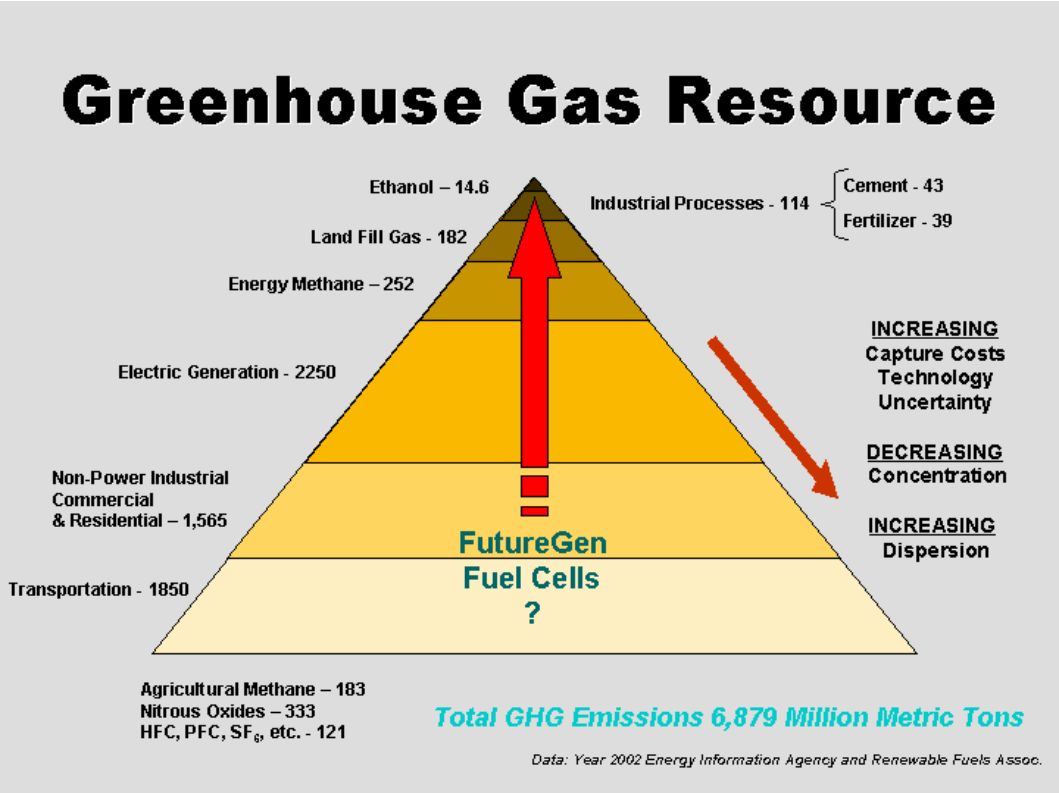

Figure 3.1.1-1 Greenhouse Gas Resource.[52]

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[52] Carr, Timothy R., Alan P. Byrnes, Martin K. Dubois, and Scott W. White, Models for Environmentally Sound and Economically Viable Carbon Dioxide Sequestration Opportunities, AAPG Annual Meeting, Dallas, Texas - April 18-21, 2004, p. A21, and Kansas Geological Survey Open-File Report 2004-19: http://www.kgs.ku.edu/PRS/publication/2004/AAPG/CO2/ofr2004-19.pdf

The separation of CO_2 from these less pure emission streams, which may contain other constituents such as oxides of sulfur and nitrogen (SO_X and NO_X), H_2S, and water (H_2O), involves many established, innovative, and developing capture technologies with associated costs that impact the economics of capture. A large body of literature is available concerning existing and developing capture technologies and associated costs. A list of DOE/NETL CO_2 capture technology literature can be found in Appendix 3. Because of the relatively high costs of capture and the unknown affects of these impurities on transport and reservoir integrity, this report will only address the relatively pure streams of CO_2 which are readily available for injection and storage. For purposes of this report, CO_2 for CCGS is defined as a direct emissions stream with purity in excess of 95% or a processed emission stream with commercial value. Given that CO_2 currently has many established industrial and EOR uses, value for CO_2 has been clearly established, therefore defining CO_2 as a commodity.

3.1.2 Capture Regulatory Recommendations

Many state/provincial and federal regulations dealing with emissions from industrial and energy generation facilities exist today in the United States and Canada. The Task Force notes that these regulations do not, for valid reasons, classify CO_2 as a pollutant, waste, or hazardous substance, and with few minor exceptions at the state level, do not regulate CO_2 emissions into the atmosphere.[53] Worldwide, some nations, in response to concern over global climate change, have put into place regulatory imperatives that limit CO_2 emissions. While the United States has not yet promulgated any regulations covering CO_2 emissions, under its *Global Climate Change Initiative*, the U.S. has set a goal to reduce greenhouse gas intensity 18% by

[53] The EPA, in response to a petition asking that it regulate certain greenhouse gas emissions under the Clean Air Act (CAA), concluded in a September 2003 Notice of Proposed Consent Decree that "[b]ased on a thorough review of the CAA, its legislative history, other congressional action and Supreme Court precedent, EPA believes that the CAA does not authorize regulation to address global climate change." 68 Fed. Reg. 52922, 52925 (September 8, 2003).

2012 through encouraging voluntary efforts by industry. Under such a voluntary system, the development of CCGS projects in the U.S. likely will be limited, beyond the use of relatively pure streams of CO_2 that prove to be economical for use in CO_2 EOR projects. This scenario could change, however, with the introduction of emission caps, economic incentives (tax and otherwise), and/or advances in technology that reduce capture costs.

Regulations for CO_2 have been promulgated by various agencies. The Occupational Safety and Health Administration (OSHA) has set time/concentration limits for exposure in confined spaces. To address ventilation and indoor air quality, other agencies such as the Federal Aviation Administration (FAA), Federal Emergency Management Agency (FEMA), the National Institute for Occupational Safety and Health (NIOSH), and others have set CO_2 limits for specific circumstances and environments.

The Task Force has concluded that given the substantial regulatory framework that currently addresses emissions standards there is little need for state regulatory frameworks in this area. Specific recommendations are set forth below.

- Existing federal air regulations do not define CO_2 as a pollutant. There is no need for state regulation to do otherwise. However, states which may have already defined CO_2 as a waste, air contaminant, or pollutant, may be advised to reassess that definition so as to not negatively impact CCGS development. While contaminants and pollutants such as NO_2, SO_2 and other emission stream constituents should remain regulated for public health and safety and other environmental considerations, CO_2 is generally considered safe and non-toxic and is not now classified at the federal level as a pollutant/waste/contaminant, and should continue to be viewed as a commodity following removal from regulated emission streams.
- Devise standards for measurement of CO_2 concentration at capture point to verify quality necessary for conformance with CCGS requirements.

- Involve all stakeholders, including the public, in the rule making process at the earliest possible time.

3.2 Transportation

For the purposes of this report, transportation is defined as the process of moving pressurized CO_2 via pipeline, tank transport, or ship from capture of the CO_2 (following processing, gathering, and compression) to the site of injection.

3.2.1 Transportation Technical Issues

The long distance transport of CO_2 has seen technological advancement but it is primarily concentrated in construction methods. There are currently 3 main modes of pipeline transportation of CO_2. These transmission modes are: 1) high pressure dense or supercritical phase transmission (above 1,180 psi); 2) lower pressure gas transmission (gas phase); and 3) refrigerated liquid transmission.

Existing long distance pipelines and those being built today fall into transportation mode 1 above and are all constructed with conventional carbon steel. They transport CO_2 in the dense or supercritical phase. The CO_2 is dried to eliminate concerns of possible corrosion with formation of carbonic acid when water is present. Gathering pipelines constitute mode 2 above and often contain water, requiring mitigation such as the use of fiberglass or plastic coating to avoid corrosion. Construction and operational safety regulations exist and are administered by the U.S. Department of Transportation's Office of Pipeline Safety (OPS) consisting of a large base of experience. States may also regulate under partnership agreements with OPS. Transportation mode 3 generally refers to rail or truck transport that is in widespread use in the marketplace serving the food and beverage industries, specialty gas industry, and the oil and natural gas hydraulic fracturing business.

There are many CO_2 pipelines currently in operation that provide a large knowledge base on construction and operational standards. A list of all major North American CO_2 pipelines can be found in Appendix 4. Some of the major pipelines are also

shown graphically on Figure 2.5-3. These pipelines are regulated by OPS.[54] The oldest of the long distance pipelines was recently required by the OPS to undergo an inspection and pressure test. This Canyon Reef Carriers pipeline, 138 miles in length, was constructed in 1971 by Gulf Oil Corporation and is now operated by Kinder Morgan CO_2 Company, L.P. The hydrotesting of this A-CO_2 pipeline was recently reported[55] and resulted in re-rating of the line to its original 1,800 psi internal pressure rating.

Many state, provincial, and federal regulations exist in the United States and Canada to deal with transportation design, construction, operations, maintenance, and emergency response for spills. In addition, groups such as the American Petroleum Institute (API), the American Gas Association (AGA), and the American Society for Testing and Materials (ASTM) have established standards for pipeline construction and material selection. These well-established regulations and pipeline construction and material standards will adequately address CO_2 transportation.

The only federal agency with regulatory responsibilities for interstate natural gas pipelines, other than OPS whose regulatory responsibilities deal mainly with safety, is the Federal Energy Regulatory Commission (FERC). FERC issues involve rate structure, gas storage facilities, certificates of public convenience, open access, facility abandonment, and environmental review. FERC has jurisdiction only with transportation involving interstate commerce. States regulate intrastate commerce. FERC presently has no legislative authority to regulate interstate CO_2 pipelines.[56]

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[54] 49 CFR Parts 190-199

[55] "Results of the Hydrotest of the 30-year old Canyon Reef Carriers CO2 Pipeline," Layne, J, 2003 CO2 Flooding Conference, December 11-12, 2003, Midland,Texas (Univeristy of Texas of the Permian Basin's Center for Energy and Economic Diversification.

