PCOR Partnership ATLAS

2nd Edition, Revised 2008

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

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Introduction

Global climate change is considered to be one of the most pressing environmental concerns of our time. This is due in part to the potential magnitude of the changes it could cause and also to the immense economic, technological, and lifestyle changes that may be necessary in order to respond to it. Although uncertainty still clouds the science of climate change, there is strong indication that we may have to significantly reduce anthropogenic greenhouse gas (GHG) emissions. Carbon sequestration 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 sequestration technologies in order to provide a safe, effective, and efficient means of managing the carbon dioxide emissions across the center of the continent.

The regional characterization activities conducted under 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 sequestration. 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 sequestration. The Prairie Pothole Region, 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 lay geologic formations that hold tremendous potential to store CO_2. Oil fields well suited for sequestering CO_2 can be found in roughly half the region, while formations of limestone, sandstone, and coal suitable for CO_2 storage exist in basins that, in some cases, extend over thousands of square miles. In many cases, large sources in the region are proximally located to large-capacity sinks, and in some cases, key infrastructure is already in place.

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

"Barnyard Lignite," North Dakota, 1940

Indiana Steel, ca. 1910

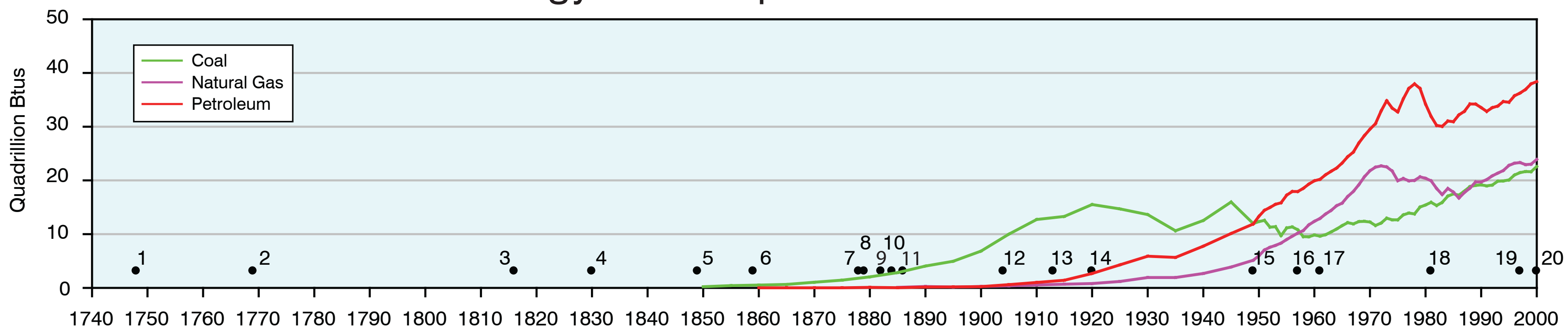
Signal Hill, California, ca. 1923

Modern refinery, Billings, Montana, 2004

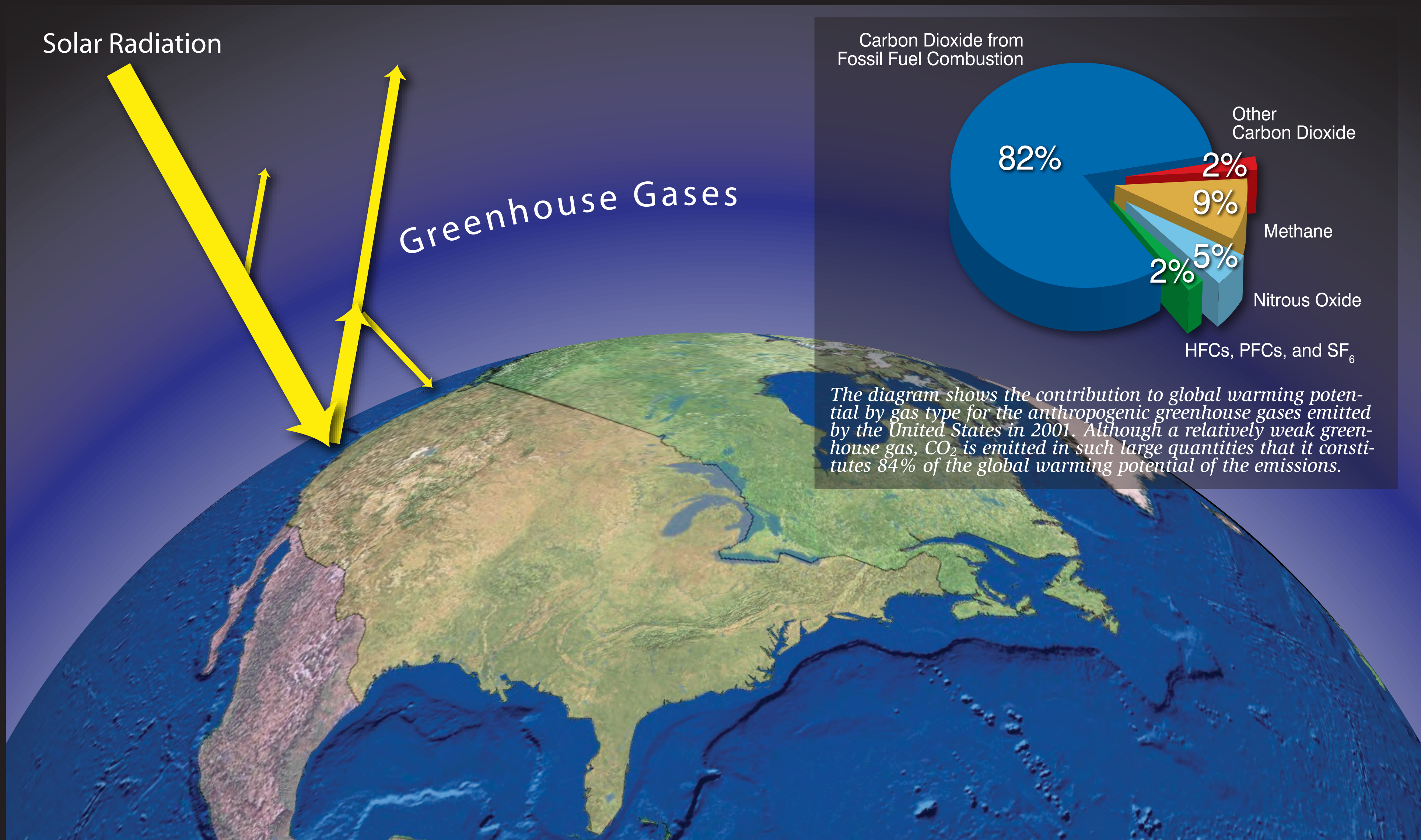
A Change Is in the Air

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 to grind 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]

Energy Consumption in the United States[2]



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]



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

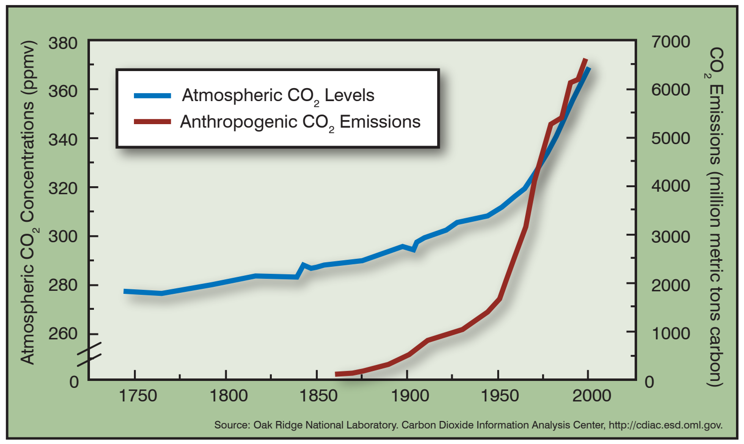
Greenhouse Effect

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

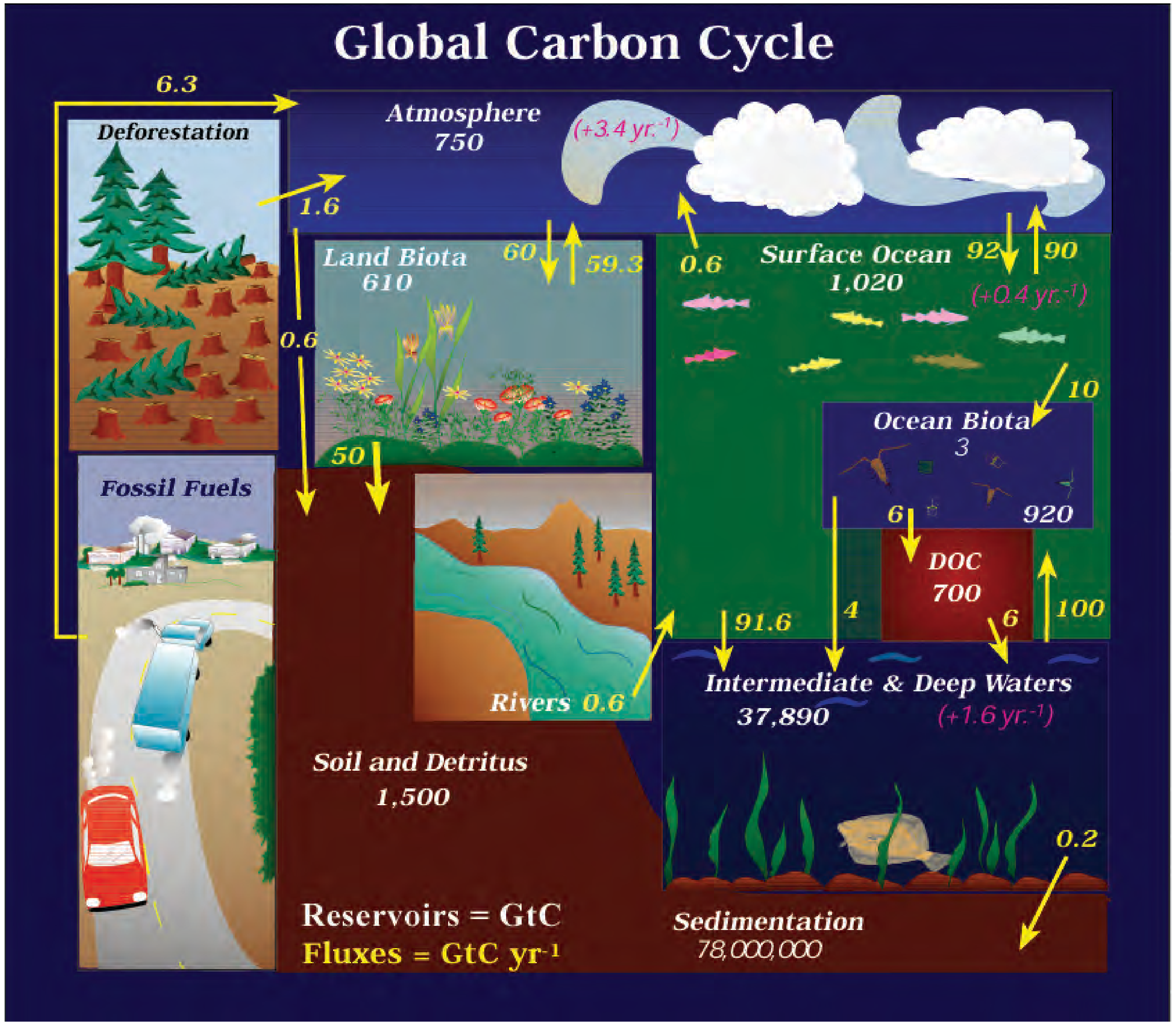
Without this natural "greenhouse effect," global temperatures would be considerably lower than they are now, and life as it is known would not be possible. However, problems may arise when the atmospheric concentration of GHGs increases.[10]

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

Human (anthropogenic) activity, including the use of fossil fuel, generates a significant volume of 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.



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



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

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

What Is CO_2?

Carbon dioxide (chemical formula CO_2) is a colorless, naturally occurring gas composed of one atom of carbon and two atoms of oxygen. At temperatures below –78°C (–109°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 again form CO_2.

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.

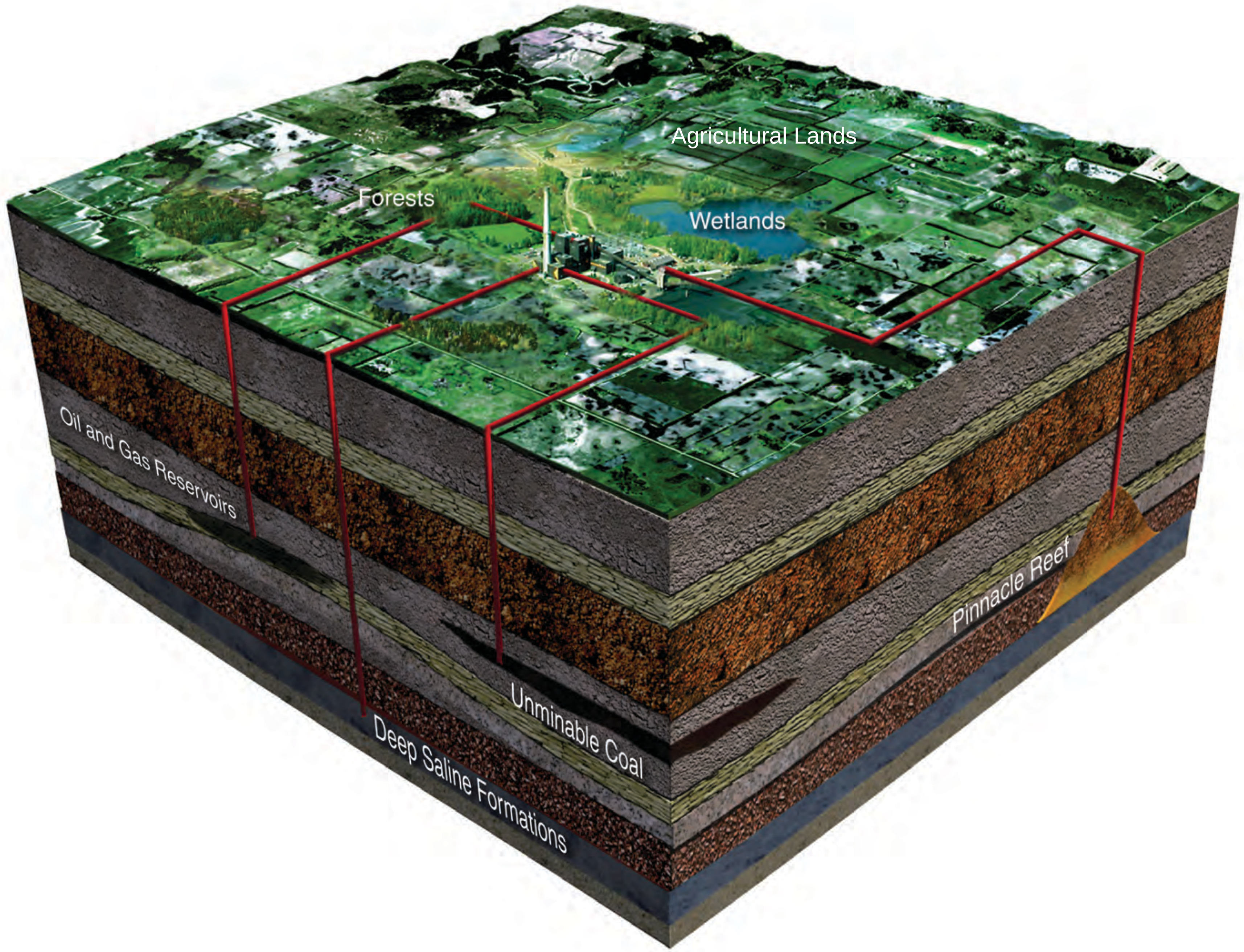

ETHANOL POWERED

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 sequestration.

