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The NatCarb Geoportal: Linking Distributed Data from the Carbon Sequestration Regional Partnerships

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ABSTRACT: The Department of Energy (DOE) Carbon Sequestration Regional Partnerships are generating the data for a "carbon atlas" of key geospatial data (carbon sources, potential sinks, etc.) required for rapid implementation of carbon sequestration at a broad scale. The NATIONAL CARBON Sequestration Database and Geographic Information System (NatCarb) provides web-based, nation-wide data access. Distributed computing solutions link partnerships and other publicly accessible repositories of geological, geophysical, natural resource, infrastructure, and environmental data. Data are maintained and enhanced locally, but assembled and accessed through a single geoportal. NatCarb, as a first attempt at a national carbon cyberinfrastructure (NCCI), assembles the data required to address technical and policy challenges of carbon capture and storage. We present a path forward to design and implement a comprehensive and successful NCCI.

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KEYWORDS: Carbon Sequestration, Carbon Sequestration Regional Partnerships, NatCarb Geoportal, Carbon Cyberinfrastructure

A new age has dawned in scientific and engineering research, pushed by continuing progress in computing, information, and communication technology, and pulled by the expanding complexity, scope, and scale of today's challenges. The capacity of this technology has crossed thresholds that now make possible a comprehensive "cyberinfrastructure" on which to build new types of scientific and engineering knowledge environments and organizations and to pursue research in new ways and with increased efficacy.

Although good infrastructure is often taken for granted and noticed only when it stops functioning, it is among the most complex and expensive things that society creates. The newer term cyberinfrastructure refers to infrastructure based upon distributed computer, information and communication technology. If infrastructure is required for an industrial economy, then we could say that cyberinfrastructure is required for a knowledge economy. (Atkins et al. 2003).

Introduction: The Need for Access to Data for Carbon Sequestration

In the face of growing concern 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 have 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 CO₂). Carbon dioxide (CO₂) capture and storage (CCS) is a process consisting of the separation of CO₂ from industrial and energy-related sources, transport to a storage location

and long-term isolation from the atmosphere (IPCC 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.

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 boreholes, 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, 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. In this paper, 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 an integrated 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 design, incor-

porating advances in informatics and geographic information systems (GIS), is essential for a national approach to carbon sequestration science and technology efforts.

We examine the concept of a national carbon cyberinfrastructure (NCCI) to provide access to the data and associated tools required for large-scale carbon capture and sequestration. First, we provide a brief background summary concerning the Department of Energy (DOE) Carbon Sequestration Regional Partnerships (NETL 2006) and the NATIONAL CARBOn Sequestration Database and Geographic Information System (NatCarb) geoportals. Next, we present a vision for an NCCI, with the goal of providing an integrated computing environment that provides access to carbon science information, models, problem solving capabilities, and communication. Then, we assess the strengths and weaknesses of the current technical design of the NatCarb geoportals in the context of our vision for carbon cyberinfrastructure. And finally we discuss the path forward toward a NCCI, with consideration of a decentralized (Jeffersonian) versus a centralized (Hamiltonian) design, and with consideration of practical steps needed for implementation.

Background: DOE Program for Carbon Capture and Sequestration

Carbon Sequestration Regional Partnerships:

If it is determined that carbon capture and storage is to be implemented on a broad scale, it will take a concerted effort of government agencies and research organizations working in cooperation with the private sector, to put into place both the process and the necessary infrastructure to achieve meaningful greenhouse gas reductions. To ensure climate change mitigation is an option, a national network of seven public-private sector partnerships was established by the DOE (Figure 1) (NETL 2006). The Carbon Sequestration Partnerships are developing the framework needed to validate and potentially deploy carbon sequestration technologies. The partnerships are charged with determining the most suitable technologies, regulations, and infrastructure needs for carbon capture, storage and sequestration in different areas of the country. Together, the partnerships include more than 240 organizations spanning 40 states, three Indian nations, and four Canadian provinces. One goal of the Partnerships is to assemble the data covering each region concerning potential storage volumes for carbon sequestration and to provide the infrastructure to monitor and verify ongoing demonstration projects.

