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The First North American Carbon Storage Atlas

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Abstract

Canada, Mexico and the United States formed the North American Carbon Atlas Partnership (NACAP) in December 2008 to collaborate in the development of a North American Carbon Storage Atlas (NACSA). This partnership was formally announced by the Presidents of the United States and Mexico and the Prime Minister of Canada at their meeting in Guadalajara, Mexico, in August 2009. The NACAP effort identified and quantified large stationary sources of carbon dioxide (CO₂) emissions, identified and screened sedimentary basins suitable for CO₂ storage, and estimated the CO₂ storage resources of the three most common types of geological media—oil and gas reservoirs, unmineable coal and deep saline formations—in those basins using publicly available geological data. To develop the atlas NACAP had to harmonize storage resource estimation methodologies, define a common scale and resolution, and develop procedures for the treatment of shared sedimentary basins across national borders. Although North America is a large emitter of CO₂, the results of the assessments by the three countries demonstrate that potential CO₂ storage resources in North America are hundreds, if not thousands, of times greater than current CO₂ emissions. Certainly, practical considerations will reduce these estimates. The maps of the large stationary CO₂ sources and of the CO₂ storage resources show that the sources and storage resources frequently either overlay each other or are within manageable distances of each other, making carbon capture and storage an attractive option to reduce CO₂ emissions.

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) says that combustion of the world's fossil energy resources is no longer environmentally sustainable unless carbon capture and storage (CCS) can be widely deployed [1]. Implementation of CCS technology in a country, and subsequently in a world region such as North America, requires knowing the location and size of both large stationary CO₂ sources and geological formations with potential for storing CO₂. An international G8-IEA-CSLF report [2] made recommendations to the G8 at their meeting in Hokkaido in July 2008 on near-term opportunities for CCS, and provided statements regarding the capability of nations to store CO₂, including:

Governments should urgently establish primary assessment of prospective sedimentary basins using an appropriate CO₂ storage capacity estimation methodology, including source-sink matching.

At the North American Leaders Summit in New Orleans in April 2008, the Presidents of the U.S. and Mexico and the Prime Minister of Canada highlighted the ongoing exchange of information and joint collaboration in CCS to reduce greenhouse gas emissions by the three countries. In December 2008 at a meeting in Houston, Texas, Canada, Mexico and the United States formed the North American Carbon Atlas Partnership (NACAP) to collaborate in the development of a North American Carbon Storage Atlas (NACSA). This partnership was formally announced by the Presidents of the United States and Mexico and the Prime Minister of Canada at their meeting in Guadalajara, Mexico, in August 2009 [3]. NACAP marks the first time in the world that the potential for carbon storage in a wide geographic region, one that crosses national borders, was to be jointly assessed. NACAP was to determine the appropriate scope of international collaboration in the area of carbon mapping for North America, and then plan and execute the work. Tasks included the mapping of both large stationary sources of CO₂ and potential storage formations, scales and resolution, methodologies for estimating the various types of storage resource, protocols for digital data sharing, the treatment of common border areas and the media for reporting the results, that is, a published atlas and a website.

2. Large stationary sources

Anthropogenic CO₂ sources can be subdivided into two types: stationary and non-stationary (e.g., transportation). Large stationary sources of CO₂ (greater than 100 kt per year of CO₂) include power plants, chemical processing facilities, oil refineries, food processing plants, and other manufacturing facilities. Implementing CCS requires that the CO₂ emitted from these sources be captured and subsequently stored in geological formations.

The regions of North America vary in the magnitude and density of large stationary CO₂ sources due to the location of energy resources (e.g., coal, oil and gas) or carbonate rocks for cement production and to the amount and nature of various industrial activities. For this effort large stationary sources of CO₂ were divided into nine (9) major industry sectors—agricultural processing, cement making, electricity production, ethanol production, fertilizer production, industrial processes, petroleum and natural gas processing, refineries and chemical processing and unclassified. Fossil fuel-based power generation sources represent the largest CO₂ emissions by category (ranging from 46% of total CO₂ emissions in Canada to 80% in the U.S.), but also have the lowest CO₂ concentration in the flue gas; hence, a challenge for CO₂ capture is doing it at low cost. Most coal-fired power plants are located near coal deposits in western Canada and the United States, and are concentrated in the midwestern and eastern United States. Most of Mexico's power generation stations are oil-fired, but some use coal. Emissions

from petroleum and natural gas processing facilities occur primarily in the western and central regions of Canada and the United States, as well as along the Gulf of Mexico, where oil and gas resources are found. Refineries and chemical production facilities are also found in these locations, although in some cases they are located around harbors to process imported oil. Petroleum and natural gas processing facilities, refineries and chemical production facilities make the capture of CO₂ more economical and efficient because their effluents are highly concentrated in CO₂. Emissions of CO₂ from these sectors range from 8% of total CO₂ emissions in the U.S. to 36% in Canada. Carbon dioxide emissions from industrial facilities and cement plants, which are spread across North America, range from 7% of total CO₂ emissions in the U.S. to 25% in Mexico.

