TITLE:

National **Carb**on Sequestration Database and Geographic Information System (**NatCarb**)

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FORWORD

This report summarizes the results of a multi-year cooperate project involving many different organizations lead by the Kansas Geological Survey of the University of Kansas (KGS) with the assistance the Department of Geology and Geography of West Virginia University (WVU). The project will continue as an internal US Department of Energy project through the National Energy and Technology Laboratory and will involve continued contributions from WVU and KGS. The project operates as a complement and enhancement of the US Department of Energy's Regional Carbon Sequestration Partnerships (RCSPs) and includes more than 300+ state agencies, universities, and private companies, spanning 42 states, three Indian nations, and four Canadian provinces (http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html). As part of the ongoing characterization, validation and deployment phases, the partnerships have accumulated a wealth of geographic and geological data and information relevant to validate and potentially deploy carbon sequestration technologies.

The RCSPs have accumulated a wealth of geographic and geological data and information relevant to validate and potentially deploy carbon sequestration technologies. The RCSPs have evaluated and determined which of the numerous sequestration approaches emerging in the last few years are best suited for specific regions of the country. In addition, the partners are contributing through their demonstration efforts to the development of regulations and infrastructure requirements that would be needed should sequestration be deployed on a wide scale in the future.

Regional partners through **NatCarb** have created and maintain the only carbon sequestration portal for matching CO_2 sources with nearby sinks—geologic and terrestrial sequestration sites—in the United States and Canada. The **Nat**ional **Carb**on Sequestration Database and Geographic Information System (**NatCarb**) provides an Internet portal that brings together data from every partnership region into a network of regional carbon sequestration atlases for the United States, which were used to identify promising sequestration opportunities; and raise awareness and support for carbon sequestration as a greenhouse gas mitigation option, both within industry and the general public. The portal is updated regularly by region, and is available to decision makers and the general public through a single website (http://www.natcarb.org/).

ABSTRACT

This annual and final report describes the results of the multi-year project entitled ***"NATional CARBon Sequestration Database and Geographic Information System (NatCarb)"*** (http://www.natcarb.org). The original project assembled a consortium of five states (Indiana, Illinois, Kansas, Kentucky and Ohio) in the midcontinent of the United States (MIDCARB) to construct an online distributed Relational Database Management System (RDBMS) and Geographic Information System (GIS) covering aspects of carbon dioxide (CO_2) geologic sequestration. The **NatCarb** system built on the technology developed in the initial MIDCARB effort. The NatCarb project linked the GIS information of the Regional Carbon Sequestration Partnerships (RCSPs) (http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html) into a coordinated regional database system consisting of datasets useful to industry, regulators and the public. The project includes access to national databases and GIS layers maintained by the **NatCarb** group (e.g., brine geochemistry) and publicly accessible servers (e.g., USGS, and Geography Network) into a single system where data are maintained and enhanced at the local level, but are accessed and assembled through a single Web portal to facilitate query, assembly, analysis and display. This project improves the flow of data across servers and increases the amount and quality of available digital data.

The purpose of NatCarb is to provide a national view of the carbon capture and storage potential in the U.S. and Canada. The digital spatial database allows users to estimate the amount of CO_2 emitted by sources (such as power plants, refineries and other fossil-fuel-consuming industries) in relation to geologic formations that can provide safe, secure storage sites over long periods of time. The NatCarb project worked to provide all stakeholders with improved online tools for the display and analysis of CO_2 carbon capture and storage data through a single website portal (http://www.natcarb.org/).

While the external project is ending, NatCarb will continue as an internal US Department of Energy National Energy Technology Laboratory (NETL) project with the continued cooperation of personnel at both West Virginia University and the Kansas Geological Survey. The successor project will continue to organize and enhance the information about CO_2 sources and developing the technology needed to access, query, analyze, display, and distribute natural resource data critical to carbon management. Data are generated, maintained and enhanced locally at the RCSP level, or at the national level in specialized data warehouses, and assembled, accessed, and analyzed in real-time through a single geoportal. To address the broader needs of a spectrum of users form high-end technical queries to the general public, NatCarb will be moving to an improved and simplified display for the general public using readily available web tools such as Google Earth™ and Google Maps™. The goal is for NatCarb to expand in terms of technology and areal coverage and remain the premier functional demonstration of distributed data-management systems that cross the boundaries between institutions and geographic areas, and forms the foundation of a functioning carbon cyber-infrastructure. NatCarb provides access to first-order information to evaluate the costs, economic potential and societal issues of CO_2 capture and storage, including public perception and regulatory aspects.

EXECUTIVE SUMMARY

The ***Nat****ional* ***Carb****on Sequestration Database and Geographic Information System* ***(NatCarb)*** is an attempt to create a national Carbon Cyberinfrastructure (CCI). NatCarb provides national coverage across the Regional Carbon Sequestration Partnerships (RCSPs). Currently, the RCSPs cover 42 states, three Indian Nations and four Canadian provinces (Figure 1, http://www.natcarb.org). In addition, agencies from six member countries of the Carbon Sequestration Leadership Forum (CSLF) are participating through the RCSP program. Advanced distributed computing solutions are used to link database servers across the partnerships and other publicly accessible servers (e.g., USGS, Google Map™) into a single system where data is maintained and enhanced at the local level, but is accessed and assembled through a single Web portal (Figures 2, 3). Cyberinfrastructure (CI) refers to infrastructure based upon distributed computer, information and communication technology. If infrastructure is required for an industrial economy, then we could say that CI is required for a knowledge economy (Atkins et al., 2003). Information important to technical and policy decisions can be queried, assembled, analyzed and displayed. The **NatCarb** project as the initial step in CCI has improved the flow of data across servers and increased the amount and quality of available carbon sequestration information at national, regional and local scales.

The online tools used in the project continue to improve in stability, security and speed in order to promote real-time display and analysis of CO_2 sequestration data, while decreasing management overhead. The software systems developed as part of the **NatCarb** project represent cutting edge approaches to constructing a national cyberinfrastructure for carbon management. The goal of NatCarb is to develop a carbon cyberinfrastructure (CCI) that can improve data flow and sharing, and to simplify the learning process as a closed loop that goes from observation often from sensors and instruments on the surface or in the subsurface to data to information to knowledge (Figures 4 and 5).

The data assembled by the NatCarb project represents one of the most comprehensive data sets assembled to address questions of carbon capture and storage (CCS). NatCarb data has contributed and organized information for the construction of the *Carbon Sequestration Atlas of the United States and Canada* (Figure 6).

Major improvements include use of more user friendly clients such as GoogleMap™ and GoogleEarth™ and **NatCarb Carbon Explorer** a simplified Internet Map Server (IMS), which are intended for decision makers and the general public who are not GIS experts. These "lite" versions of the NatCarb include information on major CO_2 sources and potential geologic storage sites coupled with limited display and analysis capabilities. There are primarily used to display national data. These images and data are presented as a series of high-quality static graphic images and interactive online images (Figure 2).

NatCarb has been involved in generating a large volume of custom maps and data tables to fulfill specific requests from both the public and private sector. Custom requests are occurring with increased frequency and we are moving to construct an online repository of frequently generated custom maps and data tables.

The project continues to add data to significant databases of aquifer geochemistry. The data consists of geographic location, stratigraphic unit, water geochemistry, temperature and depth for over 100,000 brine samples. The data consists primarily of standard water geochemistry (cations/anions), but there are samples that contain more esoteric data (e.g., isotopic values and organic species). New tools have been developed to provide improvements in the query, display and analysis of brine geochemistry, and have been used to better understand large-scale fluid flow and potential long term geologic storage potential at the basin scale.

The **NatCarb** project is a functional demonstration of carbon cyberinfrastructure (CI) as an effective federation of both distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships). A carbon cyberinfrastructure (CCI) is required to:

- share exponentially increasing amounts of heterogeneous data;
- develop tools to organize, store, preserve, retrieve, browse, process and visualize the voluminous data sets;
- improve or ability to undertake time critical learning through allocation of computational and networking resources;
- conduct analyses at regional to global spatial scales;
- curate data and technical analyses; and
- develop a collaborative approach to the learning process across teams, agencies, communities, states and countries.

Large amounts of data are required to address the complex challenges of creating a continent-wide network of partnerships to determine the most suitable technologies, regulations, and infrastructure requirements for safe and efficient carbon capture, storage and sequestration in different areas. The **NatCarb** system addresses CO_2 sequestration and other natural resource issues from sources, sinks and transportation within a spatial database that can be queried online at multiple scales from national to local (Figure 7). Visualization of high quality and up-to-date data related to CO_2 sequestration can assist decision makers.

GIS layers accessible through **NatCarb** provide access to millions of records at multiple scales from points to polygons (e.g., individual well bore or CO_2 source to saline aquifers across regions and states). Online data can be accessed, merged, queried, analyzed and displayed to fit the needs of the individual user. **NatCarb** has developed tools to examine the carbon capture and storage (CCS) process analyzing geologic storage sites in relation to emission sources meeting multiple criteria (e.g., geographic location, depth, temperature, etc.) and estimate the volume of CO_2 that can be sequestered (Figure 8).

The **NatCarb** project has demonstrated what works and what doesn't when constructing large data systems that cover multiple institutions and require high-quality data at a range of scales.

PROJECT OBJECTIVES

Atmospheric levels of CO_2 have risen significantly from preindustrial levels of 280 parts per million (ppm) to present levels of 384 ppm (Tans, 2008). Evidence suggests the observed rise in atmospheric CO_2 levels is the result of expanded use of fossil fuels for energy. Predictions of increased global energy use during this century indicate a continued increase in carbon emissions (EIA, 2007), and rising concentrations of CO_2 in the atmosphere unless major changes are made in the way we produce and use energy—in particular, how we manage carbon (Socolow and others, 2004; Greenblatt and Sarmiento, 2004). One approach to managing carbon is to use energy more efficiently to reduce our reliance on the major carbon source—fossil fuel combustion. Another option is to increase our use of low-carbon and carbon-free fuels and technologies (nuclear power and renewable sources, such as solar energy, wind power, and biomass fuels). The third strategy is to manage carbon through geological storage (GS), sometimes referred to as geologic sequestration. Geologic storage is part of the process of carbon capture and storage (CCS). CCS involves separation and capture of CO_2 at the point of emissions followed by storage in deep underground geologic formations (Figure 8) (NETL, 2007).

In the face of this growing concerning over the consequences of anthropogenic release of carbon dioxide and other greenhouse gases (e.g., Wigley et al. 1996), increasing attention has been focused on the feasibility of large-scale capture and sequestration of carbon (e.g., Pacala and Socolow 2004). The United States and 189 nations ratified the 1992 United Nations Framework Convention on Climate Change, which states as its goal, "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN 1992). One potential method to mitigating climate change is capture and storage of greenhouse gases (primarily CO_2). Geologic storage of carbon dioxide (CO_2) is a natural part of the carbon-cycle; however, due to present concerns about global climate change related to greenhouse gas (GHG) emissions, efforts are underway to better utilize CO_2 sinks as a form of carbon management to offset emissions derived from fossil fuel combustion and other human activities. Carbon dioxide (CO_2) capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere (IPPC 2005). The challenges to capture and store carbon on a sufficiently large scale and in a sufficiently timely manner present many challenges, technical, economic, political, and social. **NatCarb**, a web accessible system is an attempt to improve access to the information required to better address these challenges (Figure 9).

Technical challenges include methods for industrial-scale capture of carbon dioxide prior to atmospheric release, methods for enhancing biological uptake of carbon dioxide and conversion to biomass, methods for transportation and injection of carbon dioxide in well bore-holes, methods for safely storing carbon belowground in geologic repositories and saline aquifers, and methods for measurement and monitoring of the movement of carbon (e.g., Eswaran et al. 1995; Edmonds et al. 2004; Lal 2004; IPCC 2005). Various treatments have addressed the economic, regulatory, and social aspects of large-scale carbon capture and sequestration (IOGCC 2005, IPCC 2005). Recent attention has turned to the challenge of collecting and making available disparate data (carbon sources, potential sinks, infrastructure, etc.) and analytical tools (pipeline measurement, carbon storage capacity estimation, cost estimation, brine geochemistry, etc.) required for addressing carbon capture and sequestration. While there is a growing body of research concerning data sharing (Goodchild et al. 2006) and the design of geoportals (Maguire and Longley 2005, Beaumont et al. 2005), much work is still needed both concerning technical design and long-term viability of geoportal implementation.

We extend the concept of *cyberinfrastructure,* first defined by the National Science Foundation (Atkins et al. 2003, Estin et al. 2003, and Berman and Brady 2005), to address carbon capture and storage. Cyberinfrastructure refers to the totality of technology, policies, standards, human resources and related activities necessary to acquire, process, distribute, use, maintain and preserve spatial and temporal data throughout all levels of government, private and no-profit sectors, and academia. The NatCarb cyberinfrastructure provides a computing environment that provides access to information, problem solving capabilities, and communication (Atkins et al. 2003, Estin et al. 2003, and Berman and Brady 2005). A well-formulated cyberinfrastructure (CI) design, incorporating advances in informatics and geographic information systems (GIS), is essential for a national approach to carbon sequestration science and technology efforts.

Vision for National Carbon Cyberinfrastructure (CCI): The challenges to a cyberinfrastructure can be stated as "the 3 C's" (Connection, Complexity and Coordination). The *connection* challenge arises with the attempt within an online environment to bring society together with the information and technology to formulate possible solutions. The *complexity* challenge centers on the challenges of managing, analyzing and visualizing within a geographic frame of extremely large and constantly evolving databases of diverse qualitative and quantitative data. The *coordination* challenge involves bringing together within a robust cyberinfrastructure multiple participating organizations and numerous dedicated and public-access server nodes.

The NatCarb vision for a CCI consists of an online accessible and distributed computing environment that provides paths to the acquisition, storage and distribution of critical geospatial and tabular data from multiple sources including sensor networks and satellites, measurements from the field and experimental results, along with model simulations, and information services for search, visualization, and analysis (Figure 5). Geological sequestration data, focused on the assessment of large-scale geological sequestration, include measurements of potential storage volumes and the monitoring and verification of ongoing demonstration projects, such as those undertaken as part of the Carbon Sequestration Regional Partnerships, and efforts of other public and private entities. The data are gathered in centralized and participating data warehouses (Figure 3). Data are linked with online analysis, visualization, and modeling tools to form a *Knowledge Base*. Information is accessed and assembled through a single Web portal and provided to the decision-makers and the general public. In order to successfully design a successful CCI, we must provide on-going reliable assess to a comprehensive set of data libraries, model simulations, and associated tools.