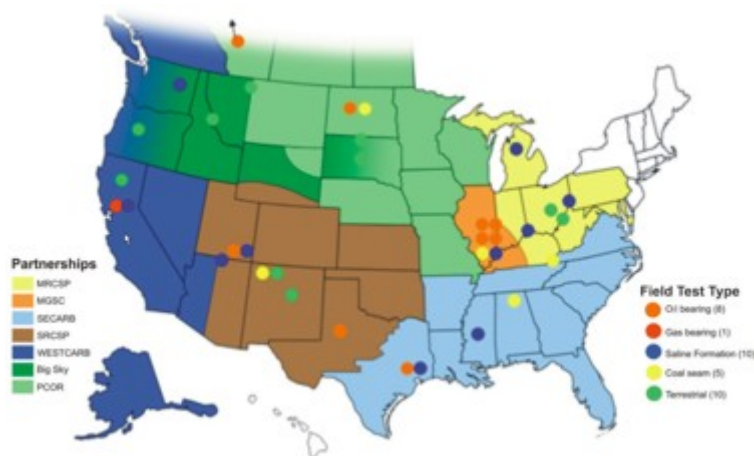


Figure 1. Map showing the areas covered by the Regional Carbon Sequestration Partnerships and proposed field tests that will be undertaken to determine the best approaches for capture, storage and sequestration of greenhouse gases such as CO₂. Map from NETL (2006).

NATional CARBon Sequestration Database and Geographic Information System (NAT-CARB): NatCarb provides a geoportal for web-based access to geospatial data of DOE's Regional Carbon Sequestration Partnerships. The partnerships have accumulated a wealth of geographic and geological data and information relevant to sequestration efforts. Regional Carbon Sequestration Partnerships create and maintain the carbon sequestration databases for matching CO₂ 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 convenient location (<http://www.natcarb.org>). This geoportal provides access to national da-

tabases and GIS layers maintained by the Nat-Carb group (e.g., brine geochemistry) and publicly accessible database and GIS servers (e.g., USGS, and Geography Network) into a single system where data is maintained and enhanced at the local level but is accessed and assembled through a single Web portal to facilitate query, assembly, analysis and display (Figure 2). NatCarb improves the flow of data across servers and increases the amount and quality of available digital data. Thus, the NatCarb project is a functional demonstration of distributed management of data systems that cross the boundaries between institutions and geographic areas and forms the first step toward a functioning NCCI.