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

There are two types of sequestration: *direct* and *indirect*. Direct, or geologic, sequestration involves capturing CO_2 at a source before it can be emitted to the atmosphere. The most efficient concept would use specialized 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 (geologic sequestration) or into the deep ocean. Indirect, or terrestrial, sequestration removes CO_2 from the atmosphere. Indirect sequestration employs land management practices that boost the ability of natural CO_2 sinks, like plants and soils, to remove carbon as CO_2 from the atmosphere, regardless of its source. Opportunities for indirect sequestration can be found in forests, grasslands, wetlands, and croplands.



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

Geologic Sequestration

Geologic sequestration 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 sequestration, 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 sequestration 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.

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 be dissolved in any fluids, such as water or oil, that are present in the formation, while another portion will be available to react with rock minerals. When CO_2 dissolves in oil, it acts as a solvent, reducing oil viscosity and increasing its mobility. The sequestration of CO_2 in a supercritical form is beneficial for two reasons: 1) the supercritical state maximizes the number of CO_2 molecules that can be injected into a given volume and 2) if injected into an oil reservoir, supercritical CO_2 can increase oil production, which, in turn, can be used to pay for the capture and transportation of the CO_2 from the original source.

As with many disciplines and technologies, a precise and descriptive vocabulary is needed to adequately describe and discuss the sequestration 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 sequestered in sedimentary basins by the following mechanisms: 1) stratigraphic and structural trapping in depleted oil and gas reservoirs, 2) solubility trapping in reservoir oil and formation waters, 3) adsorption trapping in unminable coal seams, 4) cavern trapping in salt structures, and 5) mineral immobilization.

NASA's Earth Observatory has created a series of images that show the color of the Earth's surface for each month of 2004 at very high resolution (500 meters/pixel) at a global scale. This image is of North America in June.

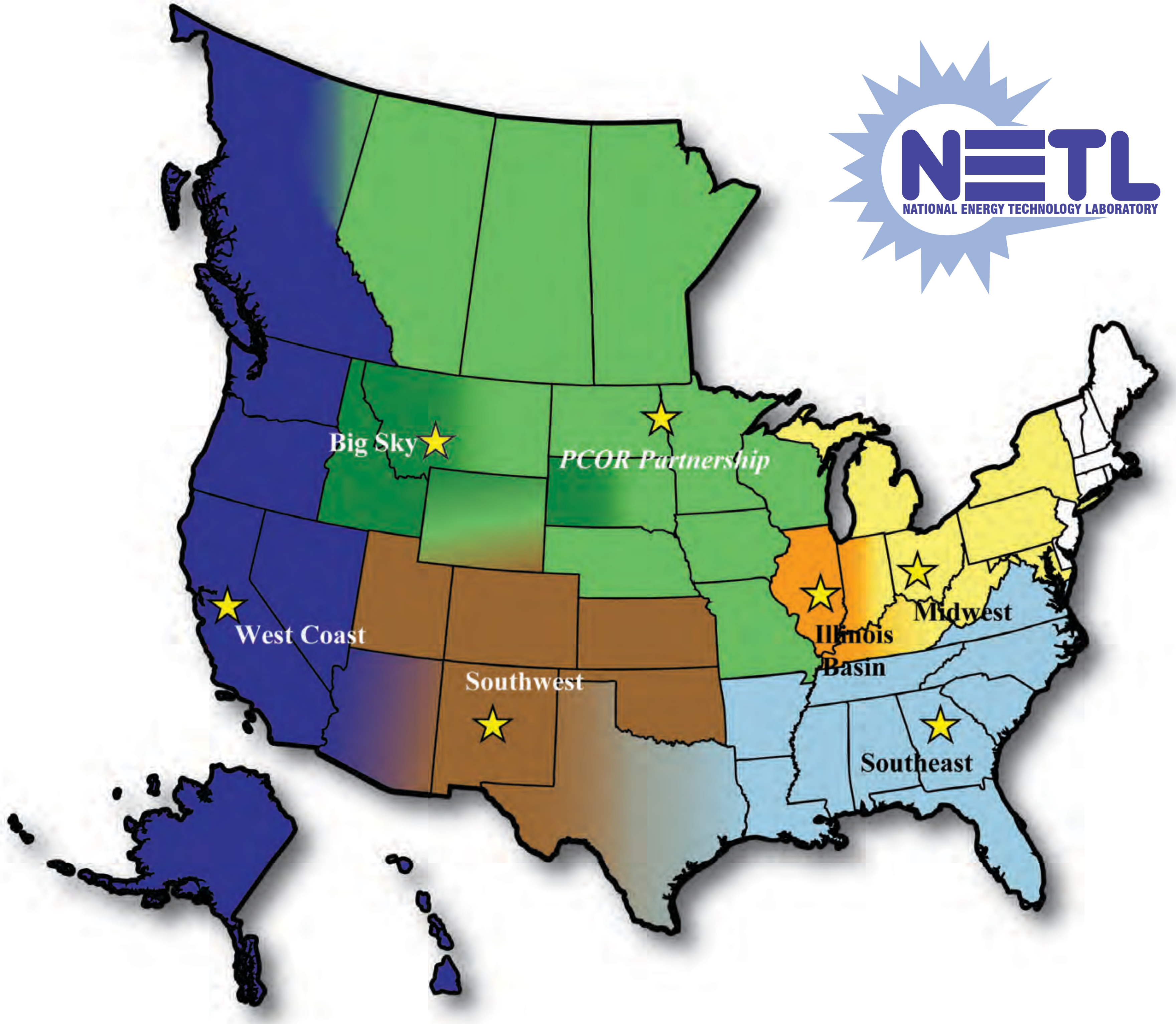
Terrestrial Sequestration

Terrestrial sequestration 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 sequestration does not store CO_2 as a gas but 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 sequestration 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 sequestered in the soil as long as the land is undisturbed and conservation land management practices are continued.

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


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

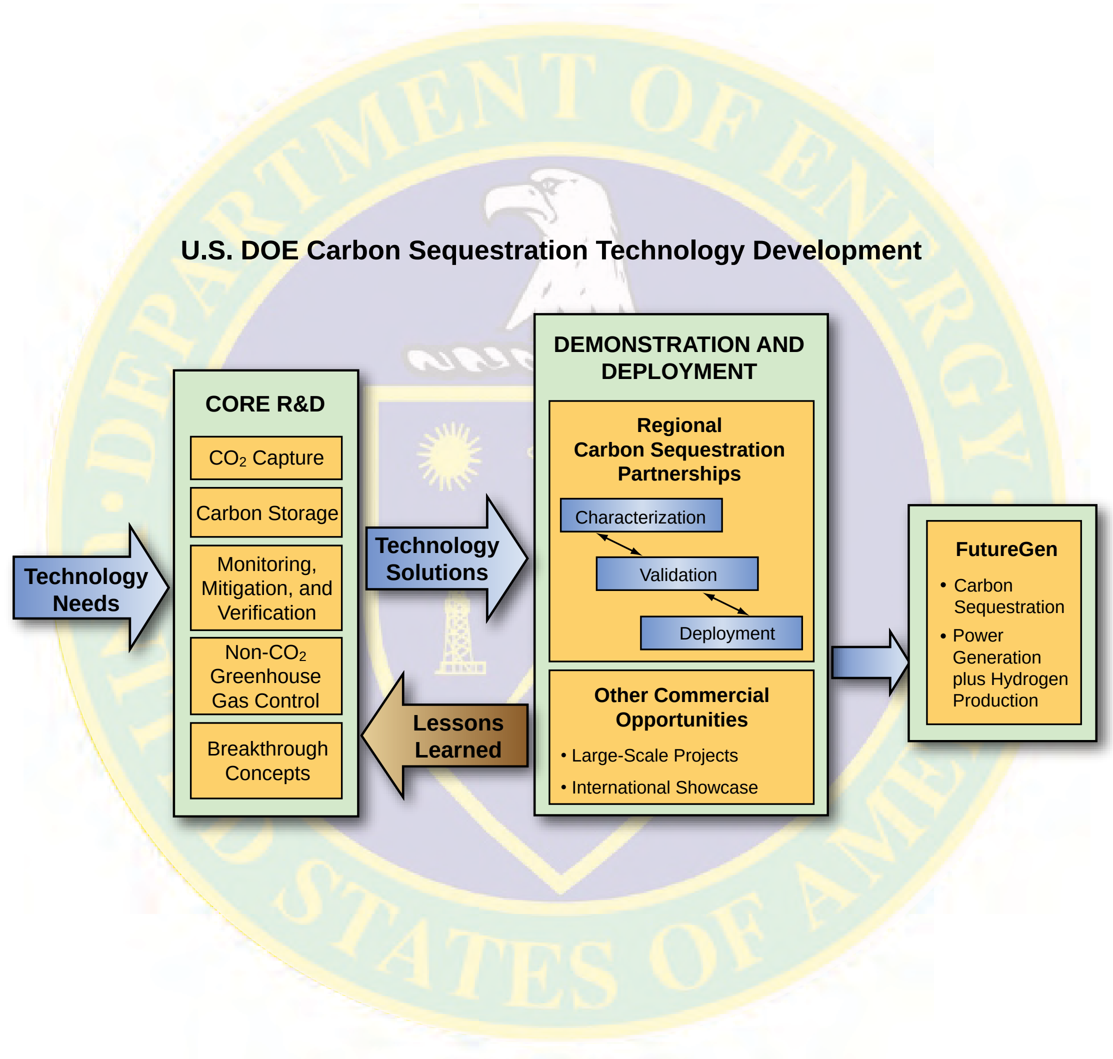
DOE's Carbon Sequestration Regional Partnerships

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

On August 16, 2003, following a competitive evaluation, Energy Secretary Spencer Abraham named seven teams, called Regional Carbon Sequestration Partnerships, to evaluate and promote the carbon sequestration technologies and infrastructure best suited to their unique regions. The original partnerships included leaders from more than 140 organizations spanning 33 states, three American Indian nations, and two Canadian provinces. By February 2007, the partnerships had expanded to include 350 organizations spanning 41 states, three American Indian nations, and four Canadian provinces.[12]

Today, the seven U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) partnerships are developing the framework needed to validate and potentially deploy carbon sequestration technologies. They are evaluating numerous sequestration 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 sequestration be deployed on a wide scale in the future.




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

The PCOR Partnership

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

- 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 reservoirs, and unminable coals in the PCOR Partnership region represent opportunities for direct (geologic) sequestration projects.
- The PCOR Partnership region is currently home to the Weyburn direct sequestration EOR demonstration project. There are four additional CO_2 sequestration field validation test sites in the PCOR Partnership region.
- Croplands, wetlands, rangelands, and forests in the PCOR Partnership region represent opportunities for indirect (terrestrial) sequestration projects.
- The PCOR Partnership region is currently home to several indirect sequestration research projects involving wetlands, cultivated land, prairie, and forest.

Current PCOR Partnership Partners

- NETL
- EERC Energy & Environmental Research Center
- UND University of North Dakota Grand Forks
- ABENGOA BIOENERGY
- ADVANCED GEOTECHNOLOGY
- AIR PRODUCTS
- Alberta ENERGY
- EUB Alberta Energy and Utilities Board
- AGS Alberta Geological Survey
- ALLETE
- Ameren
- ACCCE AMERICAN COALITION FOR CLEAN COAL ELECTRICITY
- AMERICAN LIGNITE ENERGY
- Apache CANADA LTD.
- BASIN ELECTRIC POWER COOPERATIVE A Touchstone Energy Cooperative
- Blue Source
- BNI COAL
- BRITISH COLUMBIA Ministry of Energy and Mines
- Carbozyme Inc.
- Great Plains Dakota Gasification Company
- Ducks Unlimited Canada
- DUCKS UNLIMITED
- Eagle Operating Inc.
- EICCD
- ENBRIDGE
- Encore Acquisition Company
- Environment Canada
- EXCELSIOR ENERGY
- Fischer Oil and Gas, Inc.
- GREAT NORTHERN
- GREAT RIVER ENERGY
- HESS
- HUNTSMAN
- INTERSTATE OIL AND GAS COMPACT COMMISSION 1935
- DNR
- LIGNITE Energy COUNCIL
- Manitoba
- MARATHON
- MEG Energy Corp
- Melzer COnsulting
- MINNESOTA GEOLOGICAL SURVEY 1872
- minnesota power
- Minnkota Power COOPERATIVE, INC. Your Touchstone Energy Partner
- MISSOURI DEPARTMENT OF NATURAL RESOURCES
- MISSOURI RIVER ENERGY SERVICES
- MONTANA-DAKOTA UTILITIES CO. A Division of MDU Resources Group, Inc.
- Montana Department of Environmental Quality
- National Commission on Energy Policy
- Natural Resources Canada
- Nexant
- NORTH AMERICAN COAL CORPORATION
- North Dakota DEPARTMENT OF COMMERCE OFFICE OF RENEWABLE ENERGY AND ENERGY EFFICIENCY
- North Dakota Department of Health
- NORTH DAKOTA GEOLOGICAL SURVEY 1895
- 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
- NORTH DAKOTA NATURAL RESOURCES TRUST
- NORTH DAKOTA PETROLEUM COUNCIL
- NDSU NORTH DAKOTA STATE UNIVERSITY
- OTTER TAIL POWER COMPANY
- PTRC
- Prairie Public
- Pratt & Whitney A United Technologies Company
- RAMGEN POWER SYSTEMS
- RPS Energy
- Saskatchewan Industry and Resources
- SaskPower
- Schlumberger
- Shell Canada Limited
- Spectra Energy
- Strategic West Energy Ltd.
- SUNCOR ENERGY
- TGS
- UNIVERSITY OF ALBERTA
- USGS science for a changing world
- WESTERN GOVERNORS' ASSOCIATION
- WESTMORELAND COAL COMPANY
- Wisconsin Department of Agriculture, Trade & Consumer Protection
- Xcel Energy

Current PCOR Partnership Partners

Since October 2005, the PCOR Partnership has brought together more than 75 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 direct and indirect sequestration, including value-added projects.

