Big Sky Carbon Sequestration Partnership

Quarterly Report for period April 1, 2005 – June 30, 2005

By Susan M. Capalbo

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Montana State University

207 Montana Hall; Bozeman, MT 59717-2460

Partners (as of 6/30/05)

Boise State University
CGISS, MG 206, Boise, ID 83725-1536

EnTech Strategies, LLC
1862 Mintwood Place NW #101, Washington, DC 20009

National Carbon Offset Coalition
305 W Mercury St, #408, Butte, MT 59701

South Dakota School of Mines & Technology
501 East Saint Joseph Street, Rapid City, SD 57701-3995

Texas A & M University
2126 TAMU, College Station, TX 77843-2126

University of Idaho
1776 Science Center Drive, Idaho Falls, ID 83402

Idaho National Laboratory (INL)
PO Box 1625, Idaho Falls, ID 83415

Los Alamos National Laboratory (LANL)
PO Box 1663, Los Alamos, NM 87545

Montana Governor's Carbon Sequestration Working Group
Capitol Building, PO Box 200801, Helena, MT 59620-0801

The Sampson Group
5209 York Road, Alexandria, VA 22310

The Confederated Salish and Kootenai Tribes
PO Box 278, Pablo, MT 59855

Nez Perce Tribe
PO Box 365, Lapwai, ID 83540

Inland Northwest Research Alliance
151 N. Ridge Ave., Idaho Falls, ID 83402

Idaho Carbon Sequestration Advisory Committee / Idaho Soil Conservation Commission
PO Box 790, Boise, ID 83701

Montana Bureau of Mines and Technology
Montana Tech, 1300 West Park St., Butte, MT 59701-8997

Western Governors' Association
1515 Cleveland Place, Ste 200, Denver, CO 80202-5114

Wyoming Carbon Sequestration Advisory Committee
2219 Carey Avenue, Cheyenne, WY 82002

Montana Department of Environmental Quality
PO Box 200901, 1520 East Sixth Avenue, Helena, MT 59620-0901

Wyoming Department of Environmental Quality
Herschler Building 4 West, 122 West 25th Street, Cheyenne, WY 82002

University of Wyoming Geographic Information Science Center
Dept. 4008, 1000 E. University Avenue, Ag C Bldg, Rm 337, Laramie, WY 82071

University of Wyoming Enhanced Oil Recovery Institute
Dept. 4068, 1000 E. University Avenue, Room 126, S.H. Knight Geology Bldg, Laramie, WY 82071

University of Wyoming Ruckelshaus Institute for Environment and Natural Resources
Dept. 3971, 1000 E. University Avenue, Wyo Hall Room 212, Laramie, WY 82071

Montana Natural Resource Information System – Montana State Library
1515 E Sixth Avenue, P.O. Box 201800, Helena, MT 59620-1800

Montana GIS Services Bureau Information Technology Services
125 N. Roberts, Mitchell Building, Helena, MT 59620-0113

Unifield Engineering
2626 Lillian Avenue, Billings, MT 59101

Jackson Hole Center for Global Affairs
P.O. Box 550, Jackson, WY 83001

Battelle Pacific Northwest Division
P.O. Box 999, Richland, WA 99352

Columbia University – Lamont Doherty Earth Observatory
P.O. Box 1000, 61 Route 9W, Palisades, NY 10964-8000

Puget Sound Energy
10885 N.E. 4th St., P.O. Box 97034, Bellevue, WA 98009-9734

Portland General Electric
121 SW Salmon Street, Portland, OR 97204

Sempra Generation
101 Ash Street, HQ01H, San Diego, CA 92101

Energy Northwest
P.O. Box 968, Richland, WA 99352-0968

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ABSTRACT

The Big Sky Carbon Sequestration Partnership, led by Montana State University, is comprised of research institutions, public entities and private sectors organizations, and the Confederated Salish and Kootenai Tribes and the Nez Perce Tribe. Efforts under this Partnership in Phase I fall into four areas: evaluation of sources and carbon sequestration sinks that will be used to determine the location of pilot demonstrations in Phase II; development of GIS-based reporting framework that links with national networks; designing an integrated suite of monitoring, measuring, and verification technologies and assessment frameworks; and initiating a comprehensive education and outreach program. The groundwork is in place to provide an assessment of storage capabilities for CO_2 utilizing the resources found in the Partnership region (both geological and terrestrial sinks), that would complement the ongoing DOE research agenda in Carbon Sequestration.

The region has a diverse array of geological formations that could provide storage options for carbon in one or more of its three states. Likewise, initial estimates of terrestrial sinks indicate a vast potential for increasing and maintaining soil C on forested, agricultural, and reclaimed lands. Both options include the potential for offsetting economic benefits to industry and society. Steps have been taken to assure that the GIS-based framework is consistent among types of sinks within the Big Sky Partnership area and with the efforts of other DOE regional partnerships.

The Partnership recognizes the critical importance of measurement, monitoring, and verification technologies to support not only carbon trading but all policies and programs that DOE and other agencies may want to pursue in support of GHG mitigation. The efforts in developing and implementing MMV technologies for geological sequestration reflect this concern. Research is also underway to identify and validate best management practices for soil C in the Partnership region, and to design a risk/cost effectiveness framework to make comparative assessments of each viable sink, taking into account economic costs, offsetting benefits, scale of sequestration opportunities, spatial and time dimensions, environmental risks, and long-term viability. Scientifically sound MMV is critical for public acceptance of these technologies.

Deliverables for the 7th Quarter reporting period include (i) for the geological efforts: Reports on *Technology Needs* and *Action Plan on the Evaluation of Geological Sinks and Pilot Project Deployment* Deliverables 2 and 3), and *Report on the Feasibility of Mineralization Trapping in the Snake River Plain Basin* (Deliverable 14); (ii) for the terrestrial efforts: Report on the *Evaluation of Terrestrial Sinks* and a Report of the *Best Production Practices for Soil C Sequestration (*Deliverables 8 and 15). In addition, the 7th Quarter activities for the Partnership included further development of the proposed activities for the deployment and demonstration phase of the carbon sequestration pilots including geological and terrestrial pilots, expansion of the Partnership to encompass regions and institutions that are complimentary to the steps we have identified, building greater collaborations with industry and stakeholders in the region, contributed to outreach efforts that spanned all partnerships, co-authorship on the Carbon Capture and Separation report, and developed a regional basis to address future energy opportunities in the region. The deliverables and activities are discussed in the following sections and appended to this report.

The education and outreach efforts have resulted in a comprehensive plan which serves as a guide for implementing the outreach activities under Phase I. The public website has been expanded and integrated with the GIS carbon atlas (www.bigskyco2.org). We have made presentations to stakeholders and policy makers including two tribal sequestration workshops, and made connections to other federal and state agencies concerned with GHG emissions, climate change, and efficient and environmentally-friendly energy production. In addition, the Partnership has plans for integration of our outreach efforts with students, especially at the tribal colleges and at the universities involved in our Partnership. This includes collaboration with MSU and with the U.S.-Norway Summer School, extended outreach efforts at LANL and INEEL, and with the student section of the ASME. Finally, the Big Sky Partnership was involved in key meetings and symposium in the 7th quarter including the USDOE Wye Institute Conference on Carbon Sequestration and Capture (April, 2005); the DOE/NETL Fourth Annual Conference on Carbon Capture and Sequestration (May 2005); Coal Power Development Conference (Denver, June 2005) and meetings with our Phase II industry partners and Governor's staff.

In conclusion, in Phase I the Partnership has been working to identify, assess and catalogue C sources and promising geologic and terrestrial sequestration sites, and to develop an economic and risk assessment decision support framework to optimize the region's C sequestration portfolio. These data are being integrated into a user-friendly geographical information systems framework and will be an important analysis tool for industry and regional energy planners. Furthermore, with the largest and most comprehensive terrestrial program in the nation, the Partnership has taken a lead in enhancing market-based C storage methods and improving verification protocols. Finally, the Partnership has conducted extensive public education and outreach to build a dialogue with key decision makers, regulatory officials, industry, environmental groups and the public on the region's energy future and the opportunities and risks associated with advanced coal technologies and C sequestration.

The Phase I work clearly identified the geological similarities among Montana, Idaho, Wyoming, Washington, and Oregon. There are similar land use patterns and cropland practices among these states and South Dakota, and the Canadian provinces. Thus as we proceed into Phase II, we have expanded the Partnership to include the states/provinces with similar and contiguous geological and terrestrial sinks. This expansion is also justified by the common economic interests of these States, including many regional energy companies operating across States and Provincial lines. Additionally, the Partnership is working with leading research institutions in DOE's Carbon Sequestration Leadership Forum member countries including Norway, India and China who will bring unique expertise and funding commitments to leverage DOE's Big Sky Partnership investment.

