Plains CO_2 Reduction (PCOR) Partnership

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP REGIONAL CHARACTERIZATION DATA GAP ASSESSMENT II

Task 6 – Deliverable D36

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PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP
REGIONAL CHARACTERIZATION DATA GAP ASSESSMENT

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The PCOR Partnership is a collaborative effort of more than 70 public and private sector stakeholders working toward a better understanding of the technical and economic feasibility of capturing and storing (sequestering) anthropogenic carbon dioxide (CO_2) emissions from stationary sources in the central interior of North America. The PCOR Partnership is one of seven regional partnerships that were initiated in the fall of 2003 under the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnership (RCSP) Program.

One of the key partnership activities is the assessment of the region's CO_2 production and sequestration potential in an effort to optimize source–sink opportunities within the region. This is accomplished by 1) identifying the data elements required to assess the region's CO_2 production, geologic and terrestrial storage capacity, existing transportation systems, infrastructure, and regulatory framework; 2) collecting information from many sources, including agencies governing oil and gas exploration, regulatory agencies, industrial partners, and publicly available databases; 3) analyzing, reviewing, and assembling the data into a usable format; and 4) disseminating the data to DOE and partners through the PCOR Partnership Decision Support System (DSS, © 2007 EERC Foundation) – a database-driven Web site containing both traditional Web pages and an interactive geographic information system (GIS).

From utilizing the DSS, one can gain an understanding of the magnitude, distribution, and industrial classification of CO_2 output in the region; distribution of oil and gas production, coal basins, and saline formations across the region; the sequestration potential for select oil fields and saline formations; the existing pipeline transportation network and the environmental and political features that may affect future transportation development; the sequestration potential of wetland restoration in the Prairie Pothole Region (PPR); the potential terrestrial sequestration activities such as forestry activities and modifications to agricultural practices; and the current and proposed regulatory framework regarding the transportation, injection, and storage of CO_2. The DSS also allows the partnership to evaluate the completeness of the data required for a complete characterization of the region. As such, new data are regularly added to the DSS and existing data continue to be refined through the characterization activities.

Regional characterization began at the Phase I kickoff meeting, where PCOR Partnership partners were asked to identify the key data elements that would be necessary in evaluating various sequestration options for the region. The partners represented all segments that would be involved in a sequestration effort, including utilities, oil and gas operators, and regulatory agencies. This input was invaluable in initially identifying information sources and in determining what level of characterization would be most useful for evaluating sequestration scenarios.

Six months after the kickoff meeting, the first version of the DSS was completed and put online for PCOR Partnership partners. Subsequently, the data requirements were defined and refined based on the partners' and researchers' use of the DSS. The data collected in Phase I and the first 2 years of Phase II have provided the basis for developing this regional characterization data assessment. This report provides an assessment of the characterization performed thus far and a plan for the continued characterization over the remainder of Phase II and in Phase III.

CO_2 STATIONARY SOURCE DATA

The primary production of anthropogenic CO_2 comes from the combustion of fossil fuels, with a lesser amount generated as a by-product of noncombustion chemical reactions such as fermentation. For the purpose of regional characterization of the PCOR Partnership region, CO_2 sources were defined as stationary industrial facilities which emit CO_2 during combustion and/or processing activities. The regional source characterization activities to date defined over 1000 stationary industrial CO_2 emission sources.

The variable nature of these sources reflects the geographic and socioeconomic diversity of the region. In the upper Mississippi River Valley and along the western shores of the Great Lakes, large coal-fired electrical generators power the manufacturing plants and breweries of St. Louis, Minneapolis–St. Paul, 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 support many agricultural processing industries.

Characterization Approach and Results

There is no specific agency, database, or other singular resource available that identifies all of the CO_2 sources within the partnership region. The majority of the information needed to identify sources and to obtain or calculate annual CO_2 emissions for the various sources in the PCOR Partnership region was gleaned from the Web sites of the following agencies and organizations:

- U.S. Environmental Protection Agency (EPA) Clean Air Markets
- EPA Emissions and Generation Resource Integrated Database (eGRID)
- EPA Technology Transfer Network (TTN) Ozone Implementation
- Commission for Environmental Cooperation

- Renewable Fuels Association Ethanol Biorefinery Locations
- Environment Canada's Greenhouse Gas Division
- United States Geological Survey

Most of the source locations or source industries were identified through the EPA TTN and the Environment Canada Web site databases. The TTN database was designed by EPA to provide data for implementing the Ozone Ambient Air Standards and, particularly, to determine nonattainment areas. Although CO_2 is not required to be listed by the reporting industries, the overall database is much more extensive than EPA's eGRID. The eGRID database covers only those industries that are part of the electrical grid. The TTN database, on the other hand, includes all industries that generate ozone and, therefore, almost all industries that generate CO_2. The Environment Canada Web site contains the National Inventory Report, which provides greenhouse gas emission data at the national, provincial, and sectoral levels.

Other CO_2 source industries were identified through information provided by our partners, through general knowledge of the types of industries in the partnership region, and from information obtained through networking with other regional partnerships. Once an industry was identified, the source locations and information required for determining emissions was collected from a variety of regulatory and industry-based Web sites. The only criteria for inclusion in the evaluation are that the CO_2 source must be stationary and industrial in nature. Commercial and residential sources are not included. There is no minimum level of CO_2 production that would exclude a facility from the assessment process.

Specific calculation methodologies for power plants, ethanol plants, agricultural processing facilities, petroleum and natural gas facilities, cement kilns, and other industries are presented in Appendix A.

Table 1 lists the data elements that are collected for each source when available from the reference. At a minimum, the data must include the source name, location, and a CO_2 emission amount in order to be included in the database. Sources which are not yet in operation, are off-line, or do not have enough data to calculate source emissions are not included in the database.

The map shown in Figure 1 illustrates the distribution and magnitude of the sources. The total emission from these sources is 549 million tons of CO_2 per year (1). Sherburne County (Sherco), a coal-fired power plant located 45 miles west of Minneapolis, Minnesota, is the largest single emitter at 18.2 million tons per year. The majority of the region, however, has many smaller sources. Sixty-two percent of the sources emit less than 100,000 tons per year. The top 3% (33) of the sources emit almost as much CO_2 as the remaining 97% (1073) of the sources.

The sources have been classified into two hierarchal levels: industry sector and type. The industry sectors include petroleum and natural gas, electric utility, ag-related processing, and other industrial. Table 2 presents the breakdown between sector and type. The majority of the sources are classified as other industrial (589), followed by ag-related processing (210), electric utility (162), and petroleum and natural gas (145).

Table 1. Source Data Collected

Data Element	Description
Source Name	Company name or description of the CO_2 source.
State/Province	State or province abbreviation for the location of the source.
Source Reference	Reference for the origination of the source.
Source Type	Type of source (i.e., sugar production).
Source Sector	Categorization of source type (i.e., ag processing).
Latitude/Longitude	Latitude/longitude of the source.
Total Combustion CO_2	Total CO_2 emitted from combustion.
Total Noncombustion CO_2	The CO_2 produced from the noncombustion process of the source.
Total CO_2	Combustion CO_2 + noncombustion CO_2.
SO_x	SO_2 produced from a source.
NO_x	Total NO_x produced from a source.
Fuel Type	Types of fuel for the source. A source may have more than one fuel type.
Fuel Amount	For each fuel–source combination, the amount of fuel used.
CO_2 Fuel Amount	For each fuel–source combination, the CO_2 produced from the fuel.
Commodity Type	For each noncombustion source, the type of commodity produced (i.e., lime, ethanol).
Commodity Amount	The amount of commodity produced.

Figures 2 and 3 present the count and total emissions for each state and province by source group. Wisconsin has the highest total of individual sources (533), while Alberta has the highest amount of CO_2 emissions (113.6 million tons/year).

Data Gap Assessment

The PCOR Partnership has collected or calculated CO_2 emission values on all known stationary industrial sources within our region. Where the region overlaps with the Big Sky Partnership region, the source latitude, longitude, and emission amounts are in agreement. There are no known issues with duplicate data within our database. Because the spatial proximity of sources to potential sinks and infrastructure can be very important in planning CO_2 sequestration scenarios, the PCOR Partnership has recently conducted a review of source locations, verifying many locations using Google Earth (earth.google.com). Google Earth is an on-line mapping application that contains aerial photographs. Google Earth can be used to verify or obtain the location of a facility by using a street address or geographic location of the region of interest and scanning the map for an image of the facility. All of the source calculations have been reviewed and corrected as necessary.

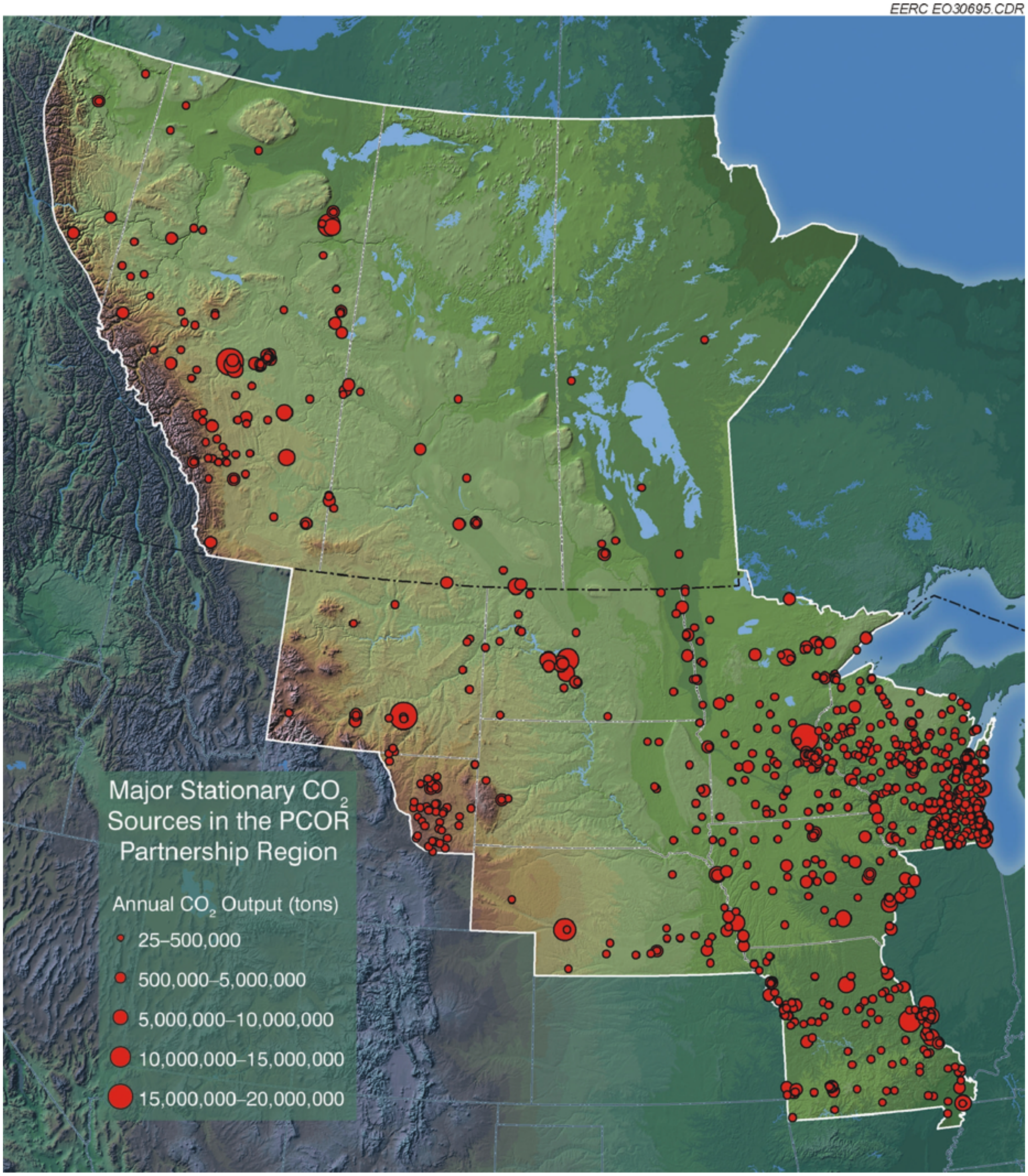


Figure 1. Distribution and magnitude of CO_2 sources in the PCOR Partnership region.

