PCOR Partnership ATLAS

PCO2R Partnership

EERC Energy & Environmental Research Center®

Department of Energy · United States of America

NETL National Energy Technology Laboratory

PCOR Partnership Atlas

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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.

NOTICE

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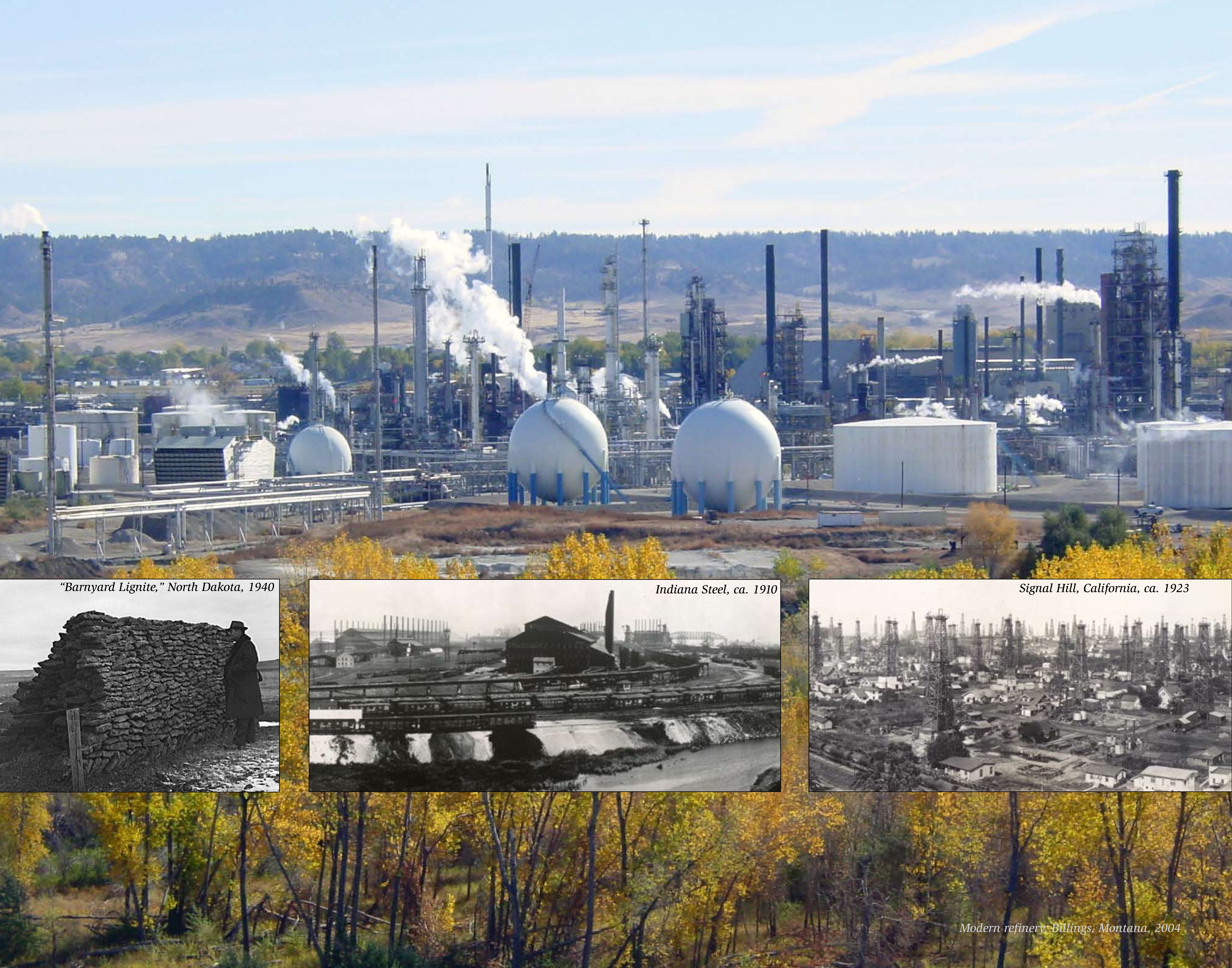
Introduction

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

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

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

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



"Barnyard Lignite," North Dakota, 1940

Indiana Steel, ca. 1910

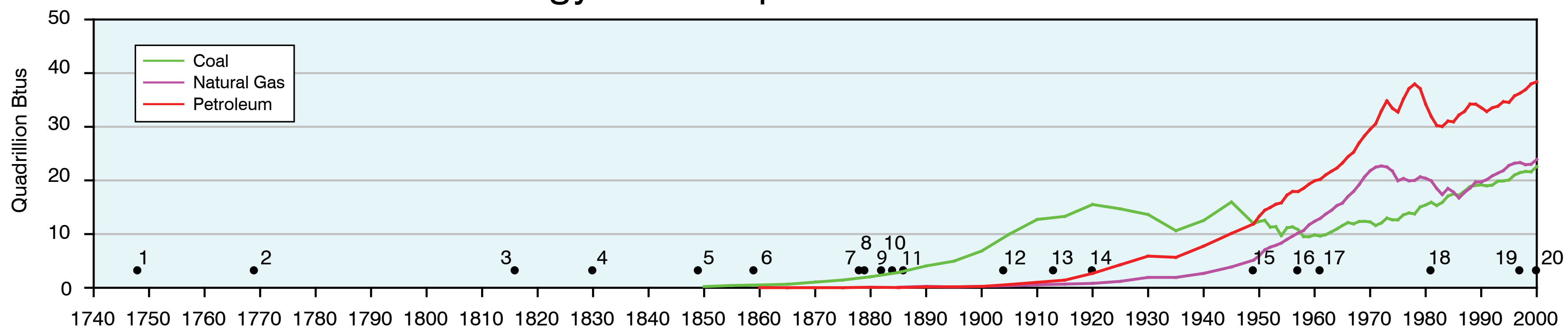
Signal Hill, California, ca. 1923

Modern refinery, Billings, Montana, 2004

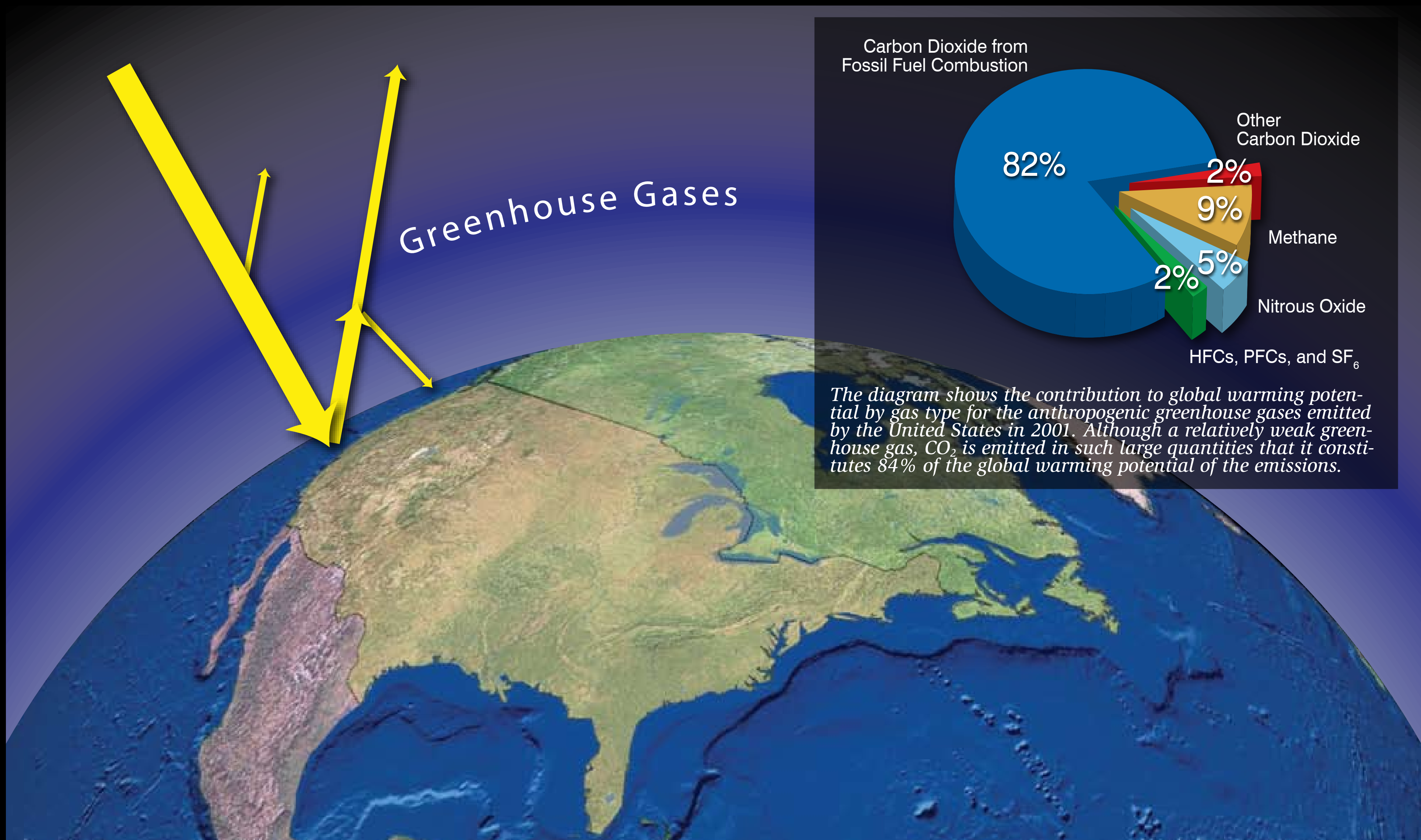
A Change Is in the Air

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

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 148.7 million[7]
16. First commercial nuclear power plant[5]
17. 61.6 million autos registered in the United States[8]
18. Beginning of the modern global warming debate[6]
19. 129.7 million autos registered in the United States[8] and an estimated 600 million motor vehicles in the world[9]
20. U.S. population at 281.4 million[7]



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

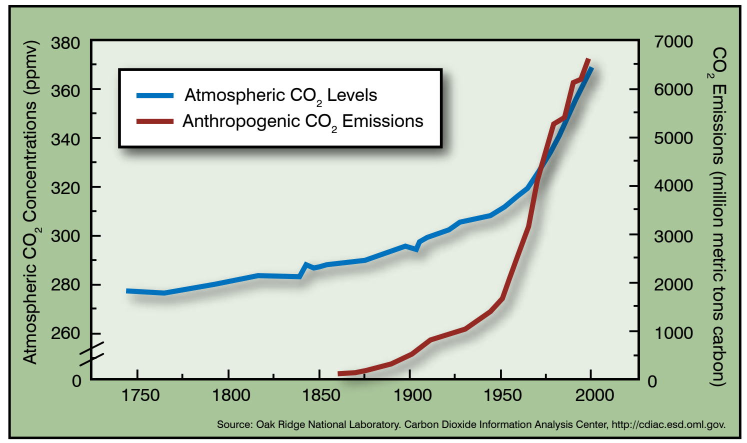
Greenhouse Effect

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

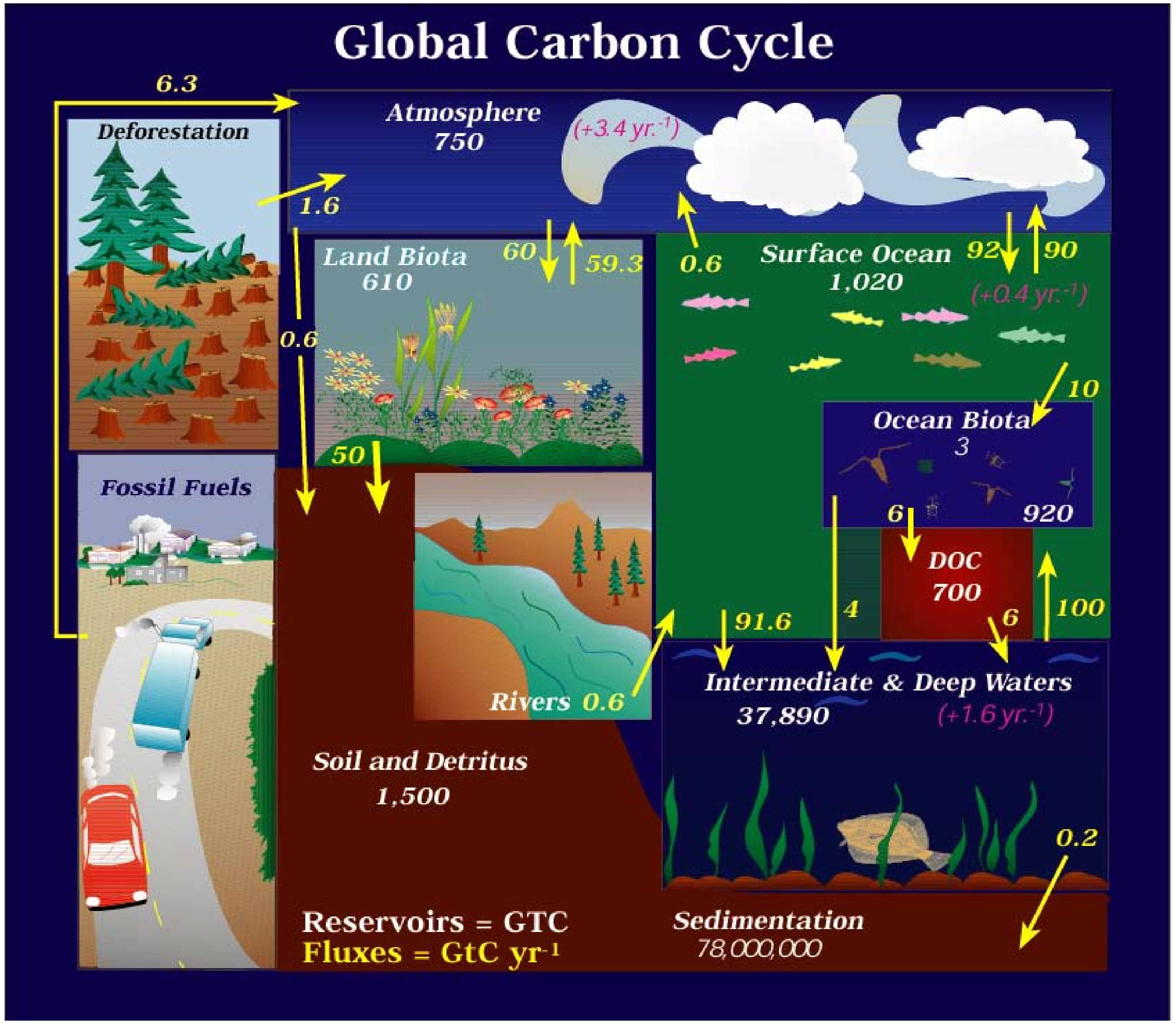
Without this natural "greenhouse effect," global temperatures would be considerably lower than they are now, and life as it is known would not be possible. However, problems may arise when the atmospheric concentration of greenhouse gases increases.[10]

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

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



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



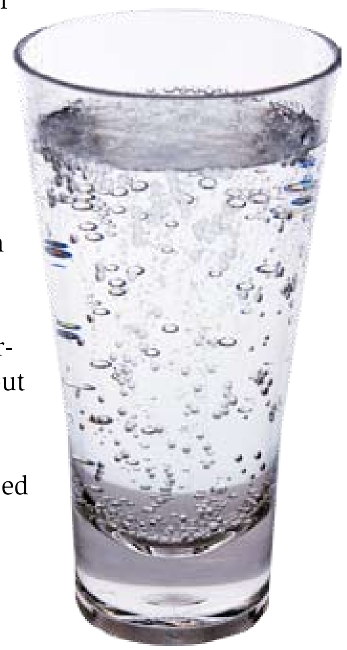
The cycle of carbon movement between the biosphere, atmosphere, hydrosphere, and geosphere is a complex and important global cycle. In the atmosphere, carbon occurs primarily as carbon dioxide. Across the landscape, carbon occurs mainly in living organisms and decaying organic matter in soils.

