Plains CO_2 Reduction (PCOR) Partnership

Practical, Environmentally Sound CO_2 Sequestration

Energy & Environmental Research Center®
Putting Research into Practice

ATLAS

3rd Edition

PCOR Partnership Atlas

3rd Edition, 2009

Wesley D. Peck, Katherine K. Anagnost, Barry W. Botnen, Lisa S. Botnen, Daniel J. Daly, Charles D. Gorecki, Megan M. Grove, John A. Harju, Melanie D. Jensen, Michael L. Jones, Steven A. Smith, James A. Sorensen, Edward N. Steadman, Stephanie L. Wolfe

Energy & Environmental Research Center
Grand Forks, North Dakota

Andrea T. McNemar, John T. Litynski, Sean I. Plasynski
U.S. Department of Energy

Prepared for the

U.S. Department of Energy
National Energy Technology Laboratory
and the PCOR Partnership

Published by the

Energy & Environmental Research Center
2009

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 storing CO_2 emissions from stationary sources in the central interior of North America. The PCOR Partnership is managed by the Energy & Environmental Research Center 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.

Notice

Printed in the United States of America and
Available from:

Energy & Environmental Research Center
Grand Forks, ND 58203

Acknowledgments

This atlas was made possible through the contributions and efforts of numerous groups from throughout the United States and Canada. We gratefully acknowledge the individuals who provided the backbone information upon which this atlas is based, specifically, Stefan Bachu, Dean Bangsund, Chip Euliss, Jim Evans, Robert Gleason, Matt Grobe, Alf Hartling, Lynn Helms, W.A. Jackson, Dick Kempka, Larry Leistritz, Claudia Miller, David Moffatt, Ed Murphy, Harvey Ness, Ron Ness, Erik Nickel, Myria Perry, Randy Renner, Bill Reynen, David Ryan, and Anne-Marie Thompson. We also acknowledge the PCOR Partnership partners for their valuable efforts in providing much of the information used for these assessments and for cooperating with us in producing a regional portfolio for public use. We extend our appreciation to the various federal, state, and private organizations and university groups for their cooperation in our search for data.

A number of individuals at the Energy & Environmental Research Center provided valuable support for this effort. We are grateful to Earl Battle and Paul Gronhovd for their work in producing many of the graphics used in this document and to Joyce Riske for editing the atlas.

This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory under Award No. DE-FC26-05NT42592.

Table of Contents

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 a strong indication that we may have to significantly reduce anthropogenic greenhouse gas (GHG) emissions. Carbon storage offers a promising set of technologies through which carbon dioxide (CO_2) and potentially other GHGs can be 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 storage 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 the initial effort of the PCOR Partnership confirmed that while there are numerous large stationary CO_2 sources, the region also has a variety of sinks that represent a tremendous capacity for CO_2 storage. The varying sources 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 rich in agricultural lands, forests, and wetlands that hold tremendous potential for terrestrial storage. The Prairie Pothole Region (PPR), which 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 lie geologic formations that hold tremendous potential to store CO_2. Oil fields well suited for storing CO_2 can be found in the western half of 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 the PCOR Partnership region of central North America.

Rise of Fossil Fuel Usage

Modern Refinery, Billings, Montana, 2004

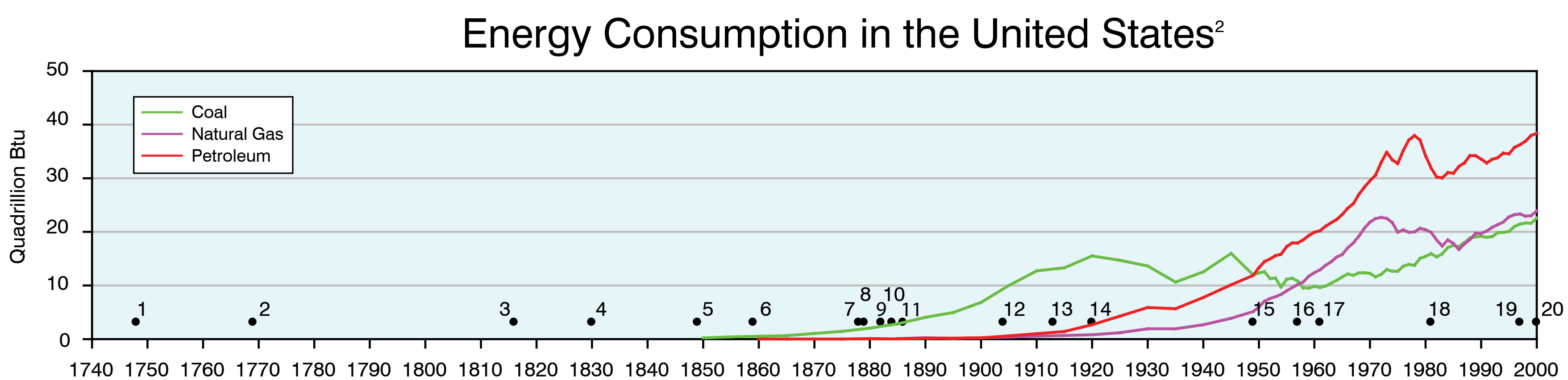
"Barnyard Lignite," North Dakota, 1940

Indiana Steel, ca. 1910

Signal Hill, California, ca. 1923

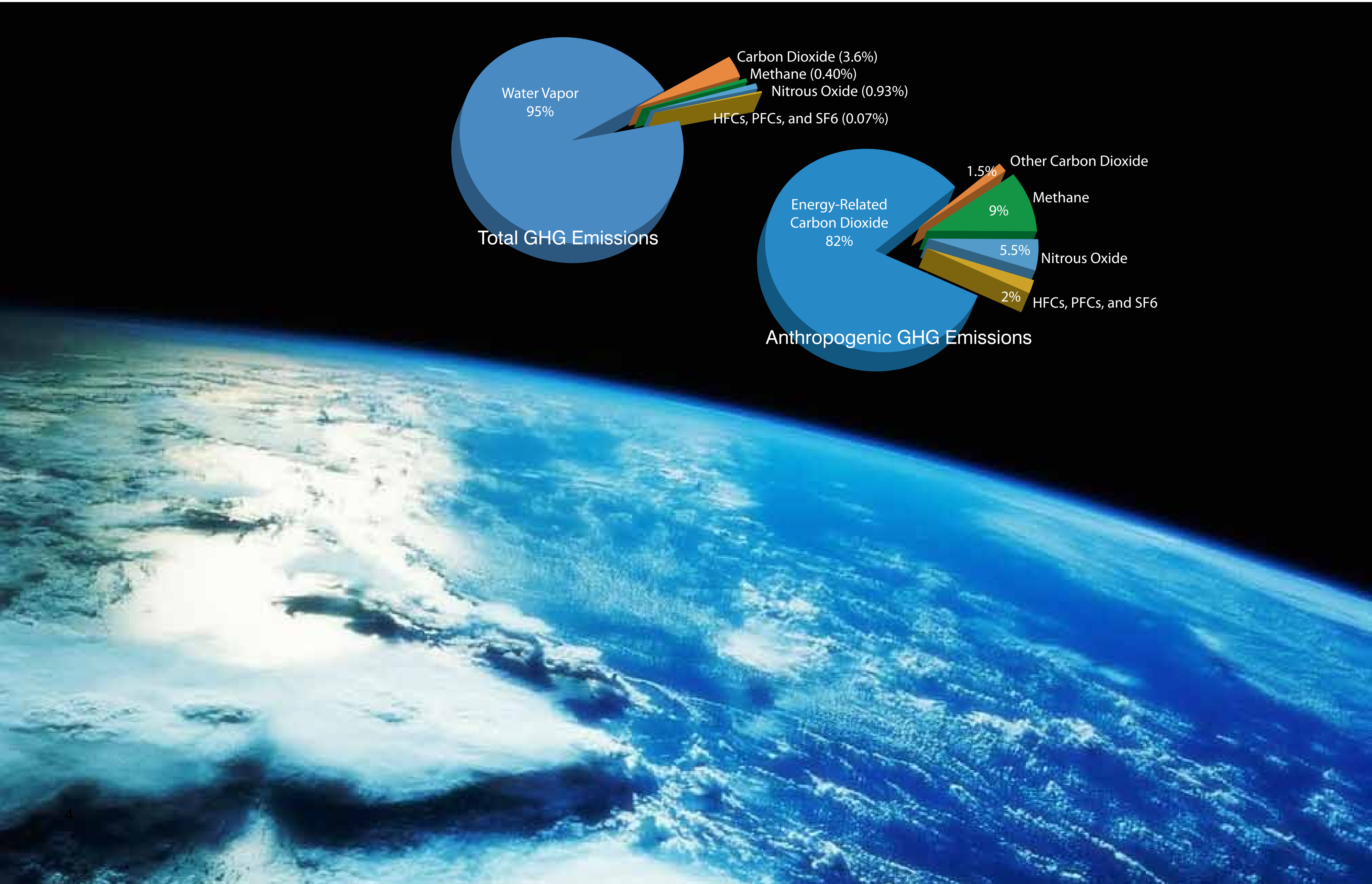
A Change Is in the Air

Just 200 years ago, before the onset of the Industrial Revolution, we had modest needs for energy, and most of the energy we used came from what we now know as renewable sources. We used horses for transportation, burned animal dung and wood for heat, and used vegetable or animal oils in lamps for light. Water supplied much of the needed power for grinding grain and for the limited manufacturing of the time. 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. Energy-rich fossil fuels, including coal, oil, and natural gas, worked well for these needs. 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 149.2 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]

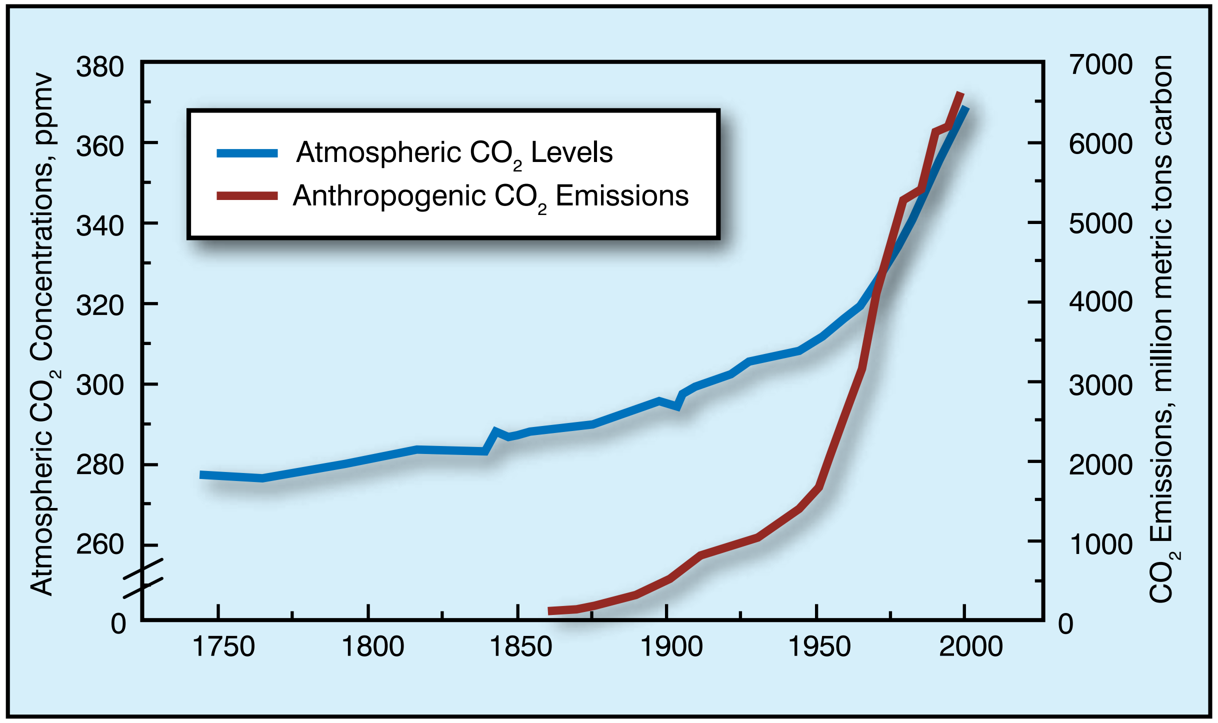
Greenhouse Gases



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 GHGs increases.[10]

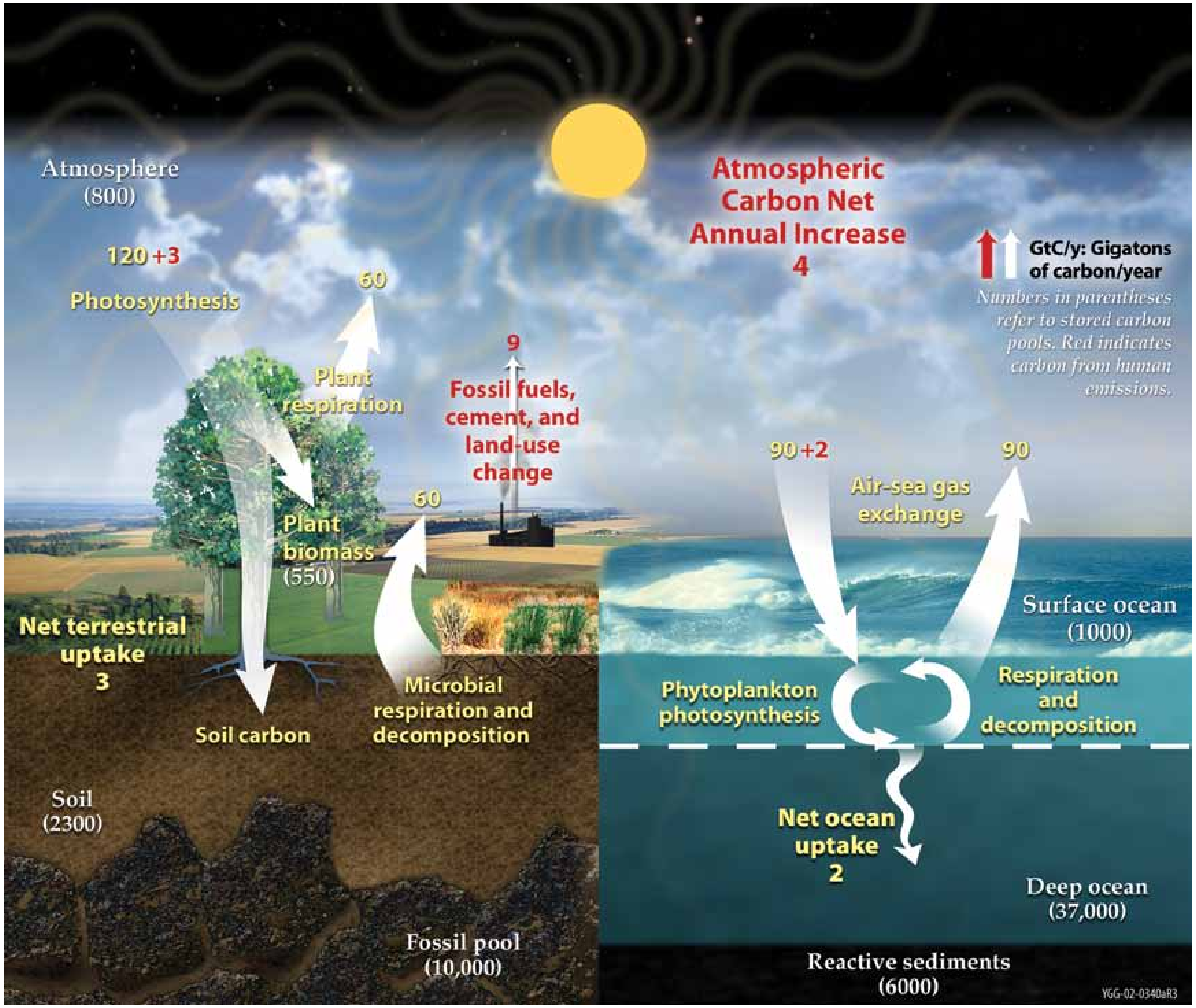


Since the beginning of large-scale industrialization about 150 years ago, the level of CO_2 in the atmosphere has increased by about 30%.

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 GHGs 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 GHGs entering the atmosphere are causing increased warming and that this warming will affect climate on a global scale.

Global Carbon Cycle



Carbon is continuously circulated between reservoirs in the ocean, land, and atmosphere. In the atmosphere, carbon 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 37,000 Gt C, compared to around 2300 Gt C on land, 800 Gt C in the atmosphere, and 1000 Gt C 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.

What Is CO_2?

Carbon dioxide is a colorless, naturally occurring gas composed of one atom of carbon and two atoms of oxygen. At temperatures below −78°C (−108°F), CO_2 condenses into a white solid called dry ice. When warmed, dry ice vaporizes directly from a solid to CO_2 gas in a process called sublimation. With enough added pressure, liquid carbon dioxide can be formed.

We use CO_2 to make the bubbles in soft drinks, and CO_2 (as dry ice) is used to keep things cold. Carbon dioxide is also used in fire extinguishers (CO_2 displaces the oxygen the fire needs to burn).

Presently, the Earth's atmosphere is composed of about 0.04% CO_2. This small amount plays an important role in maintaining the natural greenhouse effect that makes Earth hospitable to life. Carbon dioxide is essential to plant life and is a key part of the global carbon cycle. An important component of this cycle takes place when plants take in CO_2 and break it down into carbon and oxygen through the process of photosynthesis. The carbon is stored in the plant, and the oxygen is released to the atmosphere. When the plant dies or it is burned, much of the carbon recombines with oxygen to form CO_2 again.

Carbon dioxide formed through human action is referred to as anthropogenic CO_2. Examples of activities that result in the production of anthropogenic CO_2 include plowing land, which exposes the carbon in the soil to the oxygen in the air; heating limestone to make lime for cement, which releases carbon in the limestone that combines with oxygen in the air; and burning fossil fuels for energy, which combines the carbon in the fuel with oxygen. This anthropogenic CO_2 adds additional carbon to the global carbon cycle.

Carbon-Conscious Energy Management

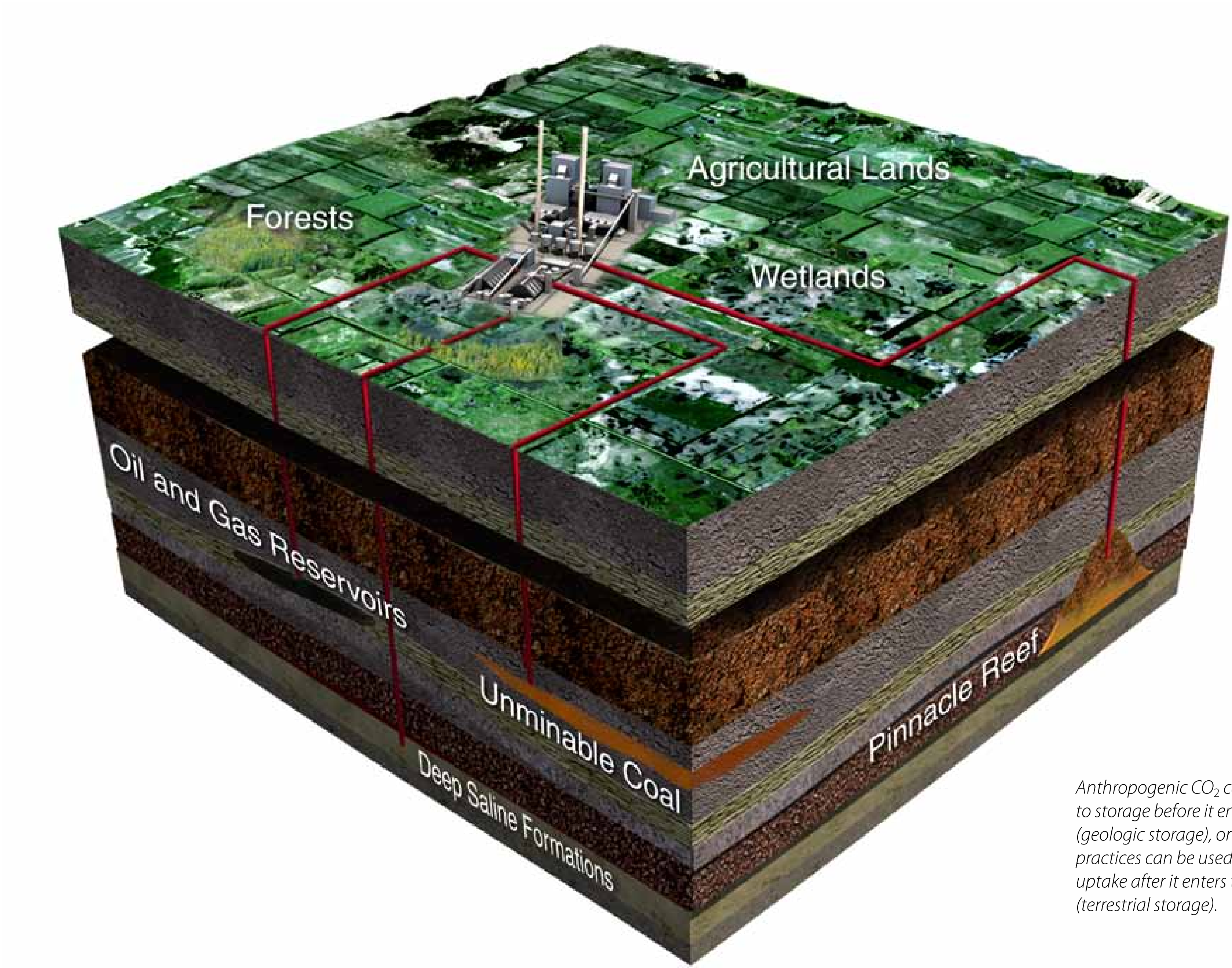
Carbon Management

To stabilize the levels of CO_2 in the environment, there needs to be a reduction in the amount of CO_2 that is released by human activity. Reducing anthropogenic CO_2 emissions with the goal of stabilizing the level of CO_2 in the atmosphere is called carbon management. Carbon management is a complex issue because most of the anthropogenic CO_2 comes from the use of fossil fuels for energy and maintaining our energy flow is critical to our economy and our quality of life. Carbon dioxide emissions can be reduced by energy conservation, the use of more efficient fossil fuel energy systems, increased use of renewable and nuclear energy, and carbon storage.