Table 2. Breakdown of the Industry Sector and Type

Ag-Related Processing	Electric Utility	Other Industrial	Petroleum and Natural Gas
Agricultural Processing	Cogeneration	Ammonia production	Natural gas processing
Animal and Animal By-Product Processing	Electric generating	Asphalt production	Natural gas transmission
Ethanol Manufacturing	Municipal heat and power	Cement/clinker production	Petroleum and natural gas processing
Fertilizer Production		Chemical production	Petroleum refining
Sugar Production		Foundries/manufacturing	Petroleum transmission
		Fuels/chemicals	
		Industrial/institutional heat and power	
		Iron ore processing	
		Lime production	
		Manufacturing	
		Metals processing	
		Minerals processing	
		Mining	
		Miscellaneous	
		Paper and wood products	
		Waste processing	

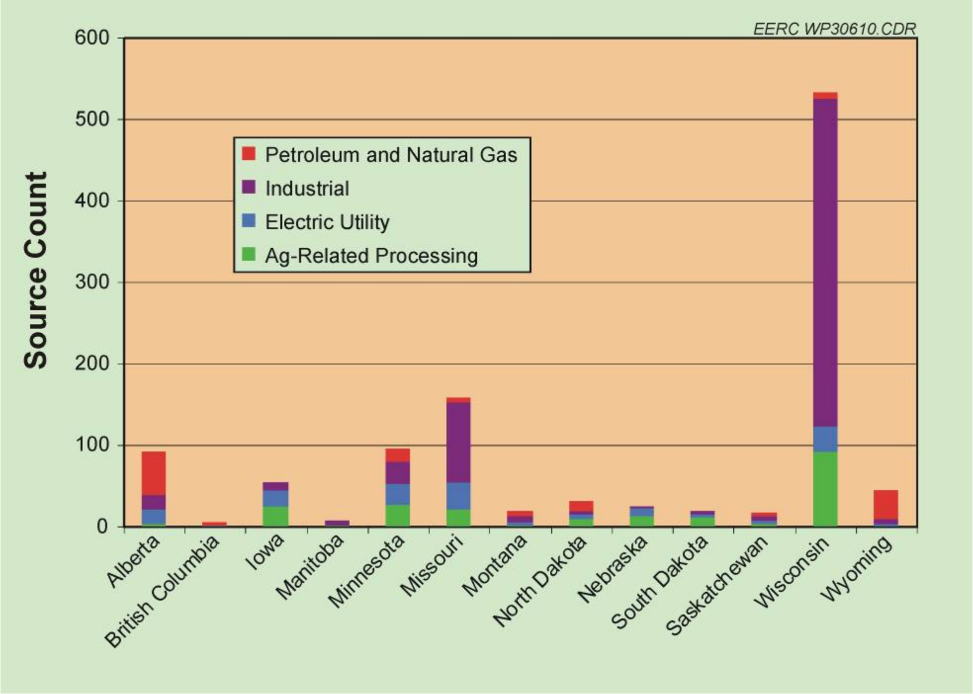


Figure 2. Number of sources by state/province.

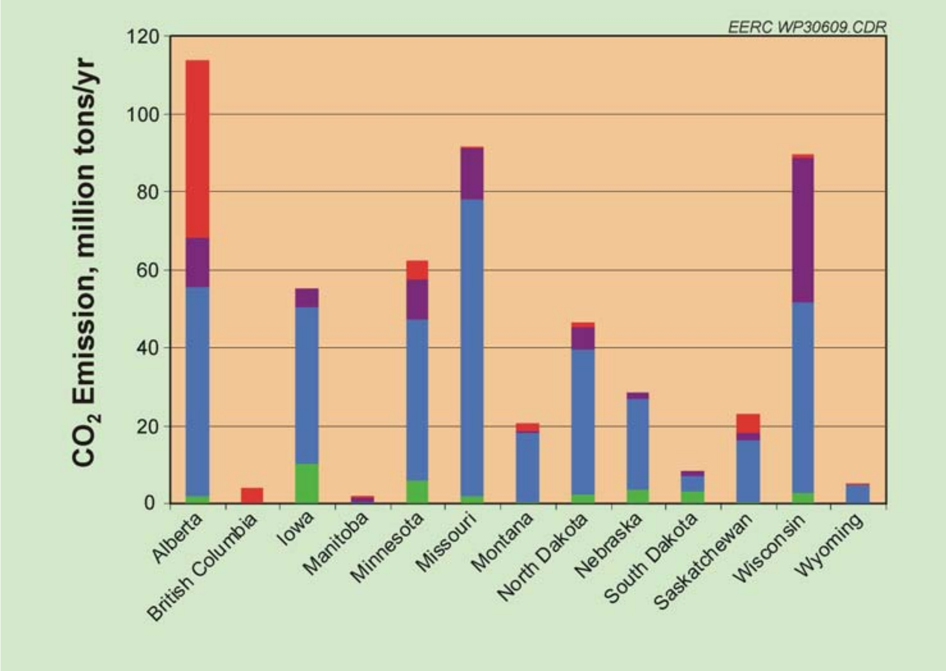


Figure 3. CO_2 emissions by state/province.

The emission amount listed for the sources does not represent historical rates, nor are the data from the same time period for all records: the data range from 1996 through 2006. Near-real-time data are available for some sources associated with the eGRID data set. However, it has been decided that this potential increase in precision is not particularly useful since it is available for only a select set of sources, and the magnitude of the annual CO_2 output does not change significantly.

At the present time, there do not appear to be any gaps in characterization of the sources within the region. There has not been a need or request to collect additional characterization information on CO_2 sources such as gas composition or other operational conditions. Future characterization activities will focus on regular reviews and updates of the database.

During the remainder of Phase II, major CO_2 sources that have come online or that have come to the attention of the PCOR Partnership since the original data were collected will be added to the database. Phase III activities for source characterization will include reviewing and updating the data elements for existing sources and adding additional operational data if required by partnership activities.

GEOLOGIC SINKS

Geologic sequestration of CO_2 involves the capture of anthropogenic CO_2 before it is released to the atmosphere and then its injection into deep underground geologic formations. 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 relatively thin and shallow sedimentary rocks or 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.

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 remain sequestered for thousands of years and not pose a danger to human health and the environment.

The diverse character of the PCOR region with respect to potential geologic sequestration of CO_2 requires that both a broad- and local-scale assessment be used. The broad-scale assessment utilizes easily obtainable data to generate sequestration magnitudes across broad areas of the PCOR Partnership region, but generally at a lower precision. Assessment of CO_2 capacity at a fine, or local, scale requires more data, yet offers a more precise sequestration potential for a smaller area.

Oil and Gas Reservoirs

Characterization Approach and Results

With the exception of Nebraska, formal oil field (or pool for Alberta and British Columbia) boundaries in GIS format were obtained directly from the respective state/province oil and gas regulatory agencies. Basic attribute data for each oil field were typically included with the supplied files. Oil field boundaries in Nebraska were created by digitizing polygon shapes around oil and gas wells that were reported to be part of the same field.

The map shown in Figure 4 shows the distribution of the oil fields (pools for Alberta and British Columbia). The basic statistics for the oil fields acquired through the first 2 years of Phase II are shown in Table 3.

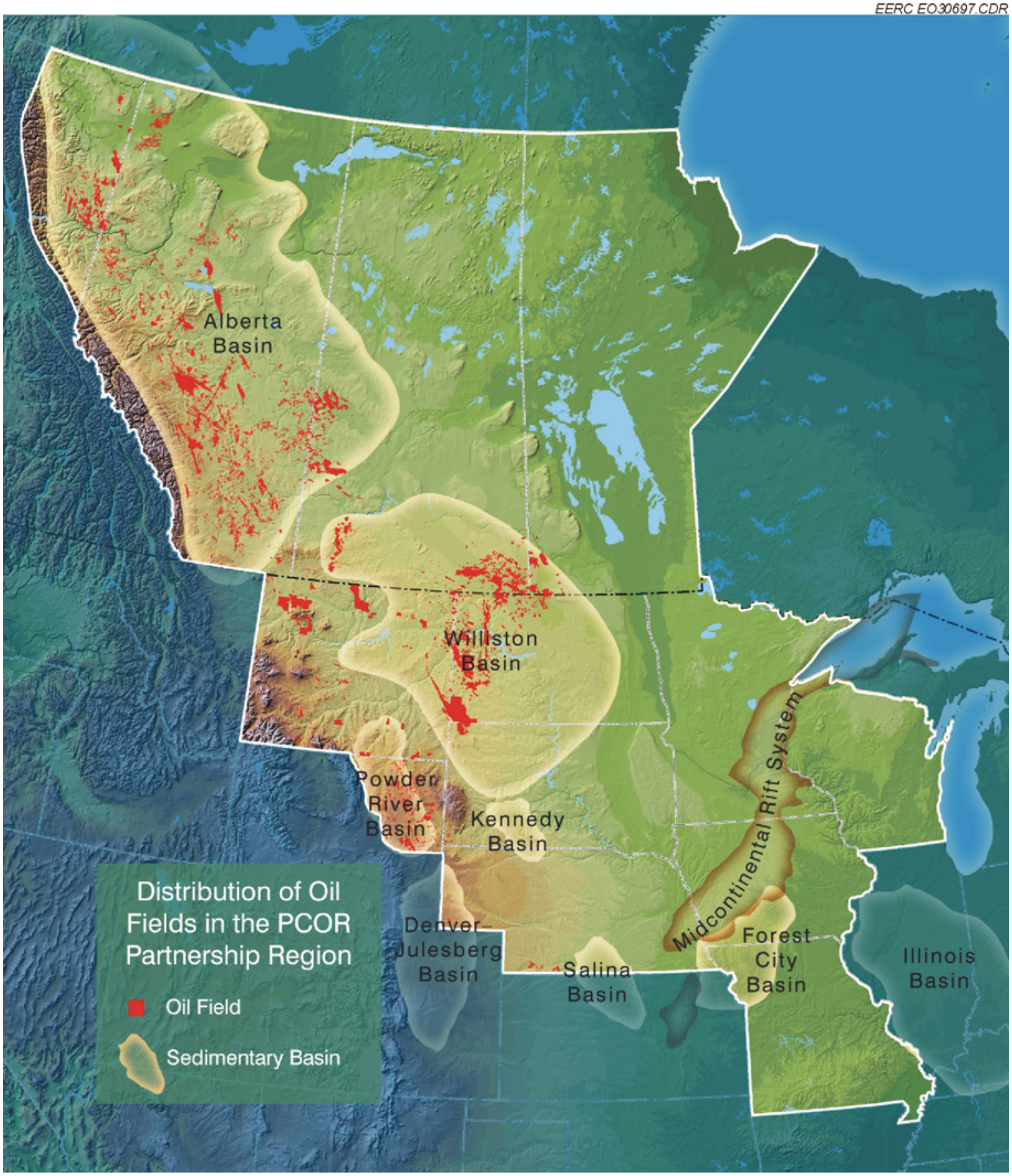


Figure 4. Distribution of oil fields in the PCOR Partnership region.

Data at the pool level are required to perform sequestration capacity calculations. Where data were not available from the digital file, select case files of the most promising fields from the oil and gas regulatory agencies were reviewed. In calculating the sequestration capacity, the following criteria were used:

Table 3. Oil Field and Gas Field Data Collected Through Year 2 of Phase II

State/ Province	No. of Fields	No. of Pools	No. – % of Fields with Pools	No. – % of Fields with Capacity Estimate	No. – % of Pools with Capacity Estimate	No. –% of Fields with Cum. Barrels
AB	995	9227	579 – 58%	579 – 58%	9227 – 100%	0 – 0%
BC	Data Collection in Progress					
MB	12	37	8 – 67%	6 – 50%	35 – 95%	12 – 100%
MO	Data Collection in Progress					
MT	473	258	90 – 19%	65 – 14%	119 – 46%	252 – 53%
ND	618	475	154 – 25%	140 – 23%	341 – 72%	600 – 97%
NE	25	26	13 – 52%	11 – 44%	21 – 81%	24 – 96%
SD	22	22	22 – 100%	18 – 82%	18 – 82%	22 – 100%
SK	438	762	423 – 97%	423 – 97%	762 – 1%	438 – 100%
WY	531	241	155 – 29%	142 – 27%	215 – 89%	380 – 72%
Region Total	3114	11,048	1444 – 46%	1384 – 45%	10,738 – 97%	1728 – 55%

- Field surface area
- Average pay thickness
- Average porosity
- Depth to pay
- Average reservoir temperature
- Initial reservoir pressure
- Water saturation
- Original oil in place
- Formation volume factor

Values for these data elements are stored in the DSS along with several other reservoir data elements that accompany the acquired data.

Appendix B contains reference documents detailing the calculations used to determine CO_2 sequestration capacities for the various pools using both the volumetric and enhanced oil recovery (EOR) methodologies. Based on the assessment thus far, the total sequestration capacity of the region for EOR is 6.9 billion tons. Using the volumetric calculation, 30.8 billion tons of CO_2 could be sequestered (1).

Data Gap Assessment

The data collected to date have been very useful in characterizing the region’s EOR and volumetric sequestration potential and in identifying potential opportunities for Phase II and Phase III demonstrations. The data assessment level thus far has been at a broad scale. With the exception of British Columbia and Missouri, we have identified the field boundaries and readily available reservoir data for all of the fields/pools in the states and provinces that have an oil and gas industry. The data for some of the states are over 3 years old and may need to be updated.

Of the field data collected, 55% of the fields do not have an estimated CO_2 capacity because of the lack of available reservoir data on those fields. The calculation of more exact sequestration capacities for a reservoir requires a systematic analysis, including detailed geologic characterization, production history, and modeling efforts. In some cases, the oil resource is very small, indicating that the sink potential is low or the field is too remote from other oil fields to justify the time and effort required to obtain the missing data. However, of the pool data that are available, 97% contains the data elements necessary for estimating capacity.

In Phase II activities, relevant Missouri and British Columbia data will be incorporated in the DSS. Existing data will be reviewed and evaluated to determine what, if any, additional data will be sought for existing fields and pools. Characterization data resulting from the field demonstration activities will also be incorporated into the DSS. Phase III activities will be focused on assessments of one or more specific sites. These focused assessments require in-depth log analysis and modeling. Through these site assessments, the PCOR Partnership hopes to learn about industry practices of reporting geologic data, which may help to qualify capacity estimates. Through these assessments and the site characterization activities for the full-scale demonstration project, the methodology will be developed that will be required for assessing the sequestration capacity of similar oil and gas geologic formations.