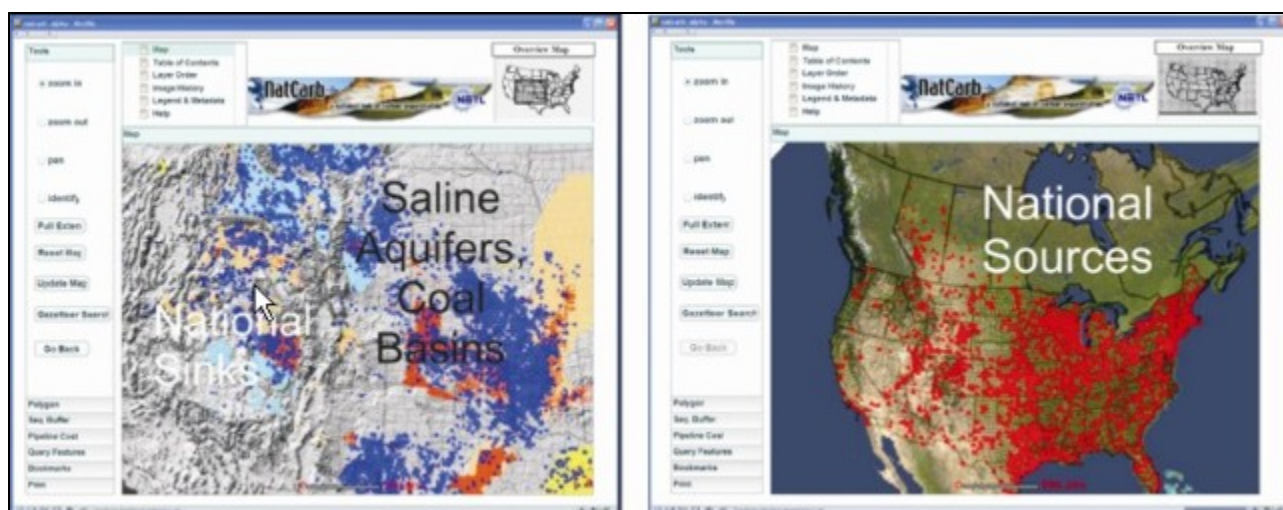


Figure 2. NatCarb provides display and analysis of CO₂ sources (right) and potential sequestration sites (left) from the national to local scale (<http://www.natcarb.org>). Example shows all the large stationary sources of CO₂ across North America accessible through NatCarb and detailed image of potential CO₂ sequestration opportunities in saline formations and coal basins across the Mid-continent United States. Figures have backgrounds of digital elevation and physiographic backgrounds from remote publicly accessible servers.

Current Technical Design of NatCarb: NatCarb provides an Internet portal that brings together data from each region of the Carbon Sequestration Partnerships in a single convenient location. The portal is updated regularly by region, and is available to the general public through a single website (<http://www.natcarb.org/>). The architecture of

the NatCarb system requests an image of the data from the remote servers of the Partnerships. The Natcarb system is built to work with ESRI ArcIMS services and Open Geospatial Consortium (OGC) WMS services. 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. 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 by moving to the new architecture. NatCarb has built a metadata repository of connection and layer information for each partner. 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.

The NatCarb site has grown to serve a large number of data layers (>125), presentation and integration within the NatCarb viewer has become cluttered and overwhelming to the user. The graphical user interface (GUI) and the database and mapping requests component were redesigned so that layers could be grouped and displayed in a more organized fashion, and allow a simplified and more

flexible design to be presented to the online user. The new portal is built as two distinct components—the viewer, which is a graphical user interface (GUI), and the database and mapping requests component. The client GUI was built with Macromedia's Flash. Flash allows integration of text and graphics in a compact interface, and has the advantage of being self-contained inside the browser. This means that it does not matter which browser a client uses, only that they are using the current version of Flash (Macromedia reports that 97% of Internet-enabled desktops worldwide contain Flash). The Flash 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 Flash viewer communicates to a series of Macromedia ColdFusion MX (CFMX) backend pages that handle the viewer-database-IMS interaction. The CFMX pages dynamically build XML requests based on Flash parameters and the metadata database. These XML 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 Flash client.

Our approach within NatCarb has been to assist the Regional Carbon Sequestration Partnerships to create and maintain carbon sequestration websites for matching CO₂ sources with nearby sinks—geologic and terrestrial sequestration sites—in the United States and Canada. In addition, 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.

In NatCarb, work on developing display tools and primitive modelling 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 4A). Large

amounts of data can be visualized with online tools using standard geochemical plots (e.g., Piper, Collins and Stiff diagrams). An early attempt at a simple model in NatCarb locates the least-cost path between any two points and generates a range of cost estimates for CO₂ pipeline transport (Zhang et al. 2006) (Figure 4B).

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 CO₂. At the present time, NatCarb is neither comprehensive nor sufficient in coverage and structure to adequately address carbon capture and storage at a continent-scale level.

NatCarb is the latest version of an attempt to construct an NCCI. Initial versions used direct server-to-server query of remote databases and a single application server. The new NatCarb system architecture no longer communicates actual data, but an image of the data from the remote servers. This significantly

reduces the quantity of data transmitted between servers as well as the amount of processing required at the NatCarb portal. This has increased system performance, stability and security. The heterogeneous nature of the data across the North American continent and the independence of the Regional Carbon Sequestration Partnerships have resulted in geographic variations in the data layers. This is both a strength and weakness of the initial effort at construction of a NCCI. Strength in that different creative ideas and regional variations in carbon sources and sinks have resulted in widely different approaches. Weakness in that a consistent and reliable resource assessment of North American sequestration potential at the basin scale remains elusive. This continent-scale weakness is now being addressed through improved coordination across the partnerships and building consensus on the “best” approach to building a continent view, while maintaining regional “best” approaches.