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

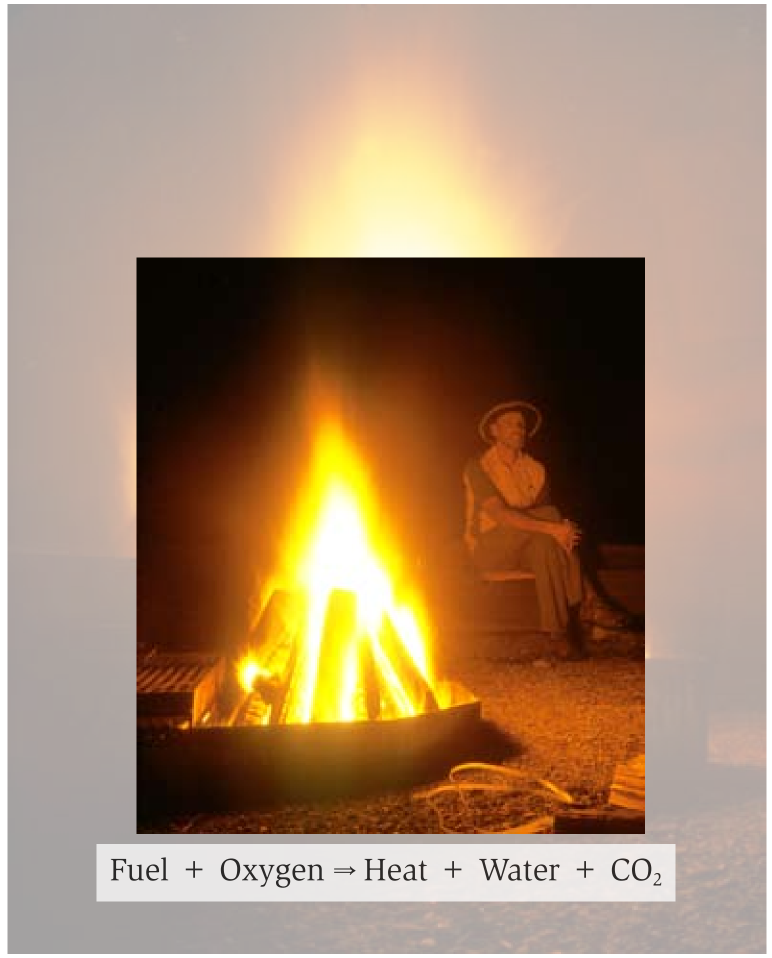
What Is CO_2?

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

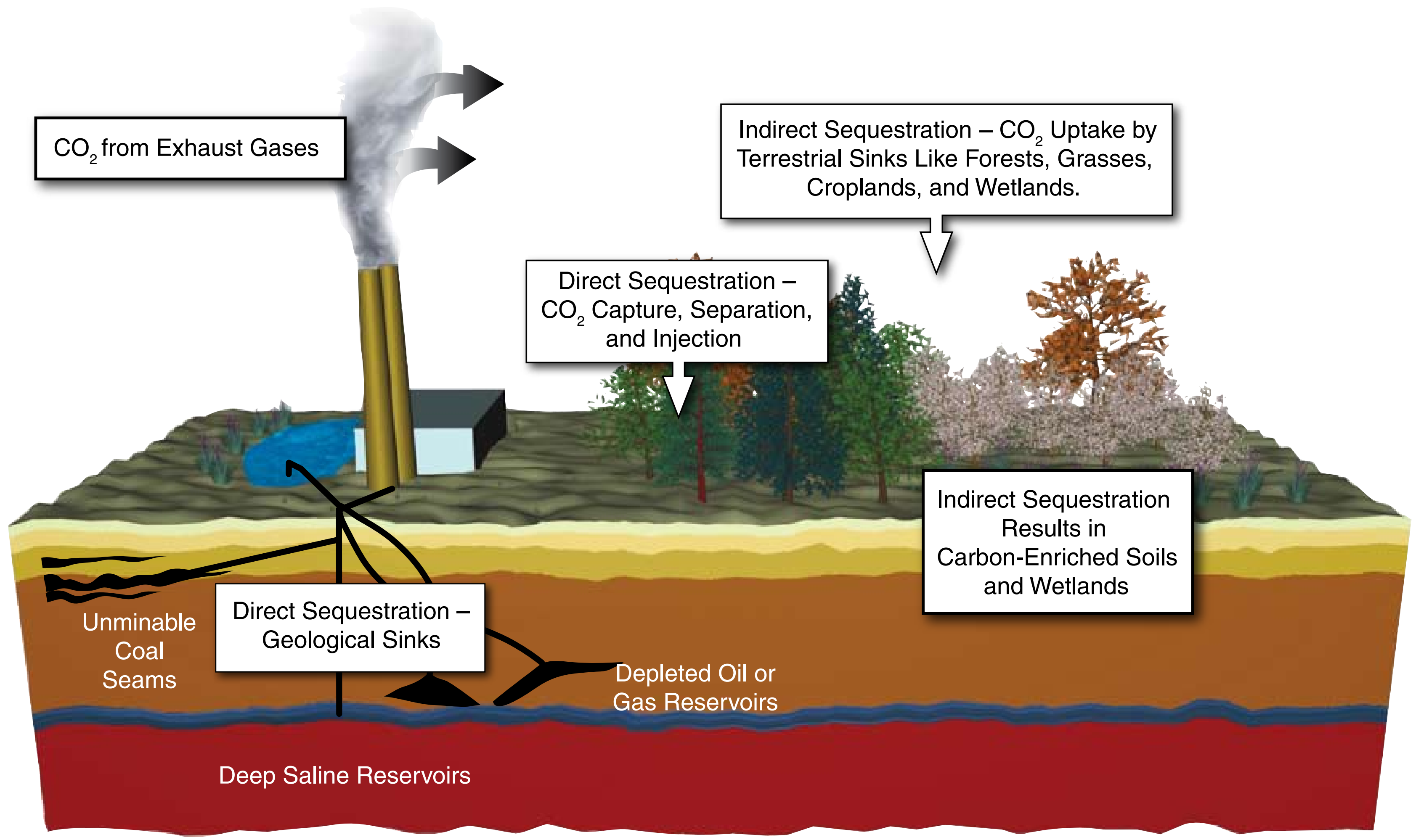
Under high temperature and pressure conditions, such as those encountered in deep geological formations (greater than 2600 feet), CO_2 will exist in a dense phase that is referred to as "supercritical." When injected into a geological formation, a portion of the supercritical CO_2 may be dissolved in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



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



Fuel + Oxygen ⇒ Heat + Water + CO_2


CO$_2$ from Exhaust Gases
Indirect Sequestration – CO$_2$ Uptake by Terrestrial Sinks Like Forests, Grasses, Croplands, and Wetlands.
Direct Sequestration – CO$_2$ Capture, Separation, and Injection
Indirect Sequestration Results in Carbon-Enriched Soils and Wetlands
Unminable Coal Seams
Direct Sequestration – Geological Sinks
Depleted Oil or Gas Reservoirs
Deep Saline Reservoirs

What Is CO_2 Sequestration?