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INTRODUCTION

The Big Sky Partnership, led by Montana State University, Bozeman, MT, seeks to: identify and catalogue CO_2 sources and promising geologic and terrestrial storage sites, develop a risk assessment and decision support framework to optimize the areas' carbon-storage portfolio, enhance market-based carbon-storage methods, identify and measure advanced greenhouse gas-measurement technologies to improve verification, support voluntary trading and stimulate economic development, call upon community leaders to define carbon-sequestration strategies, and create forums that involve the public. Idaho, Montana, Wyoming, and South Dakota are currently served by this Partnership that is comprised of 23 organizations and the Confederated Salish and Kootenai Tribes and the Nez Perce Tribe. Additional collaboration was obtained in the 6th quarter to expand the Partnership to include the neighboring states of Washington and Oregon, and the neighboring provinces in Canada. We have also entered agreements with several new industrial partners including Puget Sound Energy, Energy Northwest, Sempra Generation, Portland General Electric, and rural Cooperatives in the region. Montana Tech-Montana Bureau of Mines and Geology and the Idaho Carbon Sequestration Advisory Committee/Idaho Soil Conservation Commission, and PNNL/PNWD are new members of the Partnership. Inland Northwest Research Alliance (INRA) and Western Governors' Association (WGA) have provided support for our Partnership since the onset and are members of the Partnership.

Original Partners include

Montana State University
South Dakota School of Mines & Technology
Texas A & M University
University of Idaho
The Sampson Group
EnTech Strategies, LLC
Environmental Financial Products
Nez Perce Tribe
Idaho National Engineering and Environmental Laboratory
Los Alamos National Laboratory
Montana Governor's Carbon Sequestration Working Group
National Carbon Offset Coalition

New Partners include

Idaho Carbon Sequestration Advisory Committee/ Idaho Soil Conservation Commission
Inland Northwest Research Alliance
Montana Tech-Montana Bureau of Mines and Geology
Western Governors' Association
Wyoming Carbon Sequestration Advisory Committee
Montana Department of Environmental Quality
Wyoming Department of Environmental Quality
Univ. of Wyoming Geographic Information Science Center
Univ. of Wyoming Enhanced Oil Recovery Institute
Univ. of Wyoming Ruckelshaus Institute Environment and Natural Resources
Montana Natural Resource Information System - Montana State Library
Montana GIS Services Bureau Information Technology Services
Unifield Engineering
Jackson Hole Center for Global Affairs
Battelle Pacific Northwest Division
Puget Sound Energy
Energy Northwest
Puget Sound Energy
Sempra Generation
Portland General Electric
Columbia University-Lamont Doherty Earth Observatory

EXECUTIVE SUMMARY

For reporting purposes, the activities and results for the Big Sky Partnership are organized into four somewhat overlapping components or efforts, with the related tasks from the workplan noted by each:

- **Evaluation of sources and potential for carbon sequestration sinks**: Tasks 1,2,4,5,6,7
- **Development of GIS-based framework and carbon cyberinfrastructure**: Task 3
- **Advanced concepts for monitoring, measuring, and verification; implementation, carbon trading, and evaluation**: Tasks 9-20
- **Education and outreach efforts.** Tasks 8, 21-25

This report summarizes the activities during the 7th reporting period. Key deliverables for the 7th Quarter reporting period include: reports on *Technology Needs* and *Action Plan on the Evaluation of Geological Sinks and Pilot Project Deployment (*Deliverables 2 and 3); *Report on the Feasibility of Mineralization Trapping in the Snake River Plain Basin* (Deliverable 14); Report on the *Evaluation of Terrestrial Sinks* and a Report of the *Best Production Practices for Soil C Sequestration (*Deliverables 8 and 15). During this quarter, we also developed a summary paper on "Policy Implications from Regional Energy Growth." This is included as Appendix A. In addition, the 7th Quarter activities for the Partnership included further development of the proposed activities for the deployment and demonstration phase of the carbon sequestration pilots including geological and terrestrial pilots, expansion of the Partnership to encompass regions and institutions that are complimentary to the steps we have identified, building greater collaborations with industry and stakeholders in the region, contributed to outreach efforts that spanned all partnerships, co-authorship on the Carbon Capture and Separation report, and developed a regional basis to address future energy opportunities in the region.

The Partnership has completed state-level greenhouse gas (GHG) emission inventories for South Dakota, Montana, and Idaho; Wyoming will be completed by the end of the project. Major point sources are being located within the project GIS in order to help assess source-sink spatial relationships.

A comprehensive assessment of cropland, forestry and agroforestry opportunities for carbon sequestration in the region has been completed. Possible rangeland terrestrial sinks throughout the Big Sky project area have been identified and a literature review to support decisions for increasing carbon sequestration for areas identified as having potential as carbon sinks has been completed. Climatic potential, MLRA, and land tenure were selected to spatially stratify rangeland cover types into easily identifiable areas where sequestration programs could potentially be initiated. In addition, the Partnership is developing a decision-support framework which will be implemented in Phase II to link physical based, spatially referenced models for soil carbon, including models like C-Lock, C-store, and COMET with an economic assessment component to allow landowners to evaluate the costs and benefits of changing land use practices to sequester C. A report will be forthcoming in the 8th quarter. The Partnership has made substantial progress on the technical analysis regarding the implementation of an integrated MMV system for geological and terrestrial sequestration in the Big Sky region. These will be included with the final report.

The education and outreach efforts have resulted in a comprehensive plan which serves as a guide for implementing the outreach activities under Phase I. The public website has been expanded and integrated with the GIS carbon atlas (www.bigskyco2.org). We have made presentations to stakeholders and policy makers including two tribal sequestration workshops, and made connections to other federal and state agencies concerned with GHG emissions, climate change, and efficient and environmentally-friendly energy production. In addition, the Partnership has plans for integration of our outreach efforts with students, especially at the tribal colleges and at the universities involved in our Partnership. This includes collaboration with MSU and with the U.S.-Norway Summer School, extended outreach efforts at LANL and INEEL, and with the student section of the ASME. Finally, the Big Sky Partnership was involved in key meetings and symposium in the 7th quarter including the USDOE Wye Institute Conference on Carbon Sequestration and Capture (April, 2005); the DOE/NETL Fourth Annual Conference on Carbon Capture and Sequestration (May 2005); Coal Power Development Conference (Denver, June 2005) and meetings with our Phase II industry partners and Governor's staff.

Evaluation of sources and sinks (Tasks 1, 2, 4, 5, 6, 7). Activities during the 7th performance period were focused on characterizing the potential for geological and terrestrial sequestration sinks, compilation of data, and identifying and cataloging industrial and agricultural GHG sources. The Partnership Geologic Sequestration and Geographical Information System (GIS) support has focused on the creation of a database structure for collection of geologic sequestration data and summarizing the types of infrastructure information that are being collected in Idaho, Montana, and contiguous geologic regions of Wyoming. The Partnership has developed a uniform strategy for assessing the mineralization trapping potential across rocks types. These capabilities are being used to determine the geologic sequestration potential in the Big Sky region. We have established a geological sink assessment approach and screening criteria, and nearing completion on compiling county-level data on tillage and land use for the terrestrial component. Both the geological and terrestrial component is resulting in data layers that will allow us to assess the suitability for carbon sequestration in the Big Sky Partnership region as well as the potential for locating future energy facilities in our region. A final report on the GIS Activities for the Big Sky Partnership will be included with the final report.

For geological sinks, the potential for subsurface formation of carbon dioxide sequestration focused on solubility and mineralization trapping, and examined the technical feasibility, the time frame until implementation, and offsetting economic benefits. For the terrestrial sinks, the methodologies have been focusing on both technical and economic feasibility. Increasing soil C levels are dependent upon both the technical capacity of the soils to sequester and utilize additional carbon, and the incentives provided for landowners to change land use management practices. Activities to identify sources and assessment of transportation infrastructure are currently focused on identifying the state and federal databases and agencies, and addressing uncertainties inherent in matching/combining data sources.

Advanced Concepts (Tasks 9-20). The Partnership recognizes the critical importance of measurement, monitoring, and verification technologies to support not only carbon trading but all policies and programs that DOE and other agencies may want to pursue in support of GHG mitigation. For terrestrial sequestration, research is validating best management practices for soil

C in the Partnership region. A team of researchers from MSU have been working in the field to obtain field scale carbon estimates for ground truthing simulation models and identifying BMPs.

The Partnership has also been involved in regional assessment of future energy growth. The Big Sky region consisting of Idaho, Montana, and Wyoming holds high potential for future energy growth due to significant energy resources (e.g., coal reserves, wind) and central proximity to western energy markets. This region is also characterized by small populations, limited industry, and low greenhouse gas emissions. There are significant policy implications associated with energy development that would result in changes to the regional energy mix, water resource demands, energy transmission systems, and from the implementation of new energy technologies including carbon sequestration. The Big Sky partnership has identified key factors influencing energy development. Conference proceedings "Policy Implications from Regional Energy Growth" (Appendix A) examines some of these factors including population demographics, land and water availability, energy transmission and transportation infrastructure, energy market supplies and demands, environmental/regulatory constraints, and the availability of raw energy resources. This paper also considers the potential influence of regional climate change on energy growth. Climate change can have a direct impact on water availability, market demands, economics of power systems (e.g., carbon taxes, carbon capture, and sequestration), preference for renewable vs. fossil energy systems, and siting fossil plants near carbon sequestration sinks. The Big Sky Regional Carbon Sequestration Partnership is examining regional carbon sequestration resources that could be used to reduce or offset the carbon emissions from fossil power energy production and other industrials. The Big Sky Partnership is using this study to gain insight into the issues driving regional energy demand and facilitate the development of a regional infrastructure that can support future energy development with carbon sequestration resources. The methodologies created through this activity will be applicable to other regional applications. This methodology can be used to evaluate the economic and policy ramifications from regional energy growth.

Task 16. The objective of this task is to identify and validate best management practices (BMP), including no-till and intensive cropping, for soil C sequestration within the semi-arid Northern Great Plains. A full reporting on the design and preliminary results for this task were included in the previous quarterly report.