Current PCOR Partnership Partners:

- U.S. Department of Energy National Energy Technology Laboratory
- University of North Dakota Energy & Environmental Research Center
- Abengoa Bioenergy New Technologies
- Advanced Geotechnology, a division of Hycal Energy Research Laboratories, Ltd.
- Air Products and Chemicals
- Alberta Department of Energy
- Alberta Energy and Utilities Board
- Alberta Geological Survey
- ALLETE
- Ameren Corporation
- American Coalition for Clean Coal Electricity
- American Lignite Energy (ALE)
- Apache Canada Ltd.
- Basin Electric Power Cooperative
- Blue Source, LLC
- BNI Coal, Ltd.
- British Columbia Ministry of Energy, Mines and Petroleum Resources
- Carbozyme, Inc.
- Dakota Gasification Company
- Ducks Unlimited Canada
- Ducks Unlimited, Inc.
- Eagle Operating, Inc.
- Eastern Iowa Community College District
- Enbridge Inc.
- Encore Acquisition Company
- Environment Canada
- Excelsior Energy Inc.
- Fischer Oil and Gas, Inc.
- Great Northern Power Development, LP
- Great River Energy
- Hess Corporation
- Huntsman Corporation
- Interstate Oil and Gas Compact Commission
- Iowa Department of Natural Resources – Geological Survey
- Lignite Energy Council
- Manitoba Geological Survey
- Marathon Oil Company
- MEG Energy Corporation
- Melzer Consulting
- Minnesota Geological Survey – University of Minnesota
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Missouri Department of Natural Resources
- Missouri River Energy Services
- Montana–Dakota Utilities Co.
- Montana Department of Environmental Quality
- National Commission on Energy Policy
- Natural Resources Canada
- 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
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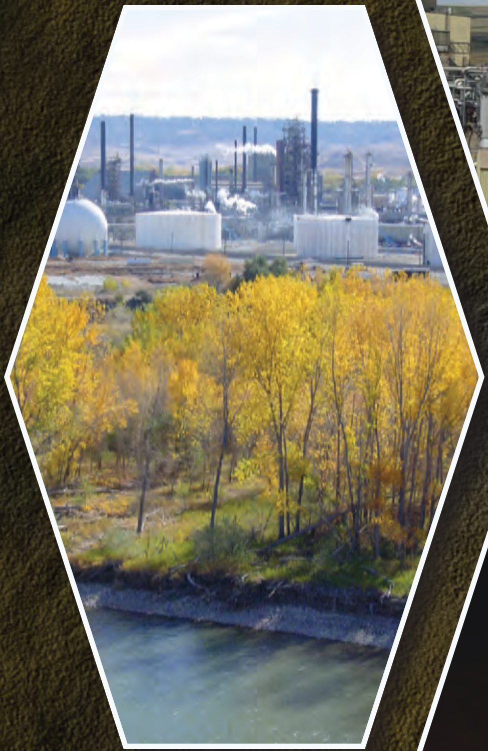
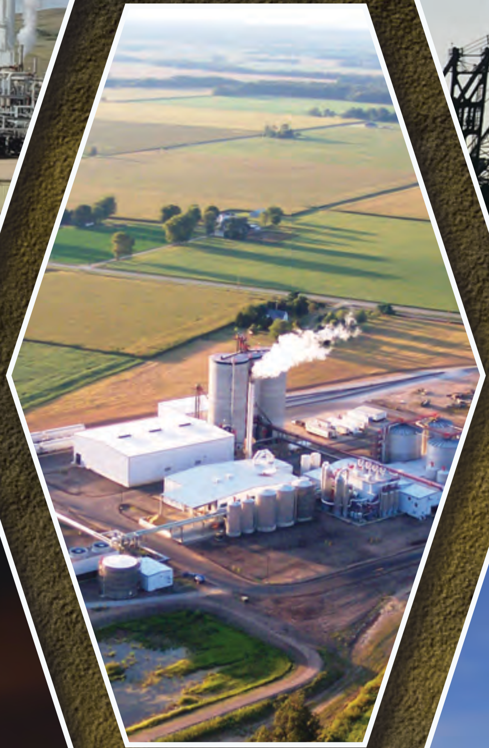
- Schlumberger
- Shell Canada Energy
- Spectra Energy
- Strategic West Energy Ltd.
- Suncor Energy Inc.
- TGS Geological Products and Services
- University of Alberta
- U.S. Geological Survey Northern Prairie Wildlife Research Center
- Western Governors' Association
- Westmoreland Coal Company
- Wisconsin Department of Agriculture, Trade and Consumer Protection
- Xcel Energy

Coal
Gasification Facility

Coal-Fired
Power Plant



Refinery



Ethanol Plant

Agricultural
Processing
Plant

Gas Processing
Plant

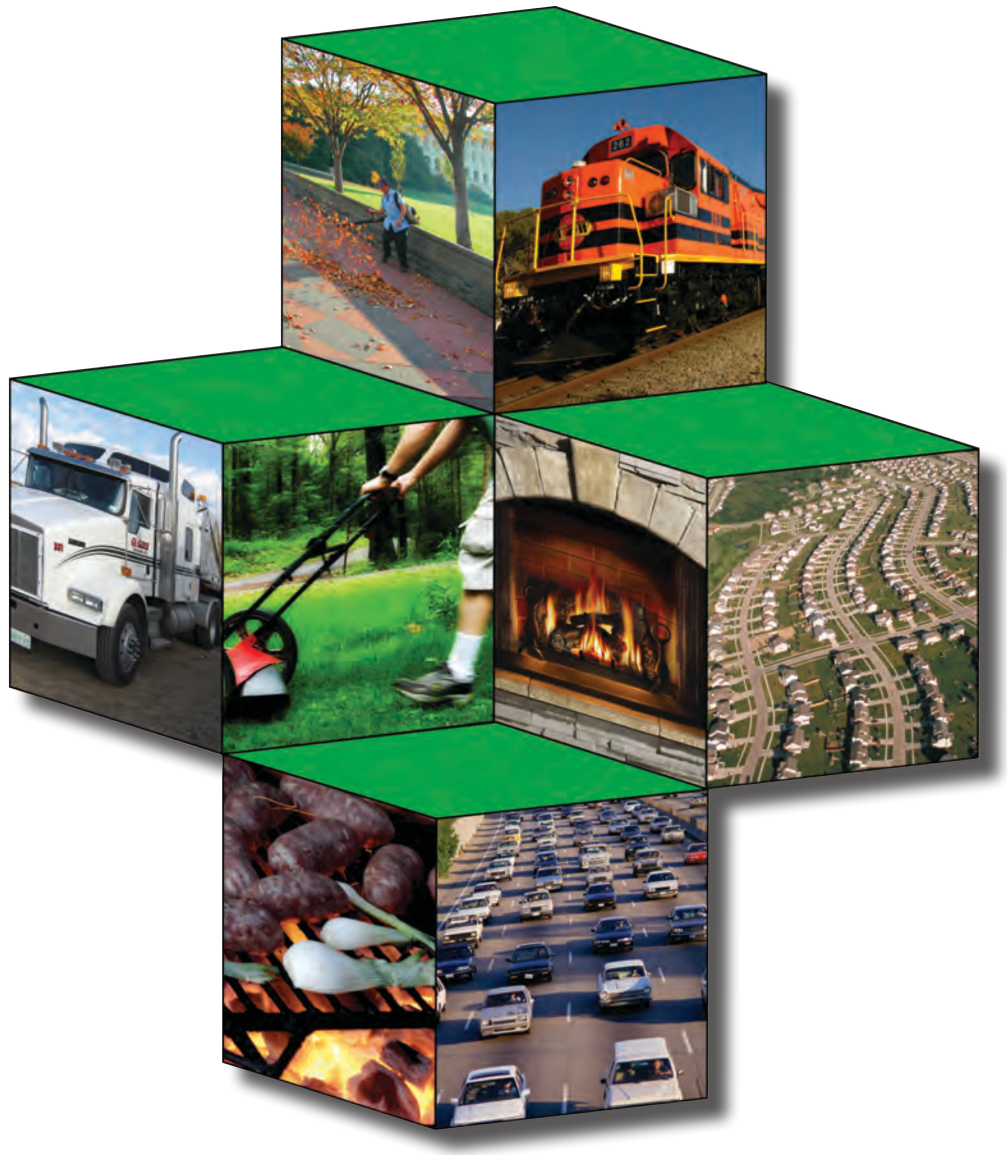
Cement Kiln

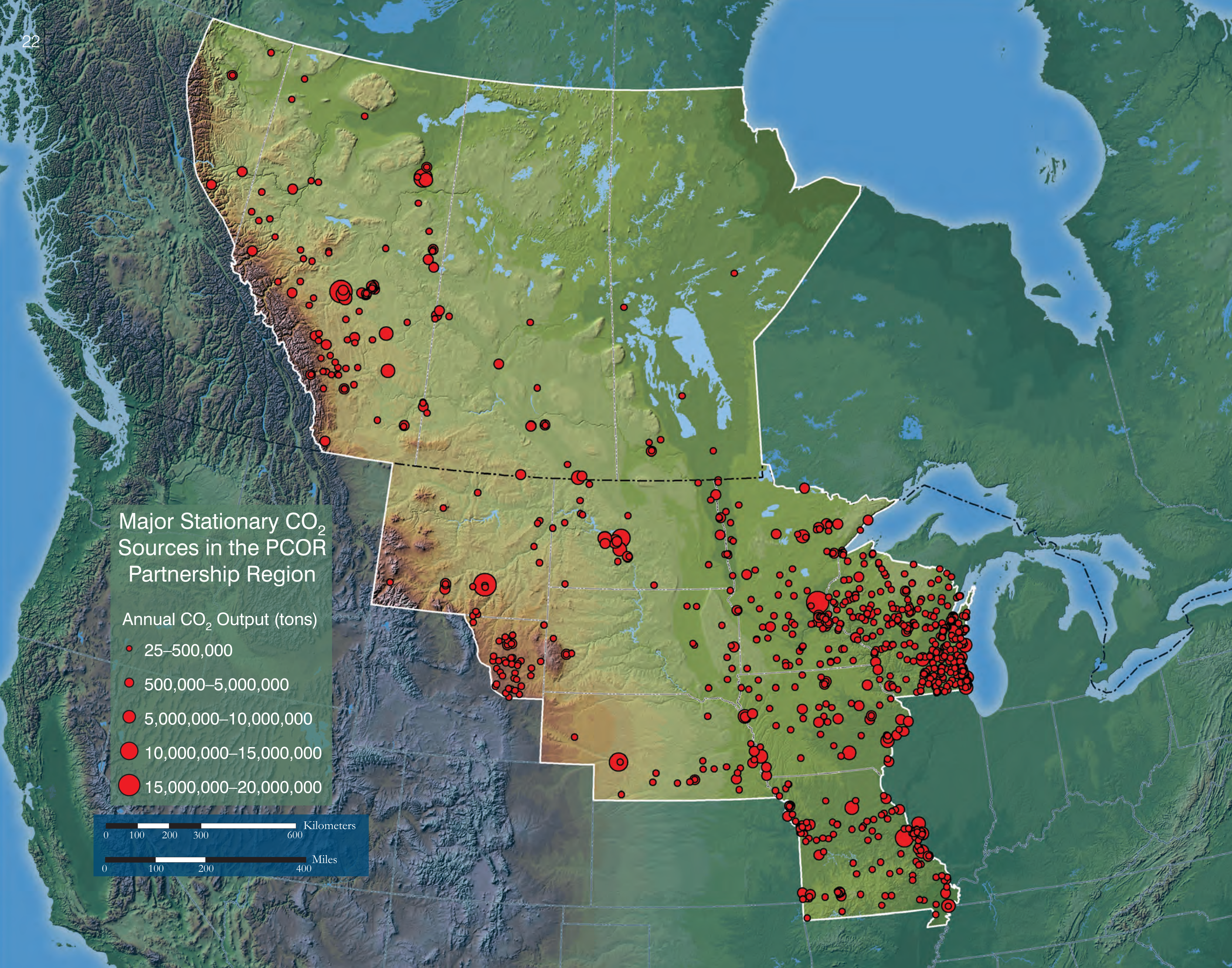
Anthropogenic CO_2 Sources

In 2004, the world produced approximately 30 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 (22%) of the global total, and Canada adds another 0.7 billion tons (over 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, chemicals, and ethanol production; and various manufacturing and industrial activities. These major stationary sources account for about 58% of anthropogenic CO_2 in the region. The PCOR Partnership is also working to implement terrestrial sequestration options that can capture and store CO_2 from the atmosphere.





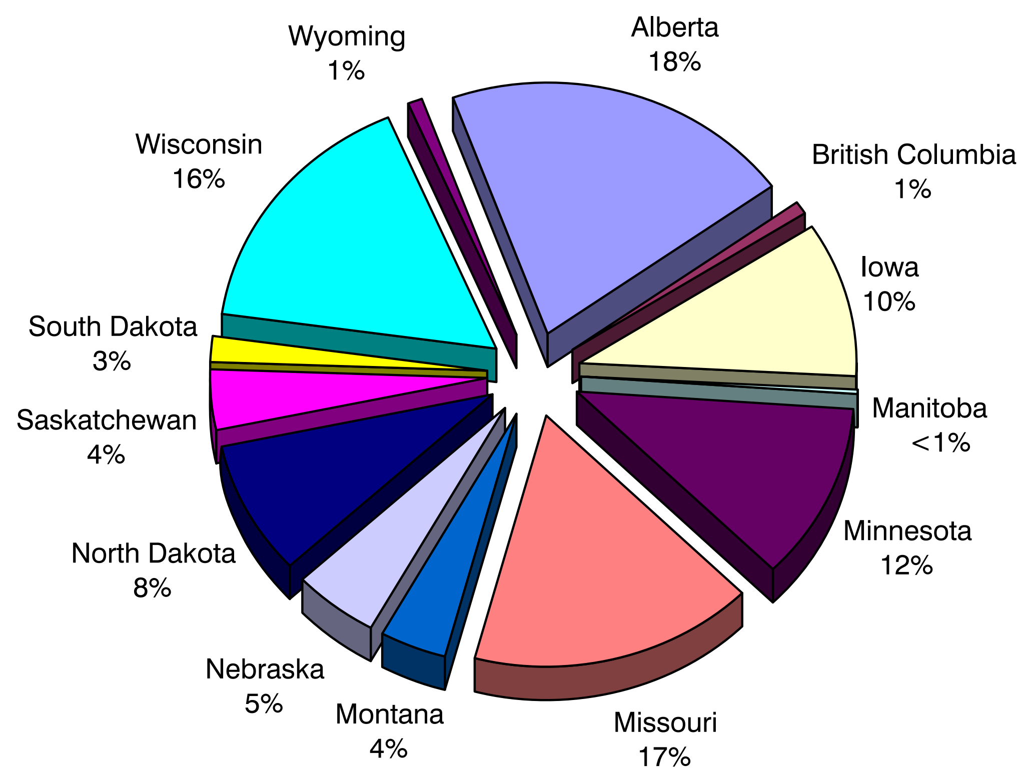
Major Stationary CO_2 Sources in the PCOR Partnership Region
Annual CO_2 Output (tons)
25–500,000
500,000–5,000,000
5,000,000–10,000,000
10,000,000–15,000,000
15,000,000–20,000,000
0 100 200 300 600 Kilometers
0 100 200 400 Miles