Each country took responsibility for tallying their CO₂ emissions. For more information on large stationary CO₂ sources and the methods each country used to determine its CO₂ emissions, refer to Appendix A in NACSA 2012 First Edition [4]. Fig. 1 shows the location (the mapping) of large stationary CO₂ sources in North America. The data indicate that CO₂ emissions from large stationary sources in North America between 2009 and 2011 were roughly 3.4 Gt/yr from 2,253 sources, and that Canada, Mexico and the United States were responsible for 6%, 6% and 88% of those CO₂ emissions, respectively. The industry sector with the largest share of CO₂ emissions was electricity generation with 76%. Each of the remaining industry sectors were in single digits.

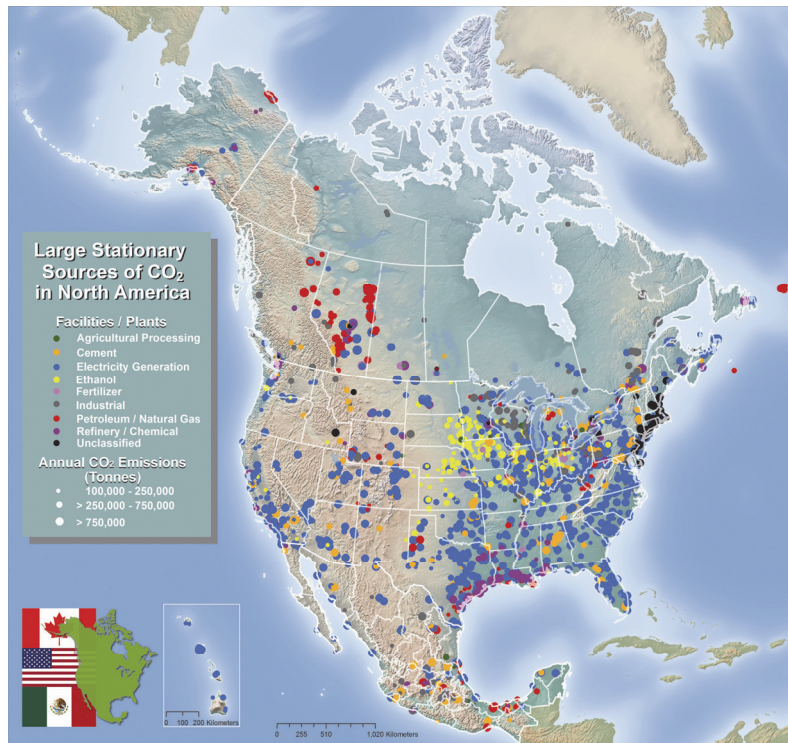


Fig. 1. Large Stationary Sources of CO₂ in North America: The dots indicate the location of large stationary sources of carbon dioxide (CO₂) in North America. The color of a dot indicates the industry sector of the carbon dioxide emitting facility, whereas the dot size represents the relative quantity of the carbon dioxide released. Data displayed on this map were collected by the governments of Canada, Mexico and the United States.

3. Formations for storing CO₂

At its core, North America is composed of ancient rocks that formed during the first 3.5 billion years of Earth's history. They are mainly crystalline, igneous, and metamorphic rocks, such as granites and gneiss, which are not suitable for CO₂ storage. These ancient rocks are exposed in the north-central part of the continent, called the Precambrian Shield. A series of sedimentary basins formed on the Precambrian Shield, such as the Williston, Illinois, and Michigan basins in the United States. These basins are generally the best suited for CO₂ storage because they are tectonically stable and have a suitable succession (usually layer-cake type) of oil and gas reservoirs, deep saline formations, and coal beds with intervening layers of shale and evaporite rocks that constitute caprocks (barriers to the flow of fluids, including CO₂).