Carbon sequestration, also known as carbon capture and storage (CCS), is the capture and storage of CO_2 that would otherwise be emitted to the atmosphere and potentially contribute to global climate change. The captured CO_2 can be used; stored in underground reservoirs or, possibly, the deep ocean; absorbed by trees, grasses, soils, and algae; or converted to rocklike mineral carbonates or other products. Carbon storage holds the potential to substantially reduce GHG emissions.

There are two types of CO_2 storage: geologic and terrestrial. Geologic storage involves capturing CO_2 at a source before it can be emitted to the atmosphere. The most efficient concept would use specialized processes 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. Terrestrial storage removes CO_2 from the atmosphere and 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 terrestrial storage can be found in forests, grasslands, wetlands, and croplands.

Geologic and Terrestrial Storage



Anthropogenic CO_2 can be captured and sent to storage before it enters the atmosphere (geologic storage), or land management practices can be used to enhance carbon uptake after it enters the atmosphere (terrestrial storage).

Geologic Storage

Geologic storage involves the capture of anthropogenic CO_2 before it is released to the atmosphere and then injection into deep underground geologic formations. These formations, or CO_2 sinks, exist in a variety of configurations in sedimentary basins and include unminable coal beds, oil and gas reservoirs, and deep geologic layers that contain salty water (brine formations).

To be considered for storage, geologic sinks must have the characteristics that can hold the CO_2 in place for a long period of time (for example, a seal above a permeable zone of rock similar to the situation that would trap and store oil or natural gas), be isolated geologically from underground sources of drinking water, and be in a stable area (that is, an area not prone to earthquake activity). Successful geologic storage requires that the CO_2 stay in place and not pose a danger to human health and the environment.

Pure CO_2 has been stored as a gas in natural underground deposits for millions of years, and since the 1970s, oil field operators in West Texas have safely pumped millions of tons of CO_2 underground into oil-producing formations to increase production. This practice continues today and has spread to other oil-producing states and provinces like Colorado, Wyoming, Mississippi, Saskatchewan, Alberta, and British Columbia.

Under high-temperature and high-pressure conditions, such as those encountered in deep geologic formations (greater than 2600 feet), CO_2 will exist in a dense phase that is referred to as "supercritical." When injected into a geologic formation, a portion of the supercritical CO_2 may dissolve in any fluids, such as water or oil, that are present in the formation, while another portion may react with rock minerals. When CO_2 dissolves in oil, it acts as a solvent, reducing oil viscosity and increasing its mobility. The storage 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 an oil reservoir, supercritical CO_2 can increase oil production, which, in turn, can be used to help pay for the capture and transport of the CO_2 from the original source.

Terminology

As with many disciplines and technologies, a precise and descriptive vocabulary is needed to adequately describe and discuss the storage of CO_2 in geologic 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 higher than drinking water standards is commonly known as a saline aquifer or a 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 stored 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.

Carbon Storage

Terrestrial Storage

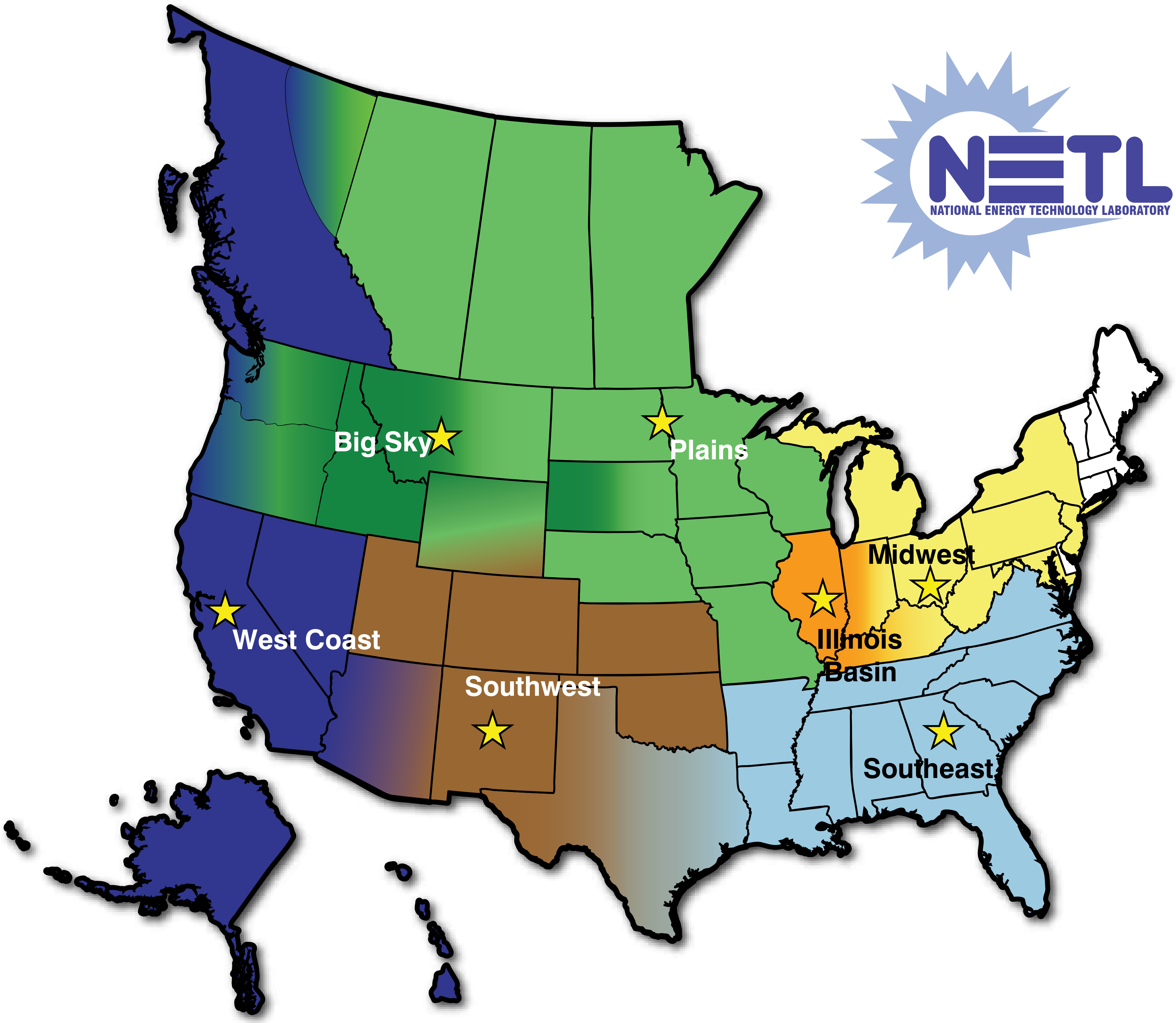
Terrestrial storage occurs at the Earth's surface through management practices that increase the amount of the carbon stored in roots and vegetable matter in the soil. It is important to remember that terrestrial storage only stores the carbon portion of the CO_2. If the soil is disturbed and the soil carbon comes in contact with oxygen in the air, the exposed soil carbon can combine with O_2 to form CO_2 gas and reenter the atmosphere, reducing the amount of carbon in storage.

Promising land and water management practices that lead to terrestrial storage of carbon include 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. Typically, land management practices that store carbon have other benefits to the ecosystem, including biodiversity, water filtration, increased soil health and fertility, and many others.

Soil can only take in and store a limited amount of carbon. On average, after a 50- to 100-year time frame, the soils will have reached equilibrium and not accept any more carbon. Once this "steady state" has been reached, the carbon will remain stored in the soil as long as the land is undisturbed and conservation land management practices are continued.

Terrestrial storage is important because it can be implemented immediately and can begin to reduce atmospheric CO_2 levels in the next few years. Using terrestrial storage now means we can get started on reducing CO_2 levels in the atmosphere while we adopt other carbon control measures.

Partnership Framework



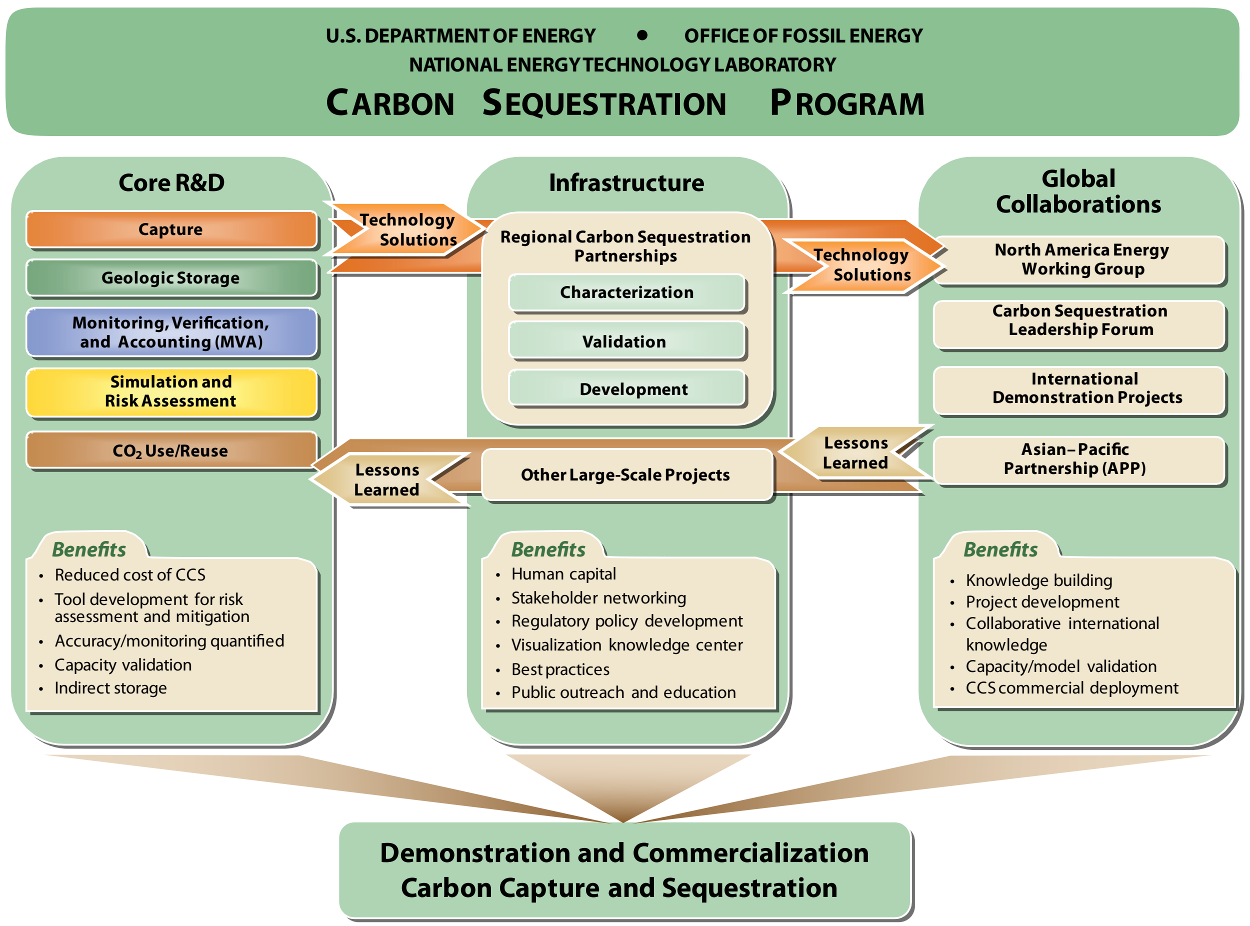
DOE's Regional Carbon Sequestration Partnerships

If the decision is made that carbon storage must be implemented in the United States on a broad scale and in a relatively short time frame (meaning over the next 10–20 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 economic framework and the necessary infrastructure to achieve meaningful carbon reductions.

To ensure that America was 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, transportation, and storage in different areas of the country. The Secretary called the partnership initiative "the centerpiece of our sequestration program." The partnerships were a key part of President Bush's Global Climate Change Initiative.

On August 16, 2003, following a competitive evaluation, Abraham named seven teams, called Regional Carbon Sequestration Partnerships, to evaluate and promote the carbon storage 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 2009, the partnerships had expanded to include over 350 organizations in 43 states, three American Indian nations, and four Canadian provinces.[12]

Today, the seven partnerships are developing the framework needed to validate and potentially deploy carbon storage technologies. They are evaluating numerous storage approaches that have emerged in the last few years to determine which are best-suited for specific regions of the country. They are also identifying possible regulations and the necessary infrastructure requirements should our society determine that storage be deployed on a wide scale in the future.



The PCOR Partnership Region

The 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 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 funded by DOE's Regional Carbon Sequestration Partnership Program and a broad array of project sponsors.

The PCOR Partnership



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

- Based on available data, the states and provinces within the PCOR Partnership region contributed roughly 13% of the total CO_2 emissions from stationary sources in the United States and Canada.[13]
- Enhanced oil recovery (EOR), depleted oil and gas zones, deep saline formations, and unminable coals in the PCOR Partnership region represent opportunities for geologic storage projects.
- The PCOR Partnership region is currently home to the Weyburn EOR demonstration project. There are four additional CO_2 storage field validation test sites in the PCOR Partnership region.
- Croplands, wetlands, rangelands, and forests in the PCOR Partnership region represent opportunities for terrestrial storage projects.
- The PCOR Partnership region is currently home to several terrestrial storage research projects involving wetlands, cultivated land, prairie, and forest.

PCOR Partnership 2003 – Present

- NETL
- EERC
- University of North Dakota
- ABENGOA BIOENERGY
- AIR PRODUCTS
- Alberta
- AERI Alberta Energy Research Institute
- ALBERTA RESEARCH COUNCIL
- ALLETE
- Ameren
- ACCCE American Coalition for Clean Coal Electricity
- American Lignite Energy
- Apache Canada Ltd.
- BAKER HUGHES
- BASIN ELECTRIC POWER COOPERATIVE
- BECHTEL
- Biorecro
- Blue Source
- BNI COAL
- British Columbia Ministry of Energy, Mines and Petroleum Resources
- Carbozyme Inc.
- CCX Chicago Climate Exchange
- CMG
- Dakota Gasification Company
- Ducks Unlimited Canada
- Ducks Unlimited
- Eagle Operating Inc.
- EICCD
- ENBRIDGE
- Encore Acquisition Company
- ERCB Energy Resources Conservation Board
- AGS Alberta Geological Survey
- Environment Canada
- EXCELSIOR ENERGY
- Fischer Oil and Gas, Inc.
- Great Northern
- GREAT RIVER ENERGY
- HESS
- HUNTSMAN
- Interstate Oil and Gas Compact Commission
- DNR
- Kiewit
- Lignite Energy Council
- Manitoba
- Manitoba Hydro
- MARATHON
- MEG Energy Corp
- Melzer Consulting
- Minnesota Pollution Control Agency
- minnesota power
- Minnkota Power Cooperative, Inc.
- MISSOURI DEPARTMENT OF NATURAL RESOURCES
- MISSOURI RIVER ENERGY SERVICES
- MONTANA-DAKOTA UTILITIES CO.
- Montana Department of Environmental Quality
- Public Service Commission Montana
- MUREX PETROLEUM CORPORATION
- National Commission on Energy Policy
- Natural Resources Canada
- Nebraska Public Power District
- Nexant
- NorthAmerican Coal Corporation
- North Dakota Department of Commerce
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Oil and Gas Division
- Industrial Commission of North Dakota Lignite Research, Development and Marketing Program
- Industrial Commission of North Dakota Oil and Gas Research Council
- Natural Resources Trust
- North Dakota Petroleum Council
- NDSU
- OTTER TAIL POWER COMPANY
- Oxand Risk Management Solutions
- ptrc Petroleum Technology Research Centre
- PTTC
- Prairie Public
- Pratt & Whitney
- RAMGEN POWER SYSTEMS
- RPS Energy
- Saskatchewan Industry and Resources
- SaskPower
- Schlumberger
- Shell Canada Limited
- Spectra Energy
- Strategic West Energy Ltd.
- SUNCOR ENERGY
- TAQA
- TESORO
- TGS
- UNIVERSITY OF ALBERTA
- UNIVERSITY OF REGINA
- USGS
- Weatherford
- ADVANCED GEOTECHNOLOGY
- WESTERN GOVERNORS' ASSOCIATION
- WESTMORELAND COAL COMPANY
- WILLISTON BASIN INTERSTATE PIPELINE COMPANY
- Wisconsin Department of Agriculture, Trade & Consumer Protection
- Xcel Energy

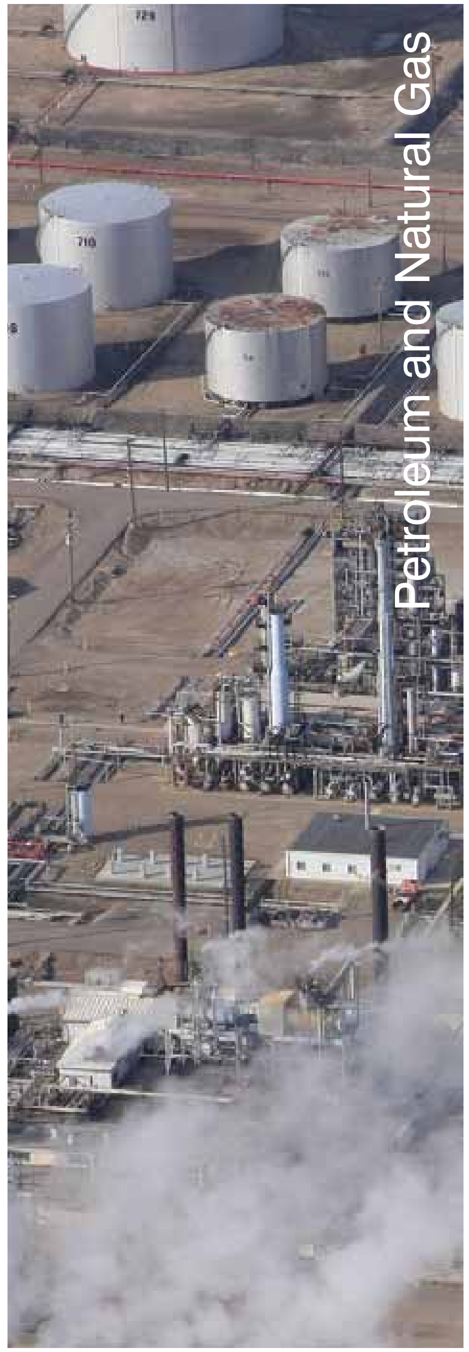
10/09

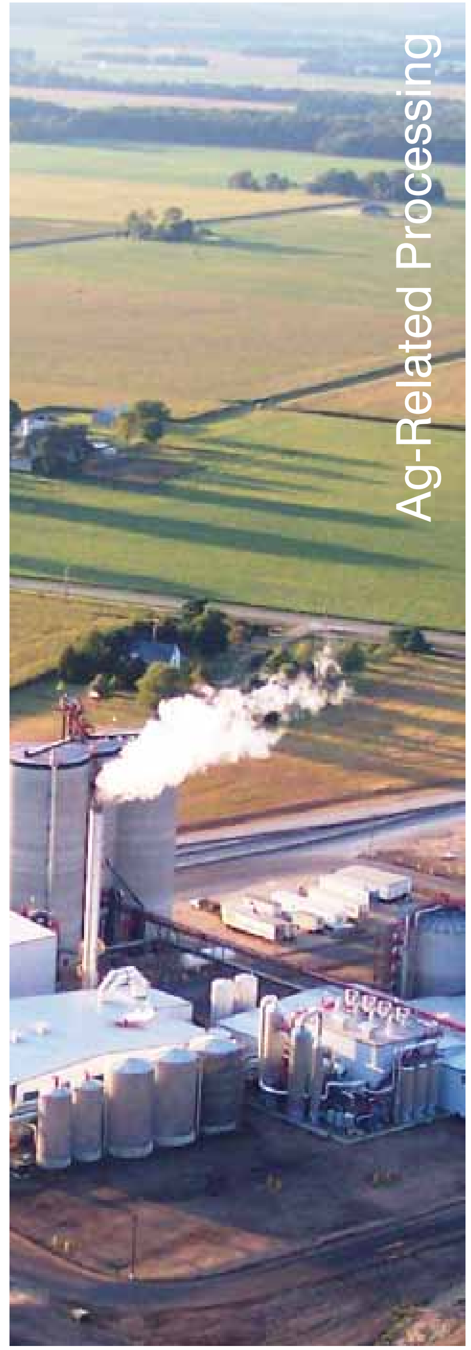
PCOR Partnership Partners

Since October 2003, the PCOR Partnership has brought together more than 90 public and private sector stakeholders 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 geologic and terrestrial storage, including value-added projects.