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

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

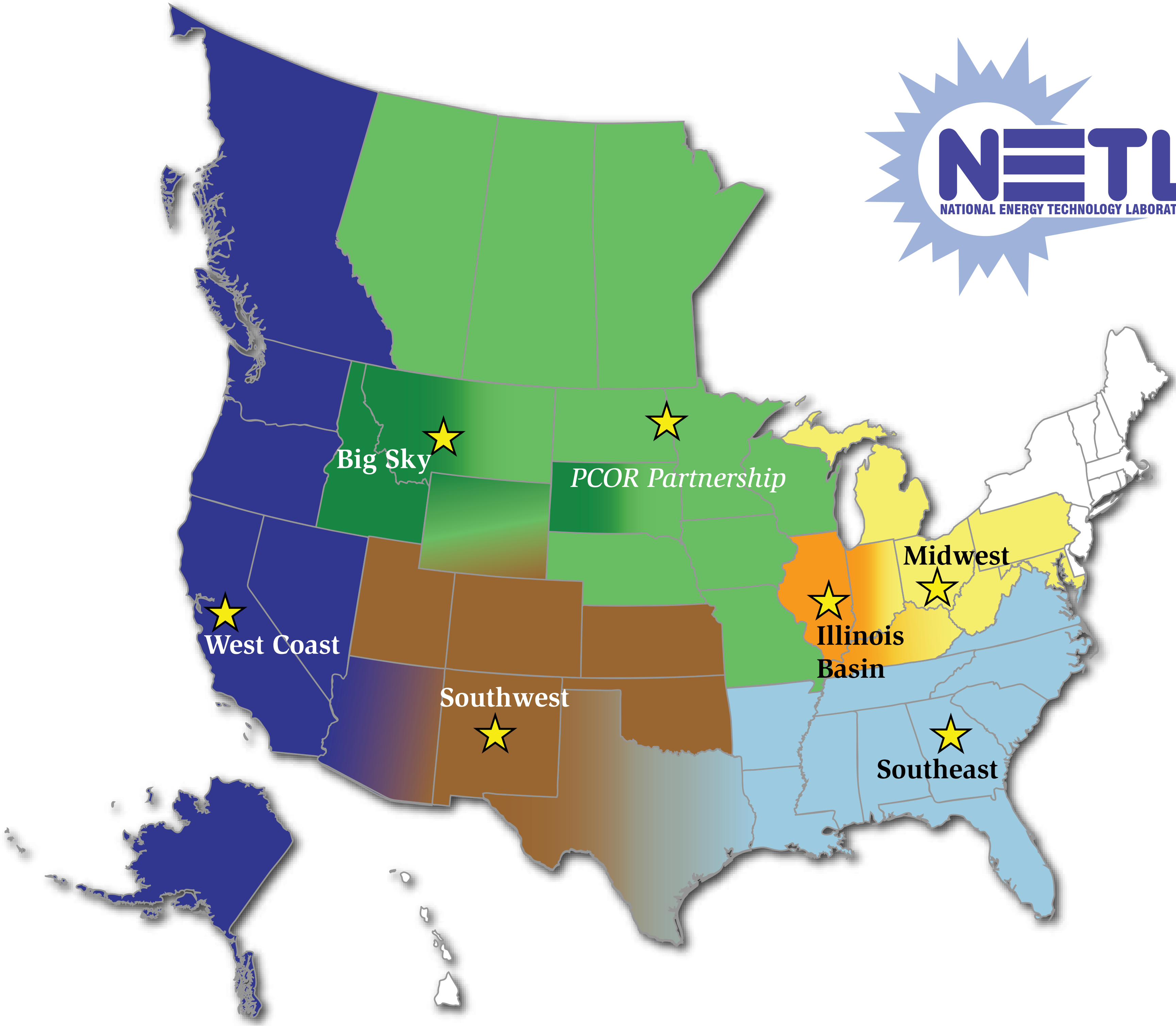
Direct CO_2 Sequestration

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

Indirect CO_2 Sequestration

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

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

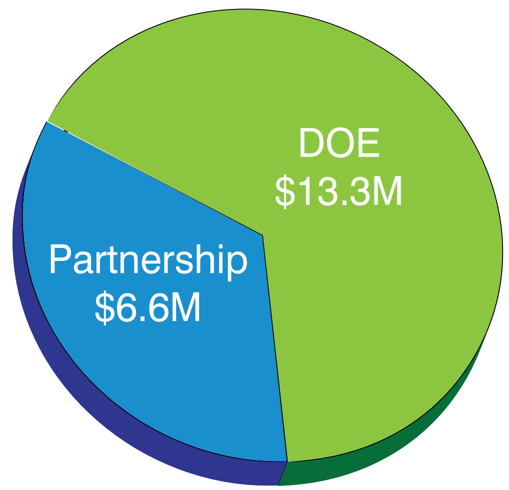

Big Sky
PCOR Partnership
West Coast
Southwest
Illinois Basin
Midwest
Southeast

DOE's Phase I Carbon Sequestration Regional Partnerships

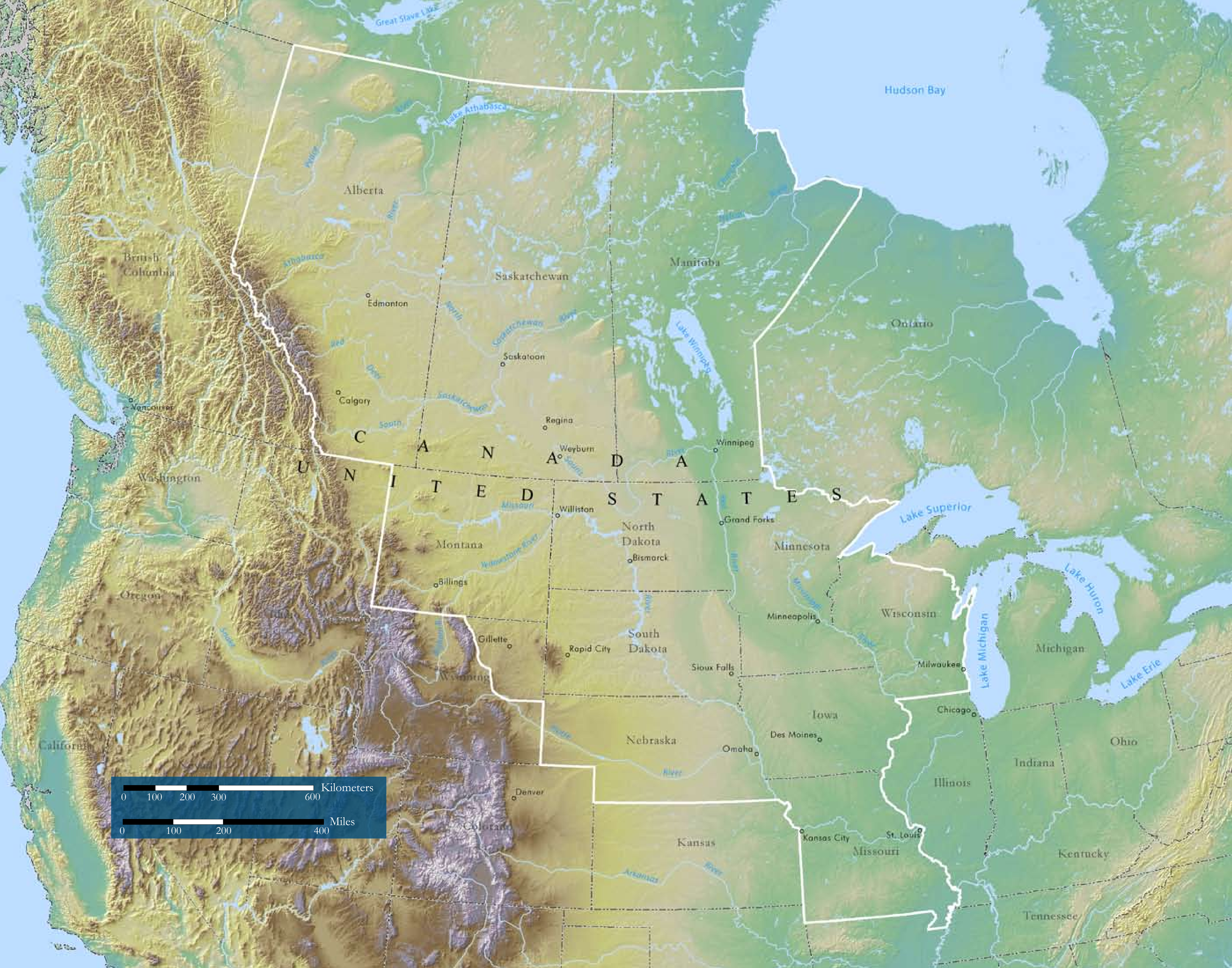
If science indicates that carbon sequestration must be implemented in the United States on a broad scale and in a relatively short time frame (meaning over several years), it will take a concerted effort of federal and state agencies, working in cooperation with technology developers, regulators, and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

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

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



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



Great Slave Lake
Hudson Bay
Lake Athabasca
Peace
River
Alberta
Athabasca
British
Columbia
Saskatchewan
Manitoba
Ontario
Edmonton
North
Saskatchewan
River
Lake Winnipeg
Red
Deer
Saskatoon
Calgary
Saskatchewan
South
Vancouver
Regina
Weyburn
Souris
River
Winnipeg
C A N A D A
U N I T E D S T A T E S
Washington
Missouri
Williston
North
Dakota
Grand Forks
Red
River
Lake Superior
Minnesota
Montana
Yellowstone River
Bismarck
Billings
Oregon
Idaho
Minneapolis
Mississippi
River
Wisconsin
Lake Huron
Lake Michigan
Michigan
Gillette
Rapid City
South
Dakota
Sioux Falls
Milwaukee
Lake Erie
Wyoming
Chicago
Iowa
Des Moines
California
Platte
Nebraska
Omaha
River
Ohio
Indiana
Illinois
Denver
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 Plains CO_2 Reduction (PCOR) Partnership is a diverse group of public and private sector stakeholders working together to better understand the technical and economic feasibility of capturing and storing CO_2 emissions from stationary sources of CO_2 in the cental interior of North America. The PCOR Partnership is managed by the Energy & Environmental Research Center (EERC) at the University of North Dakota and is one of seven regional partnerships funded by the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnership Program and a broad range of project sponsors.

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

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

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

ptrc
Petroleum Technology Research Centre

MUREX PETROLEUM CORPORATION

minnesota power
AN ALLETE COMPANY
YOUR POWERFUL PARTNER

NDSU
NORTH DAKOTA STATE UNIVERSITY

HESS

EXCELSIOR ENERGY

Manitoba Hydro

LIGNITE Energy COUNCIL

AERI
Alberta Energy Research Institute

Ducks Unlimited Canada
CANADA'S CONSERVATION COMPANY

GREAT NORTHERN

North Dakota Department of Health

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

GREAT RIVER ENERGY
A Touchstone Energy Cooperative

Great Plains SYNFUELS
Dakota Gasification Company

SaskPower

Encore Acquisition Company

NORTH DAKOTA NATURAL RESOURCES TRUST

Prairie Public Television

OTTER TAIL POWER COMPANY

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

TESORO

USGS
science for a changing world

EERC
Energy & Environmental Research Center
UND University of North Dakota
Grand Forks, North Dakota

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

NETL
NATIONAL ENERGY TECHNOLOGY LABORATORY

KIEWIT PKS SINCE 1884
Kiewit

Eagle Operating Inc.

UNIVERSITY OF REGINA
AS ONE WHO SERVES

CEED
Center for Energy and Economic Development

North Dakota Petroleum Council

INTERSTATE OIL AND GAS COMPACT COMMISSION
1935

Minnesota Pollution Control Agency

PTTC
TECHNOLOGY CONNECTIONS

BASIN ELECTRIC POWER COOPERATIVE
A Touchstone Energy Cooperative

CCX
Chicago Climate Exchange

Nexant

Alberta Environment

NORTH DAKOTA GEOLOGICAL SURVEY
1895

Fischer Oil and Gas, Inc.

Environment Canada

PUBLIC SERVICE COMMISSION MONTANA

Minnkota Power
MPC COOPERATIVE, INC.
Your Touchstone Energy Partner

Montana Department of Environmental Quality

EUB
Alberta Energy and Utilities Board

Xcel Energy

Saskatchewan Industry and Resources

WESTERN GOVERNORS' ASSOCIATION

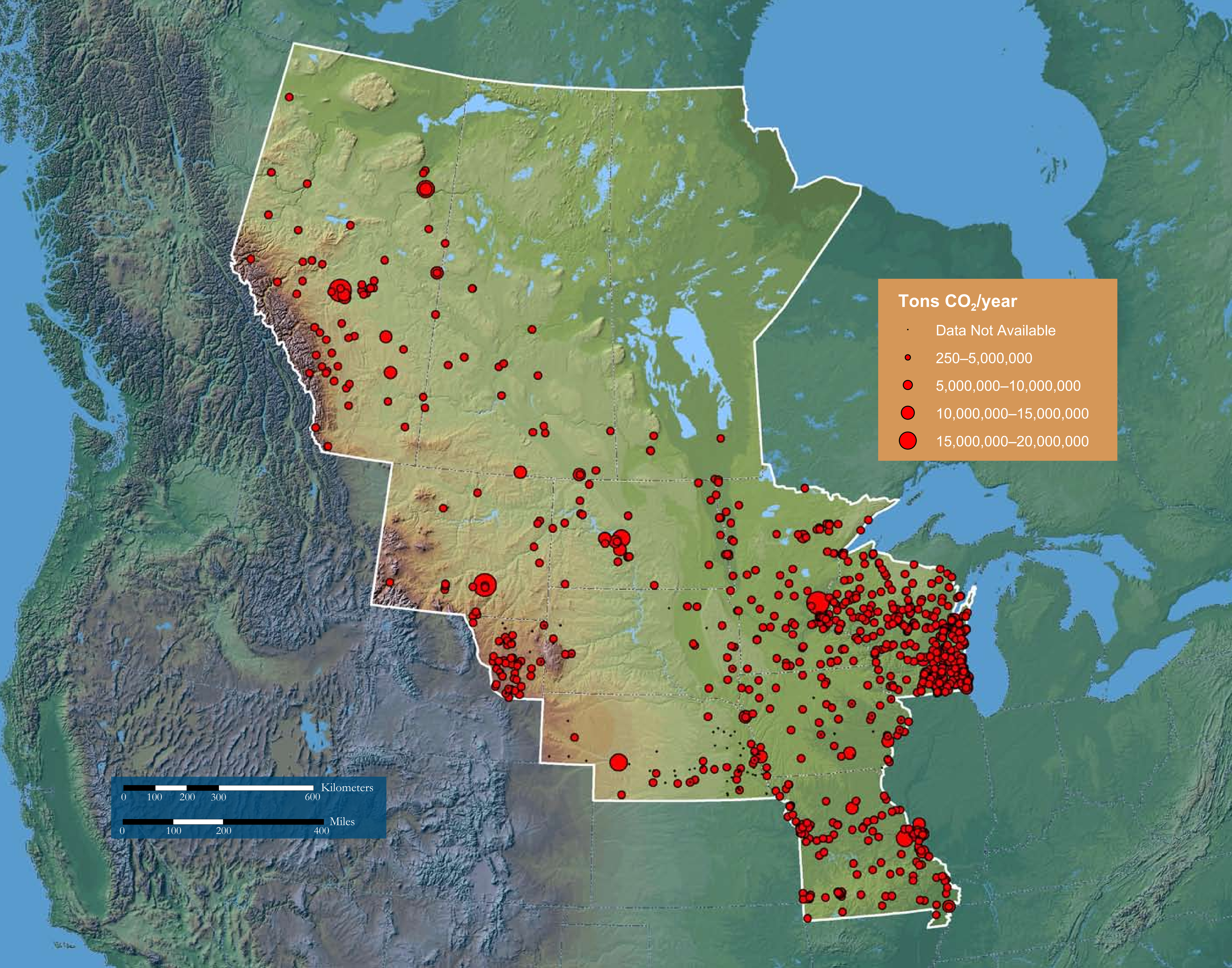
BECHTEL

PCOR Partnership Phase I Partners

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

PCOR Partnership Phase I List of Partners

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

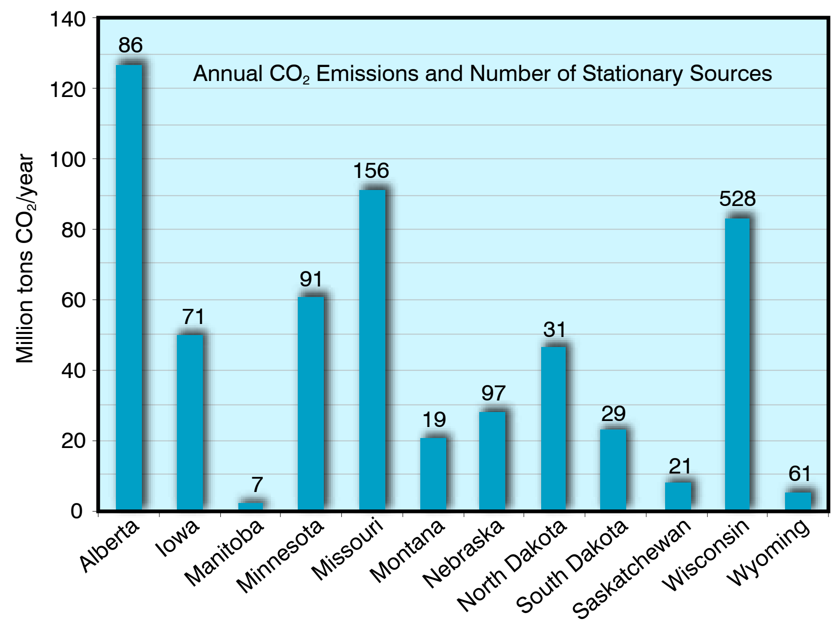


Tons CO_2/year
Data Not Available
250–5,000,000
5,000,000–10,000,000
10,000,000–15,000,000
15,000,000–20,000,000
Kilometers
0 100 200 300 600
Miles
0 100 200 400