Another significant feature of the North American continent is the collision of the North American tectonic plate with the Juan de Fuca, Pacific, and Cocos plates in the west, and the Caribbean plate in the south. As a result, mountain ranges and volcanic regions are present along the western coast of North America, which may not be suitable for CO₂ storage. Small sedimentary basins are present along the coast and within the mountain ranges. These basins contain oil and gas or coals, such as the Bowser basin in British Columbia, but due to high levels of tectonism, faulting, and fracturing, some of these basins may be unsuitable for CO₂ storage. On the eastern side of the mountain ranges in western North America are basins of various sizes located from the Mackenzie basin in northern Canada to the Veracruz basin in southern Mexico. These include the Alberta basin in Canada; the Denver, Anadarko, and Permian basins in the United States; and the Sabinas and Tampico basins in Mexico. On the eastern side of North America, mainly in the United States, the Appalachian Mountains form a mirror image to the Rocky Mountains, with basins to their west, such as the Black Warrior and Appalachian basins. The mid-continent basins between the eastern side of the Rocky Mountains and the western side of the Appalachian Mountains are separated by the Transcontinental Arch, which trends into Canada across western-central North America and consists of sedimentary rocks overlying the Precambrian basement. The basins are also underlain by Precambrian rocks and contain oil and gas and/or coals. Given their attributes and depth, they are likely suitable for CO₂ storage.

A further important geological storage feature for North America is the spread of the mid-Atlantic ridge and the formation of a series of sedimentary basins along the entire eastern coast of North America to the Gulf of Mexico and Campeche basins in Mexico. These basins usually contain oil and gas and are likely suitable for CO₂ storage, but the challenge is their offshore location. Finally, a series of sedimentary basins, rich in oil, gas, and coal, are present in Alaska and the Canadian Arctic, such as the Alaska North Slope, Beaufort, and Sverdrup basins. They are also suitable for CO₂ storage, but their distance from CO₂ sources and the Arctic environment pose challenges for CO₂ storage.

4. Shared sedimentary basins in North America

4.1 Canada-U.S. Border

The shared basins between Canada and the United States are depicted in Fig. 2. Canada and the United States share sedimentary basins in the Arctic, on the Pacific coast, along the continental border and possibly on the Atlantic coast. The Alberta basin, a large basin located mainly in Alberta and extending into northern Montana, is the Canadian basin most suitable for CO₂ storage. It is separated from the Williston basin by the Bow Island (Sweetgrass) Arch, which trends southwest-northeast stretching

through northern Montana, southeastern Alberta, and western Saskatchewan.

The Williston basin is a large basin located in eastern Montana, North and South Dakota, southern Saskatchewan, and southwestern Manitoba. It has significant CO₂ storage resource potential in the United States and is the second most important basin for CO₂ storage in Canada. Both the Alberta and Williston basins are well-explored and rich in oil and gas reservoirs, coal and salt beds, and saline formations. They occur in tectonically stable regions, have infrastructure already in place, and are located underneath or near large stationary CO₂ sources. They constitute primary targets for CO₂ storage both in western Canada and in the United States west of the Transcontinental Arch.

The Michigan basin is located in Michigan, eastern Wisconsin, Indiana, Ohio, and under Lake Huron in Ontario. It has good CO₂ storage potential, with most of the resource situated in the United States. The Appalachian basin likely also has good CO₂ storage potential, with most potential located in the United States.

Rocks overlying the Cincinnati Arch, which trends southwest-northeast from Alabama to Ohio and Ontario, include (in Canada) carbonates where oil and gas has been trapped. However, because of its shallow depth, the storage resource in Canada is likely limited, with more potential possibly under Lakes Huron, Erie, and Ontario.

Small, shared Pacific basins are located offshore along the Pacific coast from southwestern British Columbia to northwestern Washington State. No infrastructure exists and little exploration has been carried out on these basins. Generally, these basins are likely not suitable for CO₂ storage.

Among the Atlantic basins that occur offshore along the Atlantic shelf, the Scotia shelf is within Canada's territorial waters, and the Georges Bank basin is within the U.S. territorial waters, although some sediment formations may be present between the two. The small Bay of Fundy basin is shared between New Brunswick and Nova Scotia in Canada and Maine in the United States.

Along the Alaska-Yukon border, some small basins are shared. Offshore in the Arctic, the Beaufort basin is shared between the Northwestern Territories and Yukon in Canada and Alaska in the United States. The basin most likely has significant CO₂ storage potential, given the presence of oil and particularly large gas reserves, but the basin is far from major CO₂ sources and the difficult Arctic marine conditions make it an unlikely candidate for CO₂ storage.