Evaluating the Success of Carbon Cyberinfrastructure: A successful CCI will require comprehensive data libraries, together with model simulation libraries, and associated information services (search, visualization, and analysis tools) focused on the scientific, technical, environmental, economic, and social aspects of capture and storage of CO_2, with a sustainable design that links all CCI elements. One key element involves provision for collection of data and simulation libraries in a *Knowledge Base*. Knowledge base data libraries must include up-to-date national information concerning carbon sources (atmospheric greenhouse gas emissions), potential terrestrial carbon sequestration sinks, potential geologic carbon sequestration sinks, and base geospatial data layers (political boundaries, topography land use/land cover, etc.) and infrastructure (roads, pipelines, etc.). Additional pilot implementation and economic data libraries must contain supporting field and analytical data and results of economic analyses. Information services must include map-based visualization capabilities together with key analysis tools, such as tools for calculating sequestration potential and optimal routes for CO_2 transport. In addition to their scientific and technical utility, the information, simulations, and tools within the CCI could help to address legal and regulatory issues, public perception, environmental impacts and safety as well as issues related to inventories and accounting of greenhouse gas emission reductions. Data for identification and assessment of sources and storage capacity represent an extremely large information universe involving diverse geospatial, tabular, and graphical data and will require a major effort in acquisition, processing, formatting, quality assurance, and preparation of metadata.

In order to construct the CCI, management of key carbon sequestration data libraries, modeling libraries, and other resources (graphics, documents, etc.) contained in the National Carbon Atlas should be managed by distributed state and regional data managers in conjunction with national geoportal managers (Figures 3-4). The current *ad hoc* paths among the partnerships and between the partnerships and national portal for receipt of data and metadata streams from distributed data providers will need to be refined and further automated. A National Carbon Atlas geoportal can improve data and metadata archiving, backup and updating. Maintenance of data and modeling library catalogs, including data and metadata status; coordination with data providers, other data managers, and geoportal managers; communication of feedback to data provider will need to receive increased attention.

Finally CCI will require vision, technical leadership, management leadership and fiscal authority. Technical and management leadership to ensure that regional and national levels work together is critical. Effort will be required to provide management to ensure CCI operates smoothly and achieves its goals. Fiscal sustainability of the CCI, with allocation of funding for operation, update, and maintenance at all levels of organization should be considered a high priority.

The **NatCarb** project is a functional first-step demonstration of cyberinfrastructure as an effective federation of both distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships). The system links together data from the Regional CO_2 Partnerships concerning sources, sinks and transportation within a spatial database that can be queried online. Information that addresses CO_2 sequestration is provided through a single interface that accesses the coverages and data from servers in each participating partnership and other servers providing national coverages. The **NatCarb** system is completely scalable and can be expanded to access, query and display CO_2 sequestration data on any accessible server at a participating site. **NatCarb** provides complete distributed management of the system (i.e., data and GIS layers can be edited and loaded from anywhere in the **NatCarb** system). The complexity and volume of data required to address CO_2 sequestration on a national and international basis rapidly increases the demands on any system to display the information, to integrate the data with models for analysis and to manage the system. A distributed environment is required to address the complex challenges of creating a nationwide network of partnerships to bring the technical and policy expertise together with sufficient data to determine the most suitable technologies, regulations, and infrastructure for carbon capture, storage and sequestration in different areas. Access to high quality and up-to-date data related to CO_2 sequestration can assist decision makers by providing access to common sets of high quality data in a consistent manner in order to minimize the negative economic impact, and maximize the possible value of the CO_2 sequestration while addressing issues of heath safety and the environment (Figures 2-5).

PROJECT STATUS

The ***NAT****ional* ***CARB****on Sequestration Database and Geographic Information System* **(NatCarb)** provides an Internet portal that brings together data of the Carbon Sequestration Partnerships in a single convenient location. The portal is updated regularly by RCSPs and NatCarb groups, and is available to the general public through a single website (http://www.natcarb.org/). Usage on the portal has displayed a steady growth in usage. At the end of the project calendar (April, 2009), over 750 unique visitors per month accessed the NatCarb web site (Figure 10). The usage trend shows a continued increase.

The architecture of the NatCarb system routes requests for an image of the data to and from the remote servers of the partnerships (Figure 3). The **NatCarb** system is built to work with ESRI Internet Map Services (ArcIMS) and Open Geospatial Consortium (OGC) Web Map Services (WMS). The remote servers contact their database and generate an image based on the request and send it back to the NatCarb server. **NatCarb** downloads, georeferences, and merges all of the remote layer images into a final layer that it sends to the client (Figures 3 and 4). This significantly reduces the quantity of data transmitted between servers as well as the amount of processing required at the **NatCarb** portal. Attribute data is requested from the remote servers only when a user specifically queries information from a layer. The transfer of attribute data is undertaken through web services using XML in place of direct query of remote databases. As a result of these architectural changes, the **NatCarb** system is robust, responsive, scalable, and secure.

The management overhead associated with the multiple layers across multiple servers in the **NatCarb** has been significantly reduced and will continue to be reduced with the integration of new Internet server technology (e.g., ESRI ArcGIS™, ESRI Server 9.3™ and GoogleEarth™). **NatCarb** has built a metadata repository of connection and layer information for each RCSP. This is a dynamic database that is managed with minimal central administration by the individual partner administrators of the various servers. The remote administrators use an Internet web page that is served by **NatCarb** to enter the connection information for their own remote server. The **NatCarb** server automatically queries the distributed servers in order to locate all available layers. The remote administrator can then manage these layers remotely, indicating which layers the site should allow users to view, which columns should be displayed or queried and how to group the layers. Only the management information is stored on the **NatCarb** server in a relational database (Figure 3). All data processing is undertaken on the remote servers.

Our approach within **NatCarb** has been to assist the Regional Carbon Sequestration Partnerships (RCSPs) to create and maintain carbon sequestration websites for matching CO_2 sources with nearby sinks—geologic and terrestrial sequestration sites—in the United States and Canada. **NatCarb** provides an Internet portal that brings together data from each partnership region into a single location. The individual regional and national data managers link regional or national data into **NatCarb**.

The **NatCarb** site has grown to serve a large number of data layers (>150), data files, and interactive and static maps (Figures 11-13). The graphical user interface (GUI) and the database and mapping requests are grouped and displayed in an organized fashion, and allow a simplified and flexible design to be presented to the online user.

The NatCarb effort has assisted the RCSPs to develop the methodology to estimate CO_2 storage capacity. Storage capacity can be divided into reserves and resources (Figure 14). Reserves are capacity with a high probability of being used as a geologic storage (GS) site. Resources are capacity for which less information is available; resources may be exploitable, but additional data is needed. NatCarb is focused on resource estimates at the regional and national scales. Layers are available through NatCarb of the potential GS resources including oil and gas reservoirs, coal seams, saline formations, gas shale, and basalt.

Most recently, the emergence of Web 2.0 technologies has shown how core capabilities created by service providers can rapidly be 'mashed-up' (and customized to support the needs of specific projects and communities. New front ends using the Web 2.0 concepts are being developed for the general public and non-technical user (Figures 15-16).

The portal is built as two distinct components—the viewer, which is a graphical user interface (GUI), and the database and mapping requests component. The GUI handles the map layout, layer grouping, and tool grouping. Once the user selects a layer (or set of layers) from the *Layer List* to draw and then zooms to an area, the viewer communicates to a series of backend pages that handle the viewer-database-image interaction. The server dynamically builds requests based on parameters and the metadata database. These requests are sent to the remote servers that generate the maps or data requests. The resulting images are returned through the **NatCarb** server to the GUI client.

In **NatCarb**, work on developing display tools, and modeling and simulation components to display and manipulate data is at a very early stage. Examples include tools to query and display parameters such as brine geochemistry across multiple states, saline formations or other criteria (Figure 18). Large amounts of data can be visualized with online tools using standard geochemical plots (e.g., Piper, Collins and Stiff diagrams). In another example a simple model was applied to the **NatCarb** data to estimate the potential sequestration volume for all potential geologic storage sinks within five miles of a point that could be a potential stationary source of CO_2 (Figure 19).

Web-database connectivity continues to improve among the Regional CO_2 Partnerships using Internet Map Server (IMS), eXtensible Markup Language (XML), and custom tools developed in JAVA, FLASH, KLM, and ColdFusion. **NatCarb** applications access partnership and national databases for the analysis of both CO_2 sources and potential geologic sequestration sites. Software on numerous servers across the partnerships provides distributed processing for data analysis and display. Tools have been developed to provide complete distributed management of the system (i.e., data and GIS layers can be edited and loaded from anywhere in the **NatCarb** system). The software systems developed as part of the **NatCarb** project represent cutting edge approaches to online data access and management. The data assembled represents one of the most comprehensive data sets assembled to address questions of CO_2 sequestration.

Near-Term Strengths and Weaknesses of NatCarb: While it is possible with a reasonable level of accuracy to determine annual greenhouse gas (GHG) emission source data for most industrial sectors at a regional, national and state level, it is more difficult to examine monthly or daily emissions of individual point sources and predict the location of future GHG emission point sources (IPCC, 2005). In addition, an adequate resource assessment of storage capacity for individual sedimentary basins at the national and regional levels is required to establish existing opportunities for storing the CO_2. At the present time, **NatCarb** is neither comprehensive nor sufficient in coverage and structure to completely address carbon capture and storage at all levels from local to continent wide. Work was initiated to improve data and to provide tools to arrange data into areas that are amenable to policy solutions. During 2008, data was made available for potential geologic storage sites for saline formations and deep coal beds at the state level. For oil and gas fields geologic storage estimates are available at the state and reservoir level. In addition data are available to generate detailed maps for selected basins such as the Appalachian basin (Figure 20; Carr and Skeen, 2008).

The **NatCarb** portal requires a degree of GIS and relational database expertise that is not distributed across the entire technical community, and is not common among policy makers and the interested general public. This weakness was approached by developing customized **NatCarb** portals and use of commonly available GUI's such as Google Map™ and Google Earth™ that are more user-friendly (Figures 15-16). All GUIs will use the same underlying data, but provide more community focused views of carbon sequestration challenges and opportunities.

ACCOMPLISHMENTS

The ***Nat****ional* ***Carb****on Sequestration Database and Geographic Information System* **(NatCarb)** provides national coverage across the Regional CO_2 Partnerships. Currently, the partnerships cover 42 states, 3 Canadian provinces, and numerous organizations (Figure 1; http://www.natcarb.org). In addition to providing access to data from the Regional CO_2 Partnerships, **NatCarb** provides national data for states not covered by a Regional Partnership (Figure 1). Advanced distributed computing solutions link database servers across the partnerships and other publicly accessible servers (e.g., USGS, TerraServer) into a single system where data is maintained and enhanced at the local level, but is accessed and assembled through a single Web portal. Information important to technical and policy decisions can be queried, assembled, analyzed and displayed. The

NatCarb project has improved the flow of data across servers and increased the amount and quality of available carbon sequestration information at national, regional and local scales (Figures 2-5). The online tools used in the project have improved in stability and speed in order to provide real-time display and analysis of CO_2 sequestration data (Figure 7). Usage of the NatCarb site has steadily increased and represents a broad user community (Figure 10).

A major goal was to construct a national coverage that provided a simplified view of CO_2 sources and potential geologic storage sites. This was accomplished through GIS layers covering "National CO_2 Facilities and Sinks" on the **NatCarb** website and through access to maps covering North America.

Saline formations represent an enormous potential for CO_2 storage capacity. However, less is known about saline formations than is known about hydrocarbon reservoirs and coal seams, and there is a greater amount of uncertainty associated with their amenability to CO_2 storage. Depending on the chemistry of the brine and the rock, CO_2 molecules can dissolve in brine or react with minerals to form solid mineral phases (e.g., carbonates). The carbonate reactions have the potential to be both a positive and a negative. The reactions can increase permanence, but they also may drastically reduce permeability of the formation and ability to inject CO_2 in the immediate vicinity of an injection well. The national group has assembled water geochemistry data from national and regional data bases and providing an improved set of capabilities for query, visualization and analysis, including custom maps (Figure 20). These visualization and analysis tools are available for aquifers at a national, regional or local scale.

We are constantly working to improve the quantity and quality of the national databases that can supplement and enhance the work of the regional partnerships. As additional GIS layers begin to cross between regional partnerships, they will be represented at the national level with a consistent symbology, and supplemented with national data.

GIS layers and data tables accessible through **NatCarb** provide access to millions of records at multiple scales from points to polygons (e.g., individual well bore or CO_2 source to saline aquifers across regions and states). Online data can be accessed, merged, queried, analyzed and displayed to fit the needs of the individual user. **NatCarb** facilitates generation of custom images to fit the needs and scale required of the user (Figure 20). **NatCarb** has developed tools to select sequestration sites meeting multiple criteria (e.g., geographic location, depth, temperature, etc.) and estimate the volume of CO_2 that can be sequestered.

The **NatCarb** project has demonstrated what works and what doesn't when constructing large data systems that cover multiple institutions and require high-quality data at a range of scales. For example –

- Each CO_2 Partnership and outside data sources (e.g., USGS) varies in database and GIS resources, but all are now capable of constructing and linking GIS layers and databases to the **NatCarb** system.
- Each CO_2 Partnership is capable of serving large volumes of existing data relevant to CO_2 sequestration through the **NatCarb** system. **NatCarb** is more efficient and consistent than isolated servers focused on a single partnership.

- Some data are better served centrally. Example - It is more efficient to centrally process coal basin maps or digital orthophotos and serve them from a single location.
- National data that already exists (e.g., USGS Digital Elevation Model) do not have to be reconstructed and can be accessed from remote servers not part of **NatCarb** and provided to the online user and to the individual CO_2 Partnership.
- Simple and flexible display and analysis tools (e.g., CO_2 emissions versus time plots) can be developed that can query and display data in real-time. These tools can be shared among the partnerships.
- **NatCarb** provides a demonstration of cyberinfrastructure as an integration of resources (data and facilities) and multidisciplinary expertise (Regional CO_2 Partnerships). The key remains a coordinated but distributed authority and management of the data by the institutions that own and maintain the data, wherever the data are located.