- U.S. Department of Energy National Energy Technology Laboratory
- University of North Dakota Energy & Environmental Research Center
- Abengoa Bioenergy New Technologies
- Air Products and Chemicals, Inc.
- Alberta Department of Energy
- Alberta Department of Environment
- Alberta Energy Research Institute
- Alberta Research Council
- ALLETE
- Ameren Corporation
- American Coalition for Clean Coal Electricity
- American Lignite Energy (ALE)
- Apache Canada Ltd.
- Baker Hughes Oilfield Operations, Inc.
- Basin Electric Power Cooperative
- Bechtel Corporation
- Biorecro AB
- Blue Source, LLC
- BNI Coal, Ltd.
- British Columbia Ministry of Energy, Mines and Petroleum Resources
- Carbozyme, Inc.
- Chicago Climate Exchange
- Computer Modelling Group, Inc.
- Dakota Gasification Company
- Ducks Unlimited Canada, Inc.
- Ducks Unlimited, Inc.
- Eagle Operating, Inc.
- Eastern Iowa Community College District
- Enbridge Inc.
- Encore Acquisition Company
- Energy Resources Conservation Board/ Alberta Geological Survey
- Environment Canada
- Excelsior Energy Inc.
- Fischer Oil and Gas, Inc.
- Great Northern Project Development, LP
- Great River Energy
- Hess Corporation
- Huntsman Corporation
- Interstate Oil and Gas Compact Commission
- Iowa Department of Natural Resources – Geological Survey
- Kiewit Mining Group Inc.
- Lignite Energy Council
- Manitoba Geological Survey
- Manitoba Hydro
- Marathon Oil Company
- MEG Energy Corporation
- Melzer Consulting
- Minnesota Pollution Control Agency
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Missouri Department of Natural Resources
- Missouri River Energy Services
- Montana–Dakota Utilities Co.
- Montana Department of Environmental Quality
- Montana Public Service Commission
- Murex Petroleum Corporation
- National Commission on Energy Policy
- Natural Resources Canada
- Nebraska Public Power District
- Nexant, Inc.
- North American Coal Corporation
- North Dakota Department of Commerce Division of Community Services
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Industrial Commission Department of Mineral Resources, Oil and Gas Division
- North Dakota Industrial Commission Lignite Research, Development and Marketing Program
- North Dakota Industrial Commission Oil and Gas Research Council
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- North Dakota State University
- Otter Tail Power Company
- Oxand Risk & Project Management Solutions
- Petroleum Technology Research Centre
- Petroleum Technology Transfer Council
- Prairie Public Broadcasting
- Pratt & Whitney Rocketdyne, Inc.
- Ramgen Power Systems, Inc.
- RPS Energy Canada Ltd. – APA Petroleum Engineering Inc.
- Saskatchewan Industry and Resources
- SaskPower
- Schlumberger
- Shell Canada Energy
- Spectra Energy
- Strategic West Energy Ltd.
- Suncor Energy Inc.
- TAQA NORTH, Ltd.
- Tesoro Refinery (Mandan)
- TGS Geological Products and Services
- University of Alberta
- University of Regina
- U.S. Geological Survey Northern Prairie Wildlife Research Center
- Weatherford Advanced Geotechnology
- Western Governors' Association
- Westmoreland Coal Company
- Williston Basin Interstate Pipeline Company
- Wisconsin Department of Agriculture, Trade and Consumer Protection
- Xcel Energy

Major Stationary CO_2 Sources





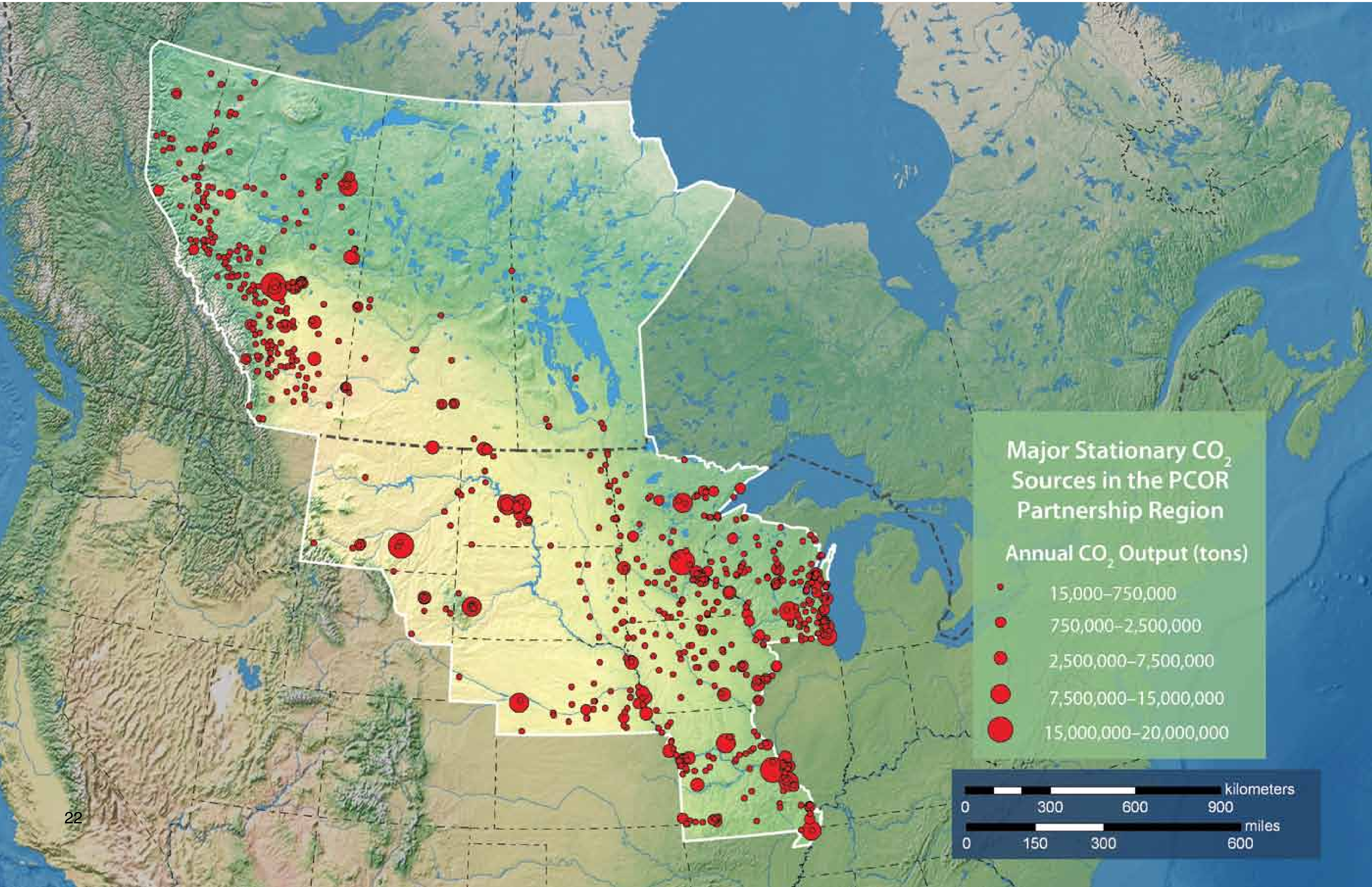
Anthropogenic CO_2 Sources

In 2007, the world produced approximately 32 billion tons of CO_2 from human activity (anthropogenic CO_2).[14] Anthropogenic CO_2 is contributed to the atmosphere primarily through the use of fossil fuels in transportation, electrical generation, heating and cooling, and industrial activities. Additional anthropogenic CO_2 is also generated through agriculture.

Together, the United States and Canada generate about a quarter of the world's anthropogenic CO_2. The United States produces about 6.5 billion tons (20%) of the global total, and Canada adds another 0.6 billion tons (2%).[14] About 40% of Canada's anthropogenic CO_2 and 9% of the anthropogenic CO_2 generated in the United States are generated in the PCOR Partnership region.

The PCOR Partnership is focused mainly on finding practical ways to manage CO_2 from major stationary sources related to electricity generation; energy exploration and production activities; agricultural processing; fuel, chemical, and ethanol production; and various manufacturing and industrial activities. Major stationary sources such as these account for about 58% of the anthropogenic CO_2 in the region, while mobile sources account for the remaining emissions (42%). The PCOR Partnership is also working to implement terrestrial storage options that can capture and store CO_2 from the atmosphere.

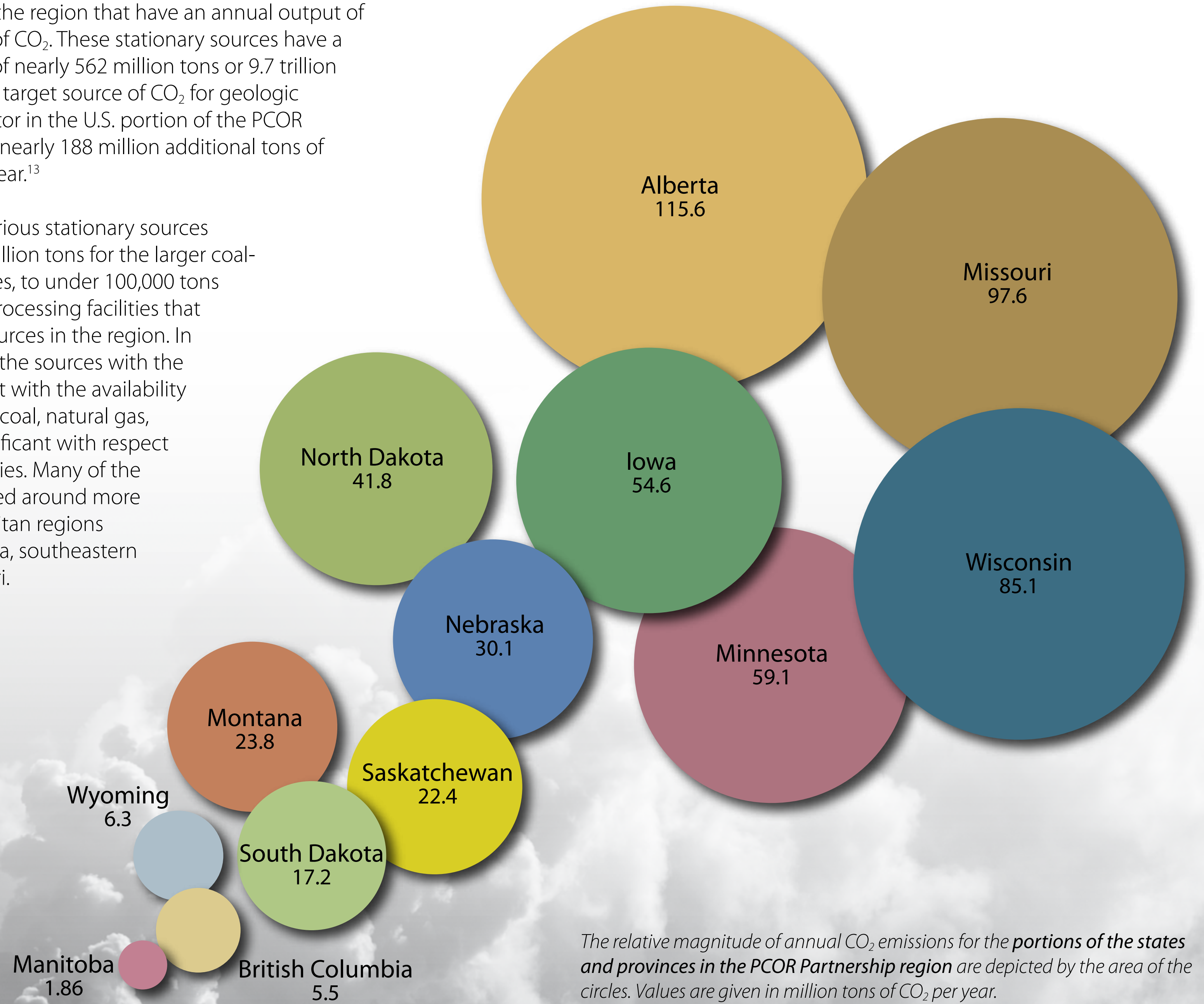
Distribution of Major Stationary CO_2 Sources



CO_2 Sources

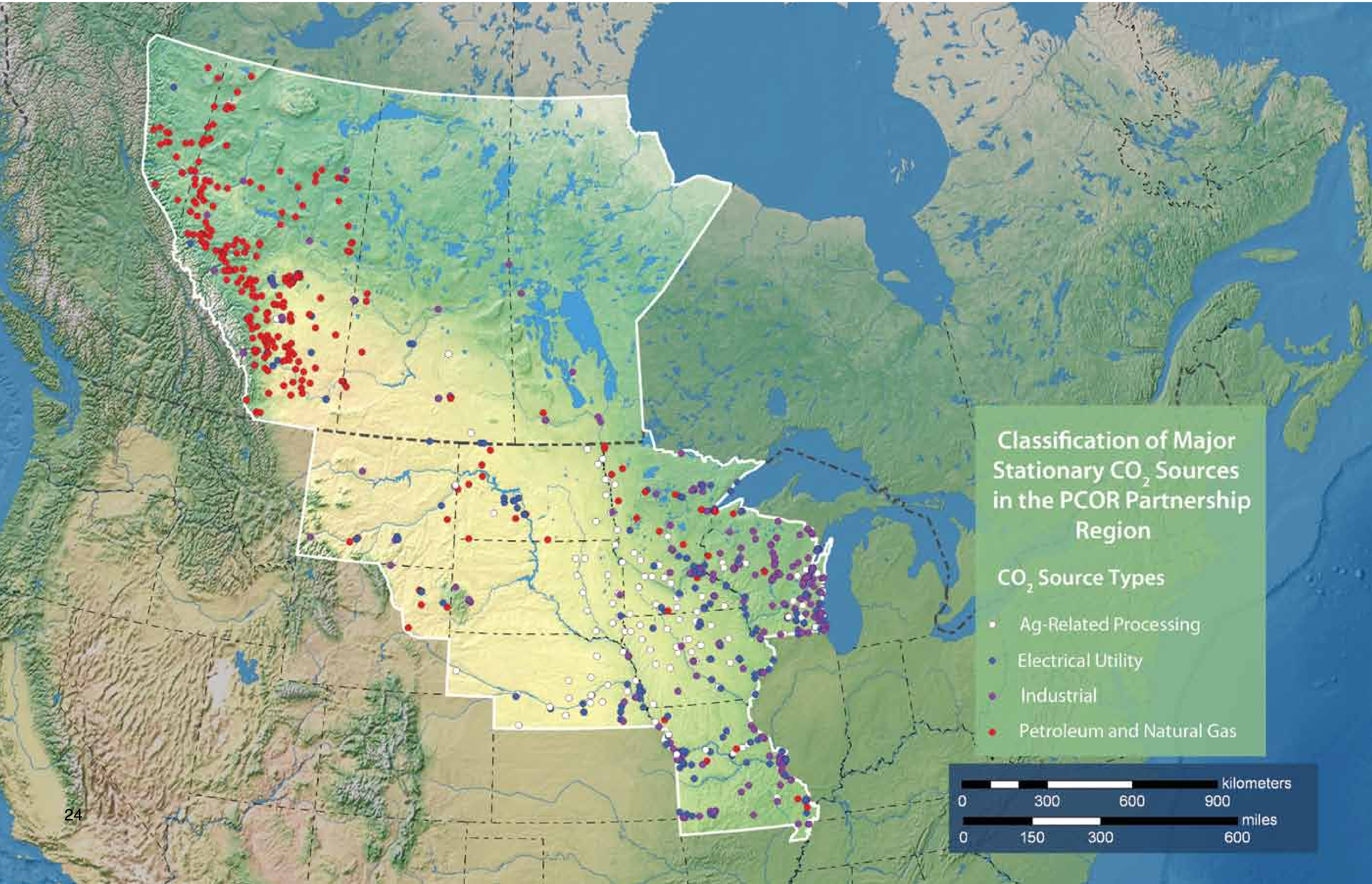
The PCOR Partnership project has identified, quantified, and categorized 927 stationary sources in the region that have an annual output of greater than 15,000 tons of CO_2. These stationary sources have a combined annual CO_2 output of nearly 562 million tons or 9.7 trillion cubic feet. And, although not a target source of CO_2 for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes nearly 188 million additional tons of CO_2 to the atmosphere every year.[13]

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 100,000 tons for industrial and agricultural processing facilities that make up the majority of the sources in the region. In some cases, 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 storage opportunities. Many of the smaller sources are concentrated around more heavily industrialized metropolitan regions such as southeastern Minnesota, southeastern Wisconsin, and eastern Missouri.



The relative magnitude of annual CO_2 emissions for the ***portions of the states and provinces in the PCOR Partnership region*** *are depicted by the area of the circles. Values are given in million tons of CO_2 per year.*

Classification of Major Stationary CO_2 Sources

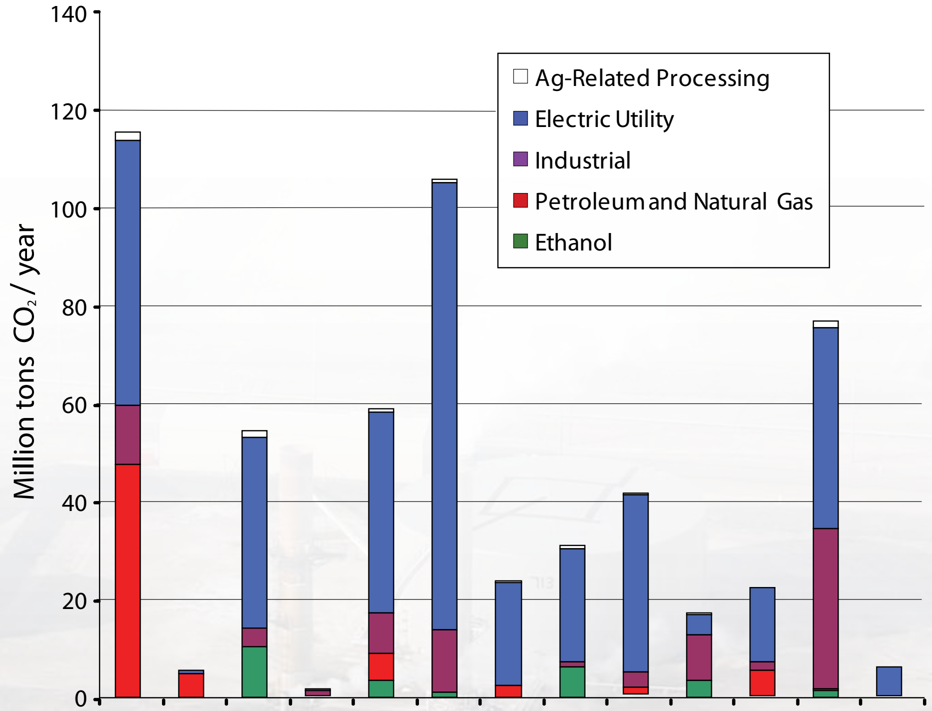


CO_2 Source Types

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

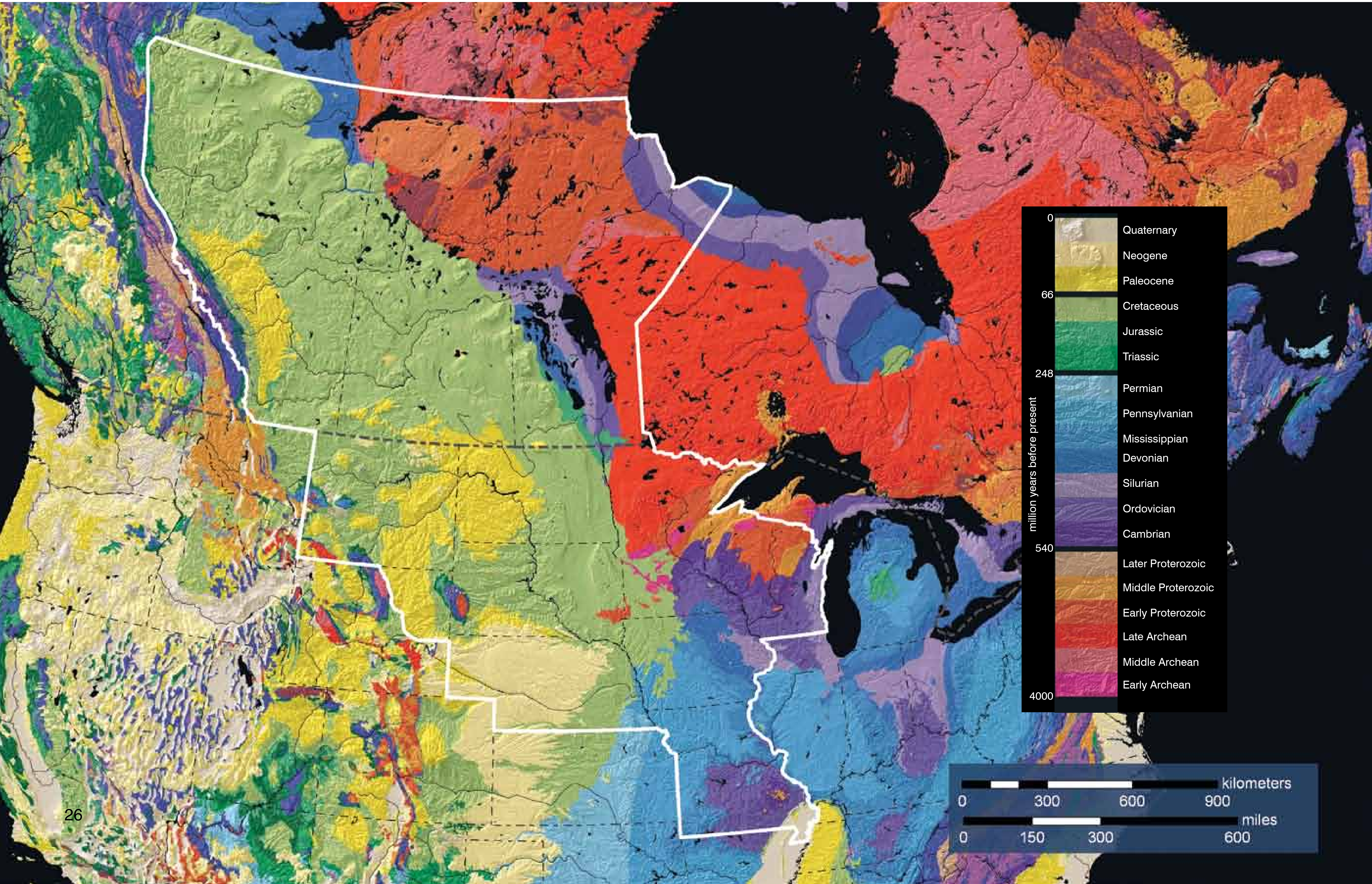
The emission profile (i.e., the percentage of CO_2 emissions from various source types) for the Canadian portion of the PCOR partnership is virtually identical to that of Canada as a whole. When compared to the total U.S. CO_2 emissions, the states in the PCOR Partnership region emit relatively more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

While the CO_2 emissions from the individual PCOR Partnership point sources are no different from similar sources located around North America, the wide range of source types within the PCOR Partnership region offers the opportunity to evaluate the capture, transport, and storage of CO_2 in many different scenarios.