4.2 Mexico-U.S. Border

The shared basins between Mexico and the United States are depicted in Fig. 2. The United States and Mexico share sedimentary basins along their border, predominantly in the east. The Gulf of Mexico basin is located in the southeastern United States and northeastern Mexico, both onshore and offshore the Gulf of Mexico. Several sub-basins exist within the broader Gulf of Mexico basin, with the Rio Grande embayment and Burgos basin occurring along the border. The Rio Grande embayment is located along the southeastern coast of Texas, while the Burgos basin is located along the northeastern coast of Mexico. The boundary between the two intersects at the international border, where the Burgos basin is considered to be the equivalent or southern limit of the Rio Grande embayment. They are geologically similar and occur both onshore and offshore. Together, they form the westernmost part of the Gulf of Mexico basin.

The Burgos basin has a high potential for gas reservoirs with a variety of traps. Considering the many oil and gas reservoirs in the Gulf of Mexico basin, significant CO₂ storage potential exists in this basin.

The South Texas basin extends from Texas into Mexico; within the South Texas basin is the Maverick basin, which straddles the border. There are potential oil and gas reservoirs in the Maverick basin. However, little exploration has taken place in this basin. The Marfa basin, located in west Texas and northeastern Mexico, may have some CO₂ storage potential.

The Orogrande basin is located in south-central New Mexico and Mexico and contains oil and gas reservoirs with CO₂ storage potential. The Pedregosa basin starts in the corner of southeastern Arizona and southwestern New Mexico and extends southeastward into north-central Mexico. The Pedregosa basin contains unexplored oil and gas reservoirs that may have CO₂ storage potential like other basins to the north.



Fig. 2. Sedimentary basins in North America: Sedimentary basins are shown in green, while shared sedimentary basins are shown in pink lavender. Data displayed on this map were collected by the governments of Canada, Mexico and the United States. NACSA 2012 First Edition contains more information on sedimentary basins in the respective country sections.

5. Methodology for estimating the CO₂ storage resource

To produce readily comparable CO₂ storage resource estimates between Canada, Mexico, and the United States, a default calculation approach was agreed upon. The NAEWG members have agreed to use the CO₂ storage resource estimation methodologies described in the third edition of U.S. DOE's Carbon Sequestration Atlas of the United States and Canada (Atlas III) [5], or, where appropriate, the methodology developed by the Carbon Sequestration Leadership Forum [6]. It has been shown that the two methodologies are equivalent and can be used as appropriate depending on data availability. These

methodologies were developed to be consistent across North America for a wide range of available data. Adopting these methodologies allowed for the integration of data compiled by Canada, Mexico, and the United States for the three types of geological formations under consideration for CO₂ storage: saline formations, unmineable coal, and oil and gas reservoirs.

The methodologies derived for estimating geological storage potential for CO₂ consist of widely accepted assumptions about in-situ fluid distributions in porous formations and fluid displacement processes commonly applied in the petroleum and groundwater science fields. The volumetric approach is the basis for CO₂ resource calculations for all three geological storage formations. At a basic level, the methods require the area of the target formation or horizon along with an understanding of the formation's thickness and porosity. There are other specific parameters unique to oil and gas fields and coal seams that are needed to compute the estimated CO₂ storage resource. Because not all of the pore space within any given geological formation will be available or amenable to CO₂, a storage coefficient (referred to as the efficiency- or E-factor) is applied to the theoretical maximum volume in an effort to determine what fraction of the pore space can effectively store CO₂.

Ranges of values for the E-factor were calculated for deep saline formations from statistical approaches that consider the variation in geological properties encountered in subsurface target formations. For coal seams and oil and gas reservoirs, the E-factor values used were those developed by U.S. DOE for *Atlas III*. The E-factor values for a particular injection horizon can be modified if more specific information about the formation is known, resulting in more precise resource estimations. In situations where this approach is taken, additional metadata will be compiled to explain why the default numbers were not employed. E-factors for coal and saline formations are available with 10, 50 and 90 percent confidence intervals. Using these E-factors, low and high storage resource estimates for coal and saline formations were calculated as shown in the tables below (mid estimates are not shown).