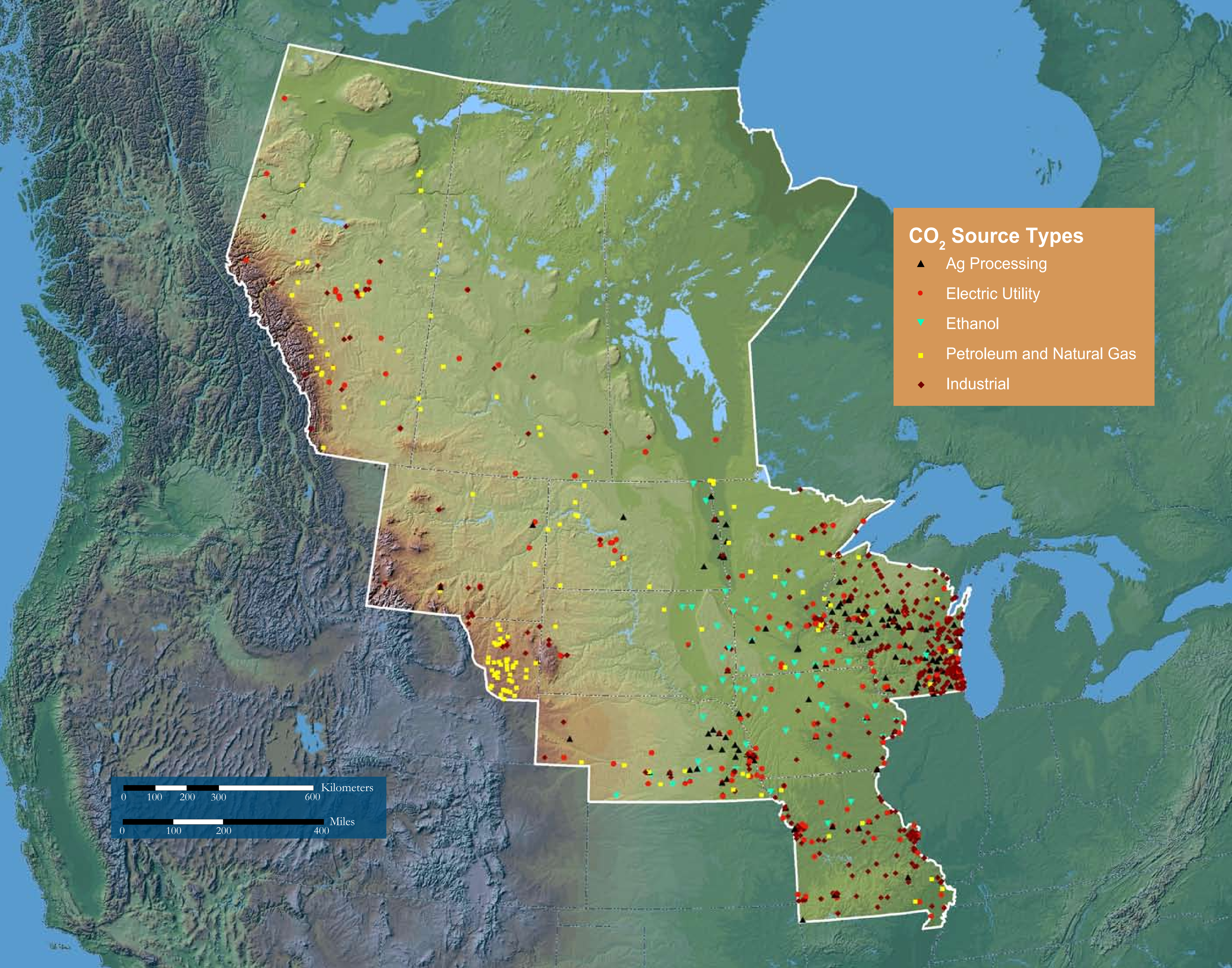
CO_2 Sources

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

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



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



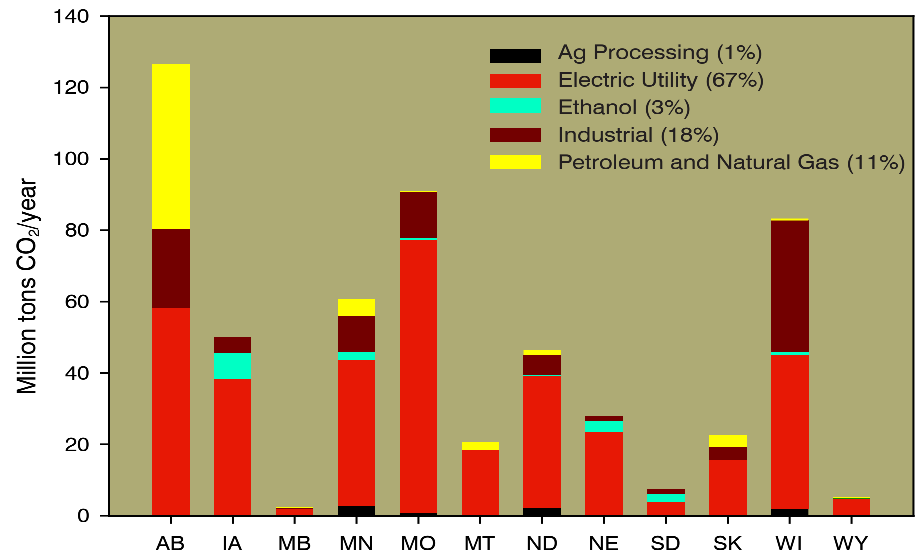
CO_2 Source Types
Ag Processing
Electric Utility
Ethanol
Petroleum and Natural Gas
Industrial
0 100 200 300 600 Kilometers
0 100 200 400 Miles

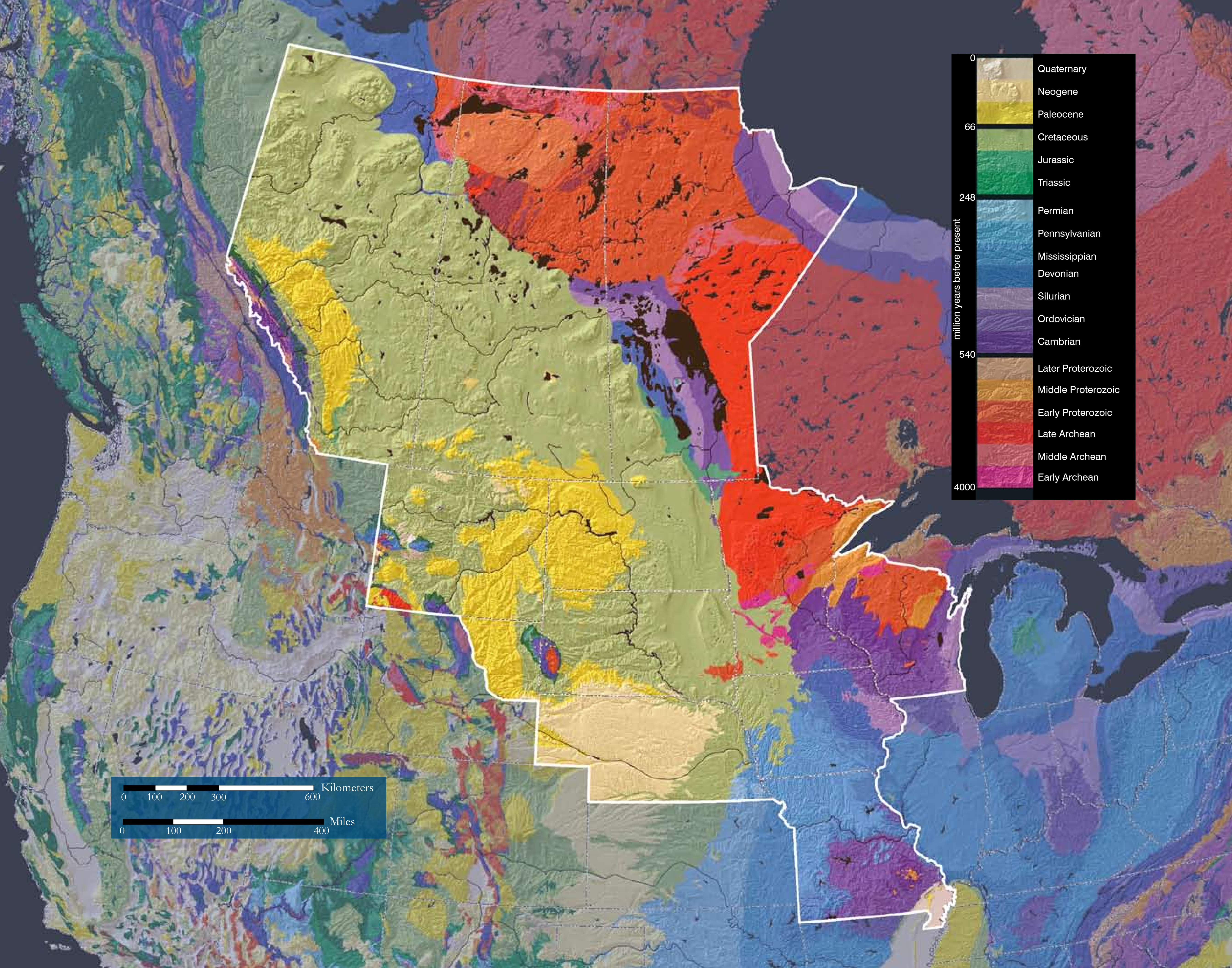
CO_2 Source Types

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

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

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




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

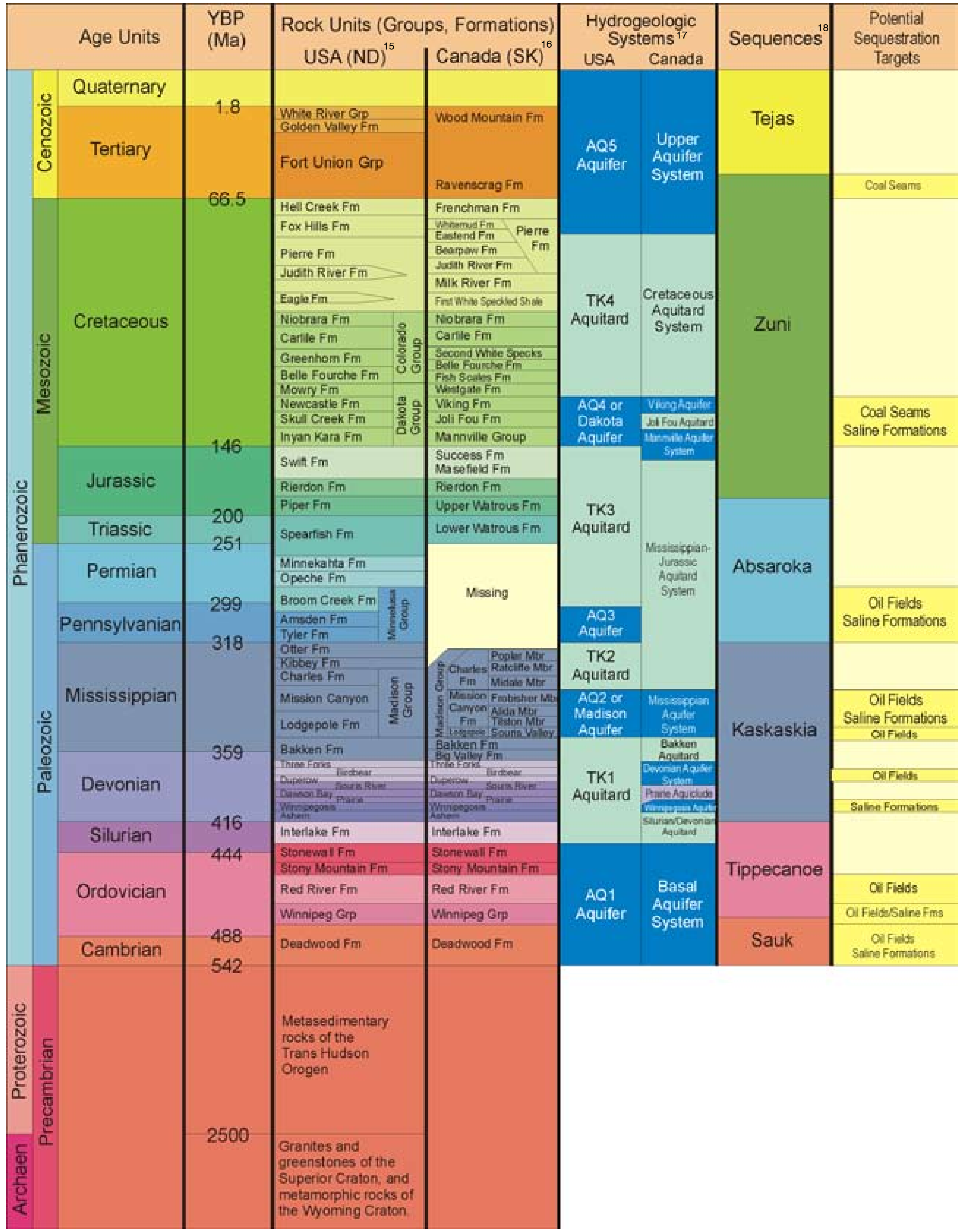
Geologic Framework

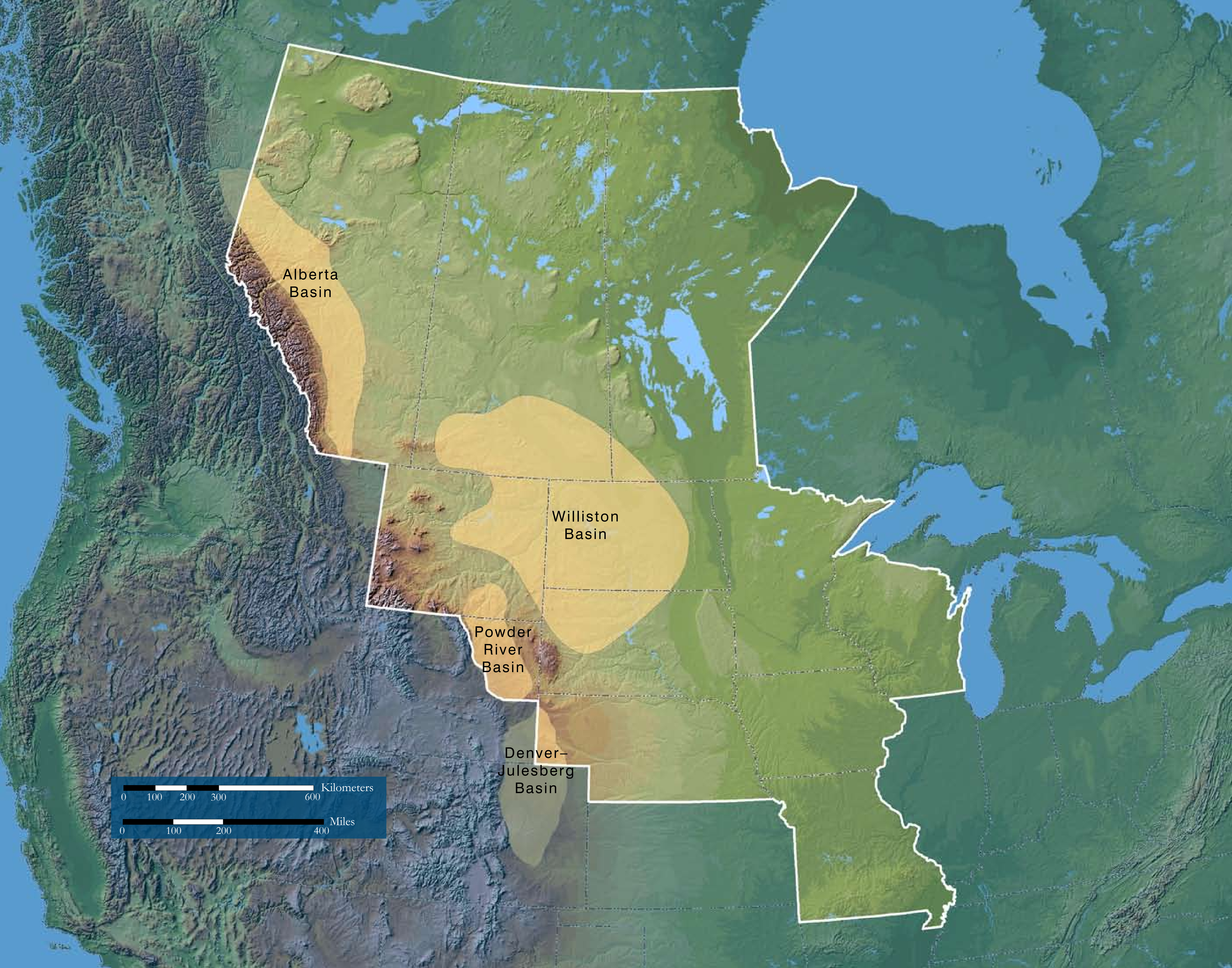
The same geological framework that makes a large percentage of the PCOR Partnership region a significant producer of fossil fuels also creates prime opportunities for CO_2 sequestration. The western two-thirds of the region is underlain by great thicknesses of sedimentary rocks that span the entire stratigraphic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