Information depicted for portions of the states and provinces in the PCOR Partnership region.

Geologic Map of the PCOR Partnership Region



Geologic Framework

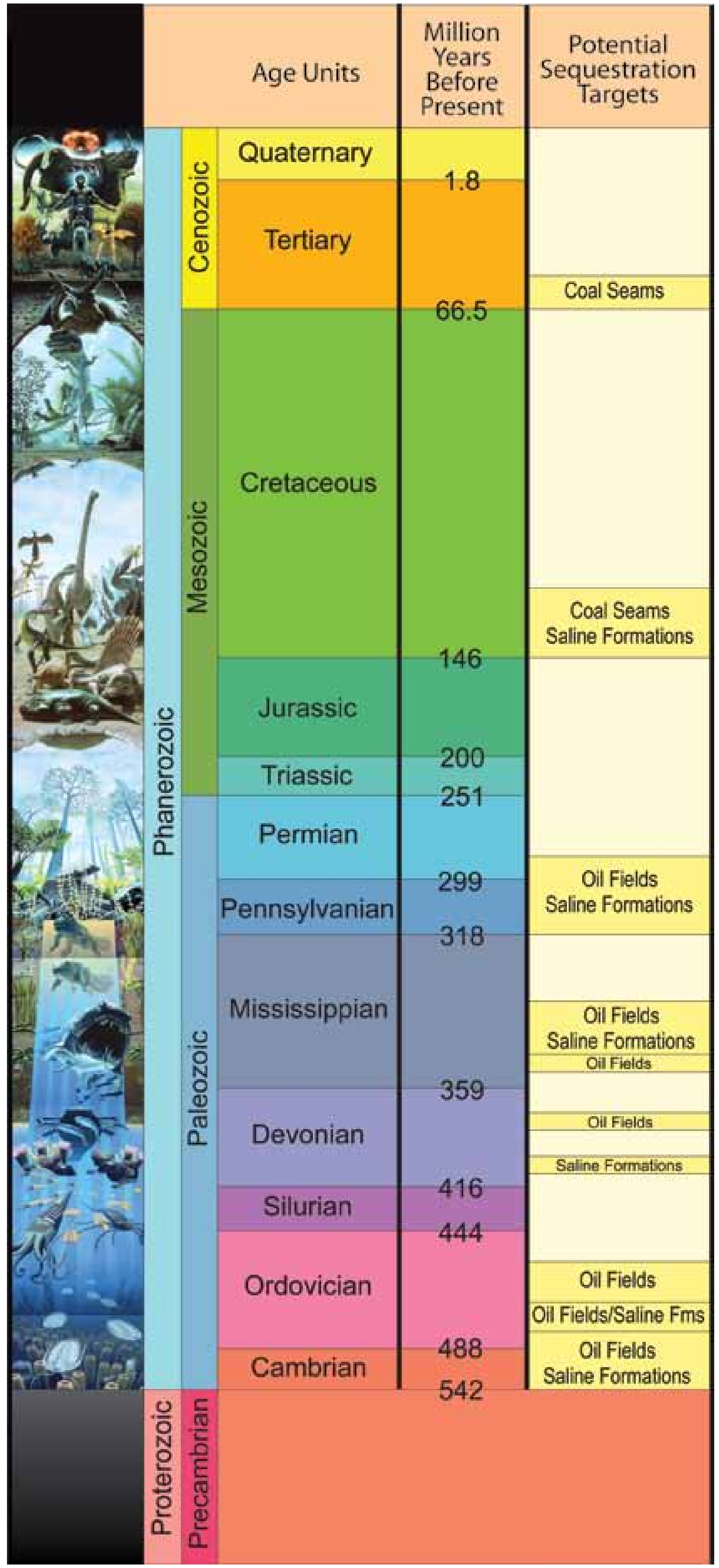
The same geologic framework that makes a large percentage of the PCOR Partnership region a significant producer of fossil fuels also creates prime opportunities for CO_2 storage. The western two-thirds of the region is underlain by great thicknesses of sedimentary rocks that span the entire stratigraphic 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 ancient sea extended from the Gulf of Mexico, across the center of North America, to the Arctic Ocean. The deeper portions of these strata and the underlying paleozoic-aged sediments offer tremendous capacity for storage.

Former extent of the Cretaceous-aged Western Interior Seaway.

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 coal and lignite reserves of Alberta, Wyoming, Montana, and North Dakota. The unminable portions of these deposits also provide opportunities for CO_2 storage.

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 CO_2 storage in deep geologic formations.



Major Depositional Basins

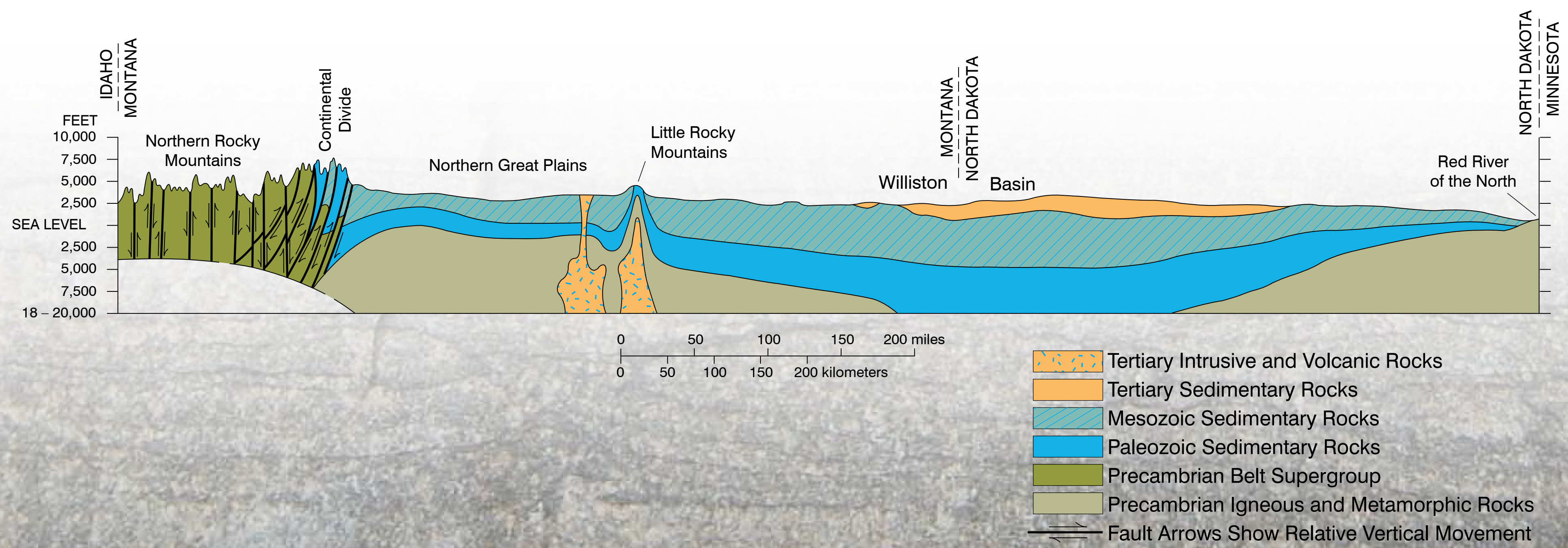
Sedimentary Basins

Several relatively large and deep basins are found in the PCOR Partnership region, each with a sedimentary cover thousands of feet thick. The basins in the PCOR Partnership region have significant potential as geologic sinks for storing CO_2. Geologic sinks that may be suitable for long-term storage 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 geologic 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 significantly more geologic investigation prior to large-scale storage.

Midcontinental Rift System

The PCOR Partnership region includes other areas besides the major petroleum-producing basins that are underlain by thick sequences of sedimentary rock. One of the largest and most notable of these areas is the Midcontinental Rift System, which stretches from eastern Nebraska across central Iowa and south-central Minnesota to the western portion of Lake Superior. The sedimentary rocks of the Midcontinental Rift System may be viable locations for CO_2 storage. Because oil and gas have never been discovered in the Midcontinental Rift System, very few deep wells have been drilled in the area; therefore, little is known about the characteristics of these rocks. Continued regional characterization activities being conducted by the PCOR Partnership will result in a better understanding of the potential for the sedimentary rocks of the Midcontinental Rift System to store large volumes of CO_2.



Distribution of Oil Fields

CO_2 Storage in Oil and Gas Fields

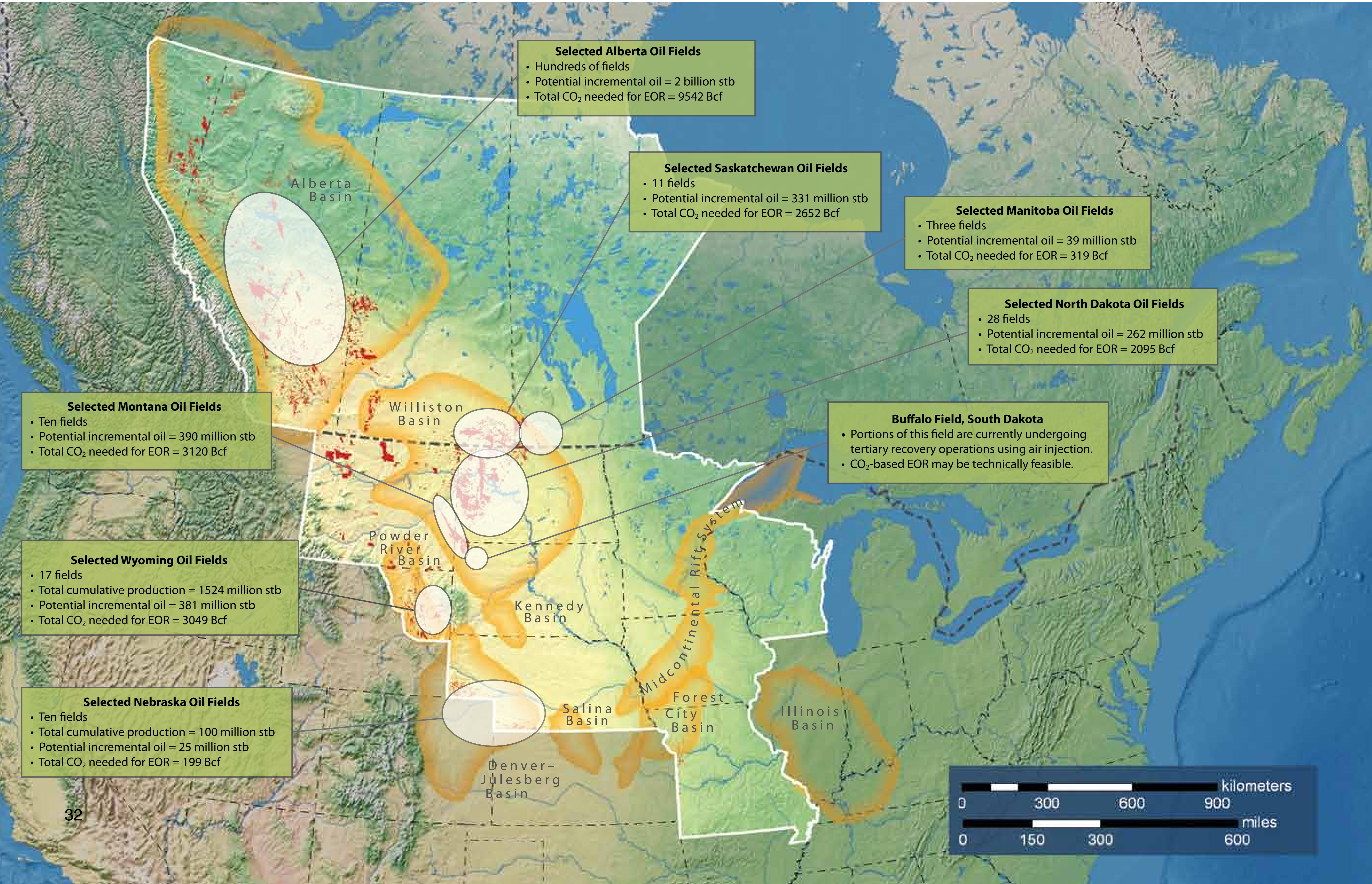
The geology of carbon dioxide storage is analogous to the geology of petroleum exploration: the search for oil is the search for stored hydrocarbons. Oil fields have many characteristics that make them excellent target locations to store CO_2. Therefore, the geologic conditions that are conducive to hydrocarbon storage are also the conditions that are conducive to CO_2 storage. The three requirements for storing hydrocarbons are a hydrocarbon source, a suitable reservoir, and an impermeable trap.

A single oil field can have multiple zones of accumulation that 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 stored 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 and up 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 nearly 70 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure storage of significant amounts of CO_2.

Enhanced Oil Recovery Potential



CO_2 Storage and Enhanced Oil Recovery

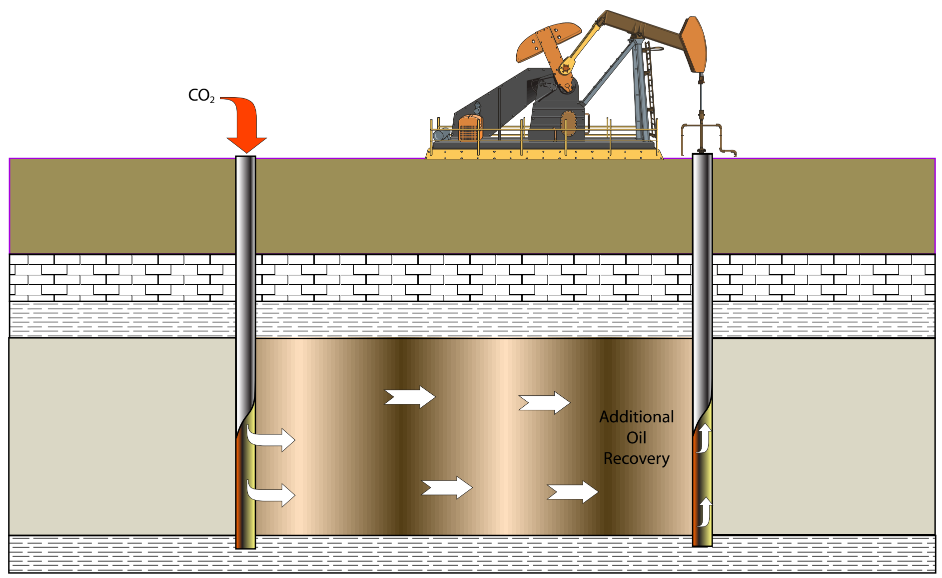
Most oil is extracted from the ground in three distinct phases: primary, secondary, and tertiary recovery. Natural pressures within the reservoir drive oil into the well during primary recovery, and pumps bring the oil to the surface. Primary recovery typically produces roughly 12%–15% of a reservoir's 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.[15]

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.[15] 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.

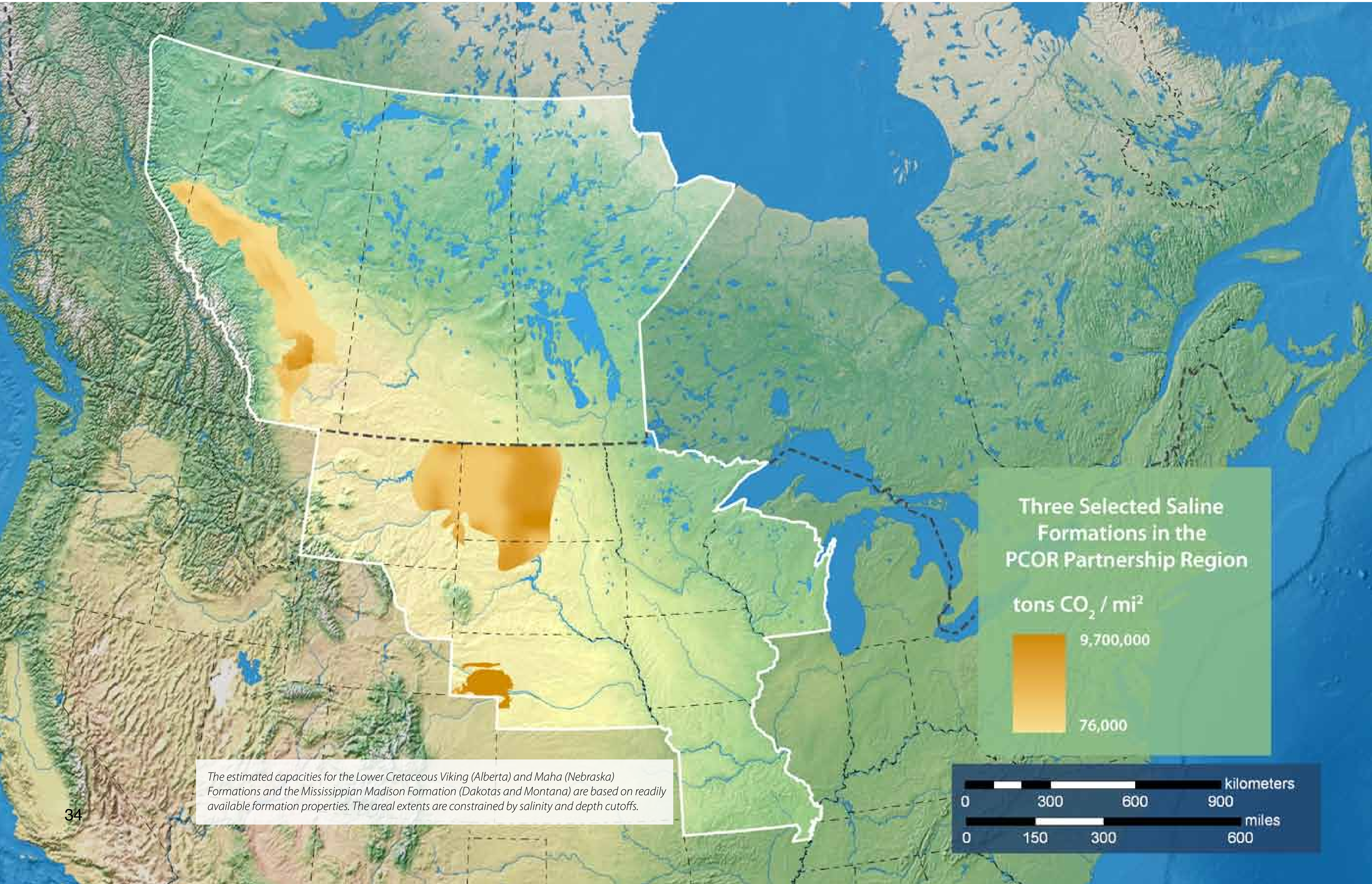
Reconnaissance-level CO_2 storage capacities were estimated for selected oil fields in the Williston, Powder River, Denver–Julesberg, and Alberta Basins. Two calculation methods were used, depending on the nature of the available reservoir characterization data for each field. The estimates were developed using reservoir characterization data 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 four basins indicate a storage capacity of over 3.5 billion tons of CO_2.

Aside from non-market-based incentives, CO_2 storage 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 storage that can provide a bridge to future non-EOR-based geologic storage. For example, a portion of the revenue generated by CO_2 EOR activities can pay for the infrastructure necessary for future geologic storage in brine formations. It is expected that major 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.