[56] Any legislation granting FERC authority over CO2 pipelines would presumably require that the transport of CO2 be considered interstate commerce and it would follow that CO2 be considered a commodity.

Unresolved state and federal issues with interstate CO_2 pipelines include eminent domain[57] and the potential need for federal, presumably FERC, authority over such pipelines as well as the subsidiary issue of open access.[58] CO_2 pipeline construction potentially will require exercising eminent domain, which is largely a state issue.[59] Existing state eminent domain statutes need to be reviewed to determine if CO_2 meets the requirements necessary to allow the use of eminent domain authority for CO_2 pipeline construction. Because they are legal issues beyond the scope of this report, they are noted for future consideration by the states.

3.2.2 Transportation Regulatory Recommendations

There are numerous parallels between CO_2 transport and natural gas transport. In fact, most rules and regulations written for natural gas transport by pipeline include CO_2 and are administered and enforced by the DOT, OPS. These rules are designed to protect the public and the environment by assuring safety in pipeline design, construction, testing, operation, and maintenance. State/federal partnership programs exist whereby states can assume all or part of OPS regulatory and enforcement responsibilities. State jurisdiction usually covers the smaller diameter, lower pressure pipelines associated with gathering facilities in oil and natural gas fields. Where CO_2 transport is by rail, road or ship, other rules, regulations, and agencies may have jurisdiction.

Consequently, given the large body of experience in pipeline operation, including CO_2 pipelines, well established regulatory frameworks, and well established materials and construction standards, there is little necessity for additional state

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[57] Eminent domain is defined as "[t]he power of a governmental entity to convert privately owned property, especially land, to public use, subject to reasonable compensation for the taking." Black's Law Dictionary, Bryan A. Garner, Editor-in-Chief, West Publishing Co. 1996.

[58] Open access refers to a regime or system under which competition in the pipeline transportation industry is fostered by "the 'unbundling' of the [pipeline companies'] transportation and merchant roles, thus allowing pipelines to provide transportation service for customers who bought gas elsewhere and had it shipped through the pipelines' transportation system." Northwest Pipeline Corporation v. Federal Energy Regulatory Commission, 61 F.3d 1479, 1482 (10th Cir. 1995).

[59] In the case of interstate natural gas pipelines, the Natural Gas Act also gives pipeline companies authority under certain conditions to bring condemnation proceedings in federal court although the federal court will apply the applicable state law. The Natural Gas Act of 1938, as amended, 15 USC 717-717W.

regulations. The Task Force recognized in its discussions that the issues of open access and the potential need for FERC jurisdiction over CO_2 pipelines might be issues that need to be addressed at the state and federal level in the future. Specific recommendations are set forth below:

- Require clarity and transparency in any potential statute and regulation development.
- For transportation of CO_2 by pipeline, utilize regulatory structures from existing DOT, OPS and state rules and regulations governing CO_2 pipeline construction, operation, maintenance, emergency responses, and reporting.
- Include CO_2 in your state's "call before you dig" protocol.
- In development of state permitting procedures, identify areas of special concern such as heavily populated areas and environmentally sensitive areas so that additional safety requirements can be considered.
- While the "open access" issue is ultimately a federal concern, states must be aware of the relevancy of the open access issue as it affects state regulatory responsibilities.
- Review existing state eminent domain statutes to determine if CO_2 meets the requirements necessary to allow the use of state eminent domain authority for CO_2 pipeline construction. Clarify state eminent domain powers affecting the construction of new CO_2 pipelines while respecting private property rights.
- Identify opportunities for use of existing rights of way, both pipeline and electric transmission, for transportation of CO_2.
- Allow for CO_2 transportation in pre-existing pipelines used to transport other commodities providing that safety, health, and environmental concerns are addressed.
- Involve all stakeholders, including the public, in the rule making process at the earliest possible time.

3.3 Injection

Injection is defined as the placement, through wells, of CO_2 under pressure into underground geological formations.

3.3.1 Injection Technical Issues

There are four primary options for the geologic storage of CO_2 discussed in more detail below: 1) storage in depleted oil and natural gas reservoirs, in some instances following EOR/EGR activities; 2) storage in deep saline formations; 3) storage in salt caverns; and 4) adsorption within coalbeds unminable because of depth, thickness or other economic factors. In addition, there is the possibility of other storage options such as organic shales, fractured basalts, and hydrates.

Depleted oil and natural gas reservoirs have demonstrated trapping mechanisms and it can be reasonably assumed they will provide confinement for CO_2 storage. In addition to CO_2 storage, use of depleted oil reservoirs may also have the potential for additional EOR as a result of CO_2 injection if CO_2 EOR has not already been used. Deep saline formations represent potentially very large storage capacities for CO_2. However, the saline formations' lack of demonstrated ability to confine a fluid, which is demonstrated in oil and natural gas reservoirs, will require additional research and site-specific evaluation to determine suitability for storage. With respect to coalbeds, storage in deep unminable coalbeds will be dependent upon the coalbed's ability for absorption of injected CO_2. In addition, the injection of CO_2 into coalbeds may result in increased natural gas recovery by displacing methane as CO_2 is adsorbed (ECBMR).

In addition to the analogues discussed above, there exists in the United States and Canada a large body of state and federal regulations dealing with injection well operations, well construction, and integrity testing for injection. Groups such as the American Petroleum Institute (API), the American Gas Association (AGA), and the American Society for Testing and Materials (ASTM) have established materials

selection standards for well casing and down hole equipment, wellhead equipment, cement types, and other relevant oil field equipment and facilities. These well-established regulations and oil field standards will adequately address materials standards for CCGS.

3.3.1.1 Depleted Oil and Natural Gas Reservoirs

Many regions of the U.S. and world have produced oil and natural gas from geologic traps that represent a substantial reservoir capacity available for storage of CO_2. Where these reservoirs are below 3,000 feet, they offer tremendous pore volume space for supercritical CO_2 injection and storage. By their very nature these geologic traps, hosting confined accumulations of oil and natural gas, have proven their ability to contain fluids and gas. Additionally, if storage pressures of CO_2 stay below original reservoir pressures and there is integrity of existing wellbores, there should be no leakage.

3.3.1.2 Saline Formations

Deep saline formations, unlike oil and natural gas reservoirs, may not have demonstrated confining mechanisms but provide potentially large storage capacities for CO_2. Detailed site-specific analyses will be required to determine suitability for storage of CO_2. Early testing of saline reservoir storage options will likely be where the CO_2 is contained within a geological structure and can be readily monitored for a period of time. The ultimate ability of saline reservoirs to store CO_2 is based upon four functions: 1) supercritical CO_2 will be contained within the formation in the form of a buoyant fluid; 2) CO_2 from the injected plume will dissolve in formation water; 3) CO_2 will react with minerals in the host formation to create stable mineral phases; and 4) as injected CO_2 migrates within the host formation, a residual saturation will be created that remains trapped within the pore space. Geochemical interactions, which may result in fixing the CO_2 within the formation, may also cause chemical reactions which could adversely affect the injectability into the reservoir and possibly also the integrity of the reservoir seal. Ongoing research, including

reservoir modeling, by the Regional Carbon Sequestration Partnerships is evaluating the potential for CO_2 storage in saline formations.

Experience with injection into saline formations comes from the natural gas storage industry, from acid gas injection, and from assessments made to support the underground injection of hazardous wastes. The U.S. currently has about 1.23 trillion cubic feet (Tcf) of natural gas storage capacity developed in 38 aquifer fields. These fields are typically cycled on an annual basis with injection in the summer and withdrawal to meet winter heating demand. Understanding gained – particularly regarding seal integrity, chemistry of formation brines, behavior of the aquifer in terms of fluid flow, and influence of reservoir heterogeneities – can be transferred to an understanding of CO_2 storage in saline reservoirs. Gupta and others (2001) estimate that just one saline formation in the Midwestern U.S., the Mt. Simon Sandstone, has a storage capacity of 160 to 800 Gt of CO_2, but much site-specific work remains to be done to fully understand the reservoir functions listed above.[60] Others have suggested that the saline reservoir storage capacity in the U.S. as a whole may be up to 500 Gt.[61]

3.3.1.3 Salt Caverns and Others

The technology and regulatory framework for storage of natural gas in salt caverns is well established and with appropriate adaptations and modifications, is readily applicable to storage of CO_2. Current regulatory requirements for salt cavern gas storage facilities generally include comprehensive site characterization and suitability analysis; facility design, construction, operation, and maintenance criteria, including provisions related to cavern integrity, operating pressures, and other conditions; well design, drilling, construction, and operation; monitoring,

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[60] Gupta, N., Wang, P., Sass, P., Bergman, P., and Byrer, C., 2001, Regional and site-specific hydrologic constraints on CO2 sequestration in the Midwestern United States saline formations: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies, CSIRO Publishing, pp. 385-390.

[61] Bergman, P.D. and Winter, E.M., 1995, Disposal of carbon dioxide in aquifers in the U.S.: Energy Conversion and Management, v. 36, pp. 523-526.

measurement, and verification (MMV); safety and environmental protection; and abandonment and restoration.

Many, if not most, of the rules and regulations which states apply to the storage of natural gas in salt caverns are relevant to the storage of CO_2. However, in some states, salt cavern CO_2 storage may not be allowed under the existing regulatory framework. For example, under Alabama's rules and regulations for storage of gas in solution-mined cavities, gas is defined as "...all natural gas, casinghead gas, and occluded natural gas found in coalbeds, and all other hydrocarbons not defined as oil…except and not including liquid petroleum gas." Therefore, in this situation, CO_2 is not included under the definition and the rules would require modification to allow the storage of CO_2 in salt caverns.

Further, current rules and regulations generally do not take into account long-term storage in salt caverns. In general, when a facility is abandoned, gas is recovered and the gas injection wells are plugged according to specified requirements. Modifications to address permanent monitoring of facilities to assure integrity and safety will need to be incorporated into current rules and regulations.