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 is being approached by developing customized NatCarb portals that attempt to address the more needs of different user communities. All portals will use the same underlying data, but provide more community focused views of carbon sequestration challenges and opportunities.

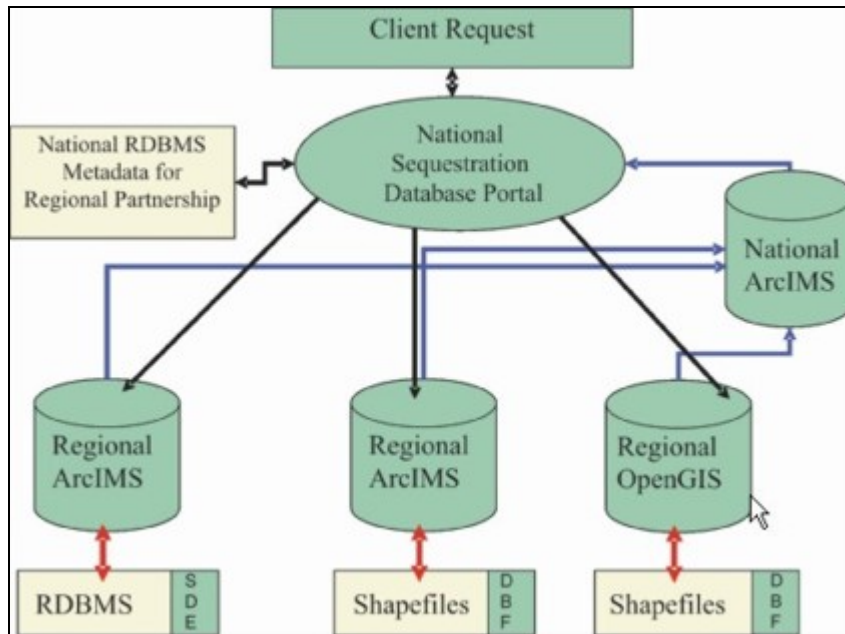


Figure 3. NatCarb system structure links regional Internet Map Servers (ESRI’s ArcIMS and OGC WMS 1.1.x) from the cooperating Carbon Sequestration Partnerships and other publicly accessible servers (e.g. EROS). Processing is undertaken on the regional servers and only the image is returned NatCarb portal.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