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

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

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





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

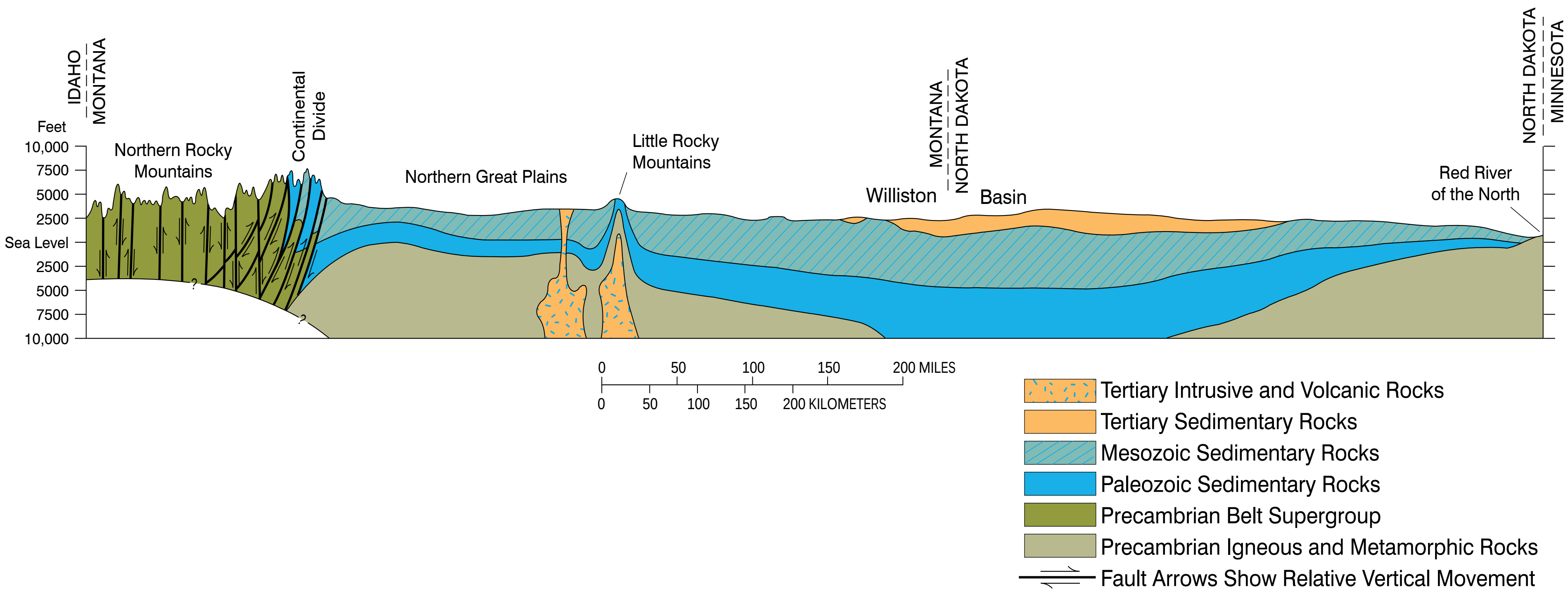
Sedimentary Basins

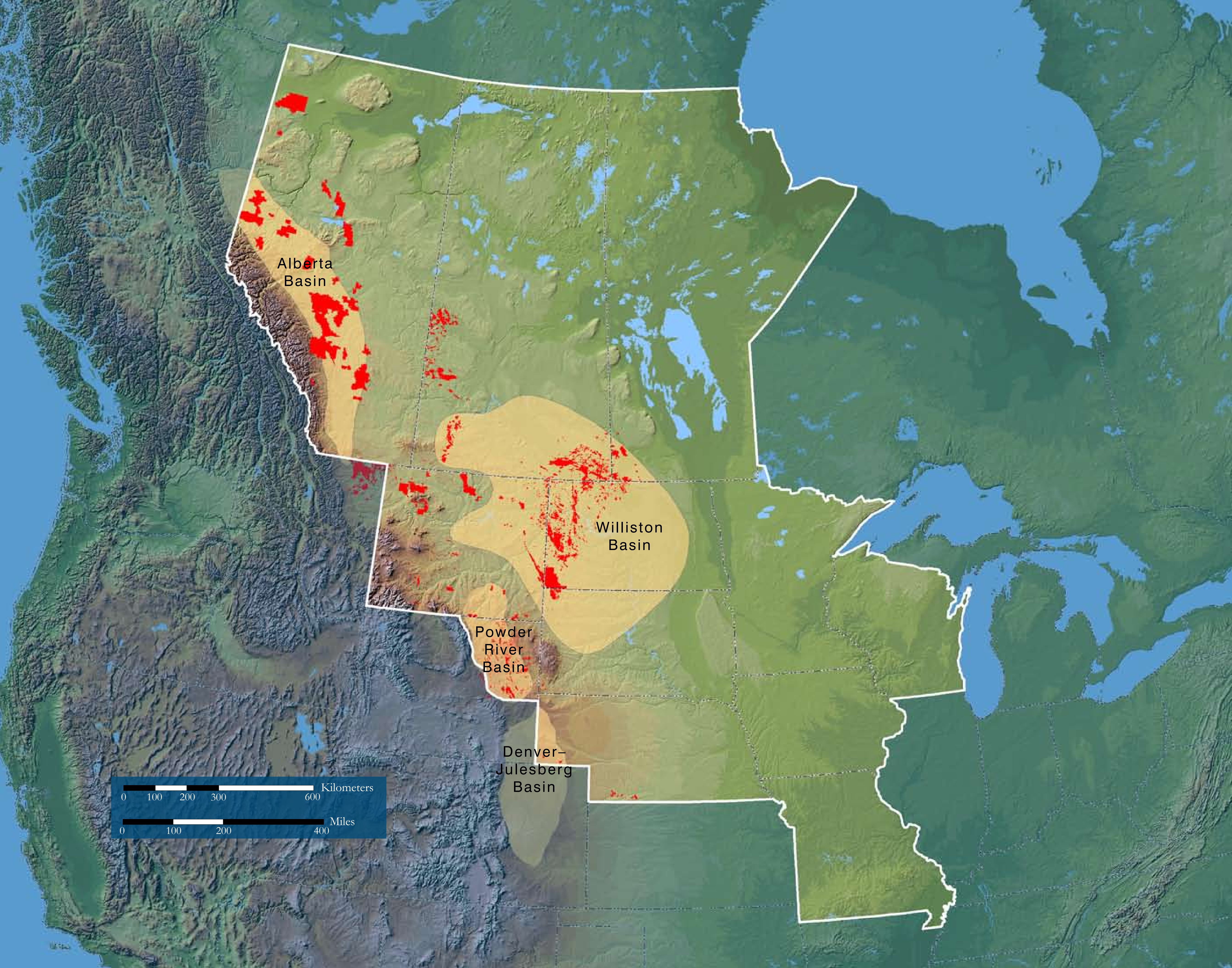
There are four relatively large and deep, intracratonic oil-producing basins intersecting the PCOR Partnership region, each with a sedimentary cover thousands of feet thick. The basins in the PCOR Partnership region have significant potential as geological sinks for sequestering CO_2. Geological sinks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

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

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

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




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

Oil and Gas Fields

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

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

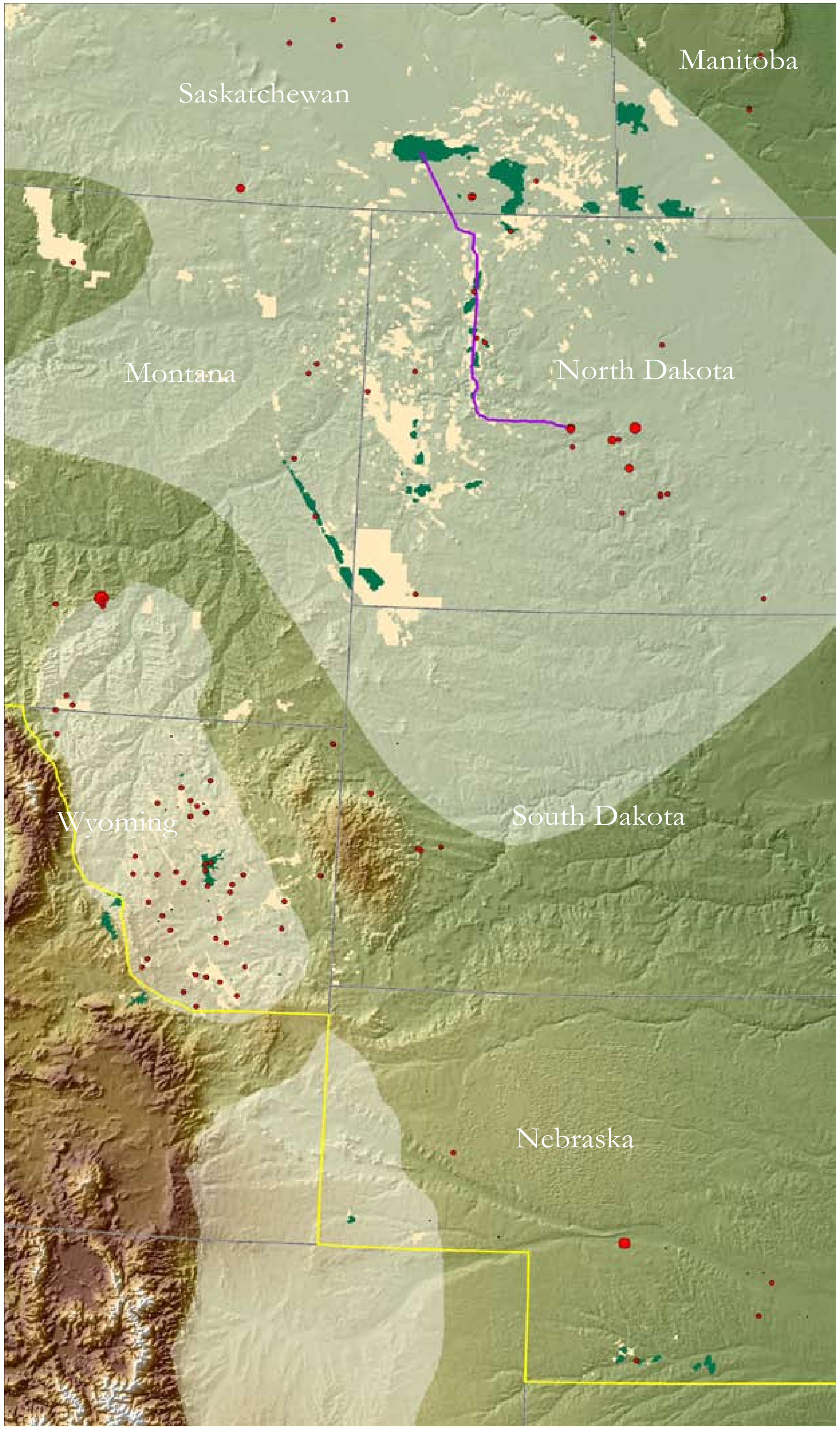
Oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from 2500 to 4000 feet for the shallower pools, to 12,000 to 16,000 feet for the deepest pools.