Task 19. As part of Task 19, we addressed problems in verifying changes in carbon stocks associated with the high cost and time involved with repeated sampling and analysis. The objective was to demonstrate the practicality of near infrared reflectance spectroscopy (NIR) as a technique for reducing the cost and time required for sample analysis. This section was based on our CASMGS 2003 report, which demonstrates a technique for identifying spectrally unique samples for laboratory analysis and equation development, and compares the accuracy and cost between NIR techniques and standard laboratory procedures. We also presented two general soil carbon equations built on a diverse assortment of soils collected throughout the country as well as the prediction results for several carbon fractions. This information was provided in the fourth quarter report and is also available at the Texas A&M web site: http://cubes.tamu.edu/bigsky.

Monitoring and Measurement Verification (MMV) activities, as they pertain to geological (and terrestrial) sinks, include some initial assessment of the state of the art for technologies that have a high likelihood of being mature enough to be applicable in Phase II small scale applications, and designing a risk/cost effectiveness framework to make comparative assessments of each viable sink, taking into account economic costs, offsetting benefits, scale of sequestration opportunities, spatial and time dimensions, environmental risks, and long-term viability. In conjunction with the GIS efforts and ongoing research at LANL, MSU, SDSMT, and INEEL, the Partnership is developing a well-integrated ensemble of diagnostics for MMV at each potential geological sequestration site, and a protocol for the terrestrial sequestration areas. These are a critical component of the Partnership Phase II efforts.

Regulatory and compliance research is being coordinated with the State agencies and with the IOGCC. Susan Capalbo is part of the IOGCC task force and met in Chicago in late August, 2004. A final report of the task force was issued in December 2004, and has been revised. A copy is available on the IOGCC website http://www.iogcc.state.ok.us/.

Education and Outreach (Tasks 8, 21-25). The primary goal of the Education and Outreach efforts is to increase awareness, understanding, and public acceptance of carbon sequestration while building support for the efforts of the Partnership. The activities this period include participation in outreach teleconference calls, development and participation in the two tribal sequestration workshops in January 2005, updates and expansions to the website to incorporate the spatial-referenced data on source, sinks, and energy infrastructure, development of handout materials for many of the conferences, and planning and designing outreach and education materials in efforts by NCOC. The partnership has added the Ruckelshaus Institute of Environment and Natural Resources, a pioneer in advancing improvements in environmental regulation and the NEPA process, to implement an innovative approach to regulatory and public outreach that can serve as a model for the nation. This well-tested process ensures that all regulatory permitting requirements (including NEPA) are met for validation tests and full scale implementation projects, enhance public involvement and trust and raise the profile and level of the discussion on the region's energy future and the role of advanced technologies such as FutureGen, IGCC and C capture and sequestration.

In addition, we have met with key industry members developing coal power plants in ID, MT, and WA. Finally the Partnership is co-author on the paper "Building Public Acceptance for the Regional Carbon Sequestration Partnerships," to be represented at the May 2005 NETL conference.

In Phase I the Partnership has been working to identify, assess and catalogue C sources and promising geologic and terrestrial sequestration sites, and to develop an economic and risk assessment decision support framework to optimize the region's C sequestration portfolio. These data are being integrated into a user-friendly geographical information systems framework and will be an important analysis tool for industry and regional energy planners. Furthermore, with the largest and most comprehensive terrestrial program in the nation, the Partnership has taken a lead in enhancing market-based C storage methods and improving verification protocols. Finally, the Partnership has conducted extensive public education and outreach to build a dialogue with key decision makers, regulatory officials, industry, environmental groups and the public on the region's energy future and the opportunities and risks associated with advanced coal technologies and C sequestration.

The efforts and results from Phase I are used to set the tone and direction for the Partnership's Phase II efforts: to assist the region utilize its natural resources to meet growing energy demand with a optimal portfolio of advanced technology options coupled with geological and terrestrial sequestration opportunities, understand potential economic impacts on a project and regional basis, raise the profile of regional energy issues, enhance public involvement and trust, and effectively communicate the opportunities and risks associated with carbon sequestration. Two of the Partnership's key industry members, Sempra Generation and Energy Northwest, are developing new coal-fired power plants in the region including an IGCC power complex. Of crucial importance to both development programs is robust C mitigation plans that include a technical and economic assessment of regional C sequestration opportunities *and* participation in the Partnership's field validation tests. Therefore, the Partnership has worked closely with its industry members and national and international collaborators to design geologic and terrestrial field tests to be effective, relevant to commercial development needs and broadly transferable.

The Partnership has a strong economic team that will build on its work in Phase I and assist the region to understand the economic impacts of terrestrial and geologic C sequestration at both the project and regional levels. In Phase I, the Partnership's economic analysis has focused on the economic potential of terrestrial sequestration which has been published in peer-reviewed journals and is considered sate-of-the-art. The Partnership will expand this framework to include its geologic field tests which will culminate in a regional C supply curve showing at each price of C, the total amount of C that could be sequestered in the region. This framework will be a valuable tool to enable the Partnership, its industry members and the region to assess the economic potential of all its sequestration options on a common basis. In fact, the Partnership's industry members recognize this activity as a key component of their carbon mitigation plans. The Phase I work has clearly identified the geological similarities among Montana, Idaho, Wyoming, Washington, and Oregon. There are similar land use patterns and cropland practices among these states and South Dakota, and the Canadian provinces. Thus as we proceed into Phase II, we have expanded the Partnership to include the states/provinces with similar and contiguous geological and terrestrial sinks. This expansion is also justified by the common economic interests of these States, including many regional energy companies operating across States and Provincial lines. Additionally, the Partnership is working with leading research institutions in DOE's Carbon Sequestration Leadership Forum member countries including Norway, India and China who will bring unique expertise and funding commitments to leverage DOE's Big Sky Partnership investment.

EXPERIMENTAL SECTION

This section is essentially unchanged from the sixth quarterly report, and thus is not repeated here.

RESULTS AND DISCUSSION

In this section the deliverables for the 7th Quarter reporting period are briefly discussed. These include:

(i) for the geological efforts: Reports on *Technology Needs* and *Action Plan on the Evaluation of Geological Sinks and Pilot Project Deployment (*Deliverables 2 and 3), and *Report on the Feasibility of Mineralization Trapping in the Snake River Plain Basin* (Deliverable 14); and

(ii) for the terrestrial efforts: Report on the *Evaluation of Terrestrial Sinks* and a Report of the *Best Production Practices for Soil C Sequestration (*Deliverables 8 and 15).

These four deliverables have been submitted with this quarterly report.

Deliverable 2/3: Technology Needs & Action Plan on the Evaluation of Geological Sinks and Pilot Project Deployment

In this report, the Partnership's effort to evaluate the location and capacity of the major geological sinks in the region is summarized.

The region encompassed by the Big Sky Partnership hosts a number of large sedimentary basins including the Powder River, Williston, and the Green River and associated basins (Figure 1). Together these basins cover more than 400,000 km^2 of Wyoming, South Dakota, and Montana. These basins range from 1,500 to 3,000 meters thick and are comprised of bedded sandstones, shales, thick coal beds, dolomites and limestone. The same geologic conditions (i.e. basins depth, structure, and permeability), that have made these basins productive coal and hydrocarbon producers also make them attractive targets for large scale CO_2 sequestration.

In addition to providing large storage potential, the basins also have desirable mineral characteristics. These minerals, when exposed to CO_2 and water, can rapidly convert to stable secondary minerals phases, effectively sequestering CO_2 indefinitely. Also contributing to CO_2 sequestration suitability are thick deposits of unmineable sub bituminous coal, located deep within many of the basins. These thick coalbeds can adsorb CO_2 onto the internal surfaces of its microporous structure releasing methane that can then be captured and used. Preliminary empirical data shows that the sub bituminous coal found in the Wyoming and Montana sections of the Powder River basin (Figure 1) is superior to other higher ranked coals for CO_2 storage.

The importance of evaluating the sequestration potential of these basins is self evident when considering the growing power demands of the west and the vast resources and energy producing potential of this region. It is clear that the resources of these basins will be used for energy production well into the future. Therefore, a full characterization of sequestration capacity will be beneficial for locating future power plants built to meet the energy demands of a growing population in the western U.S. During the performance period of Phase I, the Big Sky Partnership geology team has developed techniques to evaluate the sequestration potential of these basins. As a result of the Phase I assessment, a capacity and location catalog of sedimentary target reservoirs has been developed. These are discussed in greater detail in this deliverable.

The assessment shows the enormous volume of CO_2 in the region. According to the Energy Information Administration, (www.cia.doe.gov), the total CO_2 emissions for the United States year are 5.8 billion metric tons, while many of the saline aquifer capacities in the Big Sky region are in the 10,000 to 100,000 million metric tons range. Total sequestration volumes for the Wyoming, Montana, and South Dakota sedimentary basins have been organized by reservoir type: saline aquifer, oil and natural gas reservoir, and coal seams. These capacities range from .1 to 10^6 million metric tones of CO_2. In general, non oil producing saline aquifers represent the most volumetrically significant target for sequestration with some of these formations reaching nearly 1,000,000 million metric tones of capacity.