Major **NatCarb** project accomplishments during 2008 are:

1) Continued to maintain a distributed project team and management that cross both institutional and technical boundaries. The pooling of subject domain and computing technical expertise has resulted in a product that could not be completed by any of the individual participating research institutions. The distributed team provides both interaction and innovation within a focused area. The project structure serves as a model for addressing other natural resource issues that cross boundaries among institutional and geographic entities. This

team has been expanded to encompass personnel in each of the CO_2 Regional Partnerships.

2) The project has enhanced an online distributed system architecture that provides reliable communication and sharing among all the various servers of the **NatCarb** Consortium. The architecture incorporates open-platform methodologies that allow improved data sharing across servers, and incorporation of open GIS Consortium/Web Map Service map services. Use of spatial data engines and relational databases is not required. The interactive Web-based applications allow the Regional Partnerships in the **NatCarb** consortium to share, integrate, and display spatial data pertinent to CO_2 sources and geologic sequestration sites across the consortium states and provinces. Data remains local to be updated and expanded. However, data is available for use in regional analysis and to increase the accessibility of this information to all interested parties.

3) Simplified access through new user interfaces that is intended for decision makers and the general public who are not GIS experts was developed (Figures 15-16). In addition, the data assembled were used to construct maps of North American CO_2 sources and sinks for a hard-copy national atlas (Figure 6). These images and data are presented as a series of high-quality static graphic images and interactive online images. On request images can be customized to fit the scale and need of the user (Figure 20)

4) The project has generated and assembled a very large quantity of data elements pertaining to CO_2 sources and potential geologic sequestration sites. **NatCarb** has developed a significant database of aquifer geochemistry. The data consists

of geographic location, stratigraphic unit, water geochemistry, temperature and depth for over 100,000 brine samples. The data consists primarily of standard water geochemistry (cations/anions), but there are samples that contain more esoteric data (e.g., isotopic values and organic species). The brine data can be queried as individual sample or group of samples in a number of ways.

5) Improved tools allow clients to query and plot emissions through time for a single object to sum total emissions across an individual state, or group of sources. Additional tools allow the client to determine the estimated sequestration potential within a predetermined distance from an existing source or any other map location (Figure 19).
6) We have provided technology transfer to the geologic and sequestration community and to the general public through talks, papers and posters (see Technology Transfer Section for a listing and examples).

Short-Term Goals: The NatCarb effort will continue as an internal US Department of Energy project at the National Energy and Technology Laboratory (NETL). West Virginia University and Kansas Geological Survey personnel will work closely with NETL personnel to continue the NatCarb effort. Immediate ongoing and short-term goals that will be ongoing will be:

1) Continue to work with the Regional CO_2 partnerships to expand GIS layers and databases to address sequestration on a national basis and to develop estimates of CO_2 emissions and potential storage volumes at state and regional level. Provide the initial data sets and GIS layers that can be used and enhanced by the partnerships. Add new GIS layers and databases that increase the richness of the

NatCarb site. Assist in the expansion of coverage types in every state covered by the partnerships. Work to pioneer coverage and database types and spread the expertise to the other regions.

2) Continue to develop and add new and improved query and analysis tools. The biggest challenge remains to develop complex query and analysis capabilities that can be used to advance economic, technical, and environmental analysis of CO_2 sequestration potential at regional and state levels. Provide improved flexibility to designate scales of plots and displays. Provide improved download capabilities to move data and GIS layers to the client's machine for additional analysis.
3) Construct and demonstrate an efficient and useful national portal database to evaluate CO_2 sequestration potential at political levels such as the state/province. Work to bring all the partnerships and other interested parties into carbon sequestration information system coverage covering North America.
4) Develop the North America databases that will be used to develop the next version of the *Carbon Sequestration Atlas of the United States and Canada*.
5) Expand the coverage of NatCarb CCI to all of North America including Canadian provinces currently outside the RCSPs, and Mexico.

OVERVIEW OF TECHNICAL PROGRESS

A major challenge of the **NatCarb** project was to create an efficient, easy to access, and readily maintained knowledge management system with many millions of records pertaining to CO_2 sequestration that reside in multiple data warehouses across the Regional CO_2 Partnerships and other national sites (Figures 3, 4). When working with technical data related to CCS involves common challenges related to (i) sharing of potentially large volumes of data, (ii) computational and bandwidth requirements related to data volumes and streaming data rates, (iii) heterogeneity of data, software, and hardware technologies, (iv) management of time-critical data exchanges and analysis execution, (v) curation of data and preservation of scientific analyses, and (vi) complexity of data–software–hardware interfaces during data sharing, interactive data manipulations, and configurations of data-driven analyses. These challenges occur at different times and locations when users perform various tasks using NatCarb. This effort needs to continue to develop a improve CCI.

The **NatCarb** system provides global access across the organizations to manipulate pertinent geologic and engineering data related to the issues involved in identifying and evaluating opportunities for geologic CO_2 sequestration. Databases and GIS layers were developed in each state to characterize at multiple scales stationary sources of CO_2 and potential oil, gas, coal, and brine reservoirs for sequestration.

The **NatCarb** Consortium developed and improved a distributed approach to knowledge management. Significant new tools and GIS layers have been added to the **NatCarb** system that enhances the ability to undertake economic, technical, and environmental analysis of CO_2 sequestration potential at regional and state levels. Derived GIS layers use estimate the quantity of CO_2 that could be sequestered under various physical conditions (e.g., temperature, pressure and salinity). The **NatCarb** system is one of the first distributed systems (cyberinfrastructure) of natural resource data focused on carbon sources and potential geologic storage sites. Efforts will remain to expand the **NatCarb** model through the Regional CO_2 Partnerships to provide improved national coverage.

PROJECT HIGHLIGHTS

The original MIDCARB consortium consisting of five states (Indiana, Illinois, Kansas, Kentucky and Ohio) constructed the first online distributed Relational Database Management System (RDBMS) and Geographic Information System (GIS) covering aspects of carbon dioxide geologic sequestration (http://www.midcarb.org). That system linked the five states in the consortium through a coordinated regional database system consisting of GIS layers and datasets useful to industry, regulators and the public. The MIDCARB model was expanded as part of the **NatCarb** effort through development of coordinated working relationships and assistance to the GIS efforts of the seven Regional CO_2 Partnerships. For **NatCarb**, the overall project organization was provided through the University of Kansas and West Virginia University. Budgetary items were run through the Kansas University Center for Research (KUCR) and overall project coordination was provided through the Kansas Geological Survey.

The **NatCarb** project organization is an unique effort to bring together a team that is distributive, geographic and overlapping. The organization is structured along both geographic boundaries and broad functions. The geographic focus of the Regional Carbon Sequestration Partnerships (RCSPs) provides strong local expertise to characterize both CO_2 sources and potential geologic sequestration targets. The distributive focus provides a critical mass of technical people. A strong technical computing team was developed across institutional boundaries and has developed unique hardware and software solutions. This computing group pools technical expertise from each institution to work collaboratively on issues that are on the edge of distributed computing. No one institution has the technical computing expertise to create and maintain a system such as **NatCarb**. The technical computing leads keep the institutional management informed, and also interact closely with the individuals working on technical information concerning CO_2 sources and potential geologic sequestration sites (i.e., domain knowledge). The interaction between computing and domain teams at the local level provided unique solutions to address challenges and advanced both areas. The flexibility provided by the distributive structure of the **NatCarb** system allows for local experiments in data type, structure and display. Successful "experiments" were propagated across the RCSPs.

Interaction between domain and computing technical experts within individual institutions and across institutions is on a daily basis. This is monitored through the local institutional leads and shared through email and through periodic phone conferences of the GIS working group of the RCSPs. Project integration is to a significant degree organic, in that all information has the same geographic structure, and has a similar look and feel.

CO_2 Sources

There are two types of carbon dioxide (CO_2) emission sources: stationary sources and non-stationary sources. Non-stationary source emissions include CO_2 emissions from the transportation sector. Stationary source emissions come from a particular, identifiable, localized source, such as a power plant. CO_2 from stationary sources can be separated from stack gas emissions and subsequently transported to a geologic storage injection site. The "North American CO_2 Sources" map displays the location and relative magnitude of a variety of CO_2 stationary sources.

According to the EPA, in 2006, total U.S. GHG emissions were estimated at 7,054.2 million metric tons CO_2 equivalent. This estimate included CO_2 emissions as well as other GHGs such as methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Annual GHG emissions from fossil fuel combustion primarily CO_2 were estimated at 5,637.9 million metric tons with 3,781.9 million metric tons from stationary sources. While not all potential GHG sources have been examined, NETL's RCSPs through the **NatCarb** effort have documented the location of more than 4,796 stationary sources with total annual emissions of 3,276 million metric tons of CO_2 (Figure 13).

Geologic Storage (GS) Capacity

A primary goal of the NatCarb effort is to provide the basis to estimate CO_2 storage capacity. Storage capacity can be divided into reserves and resources (Figure 14). Reserves are capacity with a high probability of being used as a geologic storage (GS) site. Resources are capacity for which less information is available; resources may be exploitable, but additional data is needed. NatCarb is focused on resource estimates at the regional and national scales. Potential GS resources include oil and gas reservoirs, coal seams, saline formations, gas shale, and basalt. The first step is a regional theoretical CO_2 storage resource assessment. A theoretical CO_2 storage resource assessment only incorporates limited knowledge of the critical geologic parameters required for GS (e.g., storage volume, injection rates and long-term retention). All that may be known about a theoretical resource is that it has a probability of being available in a region and has adequate depth. Contingent resources represent a second step to reduce site selection risk and increase knowledge at a regional or local scale. Contingent resources indicate a level of knowledge of the GS potential for which plans and budgets can be developed to technically evaluate a specific site (e.g., 3D seismic or exploratory well), but economics, surface considerations, competing uses, and regulatory requirements have not been addressed.

The final goal of geological storage site selection process is to achieve proven and developed GS reserves, which are technically and commercially viable and include the ability to capture, compress and transport the CO_2 from source to GS site (e.g., the availability of a pipeline). Proved CO_2 storage reserves would have the highest degree of certainty and require active storage operations that have either injected CO_2 or at the minimum very strong test results showing that the GS site will be capable of injecting and safely storing CO_2 at adequate rates, volumes and retention rates.

The future capture and storage of CO_2 will depend on a number of factors, including financial incentives provided for deployment, and whether the risks of storage can be successfully managed. However, a well designed CCI can provide invaluable geospatial information at local to continent scales for scientific and technical personnel, policymakers in governments and environmental organizations, and the interested concerned public to adequately address the complex issues of CO_2 capture and storage for mitigating future climate change.

Oil and Gas Reservoirs

Mature oil and gas reservoirs have held crude oil and natural gas over millions of years. They consist of a layer of permeable rock with a layer of nonpermeable rock (caprock) above, such that the nonpermeable layer forms a trap that holds the hydrocarbons in place. Oil and gas fields have many characteristics that make them excellent target locations for geologic storage of CO_2. The geologic conditions that trap oil and gas are also the conditions that are conducive to CO_2 sequestration.

As a value-added benefit, CO_2 injected into a mature oil reservoir can enable incremental oil to be recovered. A small amount of CO_2 will dissolve in the oil, increasing the bulk volume and decreasing the viscosity, thereby facilitating flow to the wellbore. Typically, primary oil recovery and secondary recovery via a water flood produce 30-40 percent of a reservoir's original oil in place (OOIP). A CO_2 flood allows recovery of an additional 10-15 percent of the OOIP. NETL's work in this area is focused on increasing the amount of CO_2 that remains in the ground as part of CO_2 EOR injection.

While not all potential mature oil and gas reservoirs in all states and provinces have been examined, the RCSPs have documented the location of almost 129.6 billion metric tons of geologic storage potential in 10,708 oil and gas reservoirs distributed over 27 states and 3 provinces. Identified geologic storage potential in oil and gas reservoirs has increased approximately 40 billion metric tons of from the previous version of the *Atlas*. The major change is the addition of data from several Canadian provinces and from west Texas. Estimated geologic storage potential for individual mature oil and gas reservoirs by state and reservoir is available through the interactive NatCarb Atlas and as tables online (http://www.natcarb.org/Atlas2008.html).

Unmineable Coal Seams

Unmineable coal seams are too deep or too thin to be economically mined. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coalbeds to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurization, leave a considerable amount of methane in the formation. Additional recovery can be achieved by sweeping the coalbed with CO_2. Depending on coal rank three to thirteen molecules of CO_2 are adsorbed for each molecule of methane released, thereby providing an excellent storage site for CO_2 along with the additional benefit of enhanced coalbed methane (ECBM) recovery. Similar to maturing oil reservoirs, unmineable coalbeds are good candidates for CO_2 storage.

While not all potential areas of unmineable coal have been examined, the RCSPs have documented the location of 170-197 billion metric tons of CO_2 geologic storage potential in unmineable coal seams distributed over 24 states and 3 provinces. This is an increase of approximately 14 billion metric tons of identified storage from the previous version of the *Atlas*.

Saline Formations

Saline formations are layers of porous rock that are saturated with brine. They are much more extensive than coal seams or oil- and gas-bearing rock, and represent an enormous potential for CO_2 geologic storage. However, much less is known about saline formations because they lack the characterization experience that industry has acquired through resource recovery from oil and gas reservoirs and coal seams. Therefore, there is a greater amount of uncertainty regarding the suitability of saline formations for CO_2 storage.

While not all saline formations in the U.S have been examined, the RCSPs have documented the locations of such formations with an estimated sequestration potential ranging from 3,300 to more than 12,200 billion metric tons of CO_2. As a result of the inclusion of new evaluations from the Gulf Coast and other areas, identified potential for CO_2 geologic storage in saline formations has increased approximately 2,000 to 9,000 billion metric tons from the previous version of the *Atlas*.

POTENTIAL FUTURE WORK

The **NatCarb** group will continue to work with NETL to undertake the following tasks to develop a carbon cyberinfrastructure (CCI) covering North America. Tasks would include:

1) Improve the quality and coverage of the national carbon atlas that summarizes carbon sources and potential sinks. Work to provide tools to summarize data within the national CO_2 cyberinfrastructure at various geologic (e.g. basin) and geographic levels (e.g., state).
2) Provide an improved site for access by the general public to high quality information on all aspect of CO_2 capture and sequestration.
3) Work with the Regional Carbon Sequestration Partnerships (RCSPs) to maintain and improve GIS layers and data covering all aspects of CO_2 sequestration. Provide expertise to integrate the institutions within a RCSP into a regional and national cyberinfrastructure of distributed geographic information and relational database management system (GIS/RDBMS). Work

will continue to enhance, expand and integrate GIS layers and databases within and across regional partnerships. This approach would enable the regional partnerships to improve accessibility and consistency of approach among the regions.