6. CO₂ storage resources in Canada, Mexico and the U.S.

Having agreed to the methodology for estimating the CO₂ storage resource, three types of geological formations in North America, oil and gas reservoirs, coal and saline formations were assessed. As shown in Table 1, oil and gas reservoirs have some potential for storing CO₂. For the most part the depleted oil and gas reservoirs are close to the large stationary sources of CO₂—see Fig. 1 and Fig. 3. Unfortunately, oil and gas reservoir data for Mexico were not available. Note that active reservoirs were not assessed, that is, oil and gas reservoirs that are producing or could produce economically. Also, additional CO₂ storage resource created by enhanced oil recovery (EOR) using CO₂ was not assessed, as the required detailed evaluations were beyond the scope of the atlas. Currently the use of anthropogenic CO₂ for EOR is being evaluated, particularly in the United States, from the perspective of economics, regulation and storage.

Table 1. Estimates for the CO₂ storage resource in oil and gas reservoirs in North America

Country	Canada	Mexico	United States
Total (in Gt)	16	Data not available	120

Coal has potential to store some CO₂ as indicated in Table 2. Coal has a storage resource similar to the storage resource for oil and gas reservoirs. Geographically, the assessed coal formations are relatively near, and even overlap in many areas, the large stationary sources of CO₂—see Fig. 1 and Fig. 4.

Table 2. Estimates for CO₂ storage resource in unminable coal in North America

Country	Canada		Mexico	United States	
	Low Estimate	High Estimate		Low Estimate	High Estimate
Total (in Gt)	4	8	0	61	119

As shown in Table 3 it is saline formations that offer the greatest potential for storing CO₂, in all three countries. Comparing Fig. 1 and Fig. 5 reveals that for the most part the large stationary CO₂ sources are also within reasonable distances of many of the saline formations.

Table 3. Estimates for CO₂ storage resource in saline formations in North America

Country	Canada		Mexico	United States	
	Low Estimate	High Estimate		Low Estimate	High Estimate
Total (in Gt)	28	296	100	1,610	20,155

NACSA encompasses the first comprehensive assessment of Canada's CO₂ storage resources. Data on the volume, composition and type of emissions from large stationary sources were obtained from Environment Canada—219 Mt of CO₂ in 2009 was emitted from 254 sources. Well over 200 sedimentary basins were initially considered, but only three remained (Western Canada Sedimentary Basin, Michigan Basin and Appalachian Platform) after application of stringent screening criteria. The storage resources of oil and gas reservoirs, unmineable coal and deep saline formations in each of these three basins were then assessed if present and if data were available. The results were tabulated by province. The estimate for the storage resource for oil and gas reservoirs was 16 Gt, for unmineable coal 4–8 Gt, and for deep saline formations 28–296 Gt. Based on Canada's large stationary sources of CO₂ emissions in 2009, these assessments indicate that Canada has an estimated 220 to 1,500 years of CO₂ storage resource available.

Mexico's assessment for the CO₂ storage resource followed a three-step approach. The first step involved gathering data (for 2008) for CO₂ emissions from large stationary sources, including emission volumes, industry categories of the emitting facilities, and emission factors provided by the Ministry of the Environment and Natural Resources. The second step comprised the identification of geological storage provinces through careful analysis and screening of available published geological data. This phase was developed at the country level and considered only two types of territories: inclusion and exclusion. The difference between these two types of territories is their geological constitution, risk susceptibility for volcanic and seismic phenomena and their inherent permeability. This step resulted in a map in which territories in the western part of Mexico are of the exclusion type and those in the eastern part of the inclusion type. The third step of the assessment involved breaking down the inclusion zones into regions with similar characteristics for storing CO₂. This resulted in nine geological provinces with an assessed storage resource of about 100 Gt – enough capacity to store Mexico's emissions for 500 years, based on annual CO₂ emissions from large stationary sources (200 Mt in 2010). This assessment only considered deep saline formations for storing CO₂. The lack of published geological data for oil and gas reservoirs prevented an assessment of these reservoirs, and no unmineable coal has been identified in Mexico.

The United States Department of Energy's (U.S. DOE) Regional Carbon Sequestration Partnerships (RCSPs) were instrumental in gathering the large stationary CO₂ emissions from 3,959 stationary sources with total annual emissions of 3 Gt in 2011. As a whole, the RCSPs assessed the storage resource

potential in the United States for oil and gas reservoirs to be 84 Gt, for unmineable coal 61–119 Gt and for deep saline formations 1,627–20,176 Gt. The United States has an estimated 575 to 6,600 years of CO₂ storage resource available based on U.S. large stationary CO₂ emissions in 2011.