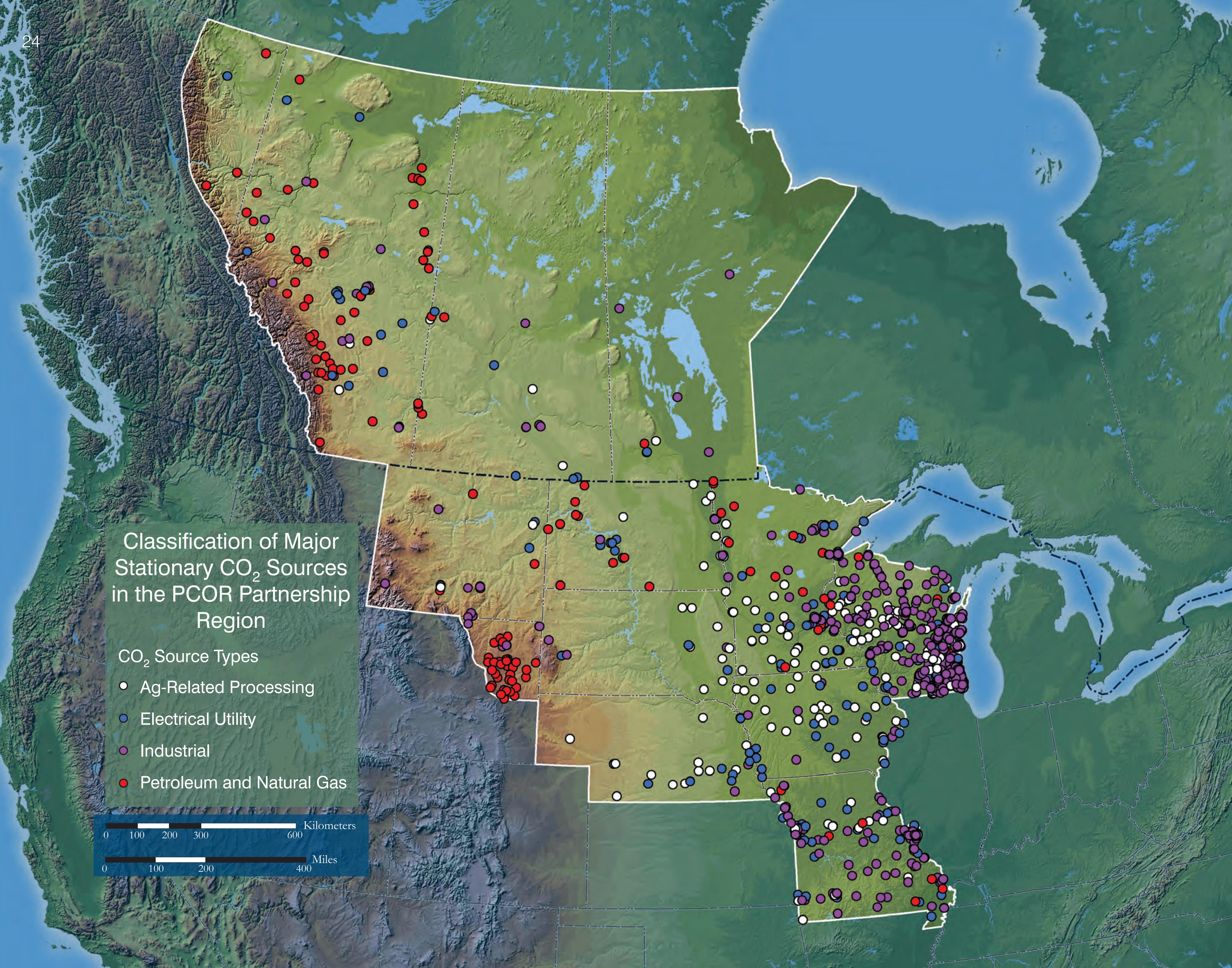
CO_2 Sources

The PCOR Partnership project has identified, quantified, and categorized 1545 stationary CO_2 sources in the region. These stationary sources have a combined annual CO_2 output of nearly 576 million tons or 9.9 trillion cubic feet. And, although not a target source of CO_2 for direct sequestration, 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 5000 tons for industrial and agricultural processing facilities. 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 sequestration opportunities. Many of the smaller sources are concentrated around more heavily industrialized metropolitan regions such as southeastern Minnesota, southeastern Wisconsin, and eastern Missouri.

Distribution of Annual CO_2 Output from Major Stationary Sources in the PCOR Partnership Region




Classification of Major Stationary CO_2 Sources in the PCOR Partnership Region
CO_2 Source Types
Ag-Related Processing
Electrical Utility
Industrial
Petroleum and Natural Gas
Kilometers
0 100 200 300 600
Miles
0 100 200 400

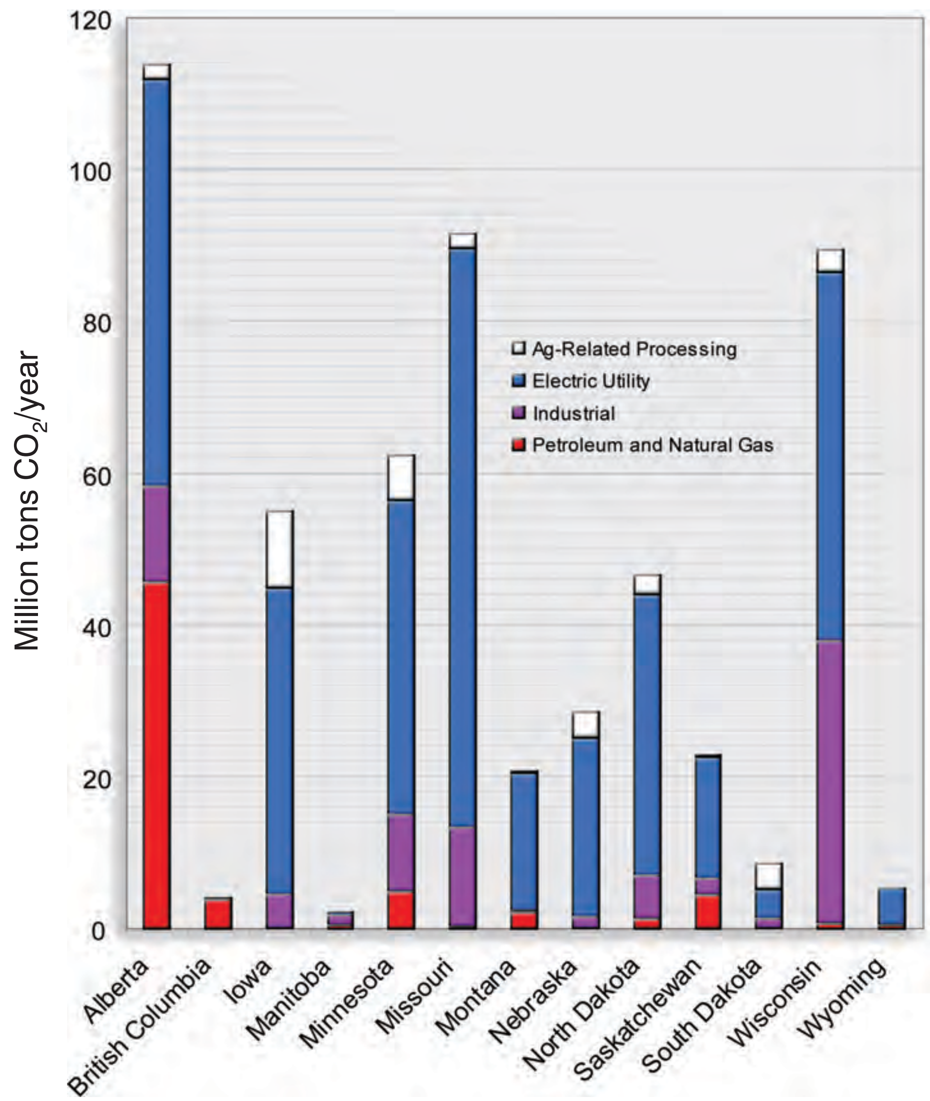
CO_2 Source Types

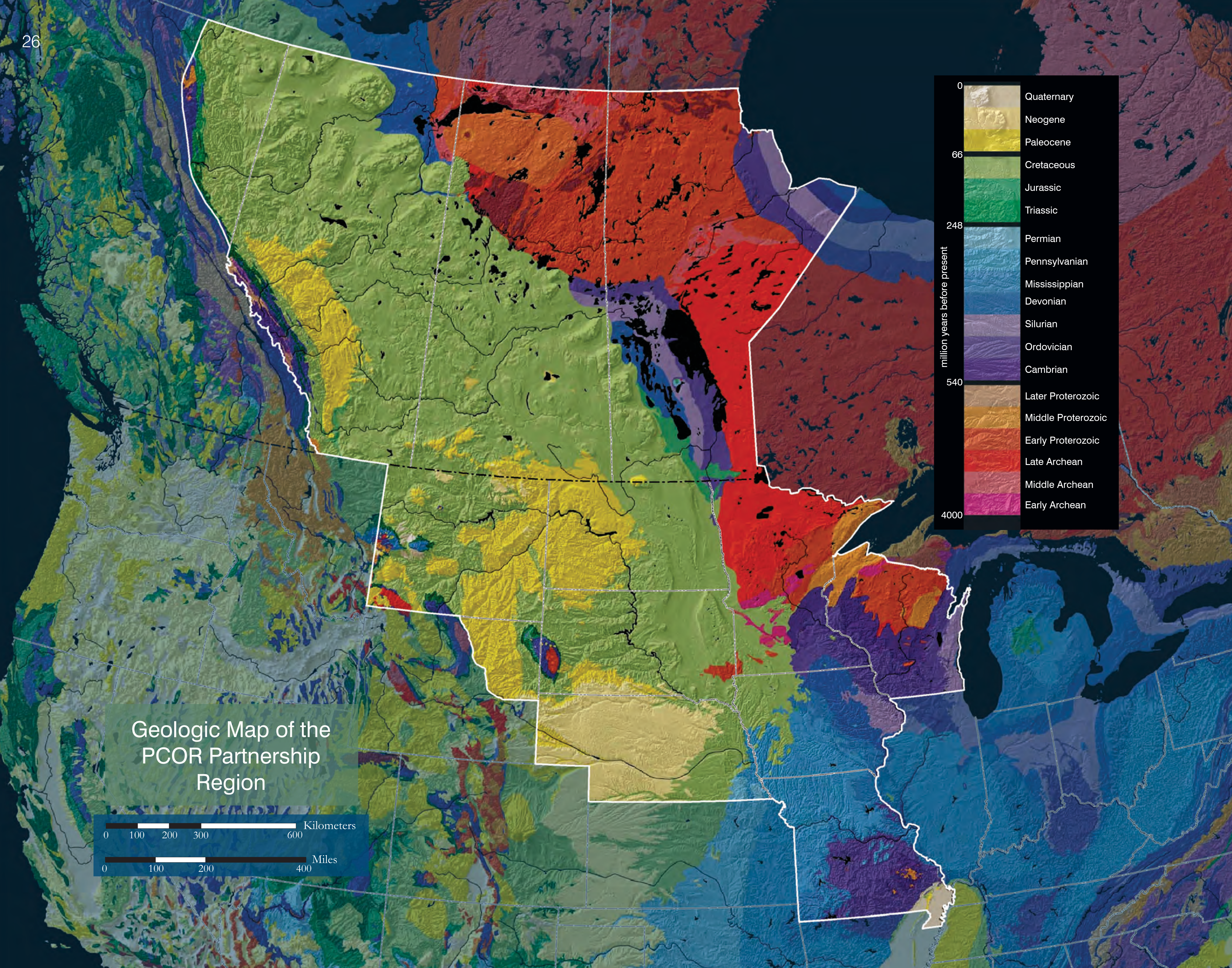
The geographic and socioeconomic diversity of the PCOR Partnership region is reflected in the diversity of the carbon dioxide sources found there. CO_2 is emitted from electricity generation; energy exploration and production activities; agricultural processing; fuel, chemicals, and ethanol production; and various manufacturing and industrial activities. The majority of the region's emissions come from just a few source types. About two-thirds of the CO_2 is emitted during electricity generation. 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.[13]

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, separation, and sequestration of CO_2 in many different scenarios.

Annual CO_2 Output by Major Source Categories for the States and Provinces in the PCOR Partnership Region




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

Geologic Framework

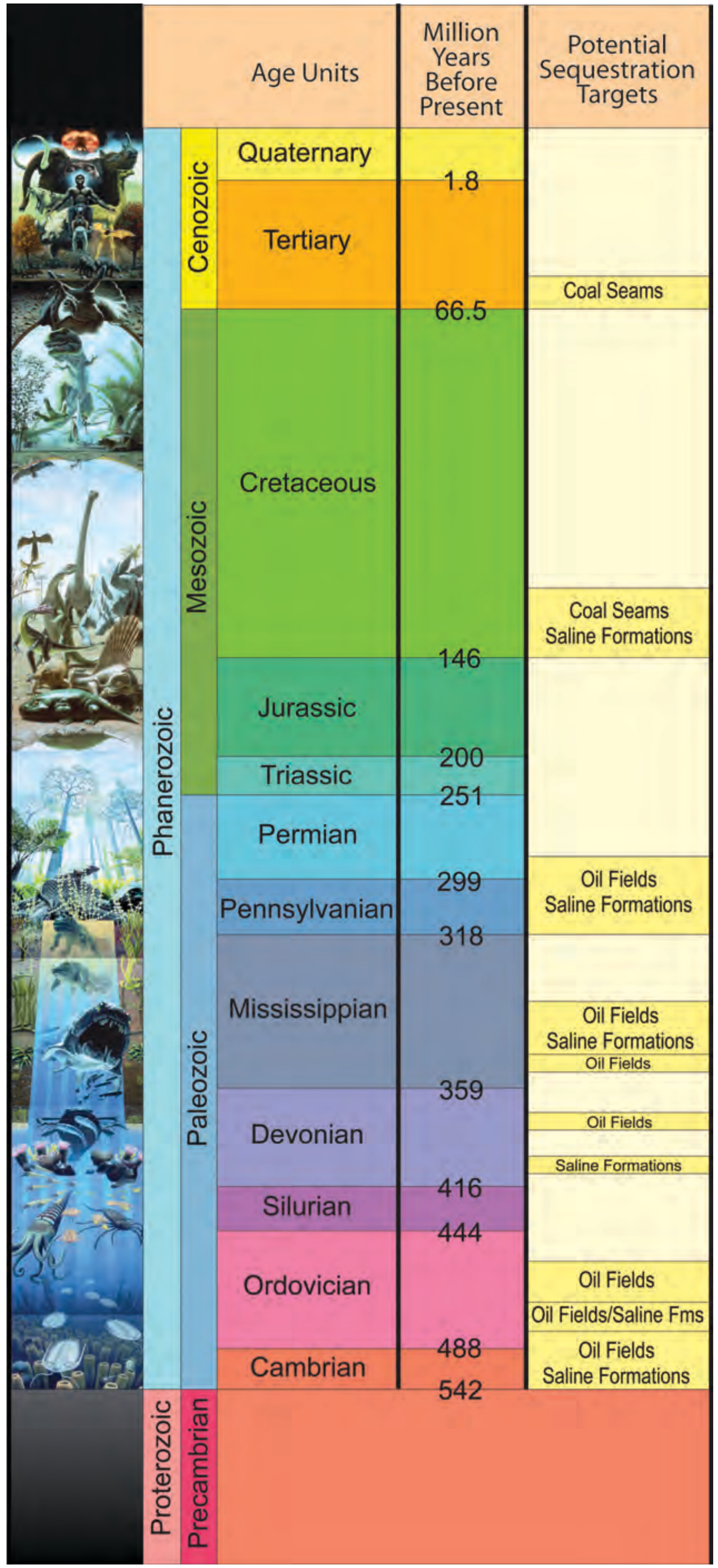
The same geologic framework that makes a large percentage of the PCOR Partnership region a significant producer of fossil fuels also creates prime opportunities for CO_2 sequestration. The western two-thirds of the region is underlain by great thicknesses of sedimentary rocks that span the entire stratigraphic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

The most extensive sequence of rocks in central North America is represented by the Cretaceous-aged marine sediments that were deposited in the former western interior seaway. This 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 sequestration.