4) Work with each regional center and each individual organization to develop and maintain the necessary expertise to fully develop a national CO_2 sequestration cyberinfrastructure. We continue to provide system schema for each region and link to each region's system.

5) Provide improved access to national GIS layers maintained on **NatCarb** servers and through outside servers (e.g., USGS, EPA, USDA). If required in the future, provide data management on our system and serve data provided by a state, region or organization.

6) Maintain and improve access to all **NatCarb** information. Increase the performance of the **NatCarb** system through improved stability and speed, enhanced online tools for visualization, query and analysis, and increased integration of regional partnerships. Continue to incorporate advanced tools into **NatCarb**. Use the latest technology to maintain the **NatCarb** front-end access to map servers and databases. Provide improved management tools that assist the partnerships in loading, maintaining and enhancing GIS layers and databases, and decrease management overhead.

7) Continue to work to enhance the GIS and online capabilities of each regional partnership and develop online methods for submitting data to shared national databases. Provide tools to facilitate loading of data that has been

supplemented by the Partnerships or NatCarb back to the originating organization.

8) **NatCarb** will continue a leadership role in data management as applied to educating the general public on carbon sequestration. We can share expertise beyond GIS and distributed databases. Improve the concept and the functionality of a federation of distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships).

9) Coordinate and work in close collaboration with other national and regional efforts and projects to develop improved scenarios and tools for carbon sequestration analysis. Work with national and regional experts on various technical aspects of cyberinfrastructure in order to provide a national system of the highest quality (e.g., MIT, Los Alamos National Lab, and San Diego Super Computer Center).

10) Continue to provide a series of updated lessons learned documents that document the challenges and rewards in the construction and maintenance of national distributed database systems. Provide access to software and procedures to construct a national CO_2 sequestration cyberinfrastructure. Provide periodic updates and present results at national and international meetings pertinent to carbon sequestration and publish technical results in appropriate scientific and technical publications.

SUMMARY OF NatCarb SYSTEM

The **NatCarb** system provides analysis and display tools at various levels for different audiences. The **NatCarb** browser provides the technical user with GIS experience the ability to query and display a large numbers of layers. The newly developed "lite" browsers using a Web 2.0 approach provide a simplified version that uses a limited number of layers and provides limited tools. The new "lite" are intended for the general audience and policy makers. In both cases the data is the same and of two types:

- Map Layers
- Data Tables

Each data type is processed locally and served through the **NatCarb** server as an image or data page. Each partnership in the **NatCarb** Consortium is responsible for construction, enhancement, and maintaining the data for the particular region. **NatCarb** provides national databases covering geographic and subject areas not adequately covered by the partnerships (e.g., New England states and brine geochemistry). Data quantity is extremely large and constantly increasing. Numbers of records are in the many millions, and cover a range of natural resource types (e.g., aquifers, to petroleum to coal). The data is extremely important to general natural resources and environmental questions in each RCSP. As a result, each RCSP has an interest in insuring the highest degree of quality control. However, with any extremely large, long-term and heterogeneous data set, individual data items can be incorrect. As a general activity of the institutions, the data is undergoing constant quality control and enhancement. The **NatCarb** effort leverages the activities of the RCSPs.

In addition to data, **NatCarb** provides a number of display and analysis tools that can be used to manipulate and display the data. All the tools work across the entire **NatCarb** system and can be accessed through the **NatCarb** browser. There are currently several hundred GIS layers that are stored on the five consortium servers.

TECHNOLOGY TRANSFER

The development of the **NatCarb** atlas is in itself a technology transfer activity. The members of the consortium have been very active in presenting results in informal settings. In addition, for the national group at KGS and WVU have participated in the following formal technology transfer activities during calendar year 2008:

Presentations

2/14/2008 Presentation at Appalachian Geological Society, Carbon Capture and Storage, The Challenge for this Century, Charleston, WV.

3/12/2008 Presentation of Science Protocol for Carbon Capture and Storage, US Department of Energy, Gaithersburg, MD.

4/11/2008 West Virginia University, Agricultural Economics Colloquium, Carbon Capture and Storage, The Challenge for this Century, Morgantown, WV

8/20/2008 Testimony to Joint Committee of the Kansas Legislature, Carbon Capture and Storage (CCS), Topeka, KS.

9/17/2008 Presentation Appalachian Section Society of Petroleum Engineers, Applied Hydrodynamics in Carbon Storage and Petroleum Exploration in the Appalachian Basin, Bridgeport, WV.

10/7/2008 Regional Carbon Sequestration Partnership Review Meeting, Development of NatCarb Methodology, Pittsburgh, PA.

12/2/2008 North American Energy Working Group - Experts Group on Energy Science and Technology, Development of NatCarb, Houston, TX.

12/16/2008 Carbon Capture and Storage Conference, Primer on Carbon Capture and Storage, Topeka, Kansas.

12/17/2008 Black and Veatch, Primer on Carbon Capture and Storage, Overland Park, Kansas.

Publications

2008 Carr, Timothy R., Asif Iqbal, Nick Callaghan, Dana-Adkins-Heljeson, Kurt Look, Shawn Saving and Ken Nelson, A national look at carbon capture and storage - National carbon sequestration database and geographical information system, Green House Gas Technology 9, Energy Procedia, 7 pages. http://www.sciencedirect.com/science/journal/18766102

2008 John Litynski, Sean Plasynski, Timothy Carr, Viola Rawn-Schatzinger and David Olsen, Classification Assessment of Geologic CO_2 Storage Reservoirs, Green House Gas Technology 9, Energy Procedia, 8 pages. http://www.sciencedirect.com/science/journal/18766102

2008 Buchanan, Rex and Timothy R. Carr, Geologic Sequestration of Carbon Dioxide in Kansas, Public Information Circular 27, Kansas Geological Survey, 4 p. http://www.kgs.ku.edu/Publications/PIC/pic27.html

In press Nissen, S. E., Carr, T. R., Marfurt, K. J., and Sullivan, E. C., Using 3-D seismic volumetric curvature attributes to identify fracture trends in a depleted Mississippian carbonate reservoir: Implications for assessing candidates for CO2 sequestration, *in* M. Grobe, J. Pashin, and R. Dodge, eds., Carbon Dioxide Sequestration in Geological Media--State of the Art: Special Publication, American Assoc. of Petroleum Geologists.

In press Sean L. Plasynski, John T. Litynski, Timothy R. Carr, Howard G. McIlvried, and Rameshwar D. Srivastava, Geologic Carbon Capture and Storage, in Encyclopedia of Soil Science, edited by Ratan Lal (ed.), Taylor and Francis, New York.

In press Sean I. Plasynski, John T. Litynski, Timothy R. Carr, Howard G. McIlvried, Bruce M. Brown, Derek M. Vikara, and Rameshwar D. Srivastava, in press, Advances in Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations, International Journal Greenhouse Gas Control.

Abstracts

2008 Saibal Bhattacharya, K. D. Newell, and **Timothy R. Carr,** The Economic Interplay Between CO_2 Sequestration and Enhanced CH_4 Production from Coal Beds: Two Scenarios from Eastern Kansas, Annual Meeting American Association of Petroleum Geologists AAPG, San Antonio, Texas, April 20-23, 2008, Programs with Abstracts. http://www.searchanddiscovery.net/documents/2008/08039annual_abst/abstracts/410251.htm?q=%2Btext%3Acarr

2008 Carr, Timothy R., A National Look at Carbon Capture and Storage - National Carbon Sequestration Database and Geographical Information System (NatCarb), AAPG Eastern Section Meeting, Pittsburgh, Pennsylvania, October 12-14, 2008, Programs with Abstracts, p. 34.

SUMMARY

NatCarb while ending as an externally grant funded project ended, the project continues as a successful venture within the National Energy Technology Laboratory (NETL) of the Department of Energy. The effort will use NETL personnel in cooperation with personnel at West Virginia University and the Kansas Geological Survey of the University of Kansas. The NatCarb effort will continue to leverage natural resource knowledge and enhance the GIS expertise of the Regional Carbon Sequestration Partnerships. The effort will expand coverage to incorporate areas of Mexico and Canada in order cover the bulk of North America. **NatCarb** provides the first steps forward in development of a Carbon Cyberinfrastructure (CCI). **NatCarb** provides the critical information to policymakers, scientists, and engineers in the field of reduction of CO_2 emissions on sources, capture, transport, and storage of CO_2 within a geospatial local to continent-scale framework. A complete CCI must also provide the information to discuss the costs, economic potential, and societal issues of CO_2 capture and storage, including public perception and regulatory aspects. A successful CCI should provide the basis to evaluate the potential of CO_2 capture and storage, and provide strategies to mitigate economic costs and maximize environmental benefits.

A primary goal of the NatCarb effort is to provide the basis to estimate CO_2 storage capacity. Storage capacity can be divided into reserves and resources (Figure 14). Reserves are capacity with a high probability of being used as a geologic storage (GS) site. Resources are capacity for which less information is available; resources may be exploitable, but additional data is needed. NatCarb is focused on resource estimates at the regional and national scales. Potential GS resources include oil and gas reservoirs, coal seams, saline formations, gas shale, and basalt. The first step is a regional theoretical CO_2 storage resource assessment. A theoretical CO_2 storage resource assessment only incorporates limited knowledge of the critical geologic parameters required for GS (e.g., storage volume, injection rates and long-term retention). All that may be known about a theoretical resource is that it has a probability of being available in a region and has adequate depth. Contingent resources represent a second step to reduce site selection risk and increase knowledge at a regional or local scale. Contingent resources indicate a level of knowledge of the GS potential for which plans and budgets can be developed to technically evaluate a specific site (e.g., 3D seismic or exploratory well), but economics, surface considerations, competing uses, and regulatory requirements have not been addressed.

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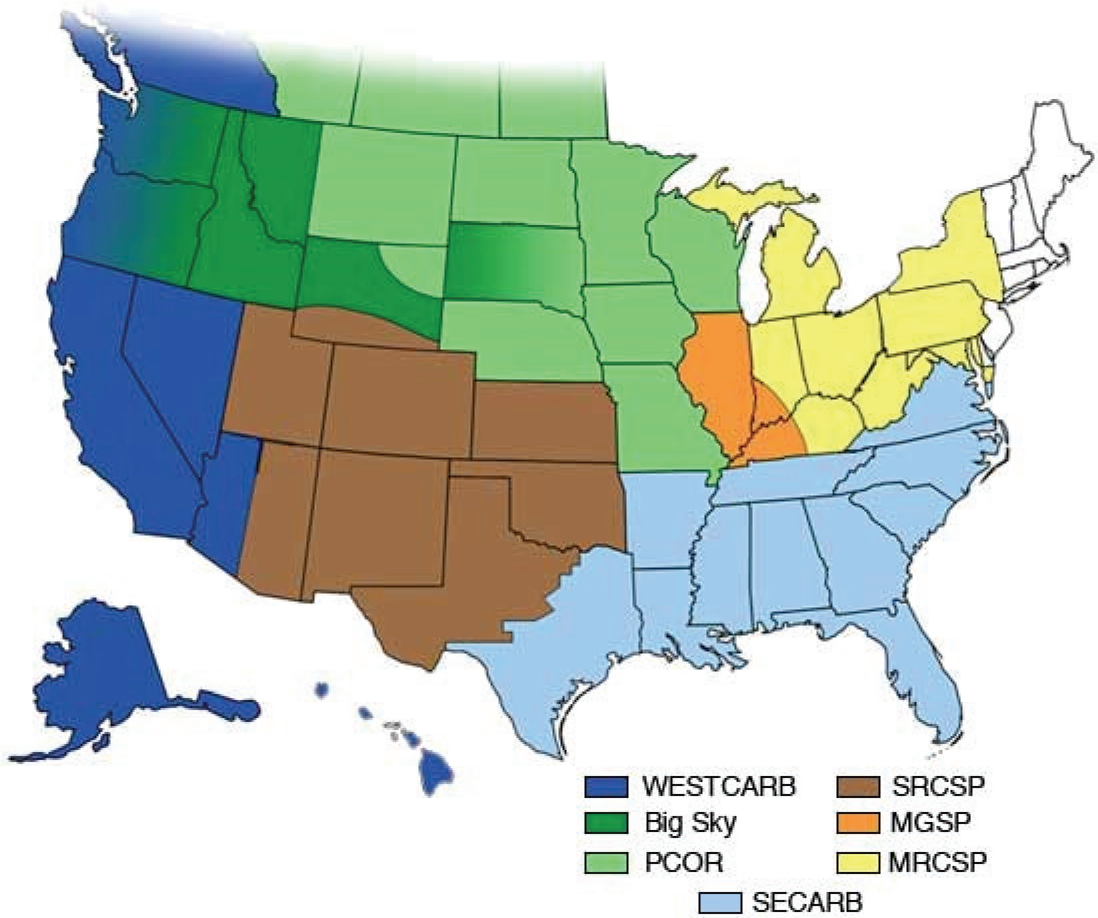

Figure 1 – Map showing the 42 states and four provinces covered by the Regional Carbon Sequestration Partnerships. Map from NETL (2008).