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

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

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

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



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

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

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

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

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

Enhanced Oil Recovery

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

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

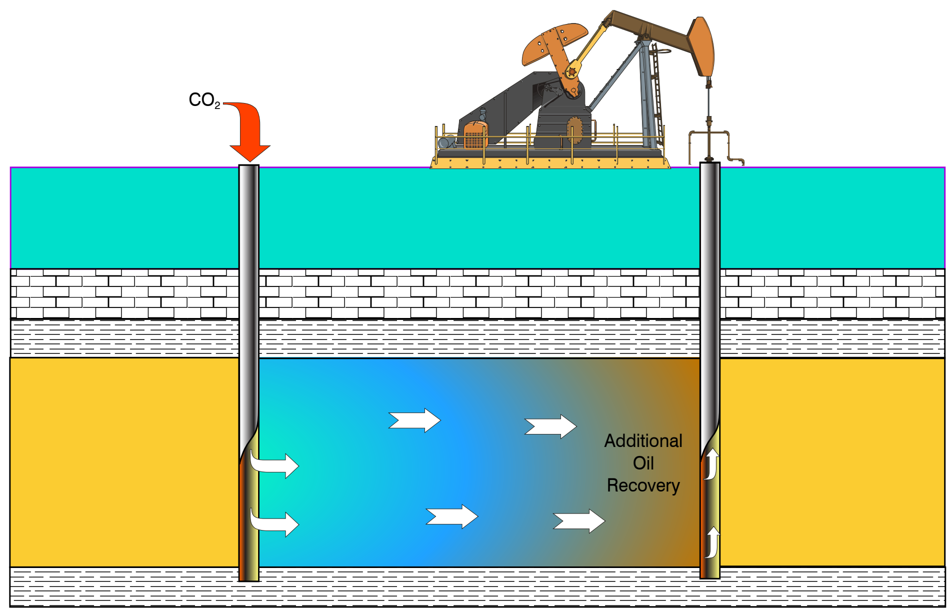
Reconnaissance-level CO_2 sequestration capacities were estimated for selected oil fields in the Williston Basin, Powder River Basin, and Denver–Julesberg Basins. Two calculation methods were used, depending on the nature of the available reservoir characterization data for each field. The estimates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

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

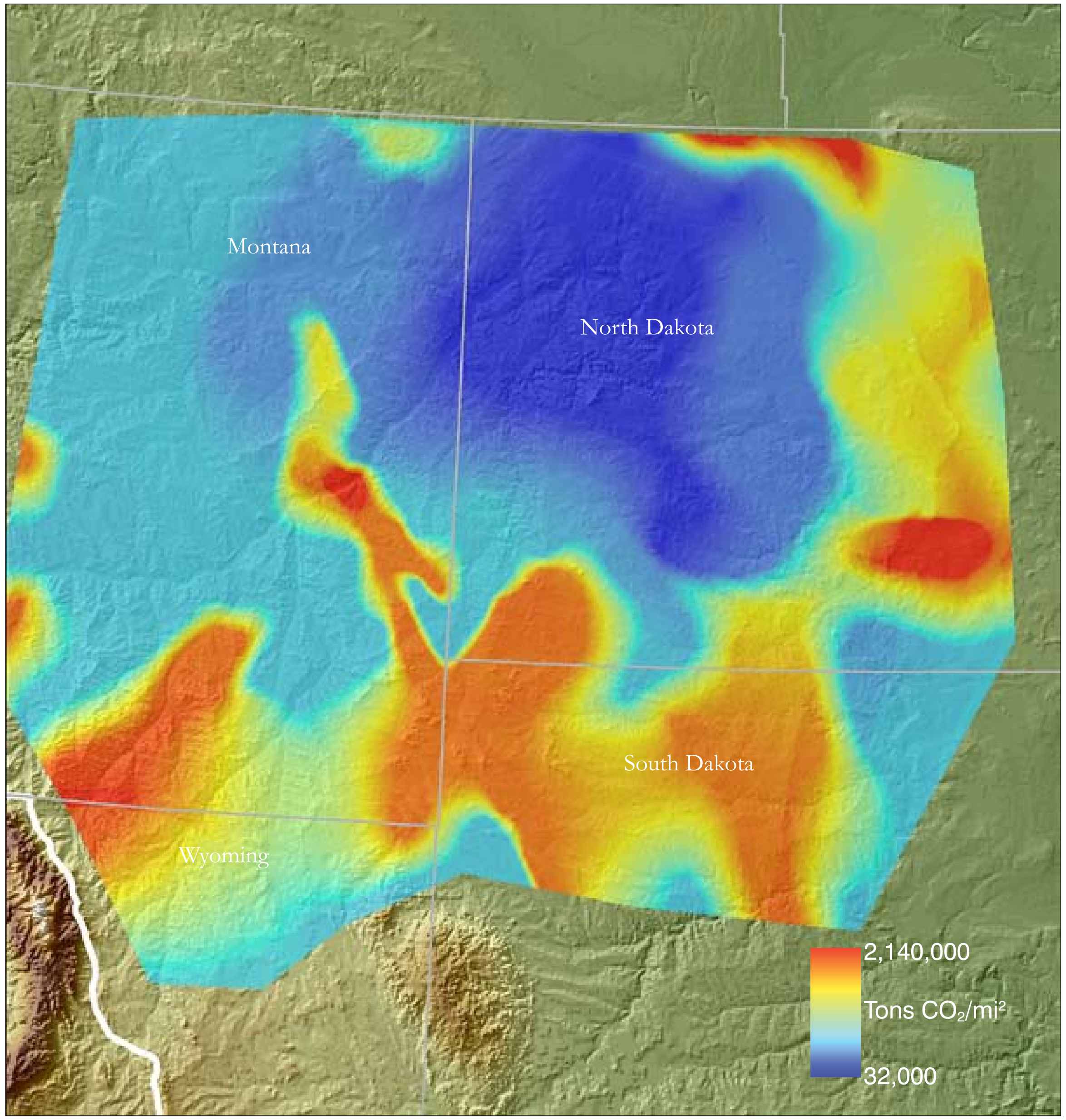
Storage and Incremental Recovery Through EOR in Selected Fields

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

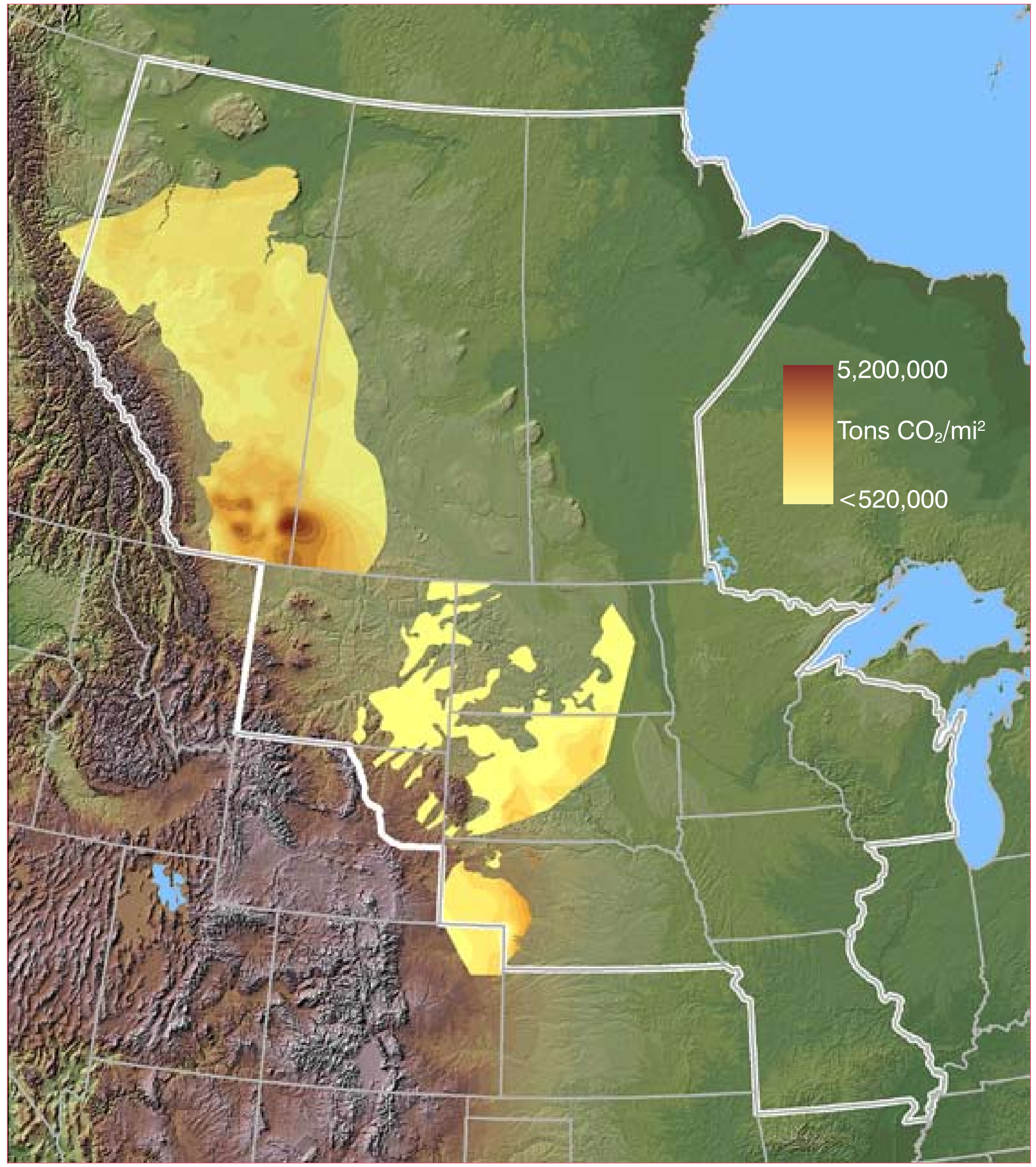
**CO_2 quantity required is the total purchase amount and does consider recycling of CO_2 from the tertiary recovery operation.*