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

In the millions of years since the seaway retreated, the central portion of the North American continent has been relatively stable. This tectonic stability is of prime importance with respect to safe and secure CO_2 sequestration in deep geologic formations.

Former extent of the Cretaceous-aged western interior seaway.




Major Depositional Basins in the PCOR Partnership Region
Sedimentary Basin
Alberta Basin
Williston Basin
Powder River Basin
Kennedy Basin
Denver–Julesberg Basin
Salina Basin
Forest City Basin
Illinois Basin
Midcontinental Rift System
Kilometers
0 100 200 300 600
Miles
0 100 200 400

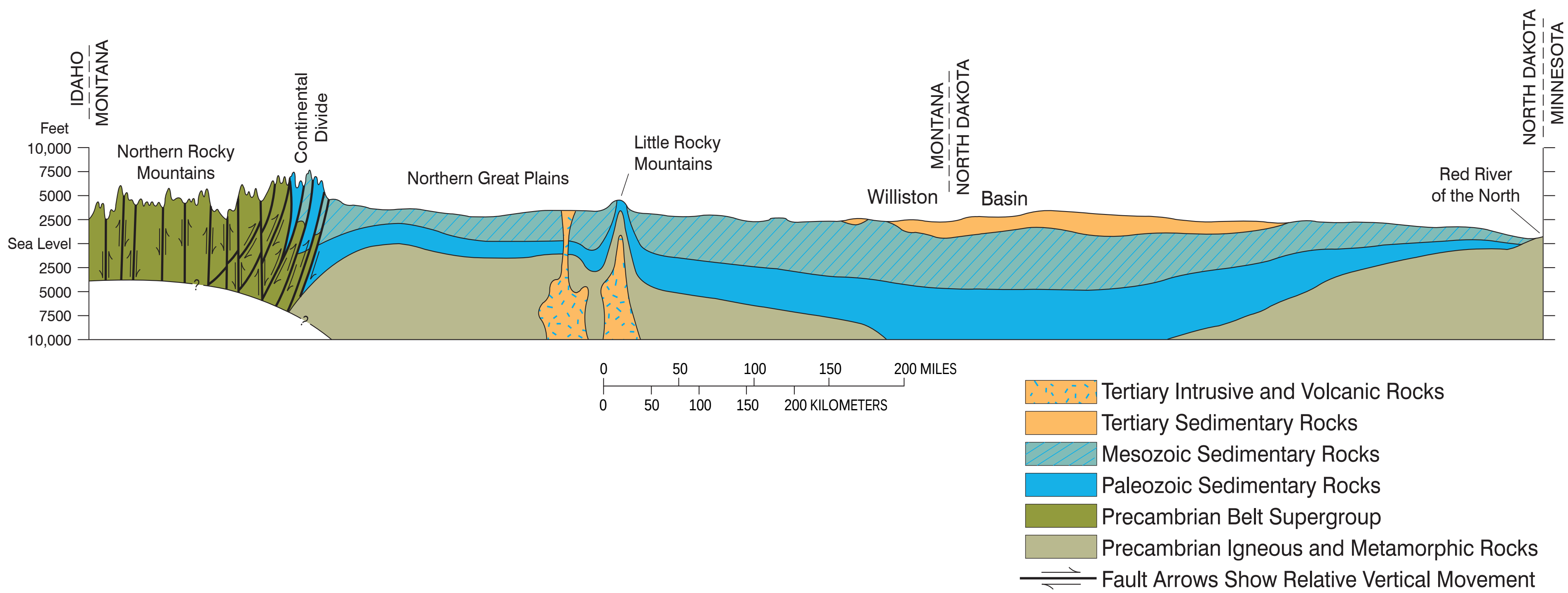
Sedimentary Basins

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 sequestering CO_2. Geologic sinks that may be suitable for long-term sequestration of CO_2 include both active and depleted petroleum reservoirs, deep saline formations, and coal seams, all of which are common in these basins.

While general information on the structural geology, lithostratigraphy, hydrostratigraphy, and petroleum geology of these basins is available, additional characterization data for specific 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 sequestration.

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 Midcontinental Rift System may be viable locations for CO_2 sequestration. 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 under Phase II of the PCOR Partnership will result in a better understanding of the potential for the sedimentary rocks of the Midcontinental Rift System to sequester large volumes of CO_2.




Distribution of Oil Fields in the PCOR Partnership Region
Oil Field
Sedimentary Basin
Alberta Basin
Williston Basin
Powder River Basin
Kennedy Basin
Denver–Julesberg Basin
Salina Basin
Forest City Basin
Midcontinental Rift System
Kilometers
0 100 200 300 600
Miles
0 100 200 400

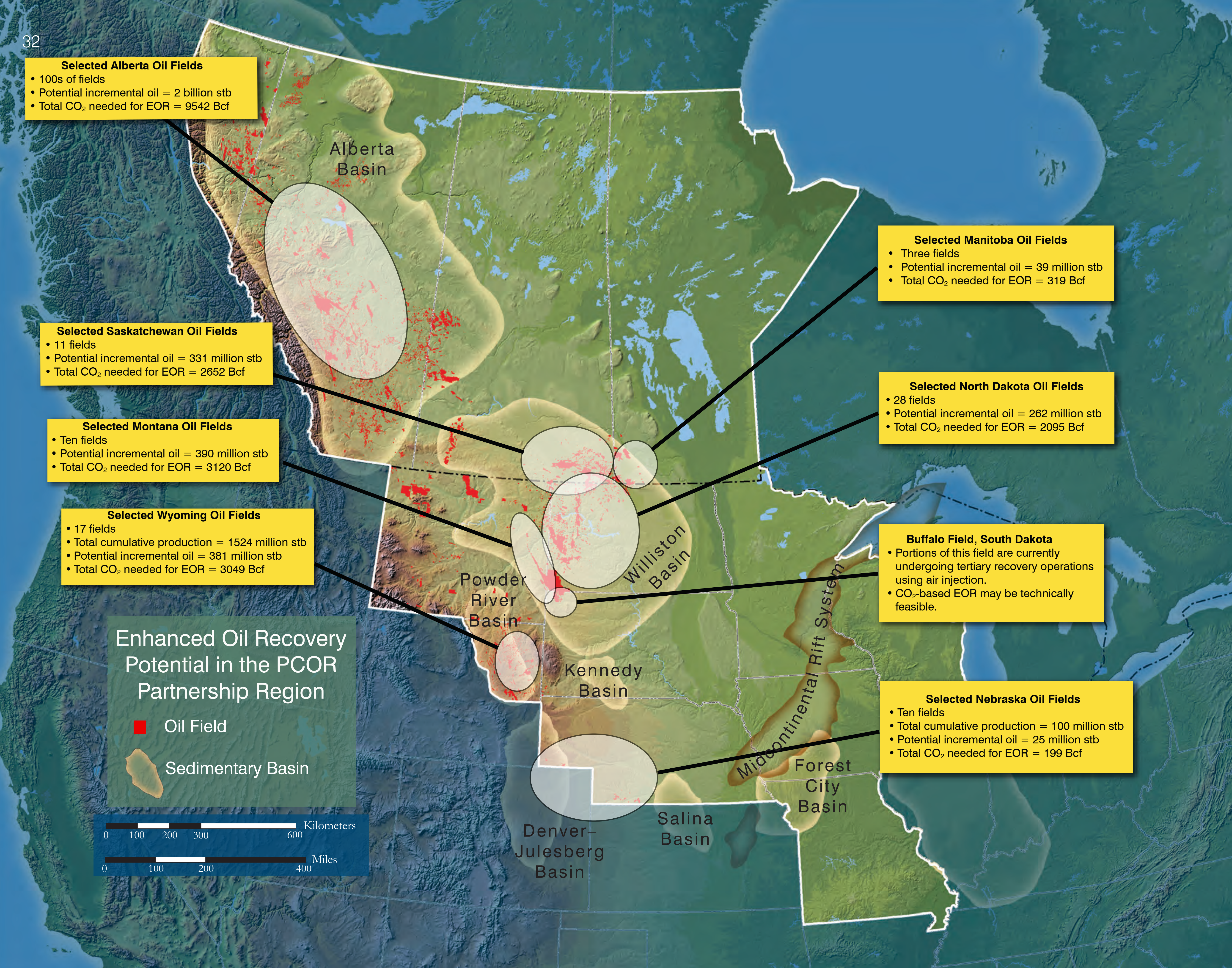
Oil and Gas Fields

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

A single oil field can have multiple zones of accumulation 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 sequestered in a pool through dissolution into the formation fluids (oil and/or water), as a buoyant supercritical-phase CO_2 plume at the top of the reservoir (depending on the location of the injection zone within the reservoir), and/or mineralized through geochemical reactions between the CO_2, formation waters, and formation rock matrix.

Oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from 2500 to 4000 feet for the shallower pools 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 past 60 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure sequestration of significant amounts of CO_2.


Selected Alberta Oil Fields
• 100s of fields
• Potential incremental oil = 2 billion stb
• Total CO_2 needed for EOR = 9542 Bcf
Selected Saskatchewan Oil Fields
• 11 fields
• Potential incremental oil = 331 million stb
• Total CO_2 needed for EOR = 2652 Bcf
Selected Montana Oil Fields
• Ten fields
• Potential incremental oil = 390 million stb
• Total CO_2 needed for EOR = 3120 Bcf
Selected Wyoming Oil Fields
• 17 fields
• Total cumulative production = 1524 million stb
• Potential incremental oil = 381 million stb
• Total CO_2 needed for EOR = 3049 Bcf
Selected Manitoba Oil Fields
• Three fields
• Potential incremental oil = 39 million stb
• Total CO_2 needed for EOR = 319 Bcf
Selected North Dakota Oil Fields
• 28 fields
• Potential incremental oil = 262 million stb
• Total CO_2 needed for EOR = 2095 Bcf
Buffalo Field, South Dakota
• Portions of this field are currently undergoing tertiary recovery operations using air injection.
• CO_2-based EOR may be technically feasible.
Selected Nebraska Oil Fields
• Ten fields
• Total cumulative production = 100 million stb
• Potential incremental oil = 25 million stb
• Total CO_2 needed for EOR = 199 Bcf
Alberta Basin
Williston Basin
Powder River Basin
Kennedy Basin
Midcontinental Rift System
Forest City Basin
Salina Basin
Denver–Julesberg Basin
Enhanced Oil Recovery Potential in the PCOR Partnership Region
Oil Field
Sedimentary Basin
Kilometers
0 100 200 300 600
Miles
0 100 200 400

Enhanced Oil Recovery

Most oil is extracted from the ground in three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. Natural pressures within the reservoir drive oil into the well during primary recovery, and pumps bring the oil to the surface. Primary recovery 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]

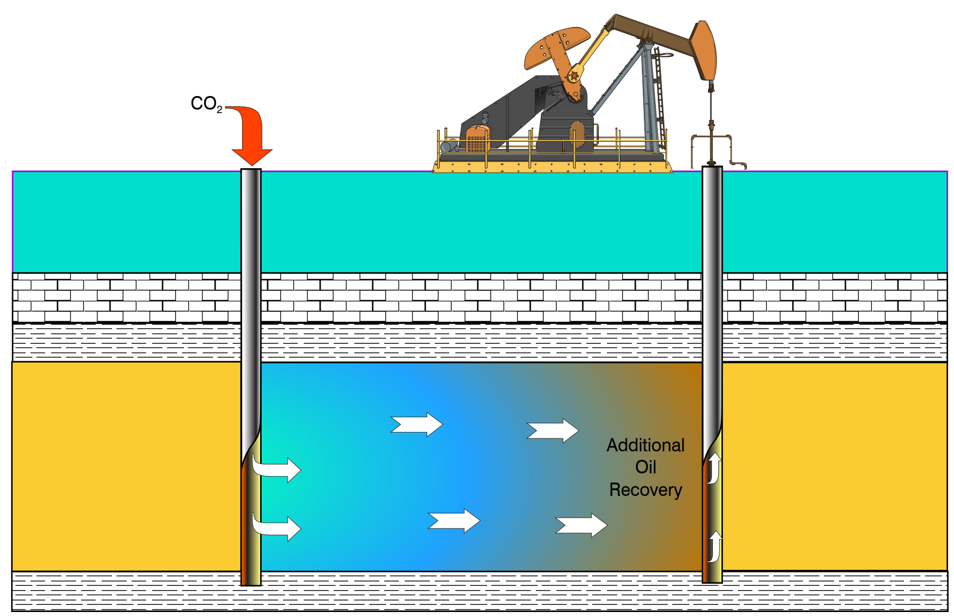
Conventional primary and secondary recovery operations often leave two-thirds of the oil in the reservoir. In the United States, EOR methods have the potential to recover much of that remaining oil, which is estimated to be 200 billion barrels.[15] However, oil recovery is challenging because the remaining 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 sequestration 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 that were obtained from the petroleum regulatory agencies and/or geological surveys from the oil-producing states and provinces of the PCOR Partnership region. Results of the estimates for the evaluated fields (using a volumetric method) in the four basins indicate a storage capacity of over 3.4 billion tons of CO_2.