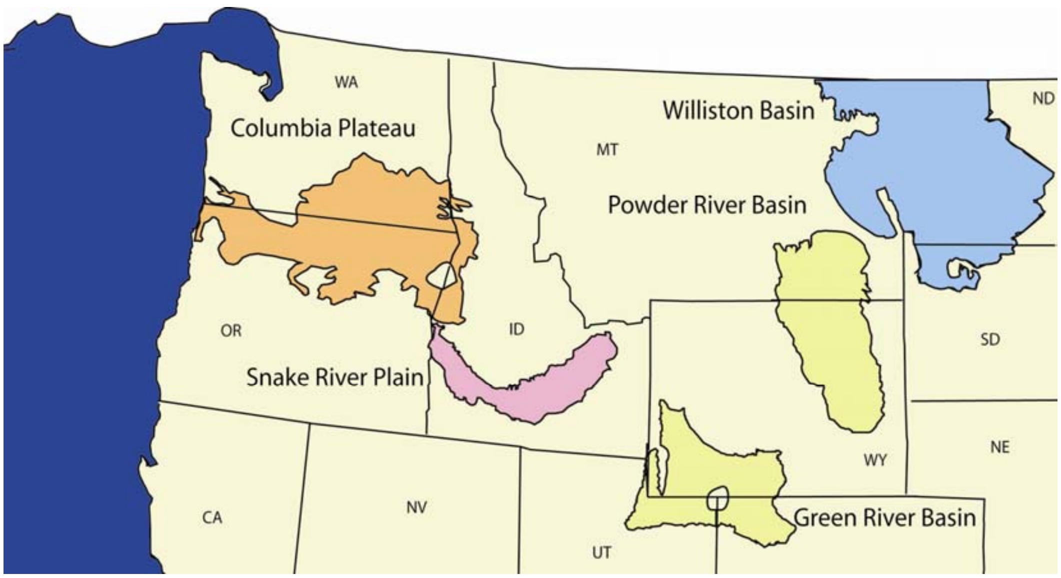


Figure 1. Major sedimentary and volcanic basins within the Big Sky Partnership.

<u>Deliverable 14: Report on the Feasibility of Mineralization Trapping in the Snake River Plain Basin:</u>

Geologic sequestration occurs via three interrelated processes. The first is hydrodynamic trapping where CO_2 is physically isolated by trapping beneath impermeable geological barriers, such as a shale bed. This is the primary sequestering process in the short-term and is largely a function of the storage capacity of the deep system and its degree of isolation from the Earth's surface. The second process is solubility trapping in which CO_2 dissolves in subsurface fluids such as brines or petroleum. Solubility trapping is slower than hydrodynamic trapping and depends on the CO_2 dissolution rate in the fluid of interest. The third process is trapping due to mineralization in which CO_2 is entombed by increased weathering of the geochemically reactive base cations (primarily Ca^{2+}, Mg^{2+}, and Fe^{2+}) in subsurface minerals. The weathering reactions result in the conversion of CO_2 into carbonate alkalinity and ultimately carbonate minerals. Because existing groundwaters are often saturated with carbonate phases, carbonate minerals formed from anthropogenic CO_2 will be permanently entombed in the subsurface. The time frame for mineralization trapping is primarily a function of the weathering rate and is much slower than the other two trapping processes. Mineral trapping will be most pronounced in rocks that have high concentration of base cations and rapid reactions rates such as mafic volcanic rock.

The permanence of sequestration by the three trapping processes is the inverse of their trapping time scale. Mineralization trapping offers the most permanent sequestration, hydrodynamic trapping the least. In an ideal sequestration site, CO_2 would be permanently stored through the presence of multiple trapping processes.

The Big Sky Partnership has evaluated the geologic sequestration potential of the 64,700 km^2 basalt bearing Snake River Plain volcanic basins in Idaho and will, in Phase II, evaluate the potential for similar rock types of the 163,700 km^2 Columbia River Basalt Group in western Idaho and eastern Oregon and Washington. In addition to the formations located in the Partnership's region, other mafic rock provinces exist within large parts of the United States (see Figure 2). Specifically considered in this report, and an example of the potential of mafic volcanic rocks, is an evaluation of sequestration in a mixed volcanic sedimentary section in southern Idaho. The evaluations of potential geologic sequences for carbon sequestration need to consider the relative contributions of hydrodynamic, solubility, and mineralization trapping. The relative contribution to sequestration of these three processes will vary with rock type and time. In sequences that include basalts, such as those located in southern Idaho, all three processes contribute to sequestration, with hydrodynamic trapping important early and mineralization trapping dominating later. The specific potential of the Snake River Plain Basin is not determined in this report, but a preliminary assessment indicates that the Basin should be further studied for its high sequestration potential.

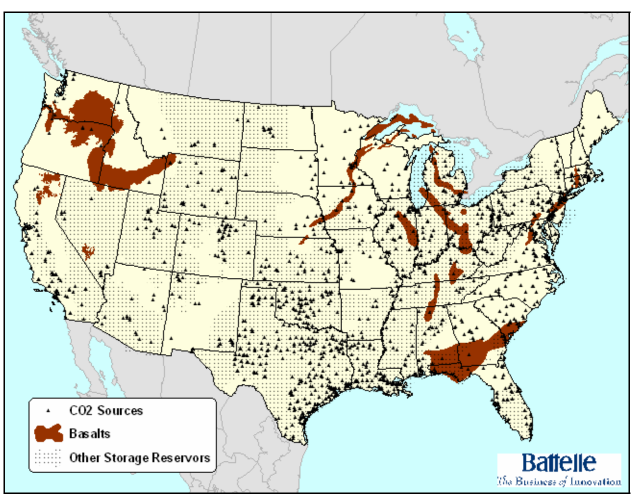


Figure 2. Map of U.S. Basalts, large CO_2 sources, and other candidate storage reservoirs.

Deliverable 8: Evaluation of Terrestrial Sinks

This deliverable summarizes efforts to date on assessing the terrestrial sinks for the Big Sky region. The assessments are done in terms of both technical potential and economic potential. Technical potential provides the most optimistic estimate of the size of the terrestrial sinks, assuming that all land use management was changes to the management regime that sequestered the maximum amount of soil carbon. The economic potential examines the amount of carbon that would be sequestered from land use changes taking into account the "cost' of changing the existing land use management to a management regime that would sequester larger amounts of carbon. In theory, the economic assessment is a realistic means of capturing both the potential size of the sinks and the opportunity cost of sequestering carbon.

Montana has the largest agricultural land base, but South Dakota has by far the largest area of harvested cropland. As a result, South Dakota may offers the largest technical potential for terrestrial sink enhancement due to cropland management, but Wyoming and Montana may provide greater potential benefits due to improved rangeland management.

The economic approach to the analysis of the potential to sequester soil C links biophysical data and models with economic data and models on a site-specific basis. In this way, the analysis can account for the spatial heterogeneity of biophysical conditions (soil C sequestration rates) and economic decisions (land use) and how these conditions interact to determine the marginal cost of sequestering C in soil. We apply an integrated assessment approach to quantify the costs of sequestering C from changes in land use and management practices in the dryland grain production systems of the Northern Plains region of the United States which encompasses the Big Sky region. In this region, changes in land use such as conversion of crop land to permanent grass, and changes in management practices such as use of reduced fallow, may be economically feasible where afforestation—the conversion of non-forest land to forest—is not. We compare the relative efficiency of sequestering soil C for two alternative policies relevant to the Northern Plains region: one that provides producers with payments for converting crop land to permanent grass (similar to the Conservation Reserve Program in the United States), and one that provides payments to farmers to switch from a crop-fallow rotation or permanent grass to a continuous cropping system. These policies are similar to ones proposed in recent U.S. legislation. Our analysis shows that the economic efficiency of C sequestration and the size of the sinks depends on site-specific opportunity costs of changing practices, the rates of soil C sequestration associated with changing practices, and the policy design.

The Partnership is also characterizing the carbon sequestration potential in the agricultural and forest areas of the 4-state region, comprising Idaho, Montana, South Dakota and Wyoming, and addressing the portion of that potential related to agroforestry practices and biomass production on agricultural lands, as well as afforestation of marginal agricultural soils and changing the management of existing private forests. None of these opportunities are overwhelmingly large, as one would expect in a region characterized by a high proportion of federal land, vast areas of arid and semi-arid ecosystems, and widely scattered production areas. But they could be important contributors to state, regional, and national efforts to mitigate greenhouse gas emissions in the near term, as these management practices are available immediately, with mature technologies that are widely known to landowners and technical agents in the region. In the event that carbon sequestration were to gain some market value, these opportunities could become a badly-needed supplement to income in a region dependent on agriculture and forestry for much of its rural economy. The estimates are reported in this deliverable.

Deliverable 15: Best Production Practices for Soil C Sequestration

The deliverable on addressing the best management practices for soil C sequestration provides some background information on how farm management practices can affect greenhouse gases, a discussion of specific management practices in the Great Plains, and provides some preliminary results for Montana.

Agricultural activities serve as both sources and sinks for greenhouse gases, so specific agricultural practices could slow the pace of global warming. Carbon sequestration refers to the removal of carbon dioxide from the atmosphere into a long-lived stable form that does not affect atmospheric chemistry. Currently, the only viable way to trap atmospheric carbon dioxide is via photosynthesis, where carbon dioxide is absorbed by plants and turned into carbon compounds for plant growth. Carbon is considered sequestered if it ends up in a stable form, such as wood or soil organic matter. Soil carbon sequestration is an important and immediate sink for removing atmospheric carbon dioxide and slowing global warming.