Mississippian Madison System



Lower Cretaceous System

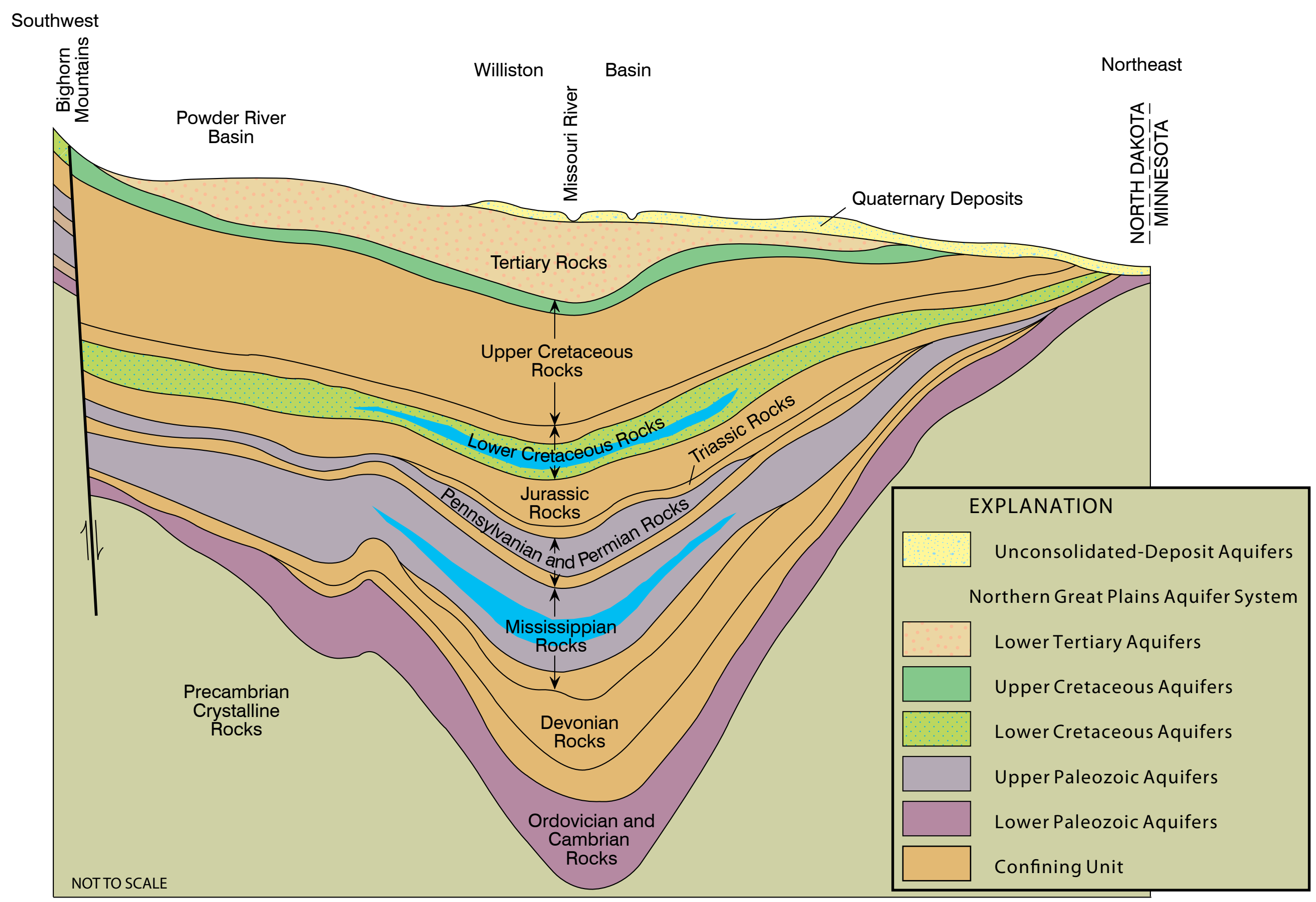


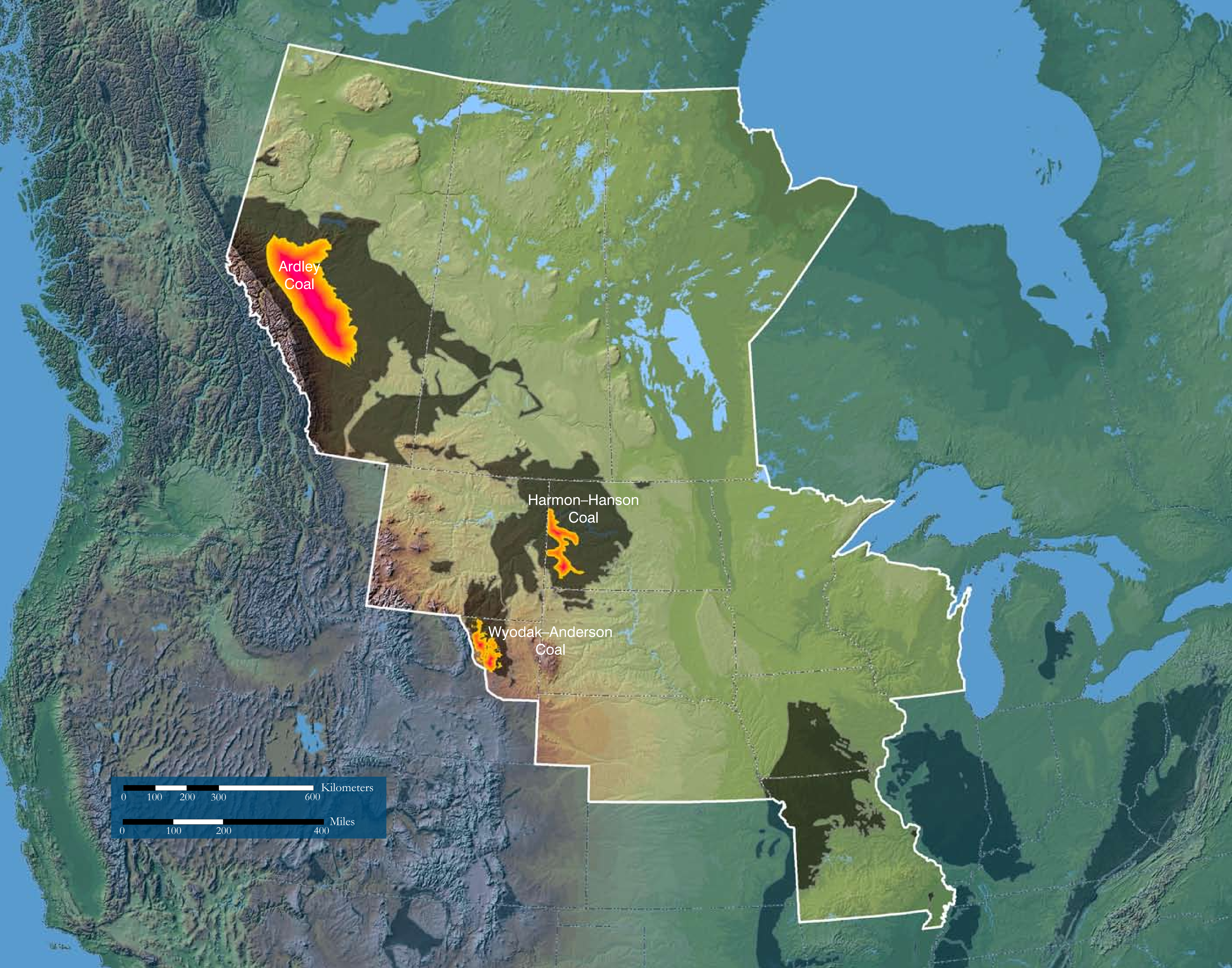
Saline Formations

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

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

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





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

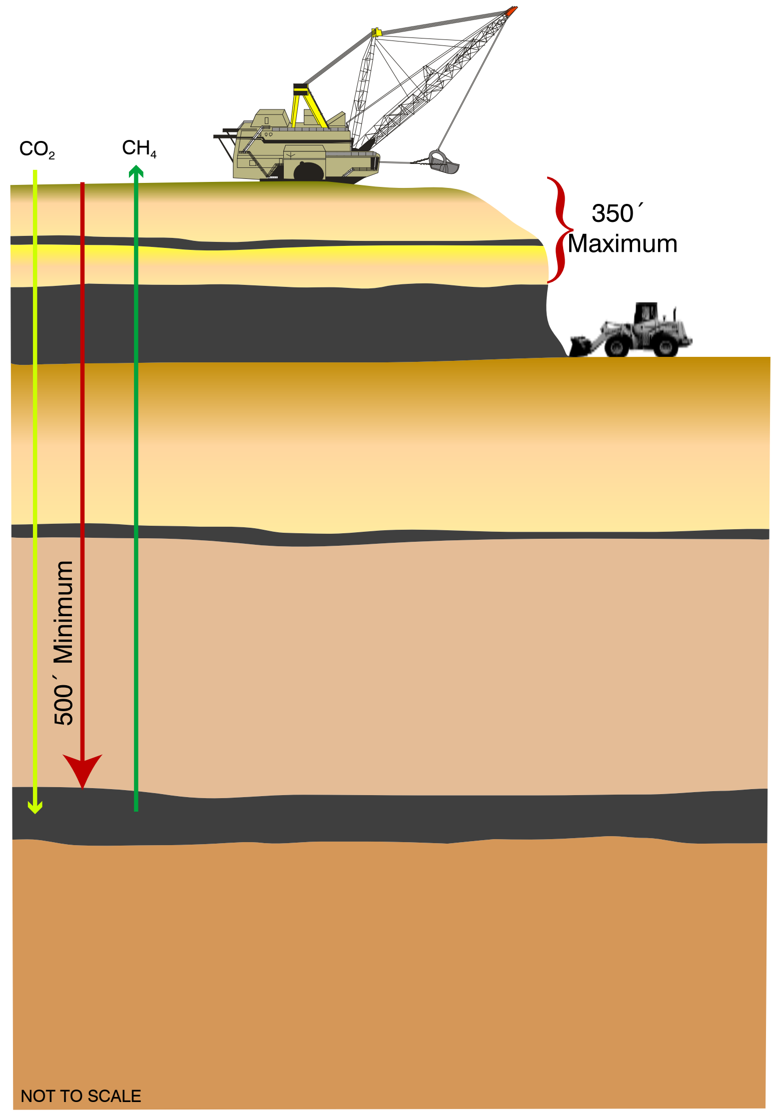
Sequestration in Coal

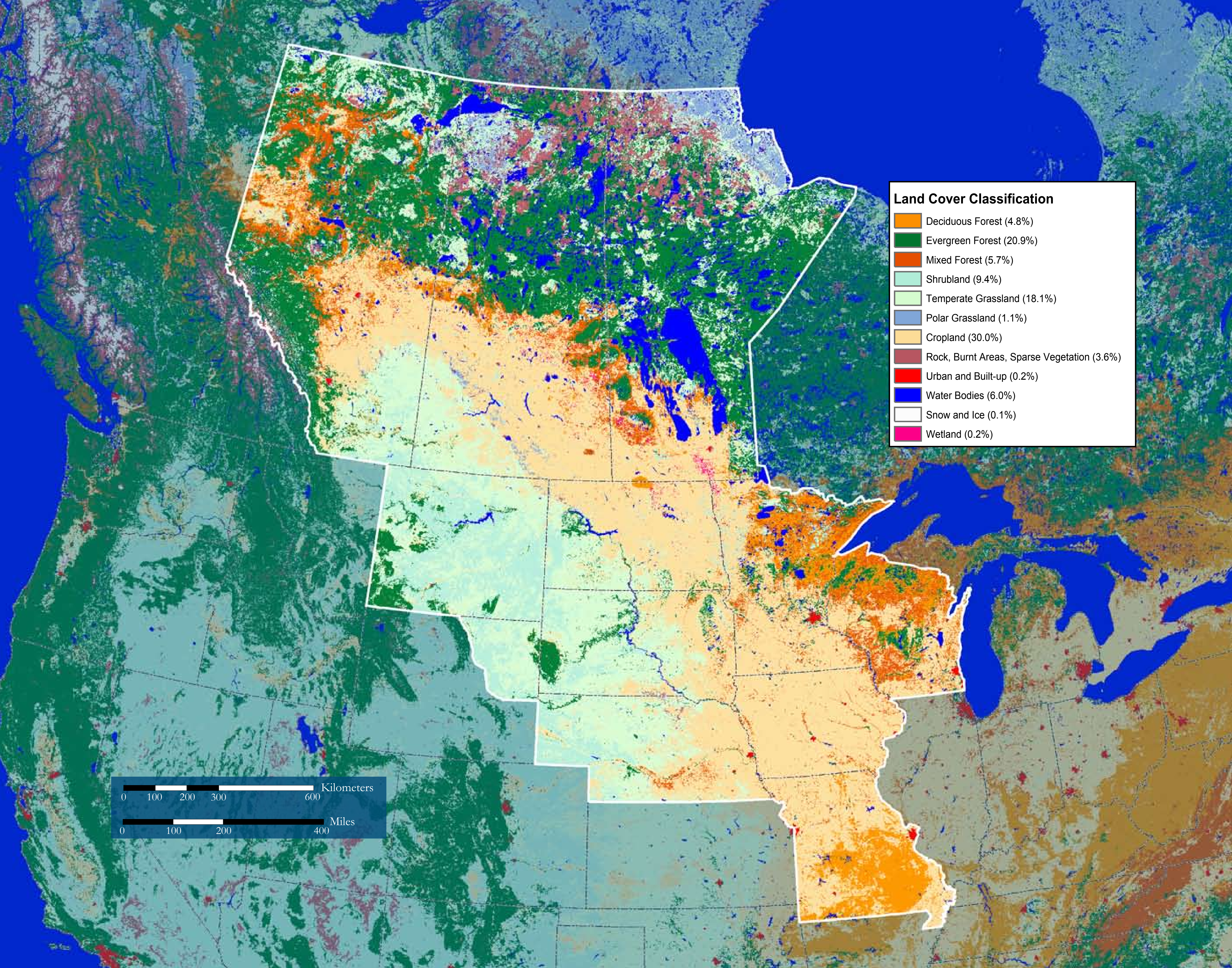
Many coal seams throughout central North America are too deep or too thin to be mined economically. However, many of these coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into the coal beds to recover this "coalbed methane" (CBM). In fact, CBM is the fastest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

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

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

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

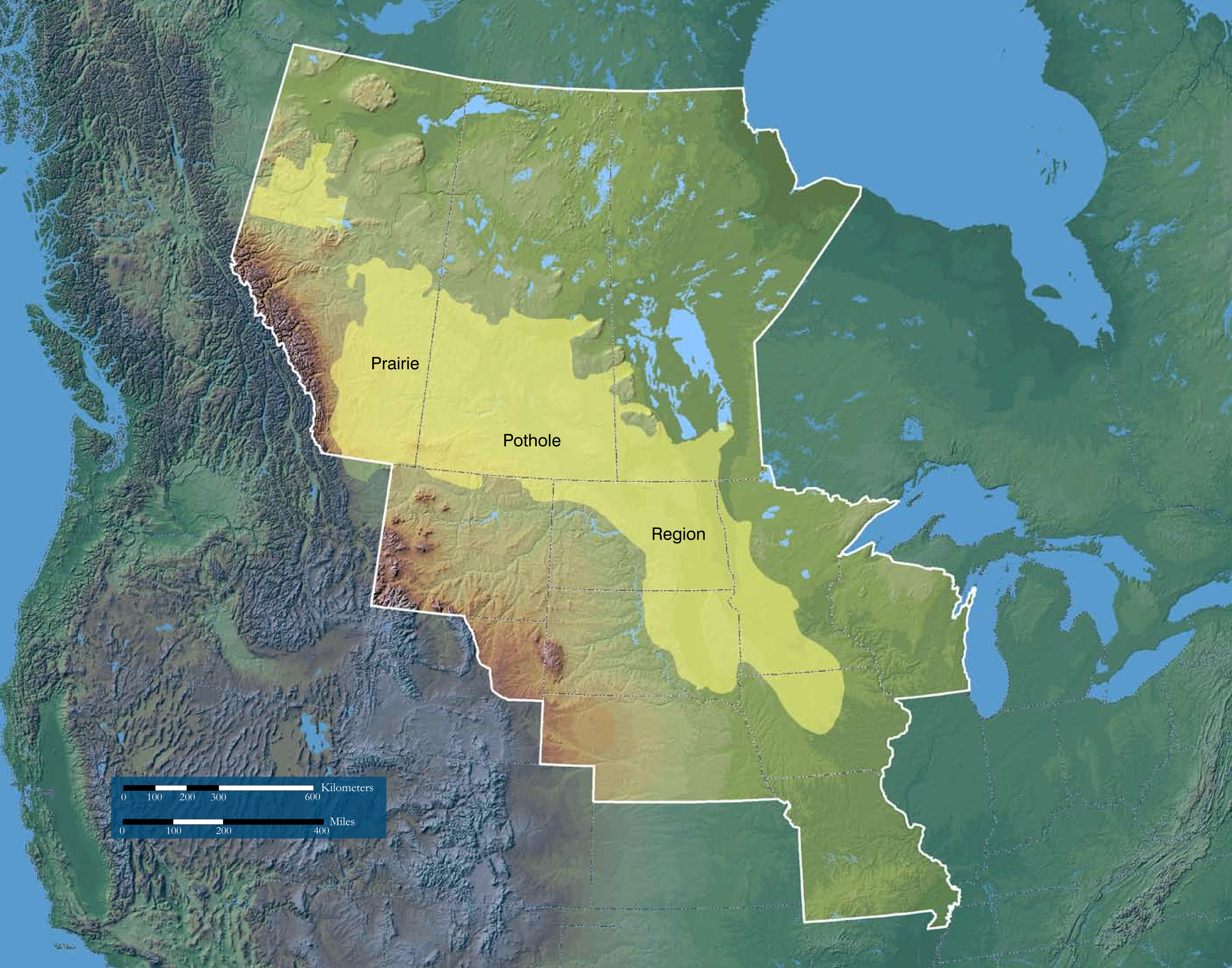



Land Cover Classification
Deciduous Forest (4.8%)
Evergreen Forest (20.9%)
Mixed Forest (5.7%)
Shrubland (9.4%)
Temperate Grassland (18.1%)
Polar Grassland (1.1%)
Cropland (30.0%)
Rock, Burnt Areas, Sparse Vegetation (3.6%)
Urban and Built-up (0.2%)
Water Bodies (6.0%)
Snow and Ice (0.1%)
Wetland (0.2%)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