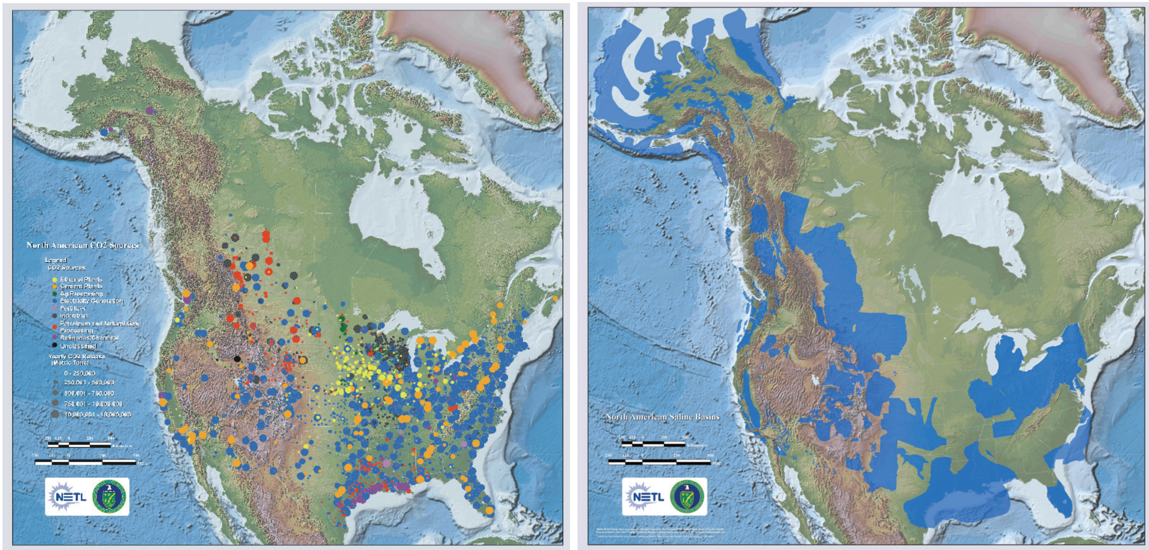

Figure 2 – NatCarb provides display and analysis of CO_2 sources (right) and potential sequestration sites such saline formations (left) from the national to local scale (http://www.natcarb.org). Example shows all the large stationary sources of CO_2 across North America accessible through NatCarb. Figures have backgrounds of digital elevation and physiographic backgrounds from remote publicly accessible servers. Images are available online and as part of the US Department of Energy's *Carbon Sequestration Atlas of the United States and Canada*.

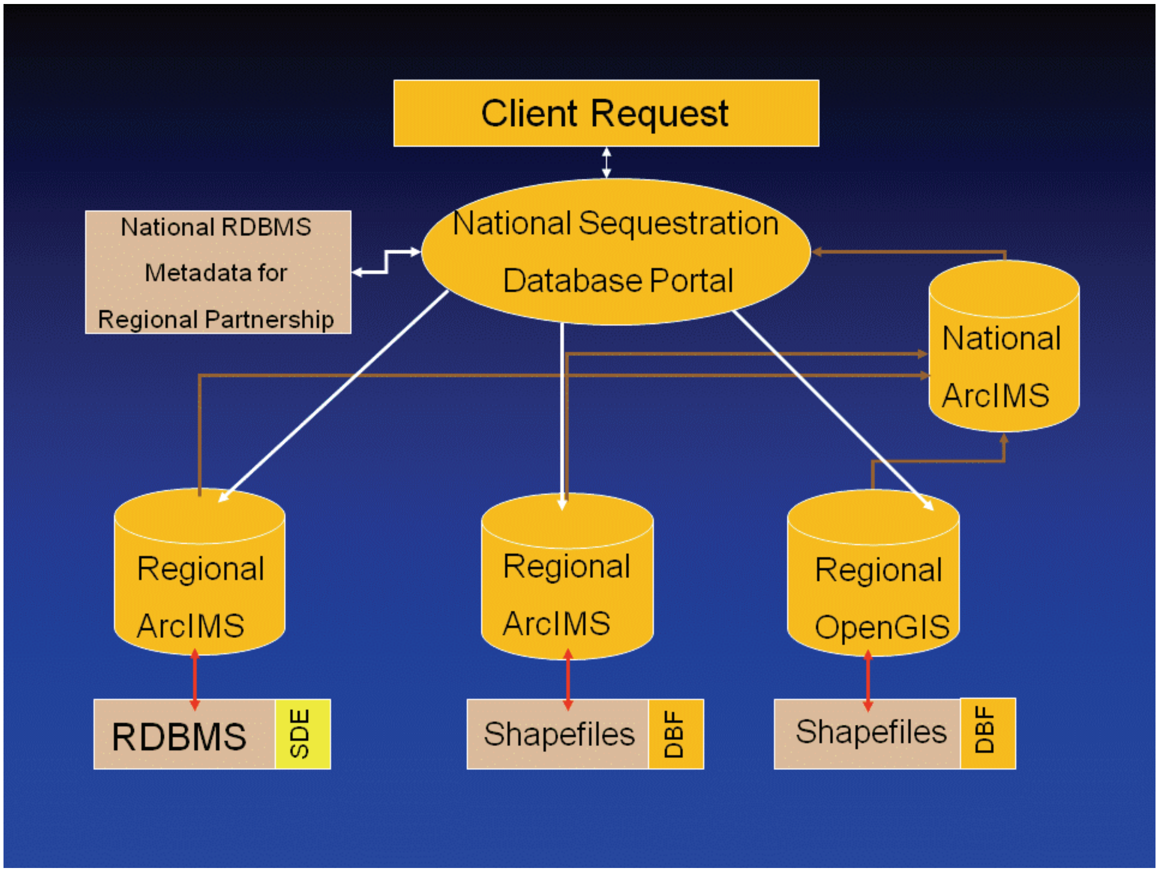

Figure 3 – NatCarb system structure links regional Internet Map Servers (ESRI's ArcIMS and OGC WMS 1.1.x) from the cooperating Carbon Sequestration Partnerships and other publicly accessible servers (e.g. EROS). Processing is undertaken on the regional servers and only the image is returned through the NatCarb portal. Data queries are also processed on regional servers and data is returned using XML.

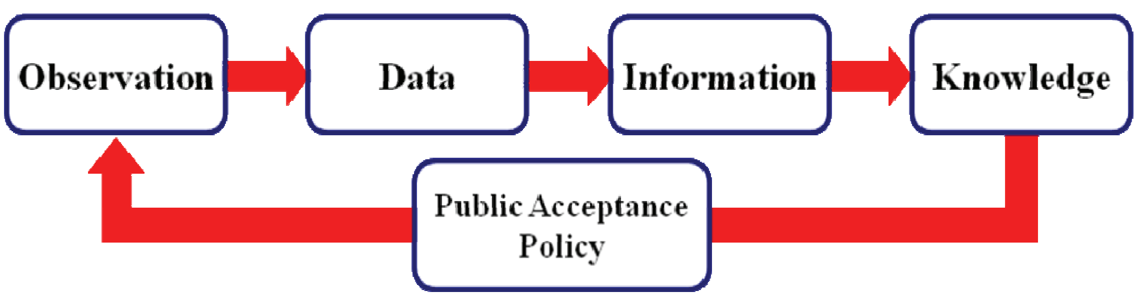

Figure 4 – In the digital era, observations and measurements become digital raw data. Raw data are processed to extract the meaning of raw data that is narrow in scope and it has a simple organization (information). From information, knowledge is derived as an interpretation of information that is broad in scope and it is orderly synthesized. Finally, the knowledge can provide the basis for public policy. One example would be the design of MVA systems for geologic storage of CO_2.

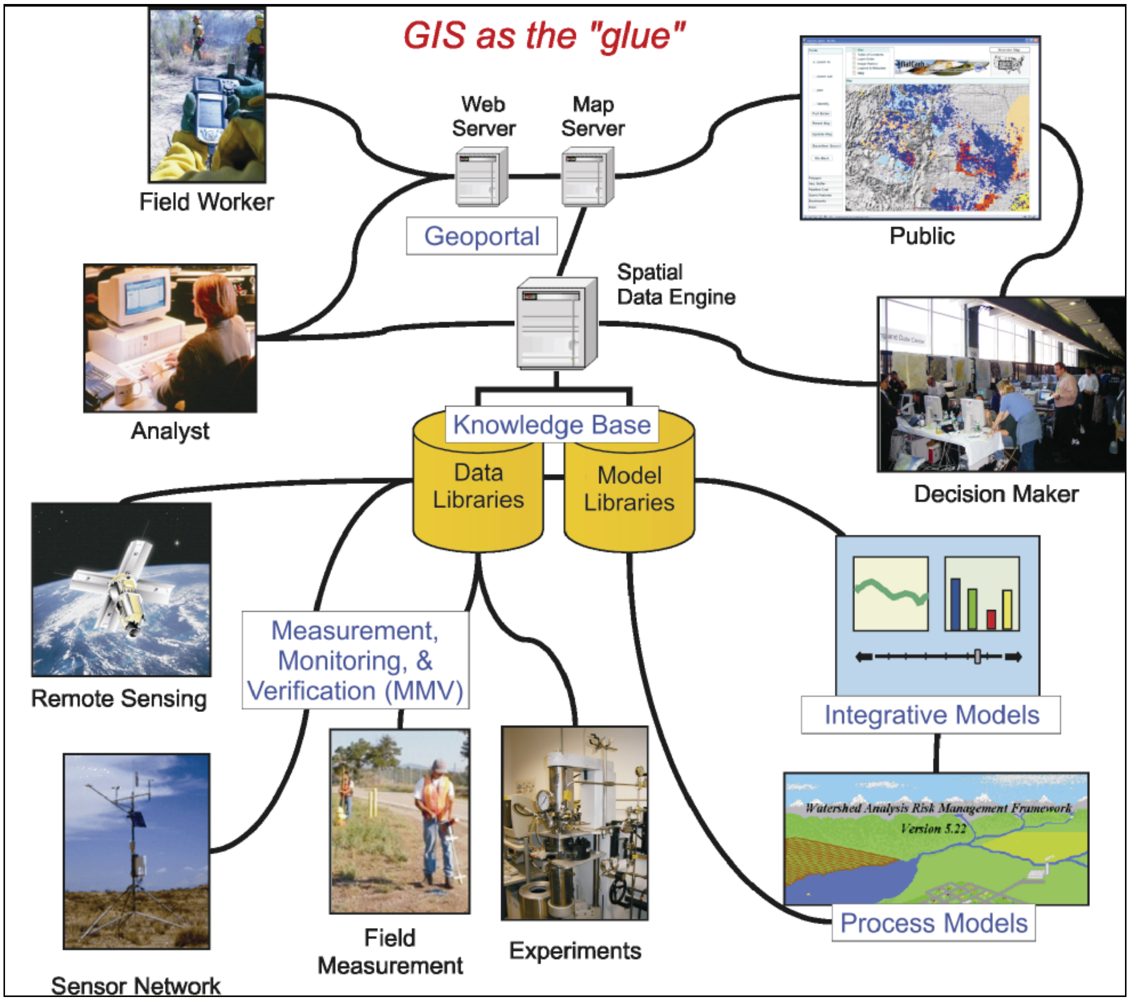

Figure 5 – Conceptual future **NatCarb** as it moves toward a *Carbon Cyberinfrastructure (CCI)* architecture consists of distributed computing solutions that are used to link acquisition of data and models into a distributed Knowledge Base across the partnerships and other publicly accessible servers (e.g., USGS, TerraServer) into a single system where data and models are maintained and enhanced by multiple managers at the local level, but are accessed and assembled through a single Web portal and provided to the decision-makers and the general public.

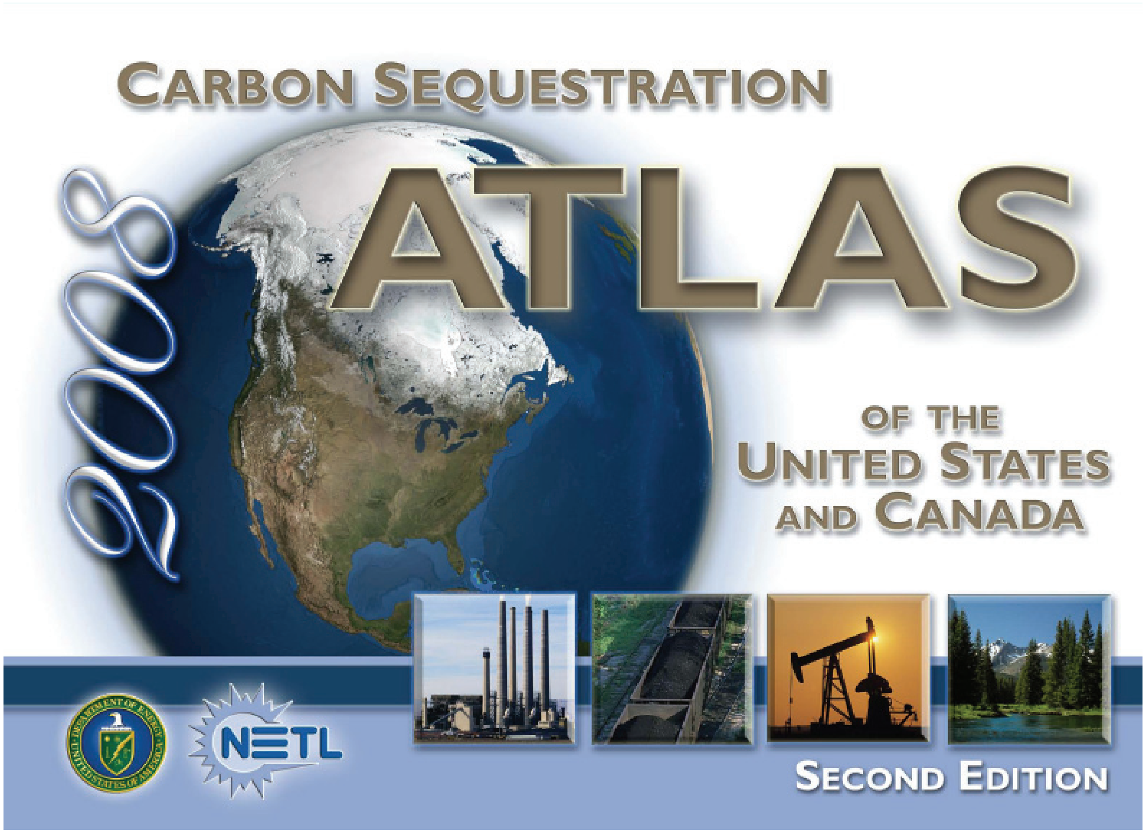

Figure 6 – Data from the NatCarb project and the RCSPs provide basic information on sources and potential geologic storage sites for CO_2 that was used in the construction of the US Department of Energy's *Carbon Sequestration Atlas of the United States and Canada* (NETL, 2008)