Practically, there are three areas of farm management that can affect soil carbon sequestration in the Great Plains: tillage, cropping intensity and fertilization. Tillage and soil carbon are negatively related. The greater the tillage, the less soil carbon. No-till systems build soil organic matter, which is about 58 percent carbon. Different no-till systems result in varying soil disturbance, but any system that reduces tillage substantially can increase soil carbon. Montana field research showed carbon storage rate from no-till adoption similar to that in southwestern Saskatchewan, but with considerable farm-to-farm variability. That variability needs to be understood. Cropping intensity and soil carbon are positively related. The more frequent the cropping and greater the biomass inputs, the more soil carbon. Summer fallow reduces cropping intensity. Reducing fallow typically increases soil carbon through greater annualized biomass inputs, but may be economically difficult. Fertilization affects soil carbon mainly through crop biomass. However the carbon:nitrogen ratio of soil organic matter results in stable organic matter typically within a range of about 8-10:1. If insufficient nitrogen is present to permit stable formation of soil organic matter via soil microbial degradation of crop residues, then little carbon may be sequestered.

The variability in the levels of soil C predicted by the Century model across the six major crop producing sub-MLRAs and production systems in Montana is shown in Figure 3. Simulations of the crop-fallow, continuous cropping, and permanent grass production systems with the Century model show that the equilibrium levels of soil C under a crop-fallow rotation range from 3–7 MT per hectare less than continuous grass over a twenty year horizon, and that soil C levels under permanent grass range from 1–5 MT per hectare less than under continuous cropping depending upon sub-MLRA. In sub-MLRA 52-low, soil C levels under permanent grass compare favorably with soil C levels under a continuous cropping system. The variability across sub-MLRAs reflects the heterogeneity in biophysical and climatic conditions, which translates into different equilibrium levels of soil C for the production systems.

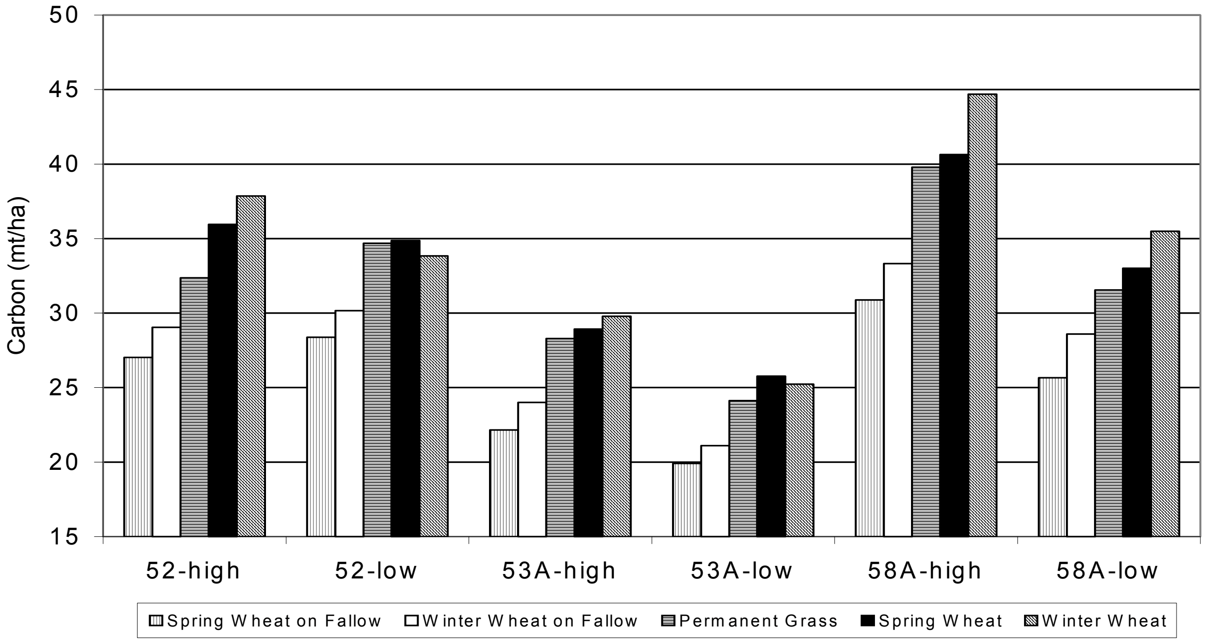


Figure 3. Soil C levels predicted by Century model for cropping systems in Montana.

From field studies, we obtained results on the adoption of no-till systems to sequester carbon in soils. This research combined field-scale soil sampling and the use of the Century model to explore field-scale SOC variability and the effects of soil texture input data sources (STATSGO and SSURGO databases) on predicted SOC dynamics in north central Montana.

Outreach and Education.

The education and outreach efforts have resulted in a comprehensive plan which serves as a guide for implementing the outreach activities under Phase I. The primary goal of this plan is to increase awareness, understanding, and public acceptance of sequestration efforts and to build support for a constituent-based network which includes the initial Big Sky Partnership and other local and regional businesses and entities. Presentations about the Partnership have been made at numerous venues including tribal workshops, industry annual meetings, state and regional meetings, and national CO2 conferences and international meetings. The Partnership has assessed future energy growth in this region. There are significant policy implications associated with energy development that would result in changes to the regional energy mix, water resource demands, energy transmission systems, and from the implementation of new energy technologies including carbon sequestration. The Big Sky partnership has identified key factors influencing energy development. The Conference proceedings "Policy Implications from Regional Energy Growth" (Appendix B) examines some of these factors including population demographics, land and water availability, energy transmission and transportation infrastructure, energy market supplies and demands, environmental/regulatory constraints, and the availability of raw energy resources. The Big Sky Regional Carbon Sequestration Partnership is examining regional carbon sequestration opportunities that could be used to reduce or offset the carbon emissions from fossil power energy production and other industrials.

The public website (www.bigskyco2.org) makes available many of the presentations to stakeholders and policy makers, provides a connection to other federal and state agencies concerned with GHG emissions, climate change, and efficient and environmentally-friendly energy production, and integrates with the Big Sky carbon atlas. The Partnership is developing an on-line decision-support framework which will allow landowners to estimate the costs of switching to a management practice which stores more carbon and the likely amounts of carbon that can be obtained. Given this information, the landowners would be able to assess the cost/benefits of participating in a carbon program or carbon market at alternative price points.

CONCLUSIONS

The Big Sky Partnership undertakes activities in four areas: evaluation of sources and carbon sequestration sinks; development of GIS-based reporting framework; designing an integrated suite of monitoring, measuring, and verification technologies; and initiating a comprehensive education and outreach program. Steps have been taken to assure that the GIS-based framework is consistent among types of sinks within the Big Sky Partnership area and with the efforts of other western DOE partnerships.

This report summarizes the activities for the seventh quarter of the Partnership. Deliverables include the Deliverables for the 7th Quarter reporting period include (i) for the geological efforts: Reports on *Technology Needs* and *Action Plan on the Evaluation of Geological Sinks and Pilot Project Deployment* Deliverables 2 and 3), and *Report on the Feasibility of Mineralization Trapping in the Snake River Plain Basin* (Deliverable 14); (ii) for the terrestrial efforts: Report on the *Evaluation of Terrestrial Sinks* and a Report of the *Best Production Practices for Soil C Sequestration (*Deliverables 8 and 15). During this quarter, we also developed a summary paper on "Policy Implications from Regional Energy Growth." This is included as Appendix A. In addition, the 7th Quarter activities for the Partnership included further development of the proposed activities for the deployment and demonstration phase of the carbon sequestration pilots including geological and terrestrial pilots, expansion of the Partnership to encompass regions and institutions that are complimentary to the steps we have identified, building greater collaborations with industry and stakeholders in the region, contributed to outreach efforts that spanned all partnerships, co-authorship on the Carbon Capture and Separation report, and developed a regional basis to address future energy opportunities in the region.

The education and outreach efforts have resulted in a comprehensive plan which serves as a guide for implementing the outreach activities under Phase I. The public website has been expanded and integrated with the GIS carbon atlas (www.bigskyco2.org). We have made presentations to stakeholders and policy makers including two tribal sequestration workshops, and made connections to other federal and state agencies concerned with GHG emissions, climate change, and efficient and environmentally-friendly energy production. In addition, the Partnership has plans for integration of our outreach efforts with students, especially at the tribal colleges and at the universities involved in our Partnership. This includes collaboration with

MSU and with the U.S.-Norway Summer School, extended outreach efforts at LANL and INEEL, and with the student section of the ASME. Finally, the Big Sky Partnership was involved in key meetings and symposium in the 7th quarter including the USDOE Wye Institute Conference on Carbon Sequestration and Capture (April, 2005); the DOE/NETL Fourth Annual Conference on Carbon Capture and Sequestration (May 2005); Coal Power Development Conference (Denver, June 2005) and meetings with our Phase II industry partners and Governor's staff.

In conclusion, in Phase I the Partnership has been working to identify, assess and catalogue C sources and promising geologic and terrestrial sequestration sites, and to develop an economic and risk assessment decision support framework to optimize the region's C sequestration portfolio. These data are being integrated into a user-friendly geographical information systems framework and will be an important analysis tool for industry and regional energy planners. Furthermore, with the largest and most comprehensive terrestrial program in the nation, the Partnership has taken a lead in enhancing market-based C storage methods and improving verification protocols. Finally, the Partnership has conducted extensive public education and outreach to build a dialogue with key decision makers, regulatory officials, industry, environmental groups and the public on the region's energy future and the opportunities and risks associated with advanced coal technologies and C sequestration.