Land Use and Sequestration Potential

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

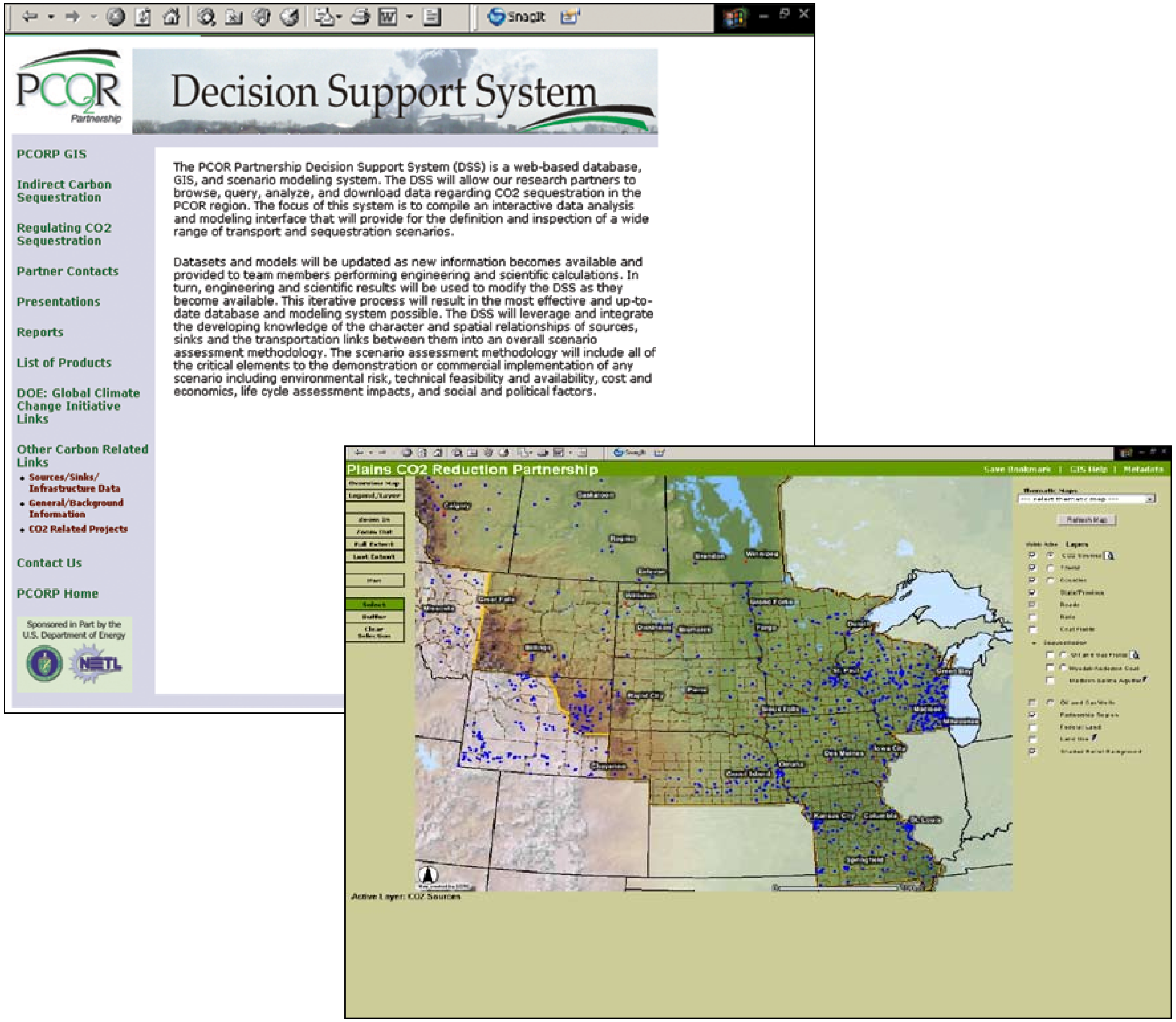
Some of the most promising terrestrial sequestration methods would promote and implement water and land management practices that enhance carbon buildup in biomass and soils, including adopting conservation tillage, reducing soil erosion, and minimizing soil disturbance; using buffer strips along waterways;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


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

Prairie Pothole Region

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

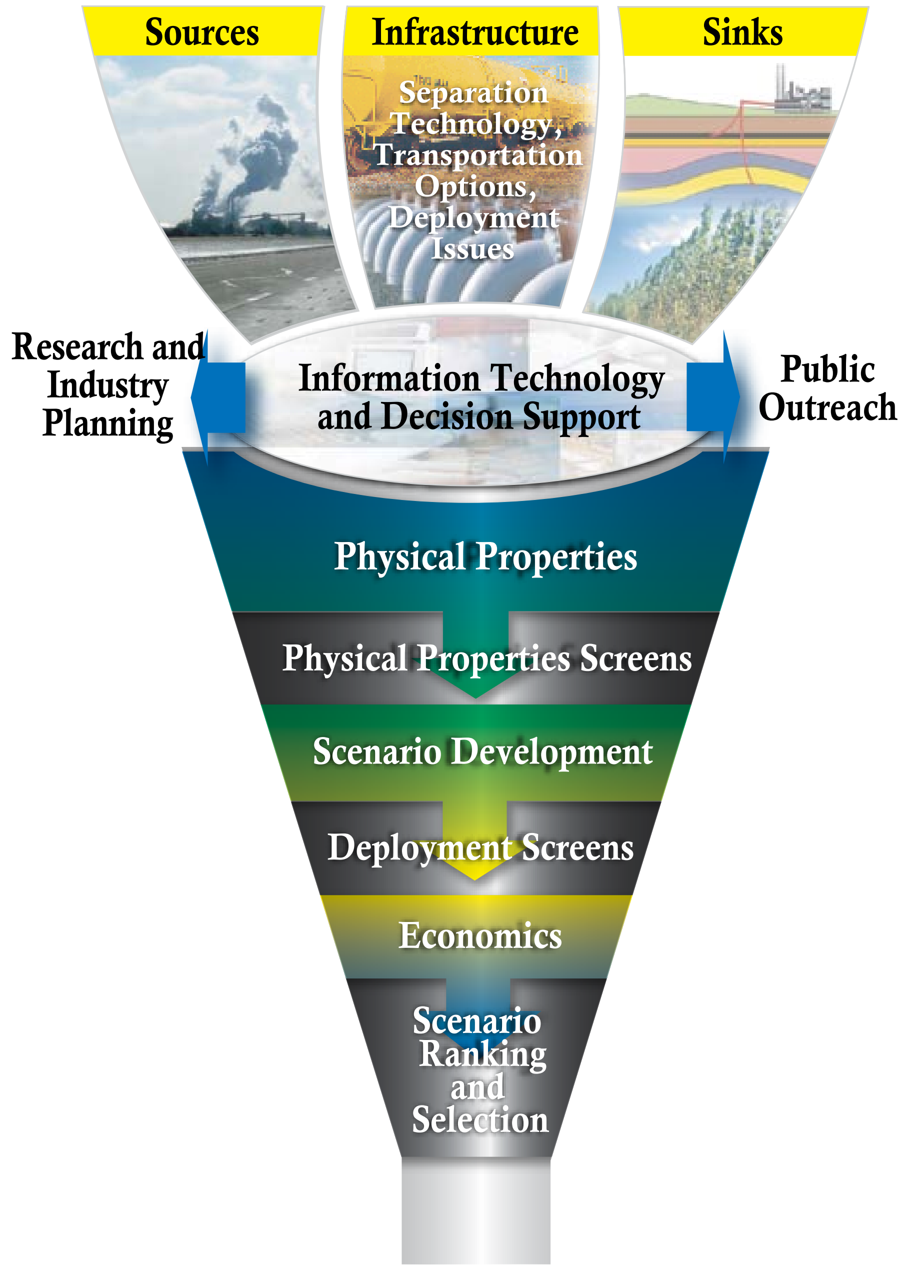
Recent work by U.S. Geological Survey and Ducks Unlimited scientists for the PCOR Partnership conducted at wetlands study sites demonstrated that restoration of previously farmed wetlands results in the rapid replenishment of SOC lost to cultivation at an average rate of 1.1 tons $acre^{-1}$ yr^{-1}.[31]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

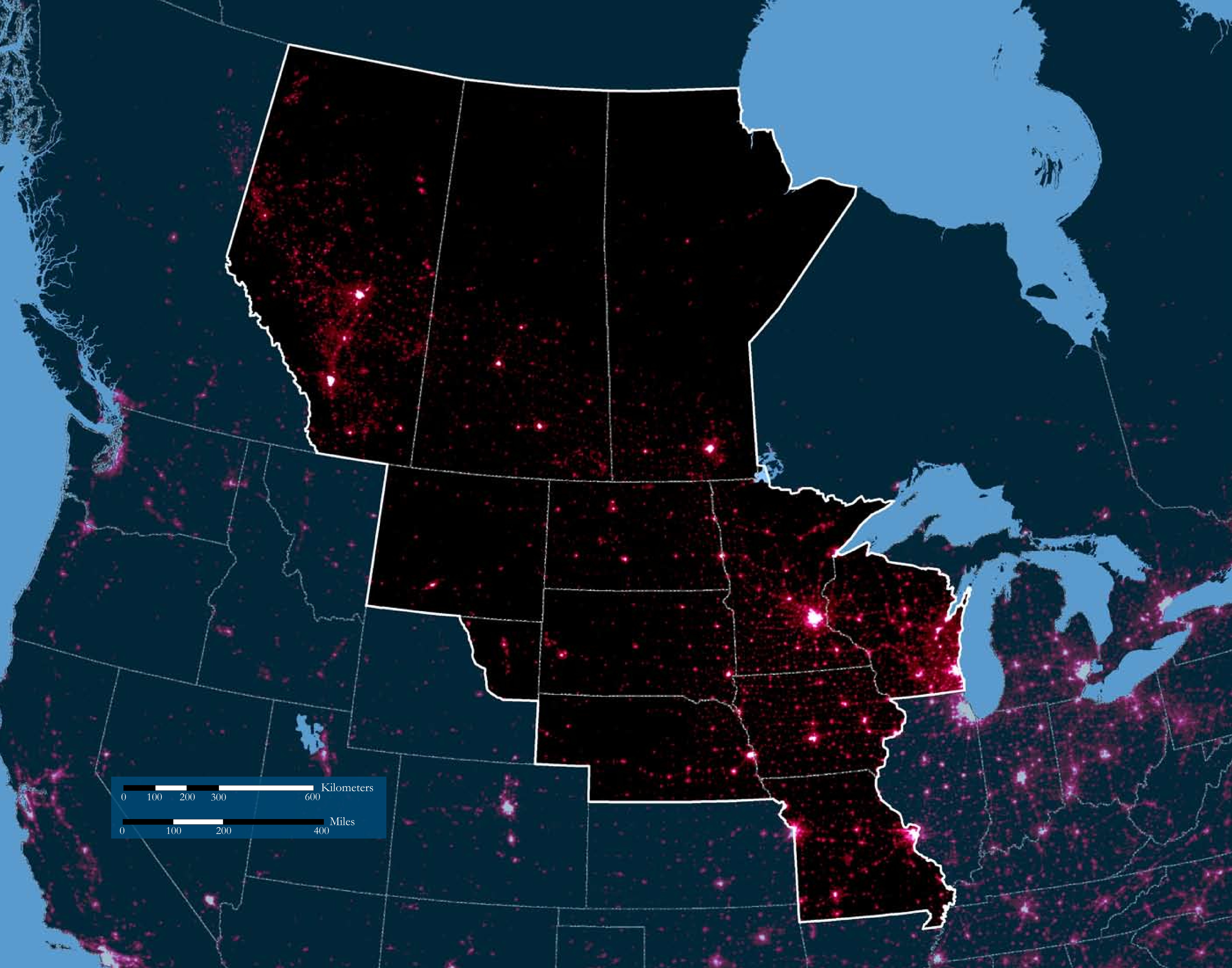

PCO2R Partnership
Decision Support System
PCORP GIS
Indirect Carbon Sequestration
Regulating CO2 Sequestration
Partner Contacts
Presentations
Reports
List of Products
DOE: Global Climate Change Initiative Links
Other Carbon Related Links
Sources/Sinks/Infrastructure Data
General/Background Information
CO2 Related Projects
Contact Us
PCORP Home
Sponsored in Part by the U.S. Department of Energy
NETL
The PCOR Partnership Decision Support System (DSS) is a web-based database, GIS, and scenario modeling system. The DSS will allow our research partners to browse, query, analyze, and download data regarding CO2 sequestration in the PCOR region. The focus of this system is to compile an interactive data analysis and modeling interface that will provide for the definition and inspection of a wide range of transport and sequestration scenarios.
Datasets and models will be updated as new information becomes available and provided to team members performing engineering and scientific calculations. In turn, engineering and scientific results will be used to modify the DSS as they become available. This iterative process will result in the most effective and up-to-date database and modeling system possible. The DSS will leverage and integrate the developing knowledge of the character and spatial relationships of sources, sinks and the transportation links between them into an overall scenario assessment methodology. The scenario assessment methodology will include all of the critical elements to the demonstration or commercial implementation of any scenario including environmental risk, technical feasibility and availability, cost and economics, life cycle assessment impacts, and social and political factors.
Plains CO2 Reduction Partnership
Save Bookmark | GIS Help | Metadata
Active Layer: CO2 Sources

Web Site (DSS)

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

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



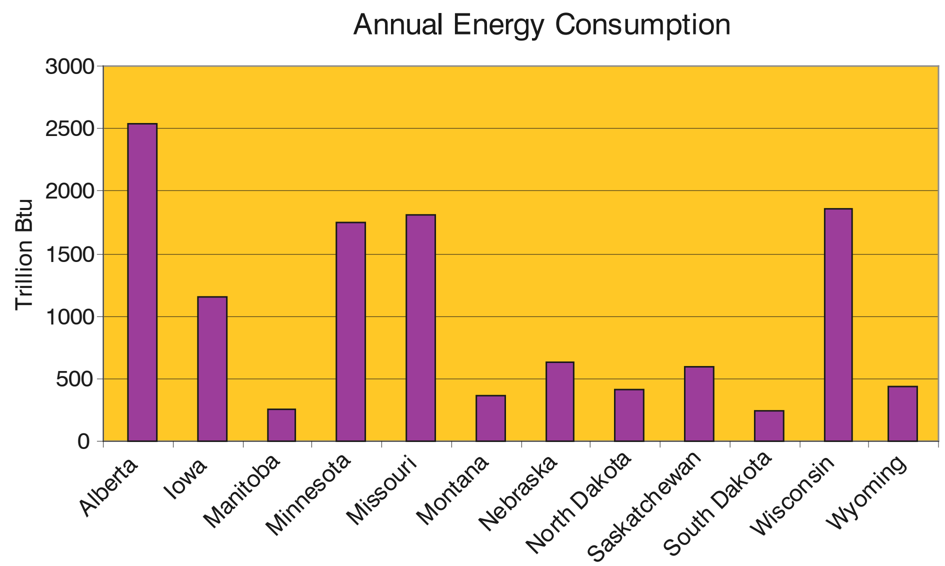

0 100 200 300 600 Kilometers
0 100 200 400 Miles

Keeping the Lights On

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

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

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



The Plains CO2 Reduction Partnership
PCOR Partnership
EERC
PARTNERS ONLY
Plains CO2 Reduction (PCOR) Partnership
Practical, Environmentally Sound CO2 Sequestration
Supporting Materials
Nature in the Balance
CO2 Sequestration
NETL
Gateway

Education and Outreach — CO_2 Sequestration

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

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

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

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

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

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

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

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A much earlier map of the PCOR Partnership Region

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