Coal Fields

Characterization Approach and Results

The PCOR Partnership region contains four coal basins which are subsets of the sedimentary basins. CO_2 sequestration in coal zones may be used for enhanced coalbed methane recovery. Figure 5 displays the major coal basins in the region.

Three areas were selected for a broad level assessment of geologic CO_2 sequestration potential in coal: the Harmon–Hanson coal zone in the Williston Basin, the Wyodak–Anderson coal zone in the Powder River Basin, and the Ardley coal zone in Alberta. These areas were selected based on one or more of the following factors: data availability, input from partners, and single-seam thickness. It was determined that only coal zones located at depths greater than 500 feet would be considered for characterization. Coals below this depth are generally considered unminable in the PCOR Partnership region.

Characterization Level

In assessing the CO_2 sequestration potential of the coal zones, geologic models were created of the area underlain by non-surface-minable portions of the coal zones. The models were used to estimate the total CO_2 sequestration potential and the effective CO_2 sequestration potential (accounting for the impacts of sorbed-phase natural gas and its composition on the total CO_2 storage capacity) at various depth intervals. A topical report was prepared for each of the three areas that provided information regarding the assessment procedure used to determine the respective CO_2 capacity estimates (2–4). The data used in the reports include the following:

- Areal extent
- Net coal thickness
- Density
- Stratigraphy
- Depth/overburden thickness
- Sorbed-phase gas content

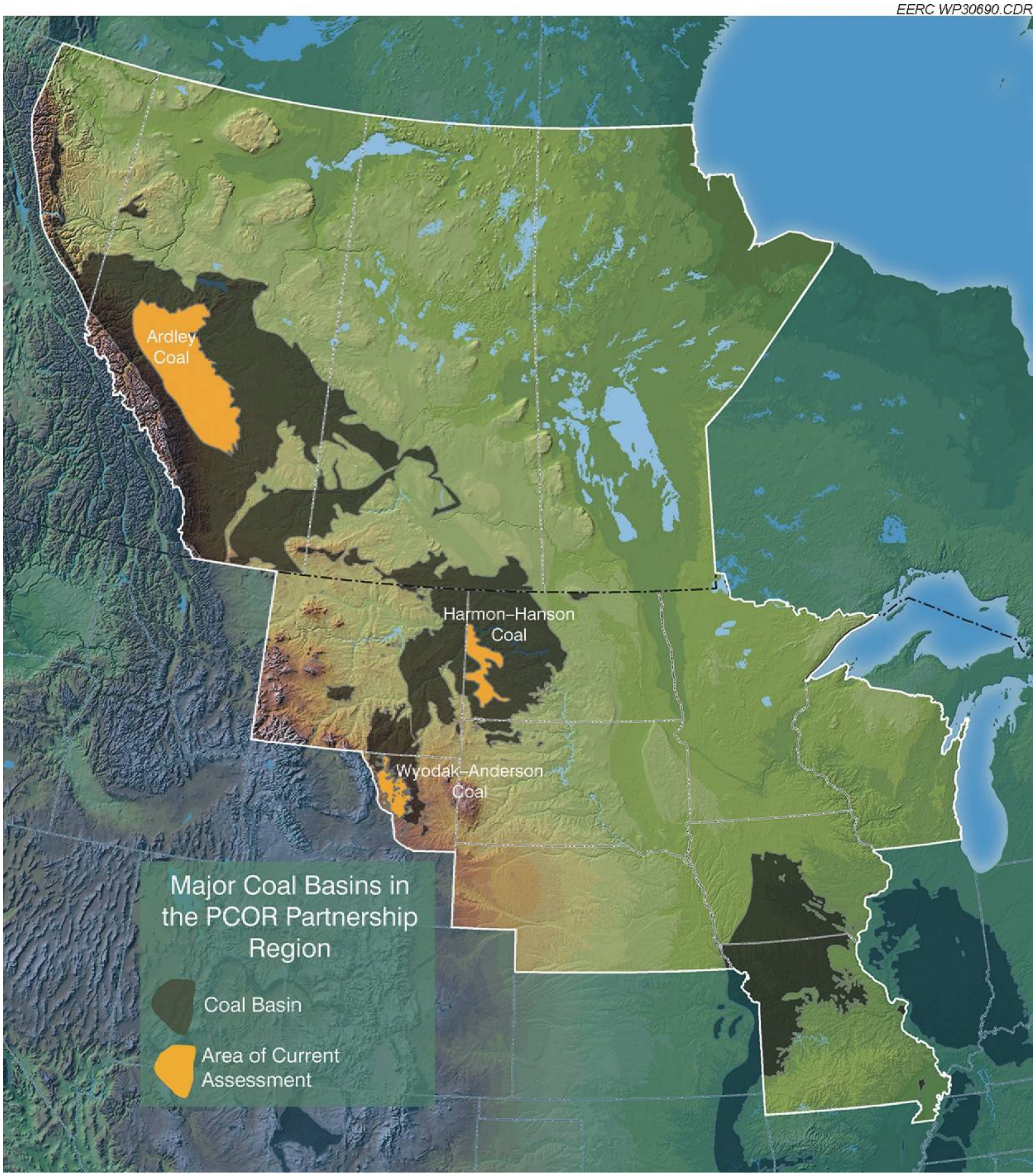


Figure 5. Major coal basins in the region.

- Coal production data
- Hydrostatic pressure
- Temperature gradient
- Natural gas production data
- Gas desorption pressure
- Regional groundwater quality

The information from the topical reports was used to construct a map layer on the DSS of potential CO_2 sequestration capacity at depth intervals of 500–1000 ft and >1000 ft. The total maximum CO_2 sequestration potential for all three coal horizons is approximately 8 billion tons (1). 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 approximately the next 150 years.

Data Gap Assessment

The broad-scale assessment in Phase I resulted in a preliminary CO_2 sequestration capacity for three coal zones. The potential for Missouri and Iowa coals is being obtained through the Missouri and Iowa Geological Surveys. In Phase II, the Iowa Geological Survey will provide a summary of known Pennsylvanian coal horizons, the stratigraphic distribution and thickness of individual coal units, and maps showing the general cumulative thicknesses of coals within larger stratigraphic groupings across Iowa. A similar subcontract is under development with the Missouri Geological Survey under Phase III. If resources and data are available, Phase III activities will also include the characterization of an additional coal zone in the Williston Basin.

Saline Formations

Characterization Approach and Results

Saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic CO_2. To maximize the amount of CO_2 that can be stored in a saline formation, it is important that the strata lie at about 800 meters below the ground surface. At this depth, CO_2 is generally at a high-density supercritical state. The primary data elements needed to calculate capacity estimations for saline formations are the area, thickness, depth, and porosity of the formation. Additionally, it is helpful to know the salinity of the formation water.

Two widespread saline systems were investigated for CO_2 sequestration: the saline formations of the Mississippian Madison Group of the Northern Great Plains aquifer system and saline formations of the Lower Cretaceous aquifer system. The Madison Group underlies both the Williston and Powder River Basins. The Lower Cretaceous aquifer system extends from northern Alberta to southern Nebraska. The sedimentary basins examined were the Williston, Powder River, Alberta, Denver–Julesberg, Kennedy, and the Salina.

The estimated CO_2 sequestration capacity of the assessed saline formations ranges from 101–221 billion tons (1). The lower estimate is based on the methodology adopted by all partnerships through the saline working group, which considers an efficiency factor for estimating capacity. The higher range does not include that factor, assumes that all pore space is available, and considers solubility of CO_2 at varying salinities.

To calculate the sequestration potential for the Madison Group, a model was developed to produce a continuous gridded surface representing the volume of CO_2 that could be sequestered per square kilometer. In general, the model is based on existing data relating to hydrological studies of regional aquifer systems; oil, gas, and water well data; and existing GIS map data. Figure 6 shows the results of the assessment for the Mississippian Madison system (5).

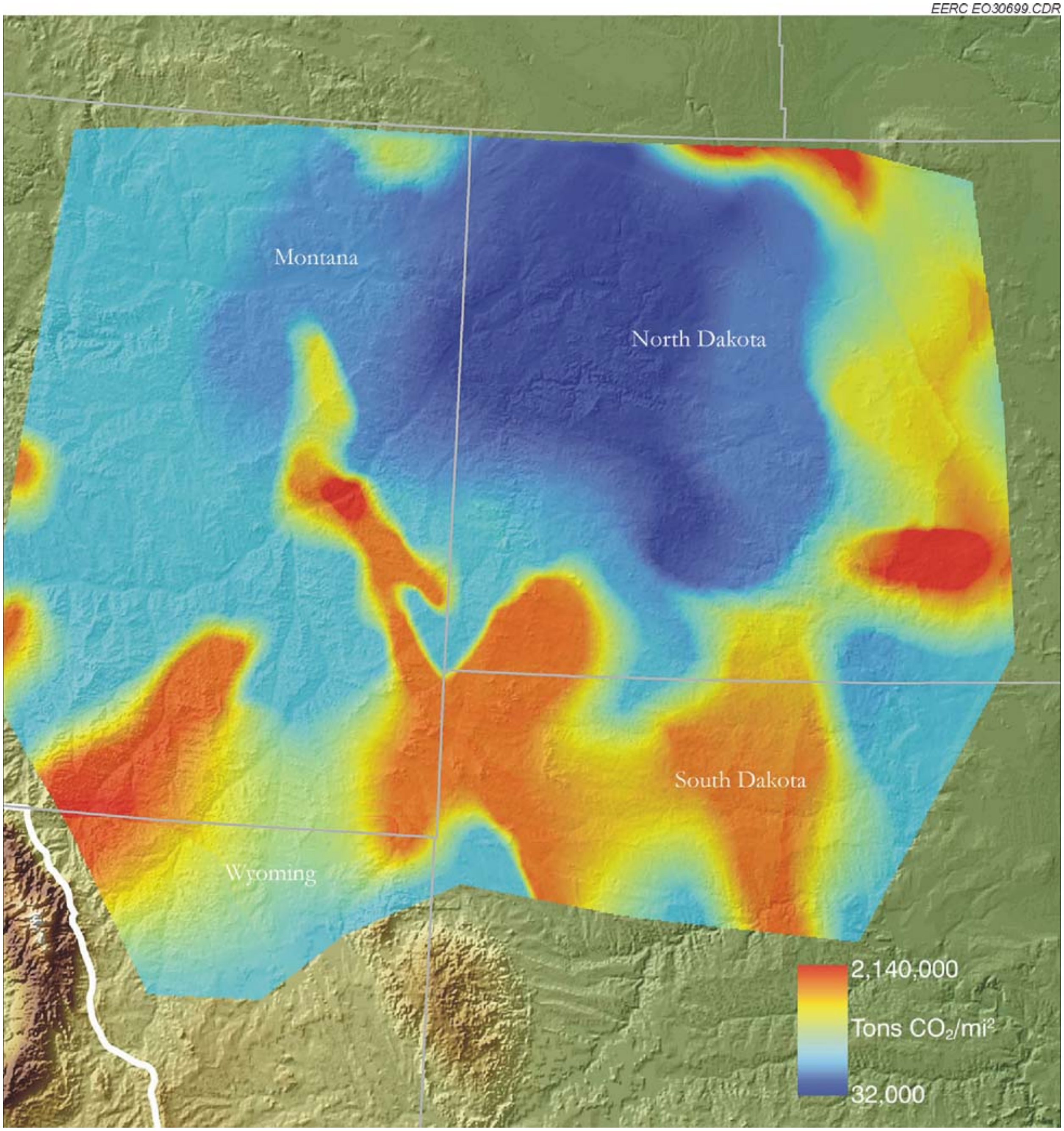


Figure 6. Extent and capacity distribution for the Mississippian Madison Formation in the Williston Basin.

In order to calculate storage potentials for the upper aquifer unit of the Lower Cretaceous saline system, a model was developed in the same fashion as for the Madison Group. A continuous gridded surface representing the volume of CO_2 that could be sequestered per square kilometer was generated from data digitized from analog maps of the Williston, Powder River, and Kennedy Basins. The natural neighbor method of grid generation was applied to the digitized data. This method was used for both interpolation and extrapolation of results, as it generally works well with clustered scattered points. Again, the model is based on existing data relating hydrological studies of regional saline systems; oil, gas, and water well data; and existing GIS map data. Sequestration potential for the portion of the upper aquifer unit in Alberta and Saskatchewan was obtained as a raster image from the Alberta Geological Survey. This image was integrated with the results of the modeling effort in the U.S. portion of the region. Figure 7 shows the results of the assessment for the Lower Cretaceous system (6).