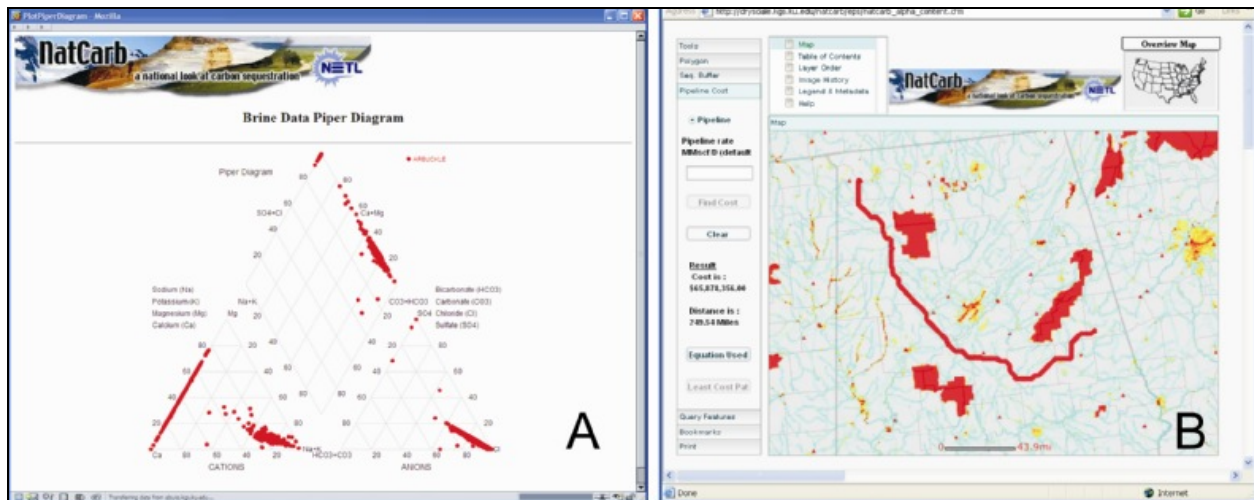


Figure 4. Examples of tools and modelling capabilities being developed within the NatCarb geoportal. A) Example of a Piper Diagram tool for query and visualization of the geochemistry of brines in saline formations. In this example data is queried by formation across multiple states. B) Example of the pipeline model to select a route that minimizes cost base on digital elevation changes, river crossings and land use (e.g., urban areas and parks).

A Vision for National Carbon Cyberinfrastructure (NCCI)

Formulating the Vision: *Carbon Cyberinfrastructure* refers to an integrated online computing environment that provides access to carbon science information, models, problem solving capabilities, and communication. 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 visualization with 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.

Our vision for an NCCI 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 4). Geological sequestration data, focused on the assessment of large-scale geological sequestration, data 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 5). Data are linked with online analysis, visualization, and modeling tools to form a *Knowledge Base*. All information are ac-

cessed and assembled through a single Web portal and provided to the decision-makers and the general public. In order to successfully design a successful NCCI, we must provide on-going reliable access to a comprehensive set of data libraries, model simulations, and associated tools.

Evaluating the Success of Carbon Cyberinfrastructure: A successful NCCI 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 CO₂, with a sustainable design that links all NCCI elements (Table 1). 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 CO₂ transport. In addition to their scientific and technical utility, the information, simulations, and tools within a the NCCI 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 acquisi-

tion, processing, formatting, quality assurance, and preparation of metadata.

In order to construct the NCCI, management of key carbon sequestration data libraries, modelling 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 (Figure 5, Table 1). 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 update. Maintenance of data and

modelling library catalogues, 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 NCCI will require vision, technical leadership, management leadership and fiscal authority (Table 1). Technical and management leadership to ensure that regional and national levels work together is critical. Effort is required to provide management to ensure NCCI operates smoothly and achieves its goals. Fiscal sustainability of the NCCI, with allocation of funding for operation, update, and maintenance at all levels of organization should be considered a high priority.