Basin	Cumulative Incremental Recovery (million stb)	CO_2 Storage Potential (Bcf)	CO_2 Storage Potential (million tons)
Williston	1023	8186	502
Powder River	381	3049	187
Denver–Julesberg	25	199	12
Alberta	6000	4856	2773



Evaluated Saline Storage Potential



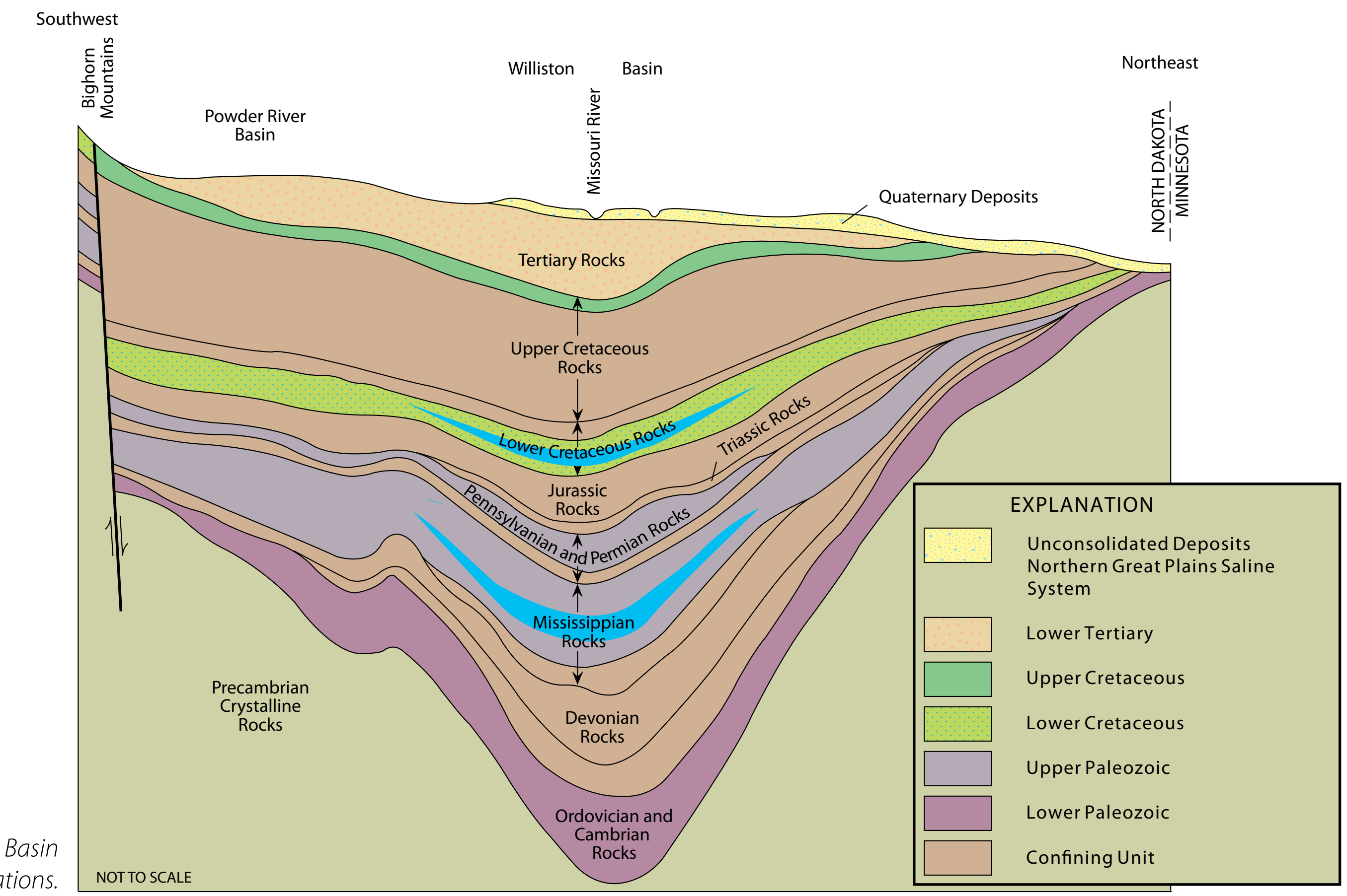
The estimated capacities for the Lower Cretaceous Viking (Alberta) and Maha (Nebraska) Formations and the Mississippian Madison Formation (Dakotas and Montana) are based on readily available formation properties. The areal extents are constrained by salinity and depth cutoffs.

CO_2 Storage in Saline Formations

Saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic carbon dioxide. Two saline systems, the Mississippian and Lower Cretaceous, were selected for broad evaluation based on their regional continuity, fluid properties, and readily available data.

The resulting lateral extent of the three selected formations in these systems is constrained by depth, to ensure optimal density of the injected CO_2, and by salinity to avoid protected groundwater resources. Reconnaissance-level estimates indicate that the Mississippian Madison Formation in the Williston Basin could store over 120 billion tons of CO_2, while the two formations in the Lower Cretaceous system could store upwards of 70 billion tons. The respective formation capacity estimates are based on formation properties and suggest that these strata may be suitable sinks for future storage needs.[16,17]

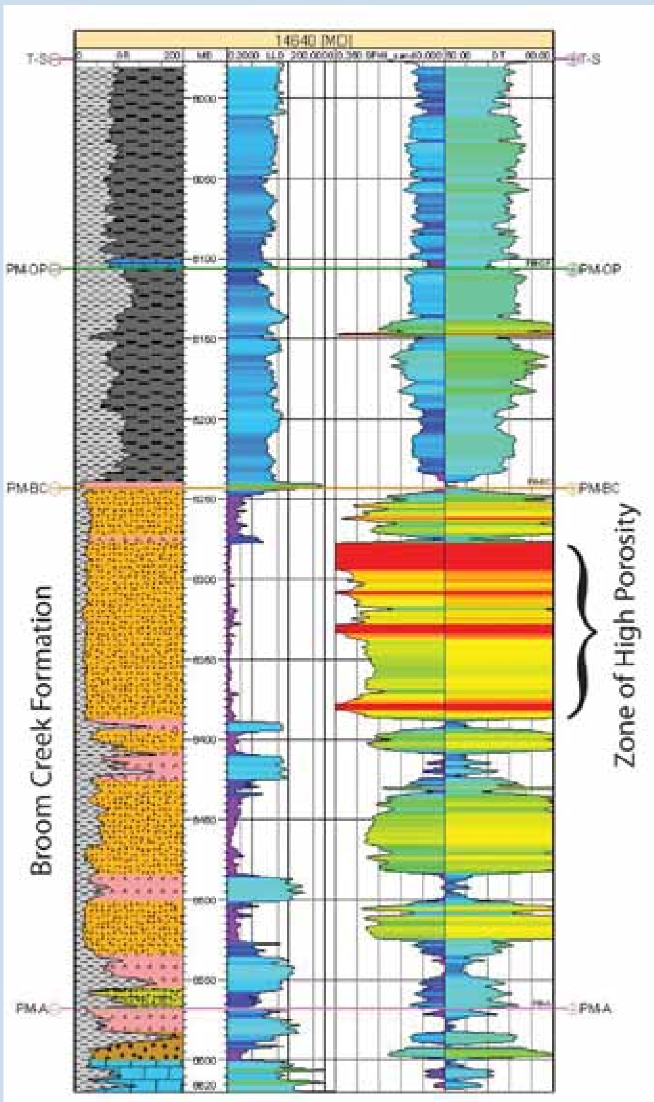
Formation	Basin	Estimated CO_2 Capacity, billion tons
Lower Cretaceous System		
Viking Formation	Alberta	36
Maha Formation	Denver–Julesberg	36
Mississippian System		
Madison Formation	Williston	123



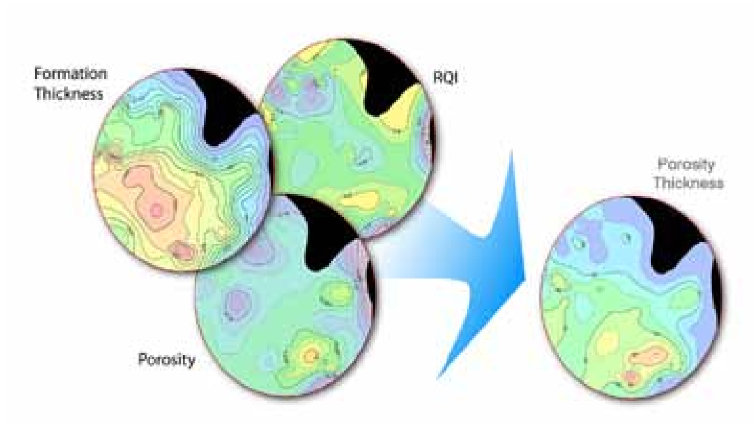
Cross section of the Williston Basin showing major saline formations.

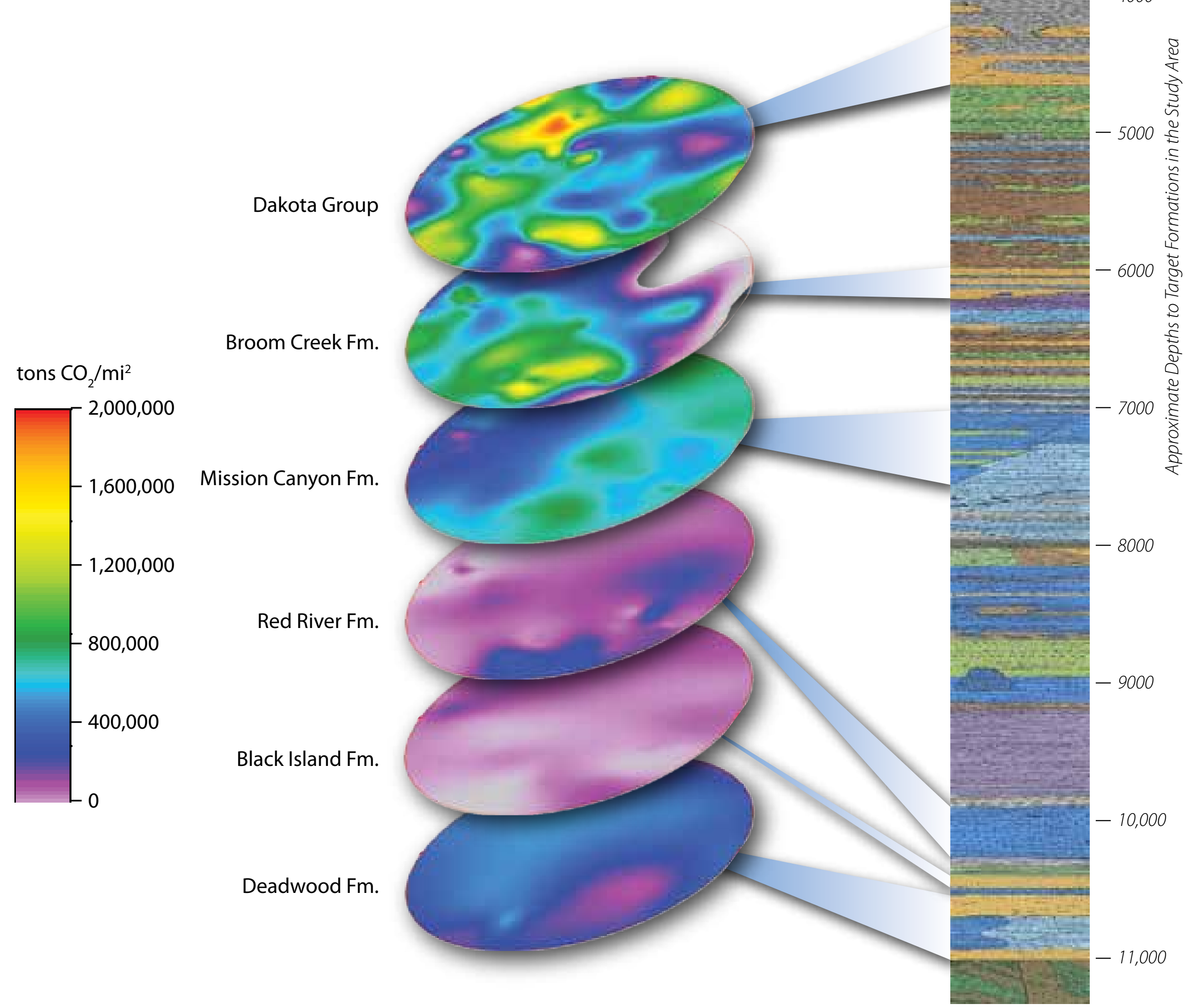
Map-Based Approach

The methodology employed used digital well logs to identify zones of porosity in the stacked sequence of rock and then create maps depicting the areal distribution of the thickness and porosity values of these rock characteristics. A reservoir quality index (RQI) representing the thickness of each formation meeting specific criteria was calculated for each target horizon.



State-of-the-art petrophysical modeling was used to derive resource estimates for multiple saline formations in the Williston Basin. This geophysical well log identifies zones of high porosity in the sands of the Broom Creek Formation at depths between 6250 and 6550 feet. These sands are excellent target zones for the injection of CO_2 in west-central North Dakota.



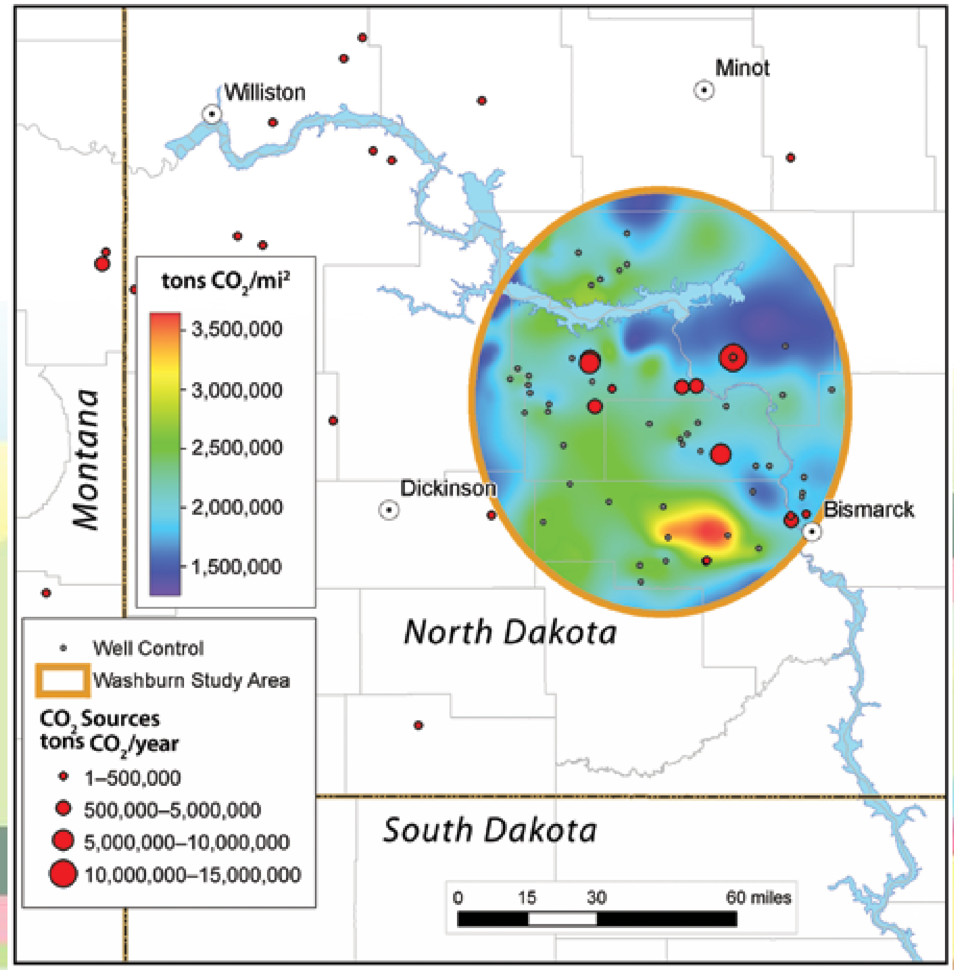


Stacked Brine-Saturated Formations

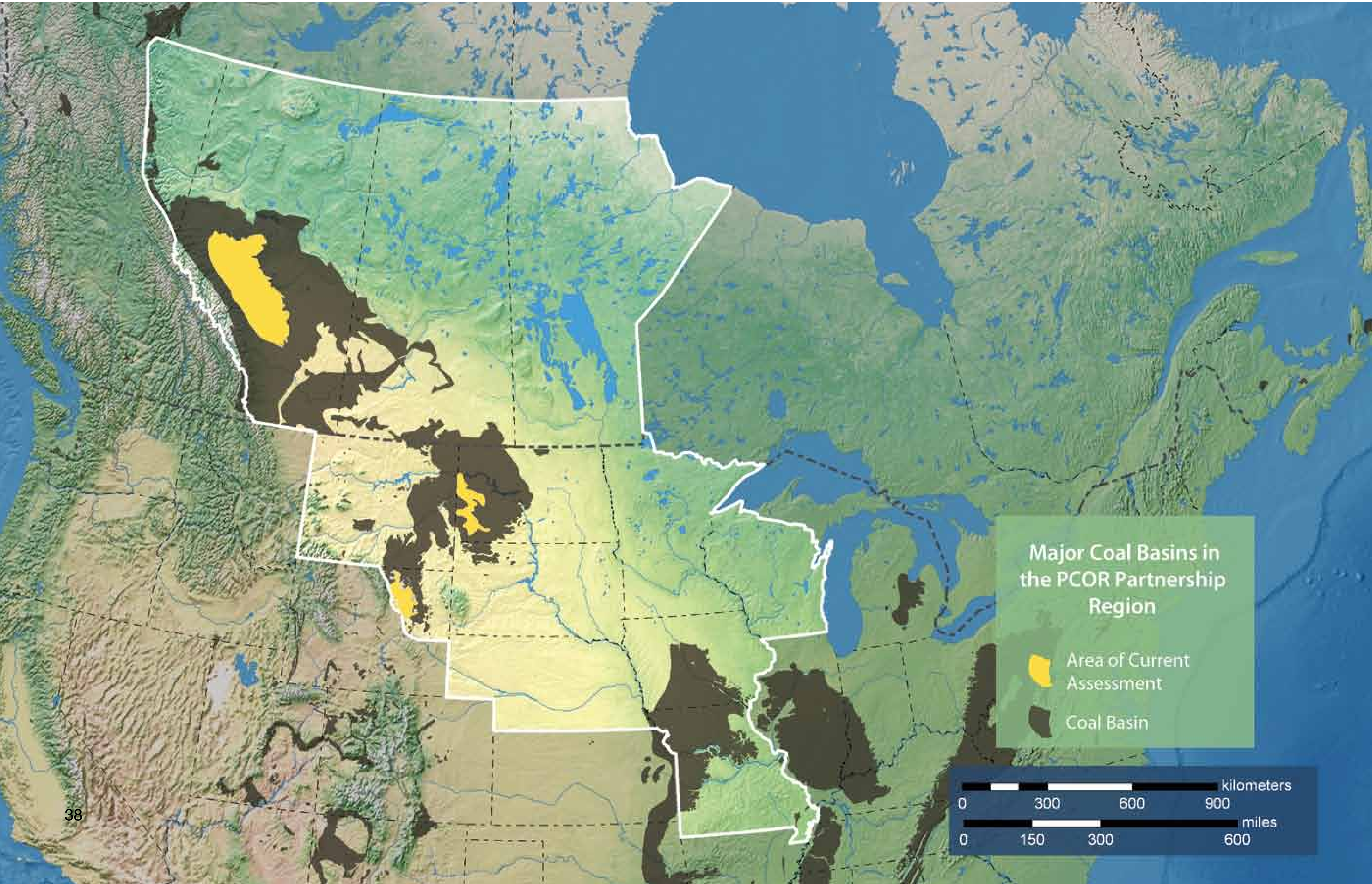
In many sedimentary basins, there may be more than one potential target horizon for CO_2 storage, each with an appropriate seal to ensure safe, long-term storage. A great example of stacked target horizons can be found in the North Dakota portion of the Williston Basin.

As part of ongoing regional characterization efforts, the PCOR Partnership conducted a detailed evaluation of the potential CO_2 storage capacity of several stacked brine-saturated formations. This area of investigation encompasses 6100 mi^2, is underlain by over 9800 ft of sedimentary rock, and was selected because of its proximity to seven large coal-fired industrial sources of CO_2.

By using publicly available well file information, a map-based approach was used to develop reconnaissance-level petrophysical models of a sequence of stacked brine-saturated formations in west-central North Dakota. This approach integrated well log data from over 50 wells, analysis of core samples from the deep formations, water analysis, and other published data. The resulting petrophysical models provided the basis for estimating CO_2 storage capacity of 11 potential target injection intervals in seven different formations. The total CO_2 storage capacity in the evaluated brine-saturated formations in this area of the Williston Basin is estimated to be about 13 billion tons.