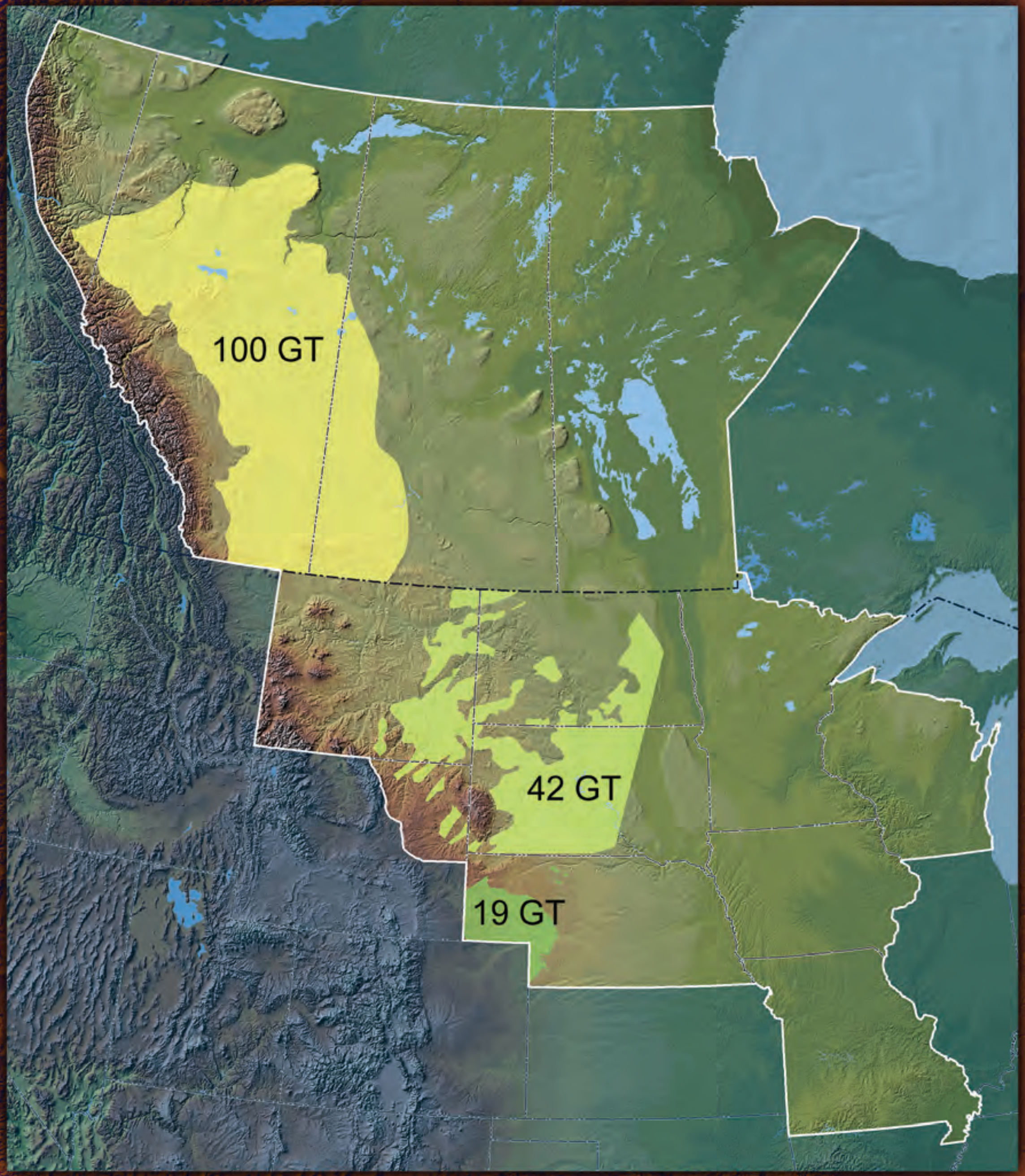
Aside from non-market-based incentives, CO_2 sequestration in many geologic sinks is not generally economically viable under current market conditions. However, EOR miscible flooding is a proven, economically viable technology for CO_2 sequestration that can provide a bridge to future non-EOR-based geologic sequestration. For example, a portion of the revenue generated by CO_2 EOR activities can pay for the infrastructure necessary for future geologic sequestration in brine formations. It is expected that 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.

Storage and Incremental Recovery Through EOR in Selected Fields

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



Lower Cretaceous Saline System Analysis



Mississippian Madison Saline System Analysis

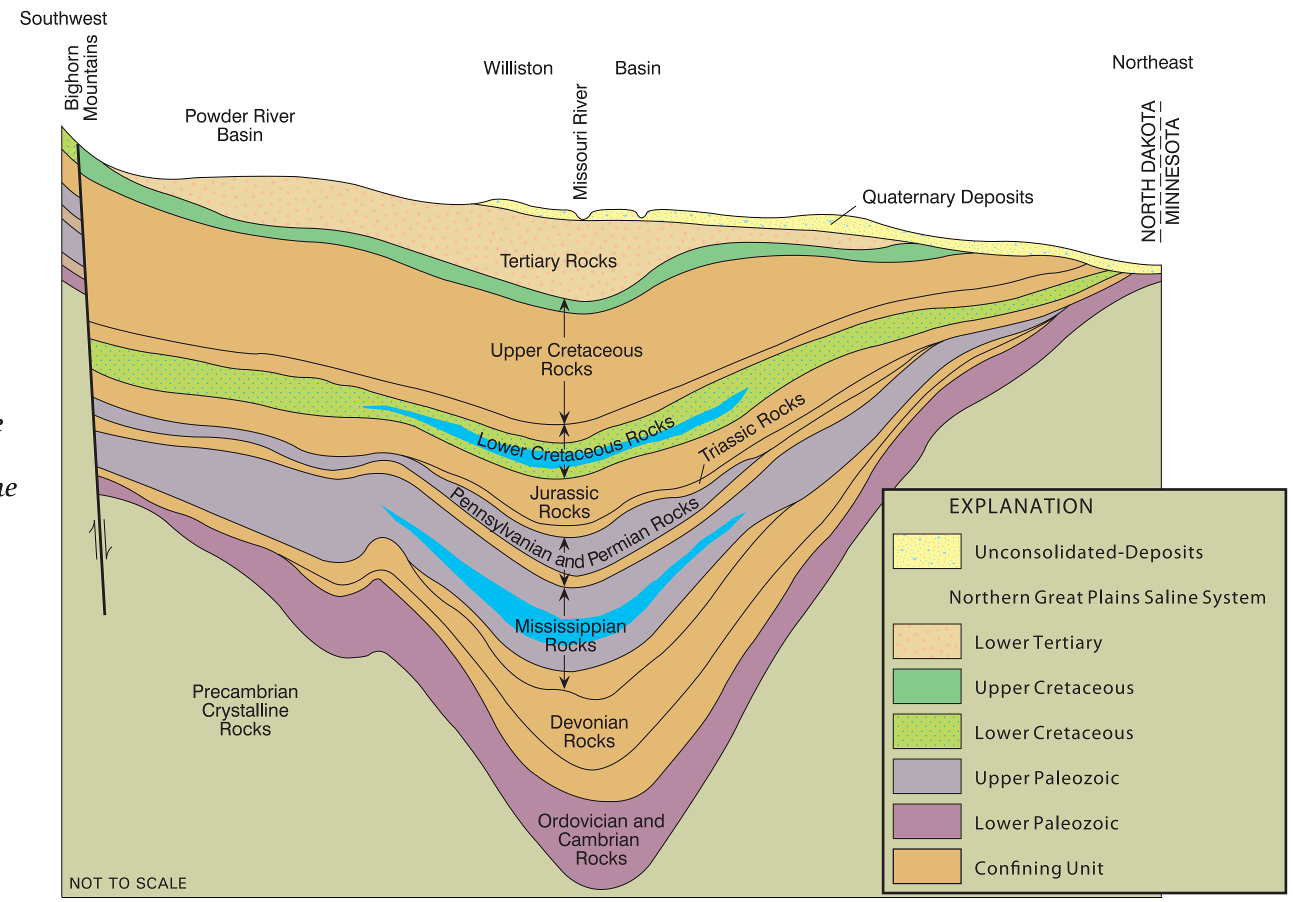
Distribution of selected saline systems evaluated in the PCOR Partnership region.
Limits of the evaluated areas are based on the extent of readily available data.

Saline Formations

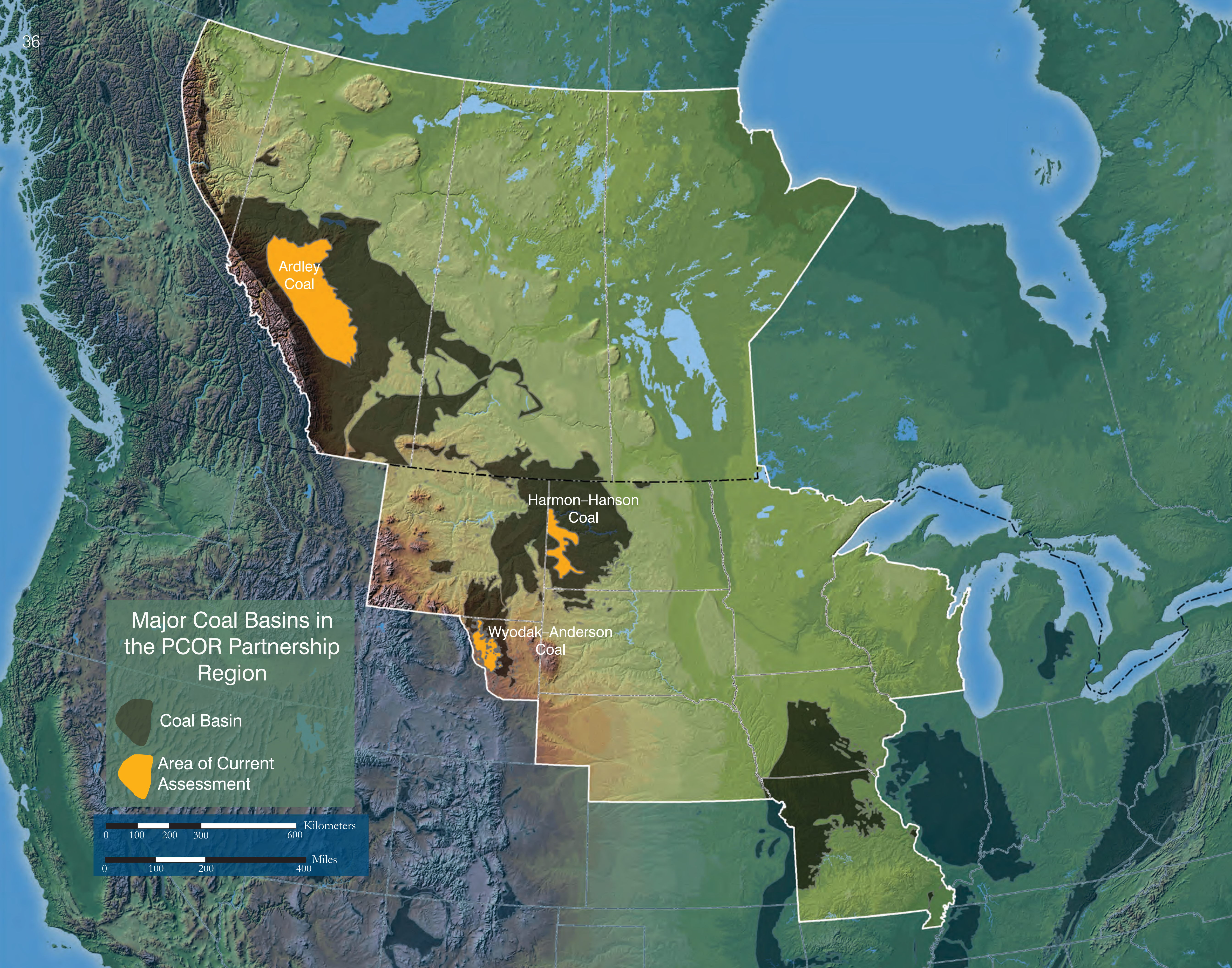
Saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic carbon dioxide. Two saline systems, the Mississippian Madison and the Lower Cretaceous, have been evaluated for their regional continuity, hydrodynamic characteristics, fluid properties,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

The lateral extent of these formations, the current understanding of their storage potential gained through injection well performance, and the geographic proximity to major CO_2 sources suggest they may be suitable sinks for future storage needs. For example, reconnaissance-level calculations on the Mississippian System in the Williston Basin and Powder River Basin suggest the potential to store upwards of 60 billion tons of CO_2 over the evaluated region, while the Cretaceous System has the potential to store over 160 billion tons.[16,17]

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



Cross section of the Williston Basin showing major saline formations.


Major Coal Basins in the PCOR Partnership Region
Coal Basin
Area of Current Assessment
Ardley Coal
Harmon–Hanson Coal
Wyodak–Anderson Coal
0 100 200 300 600 Kilometers
0 100 200 400 Miles