The Phase I work clearly identified the geological similarities among Montana, Idaho, Wyoming, Washington, and Oregon. There are similar land use patterns and cropland practices among these states and South Dakota, and the Canadian provinces. Thus as we proceed into Phase II, we have expanded the Partnership to include the states/provinces with similar and contiguous geological and terrestrial sinks. This expansion is also justified by the common economic interests of these States, including many regional energy companies operating across States and Provincial lines. Additionally, the Partnership is working with leading research institutions in DOE's Carbon Sequestration Leadership Forum member countries including Norway, India and China who will bring unique expertise and funding commitments to leverage DOE's Big Sky Partnership investment.

APPENDIX

A. Conference proceedings "Policy Implications from Regional Energy Growth." Shropshire, D. and S. Capalbo. Presented at the Fourth Annual Conference on Carbon Capture and Sequestration, *Developing Potential Paths Forward Based on the Knowledge, Science and Experience to Date,* Alexandria, VA, May 2-5, 2005. (PPT available at http://www.bigskyco2.org/presentations/CarbonSequestrationConfFile19Shropshire.ppt)

DELIVERABLES

Deliverables 2 and 3. Technology Needs and Action Plan on the Evaluation of Geological Sinks and Pilot Project Deployment
Deliverable 8. Evaluation of Terrestrial Sinks
Deliverable 14. Feasibility of Mineralization Trapping in the Snake River Plain Basin
Deliverable 15. Best Production Practice for Soil C Sequestration

Policy Implications from Regional Energy Growth

David Shropshire, Idaho National Laboratory
Susan Capalbo, Montana State University

Abstract

The Big Sky region consisting of Idaho, Montana, and Wyoming holds high potential for future energy growth due to significant energy resources (e.g., coal reserves, wind) and central proximity to western energy markets. This region is also characterized by small populations, limited industry, and low greenhouse gas emissions. There are significant policy implications associated with energy development that would result in changes to the regional energy mix, water resource demands, energy transmission systems, and from the implementation of new energy technologies including carbon sequestration. The Big Sky partnership has identified key factors influencing energy development. This paper examines some of these factors including population demographics, land and water availability, energy transmission and transportation infrastructure, energy market supplies and demands, environmental/regulatory constraints, and the availability of raw energy resources. This paper also considers the potential influence of regional climate change on energy growth. Climate change can have a direct impact on water availability, market demands, economics of power systems (e.g., carbon taxes, carbon capture, and sequestration), preference for renewable vs. fossil energy systems, and siting fossil plants near carbon sequestration sinks. The Big Sky Regional Carbon Sequestration Partnership is examining regional carbon sequestration resources that could be used to reduce or offset the carbon emissions from fossil power energy production and other industrials. The Big Sky Partnership is using this study to gain insight into the issues driving regional energy demand and facilitate the development of a regional infrastructure that can support future energy development with carbon sequestration resources. The methodologies created through this activity will be applicable to other regional applications. This methodology can be used to evaluate the economic and policy ramifications from regional energy growth.

1. Introduction

Energy growth assessment is a complex, dynamic process with many factors and drivers. The assessment of the Big Sky region was considered within the broader context of the resources and demands of the eleven Western states. A regional perspective provides a comprehensive view that considers combined geopolitical boundaries (e.g., Western Governors Association), energy transmission corridors (electricity, pipelines), transportation routes (railroad, highways), contiguous geologic characteristics, socio-economic regions, shared water resources, and other overlapping regional features.

The key factors included in this evaluation were selected for their potential to positively or negatively influence future energy growth in the Big Sky region. We have included population demographics, land and water availability, transmission and transportation infrastructure, regional energy market supplies and demands, environmental/regulatory constraints, raw energy resource availability, energy technology resources, and regional climate change. These factors are illustrated in Figure 1 to show how each factor could positively (green lines) or negatively (red lines) influence future energy growth. Additionally, some links (purple lines) between factors were drawn to show some of the complexity that can drive system behavior. For example, climate change can influence where businesses locate and where people live, but it can also influence energy demands for heating and cooling, and drive energy market demands. It is also important to consider that energy growth is not a static process, but a dynamic process where the importance of the dynamic factors may change over time, as well as the relative influence that they may assert on energy growth.

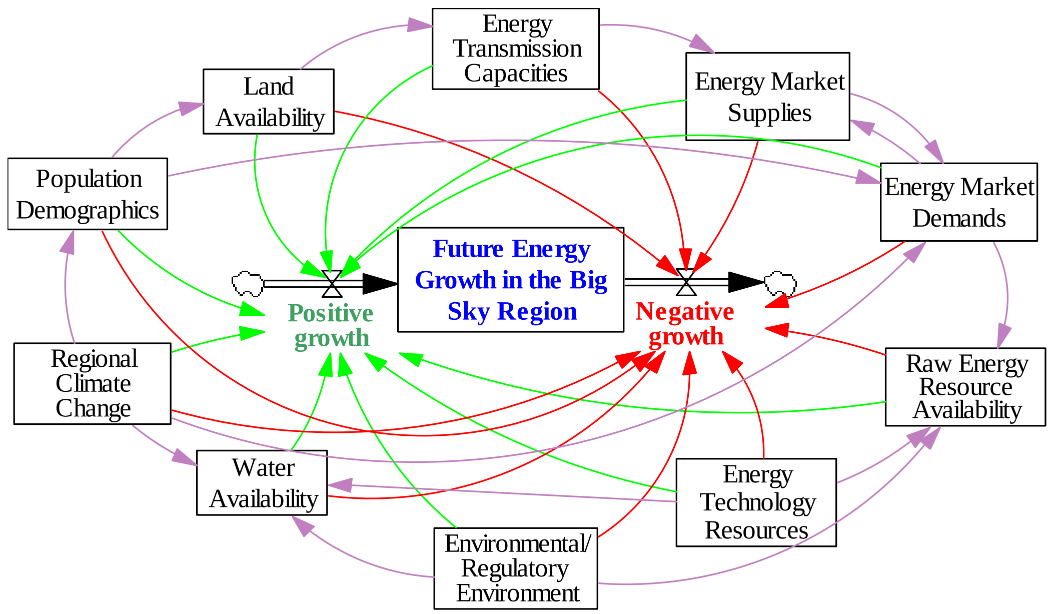


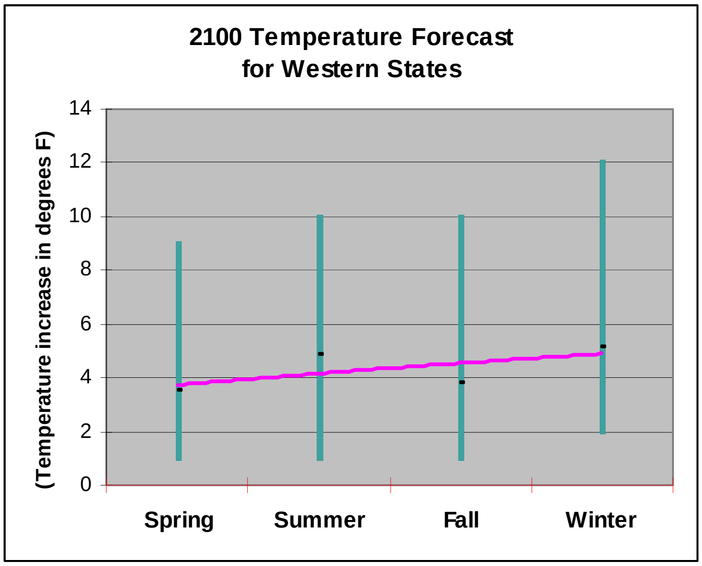
Figure 1. Causal relationships between the key dynamic factors affecting future energy growth in the Big Sky Region.

2. Factors Affecting Energy Growth

The following sections describe each of the key dynamic factors and their potential influences (positive and negative) on energy growth as they relate to the Big Sky region. In many cases, perspectives are provided for the Western U.S., with an emphasis on the Big Sky region.

2.1 Regional Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC) and the United Kingdom's Hadley Centre's climate model (HadCM2), the Western states are predicted to experience warming trends of 4–5°F over the next century, with the greatest temperature increases during winter. Figures 2 and 3 show precipitation trend lines (in red) and their range of potential variation (vertical blue line). The trends indicate wetter spring, fall, and winter seasons; but potentially dryer summers. [1,2] The data reflects a high degree of variability in the precipitation and temperature trends.