Major Coal Basins



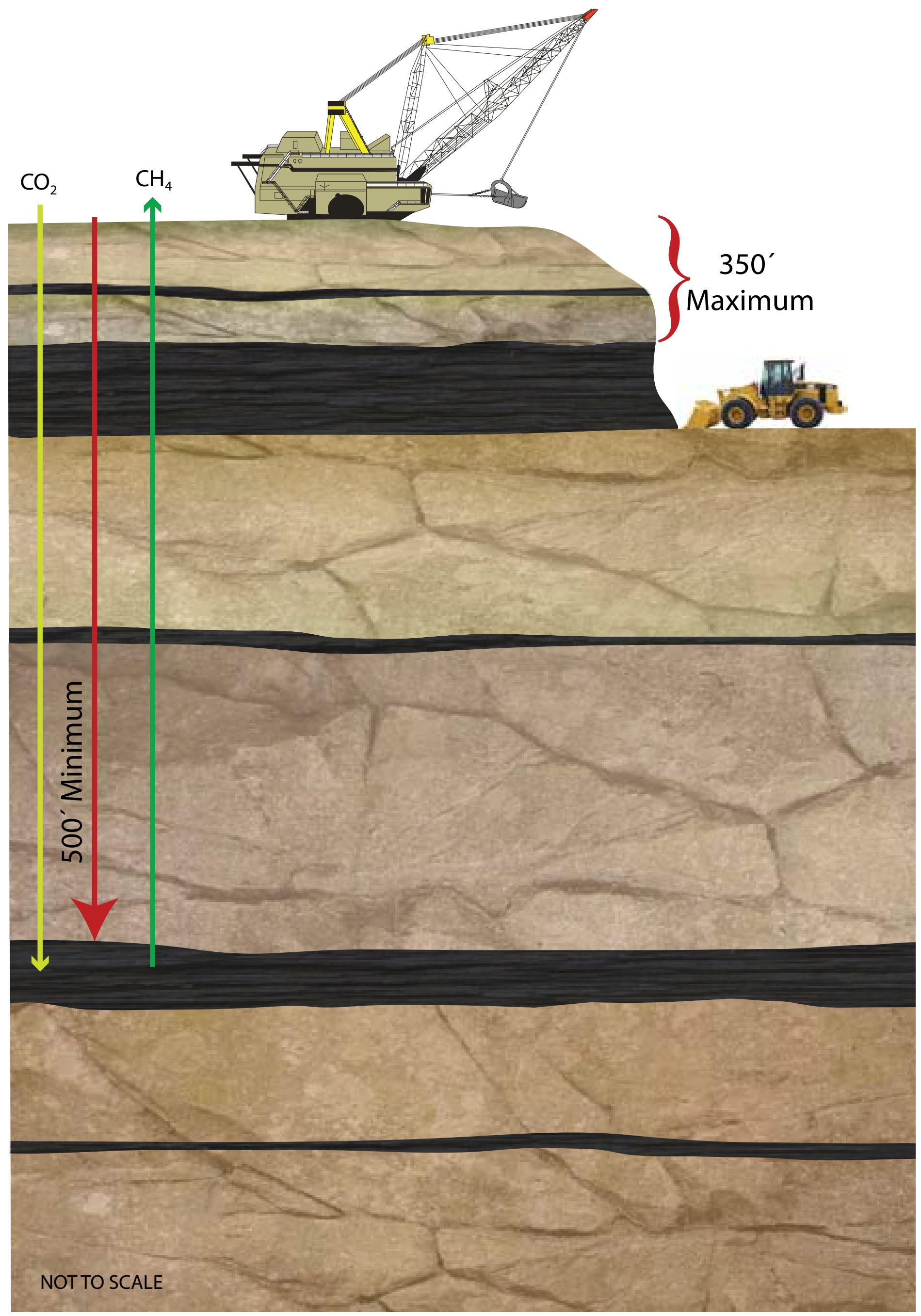
CO_2 Storage in Coal

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.[18]

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, displacing the methane. For the coals in the PCOR Partnership region, it is possible that 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.[19] Just as with depleting oil reservoirs, unminable coal beds may be a good opportunity for CO_2 storage.

Three major coal horizons in the PCOR Partnership region have been characterized with respect to CO_2 storage: 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 storage potential for all three coal deposits is approximately 8 billion tons.[20–22]

In northeastern Wyoming, the CO_2 storage potential for the areas where the coal overburden thickness is >1000 feet could store all of the current annual CO_2 emissions from nearby power plants for about the next 150 years.[22]



Prairie Pothole Region of the PCOR Partnership Region

Prairie Pothole Region

The PCOR Partnership region includes the PPR, a major biogeographical region that encompasses approximately 347,000 mi^2 (222 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.[23] 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.[24] 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 depleted significant amounts of soil organic carbon (SOC) in wetlands.

The prairie potholes are an important element of the prairie ecosystem. This region accounts for up to 70% of wild duck production in North America[24] and provides important breeding and migratory grounds for many types of wildlife. In addition to wildlife benefits, the prairie potholes provide many other ecological benefits, such as reduced erosion, improved water quality, flood and storm buffering, and recreational opportunities.

Recent work by Ducks Unlimited (DU), Inc., and U.S. Geological Survey (USGS) scientists for the PCOR Partnership 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}.[25] 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.

Prairie Pothole Region Test Sites

Out of the Air – Into the Soil

Terrestrial storage involves the process of removing CO_2 from the air by plants via photosynthesis and storing it in the soil as biomass and SOC. Terrestrial carbon storage projects can offer an immediate response to the threat of global climate change and generally enhance the quality of soil, water, air, and wildlife habitat while advancements in technologies for other methods (i.e., geologic storage) are made.

As part of the PCOR Partnership Program, the EERC; DU; Ducks Unlimited Canada (DUC), Inc.; the USGS Northern Prairie Wildlife Research Center; and North Dakota State University (NDSU) have demonstrated optimal practices for terrestrially storing CO_2 at multiple sites located in the PPR of North America.

A terrestrial field validation test was initiated to develop the technical capacity to systematically identify, develop, and apply alternate land-use management practices to the prairie pothole ecosystem (at both the local and regional scale) that result in net GHG reductions and marketable carbon offsets.

As part of this project, PCOR Partnership partners collected soil and gas samples from restored grasslands, native prairie, cropland, and wetlands of various age from the states and provinces of the PPR. In addition to carbon uptake and storage measurements, methane and nitrous oxide gas fluxes were also measured to estimate the net GHG flux of each management practice. These data have been instrumental in advancing terrestrial carbon credits in the marketplace.

Terrestrial storage projects create carbon credits that can be transacted in voluntary or mandatory regional, national, or international carbon markets. Under a mandatory GHG reduction program, these credits provide entities with alternative compliance options in addition to direct reductions that reduce GHG emissions while new technologies are developed to reduce reliance on carbon-based fuels.

Carbon market stakeholders include those involved in financing, producing, generating, providing, aggregating, and/or marketing GHG emission reductions in existing and emerging voluntary and regulated GHG emission trading markets.

PCOR Partnership project results have supported the development of protocols for terrestrial carbon credit development and trading with the launch of the DU Carbon Credit Program, intended to serve as a model to promote and implement terrestrial storage across the PPR. This program provides landowners with a revenue stream novel to the agricultural economy of the plains—stored carbon. Through this program, landowners sign perpetual grassland easements while, at the same time, conveying carbon rights to be bundled and sold on the open market. Results from this project have provided the "science" and business processes needed for aggregators and investors to advance and prosper in this rapidly emerging market.

Zama Site

Great Slave Lake
Ft. Nelson
Zama Acid Gas Injection Site
Lake Athabascan
River
Peace
Ft.St. John
Alberta
Saskatchewan
North
Saskatchewan
River
Edmonton
Manitoba
Lake Winnipeg
British Columbia
Saskatoon
Calgary
Regina
Winnipeg
CANADA
UNITED STATES
Missouri
River
Williston
North Dakota
Grand Forks
Minnesota
Montana

CO_2-Rich Gas in a Pinnacle Reef Structure

In October 2005, the Zama oil field in northwestern Alberta, Canada, became the site of acid gas (approximately 70% CO_2 and 30% H_2S [hydrogen sulfide]) injection for the simultaneous purpose of EOR, H_2S disposal, and CO_2 storage. Injection is taking place at a depth of 4900 feet into a carbonate pinnacle reef structure.

The PCOR Partnership conducted monitoring, verification, and accounting (MVA) activities at the site through September of 2009 while Apache Canada, Ltd., managed the injection and hydrocarbon recovery processes.

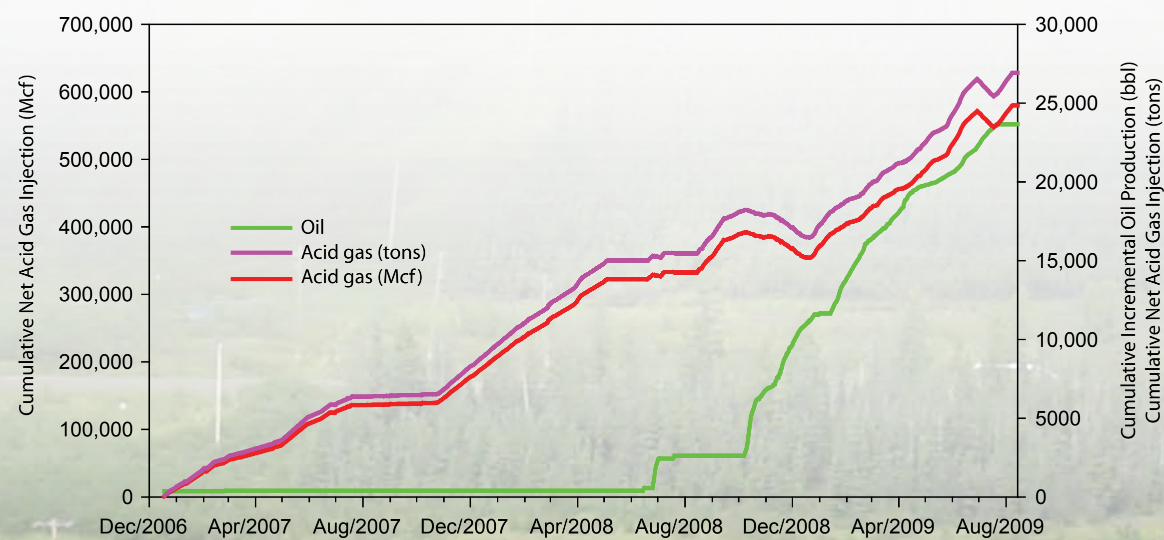
Acid gas is a by-product of oil production in the Zama Field and a subsequent fluid separation process at the on-site facilities. During the separation process, oil and gas are sent to market while acid gas is redirected back to the field for utilization in EOR operations. Prior to this project, the CO_2 portion of the acid gas was vented to the atmosphere, and sulfur was separated from the H_2S and stockpiled in solid form on-site. This project has enabled the simultaneous beneficial use of each of these materials to produce more oil and reduce GHG emissions.

The MVA portion of the Zama project was designed to address three primary issues at EOR sites: 1) determination of CO_2 and/or H_2S leakage, or lack thereof; 2) development of reliable predictions regarding the long-term fate of injected acid gas; and 3) generation of data sets to support the development and monetization of carbon credits associated with the geologic storage of CO_2.

The geological and geochemical investigations were conducted at local and regional (subbasinal) scales. Geological results indicate that the likelihood of natural leakage from this system is low and regional flow is extremely slow, on the order of thousands to tens of thousands of years to migrate out of the basin.

Monitoring of the site is achieved primarily through fluid sampling and pressure monitoring in both the target pinnacle reef and overlying strata. To more readily identify any leakage that might occur, a gas-phase tracer was injected early in the project.

As of September 2009, over 27,000 tons of acid gas has been utilized for EOR operations, resulting in an additional 24,000 barrels of oil production. While this project has been focused on one of the hundreds of pinnacle reefs that exist in the Zama Field, many of the results obtained can be applied not only to additional pinnacles in the Alberta Basin, but also to similar structures throughout the world.



This project is recognized by the international Carbon Sequestration Leadership Forum as being uniquely qualified to fill technological gaps with regard to geological storage of CO_2.

Northwest McGregor Site

CO_2 in a Deep Oil Reservoir

The PCOR Partnership is working with Eagle Operating Company to determine the effect of injecting carbon dioxide into a deep carbonate formation in the Northwest McGregor oil field of North Dakota. The purpose of the activities is to evaluate the potential dual purpose of CO_2 storage and EOR in carbonate rocks at a depth of nearly 8050 feet. A technical team that includes Eagle, the EERC, and others conducted a variety of activities to inject CO_2 into the target oil reservoir using a huff 'n' puff approach and evaluate the effect that injected CO_2 has on the ability of the oil reservoir to store CO_2 and produce incremental oil.

Oil in the Williston Basin is produced from at least a dozen rock formations at depths ranging from less than 3000 feet on the northeast margin of the basin, to greater than 14,000 feet near the basin center. While the CO_2-based EOR operations at the Weyburn and Midale Fields in Saskatchewan are good examples of economically and technically successful injection of CO_2 for simultaneous EOR and storage, the depths of injection and, therefore, reservoir condition, in those fields are relatively shallow (ca. 4600 feet) and not necessarily representative of many other Williston Basin oil fields. One of the primary goals of this field validation test is to evaluate the effectiveness of CO_2 for EOR and storage in oil fields at greater depths. To achieve that goal, a CO_2 huff 'n' puff test was conducted for a well producing oil from an interval of the Mississippian-aged Madison Group at a depth of approximately 8050 feet in the Northwest McGregor oil field of North Dakota. As an initial pilot-scale test, 440 tons of CO_2 was injected into a single well and allowed to "soak" for several weeks (the huff). The well was then placed back into production, and the amount of incremental petroleum fluids produced were measured (the puff). Huff 'n' puff operations can be an effective means of evaluating the response of a reservoir to CO_2, both with respect to EOR and CO_2 storage. The approach is economically attractive because small-volume injections yield adequate results to determine the efficacy of a larger-scale CO_2 injection. CO_2 for this validation test was purchased from a commercial vendor and transported via truck to the oil field where it was injected into the target reservoir.

North Dakota Lignite Site

CO_2 in an Unminable Lignite Seam

Deep, unminable coal seams are believed to provide a viable opportunity for large-scale underground storage of carbon dioxide. The opportunity looks even more attractive because of the possibility of simultaneous CBM production. However, despite the maturity of the idea, the implications of applying the concept to a wide range of coal types and seams are unclear. The PCOR Partnership field validation test in Burke County, North Dakota, aimed to define CO_2 storage capacity and CH_4 production potential of North Dakota lignite reserves. The results of the test can be applied to lignite seams throughout the United States and the world and will elucidate coal properties having foremost importance for CO_2 storage and CH_4 production in lignite.

North Dakota's lignite coal seams can be considered unconventional from the point of view of enhanced CBM production because of relatively poor understanding of methane storage and transport mechanisms and methane content. To predict performance of carbon dioxide storage with simultaneous CBM production, the following aspects were studied:

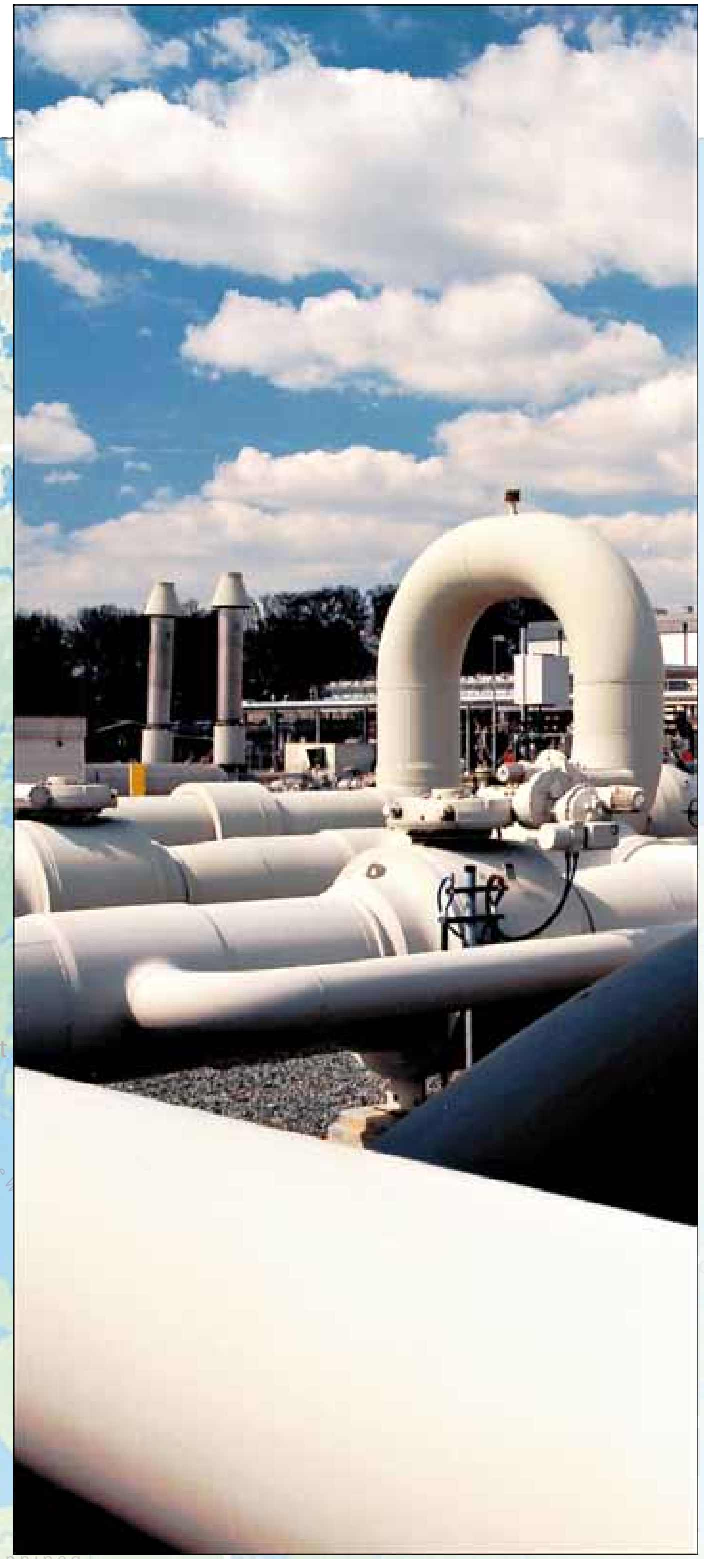
- Methane content and carbon dioxide storage capacity and applicability of the existing experimental methods to their estimation in lignite
- Features of fluid transport in lignite
- Stability of carbon dioxide stored within a lignite seam
- Factors controlling the success of storage/production operations in lignite

The goal of the field validation test in Burke County, North Dakota, was to address each of the listed factors and develop best practices for similar large-scale projects. The test adopted a five-spot production/injection well geometry to allow for efficient site characterization, replacement of natural gas by carbon dioxide, and MVA activities. The first phase of the test focused on obtaining baseline data and studying CBM production potential. CO_2 injection started in the second phase, the goal of which was to investigate the feasibility and reliability of CO_2 storage in lignite.

Approximately 90 tons of CO_2 was injected over roughly a 2-week period into a 10–12-ft-thick coal seam at a depth of 1100 feet. CO_2 injection was accomplished using a single injection well, which was surrounded by four monitoring wells. These monitoring wells employed various technologies to track the presence and movement of CO_2 in the lignite coal seam.

MVA techniques were selected based on the characteristics of the site and included a combination of many techniques. Of these techniques, reservoir saturation tool logs and time-lapse crosswell seismic tomography provided the most valuable information. These techniques demonstrated that the CO_2 did not significantly move away from the wellbore and was contained within the coal seam for the duration of the monitoring period, i.e., approximately 3 months.

Fort Nelson Site



Geologic Storage of Sour CO_2 from a Natural Gas-Processing Plant

Nearly 1600 facilities around the world remove impurities such as carbon dioxide from natural gas, and Spectra Energy's Fort Nelson facility is among the largest. For this reason, Spectra Energy and the PCOR Partnership are leading a collaborative venture involving government, industry, technologists, and researchers that will fully demonstrate the concept of CCS to manage the CO_2 emissions of natural gas-processing facilities. In this demonstration, over a million tons a year of sour CO_2 will be injected into a saline formation deep underground. The behavior of the sour CO_2 in the subsurface will be closely monitored to ensure the safe and effective operation of geologic storage sites for CO_2 in this region. Over the next decade, the demonstration will store over 10 million tons of CO_2 that would have otherwise entered the atmosphere.

The sour CO_2 stream from Spectra Energy's Fort Nelson gas-processing facility, located near Fort Nelson, British Columbia, Canada, will be piped to a nearby site where it will be injected over 7200 feet into the ground for permanent storage in a rock formation containing very salty water ("saline" formation).

The sour CO_2 stream (90% CO_2, 10% H_2S) will first be compressed to a supercritical state. This means that the CO_2-rich gas will be pressurized to meet the conditions it will encounter in the underground injection zone. The supercritical sour CO_2 has a density like a liquid but still behaves like a gas. The supercritical gas will be transported via pipeline approximately 9 miles (15 km) to an injection site. Once at the injection site, the sour CO_2 will be sent over a mile into the ground to a depth of over 7200 ft (2200 meters). There, the supercritical gas will be injected into the carbonate rocks (limestone and dolomite), where some of it will dissolve into the highly saline water that fills the pores of the rock. Once the sour CO_2 enters the pores of the carbonate rocks, the naturally high-pressure and high-temperature conditions will help maintain the sour CO_2 in the supercritical state.