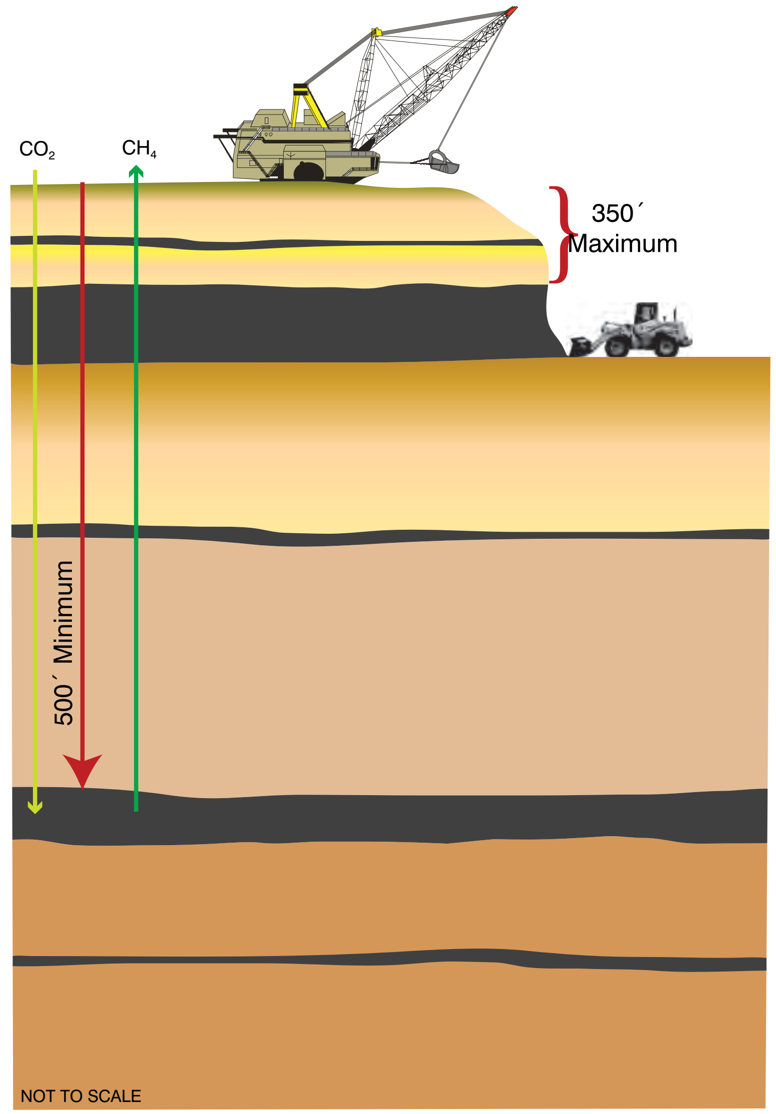
Sequestration in Coal

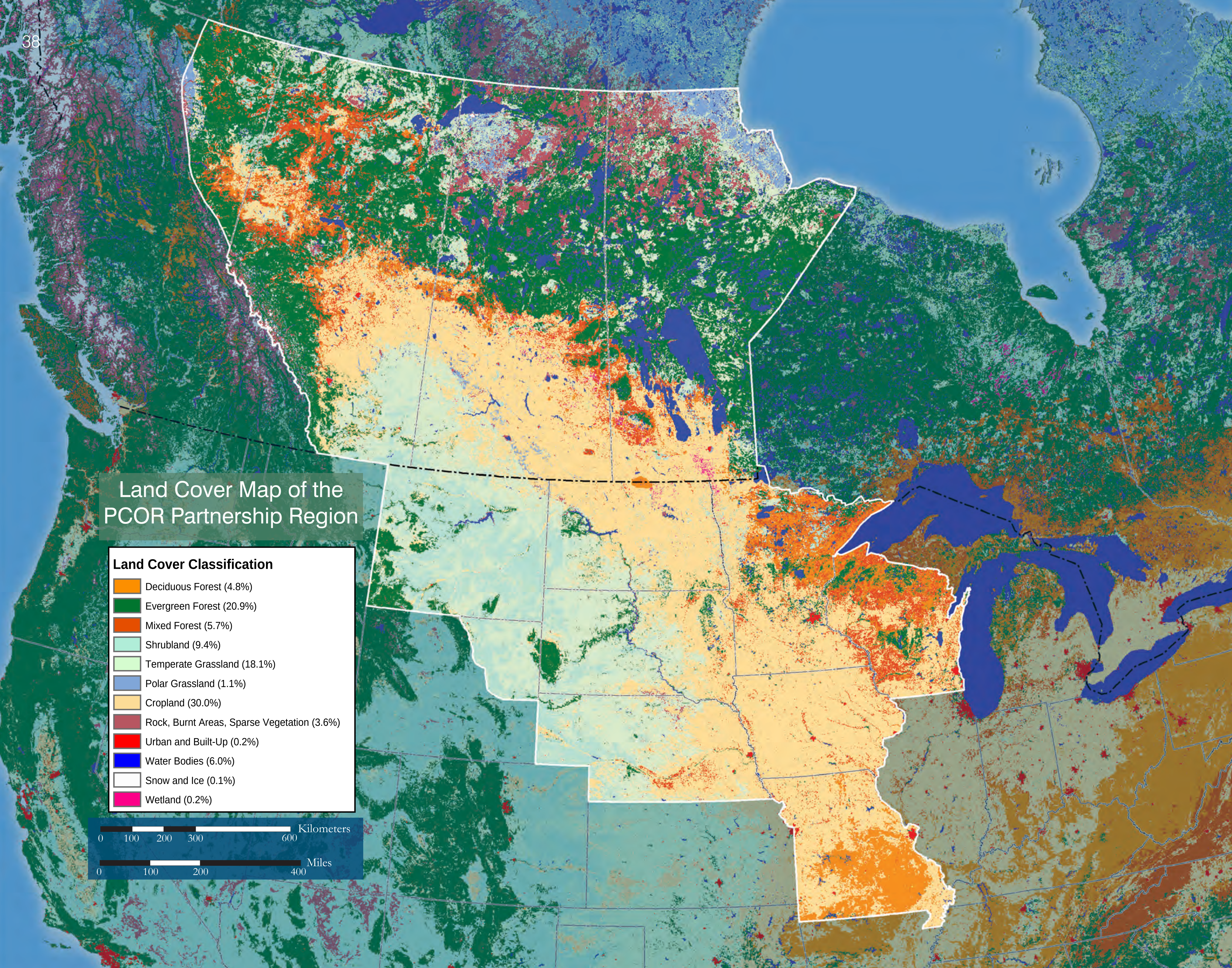
Many coal seams throughout central North America are too deep or too thin to be mined economically. However, many of these coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into the coal beds to recover this “coalbed methane” (CBM). In fact, CBM is the fastest growing source of natural gas in the United States and accounted for 7.2% of domestic production in 2003.[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 sequestration: the Wyodak–Anderson bed in the Powder River Basin, the Harmon–Hanson interval in the Williston Basin, and the Ardley coal zone in the Alberta Basin. The total maximum CO_2 sequestration potential for all three coal horizons is approximately 8 billion tons.[20–22]

In northeastern Wyoming, the CO_2 sequestration potential for the areas where the coal overburden thickness is > 1000 feet is 6.8 billion tons. The coal resources that underlie these deep areas could sequester all of the current annual CO_2 emissions from nearby power plants for about the next 150 years.[22]




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

Terrestrial Sequestration

In contrast to geologic sequestration deep within the earth, the concept of terrestrial sequestration focuses on a more passive mechanism of CO_2 storage in vegetation and soils within a few feet of the earth's surface. From the Central Lowlands forests and cropland in the southeastern portion of the region, through the expansive grasslands and croplands of the northern Great Plains, to the northern boreal forests of Canada, the PCOR Partnership region has a rich agrarian history founded on fertile soils. However, as central North America developed into the pattern of land use seen today, much of the original soil carbon was lost to the atmosphere. In this setting, the most promising potential to sequester carbon would be to convert marginal agricultural lands and degraded lands to grasslands, wetlands, and forests when favorable conditions exist.[23]

Terrestrial sequestration methods that enhance carbon buildup in biomass and soils include adopting conservation tillage, reducing soil erosion, and minimizing soil disturbance; using buffer strips along waterways; enrolling land in conservation programs; restoring and better managing wetlands; eliminating summer fallow, using perennial grasses and winter cover crops; and fostering an increase in forests.[23,24] Managing soils for increased carbon uptake will pull CO_2 from the atmosphere for a 50–100-year time frame, after which the soils will have reached a new equilibrium, i.e., a point at which the total amount of carbon in the soil does not change over time.[25] Once a steady state has been reached, the carbon will remain sequestered until the land management practices change or some other event occurs. The manipulation of soils and biomass for carbon sequestration has the advantage that it can be implemented immediately without the need for new technologies.


Prairie
Pothole
Region
The Prairie Pothole Region of the PCOR Partnership Region
Kilometers
0 100 200 300 600
Miles
0 100 200 400

Prairie Pothole Region

The PCOR Partnership region includes the Prairie Pothole Region, a major biogeographical region that encompasses approximately 347,000 mi^2 (222.4 million acres) and includes portions of Iowa, Minnesota, Montana, North Dakota, and South Dakota in the United States and Alberta, Saskatchewan, and Manitoba in Canada.[26] 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.[27] 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 the wild duck production in North America[27] 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, Inc., and U.S. Geological Survey 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}.[28] 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.

CO$_2$-Rich Gas in a Pinnacle Reef Structure
Out of the Air – Into the Soil
CO$_2$ in a Deep Oil Reservoir
CO$_2$ in an Unminable Lignite Seam
BC
AB
SK
MB
MT
ND
SD
MN
WI
IA
NE
MO

Field Validation Test Sites

Through the fall of 2009, the PCOR Partnership will be developing and conducting four CO_2 sequestration field validation tests: three that will store carbon dioxide as a gas in the deep subsurface and one that will store carbon in the near-surface soils and sediments of wetlands and grasslands. These field projects are designed to develop the expertise, real-world experience, and business models needed to implement major, full-scale, long-term CO_2 sequestration projects in the region.

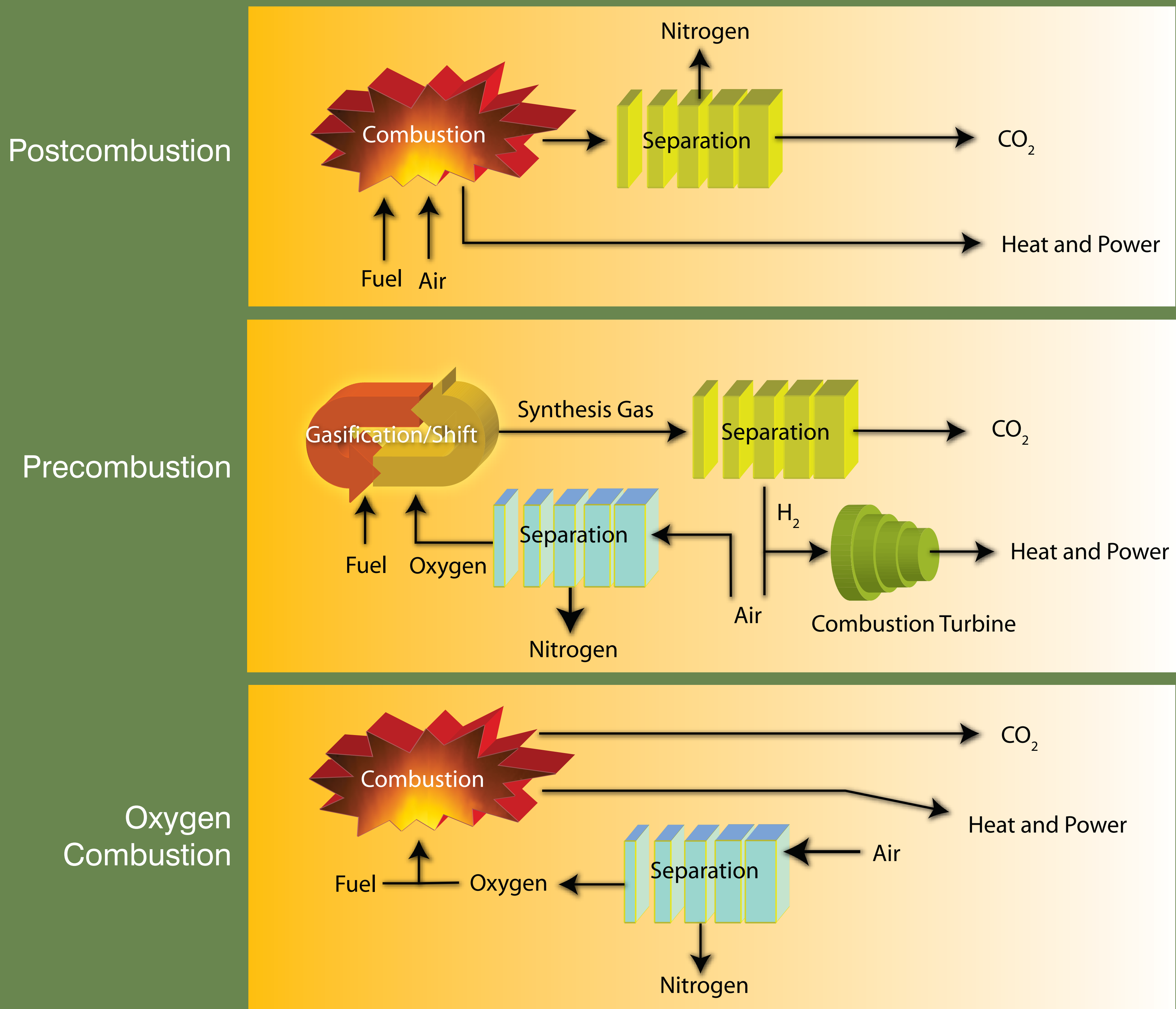
CO_2-rich gas in a pinnacle reef structure – Acid gas (approximately 70% CO_2, 30% hydrogen sulfide [H_2S]) from a natural gas processing plant in northern Alberta, Canada, is being injected into an oil-producing zone in an underground pinnacle reef structure. A pinnacle reef is an isolated domed geologic formation suitable for trapping hydrocarbons and CO_2. Results will help to determine the best practices to support sequestration in these unique geologic structures as well as further our understanding of the effects of H_2S on tertiary oil recovery and CO_2 sequestration.

CO_2 in a deep oil reservoir – CO_2 will be injected into an oil-bearing zone at great depth in the Williston Basin in northwestern North Dakota. The activity will be used to determine the efficacy of CO_2 sequestration and the use of CO_2 to produce additional oil from deep carbonate source rocks.

CO_2 in an unminable lignite seam – CO_2 will be injected into unminable lignite seams in northwestern North Dakota. The injected CO_2 will be trapped by naturally bonding to the surfaces of the fractured lignite. The injected CO_2 also has the potential to displace methane occupying the coal fractures. This validation test will provide valuable information regarding lignites for both CO_2 sequestration and enhanced coalbed methane production.

Out of the air – into the soil – A managed wetland will be implemented in north-central South Dakota to demonstrate practices that will improve CO_2 uptake. The results will help to optimize CO_2 storage, monitoring, and verification methods and facilitate the monetization of terrestrial carbon offsets in the region and elsewhere.

Fossil Fuel Conversion Platforms and CO_2 Capture



Carbon Capture and Separation

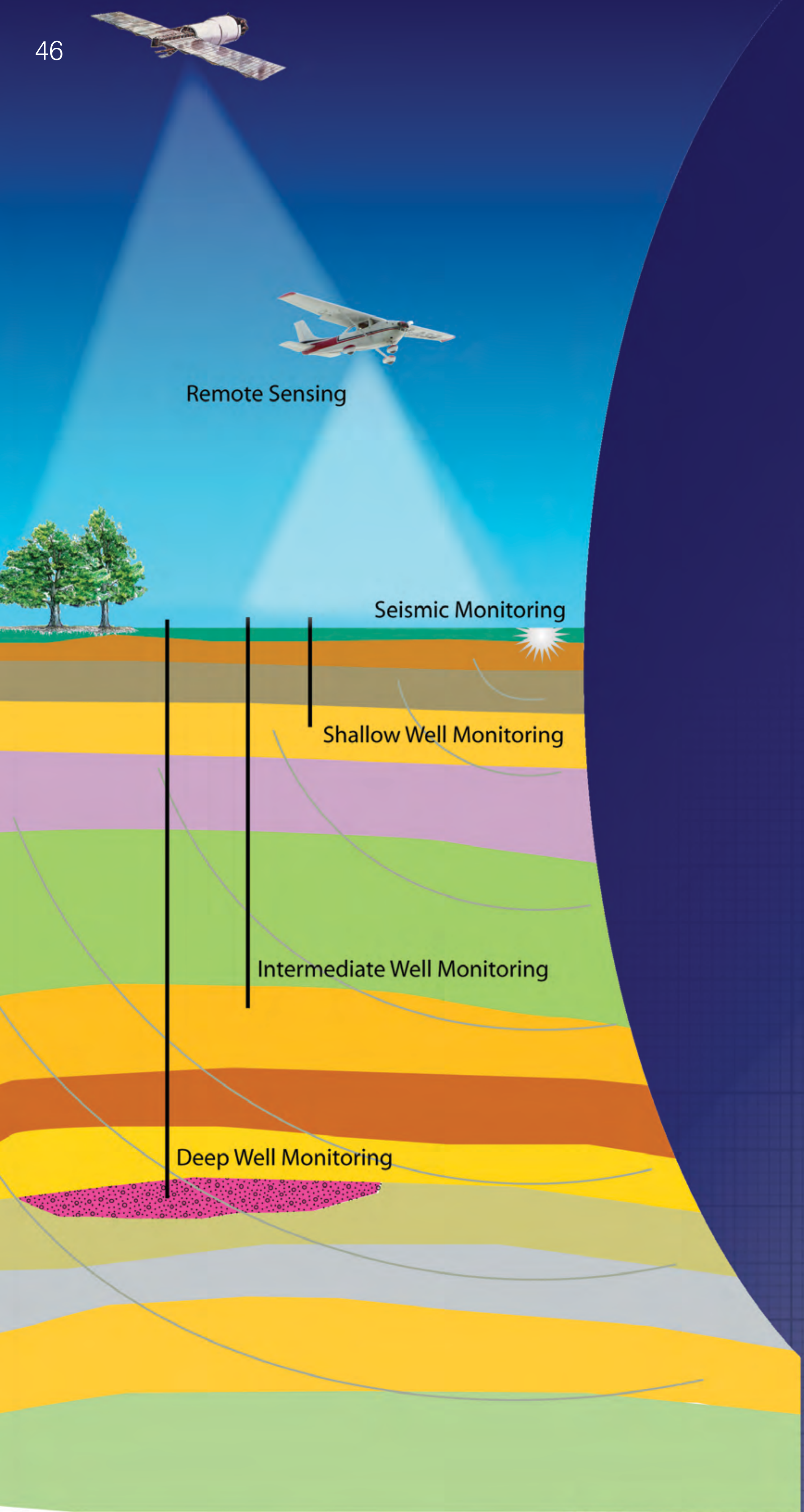
Before CO_2 can be geologically sequestered, it must be captured and separated from other gases, compressed, and transported to the geologic sink. Capture and separation of CO_2 are performed as a part of many industrial processes, from H_2 production to ammonia synthesis.[29] However, existing capture 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 sequestration. Because the concentrations of CO_2 in typical power plant flue gas are so low (ranging from 3% by volume for some natural gas-fired plants[29] to 15% by volume for some coal-fired plants[30]), any capture process must be sized to handle the large quantity of exhaust gas. The large scale of equipment and quantities of chemicals required makes 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 sequestration system.[29]

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 combustion, during combustion, and after combustion. The precombustion technologies consist of capture of CO_2 in conjunction with gasification or reforming, while capture during combustion is only possible when the combustion takes place in nearly pure oxygen rather than air. The majority of capture technologies focus 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 sequestration 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 also being developed.