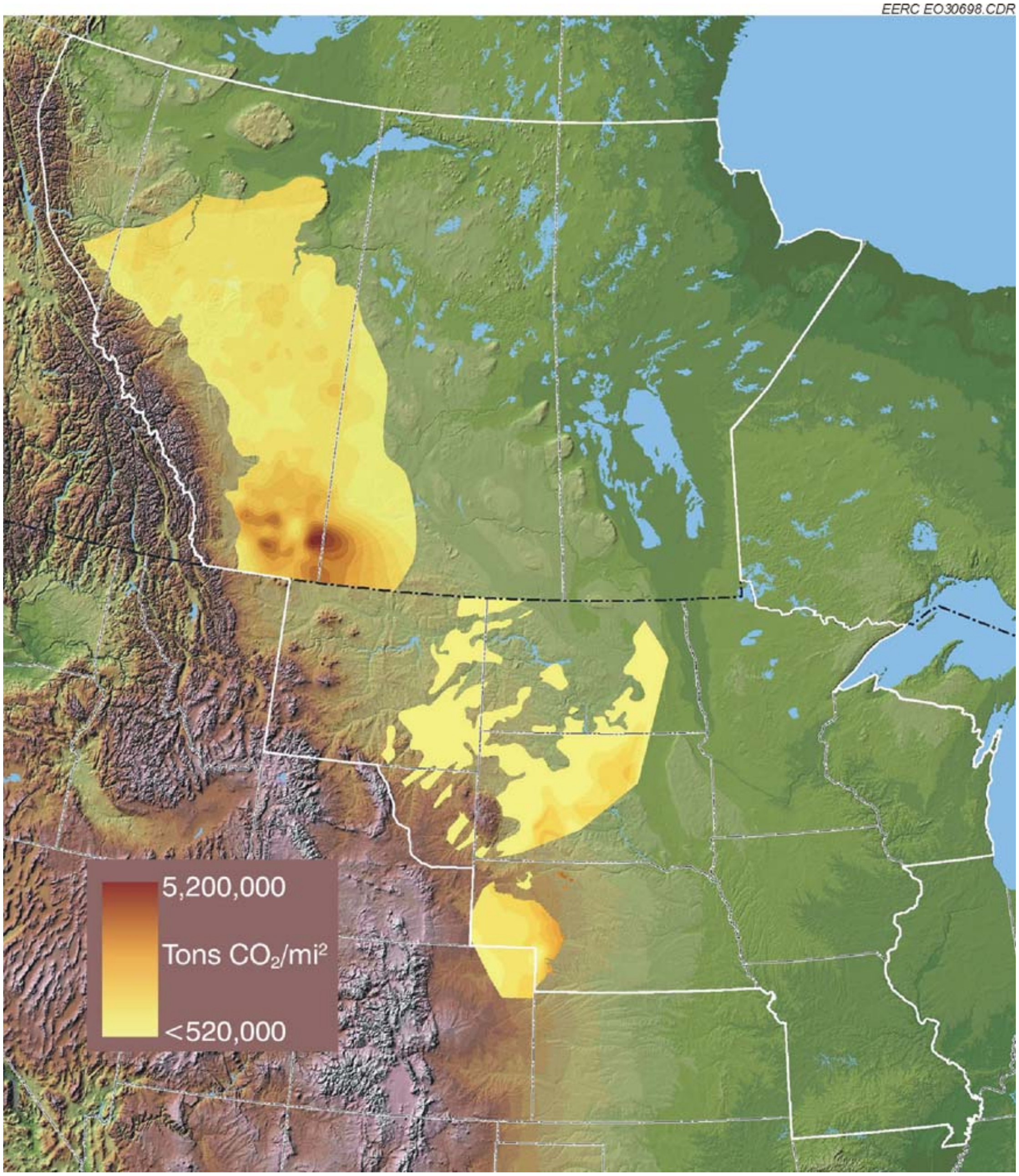


Figure 7. Extent and capacity distribution for the Lower Cretaceous system.

Data Gap Assessment

The investigation of the two saline formations provided broad-scale, regional sequestration potential for a portion of the region. The Missouri and Iowa Geological Surveys are developing very broad assessments of saline formations in their states. This initial characterization helps to identify areas for more detailed investigation.

Future assessments will be performed using a top-to-bottom approach for a smaller lateral extent. Our first assessment using this approach is for a 6000-square-mile area around a cluster of power plants in west-central North Dakota, referred to as the Washburn study area. Within this lateral area, we will target the hydrogeologic units that have promising hydrogeologic properties for sequestration. The Broom Creek Formation is currently one of the units being assessed. Assessments at this scale involve converting well log image files to vector format using Neurolog software. The logs are then imported into Schlumberger's Petrel software package to develop detailed reservoir simulation models of the potential storage site and develop estimated storage capacity for the units. Two smaller areas of approximately 100 square miles each within the Washburn project area will be studied in more detail using Schlumberger's ECLIPSE software to evaluate the movement of CO_2 in the subsurface. These studies will be used to develop a methodology that would be required for implementation of a full-scale injection project in similar formations.

Assessment of the Washburn study area will be completed in Phase II. Screening criteria for future assessments at this scale will be developed and studies performed under Phase III.

TERRESTRIAL SINKS

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 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 (7).

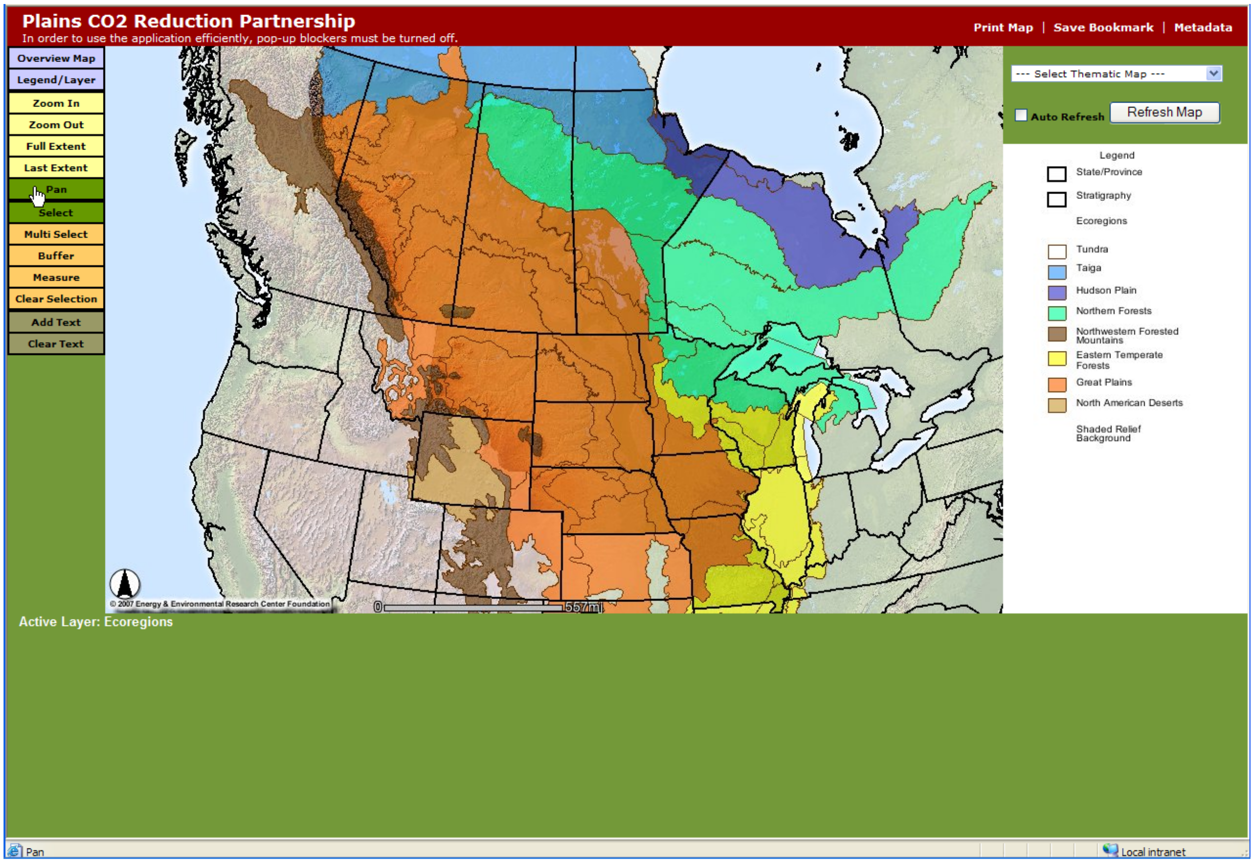
Characterization Approach and Results

Similar to the approach used for geologic characterization, two levels of data were used in terrestrial characterization: very broad, publicly available data for use in assessing the variables governing carbon accumulation and specific field-level data for carbon sequestration estimations.

At the broad-scale, the partnership region was grouped into various ecoregions, using the Omernik Level III classification system. Omernik ecoregions represent areas with generally similar ecosystems and similar types, qualities, and quantities of environmental resources. The ecoregion boundaries are determined by examining patterns of vegetation, animal life, geology, soils, water quality, climate, and human land use, as well as other living and nonliving ecosystem components. Within each ecoregion, information has been summarized for key land use categories that are significant for carbon sequestration. The ecoregion boundaries and associated information are available in the DSS (Figure 8).

Broad capacity estimates have been developed for specific land use classifications. Initial results indicate that over 220 million tons of CO_2 could be sequestered over a 10-year period through changes in land-use practices, such as wetland restoration. To put this into perspective, the wetlands have the potential to sequester up to 25% of the transportation-related CO_2 emissions for the entire PCOR Partnership region annually.

Terrestrial carbon sequestration estimates were developed for the wetland and cropland ecosystems in the region through field work by the U.S. Geological Survey (USGS), Northern Prairie Wildlife Research Center, Ducks Unlimited Canada, and North Dakota State University (NDSU). USGS and Ducks Unlimited Canada developed an estimate of the annual CO_2 potential



In order to use the application efficiently, pop-up blockers must be turned off.

Active Layer: Ecoregions

Figure 8. DSS display of ecoregions within the partnership region.

of wetland restoration by county/municipality in the PPR for a 10-year time frame (8). NDSU developed estimates of the annual potential carbon sequestration that could be achieved on cropland with improved management practices for a 10-year time frame (9). The data are reported at the county level in the DSS.

Sequestration estimates for cropland in Iowa were generated through data from the U.S. Department of Agriculture Natural Resources Conservation Services and Colorado State University – Natural Resource Ecology Laboratory. Through this database, the rate of soil carbon change for various management and conservation practices can be determined over 10- and 20-year intervals, beginning with 1994. These data were generated and converted to an annual carbon sequestration rate, representing a county's maximum agricultural soil carbon accumulation potential over a 10-year period. These data are also reported at the county level in the DSS. The completion of the data collection for the region is summarized in Table 4.

The PCOR Partnership is conducting a terrestrial field validation project to develop the technical capacity to systematically identify, develop, and apply alternate land-use management practices to the prairie pothole region (at both a local and regional scale) that will result in greenhouse gas (GHG) reductions. Current activities include the assessment of Ducks Unlimited-controlled properties, evaluating more than 50 wetlands located on native prairie and restored grasslands. From this population of wetlands, numerous sites were selected that are similar with respect to land use, water regime, size, soil type, and makeup of vegetative community. The project results are intended to serve as a model to promote and implement terrestrial sequestration across the PPR.

Over 100 studies have been performed in our region that are pertinent to terrestrial sequestration. These references have been organized by state/province, and the reference information and/or direct link to these studies have been placed in the DSS.

Data Gap Assessment

Terrestrial data provide a firm foundation for the regional assessment of terrestrial sequestration opportunities. While initial wetland and cropland projects focused on a 10-year time frame, wetlands have the potential for sustainable carbon accumulation for over 50 years, and cropland has a potential for approximately 20 years. However, the field data required to create uniform carbon sequestration estimations for cropland/grassland across the

Table 4. Completion of Data Sets (Sequestration Estimates) for Land-Use Classifications

Data Set	IA	MN	MO	MT	ND	NE	SD	WI	WY	AB	BC	MB	SK
Wetland (PPR)	X	X	–	–	X	–	X	–	–	P		X	X
Cropland	X			P	P		P						
Grassland/Shrubland	X			P	P		P						
Forest													

X Complete coverage of data set for state/province.
P Partial coverage of data set for state/province.
– Ecosystem is not relevant for the region.

entire region is not readily available. The field work to measure the movement of terrestrial-based carbon can take from 5 to 15 years to complete. In semiarid conditions where the rate of change of soil carbon is low, it can take between 10 to 15 years to monitor the soil carbon changes. Even when long-term monitoring of soil carbon has occurred, it does not always reflect the cropping diversification that has occurred over the time period. Long-term carbon storage on newer cropping systems is not well understood and difficult to quantify. As expertise and technologies develop to better assess terrestrial opportunities, those data will be incorporated into the database.

For the land-use classifications listed in Table 4, the existing capacity estimates will be refined and the data gaps filled through the following Phase II and III activities:

- The results of the field validation tests conducted by Ducks Unlimited and the USGS in Phases II and III will be incorporated into the DSS.

- A database of forestry carbon stock data for states in the PCOR Partnership region has been acquired, and the results will be incorporated into the DSS. We have been unable to locate similar forestry data for the Canadian provinces but will continue to seek this data (Phase II).

- Information gleaned from other studies performed in the region will be used to supplement data sets (Phase III).

- Carbon stock data will be incorporated from the U.S. Soil Organic Carbon Database and the Canadian Soil Organic Carbon Database, creating a uniform soil carbon database for the region (Phase II).