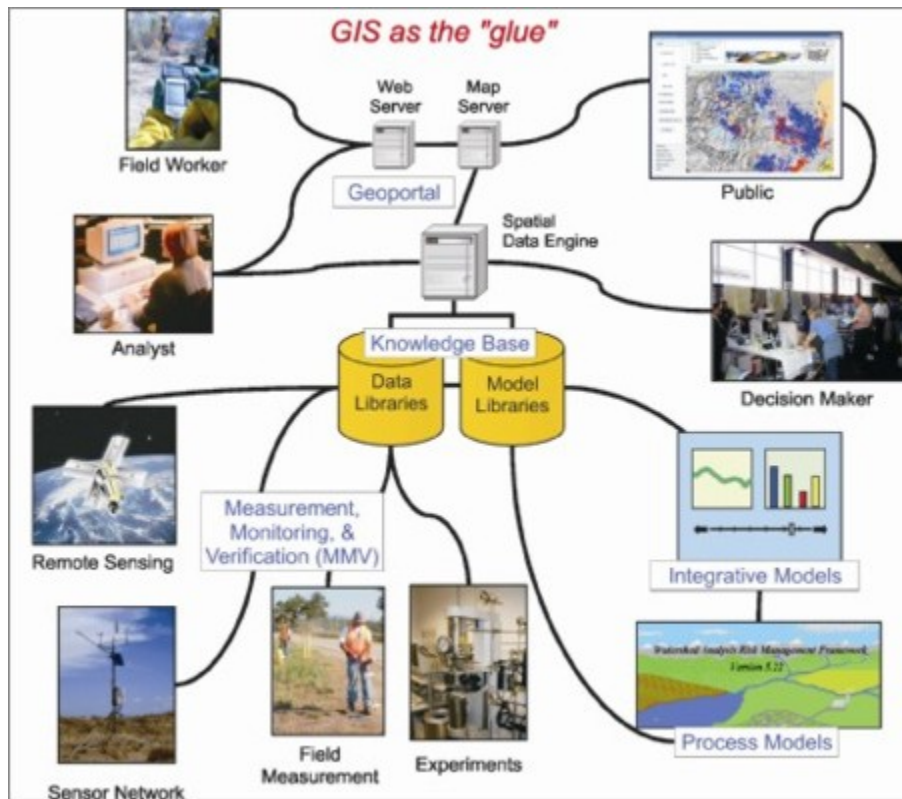


Figure 5. Conceptual *National Carbon Cyberinfrastructure (NCCI)* architecture consists of distributed computing solutions that are used to link acquisition of data and models into a distributed Knowledge Base across the partnerships and other publicly accessible servers (e.g., USGS, TerraServer) into 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.

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Table 1. Elements of the National Carbon Cyberinfrastructure (NCCI).

Element	Description	Processes
1) Carbon Sequestration Data Collection	Acquisition of data (geospatial and tabular) and other resources (graphics, documents, etc.) to place in National Carbon Sequestration <i>Knowledge Base</i> ; Data collected and managed by distributed and national data providers.	Data acquisition, processing, formatting, quality assurance, metadata preparation, and delivery to regional or national <i>Knowledge Base</i> data manager; update and correction; coordination with other data providers and managers; response to feedback from data managers and users.
2) Carbon Sequestration Modelling	Development of simulation and model components (models, model parameters, model metadata etc.) to place in National Carbon Sequestration <i>Knowledge Base</i> ; performed and managed by distributed modellers.	Model development, processing/formatting, quality assurance, metadata preparation, and delivery to regional or national <i>Knowledge Base</i> data manager; update and correction; coordination with other modellers and data managers; response to feedback from data managers and data users.
3) Carbon Sequestration Information Services	Provision of tools and services (web-based and stand-alone) for geospatial and tabular data discovery (search of metadata catalogues), access (download), visualization (mapping and other graphic views), and analysis; managed by geoportal managers.	Tool/service and documentation, acquisition, backup, and update; coordination with tool providers, other geoportal managers, and tool users; communication of feedback to tool providers.
4) National Carbon Sequestration <i>Knowledge Base</i>	Management of key carbon sequestration data libraries, modelling libraries, and other resources (graphics, documents, etc.) contained in the National Carbon Atlas; managed by distributed state/regional data managers in conjunction with national geoportal manager.	Data and metadata receipt from distributed data providers; data and metadata archiving, backup, and update; data and metadata delivery via the National Carbon Atlas Geoportal; maintenance of data and simulation library catalogue, including data and metadata status; coordination with data providers, other data managers, and geoportal managers; communication of feedback to data providers.
5) National Carbon Atlas Geoportals	Provision of interactive, web-based geoportals to access national, state or regional carbon atlases (<i>Knowledge Base</i> and Information Services); managed by national/state/regional geoportal managers.	Serve geospatial and tabular data using map services (e.g., ArcIMS) in conjunction with enterprise databases (e.g, Oracle) and spatial data engine (e.g., SDE); provide web interface to access data, metadata, models, tools, services, and other resources; coordination and communication of feedback with national/state/regional data managers.
6) NCCI Leadership & Management and Coordination	Provision of vision, technical leadership, management leadership and authority. Management to ensure NCCI operates smoothly and meets goals. Fiscal sustainability of the NCCI, with allocation of funding for operation, update, and maintenance at all levels of organization.	Establish key technical and management leadership and ensure the regional and national levels work together. Formulate policies and standards concerning data management, content/format, documentation, security, and accessibility; formulate and update detailed procedures as needed. Develop and implement business plan and procure long-term funding commitment. Ensure coordination and communication between all NCCI elements.