Top left and center: In the future, a more extensive CO_2 pipeline network will probably be constructed. Top right: Selextol™ towers at a recent integrated gasification combined-cycle start-up. Bottom: CO_2 compressors at the Dakota Gasification Company's synfuels plant in central North Dakota each move about 55 million cubic feet of CO_2 a day at a discharge pressure of 2700 psi.



Selected Technologies Used to Ensure the Safe and Secure Storage of CO_2

Terrestrial

Plant Matter Measurement
- Multispectral 3-dimensional aerial digital imagery
- Satellite imagery
- Light detection and ranging (LIDAR)

Soil Carbon Measurement
- Laser-induced breakdown spectroscopy (LIBS)
- Inelastic neutron scattering soil carbon

Geologic

CO_2 Fate and Transport Models
- Reservoir models (target formation to vadose)
- Geochemical models
- Geomechanical models
- CO_2 equation of state at reservoir conditions

Plume Tracking
- Surface to borehole seismic monitoring
- Microseismic monitoring
- Cross-well tomography
- Reservoir pressure monitoring
- Observation wells/fluid sampling

CO_2 Leak Detection
- Vadose zone soil/water sampling
- Air samples/gas chromospectrometry
- Infrared-based CO_2 in air detectors
- Vegetation growth rates
- CO_2 tracers, natural and introduced
- Subsurface monitoring wells

Mitigation
- Depressurize target formation

Regulatory and Safety Aspects of Carbon Capture and Storage

Currently, no U.S. federal regulations address CO_2 emissions. However, regulations do address the transportation 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 a CO_2 sequestration project. 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. Further, numerous federal, state, and regional regulatory and/or legislative actions are being contemplated that would address various aspects of carbon management. Additionally, in April 2007, the Supreme Court decided that the U.S. Environmental Protection Agency (EPA) has the authority to regulate carbon dioxide emissions from cars and that the agency cannot bypass its authority to regulate greenhouse gases that contribute to global climate change unless it provides a scientific basis for its refusal. For more information on this Supreme Court decision go to www.supremecourtus.gov/opinions/06pdf/05-1120.pdf.

To ensure the safe and effective terrestrial and geological storage of CO_2, projects must identify and evaluate potential ecological and environmental impacts, 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. Monitoring, mitigation, and verification (MMV) strategies will be required through all phases of CO_2 sequestration, including capture and separation, transportation, injection, and long-term storage.

The implementation of MMV 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.

What is known to date concerning risks of CO_2 sequestration includes the following:

- CO_2 can be safely stored in geological formations over long periods of time as observed with naturally existing CO_2 reservoirs.
- Environmental and ecological health effects are well understood.
- The largest risks of CO_2 capture and storage have been identified.
- Local hazards are generally more dependent on the nature of the release than the size of the release.
- CO_2 poses no health and safety risk at low concentrations.
- CO_2 is not flammable or explosive but does react with water.
- CO_2 is denser than air and has the potential to pool in low-lying areas or poorly ventilated spaces.

PCOR Partnership
DSS
Decision Support System
PCORP GIS
Indirect Carbon Sequestration
Regulating CO2 Sequestration
Partner Contacts
Phase II
Phase I
Presentations
Products/Reports
Phase II
Phase I
DOE: Global Climate Change Initiative Links
Other Carbon Related Links
Zama Zone
Terrestrial Zone
Contact Us
PCORP Home
Sponsored in Part by the U.S. Department of Energy
Zama
Lignite
Williston Basin
Wetland
Click on a site to view field validation test information.
Click here to view PCOR Partnership monthly updates.
The PCOR Partnership Decision Support System (DSS) is a web-based database, GIS, and scenario modeling system. The DSS allows our research partners to browse, query, analyze, and download data
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Plains CO2 Reduction (PCOR) Partnership
Practical, Environmentally Sound CO2 Sequestration
EERC
Oil Field: Antelope
Reference: NDIC
15,751 acres
Non-Unitized
ND
Pools
Unit
100%
75%
50%
tal Est. CO2 Capacity (mass) 9/9 tons 201,937,323 151,452,992 100,968,662
tal Est. CO2 Capacity (volume) 9/9 MMcf 3,293,598 2,470,198 1,646,799
tal Est. EOR CO2 Capacity (mass) 6/9 tons 47,421,456 35,566,092 23,710,728
tal Est. EOR CO2 Capacity (volume) 6/9 MMcf 773,444 580,083 386,722
Date
Oil (barrels)
Gas (Mcf)
Water (barrels)
mulative Production 3/2004 40,604,606 53,253,898 43,672,109
POOLS
Plains CO2 Reduction Partnership
Save Map | Save Bookmark | Metadata
Overview Map
Legend/Layer
Zoom In
Zoom Out
Full Extent
Last Extent
Pan
Select
Multi Select
Buffer
Clear Selection
Add Text
Refresh Map
Active Layer: CO2 Sources

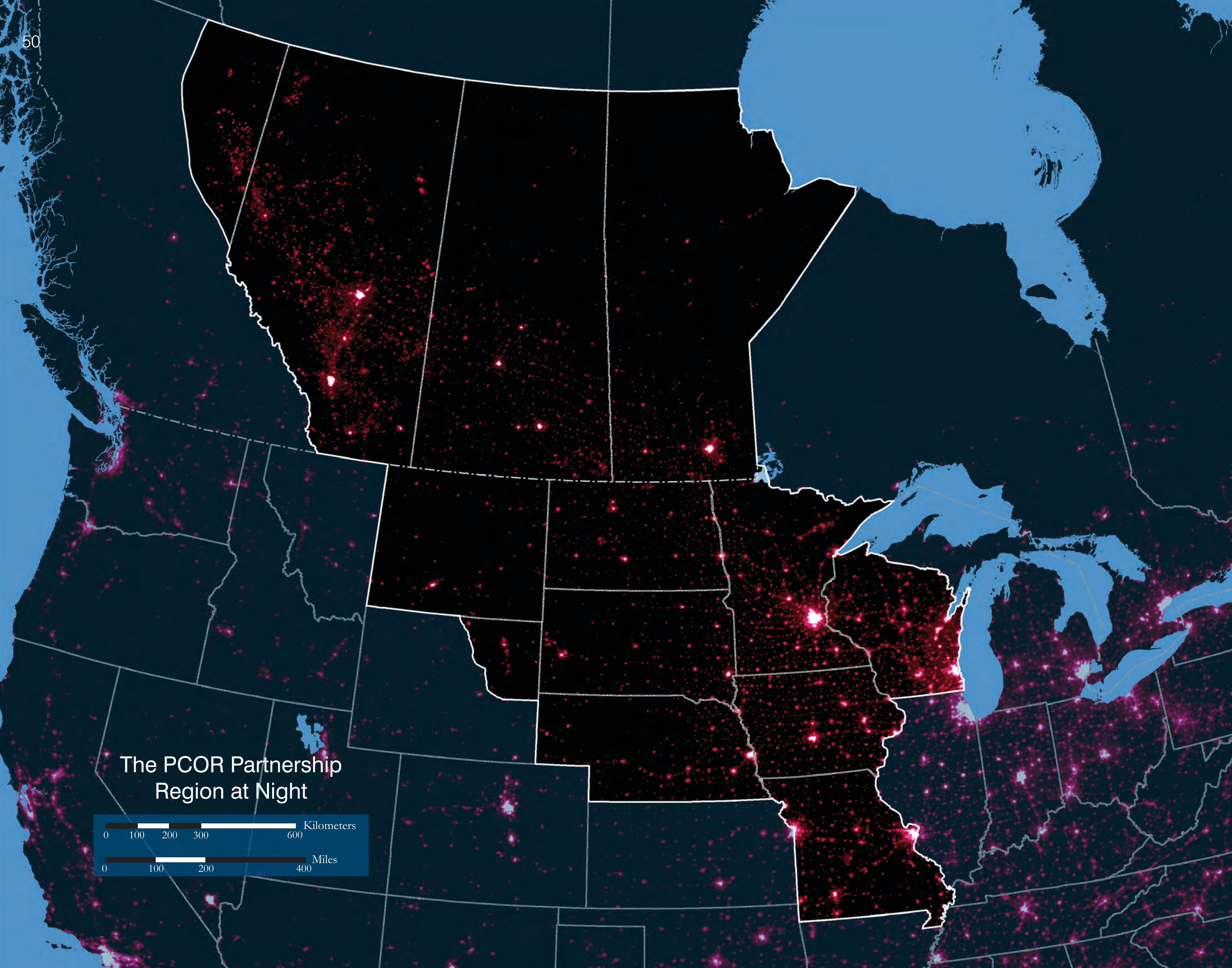
The PCOR Partnership Decision Support System (DSS)

The PCOR Partnership has accumulated a wealth of data in characterizing the partnership region with respect to CO_2 sequestration 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 sequestration 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 sequestration.

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 Decision Support System (DSS, © 2007 EERC Foundation), that provides the PCOR Partnership with a single point of access to a wide variety of research data for evaluation and the development of potential sequestration 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 sequestration 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.

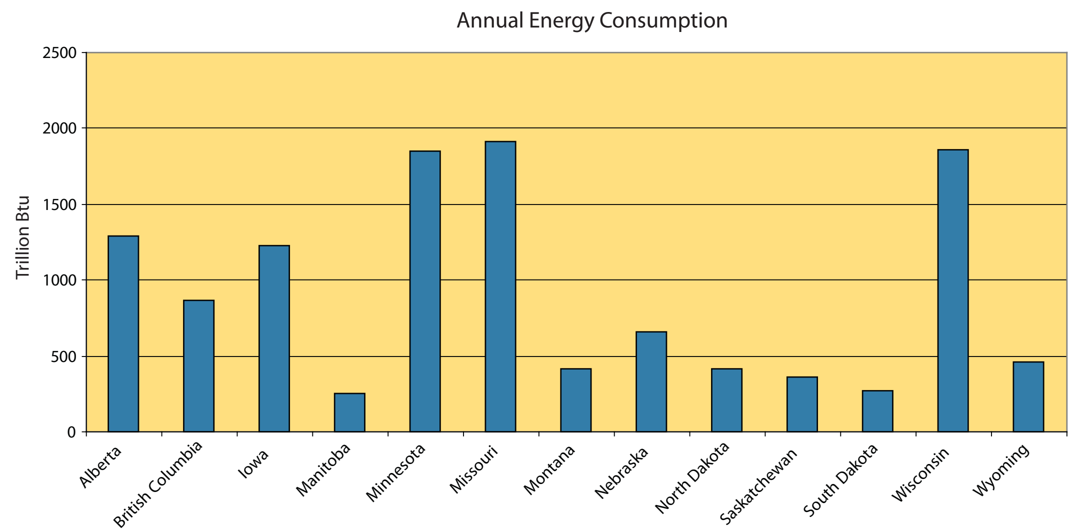

The PCOR Partnership
Region at Night
Kilometers
0
100
200
300
600
Miles
0
100
200
400

Keeping the Lights On

Affordable energy not only fuels our vehicles and electrical plants, it also fuels our economy and our quality of life. Collectively, the states and provinces of the PCOR Partnership region use approximately 12,000 trillion Btu of energy a year.[31,32] 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.[33,34] Most of the continent's barley crop, which is critical to the breweries of Milwaukee and Saint Louis, comes from North Dakota and Minnesota. Wisconsin, as the top producer of paper in the United States, generates over $12 billion in annual shipments of paper products.[35] The Missouri and Mississippi Rivers, railways, and highways of the region transport industrial output which includes heavy machinery, construction materials, and many other consumer goods.

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



1 Sequestration PowerPoint presentations geared to general audiences, educators, students, and decision makers

2 PCOR Partnership's public access Web site with sequestration background, streaming video, educational resources, and information links

3 PCOR Partnership's Members-Only Web site with DSS and Sequestration Project Resources

4 PCOR Partnership's Technical Reports on a variety of sequestration topics in the PCOR Partnership region

5 A Sequestration Atlas for the PCOR Partnership region designed to inform the general public, educators, and decision makers

6 Fact sheets that summarize key sequestration topics and projects in the PCOR Partnership region

7 30-minute, broadcast-quality documentaries, coproduced by Prairie Public Broadcasting and the PCOR Partnership, on key sequestration topics

8 Proceedings of the PCOR Partnership's annual meetings featuring PowerPoint presentations and program updates

9 PCOR Partnership's display booth and tailored outreach packets available for informational meetings and educational venues

Education and Outreach – CO_2 Sequestration

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 sequestration 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 related to CO_2 and sequestration:

- 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—coproductions 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 have speakers for your meeting, school, or community group.

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

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Or visit our Web site at www.undeerc.org/pcor.

More information concerning DOE NETL's Regional Carbon Sequestration Partnerships can be found at www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html.

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Circle with shovel of soil: Photo by Lynn Betts, USDA Natural Resources Conservation Service
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A Much Earlier Map of the PCOR Partnership Region