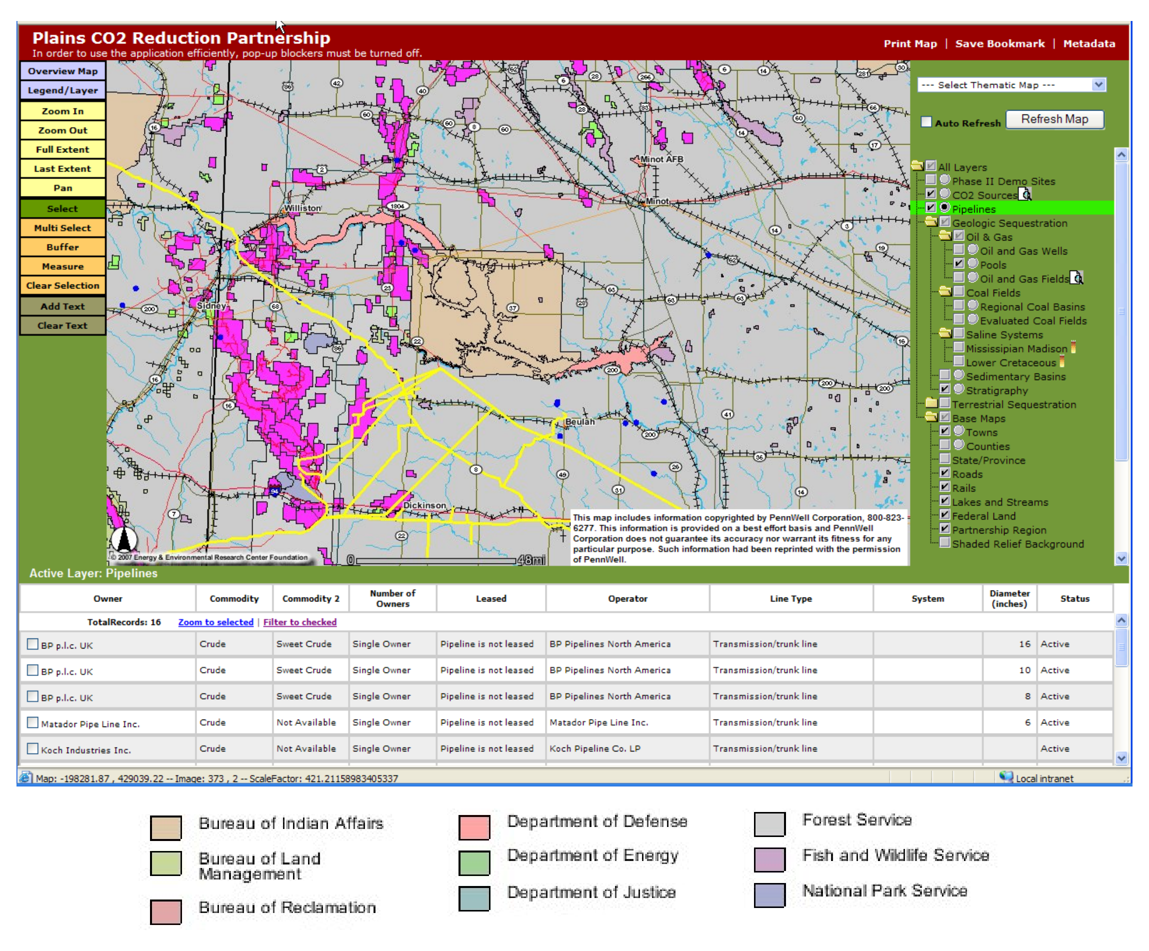
- A review of current and emerging terrestrial carbon aggregator programs will be conducted to compile regionwide net carbon storage benefits and assess impacts of expiring conservation reserve program acres during this period (Phase III).

INFRASTRUCTURE

Infrastructure is a broad category of information associated with the capture, separation, and transportation of CO_2 for sequestration, including any features that may be located between a source and a sink, such as federal lands. Infrastructure information is obtained or developed by the partnership and presented in the DSS in the form of static Web pages or through the mapping tools of the GIS.

Characterization Approach and Results

Within the GIS portion of the DSS, users can display the following infrastructure layers: pipelines, towns, roads, rails, lakes and streams, and federal lands. Figure 9 depicts a portion of



This map includes information copyrighted by PennWell Corporation, 800-823-6277. This information is provided on a best effort basis and PennWell Corporation does not guarantee its accuracy nor warrant its fitness for any particular purpose. Such information had been reprinted with the permission of PennWell.

TotalRecords: 16

Owner	Commodity	Commodity 2	Number of Owners	Leased	Operator	Line Type	System	Diameter (inches)	Status
☐ BP p.l.c. UK	Crude	Sweet Crude	Single Owner	Pipeline is not leased	BP Pipelines North America	Transmission/trunk line		16	Active
☐ BP p.l.c. UK	Crude	Sweet Crude	Single Owner	Pipeline is not leased	BP Pipelines North America	Transmission/trunk line		10	Active
☐ BP p.l.c. UK	Crude	Sweet Crude	Single Owner	Pipeline is not leased	BP Pipelines North America	Transmission/trunk line		8	Active
☐ Matador Pipe Line Inc.	Crude	Not Available	Single Owner	Pipeline is not leased	Matador Pipe Line Inc.	Transmission/trunk line		6	Active
☐ Koch Industries Inc.	Crude	Not Available	Single Owner	Pipeline is not leased	Koch Pipeline Co. LP	Transmission/trunk line			Active

Map: -198281.87 , 429039.22 -- Image: 373 , 2 -- ScaleFactor: 421.21158983405337

Figure 9. DSS display of regional infrastructure for evaluating source–sink opportunities.

the region with all of the available infrastructure displayed. The blue dots represent CO_2 sources. The pink areas are oil pools. The yellow lines are specific pipelines that have been selected and whose data are represented in the grid below the map. The remaining colored areas are federal lands defined in the legend.

The pipeline data set is being leased from PennWell MapSearch. This GIS-based data set contains the routes for nearly all the pipelines in the PCOR Partnership region. The data set will be used to display current pipeline routes that may be useful for planning new pipelines to carry CO_2 to sequestration sites.

With regard to capture and separation technologies, detailed descriptions were developed for chemical absorption, physical absorption, hybrid chemical–physical absorption, adsorption, cryogenic, and membrane technologies. Several variations of each technology were identified and included in the description. A topical report was prepared that provides a qualitative summary of a large number of existing and emerging processes that could be used to capture and separate CO_2 from combustion gases for the purpose of controlling carbon emissions (10).

Data Gap Assessment

The data developed or collected thus far provide a very broad overview of the regional infrastructure. The data gaps are being addressed in the following Phase II and Phase III activities:

- The existing CO_2 pipeline that runs from the Dakota Gasification Company in North Dakota to Weyburn, Saskatchewan, is not included in the PennWell data set. This will be manually added to the DSS (Phase II).
- Potential pipeline routes will be determined and displayed in the DSS (Phase III).
- A routing model for pipelines will be incorporated into the DSS. Users will be able to choose the beginning and end point, and the model will generate the least-cost route (Phase III).
- Much of the infrastructure data on capture, separation and compression are not readily available or are frequently simplified, presumably because of intellectual property considerations. The PCOR Partnership will continue to maintain a database of existing and emerging capture and compression technologies applicable to CO_2, and this data will be available on the DSS (Phases II and III).

REGULATORY

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. 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. The regulatory framework of the region is an important characteristic in assessing sequestration opportunities.

Characterization Approach and Results

Information relating to the regulation of CO_2 sequestration in the PCOR Partnership region is gathered by conducting literature reviews, Internet searches, and interviewing pertinent regulatory agencies and PCOR Partnership partners. The partnership actively participates with the Interstate Oil and Gas Compact Commission (IOGCC) Regulatory Working Group to provide an accurate picture of the current regulatory framework as well as recommendations for further regulatory strategies. A topical report entitled “Deployment Issues Related to Geological and Terrestrial CO_2 Sequestration in the PCOR Partnership Region" was developed and is available on the DSS (11). The topics covered in the report include the following:

- Ecological and environmental impacts of geological storage
- Ecological and environmental impacts of terrestrial sequestration
- Measurement, mitigation, and verification of geological carbon capture and storage
- Measurement, mitigation, and verification of terrestrial sequestration
- Regulating carbon capture and geologic storage

Much of the data in the topical report were obtained from published reports and papers as well as from discussions with key partners and collaborators.

Current regulations, as they relate to CO_2 sequestration, are gathered at the federal and state/provincial level. A summary of the current regulatory framework for CO_2 sequestration projects in the PCOR Partnership region is found within the DSS.

Data Gap Assessment

Activities to date provide an accurate picture of the current regulatory framework on a regional basis. Local regulations were not gathered but will be collected on a project-specific basis. A flowchart of permitting activities for each field project will be developed in Phase II. In Phase III, anticipated permitting activities for potential projects in the states and provinces will be developed.

SUMMARY

The wealth of data developed or obtained in Phase I and Phase II provide the PCOR Partnership with the information necessary for defining and assessing regional sequestration opportunities. The data are compiled, stored, and managed in the DSS as a means to develop knowledge of the character and spatial relationship of sources, sinks, and infrastructure. Partners who utilize the DSS provide the PCOR Partnership with valuable input regarding key data elements and sources of information for further characterization.

Having exhausted the readily available characterization data, the partnership is moving into more focused assessments. These assessments provide finer data on a smaller scale but generally require more resources. The strategy will be to identify assessment areas that are found throughout the region such that the results can potentially be aggregated to a larger area.

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APPENDIX A

METHODOLOGIES USED TO IDENTIFY OR ESTIMATE CO_2 EMISSIONS

METHODOLOGY 1: ESTIMATION OF CO_2 EMISSIONS FROM ELECTRICITY-GENERATING FACILITIES

IDENTIFICATION OF ELECTRICITY-GENERATING PLANT LOCATIONS

Identification of electricity-generating facilities located in the Plains CO_2 Reduction Partnership region was accomplished through the use of the U.S. Environmental Protection Agency (EPA) Clean Air Markets Web site (http://camddataandmaps.epa.gov/gdm), the EPA Emissions and Generation Resource Integrated Database (eGRID) spreadsheet (www.epa.gov/cleanenergy/ egrid/index.htm), the EPA Technology Transfer Network Ozone Implementation Web site (www.epa.gov/ttn/naaqs/ozone/areas), and the Commission for Environmental Cooperation Web site (www.cec.org/files/PDF/POLLUTANTS/US_2002_metric_en.xls for US plants and www.cec.org/files/PDF/POLLUTANTS/Canada_2002_metric_en.xls for Canadian plants). Where latitude and longitude information was absent in the databases, the street address was used with Google Earth to locate the plant (http://earth.google.com). Often the street address or the latitude and longitude are for an office removed from the utilities operations. In such instances, the locations have been corrected using the Google Earth imagery, as the electricity-generating facilities are obvious.

COMBUSTION EMISSIONS

In electricity-generating facilities, CO_2 is generated through the combustion of fuel to create heat for process steam. The primary sources of fuel are coal (subbituminous coal, bituminous coal, and lignite) and natural gas, with secondary fuels including distillate oil, fuel oil, residual oil, and gasoline.

The emissions of CO_2 produced by the combustion of fuel were determined by several methods. The first step taken was to identify the fuel type or types and their respective usages. This was done by using the Technology Transfer Network (TTN) database (www.epa.gov/ttn/naaqs/ozone/areas/state/stindex.htm) and the EPA Emissions and Generation Resource Integrated Database (eGRID) spreadsheet (www.epa.gov/cleanenergy/egrid/index.htm) for the sources identified. The TTN database was designed by EPA to provide data for implementing the Ozone Ambient Air Standards and, particularly, to determine nonattainment areas. The reporting for the TTN database had the force of law behind it. Although CO_2 is not required to be listed by the reporting industries, the overall database is much more extensive than EPA's eGRID. The eGRID database covers only those industries that are part of the electrical grid. The TTN database, on the other hand, includes all industries that generated ozone and, therefore, almost all industries that generate CO_2. It includes information on fuel type and fuel usage, SO_2 emissions, NO_x emissions, and data from the 1996 National Emission Trends Inventory and Emission Tracking System/Continuous Emissions Monitoring data, census-related data, air quality data, and maps. Other sites were also used to obtain CO_2 emissions from electricity-generating facilities such as the EPA Clean Air Markets Web site (http://cfpub.epa.gov/gdm/index.cfm?fuseaction=quickreports.choose). The EPA Clean Air Markets Web site provides data on CO_2

emissions from utility and large municipal combustion sources for heat and power. In the instances where data were found on this site, no combustion calculations were required.

To calculate CO_2 emissions based on the TTN data, CO_2 emission factors for the various fuels were required. Those were obtained from a variety of sources and were based on the percentage of carbon (%C) in the fuel. The %C for each fuel is given in Table 1-1. The %C and fuel usage were then used to calculate the CO_2 emissions for sources where CO_2 emission data were absent. After the CO_2 emissions were calculated, these were compared to the eGRID data for those industries. The results were remarkably similar.

Table 1-1. Percentage of Carbon in Typical Fossil Fuels

Fuel	%C, as-received	Basic Fuel Units
Eastern Bituminous Coal[1]	72.7	tons
Subbituminous Coal[1]	50.6	tons
Lignite[1]	36.4	tons
Natural Gas[2]	74.9	million ft^3
Fuel Oil[3]	86.7	1000 gal
Municipal Solid Waste[4]	38.0	tons
Propane[2]	81.7	1000 gal
Biomass (wood and wood wastes)[4]	21.5	tons
Residual Oil[3]	86.9	1000 gal
Coke (derived from coal)[5]	86.0	tons
Gasoline[6]	85.5	1000 gal

[1] EERC ultimate analysis (eastern bituminous is a Pittsburgh No. 8 Seam, Powder River Basin subbituminous coal is a Cordero Rojo, and lignite is a Fort Union lignite).

[2] Direct calculations (natural gas is CH_4, and propane is $CH_3CH_2CH_3$).

[3] www.ec.gc.ca/energ/fuels/reports/cnslt_rpts/fqp/tables1_e.htm.

[4] www.trmiles.com/alkali/fulesc3.html.

[5] www.rexresearch.com/coal/4chap/4chap.htm.