Realization of a National Carbon Cyberinfrastructure

Decentralized (Jeffersonian) Versus Centralized (Hamiltonian) Design: The construction of a successful NCCI is a classic struggle to create a complex product or system using the strengths of both decentralized and centralized approaches, while attempting to minimize their disadvantages. A decentralized approach maintains data responsibility near its source, ensuring deep coverage, avoids redundancy and overlap, and insures uniform quality assurance/quality control (QA/QC) within the region. However, centralized approach can ensure broad data coverage, avoid missing data and gaps between regions, and ensure uniform QA/QC across the continent. The weaknesses of each approach are the converse in that a continent-scale resource assessment of CO₂ sequestration is not possible under the decentralized approach and one could not evaluate a specific small-scale region with a centralized cyberinfrastructure. There are limits to this dichotomy and NatCarb is attempting to strike a balance among centralized and decentralized elements. The question is what elements to centralize (e.g., policies, standards, protocols) versus what not to standardize (e.g., opportunities for innovation in data type and format, model development, and management of data by those who know it best). What we seek is the ability for geoportal users to access data, model simulations, and information services in seamless manner, while at the same time have distributed or decentralized management of regional data close to the data sources.

Path forward: The following summarizes critical elements of a conceptual path forward to development of a successful and robust NCCI:

- Construct the framework for periodic update of a **NCCI Plan**, including goals, de-

sign, policies/standards, protocols, and metrics of success. Periodic review of quality and success at all levels from local to national. It is recommended that a planning committee be established with charge of developing and updating a formal NCCI plan. Technical and policy review committees should be established with the charge of expert review.

- Establish formal mechanisms for **coordination and communication** to share resources (e.g., methods, design, data sources, and tools), provide feedback, resolve problems (e.g., gaps, overlaps, errors, and inconsistencies) required to produce a complete National Carbon Atlas. These mechanisms exist but could be enhanced among the Regional Carbon Sequestration Partnerships and NatCarb in terms of informal coordination/communication and participation in formal coordination/communication (e-mail lists, teleconferences, meetings, etc.).
- Provide **formalized management** to ensure that the NCCI operates smoothly and meets its goals. In addition establish key technical and management leadership and ensure they work together to provide vision, technical leadership, leadership and authority to undertake a continent-scale project. The management along with funding agencies should formulate and enforce policies and standards concerning data management, content, documentation, security, and accessibility
- Develop and implement **business plan** as part of the NCCI to ensure fiscal sustainability of the NCCI, with allocation of funding for operation, update, and maintenance at all levels of organization.

- Provide links to related national efforts, such as the Geospatial One-Stop Geoportal (Goodchild et al. 2007).

Conclusion: Importance of National Carbon Cyberinfrastructure

The Regional Carbon Sequestration Partnerships and NatCarb provide the first steps forward in development of a National Carbon Cyberinfrastructure (NCCI). NCCI will provide the critical information to policymakers, scientists and engineers in the field of reduction of CO₂ emissions on sources, capture, transport, and storage of CO₂ within a geospatial local to continent-scale framework. A complete NCCI must also provide the information to discuss the costs, economic potential, and societal issues of CO₂ capture and storage, including public perception and regulatory aspects. Thus, a successful NCCI should provide the basis to evaluate the potential of CO₂ capture and storage, and provide strategies to mitigate economic costs and maximize environmental benefits. The future capture and storage of CO₂ 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 NCCI 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 CO₂ capture and storage for mitigating future climate change.

AUTHOR'S NOTE

The DOE's Carbon Sequestration Partnerships are an integral part of the present NatCarb portal, and will be major contributors to development of a future National Carbon Cyberinfrastructure.

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