3.3.1.4 Enhanced Coalbed and Organic Shale Methane Recovery

The development of methane production from coalbeds – coalbed methane (CBM) – is a relatively new source of natural gas, growing from reserves of 5.1 Tcf and production of 196 Bcf in 1990 to reserves of 18.7 Tcf and production of 1,600 Bcf in 2003.[62] Coalbed methane accounted for about 8% of U.S. natural gas production in 2002.[63] Production of methane from coalbeds requires depressurizing the seams by pumping off the formation water to allow desorption of methane from the coal

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[62] Energy Information Administration, Advance Summary, U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, p. 17 2004.

[63] Advance Summary, U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 2004, DOE/EIA-0216 2003, at: http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/advanced_summary_2003/adsum2003.pdf

matrix. Given that coal has an affinity for CO_2 adsorption and that CO_2 can preferentially adsorb onto the coal resulting in a release of methane, exposure of coalbeds to injected CO_2 is a likely means to enhance CBM production, a process termed ECBM. If CO_2 was injected and retained in unminable coalbeds, enhanced natural gas supplies may result in the process of storing CO_2. Several pilot projects concerning CO_2 injections into coal to enhance methane recovery have been initiated.[64]

3.3.1.5 Other Storage Options

Other storage options, including organic shales and basalts, are currently under study and may provide specialized storage options. Additional studies will determine the viability of these applications. However, regulatory frameworks could utilize experience gained in other storage options but would require new regulations applicable to new processes and new host geologic formations.

3.3.2 Injection Regulatory Recommendations

Injection and storage of CO_2 effectively incorporates the experience base of CO_2 EOR, Natural Gas Storage, and acid gas injection. These commercial activities have had a long history of operations, and analogues to CO_2 injection abound. The one feature overlaid upon the three bodies of experience is long-term containment assurance. State agencies have a long and successful history of regulating the

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[64] One important experiment has been completed and two are underway with respect to ECBM. In the San Juan Basin, New Mexico, 280,000 tons of CO_2 were injected over six years to assess the absorption capacity of the coal. Based on the conditions at the Allison Unit, the added recoverable methane can offset costs of CO_2 capture and transportation on the order of $2-5/ton of CO_2. Reeves, S., Taillefert, A., and Clarkson, C., The Allison Unit CO_2 – ECBM Pilot: A Reservoir Modeling Study, U.S. Department of Energy, Award Number DE-FC26-0NT40924 (2003). In another project, Consol Energy has drilled several horizontal wells at a test site in West Virginia and will test the injection of 26,000 tons of CO_2 over a one-year period. U.S. Department of Energy, Carbon Sequestration Project Portfolio, Office of Fossil Energy, National Energy Technology Laboratory, p. 305 2004. In Europe, the RECOPOL project involves CO_2 injection into coals in the Upper Silesian coal basin of Poland. Pagnier, H. and van Bergen, F., Netherlands Institute of Applied Geoscience TNO, National Geographic Survey, CO_2 Storage in Coal: The RECOPOL Project, at: http://www.coal-seq.com/Proceedings/FrankVanBergen-CO2-Presentation.pdf

injection of fluids and gasses into the subsurface under the Underground Injection Control (UIC) Program under the Federal Safe Drinking Water Act.[65] Those states which have CO_2 injection wells for EOR purposes, and which have primacy under the UIC program, currently regulate these wells as Class II wells. As concerns non-EOR CO_2 injection wells, the Task Force has concluded, given the commodity status of CO_2 in the market and utilizing the natural gas storage analogue, that future CCGS projects should be regulated under state natural gas storage statutes and existing regulatory frameworks.

The states' natural gas storage statutes and regulations include the necessary components – such as reservoir selection, injection and withdrawal parameters, unauthorized gas releases, and pressure limitations – all of which can be adapted to CCGS projects.

Given the regulatory experience of the states and provinces in the area of CO_2 EOR, natural gas storage and acid gas injection, future CO_2 regulations should build upon the regulatory frameworks already tested and in place in state and provincial statutes and regulations. In addition, given the commodity status of CO_2, which is akin to natural gas storage as a commodity, future CO_2 regulation not involving EOR projects, which are currently regulated under UIC programs, should be regulated as natural gas storage projects utilizing the framework of existing state and provincial statutes and regulations.

As concerns non-EOR injection wells, the Task Force acknowledges that EPA may recommend application of the UIC to such non-EOR CO_2 injection wells. The Task Force suggests that EPA, before it makes any recommendation concerning UIC applicability to non-EOR CO_2 injection, work closely with states.

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[65] 42 U.S.C. § 300h.

Specific recommendations are included below:

- Require clarity and transparency in all statute and regulation development.
- States with Oil and Natural Gas Conservation Acts and with existing CO_2 injection related to EOR projects or future ECBM and EGR, currently regulate these projects under UIC programs.[66] These existing regulatory frameworks provide a successful analogue for CCGS and should be examined as to whether they will adequately address the unique properties of CCGS in depleted oil and natural gas reservoirs dealing with well construction, casing, cementing, and well abandonment. To the extent necessary, these statutes and regulations should be modified to include geologic storage as suggested in the IOGCC Model Conservation Act.[67] States without experience in CO_2 EOR can look to those states with ongoing CO_2 EOR projects whose statutes and regulations have proven to be successful.
- States and provinces with natural gas storage statutes should utilize their existing natural gas regulatory frameworks, with appropriate modifications, for CCGS as suggested in a Conceptual Framework for a CO_2 Geological Statute that can be found in Appendix 6. Those states without experience can look to the referenced conceptual framework or other states whose regulations have proven successful. Should EPA recommend that injection of CO2 for non-EOR purposes be regulated under the UIC program, the Task Force strongly recommends reclassifying such wells either as a subclass of Class II or a new classification. The Task Force strongly believes that inclusion of non-EOR CCGS wells under Class I or Class V of the UIC program would not be appropriate.
- States and provinces with regulations for acid gas injection should utilize their regulatory frameworks, with appropriate modifications, for CCGS.

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[66] Similarly, in Canada CO_2 injection for EOR or ECBM operations is regulated under provincial Oil and Natural Gas Conservation Acts.
[67] The IOGCC Model Conservation Act can be found at the IOGCC Web site at: http://iogcc.state.ok.us/COMMPGS/FinalModelAct.pdf

- Regulations governing permitting processes should adequately address reservoir properties relative to the interaction of CO_2 with rock matrix and reservoir fluids. For example, carbonate precipitation is an unknown factor where there is CO_2 exposure within the reservoir over a long period of time. Further study is needed to define this issue.
- Well and equipment operational regulations should take into account the unique properties of CO_2. For example, CO_2, when exposed to water, forms carbonic acid, which is corrosive to oil field equipment and cement. Further study is needed to define the scope of the issue from the standpoint of standards and regulations.
- Regulations governing permitting processes for non-EOR CO_2 injection projects should respect existing property rights dictated by state law in issuing CO_2 storage site permits.
- Existing monitoring regulations currently in use for CO_2 EOR, natural gas storage, and acid gas injection may not adequately address monitoring and verification requirements for CO_2 storage to ensure injected CO_2 is accounted for. These regulations will need to be amended to ensure that the CCGS is performing as expected relative to safely storing CO_2 away from the atmosphere, accounting for those volumes, and establishing leak detection protocols.
- Review existing CO_2 EOR, natural gas storage, and acid gas regulations to ensure that operational plans for addressing public health and safety, as well as release or leakage mitigation procedures, are adequate.
- Adapt and modify established permitting regulations and standards for site characterization for purposes of CCGS. Consider results of DOE-sponsored partnership research and other ongoing research.
- Involve all stakeholders, including the public, in the rule making process at the earliest possible time.

3.4 Post-Injection Storage

Post-Injection Storage is defined as storage in depleted oil and natural gas reservoirs (including terminated CO_2 EOR projects), saline aquifers, salt caverns, and unminable coalbeds.

3.4.1 Post-Injection Technical Issues

The licensing and permitting process for CCGS projects is designed to establish suitability and capability of a potential geologic storage structure to confine CO_2. The permitting process developed for EOR projects and natural gas storage projects contains reservoir characterization elements which should be reviewed to ensure that they properly address CCGS issues. Following completion of the injection phase, a regulatory framework needs to be established to address monitoring and verification of emplaced CO_2, leak mitigation for the stored CO_2, and determination of long-term liability and responsibility.

The oil and natural gas regulatory framework does provide some guidance on the issue of long-term liability. In some states and provinces, the last oil and natural gas operator of record would be held as the responsible party following final closure of an active oil and/or natural gas project. This model may or may not provide guidance for assessing future liability for CCGS projects. In most oil and natural gas producing states and provinces where a responsible party cannot be established by regulation or is no longer in business, the state or provincial government assumes responsibility for plugging abandoned wells and remediating or restoring associated production facilities. Whether this framework can serve as a model for the liability issue of long-term CCGS is a subject for discussion.

3.4.2 Post-Injection Storage Regulatory Recommendations

Abandoned underground natural gas storage fields provide the closest analogy to projected CO_2 storage reservoirs. The difference, however, lies with the fact that abandoned natural gas storage fields are usually blown down prior to closure, thus

reducing substantially the bottom hole pressure, whereas CO_2 storage reservoirs are projected to be pressured up throughout the storage time frame. The EOR model provides a technical, economic and regulatory pathway for long-term CO_2 storage, but the sparsity of post-injection EOR projects has not provided adequate guidance for a CO_2 storage framework. Consequently, a new framework will need to be established to address the long-term monitoring and verification of emplaced CO_2 and determination of long-term liability.

During the operational phase of the CO_2 storage project the responsibility and liability for operational standards, release, and leakage mitigation lies with either the owner of the CO_2, established through contractual or credit arrangements, and/or the operator of the storage facility. Long-term ownership (post-operational phase) will remain with the same entities.