[6] www.woodgas.com/proximat.htm.

A sample calculation of CO_2 emissions from the burning of residual oil:

$$[\text{Fuel used (1000 gal/yr)}] \times [\text{\%C (from Table 1)}]/100 \times [1000\ (\text{gal/1000gal})] \times [\text{fuel density (lb/gal)}] \times [3.664\ (\text{lb } CO_2/\text{lbC})]/[2000\ (\text{lb/ton})]$$

METHODOLOGY 2: ESTIMATION OF CO_2 EMISSIONS FROM ETHANOL PRODUCTION FACILITIES

LOCATION OF ETHANOL PLANTS

Identification of ethanol plants in the Plains CO_2 Reduction (PCOR) Partnership region was accomplished through the use of the Renewable Fuels Association's Ethanol Biorefinery Locations Web site (www.ethanolrfa.org/industry/locations). This Web site lists the name of cities in which ethanol plants are located but does not always provide enough direction to effectively use Google Earth (http://earth.google.com/) to locate the plant's latitude and longitude. Web searches for the facilities can result in street addresses that can be helpful when locating a plant on Google Earth. At this time, 80 ethanol facilities have been identified in the PCOR Partnership region.

PROCESS EMISSIONS

Ethanol plants produce CO_2 during the fermentation step. The quantity of ethanol produced by a plant was found at the Renewable Fuels Association's Ethanol Biorefinery Locations Web site (www.ethanolrfa.org/ industry/locations). For every gallon of anhydrous ethanol produced, 6.6 lbs of CO_2 are produced (1). The quantity of CO_2 produced during the fermentation step in the production of the ethanol is:

$$\text{tons/yr } CO_2 = (\text{gal ethanol/yr}) \times (6.6 \text{ lb } CO_2/\text{gal ethanol}) \times (1 \text{ ton}/2000 \text{ lb}) \qquad [\text{Eq. 1}]$$

COMBUSTION EMISSIONS

Power for the ethanol facility (primarily for heat) is produced through the combustion of fossil fuels, usually natural gas, although there are a few coal-fired plants in the PCOR Partnership region. The CO_2 emissions produced during the combustion were calculated using the following procedure.

A rule of thumb is that 39,000 Btu of energy is required to produce a gallon of anhydrous ethanol (2). The quantity of fuel used by the plant must be calculated and its heat content defined.

A cubic foot of natural gas has a heat content of roughly 1000 Btu (3). The amount of CO_2 produced is calculated using typical combustion calculations. For example:

$$\begin{aligned}\text{tons } CO_2/\text{yr} = {} & (\text{gal ethanol/yr} \times 39{,}000 \text{ Btu/gal}) \times (1 \text{ ft}^3 \text{ natural gas}/1000 \text{ Btu}) \times (1 \text{ lb-mole} \\ & \text{natural gas}/359 \text{ ft}^3) \times (1 \text{ lb-mole } CO_2/1 \text{ lb-mole natural gas}) \times \qquad [\text{Eq. 2}] \\ & (44.01 \text{ lb } CO_2/\text{lb-mole } CO_2) \times (1 \text{ ton}/2000 \text{ lb})\end{aligned}$$

If the coal that is burned at the ethanol plant is described, then the higher heating value for that coal can be used in the calculations. The PCOR Partnership ethanol plants that burn coal did not specify a coal, so an average value of 20.33 million Btu/short ton (4) was used. Because the coal type was unknown, the percentage of carbon for the coal was unknown, so CO_2 emissions for coal from each state, which can be found on the U.S. Department of Energy Energy Information Agency Web site (5), were utilized. The combustion calculations for CO_2 produced from coal-fired ethanol plants when the specific coal is not known can be determined as follows:

$$\text{tons } CO_2/\text{yr} = \text{gal ethanol/yr} \times 39{,}000 \text{ Btu/gal ethanol} \times (CO_2 \text{ emission factor for coal in lb } CO_2/\text{million Btu}) \times (\text{ton } CO_2/2000 \text{ lb } CO_2) \quad \text{[Eq. 3]}$$

The total CO_2 emitted by the ethanol plant is the sum of the process- and combustion-produced CO_2.

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METHODOLOGY 3: ESTIMATION OF CO_2 EMISSIONS FROM AGRICULTURAL PROCESSING FACILITIES

IDENTIFICATION OF AGRICULTURAL PROCESSING LOCATIONS

Agricultural processing facilities in the Plains CO_2 Reduction (PCOR) Partnership region include a wide array of industries ranging from dairies to meat-packing plants and pasta-making facilities. The facilities were located using the U.S. Environmental Protection Agency (EPA) Technology Transfer Network (TTN) Ozone Implementation Web site (www.epa.gov/ttn/naaqs/ozone/areas), the EPA Clean Air Markets Web site (http://camddataandmaps.epa.gov/gdm) and a Web site for Canadian sources (www.ec.gc.ca/pdb/ghg/ onlinedata). Where latitude and longitude information was absent in the databases, the street address was used with Google Earth (http://earth.google.com/) to locate the plant. Often the street address or the latitude and longitude are for an office removed from the facility operations. In such instances, these locations are being corrected using the Google Earth imagery because most facilities are obvious then.

COMBUSTION EMISSIONS

The CO_2 emitted by the agricultural processing sources is virtually all produced during combustion. The major sources of fuel for these industries are coal (subbituminous coal, bituminous coal, and lignite), natural gas, distillate oil, fuel oil, residual oil, municipal solid waste, and gasoline.

The quantity of CO_2 emitted by the combustion of fossil fuel was determined using several methods. The first step taken was to identify the fuel type or types and their respective usages. This was accomplished using the TTN database (www.epa.gov/ttn/naaqs/ozone/areas/state/stindex.htm). The TTN database was designed by EPA to provide data for implementation of the Ozone Ambient Air Standards and, particularly, to determine nonattainment areas. The TTN database includes all industries that generate ozone and, therefore, almost all industries that generate CO_2. It includes information on fuel type and fuel usage, SO_2 emissions, NO_x emissions, and data from the 1996 National Emission Trends Inventory and Emission Tracking System/Continuous Emissions Monitoring data, census-related data air quality data, and maps.

To calculate CO_2 emissions based on the TTN data, the carbon content and usage amount of the various fuels were required. The carbon content (%C) for each fuel can be seen in Table 3-1. An example of a CO_2 emissions calculation for the burning of residual oil follows:

$$[\text{Fuel used (1000 gal/yr)}] \times [\text{\%C (from Table 1)}]/100 \times [1000\ \text{(gal/1000gal)}] \times [\text{fuel density(lb/gal)}] \times [3.664\ (\text{lb } CO_2/\text{lbC})]/[2000\ \text{(lb/ton)}]$$

CO_2 emissions from the combustion of other fuel types were calculated in the same manner.

Table 3-1. Percentage of Carbon in Typical Fossil Fuels

Fuel	%C, as-received	Basic Fuel Units
Eastern Bituminous Coal[1]	72.7	tons
Subbituminous Coal[1]	50.6	tons
Lignite[1]	36.4	tons
Natural Gas[2]	74.9	million ft^3
Fuel Oil[3]	86.7	1000 gal
Municipal Solid Waste[4]	38.0	tons
Propane[2]	81.7	1000 gal
Biomass (wood and wood wastes) [4]	21.5	tons
Residual Oil[3]	86.9	1000 gal
Coke (derived from coal)[5]	86.0	tons
Gasoline[6]	85.5	1000 gal

[1] EERC ultimate analysis (eastern bituminous is a Pittsburgh No. 8 Seam, Powder River Basin is a Cordero Rojo subbituminous coal, and lignite is a Fort Union lignite).

[2] Direct calculations (natural gas is CH_4, and propane is $CH_3CH_2CH_3$).

[3] www.ec.gc.ca/energ/fuels/reports/cnslt_rpts/fqp/tables1_e.htm.

[4] www.trmiles.com/alkali/fulesc3.html.

[5] www.rexresearch.com/coal/4chap/4chap.htm.

[6] www.woodgas.com/proximat.htm.

METHODOLOGY 4: ESTIMATION OF CO_2 EMISSIONS FROM PETROLEUM- AND NATURAL GAS-PROCESSING FACILITIES

IDENTIFICATION OF PETROLEUM- AND NATURAL GAS-PROCESSING FACILITIES AND THEIR LOCATIONS

Petroleum- and natural gas-processing facilities in the Plains CO_2 Reduction (PCOR) Partnership region include petroleum refineries, natural gas-processing plants, and petroleum transmission facilities. The facilities were located using the U.S. Environmental Protection Agency (EPA) Technology Transfer Network (TTN) Ozone Implementation Web site (www.epa.gov/ttn/naaqs/ozone/areas/), the EPA Clean Air Markets Web site (http://camddataandmaps.epa.gov/gdm) and a Web site for Canadian sources (www.ec.gc.ca/pdb/ghg/ghg_home_e.cfm). Gas-processing facility data were also gathered from the North Dakota Department of Health; the *Oil & Gas Journal* Web site, which is accessible only by subscribing members; and from Reference 1. Where latitude and longitude information was absent in the databases, the street address was used with Google Earth (http://earth.google.com/) to locate the plant. Often the street address or the latitude and longitude are for an office removed from the facility operations. In such instances, these locations are being corrected using the Google Earth imagery because most facilities are then made obvious.

PETROLEUM REFINERY EMISSIONS

The combustion CO_2 emission rate was estimated for each fuel within each Petroleum Administration for Defense District (PADD) by multiplying the fuel usage rate (2, 3) (unit volume/yr) with the CO_2 emission coefficient (4) (lb CO_2/unit volume). The total CO_2 emission rate for each PADD was determined by summing the CO_2 emission rates for all fuels. An emission factor (tons CO_2/barrel per calendar day) was then calculated for each of the PADDs by dividing the total CO_2 emission rate for the district by the refining capacity (barrels per calendar day) for the district. States in the PCOR Partnership region are represented in PADDs 2 and 4. The CO_2 emission factors for PADDs 2 and 4 were estimated to be 11.00 and 11.84 tons CO_2/barrel per calendar day, respectively. (Note: These values must be recalculated each year when new refinery statistics are issued.)

As an example, for the calculation of an emission factor for a refinery in North Dakota, an emission factor of 11.00 tons CO_2/barrel per calendar day of the major product was used to calculate the total combustion-related emissions as follows:

$$CO_2 \text{ Emissions (ton/y)} = 11.00 \text{ [ton } CO_2\text{/(barrel/day)]} \times \text{Refinery production [barrel/day]}$$

NATURAL GAS-PROCESSING PLANT EMISSIONS

Emissions from these plants come from the natural gas-sweetening process, which requires heat to regenerate the amine sorbent. In this case, the CO_2 emissions are formed during the combustion of natural gas and can be calculated as:

$$\text{tons } CO_2/\text{yr} = (\text{scf NG}) \times (1 \text{ lb-mole NG}/379 \text{ scf}) \times (1 \text{ lb-mole } CO_2/\text{lb-mole NG}) \times (44.01 \text{ lb } CO_2/\text{lb-mole } CO_2) / (2000 \text{ lb/ton}) \qquad \text{[Eq. 3]}$$

(standard conditions in this case are 60ºF and 1 atm)

Table 4-1. Percentage of Carbon in Typical Fossil Fuels

Fuel	%C, as-received	Basic Fuel Units
Eastern Bituminous Coal[1]	72.7	tons
Subbituminous Coal[1]	50.6	tons
Lignite[1]	36.4	tons
Natural Gas[2]	74.9	million ft^3
Fuel Oil[3]	86.7	1000 gal
Municipal Solid Waste[4]	38.0	tons
Propane[2]	81.7	1000 gal
Biomass (wood and wood wastes) [4]	21.5	tons
Residual Oil[3]	86.9	1000 gal
Coke (derived from coal)[5]	86.0	tons
Gasoline[6]	85.5	1000 gal

[1] EERC ultimate analysis (eastern bituminous is a Pittsburgh No. 8 Seam, Powder River Basin subbituminous coal is a Cordero Rojo, and lignite is a Fort Union lignite).

[2] Direct calculations (natural gas is CH_4, and propane is $CH_3CH_2CH_3$).

[3] www.ec.gc.ca/energ/fuels/reports/cnslt_rpts/fqp/tables1_e.htm.

[4] www.trmiles.com/alkali/fulesc3.html.

[5] www.rexresearch.com/coal/4chap/4chap.htm.

[6] www.woodgas.com/proximat.htm.

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1. DeBruin, R. et al., 2003, Carbon dioxide (CO_2) map of Wyoming: Open File Report 04-1.

2. www.eia.doe.gov/oil_gas/petroleum/data_publications/ petroleum_supply_ annual/psa_volume1/psa_volume1.html.

3. www.eia.doe.gov/oil_gas/petroleum/data_publications/ petroleum_supply_ annual/psa_volume2/psa_volume2.html.

4. www.eia.doe.gov/oiaf/1605/coefficients.html.

METHODOLOGY 5: ESTIMATION OF CO_2 EMISSIONS FROM OTHER INDUSTRIAL FACILITIES

IDENTIFICATION OF INDUSTRIAL LOCATIONS

Identification of Industrial facilities located in the PCOR Partnership region was accomplished through the use of the U.S. Environmental Protection Agency (EPA) Technology Transfer Network (TTN) Ozone Implementation Web site (www.epa.gov/ttn/naaqs/ozone/areas), the EPA Clean Air Markets Web site (http://camddataandmaps.epa.gov/gdm) and a Web site for Canadian sources (www.ec.gc.ca/pdb/ghg/onlinedata). Other sites used to determine sources for specific plant types not found in the previously mentioned Web sites are below.