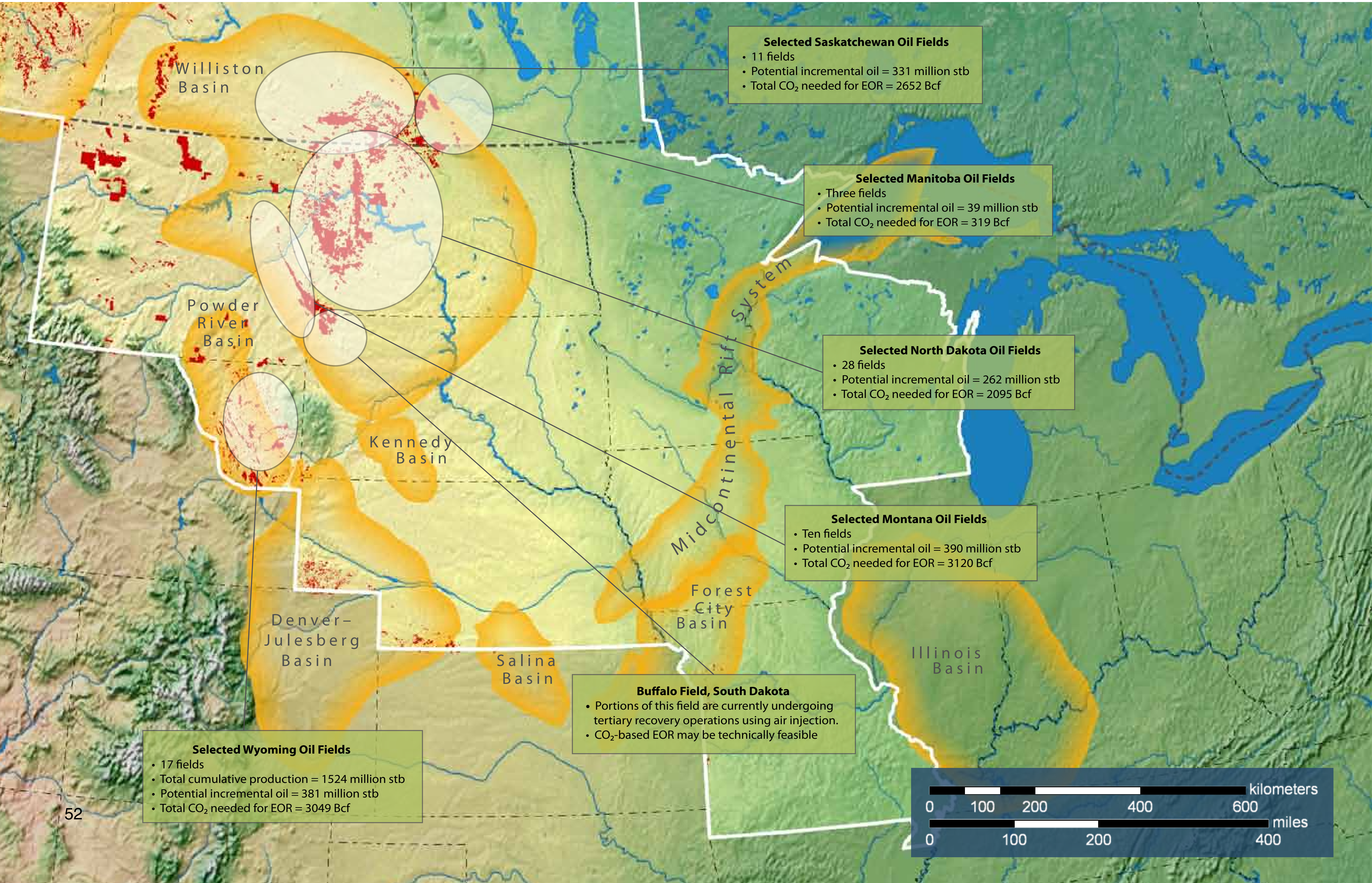
The primary objective of the Fort Nelson demonstration is to verify and validate the concept of utilizing the region's large number of saline formations for large-scale injection of anthropogenic CO_2 for permanent storage. Specific goals include:

- Cost-effective risk management, simulation, and MVA strategies for large-scale CO_2 sequestration in deep brine reservoirs.
- Testing and refinement of reservoir modeling intended to predict and estimate CO_2 injectivity (the potential for placing CO_2 into the reservoir), areal extent and mobility of the supercritical CO_2 plume in the reservoir, and improved methodologies to ensure that site characterization and MVA results better support risk management objectives and modeling efforts.
- Testing strategies to predict the effects of CO_2 on the integrity of overlying sealing formations, including the testing and modeling of key geomechanical and geochemical parameters.

The PCOR Partnership's role in the Fort Nelson CCS project will run from the fall of 2007 to the fall of 2017. The injection site was chosen in 2008, and the drilling for the exploration well (potentially the first injection well also) and shallow groundwater-monitoring wells was completed in the spring of 2009. Injection is planned to begin in 2012, and Spectra Energy intends to continue injection of sour CO_2 over the remaining operational lifetime of the Fort Nelson gas-processing plant. An MVA plan will be implemented to monitor the underground movement of CO_2. The MVA data may also be used to modify and improve the injection design, if needed. A comprehensive report will be issued in the fall of 2017.

This project is recognized by the international Carbon Sequestration Leadership Forum as being uniquely qualified to fill technological gaps with regard to geological storage of CO_2.

Development-Phase, Commercial-Scale Demonstrations



Market-Ready EOR Opportunities

Many of the geologic formations deep beneath a wide area of the PCOR Partnership region hold great potential to sequester CO_2. The western half of the region contains numerous mature oil fields that are well suited for EOR through the injection of CO_2. Enhanced oil recovery has been identified as a means not only to store CO_2 emissions but also to manage CO_2 as a potential value-added product. In an example of a regional government initiative, in 2008 the province of Alberta announced a $2 billion fund to advance projects that include CO_2 capture and EOR.

Aside from the EOR aspect, several areas of the PCOR Partnership region overlie stacked sequences of prime geologic sequestration targets in saline formations. The arrangement of multiple target zones in close proximity to multiple CO_2 sources enables optimum sequestration potential with minimal transportation constraints. In some cases, key infrastructure is already in place. Examples include the well-known Weyburn sequestration project in Saskatchewan and the associated CO_2 capture and pipeline infrastructure operated by the Dakota Gasification Company.

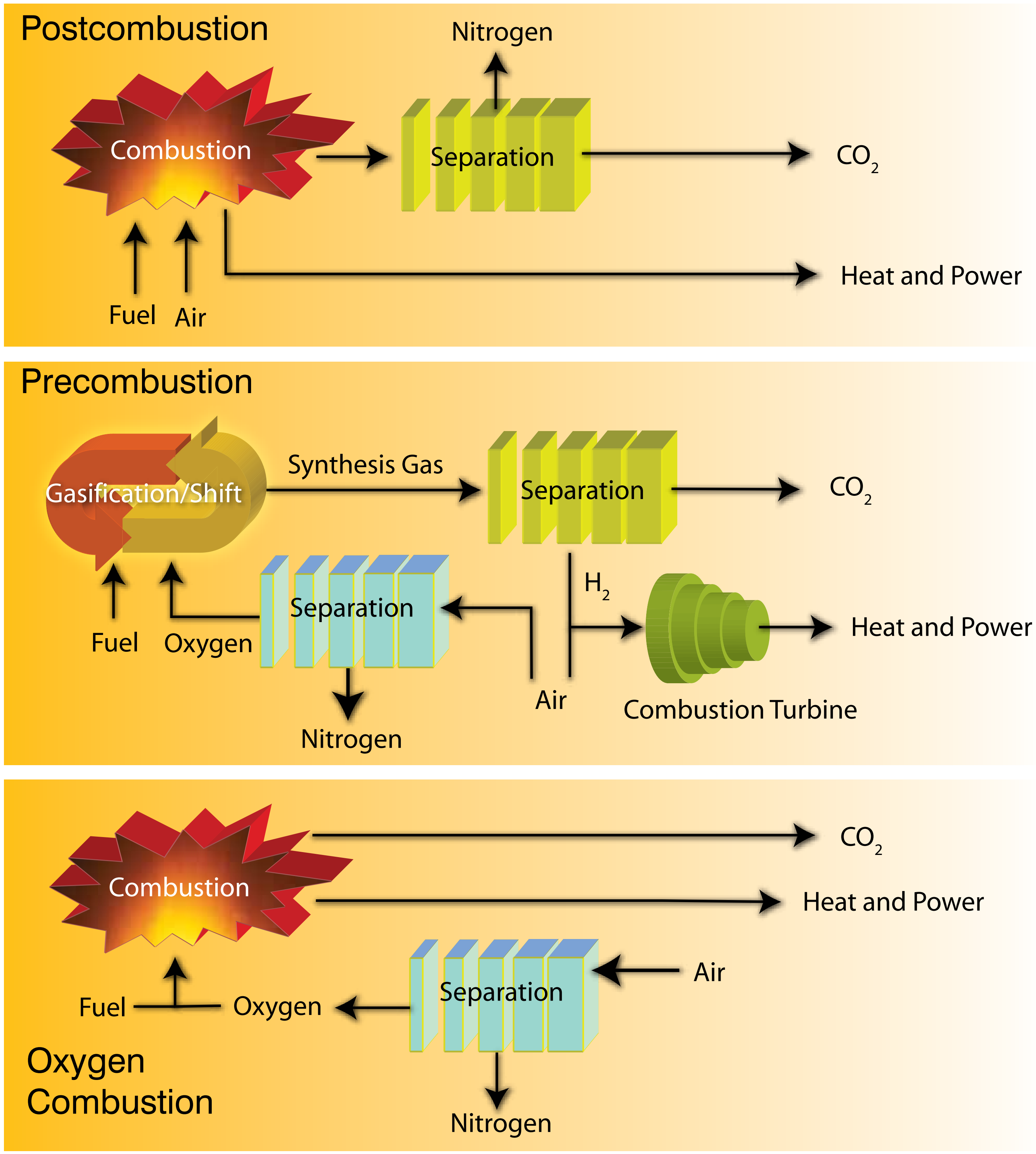
Proactive industries in the region have recently initiated additional capture and sequestration activities. These include Basin Electric's plan to capture over 1 million metric tons (1.1 million tons) of CO_2 annually from the Antelope Valley Station in North Dakota, as well as several others.

In July of 2009, Encore Acquisition Company announced plans to construct a 226-mile-long pipeline to bring CO_2 from the Lost Cabin gas plant in north-central Wyoming to the Bell Creek oil field in the southeastern corner of Montana. This EOR project will utilize nearly 50 million cubic feet a day (nearly 1 million tons a year) of CO_2 and is estimated to recover an incremental 35 million barrels of oil over the project's 20–25-year life.

Early commercialization opportunities will be realized in meeting existing unmet CO_2 demand for EOR purposes. The potential to recover over 3 billion barrels of incremental oil through EOR will be a strong driver in the commercialization of capture and transportation efforts in the PCOR Partnership region.

Railcars loaded with material for new oil pipeline components.

Fossil Fuel Conversion Platforms and CO_2 Capture



Opposite page: CO_2 compressor at the Dakota Gasification Company's synfuels plant in central North Dakota. The compressor is capable of moving about 55 million cubic feet of CO_2 a day at a discharge pressure of 2700 psi.

Carbon Capture and Separation

Before CO_2 can be geologically stored, it must be captured and separated from other gases, compressed, and transported to the geologic sink. Capture and separation of CO_2 are performed as a part of many industrial processes, from natural gas and hydrogen production to ammonia synthesis.[26] However, existing capture technologies are not yet optimized for application on a typical power plant exhaust stream. Power plants typically burn coal or natural gas in the presence of air. This approach produces an exhaust gas that contains large amounts of nitrogen that must be separated from the CO_2 prior to storage. Because the concentration of CO_2 in typical power plant flue gas is so low (ranging from 3% by volume for some natural gas-fired plants to 15% by volume for some coal-fired plants),[27] any capture process must be sized to handle the large quantity of exhaust gas. The large scale of equipment and quantities of chemicals required make the capture process relatively expensive. In fact, the cost of capturing the CO_2 can represent three-fourths of the total cost of a capture–storage–transportation–geologic storage system.[26]

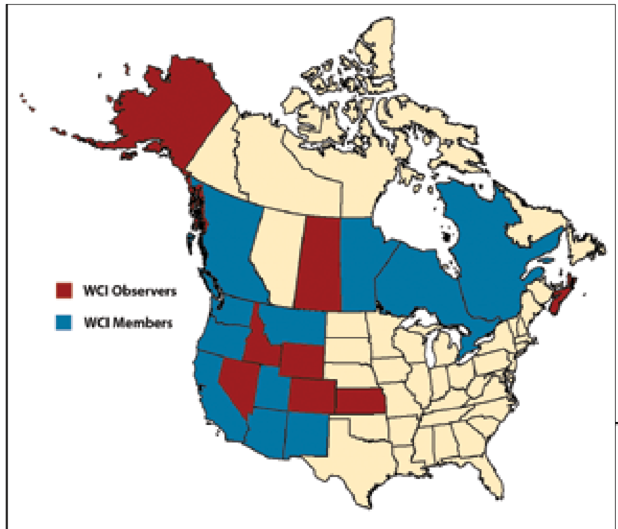
Research is being performed to develop new CO_2 capture processes and improve the economics of existing ones. Capture of CO_2 can be performed at three points in the power production process: before, during, and after combustion. The precombustion technologies consist of capture of CO_2 in conjunction with gasification or reforming. Capture during combustion is only possible when the combustion takes place in nearly pure oxygen rather than air. The majority of capture technologies focuses on separating the CO_2 from the exhaust gas stream after combustion.

Five different approaches can be taken in postcombustion capture: absorption (both chemical and physical), adsorption, membrane separation, cryogenic cooling, and others such as chemical looping and CO_2 hydrate formation. The most common commercial technology available is amine scrubbing, a chemical absorption technology. Two of the more common commercial physical absorption processes are the Rectisol and Selexol processes.

After the CO_2 is captured, it must be compressed for either storage prior to truck transport or directly put into a pipeline to the storage site. CO_2 must be compressed to about 1200 to 1500 psi for transport in a pipeline. Compression is energy-intensive, so improved methods of compression are being developed.

Regional Initiatives

Three regional GHG initiatives are now in place to reduce CO_2 emissions through the adoption of cap-and-trade programs and the implementation of complementary processes focused on topics such as energy efficiency, low-carbon transportation fuels, and renewable electricity production, to name a few. These initiatives now include 23 states as full members and nine states as observers. The initiatives also include six of the ten Canadian provinces, four as full members and two as observers.



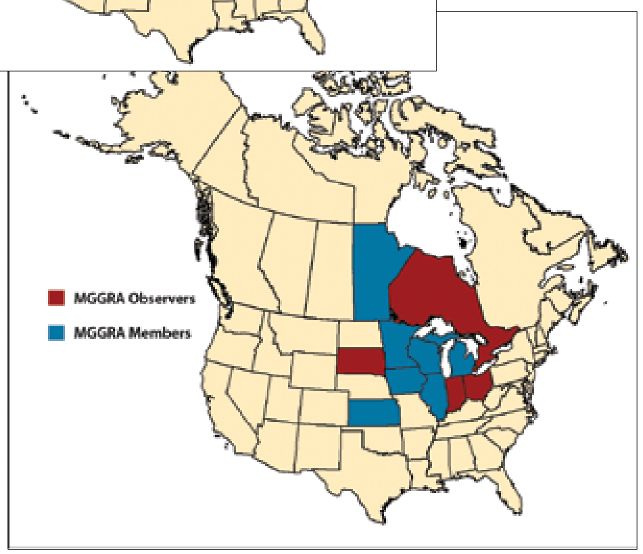
Western Climate Initiative (WCI)

With a goal to establish a regional emission target and market-based system, such as a cap-and-trade program, covering multieconomic sectors, WCI hopes to achieve a GHG emission target of 15% below 2005 levels by 2020. Beginning in 2012, the program will cover emission from electricity generation and large (>27,500 tons a year of CO_2 equivalents) industrial and commercial sources. This program would be extended to emissions from transportation and other residential, commercial, and industrial fuel use in 2015.

Mandatory reporting is proposed in early 2011 for calendar year 2010 for facilities emitting over 11,000 tons a year of CO_2 equivalents. Third-party verification of reporting data would be required for facilities over the 27,500-ton-a-year threshold. Like the Midwestern Greenhouse Gas Reduction Accord (MGGRA), WCI will also address other GHGs as defined by the United Nations Framework Convention of Climate Change (i.e., methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride).

Regional Greenhouse Gas Initiative (RGGI)

RGGI has a goal of implementing the first cap-and-trade program for CO_2 to establish CO_2 emission caps from power plants and allow sources to trade emission allowances. RGGI has a mandate to initially cap CO_2 emissions at 2009 levels and then to reduce emissions by 10% by 2019.



MGGRA

MGGRA has a long-term target of a 60% to 80% decrease in CO_2 from current emission levels by 2050. Also, MGGRA has a goal to develop a multisector cap-and-trade system, a GHG emission-tracking system, and other policies to aid in reducing emissions, such as low-carbon fuel standards. Additionally, MGGRA will address other GHGs as defined by the United Nations Framework Convention of Climate Change (i.e., methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride).

Regulatory and Safety Aspects of Carbon Capture and Storage

Currently, no U.S. federal regulations address CO_2 emissions. However, several efforts are under way in Congress to address this issue, and the U.S. Environmental Protection Agency (EPA) has started rulemaking activities for mandatory reporting requirements and emission limits. Regulations do address the transport of CO_2, the injection of CO_2 for enhanced resource recovery purposes, and worker safety issues. Also, various state and federal regulations could affect CO_2 storage projects. Most of these regulations would have bearing on the siting of a potential CO_2 source (e.g., power plant), pipeline routing, and injection of the CO_2.

CCS policy is taking a prominent position in the climate change debate occurring in the U.S. Congress. Both the House and Senate have focused on fundamental legal, economic, and policy issues that may ultimately drive the success or failure of geological storage as a carbon mitigation strategy. While EPA has proposed rules for geologic storage wells under the auspices of the Safe Drinking Water Act, many states are moving forward with their own rules and regulations to accommodate CCS projects. Also, many regional initiatives have formed across the United States and Canada to develop GHG emission strategies, in which CCS may, or may not, play a role as an offset option.

To ensure the safe and effective terrestrial and geological storage of CO_2, projects must appropriately characterize and judiciously select potential injection sites, effectively monitor and assess storage efficiency, and be prepared to take remedial action in the event of failure.

Assessing the effectiveness of terrestrial or geologic sinks for storing CO_2 is critical. MVA strategies will be required through all phases of CO_2 storage, including capture and separation, transportation, injection, and long-term storage. The implementation of MVA serves to 1) protect worker health and safety; 2) ensure environmental and ecological safety; 3) verify safe and effective storage, including providing assurances of carbon credits of transactions in a carbon-trading market; 4) track plume migration; 5) provide early warning for failure; and 6) confirm model predictions.

DSS Framework

The PCOR Partnership Decision Support System (DSS)

The PCOR Partnership has accumulated a wealth of data in characterizing the partnership region with respect to CO_2 storage opportunities. Major components of this characterization include creating an inventory of large stationary sources of CO_2 and identifying and mapping geologic and terrestrial targets, or sinks, for CO_2 storage across the PCOR Partnership region. Knowledge of the character and spatial relationships of sources, sinks, and regional infrastructure is crucial to developing and assessing approaches to economical and environmentally sound CO_2 storage.

The most efficient way to communicate this information to the partners has been through a geographic information system (GIS)-enabled Web site. This site is a major component of a larger Web-based DSS (© 2007–2009 EERC Foundation), which provides the PCOR Partnership with a single point of access to a wide variety of research data for evaluation and the development of potential storage scenarios. This password-protected (members-only) Web-based platform contains the tools and capabilities designed to deliver functional and dynamic access to data acquired through the project. The data are housed in a relational database and accessed through a map-based portion of the Web site. More traditional Web pages provide access to relatively static data, such as reports, CO_2-related Web sites, terrestrial maps, and snapshots of regional data.

GIS technology enhances the users' understanding of regional opportunities by allowing them to visualize the spatially distributed nature of the data. The Web-based GIS interface contains several analytical methods that allow members of the research teams to browse, query, analyze, and download data regarding CO_2 generation and storage in the PCOR Partnership region. Researchers can use the GIS to:

- Examine attributes of individual features or groups of features and their spatial relationships to other features.
- Query the underlying data to analyze the region and export selected data for manipulation in other software.
- Explore the nature of the data through thematic maps.