Figures 2. 2100 Temperature trends for Western states. [EPA data]

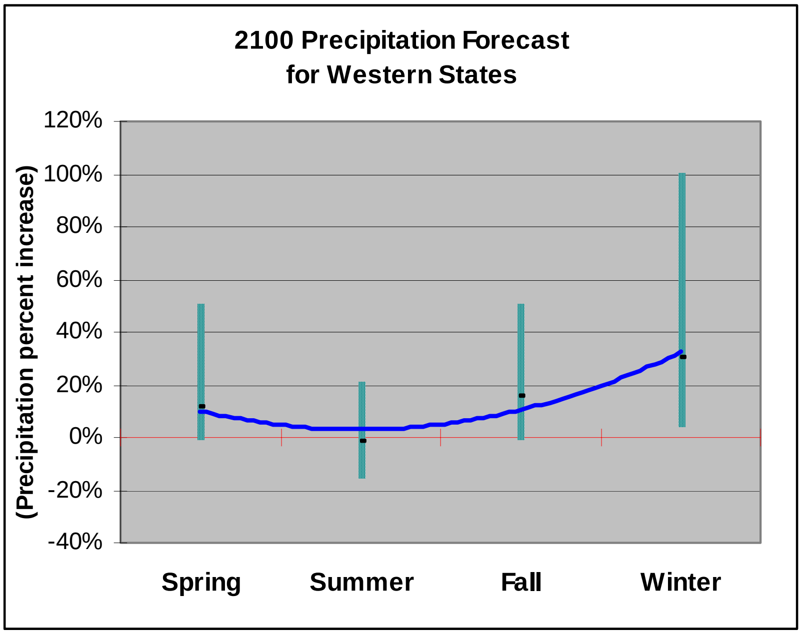


Figure 3. 2100 Precipitation Trends for Western States. [EPA data]

Over the past century, the average temperatures in the Big Sky region have increased between 1 and 1.6°F. Precipitation has increased by 20% in some parts of Idaho, while decreasing by 20% in most of Montana and Wyoming. Figure 4 shows the United States precipitation trends for 1900 to 1994. Climate models predict that the Big Sky regional weather during the next century will continue warming (1 to 11°F) and turn toward wetter (5% to 100% increases) spring, fall, and winter seasons. Summers may have up to 20% less precipitation. [3]

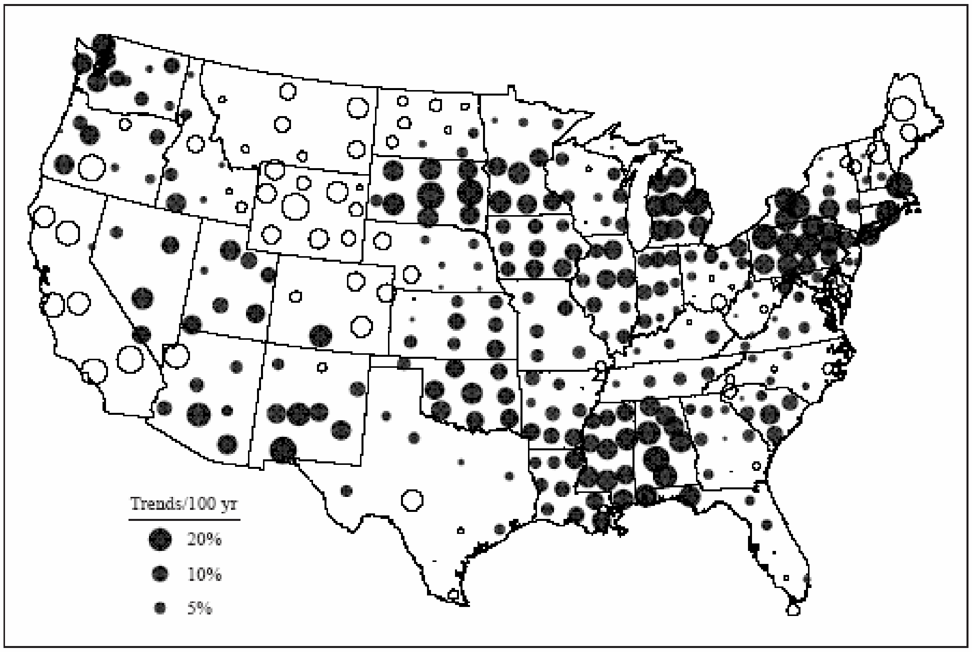


Figure 4. U.S. precipitation trends for 1900-1994 (converted to %/century), the black circles indicate an increase in precipitation while the hollow white circles indicate a decrease. [IPCC]

There are various potential implications from the changing weather patterns. Wetter conditions could benefit hydropower production, but could also increase flooding in some areas. In mountainous regions, warming could lead to a long-term reduction in peak snow-water equivalent, with the snowpack building later and melting sooner.

Ironically, wetter weather could result in streams without significant summer flows and lower reservoirs and water supplies to support hydropower electricity production.

In the Western U.S., the upper Colorado River is predicted to experience a -33 to +12% change in annual discharge. Reduced river flows and dry hot summer conditions in the Western states dependent on the Colorado River (e.g., California) could place a premium on water availability. Climate change may cause some areas to switch from a winter peaking regime to a summer peaking regime. If peak demand occurs in the winter, maximum energy demand is likely to fall, whereas if there is a summer peak, maximum demand will rise. Additional investments would be needed to supply electricity demands if the peak occurs in the summer.

Drier summer conditions would intensify competition for water among the diverse interests (e.g., power production, recreation, tribal rights, salmon, agriculture, etc.) and demands from growing populations in the West. Changes in water availability could complicate the complex water rights and allocations issues in Western states. Climate changes in the Pacific Northwest could result in dryer conditions and less water available to produce electricity for markets in the Intermountain and Rocky Mountain region.

Hydropower electrical output is subject to fluctuations reflecting year-to-year variation in precipitation. Idaho Power reports that in 1998, the share of electricity from hydropower exceeded 50%, but in recent years the proportion has lowered to 37%, due to customer growth plus below normal precipitation.

Groundwater supplies may also be affected by regional climate change. Unless precipitation increases, the increased evaporation that would accompany warmer temperatures probably would reduce groundwater supplies. Lower stream flows and runoff could reduce rates of groundwater recharge and exacerbate water supply problems.

Within the Big Sky region and the Northwest, high hydropower usage could be vulnerable to climate change impacts. Additional sources of energy may be needed to offset hydro reductions due to limited summer water supplies, support summer peaking loads, and increasing demands for water from growing regional population. Power companies, like Idaho Power, have an obligation to serve customer loads regardless of the water conditions that may occur. If hydropower is not available due to water shortages, then other non renewable sources may be tapped.

Weather conditions are the primary factor affecting load forecasts on the weekly, monthly, and seasonal time horizon. Economic and demographic conditions affect the load forecast in the long-term horizon.

Conclusions regarding the affects from climate change: 1) there is potential for a switch to summer peaking energy demands which could require additional energy resources, 2) less dependence should be placed on hydroelectricity, due to restricted summer flows and multiple conflicting demands, 3) future energy sources need to conserve water usage and be located in areas less likely to experience major variations in water availability, 4) hydropower dam reserves need to be sufficient to hold early runoff for use during the summer, and 5) existing less efficient power plants should be replaced by more efficient systems that require less cooling water.

2.2 Water Availability

Availability of cooling water is critical to the siting of future power plants. Thermoelectric power has been the largest water user in the U.S., accounting for 48 percent of total withdrawals (195 Bgal/day in 2000). Most of this water is derived from surface water and is used for once through cooling at power plants. In the West, California has the largest withdrawals for irrigation and thermoelectric power, as seen in Figure 5. In the Pacific Northwest, hydroelectric-power generation is used to supply a substantial part of the regional demand for electricity; therefore relatively small water withdrawals from fresh or saline-water sources are required. Idaho reports no withdrawals for thermoelectric power, due to the abundance of in-state hydroelectric-power generation. [4]

The headwaters of several rivers originate in the Big Sky region and flow in all directions to the Missouri, Snake, Colorado, Yellowstone, and Colombia. Changing water supplies in the Big Sky will directly impact down stream water users throughout the West.

Groundwater withdrawals also impact the water availability for power production. In the West, the Eastern Snake River Plain aquifer (shown in Figure 6) stretching across Southern Idaho, is one of the least tapped, but largest (1 billion acre-feet) water resources in the Western U.S. The aquifer annually supplies approximately 40,000 acre-feet (about 642 billion gallons) of water for drinking and nearly 2 million acre feed of water for irrigation and industry. In the West, Idaho has one of the highest intensity of freshwater withdrawals, in terms of gallons per day per square mile. Over the past 50 years, water levels in the Snake River aquifer have been impacted by increased pumpage from the groundwater, changes in irrigation practices (to sprinklers that do not replenish the groundwater), and prolonged droughts (1987–1994). Lower stream flows and runoff could reduce rates of groundwater recharge and exacerbate water supply problems. [5,6]

Future energy development should consider sustainable uses of water supplies. Tradeoffs between storing water for hydropower and expending water for thermal cooling should be considered. Thermal technologies using closed-loop cooling systems or air-cooled systems reduce the water requirements at the power plant, resulting in reduced water withdrawals. Renewable technologies, such as wind power, require no cooling water and are also being considered in future energy portfolios.