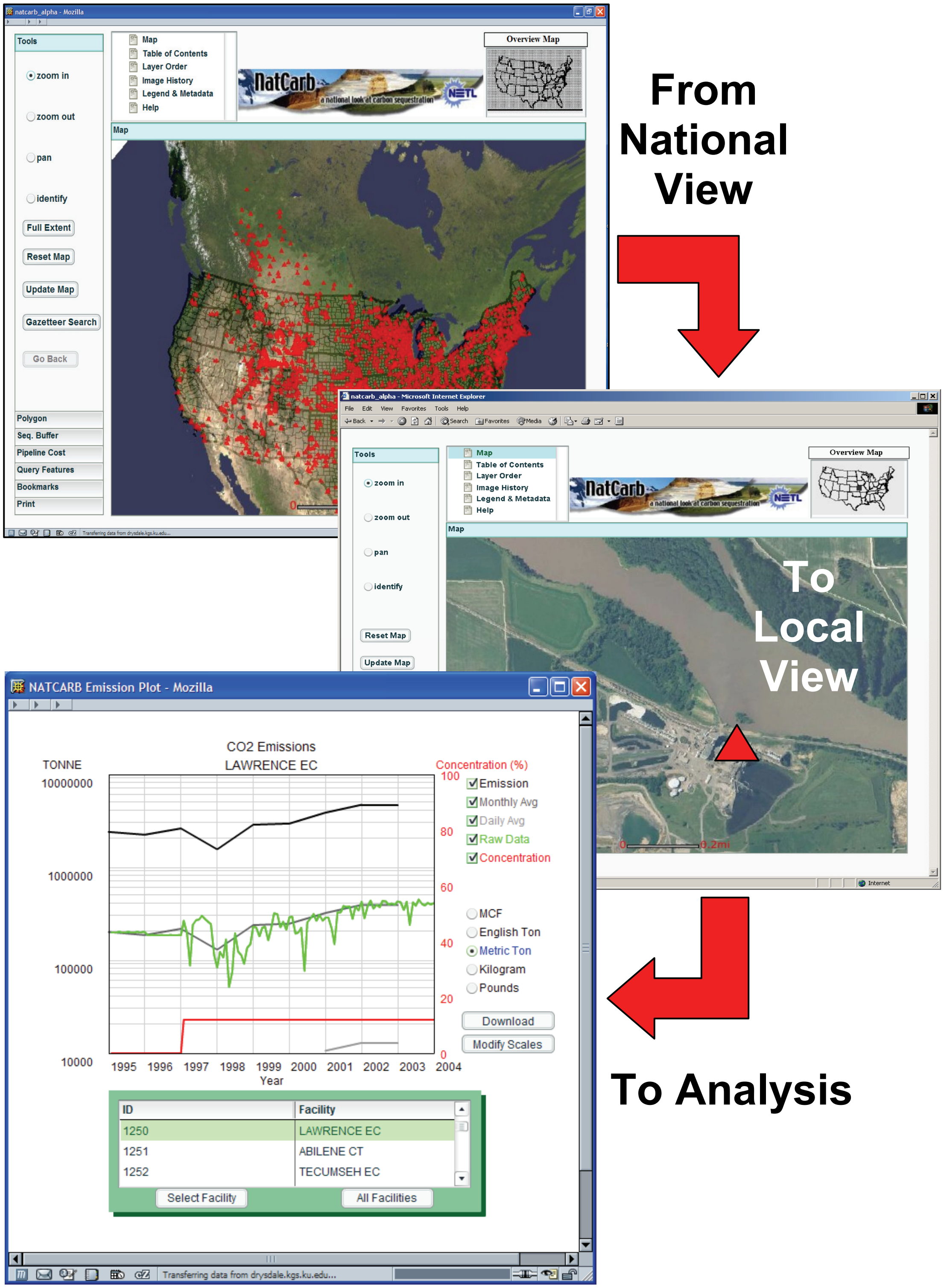

Figure 7 – NatCarb allows display and analysis of CO_2 sources and potential sequestration sites from the national to local scale (http://www.natcarb.org). Example shows all the large stationary sources of CO_2 across North America accessible through **NatCarb** and detailed image and display of CO_2 emissions from a single source.

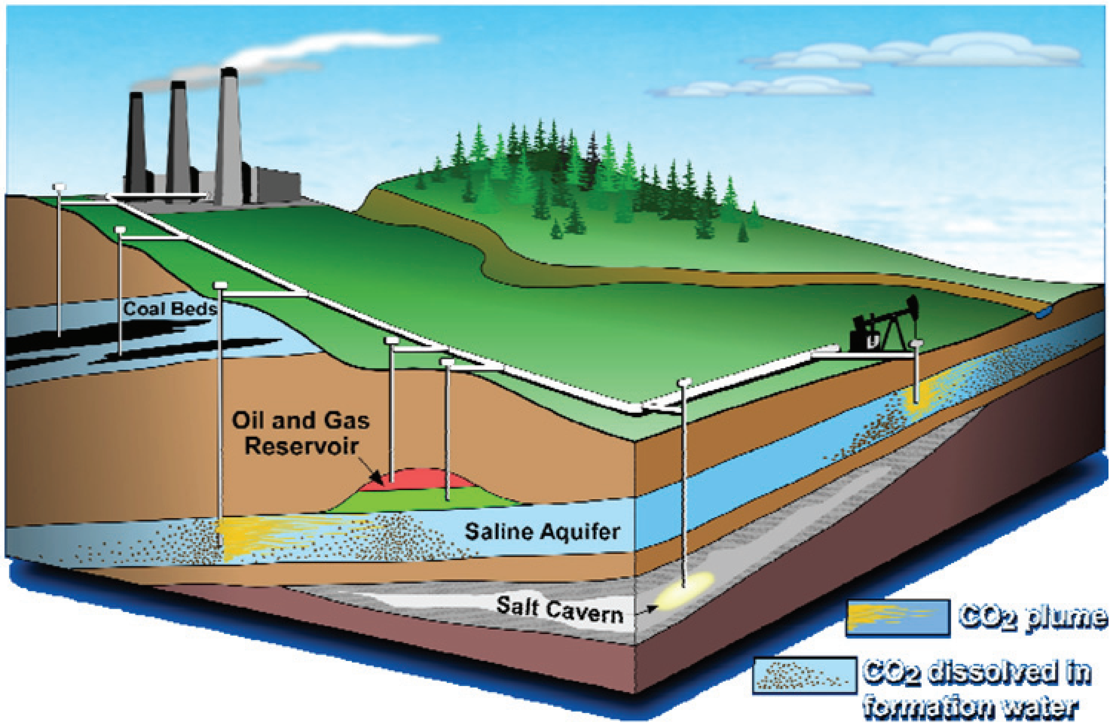

Figure 8 – Illustration of carbon capture and storage (CCS) process showing major pathways for geologic storage and terrestrial storage for emission sources and geologic storage (GS) sites. Image source: (pers. comm., Bachu, 2008).

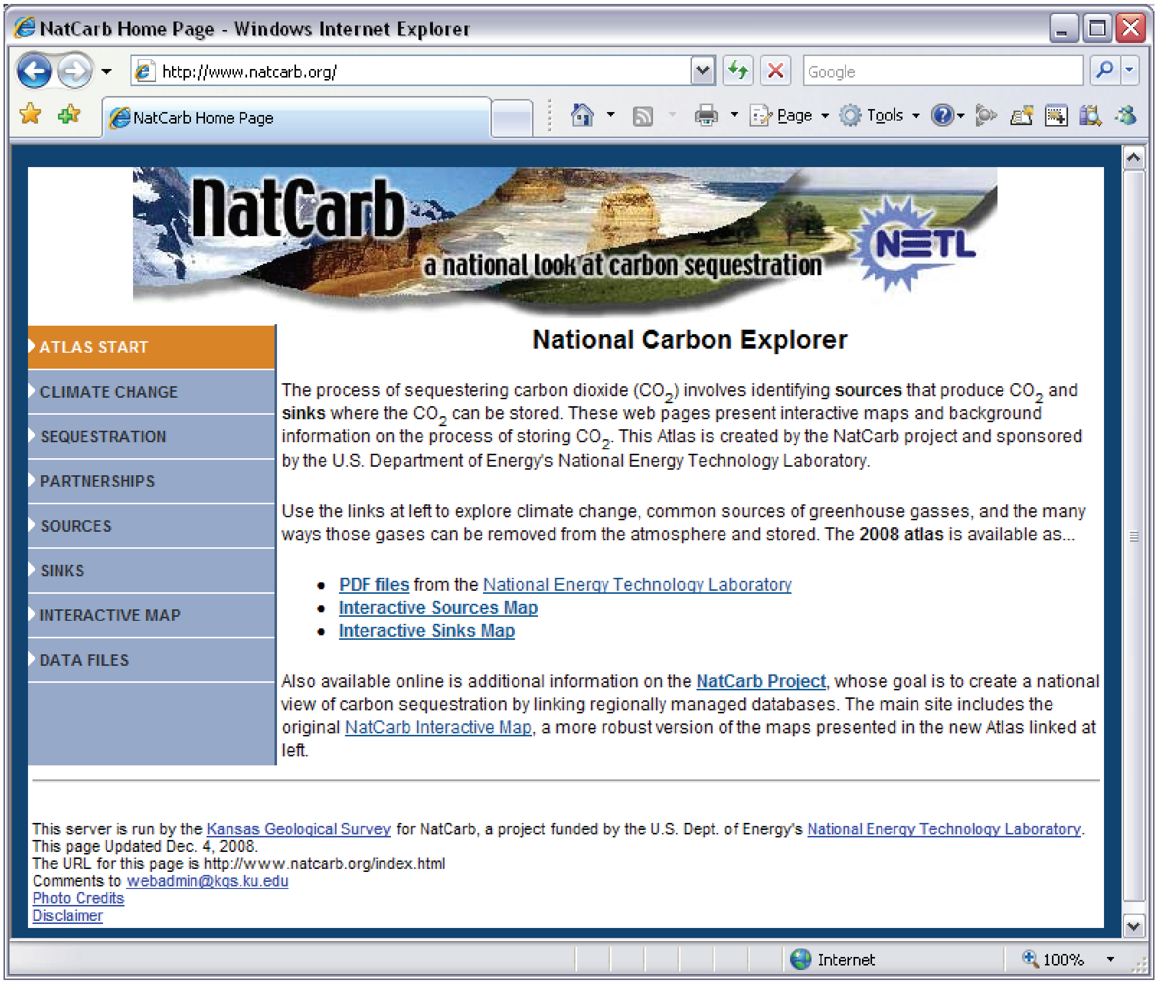

Figure 9 – Web page for **NatCarb**, which provides links to general information, the high-end "NatCarb Interactive Map" intended for the technical user, and to more general maps of CO_2 sources and potential sinks of the **Carbon Explorer** intended for a more general audience.

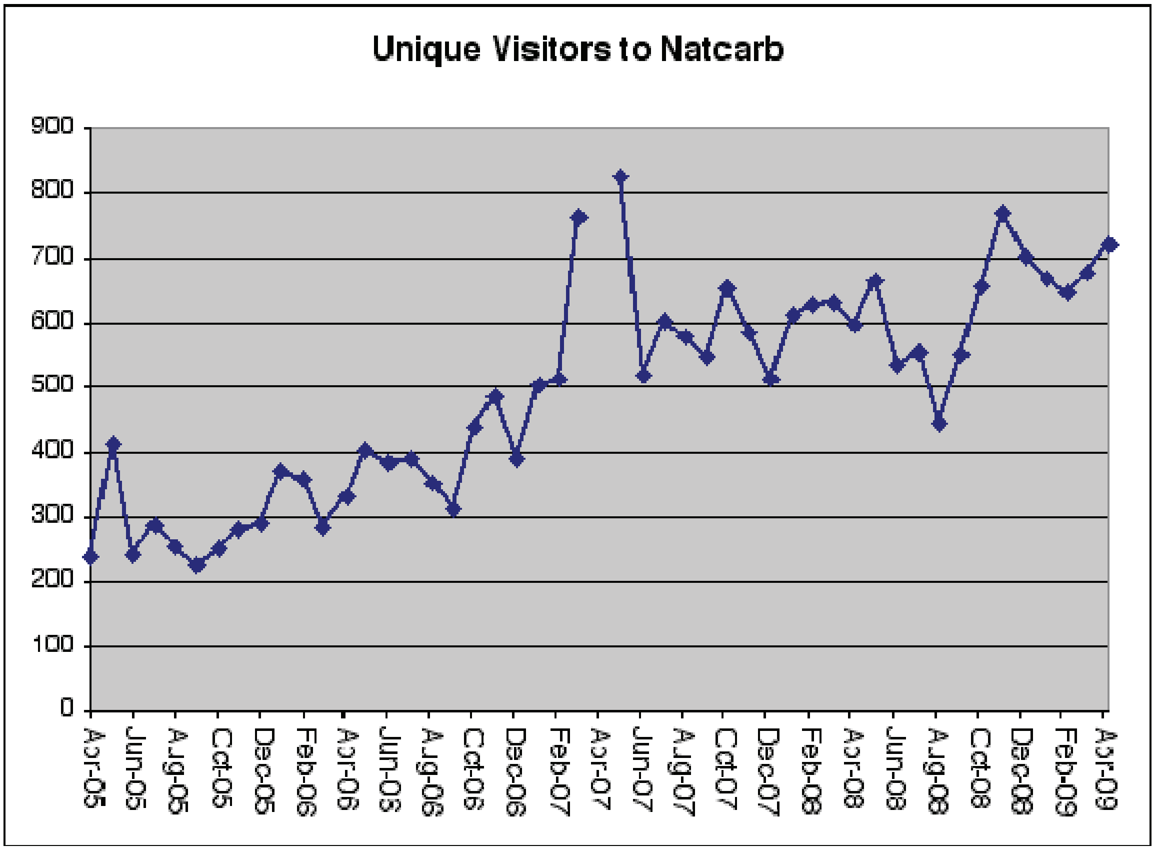

Figure 10 – Monthly number of unique visitors to the NatCarb website. Single visitors visiting multiple times or requesting multiple views are counted only once. This is a very conservative measure of usage.

Figure 11 – NatCarb web page for potential CO_2 geological storage sites providing links to static maps with high-resolution graphics that can be downloaded and printed and to interactive maps that can be customized and queried.