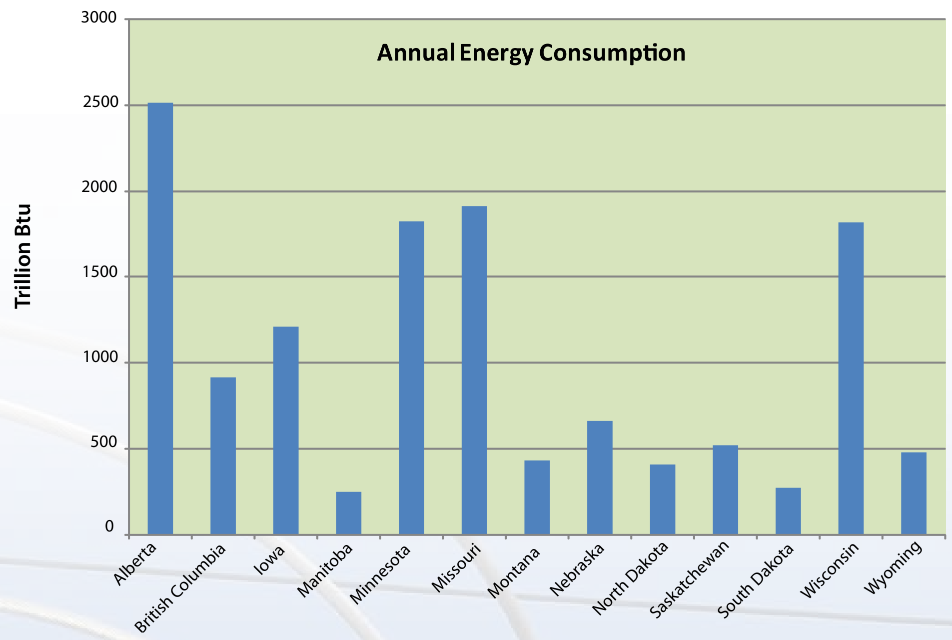
Energy and the Environment

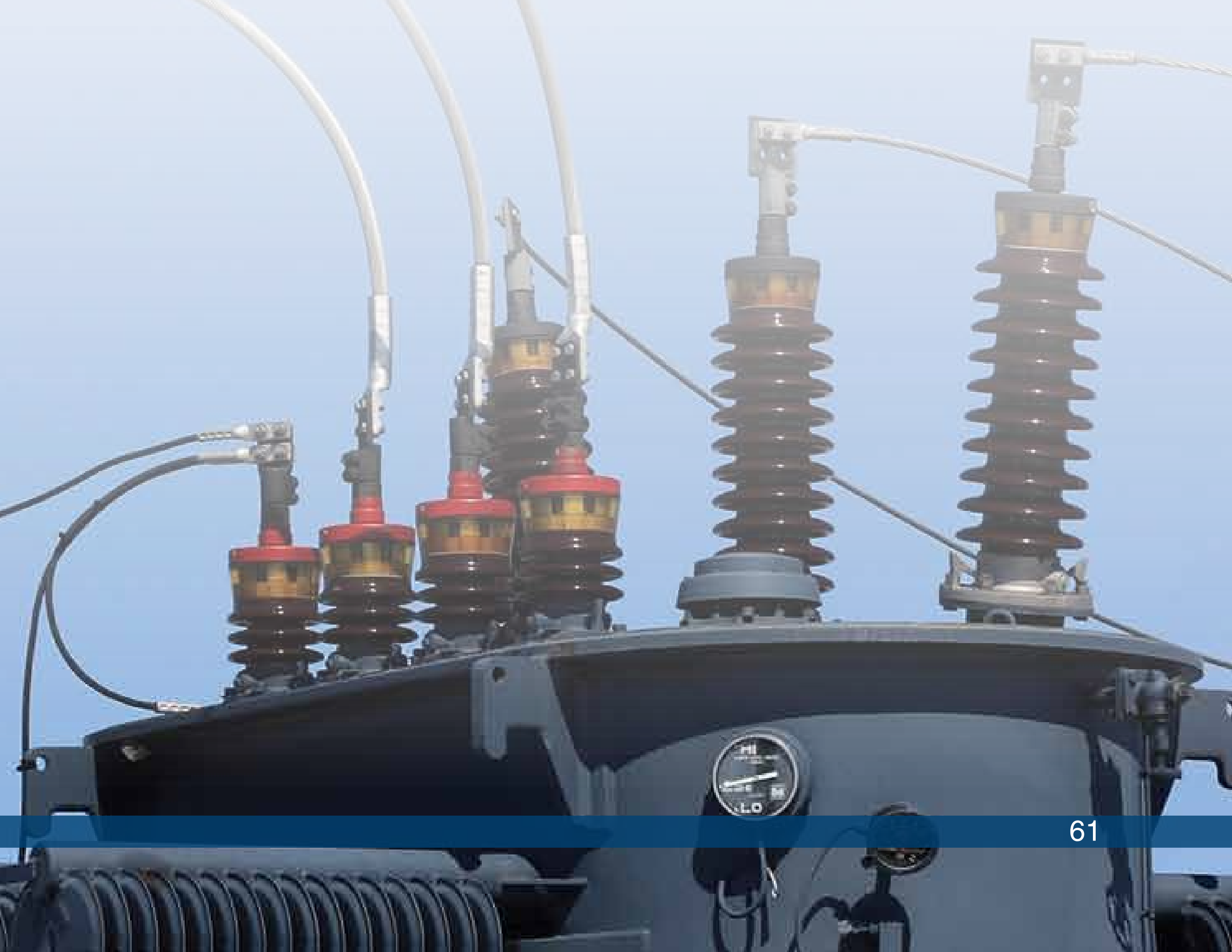
Keeping the Lights On

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 12,000 trillion Btu of energy a year.[28,29] 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.

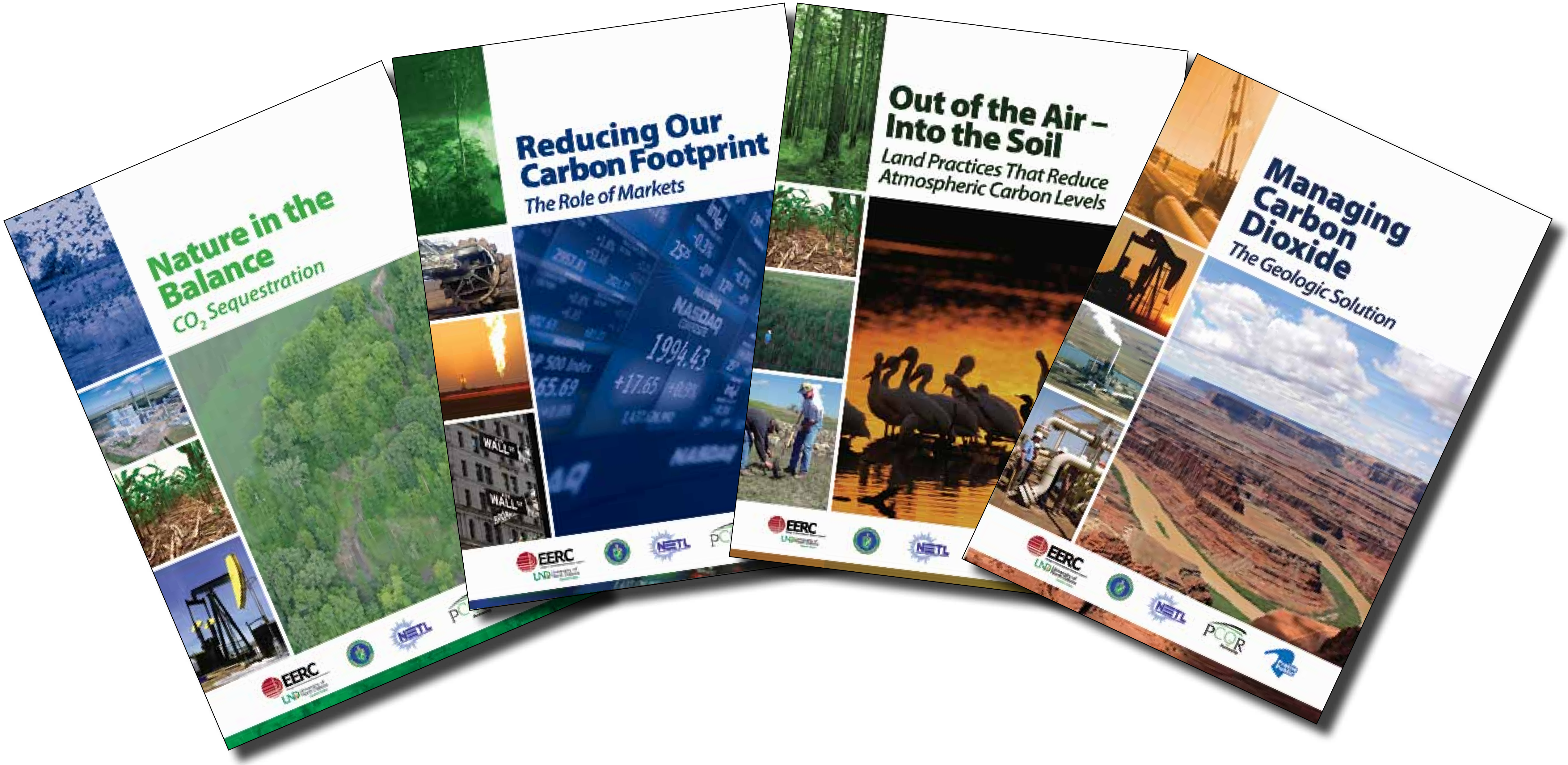
The abundant, affordable energy provided by the PCOR Partnership region's fossil fuel resources powers a very productive part of the world. For example, the three Canadian provinces of the PCOR Partnership produce over 90% of Canada's wheat, while the U.S. portion of the PCOR Partnership contributes over 30% of U.S. wheat production.[30,31] 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.[32] The Missouri and Mississippi Rivers, railways, and highways of the region transport 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 storage. 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.





DVD Documentaries



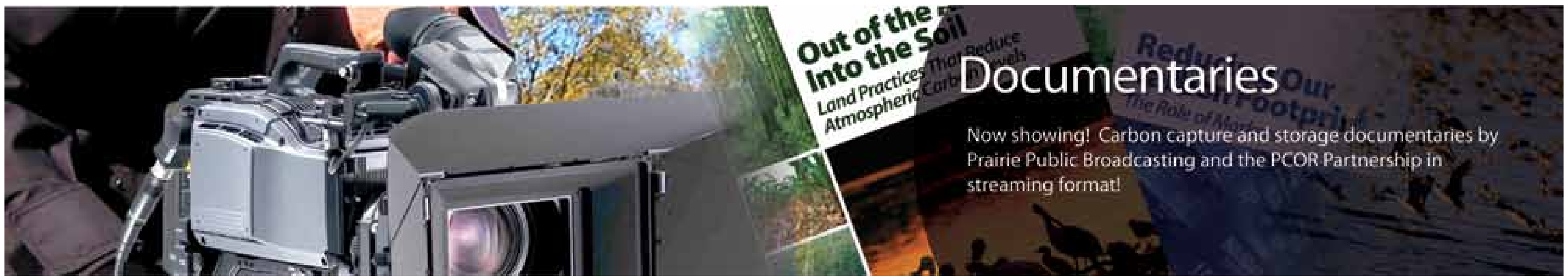
Education and Outreach – CO_2 Storage

The PCOR Partnership fully recognizes that the changes in land management, industrial operations, and CO_2 transport infrastructure needed to make large-scale, practical, and environmentally sound CO_2 storage a reality in the region cannot occur without an informed and supportive public.

For this reason, the PCOR Partnership has developed a number of outreach tools intended to educate and inform the public and decision makers about issues relate to CO_2 and storage:

- A variety of PowerPoint presentations
- Display booth and materials
- Public Web site
- Members-only Web site
- Knowledge in brief – fact sheets on key topics and validation projects
- Knowledge in-depth – scientific and technical reports
- Documentaries, available on DVD – coproduction of Prairie Public Broadcasting and the PCOR Partnership
- Proceedings from the annual PCOR Partnership meetings and access to other meeting materials

The PCOR Partnership also may provide speakers for your meeting, school, or community group.



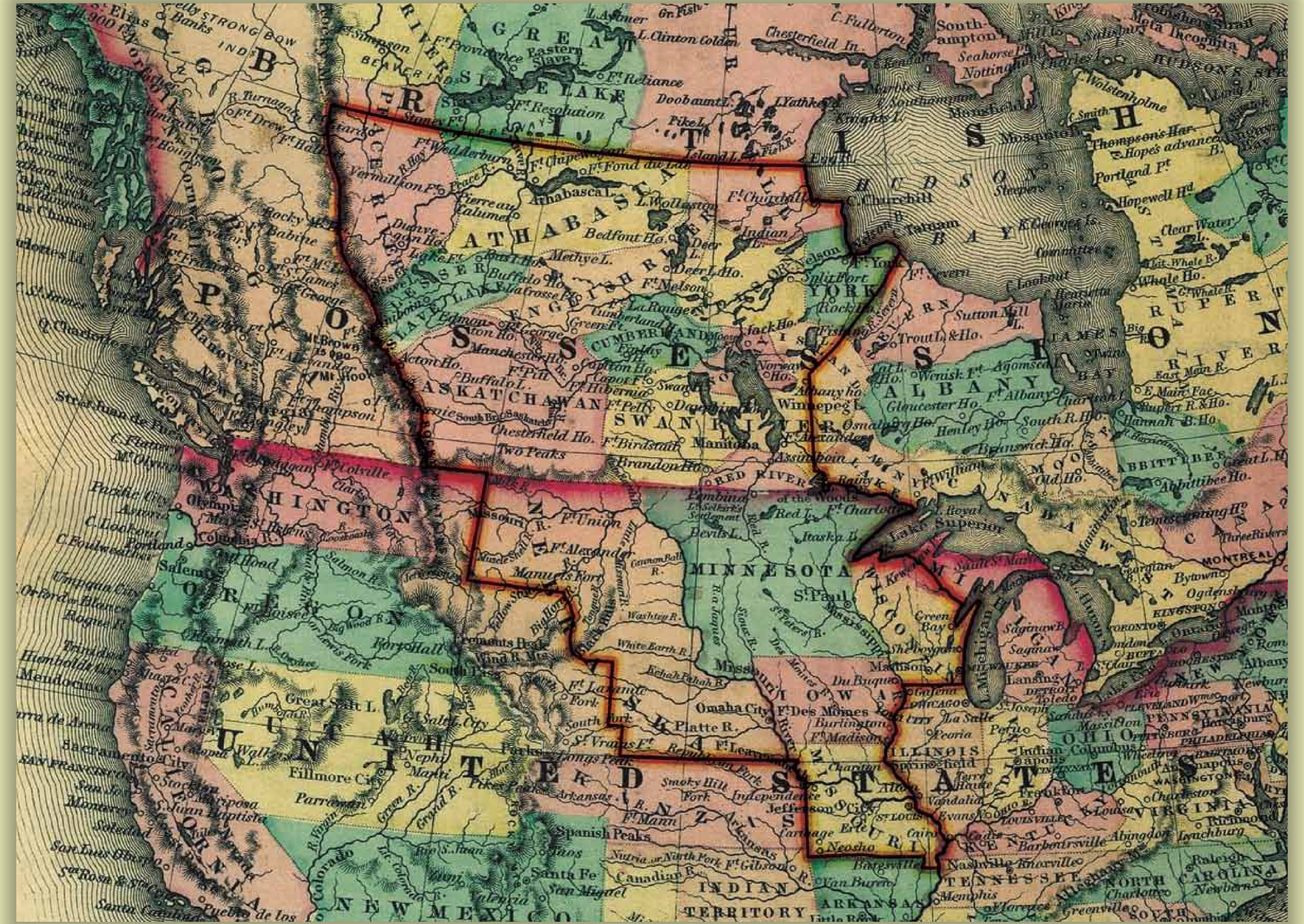
References

1. www.eia.doe.gov/oiaf/1605/ggccebro/chapter1.html (accessed August 2009).
2. www.eia.doe.gov/emeu/aer/contents.html (accessed August 2009).
3. www.instituteforenergyresearch.org/pdf/bradley/Bradley_app_A.pdf (accessed August 2009).
4. www.sjgs.com/history.html (accessed August 2009).
5. www.eia.doe.gov/kids/history/timelines/energy.html (accessed August 2009).
6. www.pbs.org/now/science/climatechange.html (accessed August 2009).
7. www.eia.doe.gov/emeu/aer/txt/ptb1601.html (accessed August 2009).
8. www.bts.gov/publications/national_transportation_statistics/2005/html/table_automobile_profile.html (accessed August 2009).
9. http://hypertextbook.com/facts/2001/MarinaStasenko.shtml (accessed August 2009).
10. www.epa.gov/climatechange/effects/index.html (accessed August 2009).
11. http://earthobservatory.nasa.gov/Library/Giants/Arrhenius (accessed August 2009).
12. www.fe.doe.gov/programs/sequestration/partnerships (accessed August 2009).
13. Jensen, M.D., Steadman, E.N., and Harju, J.A., 2005, CO_2 source characterization of the PCOR Partnership region: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center, June 2005.
14. www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm; www.eia.doe.gov/emeu/iea/carbon.html Table H.1 CO_2 World Carbon Dioxide Emissions from the Consumption and Flaring of Fossil Fuels (million metric tons of carbon dioxide), 1980–2006; http://unfccc.int/national_reports/annex_i_ghg_incentives/national_inventories_submissions/items/4771.php Canada NIR document.
15. www.netl.doe.gov/technologies/oil-gas/publications/eordrawings/Color/colop.pdf (accessed August 2009).
16. Fischer, D.W., Smith, S.A., Peck, W.D., LeFever, J.A., LeFever, R.D., Helms, L.D., Sorensen, J.A., Steadman, E.N., and Harju, J.A., 2005, Sequestration potential of the Madison of the northern Great Plains aquifer system (Madison geological sequestration unit): Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.
17. Fischer, D.W., Sorensen, J.A., Smith, S.A., Steadman, E.N., and Harju, J.A., 2005, Potential CO_2 storage capacity of the Lower Cretaceous aquifer system in the PCOR Partnership area: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.
18. www.fe.doe.gov/programs/oilgas/environment/Water_Resources_R&D.html (accessed August 2009).
19. Burruss, R., 2003, CO_2 adsorption in coals as a function of rank and composition—a task in USGS research on geologic sequestration of CO_2: The Second International Forum on Geologic Sequestration of CO_2 in Deep, Unminable Coal Seams (Coal-Seq II), March 6 and 7, 2003, in Washington, D.C., www.coal-seq.com/Proceedings2003/Burruss.pdf. (accessed August 2009).
20. Nelson, C.R., Steadman, E.N., and Harju, J.A., 2005, Geologic CO_2 sequestration potential of lignite coal in the U.S. portion of the Williston Basin: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.
21. Bachu, S.B., Steadman, E.N., and Harju, J.A., 2005, Carbon dioxide storage capacity in Upper Cretaceous–Tertiary Ardley coals in Alberta: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.
22. Nelson, C.R., Steadman, E.N., and Harju, J.A., 2005, Geologic CO_2 sequestration potential of the Wyodak–Anderson coal zone in the Powder River Basin: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.
23. Mann, G.E., 1974, The Prairie Pothole Region—zone of environmental opportunity: Naturalist, v. 25, no. 4, p. 2, C. 7.
24. Wilkins, K.A., Otto, M.C., and Koneff, M.D., 2006, Trends in duck breeding populations, 1995–2006: U.S. Department of the Interior, Washington, D.C., 26 p.
25. Gleason, R.A., Euliss, N.H. Jr., McDougal, R., Kermes, K.E., Steadman, E.N., and Harju, J.A., 2005, Potential of restored prairie wetlands in the glaciated North American prairie to sequester atmospheric carbon: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.
26. http://fossil.energy.gov/programs/sequestration/capture/index.html (accessed August 2009).
27. www.netl.doe.gov/technologies/carbon_seq/core_rd/co2capture.html (accessed August 2009).
28. www40.statcan.gc.ca/l01/cst01/prim71-eng.htm (accessed August 2009).
29. www.eia.doe.gov/bookshelf/brochures/epa/epa.html (accessed August 2009).
30. www1.agric.gov.ab.ca./$department/deptdocs.nsf/all/sdd11870/$FILE/table74.pdf (accessed August 2009).
31. www.nass.usda.gov (accessed August 2009).
32. www.wipapercouncil.org/industry.htm (accessed August 2009).

Photo and Image Credits

Except for those noted below, all photos and images were created by the EERC or obtained from royalty-free stock.

Page 2. Barnyard lignite: Vachon, John, 1940, FSA supervisor looking at pile of "barnyard lignite," America from the Great Depression to World War II: Photographs from the FSA-OWI, 1935–1945. http://memory.loc.gov/ammem/fsowhome.html [fsa 8c18205] (accessed July 2005).
Gary, Indiana, Steel Plant: Haines Photo Company, 1910, Indiana Steel Co. #1, Gary, Indiana, Taking the Long View: Panoramic Photographs, 1851–1991. http://memory.loc.gov/ammem/collections/panoramic_photo/index.html [pan 6a19311 http://hdl.loc.gov/loc.pnp/pan.6a19311] (accessed July 2005).
Signal Hill, California: Aerograph Company, 1923, Signal Hill, Taking the Long View: Panoramic Photographs, 1851–1991. http://memory.loc.gov/ammem/collections/panoramic_photo/index.html [pan 6a17401 http://hdl.loc.gov/loc.pnp/pan.6a17401] (accessed July 2005).
Page 4. www.vistawallpaper.org/vista-space-wallpapers/free-the-planet-earth-wallpaper (accessed July 20009).
Page 5. Image of Svante: www.nndb.com/people/875/000092599 (accessed August 2009).
Page 6. Carbon cycle. Genome Management Information System, Oak Ridge National Laboratory, http://genomics.energy.gov/gallery/carboncycling/detail.np/detail-24.html (accessed August 2009).
Page 8. Compact fluorescent bulb: Tiago Silva.
Page 9. Weyburn photo: Courtesy of PTRC and the IEA GHG Weyburn CO_2 Monitoring and Storage Project.
Page 13. Prairie Pothole Region: Ducks Unlimited.
Page 17. Center photo by Lynn Betts, USDA Natural Resources Conservation Service.
Page 20. Ag-related processing: Lincolnland Agri-Energy; Cement kiln: Gas Technology Institute.
Page 27. Evolution of life "Tower of Time" from John Gurche.
Page 29. Cross section modified from Ground Water Atlas of the United States, Montana, North Dakota, South Dakota, Wyoming. HA 730-I. http://pubs.usgs.gov/ha/ha730/ch_i/gif/I011.GIF (accessed July 2008).
Page 35. Cross section modified from Ground Water Atlas of the United States, Montana, North Dakota, South Dakota, Wyoming. HA 730-I. http://pubs.usgs.gov/ha/ha730/ch_i/gif/I052.GIF (accessed July 2008).
Page 42. North Dakota State University.
Page 51. Spectra Energy.
Page 55. Great Plains Gasification Plant, Dakota Gasification Company.
Page 57. Canadian Parliament: www.wordpress.com (accessed August 2009).
Back North America. No. 2. Published by J.H. Colton & Co., No 172 William St., New York. Entered according to the Act of Congress in the year 1855 by J.H. Colton & Co. in the Clerk's Office of the District Court of the United States for the Southern District of New York. Published 1857.



The PCOR Partnership region superimposed on an 1857 map of North America published by J.H. Colton & Co.