However, given the nonpermanence of responsible parties, detailed examination of long-term oversight of CCGS projects will be necessary. This examination will require creation of specific provisions regarding financial responsibility in the case of insolvency or failure of the licensee. These options may include establishment of:

1. Surety bonds
2. Insurance Funds
3. Government Trust Funds
4. Public, Private or Semi-Private Partnerships

Specific recommendations are included below:

- Require clarity and transparency in all statute and regulation development.
- Consider the potential need for legislation to clarify and address the unknown issues which may arise in the ownership of storage rights (reservoir pore space) and payment for use of those storage rights.

- Research the chemical transformations that are likely to take place in the reservoirs over long periods of time which may impact, positively or negatively, reservoir integrity in CO_2 storage time frames. Some work has already been done in this area.[68]
- Construct a regulatory framework for the storage stage that allows for the potential of future removal of CO_2 for commercial purposes.
- Given the long time frames proposed for CO_2 storage projects, innovative solutions to protect against orphaned sites will need to be developed. The current model utilized by most oil and natural gas producing states and provinces – whereby the government provides for ultimate assurance in dealing with orphaned oil and natural gas sites – may provide the only workable solution to this issue. This can be accomplished through state and provincial government administration of federally guaranteed industry-funded abandonment programs.
- Establish technical standards for well abandonment and site closure accounting for specialized concerns dealing with the unique properties of CO_2 impacts on reservoir characteristics, well construction, and cementing techniques normally used in the oil and natural gas industry.
- Establish procedures for long-term reservoir management and monitoring. A new framework will need to be established to address the long-term monitoring and verification of emplaced CO_2 to confirm that injected volumes remain in place.
- Establish a regulatory threshold requiring mitigation procedures to be initiated.
- Involve all stakeholders, including the public, in the rule making process at the earliest possible time.

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[68] *See*: White S.P., Allis R.G., Bergfeld D., Moore J.N., Chidsey T.C., Morgan C., McClure K., Adams, M., Rauzi S., "Evaluating the Seal Integrity of Natural CO_2 Reservoirs of the Colorado Plateau," Proceedings of the Third Annual Carbon Capture & Sequestration Conference, May 3-6, 2004, at the Mark Center Hilton Hotel in Alexandria, VA, U.S. Department of Energy National Energy Technology Laboratory.

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Nomenclature

Abbreviations:	Description:
AASG	Association of American State Geologists
AGA	American Gas Association
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
bcfd	Billion cubic feet per day
bbl	Barrel
CBM	Coalbed Methane
CCGS	Carbon Capture and Geologic Storage
CCS	Carbon Capture and Storage
CFC	Chlorofluorocarbons
CH_4	Methane
CO_2	Carbon Dioxide
CO_2CRC	Carbon Dioxide Cooperative Research Centre, Australia
CRC	Canyon Reef Carriers
Degrees C	Degrees Celsius
Degrees F	Degrees Fahrenheit
DOE	U.S. Department of Energy
ECBMR	Enhanced Coalbed Methane Recovery
EGR	Enhanced Natural Gas Recovery
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
FAA	U.S. Federal Aviation Administration
FEMA	U.S. Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
Ft	Feet
Gt	Gigatons (billion metric tons)
H_2O	Water
H_2S	Hydrogen Sulfide
IOGCC	Interstate Oil and Gas Compact Commission
IPCC	Intergovernmental Panel on Climate Change
Kbopd	Thousands of barrels of oil per day
Mcf	million cubic feet
MMV	Monitoring, Measurement, and Verification

Abbreviations:	**Description:**
Mt (No period)	Megatons (million metric tons)
Mt. (period)	Mount
NaCl	Sodium Chloride
NETL	National Energy Technology Laboratory
NIOSH	National Institute for Occupational Safety and Health
NO_2	Nitrous Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone
OSHA	U.S. Occupational Health and Safety Administration
Ppm	parts per million
Psi	pounds per square inch
Scf	Standard cubic foot
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
Tcf	Trillion cubic feet
UIC	Underground Injection Control
U.S.	United States

Appendices

Appendix 1 Participants in IOGCC Geological CO_2 Sequestration Task Force

Appendix 2 State and Provincial Regulatory Frameworks for Carbon Dioxide

Appendix 3 NETL CO_2 Capture Technology Literature

Appendix 4 North American CO_2 Pipelines

Appendix 5 State References for Pipeline & Natural Gas Storage Regulations

Appendix 6 Conceptual Framework for a CO_2 Geological Storage Statute

Appendix 1

Participants in IOGCC Geological CO2 Sequestration Task Force

1. Lawrence Bengal, Chairman
   Arkansas Oil and Gas Commission

2. Robert Finley (An Assessment of Geological Carbon Sequestration Options in the Illinois Basin Partnership), Vice-Chairman
   Illinois State Geological Survey

3. Mike Stettner
   California Division of Oil and Gas and Geothermal Resources

4. Charles Mankin
   Oklahoma State Geological Survey

5. Steven Seni
   Texas State Railroad Commission

6. Lynn Helms
   North Dakota Industrial Commission

7. Doug Patchen
   University of West Virginia

8. Dave Bassage
   West Virginia Department of Environmental Protection

9. Stephen Melzer
   Consulting Petroleum Engineer

10. Morris Korphage
    Kansas Corporation Commission

11. John King
    Michigan Public Service Commission

12. Lawrence Wickstrom
    Ohio Geological Survey

13. Timothy Carr
    Kansas Geological Survey

14. John Harju (Plains CO2 Reduction Partnership)
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15. Jack Ford (Southwest Regional Partnership for Carbon Sequestration)
    New Mexico Department of Energy, Minerals & Natural Resources

16. Patrick Esposito II (Southeast Regional Partnership for Carbon Sequestration)
    Augusta Systems

17. Raymond Lawton (Midwest Regional Carbon Sequestration Partnership)
    Ohio State University

18. Jean Young (West Coast Regional Carbon Sequestration Partnership)
    Terralog Technologies USA, Inc.

19. Susan Capalbo (Big Sky Regional Carbon Sequestration Partnership)
    Montana State University

20. David Hyman
    National Energy Technology Laboratory

21. Nick Tew
    Alabama State Oil and Gas Board

22. Daniel Seamount
    Alaska Oil and Gas Conservation Commission

23. Stefan Bachu
    Alberta Energy and Utilities Board

24. Christine Hansen
    Interstate Oil and Gas Compact Commission

Administrative:

Kevin J. Bliss, IOGCC Project Coordinator
Bill LeMay, IOGCC Task Force Regulatory Expert

Appendix 2

State and Provincial Regulatory Frameworks for Carbon Dioxide

State	Has State defined CO2? Yes	No	Is CO2 Being Injected?	If Yes, Reason	Under What Regulatory Authority ?	Long Term CO2 Storage-How would State Regulate ?	Is State Considering New Laws?	Gas Storage Regulatory Authority? (UIC, Non UIC)
Alabama		X	Yes	EOR	UIC - Class II	Underground gas storage	No	non UIC
Alaska		X	Yes	EOR	UIC - Class II	Gas storage & UIC Class II	No	UIC
Arizona		X	No			Aquifer Protection Permit	No	UIC & non UIC
Arkansas		X	Yes	EOR	UIC - Class II	New Authority OGC&DEQ	No	No Response
California	X, motor vehicle		Yes	EOR	UIC - Class II	DOGGR&SWRCB under MOU	No	UIC & non UIC
Colorado		X	Yes	EOR	UIC - Class II	Under EPA Class I or V	No	UIC
Florida		X	No			Underground gas storage	No	UIC & non UIC
Illinois		X	No			UIC Class II	No	non UIC
Indiana		X	No			Underground gas storage	No	No Response
Kansas		X	Yes	EOR	UIC - Class II	Underground gas storage	No	non UIC
Kentucky		X	Not now	past EOR	EPA	UIC Class II	No	No Response
Louisiana		X	Yes	EOR & EGR	UIC - Class II	Underground gas storage	No	UIC
Maryland		X	No Response			No Response	No	non UIC
Michigan		X	Yes	EGR	UIC - Class IIR	Part 625, Mineral wells of NREPA	No	non UIC
Mississippi		X	Yes	EOR	UIC - Class II			non UIC
Missouri		X	No			UIC Class V	No	No Response
Nebraska		X	No			New Authority under O&GCC	No	No Response
Nevada		X	No			New Authority under NDEP	No	No Response
New Mexico		X	Yes	EOR & EGR	UIC - Class II	NMOCD rules and regulations	No	non UIC
New York	X, air pollutant		No			Underground gas storage	No	non UIC
North Dakota		X	Yes-Canada	Exported	NDAC 43-02-01	Underground gas storage	No	No Response
Ohio		X	No			Class II Proposed	Yes	UIC
Oklahoma		X	Yes	EOR	UIC - Class II	OCC regulations pending study	No	UIC
Oregon	No Response		No Response			No Response		UIC & non UIC
Pennsylvania		X	Not now	past EOR	EPA	Pilot project with EPA & DEP	No	No Response
South Dakota		X	No			UIC project under SDDENR	No	No Repsonse
Texas		X	Yes	EOR	UIC - Class II	Probable MOU - RRC & CEQ	No	No Response
Utah		X	Yes	EOR	UIC - Class II	UIC & Gas Storage	No	UIC
Virginia		X	No			UIC program with EPA primacy	Yes DEQ eval.	non UIC
West Virginia		X	Yes	EOR & EGR	UIC - Class II	UIC Disposal; Non UIC Storage`	No	No Response
Wyoming		X	Yes	EOR & EGR	UIC - Class II	Underground gas storage	No	non UIC
Alberta	X		Yes	EOR &Acid Gas	EUB-Class III	Yes, EOR and acid gas	No	EUB
British Columbia		X	No	Acid Gas		Gas Disposal Wells	No	B.C. Oil & Gas Comm.
Saskatchewan		X	Yes	EOR		Gas Injection Wells	No	

Note: Well classification in Canada differs from the United States. Class III in Canada similar Class II in the U.S. EUB: Alberta Energy and Utilities Board. Also, Canadian Regulatory Schemes are different and are not at all related to the EPA or the states. Regulation occurs by the provinces pursuant to their legislation. See also footnote 12 to the Final Report to which this appendix is attached.