For iron ore processing, three Web sites were used:

1. www.duluthsuperior.com/mld/duluthtribune/7880078.htm
2. www.duluthsuperior.com/mld/duluthtribune/business/7129904.htm
3. www.virginiamn.com/placed/index.php?sect_rank=1&story_id=160725

For lime production, several sources were used:

1. U.S. Geological Survey directory of U.S. lime plants for 2003. http://minerals.usgs.gov/minerals/pubs/commodity/lime/limedir03.pdf (accessed May 2004).
2. U.S. Geological Survey production data (no per plant data) for 2002. http://minerals.usgs.gov/minerals/pubs/commodity/lime/limemyb02rev.pdf (accessed May 2004). Table 2. Lime Production by Region. Table 4. Lime Use by Industry.
3. Graymont Western (Townsend, Montana) plant production capacity (2004). www.graymont-ut.com/indiancreek.htm (accessed May 2004), 300,000 tons/yr.
4. Mississippi Lime Co. (Ste. Genevieve, Missouri) plant production capacity (2004). www.mississippilime.com/about/divisions_view.asp?divisionID=1 (accessed May 2004), 1,000,000 tons/yr.
5. Western Lime Co. (Eden and Green Bay, Wisconsin) plant production capacity (2004). www.westernlime.com/locations.html (accessed May 2004), 250,000 and 225,000 tons/yr, respectively.
6. Wyoming Lime Producers (Frannie, Wyoming) plant production capacity (2004). www.basinelectric.com/dcc/limeplan.htm (accessed May 2004), 146,000 tons/yr.

Where latitude and longitude information was absent in the databases, the street address was used with Google Earth (http://earth.google.com/) to locate the plant. Often the street address or the latitude and longitude are for an office removed from the facility operations. In such instances, these locations are being corrected using the Google Earth imagery because most facilities are obvious.

The types of facilities that are considered to fit within the industrial category are:

- Asphalt production
- Cement/clinker production (which is discussed in a separate section)

- Chemical production
- Cogeneration
- Foundries/manufacturing
- Fuels/chemicals
- Industrial/institutional heat and power
- Iron ore processing
- Lime production
- Manufacturing
- Metals processing
- Mineral processing
- Mining
- Miscellaneous
- Municipal heat and power
- Paper and wood products
- Sugar production
- Waste processing

These sources fall into two categories for the generation of CO_2: combustion only (from fuel) and combustion plus process-related emissions.

COMBUSTION ONLY

Of the industrial sources, the following plant types emit CO_2 only during the combustion of fuel:

- Asphalt production
- Chemical production
- Cogeneration
- Foundries/manufacturing
- Industrial/institutional heat and power
- Waste processing
- Manufacturing
- Metals processing
- Mineral processing
- Mining
- Miscellaneous
- Municipal heat and power
- Paper and wood products

The major sources of fuel for these processes include coal (subbituminous coal, bituminous coal, and lignite), natural gas, distillate oil, fuel oil, residual oil, municipal solid waste, and gasoline.

The quantity of CO_2 emitted by the combustion of fossil fuel was determined using several methods. The first step taken was to identify the fuel type or types and their respective usages.

This was accomplished using the TTN database (www.epa.gov/ttn/naaqs/ozone/areas) and the EPA Emissions and Generation Resource Integrated Database (eGRID) spreadsheet (www.epa.gov/cleanenergy/egrid/index.htm) for the sources identified. The TTN database was designed by EPA to provide data for implementing the Ozone Ambient Air Standards and, particularly, to determine nonattainment areas. The TTN database includes all industries that generate ozone and, therefore, almost all industries that generate CO_2. It includes information on fuel type and fuel usage, SO_2, NO_x, and data from the 1996 National Emission Trends Inventory and Emission Tracking System/Continuous Emissions Monitoring data, census-related data, air quality data, and maps. The EPA Clean Air Markets Web site provides data on CO_2 emissions from utility and large municipal combustion sources for heat and power. In the instances where data were found on this site, no combustion calculations were required.

To calculate CO_2 emissions based on the TTN data, CO_2 emission factors for the various fuels were required. Those were obtained from a variety of sources and were based on the percentage of carbon (%C) in the fuel. The %C for each fuel can be seen in Table 5-1. The %C and fuel usage amount were then used to calculate the CO_2 emissions for sources where CO_2 emission data were missing. An example of CO_2 emissions calculation for the burning of residual oil follows:

$$[\text{Fuel used (1000 gal/yr)}] \times [\text{\%C (from Table 5-1)}]/100 \times [1000\ \text{(gal/1000gal)}] \times [\text{fuel density (lb/gal)}] \times [3.664\ (\text{lb } CO_2/\text{lbC})]/[2000\ \text{(lb/ton)}] \qquad \text{[Eq. 1]}$$

CO_2 emissions from other fuel types were calculated in the same manner.

COMBUSTION PLUS PROCESS-RELATED EMISSIONS

The following plant types emit CO_2 from both the combustion of fuel and process-related emissions:

- Fuels/chemicals
- Iron ore processing
- Lime production
- Sugar production

The major sources of fuel for these processes include coal (subbituminous coal, bituminous coal, and lignite), natural gas, distillate oil, fuel oil, residual oil, municipal solid waste, and gasoline. For the amount of CO_2 produced during the combustion of fuel for these plant types, the reader can refer to the combustion-only section.

Table 5-1. Percentage of Carbon in Typical Fossil Fuels

Fuel	%C, As-received	Basic Fuel Units
Eastern Bituminous Coal[1]	72.7	tons
Subbituminous Coal[1]	50.6	tons
Lignite[1]	36.4	tons
Natural Gas[2]	74.9	million ft^3
Fuel Oil[3]	86.7	1000 gal
Municipal Solid Waste[4]	38.0	tons
Propane[2]	81.7	1000 gal
Biomass (wood and wood wastes)[4]	21.5	tons
Residual Oil[3]	86.9	1000 gal
Coke (derived from coal)[5]	86.0	tons
Gasoline[6]	85.5	1000 gal

[1] EERC ultimate analysis (eastern bituminous is a Pittsburgh No. 8 Seam, Powder River Basin is a Cordero Rojo subbituminous coal, and lignite is a Fort Union lignite).

[2] Direct calculations (natural gas is CH_4, and propane is $CH_3CH_2CH_3$).

[3] www.ec.gc.ca/energ/fuels/reports/cnslt_rpts/fqp/tables1_e.htm.

[4] www.trmiles.com/alkali/fulesc3.html.

[5] www.rexresearch.com/coal/4chap/4chap.htm.

[6] www.woodgas.com/proximat.htm.

FUEL/CHEMICAL PLANTS

Only one fuel/chemical plant has been identified in the PCOR Partnership region, and that is the Dakota Gasification Company Great Plains Synfuels plant. This plant emits CO_2 emissions during combustion (described earlier) and from the production of ammonia.

The following describes how the CO_2 emissions were calculated for the ammonia production during natural gas reforming:

Assumptions: Ammonia is produced via steam reforming of natural gas.
Reference: www.efma.org/Publications/BAT%202000/Bat01/section06.asp gives the emission factors (accessed May 2004).
Emission factor = 1.15 kg CO_2/kg NH_3 = 1.15 lb CO_2/lb NH_3
(Depending upon the degree of reforming, the ratio may range from 1.15 to 1.3.)

$$CO_2\ (\text{tons/yr}) = \text{tons } NH_3/\text{yr} \times 1.15 \text{ tons } CO_2/\text{ton } NH_3 \qquad [\text{Eq. 2}]$$

IRON ORE PROCESSING

Iron ore processing emits CO_2 during the combustion of fuel, as described above, and from the processing of taconite pellets. The following describes how the CO_2 emissions were calculated for the induration of flux pellets containing limestone–dolomite:

Assumptions: Emission of CO_2 from calcination is based on the difference in total CO_2 emissions from flux pellet production and total CO_2 emissions from acid pellets (which do not contain limestone flux) production. That is, the firing of acid pellets produces no additional CO_2 beyond that from fuel combustion for pellet induration, while the firing of flux pellets also produces additional CO_2 from the calcination of limestone within the pellets. It was assumed, therefore, that all plants produced flux pellets, thus showing the maximum possible additional CO_2 contribution.

Reference for emissions factors: www.epa.gov/ttn/chief/ap42/ch11/final/c11s23.pdf, Tables 11.23-4 and 11.23-5 (accessed May 2004).

Emission factor (flux pellet) = 130 lb CO_2/ton pellet = 0.065 tons CO_2/ton pellet
Emission factor (acid pellet) = 99 lb CO_2/ton pellet = 0.0495 tons CO_2/ton pellet

Emission factor = (0.065 – 0.0495) tons CO_2/tons pellet = 0.0155 tons CO_2/ton pellet

$$CO_2 \text{ (ton/yr)} = \text{tons pellet/yr} \times 0.0155 \text{ tons } CO_2\text{/ton pellet} \qquad \text{[Eq. 3]}$$

LIME PRODUCTION

Lime production emits CO_2 from the combustion of fuels, as described above, and from the calcination of limestone–dolomite. The following describes how the CO_2 emissions were calculated:

Assumptions: Lime is produced from limestone (Ca-based), not dolomite.
From stoichiometry, 56.1 lb CaO and 44.0 lb CO_2 are produced from 100.1 lb $CaCO_3$.
Emission factor = 44.0 lb CO_2/56.1 lb CaO = 0.785 lb CO_2/lb clinker

$$CO_2\text{(tons/yr)} = \text{tons clinker/yr} \times 0.785 \text{ tons } CO_2\text{/ton clinker} \qquad \text{[Eq. 4]}$$

SUGAR PRODUCTION

Sugar production emits CO_2 during the combustion of fuels, as described above, and from the calcination of limestone–dolomite. Refer to the section discussing lime production for the method used to calculate the emission factor used to determine CO_2 emissions from the calcination of limestone–dolomite.

METHODOLOGY 6: ESTIMATION OF CO_2 EMISSIONS FROM CEMENT KILNS

IDENTIFICATION OF CEMENT KILN LOCATIONS

Identification of cement facilities located in the Plains CO_2 Reduction (PCOR) Partnership region was accomplished through the use of the U.S. Environmental Protection Agency (EPA) Aerometric Information Retrieval System databases (www.epa.gov/enviro/html/airs/index.html) using the National Industry Classification System Code for Cement Manufacturing (37231). Several other Internet sites were used to check and verify the sources within the PCOR Partnership region, primarily a list of U.S. portland cement plants from the EPA Technology Transfer Network data base (www.epa.gov/ttn/atw/pcem), data published by the Portland Cement Association (www.cement.org/), and data published by the Cement Association of Canada (www.cement.ca). Where latitude and longitude information was absent in the databases, the street address was used with Google Earth (http://earth.google.com/) to locate the plant. Often the street address or the latitude and longitude are for an office removed from the kiln operations. In such instances, these locations have been corrected using the Google Earth imagery because the kilns and quarry operations are obvious there. This procedure provided a list and locations for 15 kilns operating during 2007 in the PCOR Partnership region of United States and Canada.

In cement manufacturing, CO_2 is produced as a result of both calcination and fuel combustion. Most combustion-related CO_2 emissions result from clinker production, specifically the fuel used for pyroprocessing. Carbon dioxide emissions from combustion depend on whether a wet process or dry process is used for the clinker production, as well as the carbon intensity of the fuel inputs.

PROCESS EMISSIONS

The PCOR Partnership used the World Business Council for Sustainable Development cement CO_2 protocol (1), which recommends a default emission factor of 525 kg CO_2/tonne (0.525 tonne CO_2/tonne) of clinker produced. As this emissions factor does not account for the fact that a percentage of the clinker precursor materials remain in the kiln in the form of cement kiln dust (CKD), the recommendation of the Intergovernmental Panel on Climate Change that emissions from CKD are equal to 2% of total process-related CO_2 emissions was followed. As a result, the following equation is used to calculate process-related CO_2 emissions:

> Process-related CO_2 emissions = (clinker production tonne × 0.525 tonne CO_2/tonne clinker) + (clinker production tonne × 0.02 CKD × 0.525 tonne CO_2/tonne clinker)

This yields an overall emission factor of 0.536 ton CO_2/ton of clinker produced.

COMBUSTION EMISSIONS

Although the actual dry process is more complex and dry kilns require more electricity to operate because of the need for fans and blowers, dry kilns consume significantly less energy in the pyroprocessing. On average, the wet process has been estimated to require 6.3 million Btu per short ton (MBtu/st) versus 5.2 MBtu/st for the dry process (Table 6-1) (2). In the PCOR Partnership region there are seven dry plants and three wet plants. To determine the energy consumption per short ton, a weighted average was used; therefore, 5.53 MBtu/st was used to calculate the amount of energy consumed. Because specific data as to the type of fuel burned were unavailable, an average ton CO_2/MBtu was calculated based on the average of all CO_2 emission factors of kiln fuels provided by the World Business Council for Sustainable Development (www.ghgprotocol.org). Table 6-2 lists these factors with the average being 0.104 ton CO_2/MBtu. This is slightly higher than the average for the conventional fossil fuels (0.100 ton CO_2/MBtu) that make up the majority of the fuel burned in the cement process. While cement kilns are energy omnivores, coal supplies the largest share of energy consumed at cement kilns, approximately 71% in 2001. Approximately 12% of energy consumption is derived from petroleum coke, 9% from liquid and solid waste fuels, 4% from natural gas, and the remainder from oil and coke (3, 4). Using these factors and converting to an emission factor based on the tonnage of clinker produced gives an emission factor of 0.575 ton of CO_2/ton of clinker produced.