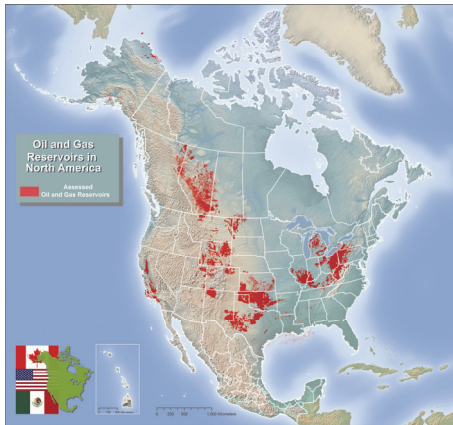


Fig. 3. Oil and Gas reservoirs assessed for CO₂ storage are shown in red.

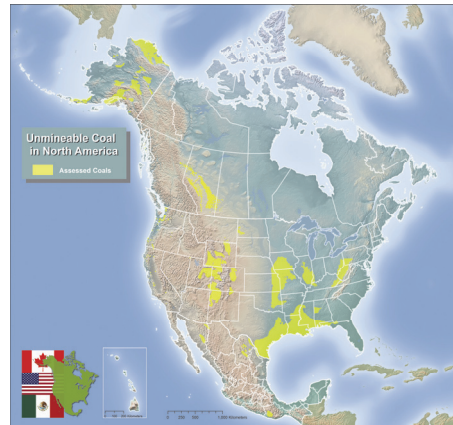


Fig. 4. Coal assessed for CO₂ storage is shown in yellow.

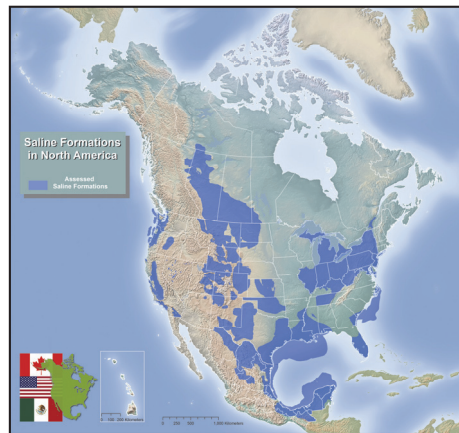


Fig. 5. Saline formations assessed for CO₂ storage are shown in blue.

7. NACSA Website and Online Viewer

The NACSA website (www.nacsap.org) serves as a resource for information on large CO₂ stationary sources and CO₂ storage resources in North America. The website houses full storage resource estimation methodologies and links to valuable information from the three countries involved in the NACAP effort.

The NACSA Viewer, accessible from the NACSA website, provides web-based access to all data (CO₂ stationary sources, potential geological CO₂ storage resources, etc.) and analytical tools required for addressing CCS deployment. Distributed computing solutions link the three countries' data and other publicly accessible repositories of geological, geophysical, natural resource, and environmental data.

The NACSA website and NACSA Viewer are hosted by West Virginia University and the U.S. DOE's National Energy Technology Laboratory (NETL), respectively. Canadian and Mexican data are uploaded when new information becomes available. U.S. data are made available in real time from the National Carbon Sequestration Database and Geographic Information System (NATCARB at www.natcarb.org), which in turn receives its data from the seven RCSPs in the U.S. and from specialized data warehouses and public servers.

The atlas, NACSA 2012 First Edition, and the NACSA website contain substantially more information than presented in this paper. In addition, the atlas has chapters on CCS activities in each of the countries. The Atlas is annotated well so that individuals seeking details regarding references and processes will know where to find them.

8. Conclusion

North America, a large stationary source emitter of CO₂, has the storage resources to store its emissions for hundreds, potentially thousands, of years. Establishing effective, safe, permanent and environmentally sound CO₂ storage is a key element in moving toward commercial deployment of carbon capture, utilization and storage (CCUS) technologies, considered by experts as an important option for reducing human-generated CO₂ emissions linked to climate change.

Additional outcomes of the partnership include (1) the ability to share geological information digitally across national borders allowing for a common GIS system; (2) the matching of stationary CO₂ sources with potential storage sites without restriction due to national borders; and (3) a comprehensive understanding of the similarities in the methodologies used to assess the CO₂ storage resource in the three countries—Canada, Mexico and the U.S.

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