Appendix 3

NETL CO_2 Capture Technology Literature

December 6, 2004

1. *Updated Cost and Performance Estimates for Fossil Fuel Power Plants with CO_2 Removal*, EPRI, Palo Alto, CA, U.S. Department of Energy—Office of Fossil Energy, Washington, DC, and U.S. Department of Energy/NETL, Pittsburgh, PA: 2002. 1004483 (http://www.netl.doe.gov/coal/Gasification/pubs/pdf/EpriReport.PDF)

2. *Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal*, EPRI, Palo Alto, CA, U. S. Department of Energy — Office of Fossil Energy, Germantown, MD and U. S. Department of Energy/NETL, Pittsburgh, PA: 2000. 1000316. (http://www.netl.doe.gov/coal/Gasification/pubs/pdf/1004483.pdf)

3. Klara, S.M., Srivastava, R.D., *U.S. DOE Integrated Collaborative Technology Development Program for CO_2*, Environmental Progress, December 2002. (http://www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/articles/EnvirProgress.pdf)

4. *Evaluation of Fossil Fuel Power Plants with CO_2 Recovery*, U.S. Department of Energy/National Energy Technology Laboratory, Pittsburgh, PA, Parsons Infrastructure and Technology Group, Inc., Contract No. DE-AM26-99FT40465, February 2002 (http://www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/analysis/Evaluation_of_Fossil_Fuel_Power_Plants_with_CO2_Recovery.pdf)

5. Dipietro, P. J., Tarka, T., Ciferno, J.P., *An Economic Scoping Study for CO_2 Capture using Aqueous Ammonia*, U.S. Department of Energy/National Energy Technology Laboratory, Pittsburgh, PA, Advance Research International, Energetics, Inc., Novemebr 2004 (http://www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/analysis/Final%20AA%20Systems%20Analysis.pdf)

Appendix 4

North American CO2 Pipelines

Pipeline	Owner/Operator	Length (mi)	Diameter - in	Location
Anadarko Powder River Basin CO_2 PL	Anadarko	125	16	WY
Anton Irish	Oxy	40	8	TX
Bravo	Oxy Permian	218	20	NM,TX
Canyon Reef Carriers	Kinder Morgan	139	16	TX
Centerline	Kinder Morgan	113	16	TX
Central Basin	Kinder Morgan	143	26-16	TX
Chaparral	Chaparral Energy	23	6	OK
Choctaw	Denbury Resources	110	20	MS
Cordona Lake	ExxonMobil	7	6	TX
Cortez	Kinder Morgan	502	30	TX
Dakota Gasification	Dakota Gasification	204	12	ND/Sask
Dollarhide	Pure Energy	23	8	TX
El Mar	Kinder Morgan	35	6	TX
Enid-Purdy (Central Oklahoma)	Anadarko	117	8	OK
Este I - to Welch, Tx	ExxonMobil, et al	40	14	TX
Este II - to Salt Creek Field	ExxonMobil	45	12	TX
Ford	Kinder Morgan	12	4	TX
Joffre Viking	Penn West Petroleum Ltd.	8	6	Alberta
Llano	Trinity CO_2	53	12-8	NM
Pecos County	Kinder Morgan	26	8	TX
Raven Ridge	ChevronTexaco	160	16	WY/Co
Sheep Mountain	British Petroleum	408	24	TX
Shute Creek	ExxonMobil	30	30	WY
Slaughter	Oxy Permian	35	12	TX
Transpetco	TransPetco	110	8	TX
Val Verde	PetroSource	83	10	TX
W. Texas	Trinity CO_2	60	12-8	TX,NM
Wellman	Wiser	25	6	TX
White Frost	Core Energy, LLC	11	6	MI
Wyoming CO_2	ExxonMobil	112	20-16	WY

Reference: Melzer, L.S. , Personal Data Tabulations (2004).

Appendix 5

State References for Pipeline and Natural Gas Storage Regulations

The following is a compendium of state references for pipeline and gas storage regulations based on the responses by the states to a questionnaire submitted by the IOGCC Task Force.

Alabama:

State Oil And Gas Board Of Alabama

Administrative Code

Oil And Gas Report 1

http://www.ogb.state.al.us/HTMLS/ogbrules/OGB_Rules_TOC.htm

Pipeline: Onshore Operations Rule 400-1-8-.03 (Gathering Lines); Coalbed Methane Gas Operations Rule 400-3-7-.03 (Gathering Lines)

Gas Storage Project: Rule 400-5 (Reservoirs); Rule 400-6 (Solution Mined Cavities)

The Code of Alabama 1975

http://www.legislature.state.al.us/CodeofAlabama/1975/coatoc.htm

Pipeline: Title 9, Chapter 17: Article 3 (Gas Pipeline Systems); Article 1 (Conservation and Regulation of Production), specifically Section 9-17-6

Gas Storage Project: Title 9, Chapter 17: Article 6 (Underground Gas Storage)

Alaska:

The Alaska Statutes - 2003

http://www.legis.state.ak.us/cgi-bin/folioisa.dll/stattx03/query=*/toc/{@21}?next

Pipeline: AS 42.06.240

AS 42.06.310

AS 09.55.240

Gas Storage Project: AS 31 (New Regulations would have to be written)

Arizona:

Arizona Revised Statutes

http://www.azleg.state.az.us/ArizonaRevisedStatutes.asp

Pipeline: A.R.S. 40-441, 40-442, 40-443, and 49-1001

Gas Storage Project: A.R.S. 27-516(A)(20)

A.R.S. 49-241.01

Arkansas:

http://www.arkleg.state.ar.us/NXT/gateway.dll?f=templates&fn=default.htm&vid=blr:code

Pipeline: Arkansas Pipeline Saftey Act

Arkansas Code Annotated Sections 23-15-201 thru 217

Gas Storage Project: Arkansas Underground Storage of Gas Law

Arkansas Code Annotated Sections 15-72-601 thru 608

California:

California Code of Regulations (CCR)

Title 14, Division 2, Chapter 4

http://www.consrv.ca.gov/DOG/pubs_stats/law_regulations.htm

Pipeline: Subchapter 2, Article 3, Section 1774

Gas Storage Project: Subchapter 1, Article 3, Section 1724.9

Colorado:

Colorado Revised Statutes

http://www.state.co.us/gov_dir/olls/HTML/colorado_revised_statutes.htm

Pipeline: including but not limited to C.R.S 7-43-102 and 40-1-103

Gas Storage Project: C.R.S. 34-60-101 through 107

Florida:

The 2004 Florida Statutes

http://www.flsenate.gov/Statutes/index.cfm?Mode=View%20Statutes&Submenu=1&Tab=statutes

Pipeline: Chapter 368 and 377

Gas Storage Project: Chapter 377.242(3)

Georgia:

No Response

Idaho:

No Response

Illinois:

Illinois Compiled Statutes

www.ilga.gov/legislation/ilcs/ilcs2.asp?chapterID=23

Pipeline: 220 ILCS 15 Illinois Gas Storage Act

Gas Storage: 220 ILCS 20 Illinois Gas Pipeline Safety Act

Indiana:

The Indiana Statutes

http://www.in.gov/legislative/ic/code/

Pipeline: IC 8-1

Gas Storage Project: IC 14-37

Kansas:

The Kansas Statutes

http://www.kslegislature.org/cgi-bin/statutes/index.cgi

Pipeline: K.S. 66-1,150

K.S. 66-1,153

Gas Storage Project: K.S. 55-12

K.S. 74-623

K.S. 55-1,115

K.S. 65-171d

K.S. 55-1,117

Kentucky:

No Response

Louisiana:

Louisiana Laws-Revised Statutes

http://www.legis.state.la.us/tsrs/search.htm

Pipeline: LA R.S. 30:501 et seq.

Gas Storage Project: Title 30: LA R.S. 30:23

Maryland:

Pipeline: N/A

Gas Storage Project: Article 14-101

Michigan:

Pipeline: ACT 9PA1929

ACT 165PA1969

Gas Storage Project: ACT 238PA1923

ACT 9PA1929

ACT 165PA1969

ACT 451PA1994

Mississippi:

Mississippi Code of 1972 (As Amended)

http://www.mscode.com/free/statutes/53/001/0017.htm

Pipeline: Not Available

Gas Storage Project: Code Section 53-1-17, Part 3(p)

Missouri:

No Response

Montana:

No Response

Nebraska:

Laws of Nebraska

Nebraska Statutes and Constitution

http://statutes.unicam.state.ne.us/

Pipeline: §57-401 through 402
§57-1101 through 1106
§66-1801 through 1857
§75-501 through 503
§81-542 through 552

Gas Storage Project: §57-601 through 609

Nevada:

Nevada Revised Statutes

http://www.leg.state.nv.us/nrs/nrs%2D708.html

Pipeline: Chapter 708

Gas Storage Project: Not Considered

New Mexico:

New Mexico Statutes and Court Rules

http://www.nmcpr.state.nm.us/nmac/

www.emnrd.state.nm.us./ocd/

Pipeline: NMAC 70.3.A.1 through NMAC 70.3.A.7

Gas Storage Project: NMAC 70.6.A.1 through NMAC 70.6.8

New York:

New York State Consolidated Laws

http://assembly.state.ny.us/leg/?cl=95

Pipeline: Chapter 48 Article 7

Gas Storage Project: Chapter 43-B Article 23 Title 13

North Dakota:

North Dakota Century Code

http://www.state.nd.us/lr/information/statutes/cent-code.html

Pipeline: NDCC 49-02-01.2

Gas Storage Project: NDCC 38-08-04 2. f.