Table 6-1. Energy Requirements for Cement Processes

	MBtu/Short Ton	MBtu/Metric Ton
Wet Process	6.3	6.93
Dry Process	5.2	5.72
Total All Cement	5.5	6.05

CLINKER PRODUCTION

Because individual plant data for annual clinker production were not available, average values were calculated from district data. These data were taken from the U.S. Geological Survey report *Cement*, which gives data for 2005 (5). The average values for districts containing PCOR Partnership states are:

Iowa, Nebraska, South Dakota	902,000 tons/yr/plant
Missouri	1,074,000 tons/yr/plant
Wyoming	885,000 tons/yr/plant
Montana	514,000 tons/yr/plant

There are no clinker plants in Minnesota, Wisconsin, or North Dakota.

Table 6-2. CO_2 Emission Factors of Cement Kiln Fuels (per lower heating value)

	CO_2/GJ, kg	CO_2/MBtu, ton
Conventional Fossil Fuels		
Coal + Anthracite + Waste Coal	96.0	0.112
Petrol Coke	92.8	0.108
(Ultra) Heavy Fuel	77.3	0.090
Diesel Oil	74.0	0.086
Natural Gas	56.1	0.065
Shale	107.0	0.124
Lignite	101.0	0.117
Alternative Fossil Fuels		
Waste Oil	74.0	0.086
Tires	85.0	0.099
Plastics	75.0	0.087
Solvents	74.0	0.086
Impregnated Saw Dust	75.0	0.087
Mixed Industrial Waste	83.0	0.097
Other Fossil-Based Wastes	80.0	0.093
Biomass Fuels		
Sewage Sludge	110	0.128
Wood, Nonimpregnated Sawdust	110	0.128
Paper, Carton	110	0.128
Animal Meal	89	0.104
Animal Bone Meal	89	0.104
Animal Fat	89	0.104
Agricultural, Organic, Diaper Waste, Charcoal	110	0.128
Other Biomass	110	0.128
Overall Average	89.4	0.104

References

1. World Business Council for Sustainable Development, 2005, The cement CO_2 protocol—CO_2 accounting and reporting standard for the cement industry, Version 2.0, June 2005: The Cement Sustainability Initiative, www.gispri.or.jp/calculation/ghg/pdf/cement_protocol_v2-or.pdf#search=%22The%20Cement%20CO2%20Protocol%3A%20CO2%20Accounting%20and%20Reporting%20Standard%20for%20the%20Cement%20Industry%2C%20Version%202.0%20WBCSD%22 (accessed 2007).

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3. U.S. Geological Survey, 2003, Minerals yearbook—Vol. 1–metals and minerals, 2002: U.S. Department of the Interior.

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APPENDIX B

ORIGINAL OIL-IN-PLACE CALCULATION AND CO_2 SEQUESTRATION CALCULATIONS

ORIGINAL OIL-IN-PLACE (OOIP) CALCULATION

Created by the Energy & Environmental Research Center – Steven A. Smith and David W. Fischer

Source Date: April 4, 2005

The original oil-in-place (OOIP) calculation was completed using the volumetric method.

Variable	**Variable Name**
A	**Field surface area, acres**
h	**Average pay thickness, ft**
Φ	**Average porosity, %**
Soi	**Oil saturation, %**
OOIP	**OOIP, stb**
FVF	**Oil formation volume factor (initial), rb/stb**

7758 is a conversion factor relating acres to barrels

7758 bbl/ac-ft = (43,560 ft^2/acre) × (.1781 bbl/ft^3)

This calculation assumes that the entire field area is productive. This is to be viewed as a maximum value, with the actual oil in place to be determined by detailed field-level reservoir studies.

$$OOIP = \frac{7758\ Ah\Phi Soi}{FVF}$$

CO_2 SEQUESTRATION CALCULATIONS

January 27, 2006

Created by the Energy & Environmental Research Center – Steven A. Smith

SEQUESTRATION CAPACITY CALCULATION FOR OIL-BEARING RESERVOIRS

This calculation is based on the assumption that the entire pool area will be used to sequester CO_2. This estimate is, without question, higher than the probable sequestration capacity of most reservoirs and should only be used as a tool to approximate the relative magnitude of CO_2 storage in oil-bearing strata. The estimated capacity represents the sum of each producing interval (pool) within a field. The total number of intervals is indicated as a pool count. The calculation is as follows:

$$\mathbf{Q = (A) \times (T) \times (\varphi) \times (\rho_{co2}) \times (1-S_w)}$$

Where

Q = Storage capacity of the oil reservoir, lb CO_2

A = Field area, ft^2

T = Producing interval thickness, ft

Φ = Average reservoir porosity, %

$\boldsymbol{\rho_{co2}}$ = Density of CO region $_2$, lb/ft^3

$\mathbf{(1-S_w)}$ = Saturation of oil, where S_w is the initial reservoir water saturation (%)

This calculation yields the maximum storage capacity of an oil-bearing reservoir in pounds (lb) of CO_2.

Methods:

- For areas outside of Alberta, the pool area considered represents the entire boundary of the oil field. We expect that this figure may be larger than the actual productive areal extent used in detailed reservoir analyses.

- The thickness, porosity, and water saturation figures used represent the reported reservoir thickness as collected from hearing files, reservoir annuals, and published oil field data.

- Where no data exist, the water saturation was estimated to be 50%.
  - CO_2 density is based on temperature and pressure data for individual pool characteristics. This was acquired from the National Institute of Standards and Technology (NIST) Web site, http://webbook.nist.gov/chemistry/fluid/.
  - Temperature and pressure were calculated according to the following formulae:

$$\mathbf{T} = ([.0173] \times [\text{top of pay}] + 54.61)$$

$$\mathbf{P} = ([.4806] \times [\text{top of pay}] - 427.39)$$

These formulae were derived from the existing values of temperature and pressure in the Plains CO_2 Reduction Partnership (PCOR) region data set, obtained from publicly available sources. Both variables were compared with their corresponding depth and assigned a best-fit linear curve, from which an equation was computed (Figures 1 and 2).

- Where temperature and or pressure data could not be calculated, a density figure of 27.49 lb/ft^3 is used. This is an approximation based on the average density data found throughout the PCOR Partnership region.

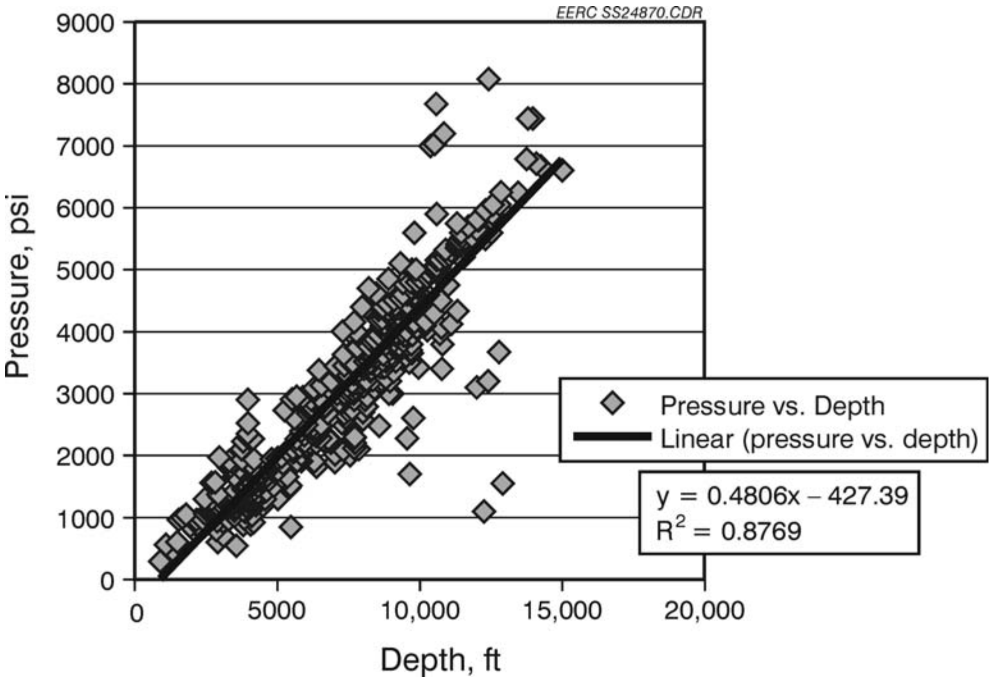

Figure 1. Pressure assessment based on oil-producing PCOR Partnership region.

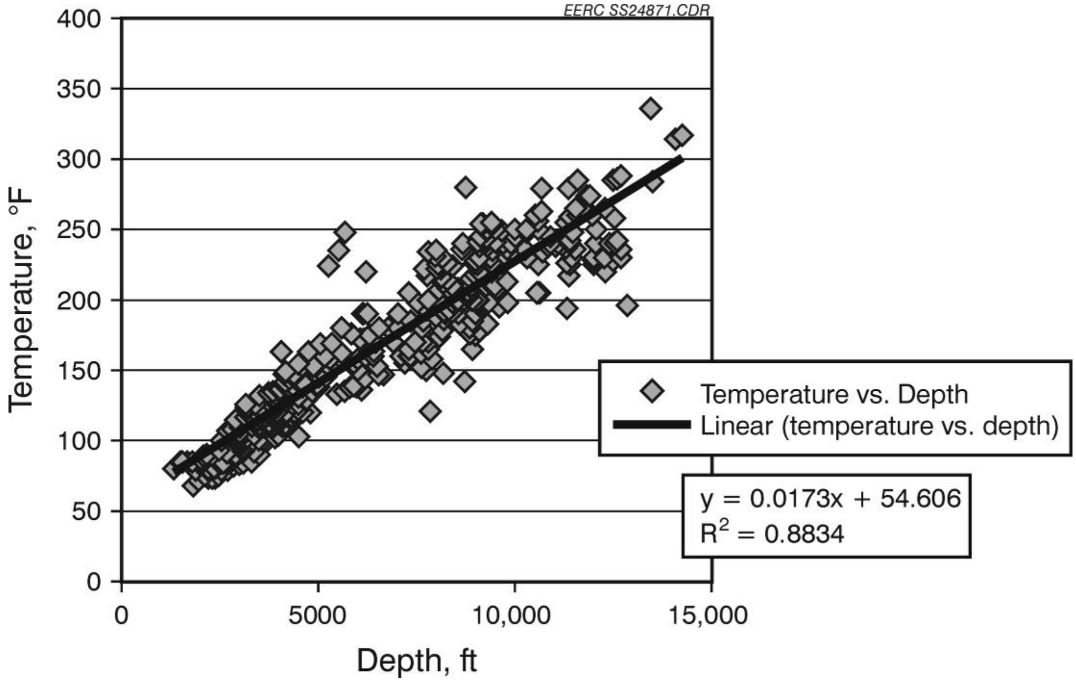

Figure 2. Temperature assessment based on oil-producing PCOR Partnership region.

SEQUESTRATION CAPACITY CALCULATION FOR ENHANCED OIL RECOVERY

This calculation is based on the volume of oil estimated to be in place at the time of discovery and relative percentages of tertiary recovery from CO_2 injection. The estimated capacity represents the sum of each producing interval within a field. The total number of intervals is indicated as a pool count. The calculation is as follows:

$$\mathbf{Q = (OOIP) \times (0.12) \times (8000)}$$

Where

Q = CO_2 remaining in the reservoir after flooding process is complete, ft^3

OOIP = Original oil in place, stb

0.12 = Estimated recovery of oil from CO_2 flood, %

8000 = CO_2 purchase requirement to produce 1 barrel of oil from CO_2 flooding, ft^3

Methods:

- Where OOIP was not available, a calculation was made to estimate it.
- Recovery factors, purchase requirements, and remaining CO_2 are figures taken directly from published literature.

More information on both methods of calculation can be found in the EERC Topical Report “Sequestration Potential of Petroleum Reservoirs in the Williston Basin”

SEQUESTRATION CAPACITY IN SALINE AQUIFERS

The calculation used is a straightforward estimate that relates the pore volume in the reservoir (area × thickness × porosity) and the solubility of NaCl in the reservoir water at spatially varying pressures and temperatures. Solubility factors for temperatures and concentrations in excess of 200°F and 200,000 ppm NaCl, respectively, were not readily available at the time of this study (temperatures and concentration values are routinely above these values in the Powder River and Williston Basins). As such, data were extrapolated to above 500°F and 300,000 ppm from tables provided through personal communication with the Indiana Geological Survey (April 2004) in order to attain the necessary solubility correction factors. This methodology is the same as the Midcontinental Interactive Digital Carbon Atlas and Relational Database (MIDCARB) CO_2 sequestration tool. The only modification made for this report was the extrapolation of the solubility parameters of CO_2 in water to account for the higher temperature and salinity present in the study area.

$$\mathbf{Q = 7758 \times (A) \times (T) \times (\varphi) \times (CO_2s)}$$

Where

Q = CO_2 remaining in the aquifer after injection, ft^3
7758 = (43,560 ft^2/acre) × (0.178 bbl/ft^3)
A = Area, acres
T = Producing interval thickness, ft
Φ = Average reservoir porosity, %
CO_2s = Solubility of CO_2, ft^3/bbl