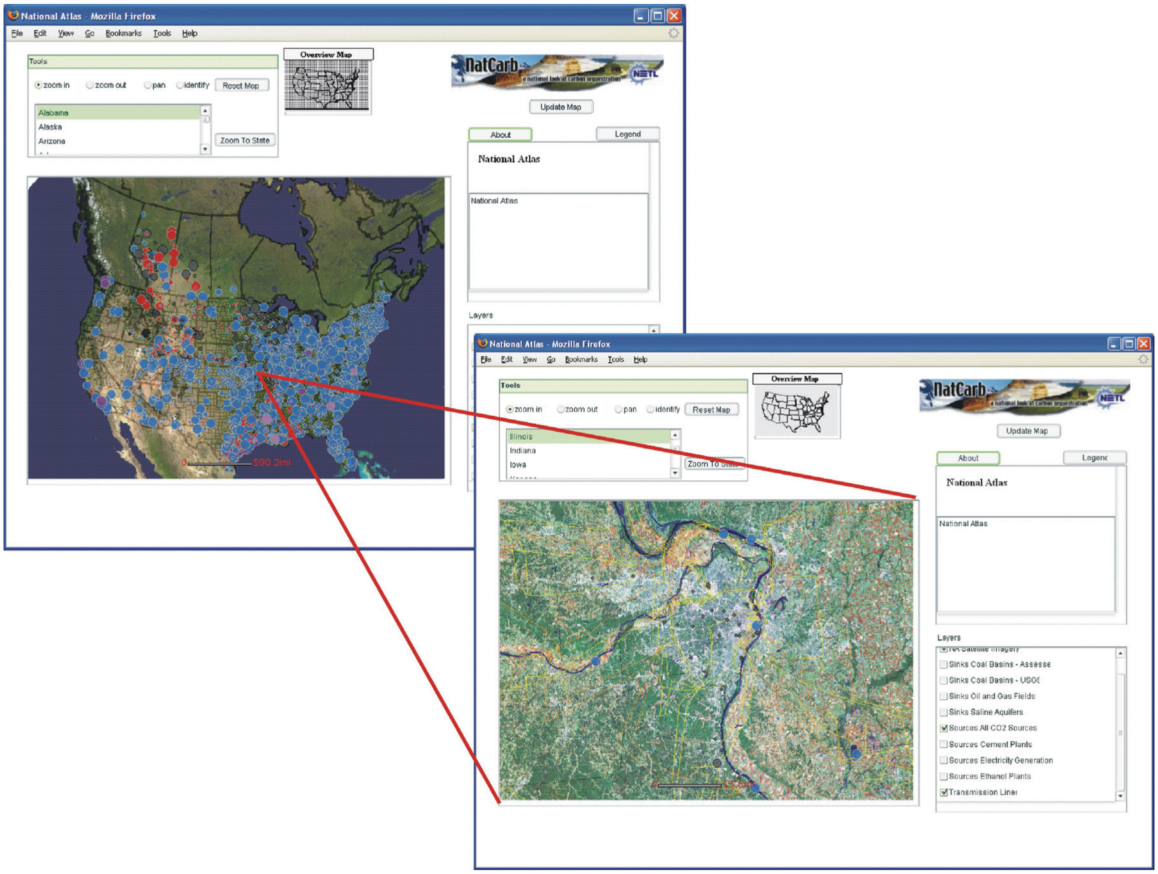

Figure 12 –NatCarb Carbon Explorer (“**NatCarb** lite”) interactive browser showing CO2 sources at the national level and ability to zoom into smaller areas such as St. Louis, Missouri. Also zoomed image is showing digital satellite image and location of major electrical transmission lines.

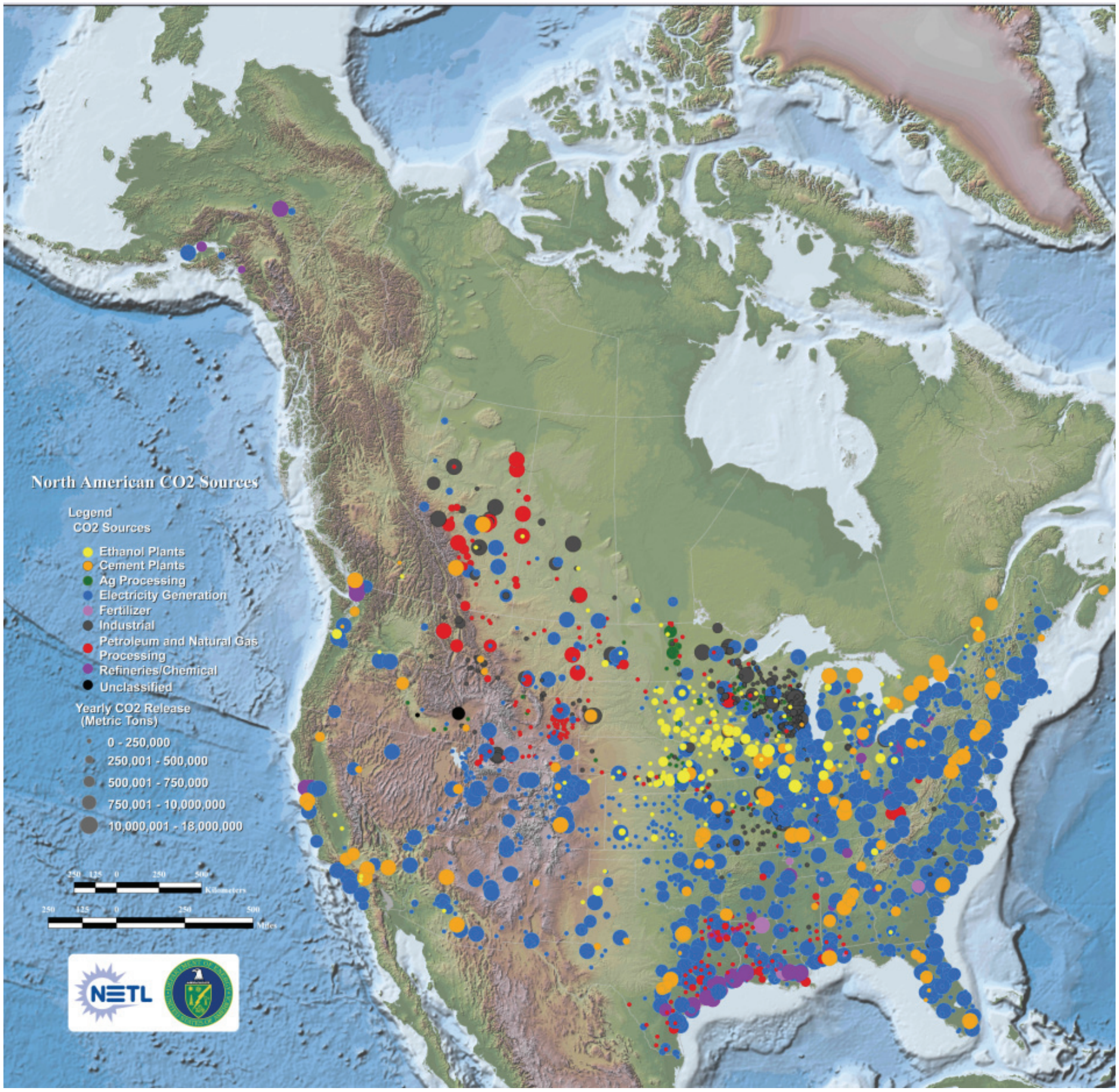

Figure 13 – Example of high resolution graphic static image from the **NatCarb** site showing the distribution of all CO_2 sources identified by the regional partnerships and served through **NatCarb**. Image can be downloaded and printed.

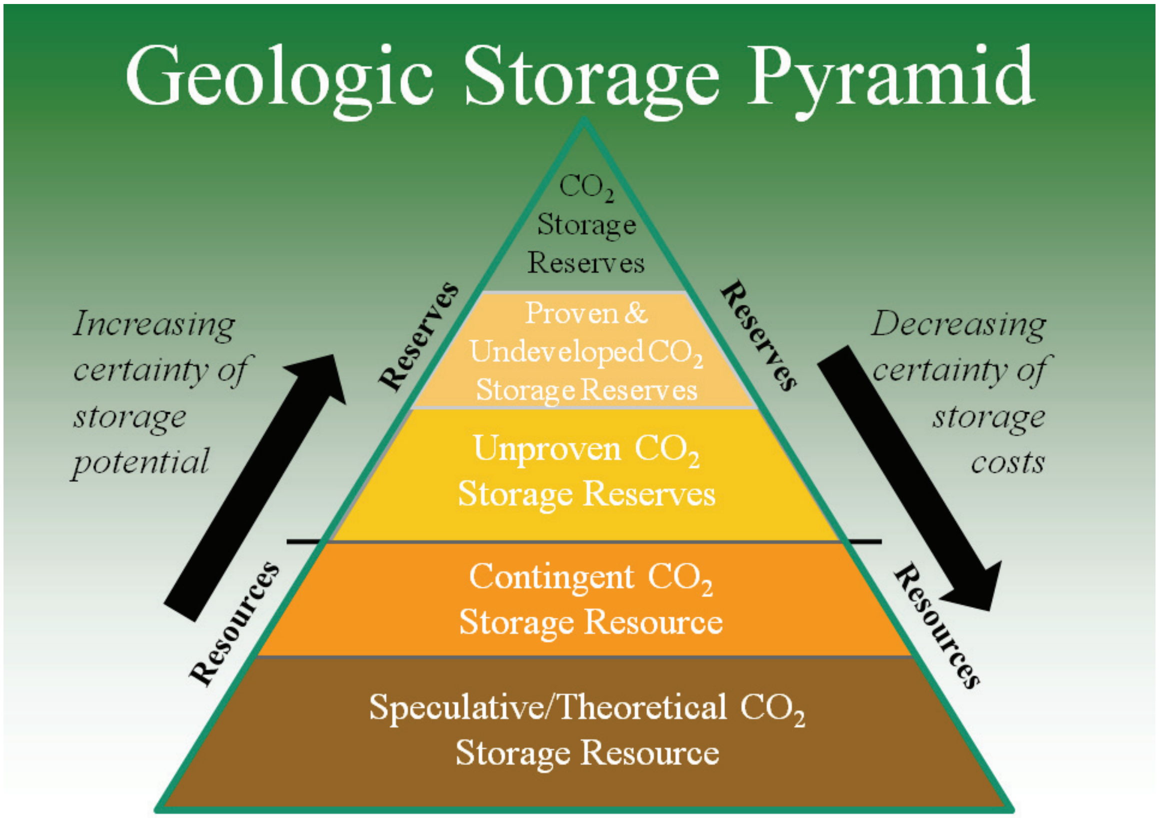

Figure 14 – NatCarb provides the first steps in identifying geologic storage (GS) sites. The process involves moving from the base of the generating geologic storage capacity pyramid (regional assessments of CO_2 storage resource that only account for physical constraints such as volume, temperature and pressure (Theoretical Capacity)) to improved evaluations of the potential and costs of resources and reserves until a point CO_2 storage reserves are proven and developed.

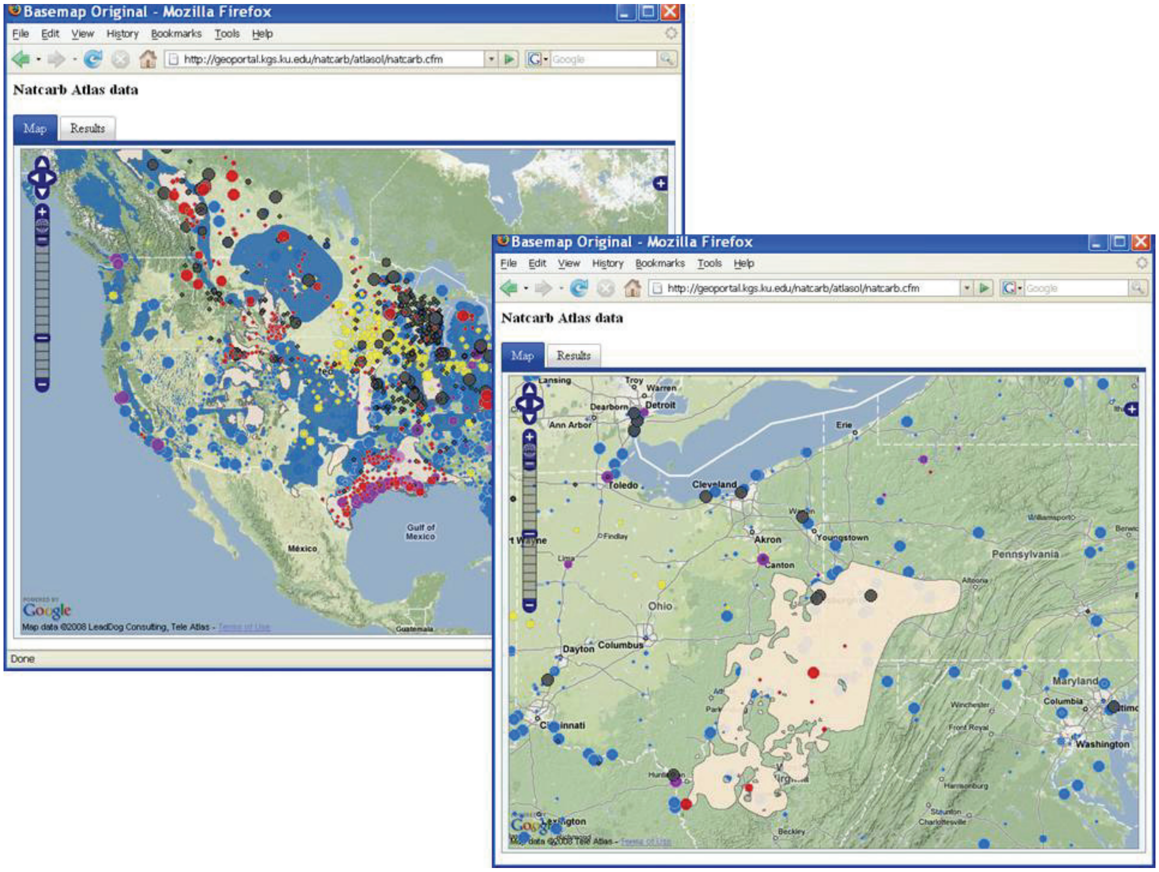

Figure 15 – Example of use of Google Map™ as a user interface to access NatCarb information. User can access information from the national atlas on sources and potential geologic storage locations. Volumetric information can be accessed through the *results* tab (See Figure 13). Site is located at http://geoportal.kgs.ku.edu/natcarb/atlasol/natcarb.cfm.