Ohio:

No Response

Oklahoma:

Oklahoma Statutes

-Oklahoma Carbon Sequestration Enhancement Act

-OK Statute Title 27A §3-4-101 through 3-4-105

Oklahoma Administrative Code

Gas Storage Project: OK Admin. Code 165: § 10-3-5

Oregon:

Oregon Revised Statutes - 2003 Edition

http://www.leg.state.or.us/ors/520.html

Pipeline: DOE regulates all above hole well operations pipelines and facilities

Gas Storage Project: ORS 520

Pennsylvania:

No Response

South Carolina:

No Response

South Dakota:

Statutory Titles In South Dakota

http://legis.state.sd.us/statutes/index.cfm?FuseAction=StatutesTitleList

Pipeline: 49-34B

Gas Storage Project: N/A

Texas:

Texas State Statutes

http://info.sos.state.tx.us/pls/pub/readtac$ext.viewtac

http://www.capitol.state.tx.us/statutes/nr.toc.htm

Gas Storage Project: Texas Administrative Code Title 16 Part 1 Chapter 3.96
Natural Resources Code Chapter 91, Subchapter H

Utah:

Utah Code

Utah Administrative Code

http://www.le.state.ut.us/~code/code.htm

http://www.rules.utah.gov/publicat/code.htm

Pipeline: Utah Code 54-13

Rule: R746-409

Gas Storage Project: Utah Code 40-6

Rule: R649-3, R649-5

Virginia:

Code of Virginia

http://leg1.state.va.us/cgi-bin/legp504.exe?000+cod+45.1-361.1

Pipeline: 45.1-361.1 et. seq. Title 56

Gas Storage Project: Title 56

Washington:

No Response

West Virginia:

West Virginia Code

http://129.71.164.29/WVCODE/masterfrm3Banner.cfm

Pipeline: WV Code 22-6-30(d)

35 CSR 4-16.7

Gas Storage Project: WV Code 22-9

Wyoming:

2004 Wyoming Statutes

http://legisweb.state.wy.us/statutes/sub30.htm

Pipeline: N/A

Gas Storage Project: Wyo. 30-5-104

Appendix 6

Conceptual Framework For A CO_2 Geological Storage Statute

(Not an IOGCC-approved model statute)

(Although this conceptual framework statute was designed for U.S. states, it is assumed that Canadian provinces could, if desired, easily adapt the document to meet the requirements of their specific jurisdictions and regulatory legislation.)

Preface

The Interstate Oil and Gas Compact Commission (IOGCC) has prepared the following provisions to supplement Part VIII of the Model Oil and Gas Conservation Act, which deals with the regulation of Underground Gas Storage including geologic storage of CO_2. These provisions address the acquisition of properties suitable for geologic storage of CO_2 through eminent domain and recognize certain property rights in stored CO_2. These Model Provisions do not address the initial ownership of CO_2 storage rights vis-à-vis the surface and mineral interest owner. These supplementary provisions should not be codified under a state's conservation act, but Part I should be included in a state's eminent domain or public utilities code and Part II should be included in a state's property code.

Declaration of Purpose

Because of the economic and environmental importance of CO_2, the conservation of property suitable for geologic CO_2 storage, the prevention of waste, and the protection of public health, public safety, and the environment, the geologic storage of CO_2 is declared to be in the public interest. Accordingly, the purpose of these provisions is to conserve property suitable for geologic CO_2 storage, to prevent waste of the storage facility, and to protect correlative rights, public health, public safety, and the environment.

PART I

SECTION 1. DEFINITIONS.

"CCGS operator" means any person, firm or corporation authorized to do business in this state and that holds a certificate of convenience from the [commission] or the Federal Energy Regulatory Commission to engage in the business of transporting, injecting, storing or distributing CO_2 by means of pipelines into, within or through this state for use in enhanced oil and gas recovery, other industrial processes or storage for the purpose of greenhouse gas mitigation.

"CO_2" means CO_2 from an anthropogenic source as a gas or as a supercritical fluid with physical properties between a liquid and a gas at pressures greater than 1073 psi at 87.7 degrees F, and with a purity of 95% or as a constituent in a processed emission stream with commercial value.

"Geologic Storage Facility" means underground geologic formations, strata, reservoirs, or caverns into which CO_2 is injected for storage.

SECTION 2. PUBLIC INTEREST.

The geologic storage of CO_2 provides a mitigation strategy aimed at reducing CO_2 emissions into the atmosphere, which has been shown to be a contributing factor in global warming, thereby promoting the public interest and the general welfare. Therefore, the [legislature of this state] finds that the orderly and efficient geologic storage of CO_2 is in the public interest.

SECTION 3. APPROPRIATION OF CERTAIN PROPERTY.

Any CCGS operator may appropriate for its use for the geologic storage of CO_2 any subsurface stratum or formation in any land which the [<u>oil and gas conservation commission</u>] shall have found to be suitable and in the public interest for the geologic storage of CO_2, and in connection therewith may appropriate other interests in property as may be required adequately to examine, prepare, maintain, and operate geologic storage facilities. The right of appropriation shall be without prejudice to the rights of the owner of the land, minerals, or other rights or interests therein, as to

all other uses of property, including the right to drill or bore through the appropriated geologic storage facility, if done in accordance with any order, permit, rule, or regulation that the [oil and gas conservation commission] may issue for the purpose of protecting the geologic storage facility against waste and against the escape of CO_2.

SECTION 4. APPLICATION FOR CO2 GEOLOGIC STORAGE FACILIITY CERTIFICATE; NOTICE AND HEARING; ASSESSMENT OF COSTS.

(a) Any CCGS operator desiring to exercise the right of eminent domain as to any property for use for geologic storage of CO_2 shall, as a condition precedent to the filing of its petition in the district court, obtain from the [oil and gas conservation commission] a certificate setting out findings of the [oil and gas conservation commission] that:

(1) the geologic storage facility sought to be acquired is suitable for the storage of CO_2 and that its use for this purpose is in the public interest; and

(2) the amount of proven commercially producible accumulations of oil or native gas, or both, if any, remaining in the proposed geologic storage facility.

(b) The [commission's] finding under subparagraph (2) above that the geologic storage facility is suitable for the geologic storage of CO_2 shall include specific findings, including:

(1) that the use of the geologic storage facility for CO_2 storage will not contaminate other formations containing fresh water or containing oil, natural gas or other commercial mineral deposits; and

(2) that the proposed geologic storage facility will not unduly endanger lives or property.

(c) the [oil and gas conservation commission] shall not issue a certificate without reasonable notice to interested parties and an opportunity for a hearing. [The applicant shall be responsible for all costs of this proceeding.]

SECTION 5. EMINENT DOMAIN PROCEDURE.

Any CCGS operator having first obtained the certificate specified in [Section 4] from the [oil and gas conservation commission] and desiring to exercise the right of eminent domain for the purpose of acquiring property for the geologic storage of CO_2, shall proceed in accordance with [eminent domain procedure of this state]. The petitioner shall file the certificate as a part of its petition and no order by the court granting said petition shall be entered unless accompanied by the certificate. The appraisers in awarding damages shall also take into consideration the amounts of proven commercially producible accumulations of oil or natural gas or both, if any, remaining in the property sought to be appropriated and, for this purpose, shall receive the findings of the [oil and gas conservation commission] as prima facie evidence of these amounts.

SECTION 6. NOTICE OF CLOSURE OF GEOLOGIC CO_2 STORAGE FACILITY; DISPOSITION OF PROPERTY RIGHTS.

When the owner of a geologic storage facility has ceased active injection operations of CO_2 and closes the storage facility and that facility was certificated by the [oil and gas conservation commission], the owner shall file with the [oil and gas conservation commission] a notice of cessation of injection. If any storage facility was certificated pursuant to federal authority, the owner shall file a copy of any federal closure authority with the [oil and gas conservation commission]. Unless notice of closure authority has been filed with the [oil and gas conservation commission], there shall be a presumption that the geologic storage facility and all rights associated with it remain as certificated. In either case the owner shall file an instrument with the [recorder] in the appropriate county or counties, stating that injection has ceased and that the ownership of all property acquired by the CCGS operator, both mineral and surface, remains with or will be transferred to a successor owner with approval of the [oil and gas commission].

PART II.

SECTION 1. OWNERSHIP OF INJECTED CO_2.

All CO_2 that has previously been reduced to possession, and which is subsequently injected into a geologic storage facility, whether storage rights were acquired by eminent domain or otherwise, shall at all times be the property of the injector, or the injector's heirs, successors or assigns, whether owned by the injector or stored under contract. Absent a final judgment of willful abandonment rendered by a court of competent jurisdiction, in no event shall this CO_2 be deemed the property of a surface owner or mineral owner, or the property of persons claiming by or under these owners, under whose lands the CO_2 is stored. Only the injector, or the injector's heirs, successors and assigns, may produce, take, reduce to possession this stored CO_2.

SECTION 2. EFFECT ON SURFACE AND MINERAL RIGHTS.

Nothing in this subsection shall be deemed to affect the otherwise lawful right of a surface or mineral owner to drill or bore through the geologic storage facilities, if done in accordance with [commission] rules for protecting the geologic storage facility against the escape of CO_2.

SECTION 3. IDENTIFICATION OF MIGRATING CO_2 —COSTS— INJUNCTION.

(a) If CO_2 that has been injected into property or has migrated to adjoining property or to a stratum, or portion thereof, which has not been acquired by eminent domain or otherwise acquired, the injector shall not lose title to or possession of injected CO_2 if the injector can prove by a preponderance of the evidence that the CO_2 was originally injected into the geologic storage facility. The court, on its own motion or upon motion of a party, may appoint the [oil and gas conservation commission] as a special master to provide assistance regarding this issue.

(b) If CO_2 that has been injected into property or has migrated to adjoining property or to a stratum, or portion thereof, which has not been acquired by eminent domain

or otherwise acquired, the injector, at the injector's sole risk and expense, shall have the right to conduct reasonable testing on any existing wells on adjoining property including tests to determine ownership of the CO_2, and to determine the value of any lost production of other than the injector's CO_2.

(c) If CO_2 that has been injected into property or has migrated to adjoining property or to a stratum, or portion thereof, which has not been acquired by eminent domain or otherwise acquired, the owner of the stratum and the owner of the surface shall be entitled to compensation for use of or damage to the surface or substratum, the value of the storage right, and shall be entitled to recover all costs and expenses, including reasonable attorney fees.

(d) The injector shall have the right to interim relief through injunctive or other appropriate relief.

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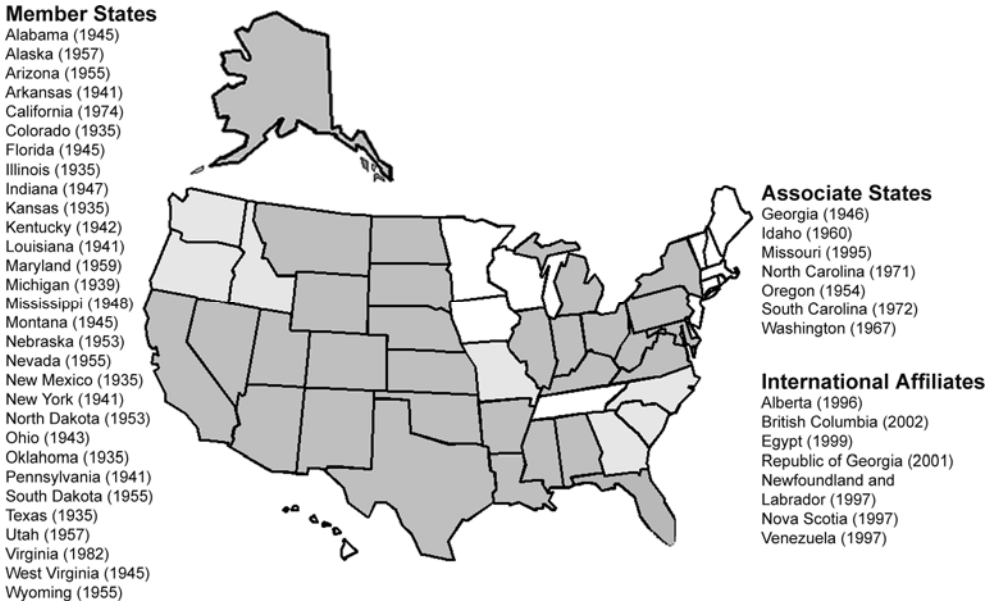

The Member and Affiliate States of the Interstate Oil and Gas Compact Commission

APPENDIX F

ACTION PLANS

ACTION PLANS

Appendix F contains Action Plans in support of Plains CO_2 Reduction (PCOR) Partnership Phase II geological and terrestrial sequestration activities. Action Plans are presented for each of the three geologic validation tests, terrestrial sequestration in general, deployment, and education and outreach.

Geologic Sequestration Action Plans

Phase I assessment activities delineated three geologic sequestration projects:

- *Project 1* – Injection of carbon dioxide (CO_2) into Carbonate System at Beaver Lodge Oil Field, North Dakota
- *Project 2* – Injection of CO_2/H_2S (acid gas) into Carbonate System at Zama, Alberta
- *Project 3* – Injection of CO_2 into Lignite Coal Seam in the Williston Basin

Each of the geologic sequestration projects will be implemented in three phases as follows:

- **Preinjection Phase** – Baseline site characterization efforts will include reservoir simulation modeling, calculations to estimate the expected storage capacity, and laboratory tests to predict possible interaction of the injected gases/fluids with the reservoir rock and fluids.
- **Injection Phase** – CO_2 will be injected into the storage reservoir, and inputs will be monitored.
- **Postinjection Phase** – The reliability of the preinjection modeling predictions and calculations will be assessed using material balances, determination of the percentage of effective utilization of the available storage capacity, and evaluation of postinjection reservoir conditions.

Geological Sequestration Project 1 – Injection of CO_2 into Carbonate System at Beaver Lodge Oil Field, North Dakota.

Activities will be conducted in the Beaver Lodge oil field in northwestern North Dakota to evaluate the potential for geological sequestration of CO_2 in a deep carbonate reservoir for the dual purpose of CO_2 sequestration and enhanced oil recovery (EOR). Phase I studies indicated that the Beaver Lodge field may have up to 212 million tons of CO_2 storage capacity. The CO_2 will likely be obtained from Dakota Gasification Company (DGC). The target injection zone for the project will be the Duperow Formation, which is located at a depth of between 10,000 and 10,500 ft. In comparison, the Weyburn CO_2 project is operated at depths of 4750 ft. The Duperow is primarily dolomite, with an average porosity of 13.7%, permeability of 3.6 mD, and other reservoir properties that make it a suitable target for CO_2 sequestration. The Beaver Lodge also has several other horizons that may be conducive to CO_2 sequestration, making the field ideal for potential future studies of multizone injection or CO_2 fate in other rock types. Amerada Hess Corporation owns and operates the field and will assist with construction and permitting.

Amerada Hess Corporation has rigorously evaluated the properties of the site selected for the EOR demonstration project, including performing robust reservoir-modeling activities. PCOR Partnership Phase II activities will include additional reservoir modeling based on data collected over the course of the injection operations. The permits needed for this project will be obtained by Amerada Hess in accordance

with all local, state, and federal regulations. Construction requirements will likely include the installation of CO_2 injection wells and the infrastructure and facilities necessary to transport the CO_2 from an existing DGC pipeline to the Beaver Lodge field, a distance of less than 5 miles. With respect to injection operations, it is anticipated that CO_2 will be injected into the target zone using two injection wells at a rate that is appropriate for pilot-scale EOR operations. Injection is expected to be conducted over at least 1 year of the project. Monitoring and verification equipment will be installed and operations conducted to monitor pressure, temperature, pH, and resistivity as well as changes in bulk fluid density and volume within the reservoir. Microseismic monitors may be used to monitor potential movement of caprock due to CO_2 injection. Monitoring of CO_2 via natural stable isotopes and/or other tracers will be evaluated. Risk mitigation will be accomplished via the elements of a site-specific health and safety plan generated in partnership with Amerada Hess Corporation and in conjunction with all appropriate regulatory agencies. Current production wells in units both overlying and underlying the Duperow will allow for fluid sampling to evaluate potential CO_2 migration into those units.

The results from Beaver Lodge will be compared to those generated by research activities at other carbonate reservoirs in the region, including the Zama test and the International Energy Agency (IEA) project at Weyburn. Results will provide insight regarding the nature and magnitude of technical challenges associated with CO_2 injection under the pressure (4900 psi) and temperature (250°F) conditions found at depths greater than 10,000 ft. Sampling protocols developed for this activity will be applicable to other high-pressure/ temperature reservoir environments.

This demonstration will 1) test the accuracy with which CO_2 storage capacity can be predicted; 2) demonstrate monitoring, mitigation, and verification (MMV) technologies and protocols; and 3) provide field validation testing of sequestration technologies and infrastructure approaches that can lead to wide-scale deployment in the region. These topics are part of three performance targets of the Carbon Sequestration Technology Road Map.

Geological Sequestration Project 2 – Injection of CO_2/H_2S (acid gas) into Carbonate System at Zama, Alberta

The field validation test conducted in the Zama field of Alberta will evaluate the potential for geological sequestration of CO_2 as part of an acid gas stream that also includes high concentrations of H_2S. The acid gas will be injected for the concurrent purposes of CO_2 sequestration, H_2S disposal, and EOR. The results of the Zama activities will provide insight regarding the impact that high concentrations of H_2S (30% or greater) can have on sink integrity (i.e., seal degradation); MMV; and EOR success within a carbonate reservoir. Apache Canada Ltd. owns and operates the portion of the Zama oil field that will be available for these activities as well as the Zama gas-processing plant that will supply the acid gas.

The acid gas will be injected into a pinnacle reef. Pinnacle reefs at Zama are steep-sided, moundlike carbonate structures in the Keg River Formation, having an average size of 40 acres at the base and 400 ft in height. The depth from surface to the pinnacles is typically 4900 ft. The reefs are typically dolomitized, with variable porosity (average 10%) and permeability. The pinnacle reefs are encased laterally and vertically by impermeable anhydrites and underlain by a saline aquifer. The stratigraphic and structural isolation of the pinnacles, their

adequate porosity and permeability, and the close proximity to an anthropogenic source make them suitable candidates for conducting a CO_2 sequestration technology validation test. Beyond Alberta, similar pinnacles are known to occur in the Saskatchewan and North Dakota portions of the Williston Basin as well as in the Michigan Basin.

The results from Zama will be compared to those generated at Beaver Lodge and Weyburn to examine the impact that high concentrations of H_2S may have on geologic MMV technologies and protocols. The Zama activities will also provide additional data on the accuracy with which CO_2 storage capacity can be predicted and provide field validation testing of geologic sequestration technologies and infrastructure approaches under acid gas conditions.

Apache Canada Ltd. has rigorously evaluated the properties of the selected pinnacle reef, including robust reservoir-modeling activities. Technology evaluation activities will include additional reservoir simulation modeling based on data collected over the course of the injection operations. The permits needed for this project will be obtained by Apache Canada in accordance with all local, provincial, and federal regulations. Construction requirements will be minimal, as CO_2 injection wells and the infrastructure and facilities necessary to transport the CO_2 are currently in place. With respect to injection operations, it is anticipated that acid gas will be injected into the pinnacle using one injection well at a rate of 100 tons of acid gas per day. Injection will occur over 2 years of the project. Monitoring and verification equipment will be installed and operations conducted to monitor pressure, temperature, pH, resistivity, changes in bulk fluid density, and volume within the reservoir. Microseismic monitors may be used to monitor potential movement of caprock. The potential for indirect monitoring of CO_2 via natural stable isotopes and/or other tracers will be evaluated. Risk mitigation will be accomplished via the elements of a site-specific health and safety plan generated in partnership with Apache Canada Ltd. and in conjunction with all appropriate regulatory agencies.