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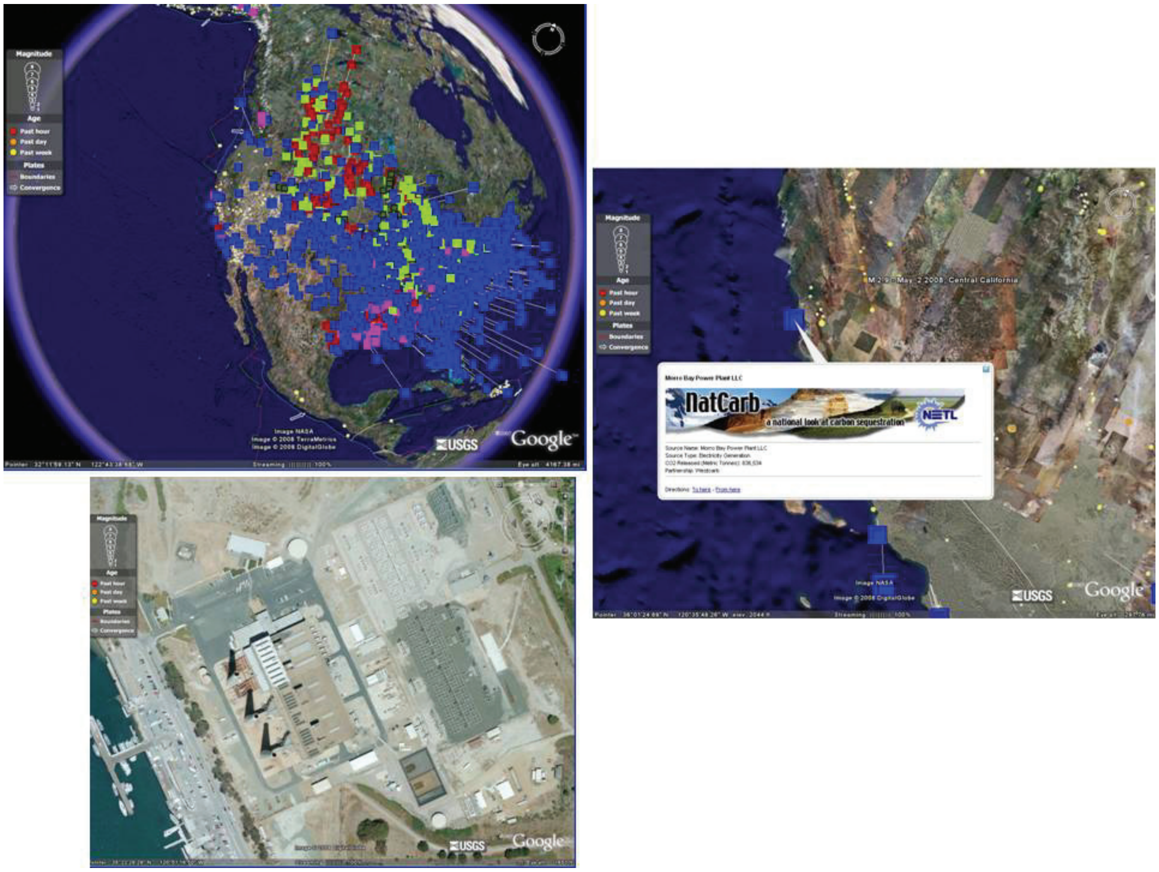

Figure 16 – Example of use of Google Earth™ as a user interface to access NatCarb data for an individual CO_2 source on the California coast. Images are from Google. Earthquake magnitudes are extracted from the USGS display of real-time earthquakes and plate boundaries (http://earthquake.usgs.gov/research/data/google_earth.php). All data is assembled through the interface.

Figure 17 – Prototype example of use of Google Earth™ showing global CCS projects and zooming into a selected project (e.g., AEP Mountaineer Project). All data is assembled through the interface.

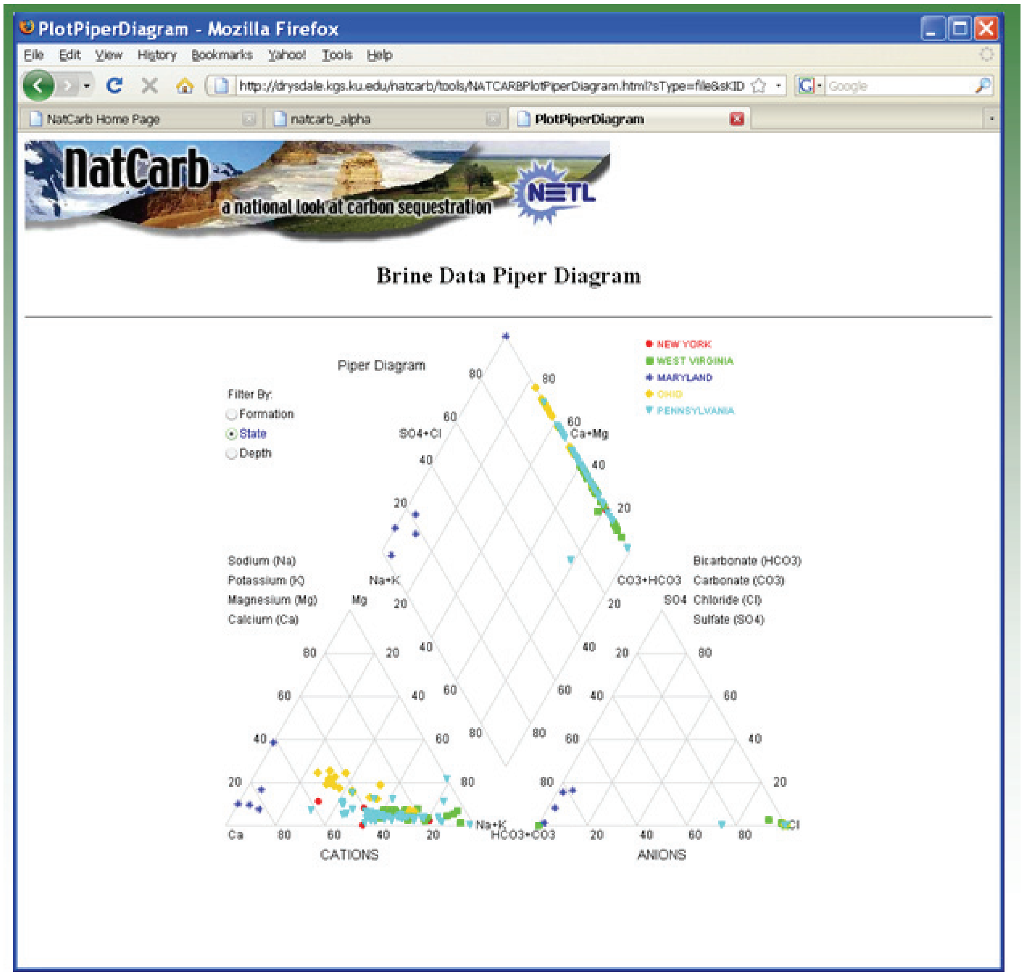

Figure 18 – Example of tools and modeling capabilities developed within the NatCarb geoportal. Example of a "Piper Diagram" tool that was used for query and visualization of the geochemistry of brines in the Oriskany Sandstone saline formation from the Appalachian basin. In this example data is queried by state across multiple depths, data from Ohio has a different Ca/Mg ratio suggesting biogenic processes in the eastern parts of the basin. All data was assembled through NatCarb. Image from Carr and Skeen, 2009.

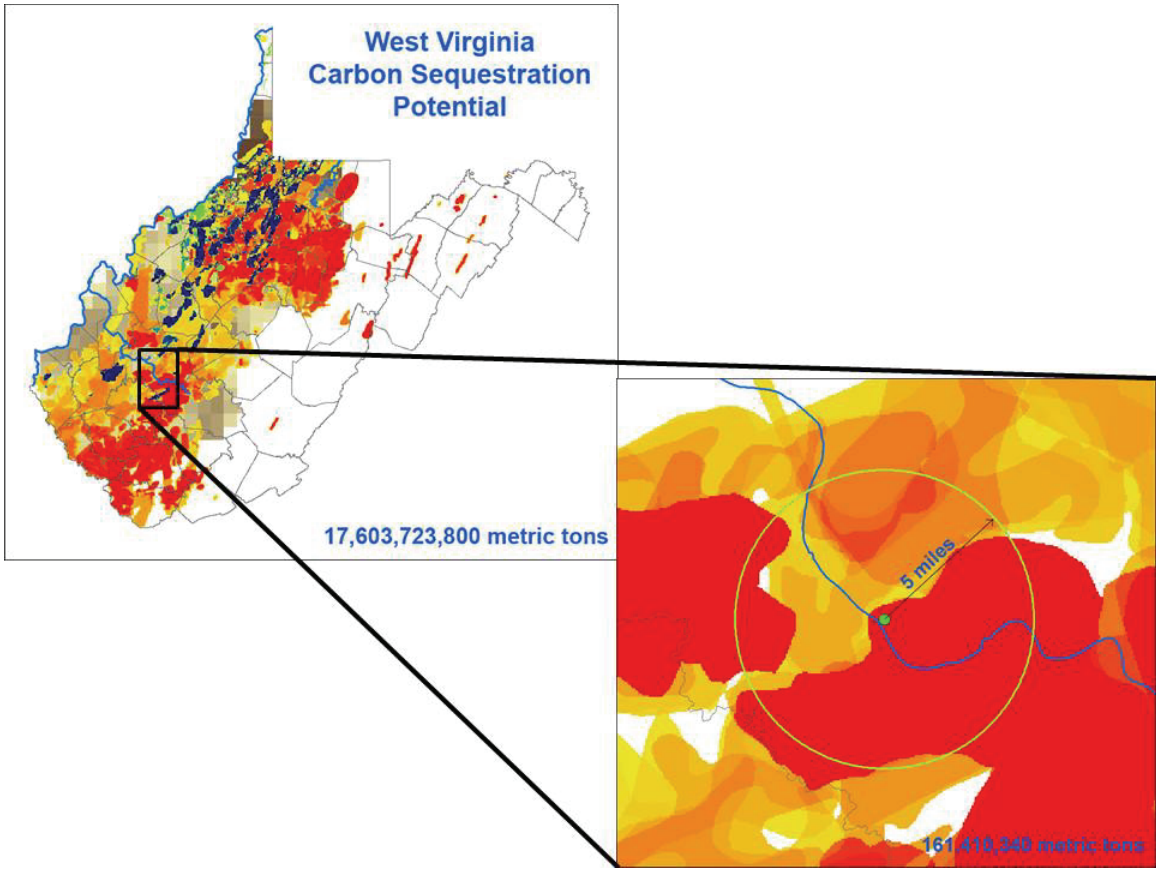

Figure 19 – Example of tools and modeling capabilities being developed within the NatCarb geoportal. An example showing total potential geologic storage volume for West Virginia and the estimated volume within a five mile radius of a selected point that could represent a potential source of CO_2.

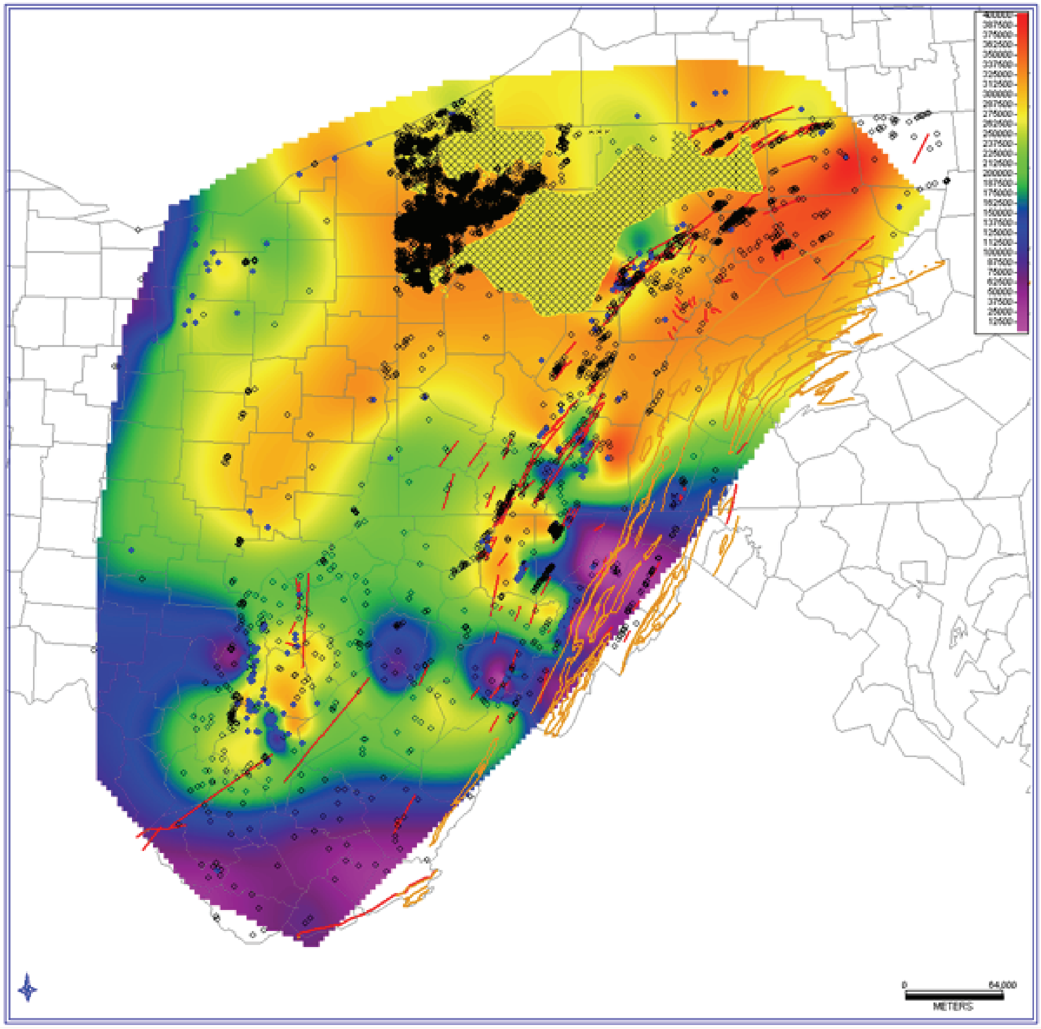

Figure 20 – Custom request generated using NatCarb data from the northern Appalachian basin. Data is categorized by total dissolved solids (TDS). Samples range from less than 10,000 mg/l TDS to over 300,000 mg/l. Formations containing TDS concentrations above 10,000 mg/l are potential sites that merit further evaluation for potential CO2 storage. Data on brine geochemistry can be accessed and summarized with several additional online tools. All data was assembled through NatCarb. Image from Carr and Skeen, 2009.