Significant differences exist between the proposed Zama project and other regional CO_2 sequestration projects. Through acid gas injection, significant volumes of CO_2 can be readily sequestered while providing operators an added economic benefit/incentive by eliminating the need to strip H_2S from the gas stream and through EOR. The stratigraphically isolated nature of the pinnacle reef provides a highly controlled in situ laboratory setting that will be invaluable for work to determine long-term fate and mass balance of geologically sequestered CO_2. Sampling protocols will be developed for acid gas reservoir environments.

Geological Sequestration Project 3 – Injection of CO_2 into Lignite Coal Seam in the Williston Basin.

The effectiveness of lignite seams to act as sinks for CO_2 during simultaneous CO_2 sequestration and enhances coalbed methane recovery (ECBM) production will be evaluated in the Williston Basin. CO_2 from an undetermined source will be injected into the Harmon coal seam to examine whether long-term contact with CO_2 affects the physical stability and gas storage capacity properties of lignite. At 50 ft, the Harmon seam is the thickest known lignite in the Williston Basin. Preliminary estimates of the potential coalbed methane reserves and effective CO_2 storage capacity of the Harmon coal seam have been tabulated under PCOR Partnership Phase I. The total coalbed methane gas in place for the Harmon coal seam has been calculated to be as high as 4.4 tcf. The effective CO_2 storage capacity of the Harmon coal seam is estimated at

5.6 tcf (328 million tons). Together, these calculations support the conclusion that the Harmon coal seam is desirable for further evaluation.

The goal of the demonstration will be to determine whether long-term contact with CO_2 affects the physical stability and gas storage capacity properties of lignite and the hydrodynamic properties of the seam. In addition, the practicality and economics of using CO_2 to enhance natural gas recovery from lignite seams will be evaluated. Construction requirements include the drilling of injection, production, and observation wells into the coal seam. The necessary permits will be obtained by the appropriate local, state, and federal agencies. The target zone is typically less than 600 ft deep, which means that drilling can be accomplished with a water well drilling rig. CO_2 will be brought to the site via truck. Monitoring and verification equipment will be installed and operations conducted to monitor pressure, temperature, pH, and resistivity as well as changes in bulk fluid density and volume within the reservoir. Risk mitigation will be accomplished via the elements of a site-specific health and safety plan generated in partnership with Encore Acquisition Company and in conjunction with all appropriate regulatory agencies.

Encore Acquisition Company has expressed an interest to work with the PCOR Partnership to install, operate, and maintain the injection, production, and observation wells that will be utilized. Complementary research activities funded by the National Association of State Energy Offices (NASEO) will be conducted at the Energy & Environmental Research Center (EERC) from 2005 to 2007. These activities will generate permeability and sorption isotherm data to determine how CO_2 injection may enhance CH_4 recovery from a lignite reservoir. The NASEO project will experimentally quantify the permeability and the CO_2 and CH_4 sorption characteristics of the Harmon coal seam, which will result in more scientifically robust estimates of the seam's CO_2 storage capacity. The permeability and isotherm data will facilitate planned reservoir modeling in predicting the long-term fate of the injected CO_2. The field-based activities proposed herein will verify and validate these laboratory results. Specifically, these activities will determine the impact that CO_2 injection has on the properties of the target coal seam with respect to both CO_2 sequestration and ECBM production. The laboratory and field-based findings will result in development of refined sampling protocols for the determination of lignite coal sequestration capacity. While there are currently no wells or infrastructure in place to facilitate CO_2 sequestration into the Harmon coal seam and there is a lack of modeling information with respect to lignite reservoirs in general, the complementary NASEO and PCOR Partnership activities will function as a means of closing the data gap and possibly spurring commercial interest in developing the infrastructure necessary for a future large-scale demonstration.

The results of the three geologic field trials will facilitate potential monetization of geologic carbon sequestration credits, which will increase the likelihood of near-term implementation of these types of geologic storage operations. The establishment of a robust carbon-trading market for geologic credits is critical to the implementation of carbon sequestration technologies on the scales and time frames that are necessary for a significant impact on regional CO_2 emissions.

Terrestrial Sequestration Action Plan

There is one terrestrial project, T1, recommended as a field verification test in Phase II. This recommendation reflects the tremendous potential for carbon sequestration in the wetlands of the PCOR Partnership region.

To measure, monitor, and verify greenhouse gas (GHG) offsets derived from restored wetlands, we will conduct an intensive field investigation of farmed (baselines), restored, and native wetlands (maximum potential). Fluxes of CO_2, nitrous oxide (N_2O), and methane (CH_4), and associated characteristics critical to understanding the sequestration process, will be measured biweekly during the ice-free months. To account for climatic factors that influence net gas emissions, each wetland will be equipped with a weather station, temperature data loggers (near each chamber), and rain gauges to provide hourly or biweekly measurements of climatic data. To account for variation in soil properties that influence net sequestration, soil will be collected along transects each season for determination of physical and chemical attributes using standard methods.

Ultimately, these data will be analyzed to compare GHG emissions among wetland land use categories. Information on soil organic carbon sequestration and gas emissions will be used to estimate global warming reduction potential of restored wetlands relative to baseline conditions (i.e., farmed wetlands).

Protocols will be developed that will allow for the sale of wetland terrestrial CO_2 offsets to industry. The information needed to develop the wetland CO_2 offsets will include 1) the development of criteria for a legal document to transfer carbon to the investor; 2) the development of an education, marketing, and outreach strategy for promoting terrestrial carbon sequestration and subsequent sale of offsets; 3) the development of criteria for a private carbon/conservation easement legal document including a site management plan that allows aggregation of carbon offsets; and 4) the conduct of a carbon sequestration cost feasibility study. A landowner solicitation strategy will be developed to determine the economic incentive required for an aggregation program enrollment for various geographic/political regions.

Risk Assessment Action Plan

The PCOR Partnership will develop and implement action plans that satisfy local, state, and federal permitting requirements for demonstration projects conducted in the region. The necessary National Environmental Policy Act (NEPA) activities will be completed as required as will any others necessitated by local, state, and federal regulations. The appropriate data will be identified, acquired, and compiled into a format that will be useful to regulatory agencies, permitting authorities, and other carbon sequestration stakeholders. The PCOR Partnership will also provide regulatory guidelines for the projects implemented in the region. Knowledge gained and resources collected throughout Phase II will be compiled and synthesized into a best management practices document for future sequestration projects.

Of particular importance for geologic sequestration is the development and application of CO_2 leakage monitoring techniques. Numerous well-established procedures and monitoring technologies currently in use by industry are applicable to CO_2 sequestration. However, at this time, a standard procedure for monitoring the effectiveness and safety of CO_2 capture and geologic storage does not exist. Table F-1 summarizes some of the current monitoring methods that are applicable to geologic sequestration and that will be evaluated for specific utilization during demonstration activities in the PCOR Partnership region. MMV technologies will provide the information needed to ensure that sequestration can be monitored in a cost-effective manner over extended periods of time.

It is anticipated that MMV will be required for future CO_2 sequestration and long-term

Table F-1. Monitoring Methods Applicable to Geologic CO_2 Sequestration

Parameter	Monitoring Approaches/Technology
CO_2 Plume Location	• 2- and 3-D time-lapse seismic reflection surveys • Vertical seismic profiling (VSP) • Electrical and electromagnetic surveys • Gravimetric surveys • Reservoir pressure monitoring • Wellhead and formation fluid sampling • Natural and introduced tracers • Geochemical changes identified in observation or production wells
Early Warning of Storage Reservoir Failure	• Injection well and reservoir pressure monitoring • Pressure and geochemical monitoring in overlying formations • Microseismicity or passive seismic monitoring
CO_2 Concentrations and Flux at Ground Surface	• Real-time infrared-based detectors • Air sampling and analysis • Eddy flux towers • Monitoring for natural and introduced tracers • Hyperspectral imagery to detect changes in vegetation
Groundwater Quality	• Groundwater sampling and geochemical analysis from drinking water or monitoring wells • Natural and introduced tracers
Ecosystem Impacts	• Soil gas surveys • Soil sampling • Direct observation of biota • Hyperspectral imagery to detect changes in vegetation

storage in geologic formations to ensure public safety and protection of underground sources of drinking water and that MMV will also be a necessary component of a robust GHG emission-trading platform and/or framework.

Action Plan to Perform Public Outreach and Education

Public education and outreach consists of two parts:

- Continuing to educate the public about terrestrial and geologic sequestration in general.

- Education and outreach in support of specific validation test activities.

General education on outreach will feature a multifaceted approach to public outreach and education that is being designed to ensure that the community is well informed about CO_2 sequestration and clearly understands its potential within the region. The public will be engaged at each step of the Phase II effort through mechanisms that raise the public awareness regarding sequestration opportunities in the region.

Highlights of the plan include:

1) Expansion of the outreach toolkit developed during Phase I. This will include an outreach booth, a fact sheet on Phase II activities and a fact sheet on each of the

demonstration projects, a slide show presentation, and four 30-minute videos produced by Prairie Public Television that describe in detail geologic sequestration, terrestrial sequestration, sequestration markets, and the National Energy Technology Laboratory (NETL) Regional Carbon Sequestration Partnership.

2) Accessing the expertise of communications and marketing professionals in the utility, oil and gas, and nongovernmental organizations (NGOs) in the region to assist with the development and delivery of an outreach plan.

3) Expansion of the Phase I general outreach activities, including updating and expanding the public PCOR Partnership Web site and general outreach to decision makers in which PCOR Partnership management and technical staff will utilize the outreach toolkit described previously.

4) Public outreach during the project-permitting process for each demonstration, which will be focused locally. This will take the form of providing outreach materials to the site contractor, including fact sheets, DVDs of television productions, booth materials, and PowerPoint presentations, for use in public meetings and to make available as appropriate to libraries and schools. The outreach group would also work with the contractor to develop community or school presentations regarding the project.

5) Development of a plan for public outreach and education, based on the materials and lessons learned, in support of future full-scale deployment of geologic and terrestrial sequestration projects in the region.