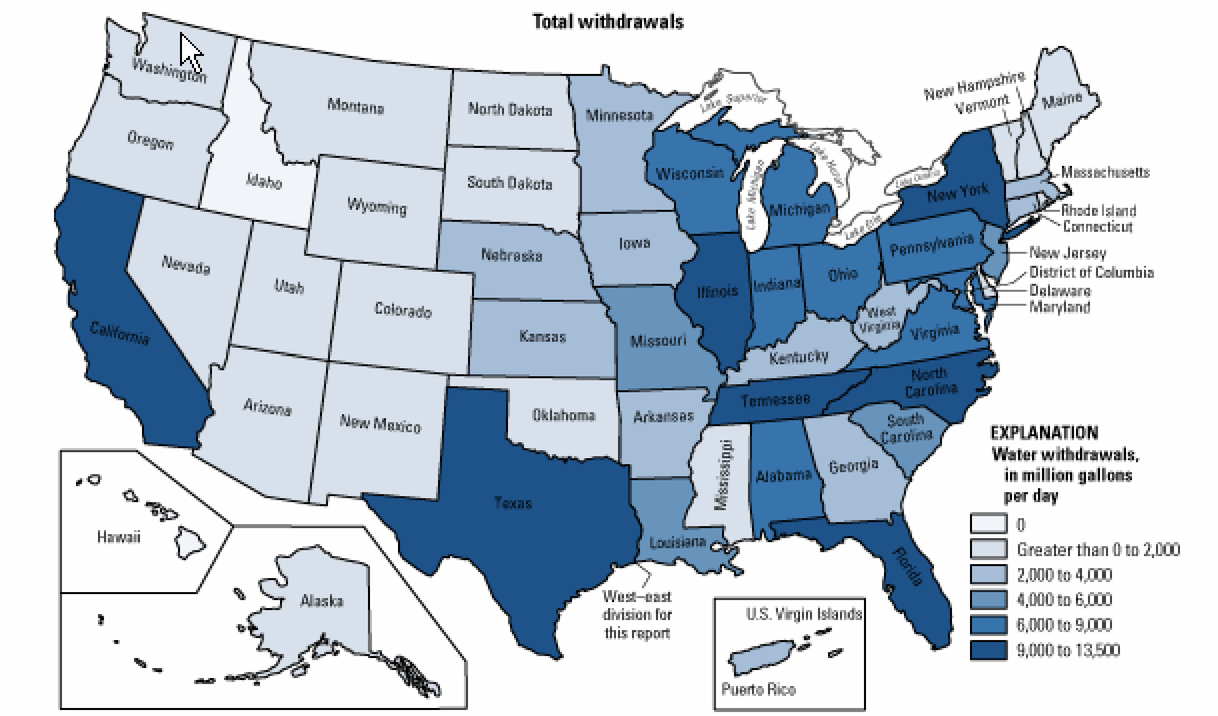


Figure 5. Thermoelectric-power withdrawals by water quality and state, 2000. [USGS]

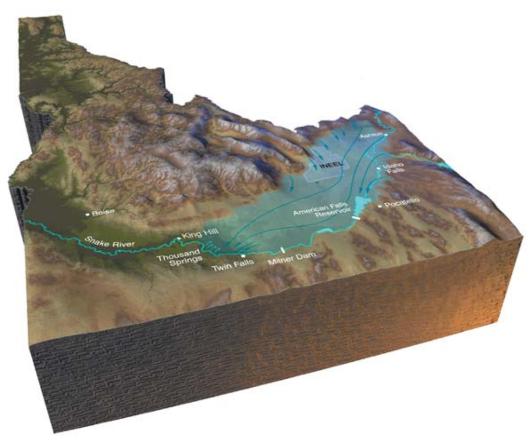


Figure 6. The Snake River Plain aquifer in Southern Idaho. [USGS, INEEL]

Conclusions regarding water availability: 1) the addition of thermoelectric power will put additional demands on surface and groundwater supplies, 2) the importance of the water resources produced in the Big Sky region will grow in step with energy demands and population expansion in the region, 3) climate change can impact groundwater and surface water supplies, which can directly influence the availability of water needed for power production from hydro or thermal energy systems, and 4) efficient thermal technologies can reduce the load on water supplies.

2.3 Population Demographics

The Western states are the fastest growing region in the United States. Population growth in six Western states has averaged more than twice the U.S. average of 16% percent, from 1990–2003, as indicated in Figure 7 and Figure 8 during the period of 1995 to 2025, the West is projected to grow at ~1.4-1.8% per year, versus the national average of ~0.9%. Growth is projected from factors including the base population, fertility, mortality, international migration, and domestic migration. Seven of the ten highest projected growth states in the U.S. are in the West (see Figure 9). Expanding populations, if coupled to growing economies, will drive the demand for electricity. In Idaho, the energy growth is estimated to expand at 80% of GDP growth. [7]

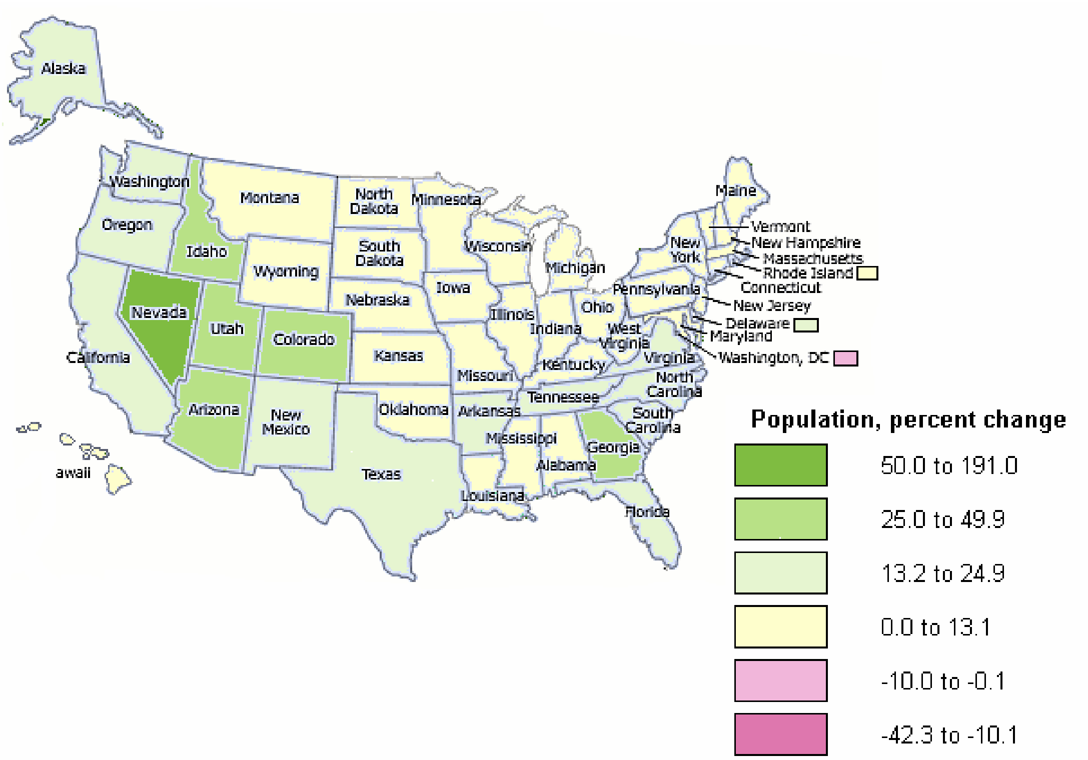


Figure 7. U.S. population change from 1990 to 2000. [US Census Bureau]

Within the Big Sky region, Idaho has seen the highest rate of population change from 1990–2000, at 49.5%; with Wyoming and Montana growing at slower rates (44.6% and 28.8%, respectively). These states combined, represent only 1% of the total US population (281 million in 2000) while occupying over 9% of the land area, hence resulting in a low population density.

Conclusions regarding population demographics: 1) expanding populations in the West, if coupled to growing economies, will drive demands for electricity, and 2) population migration to the intermountain West can cause greater interregional demands in addition to energy exports to the West Coast and Southwestern states, and 3) regional climate change can affect the desirability of the Big Sky region for businesses and individuals relative to other regions of the U.S.

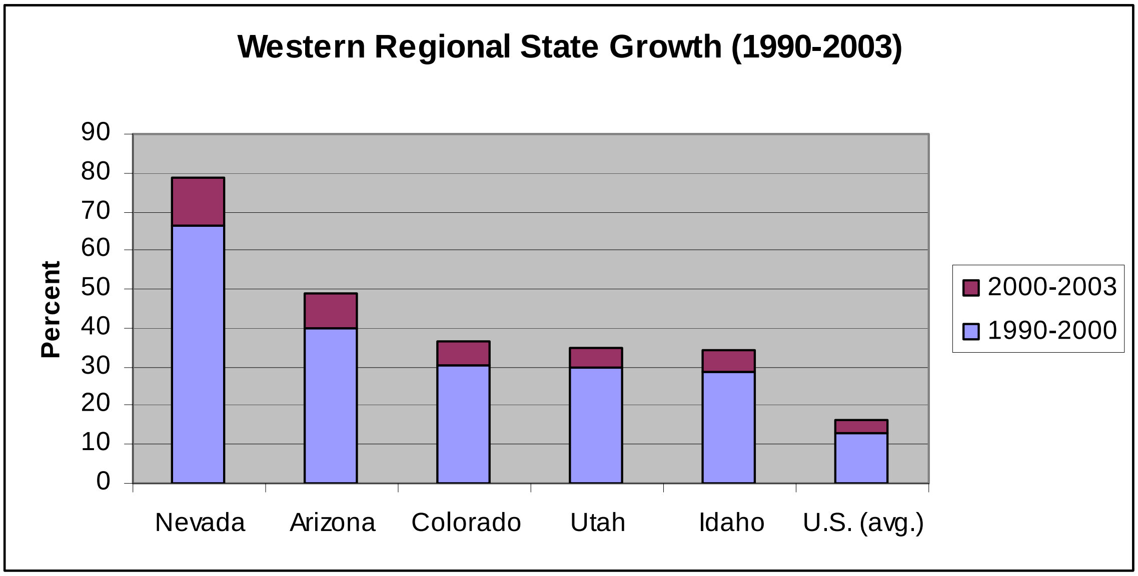


Figure 8. Western regional state growth from 1990 to 2003. [US Census Bureau]

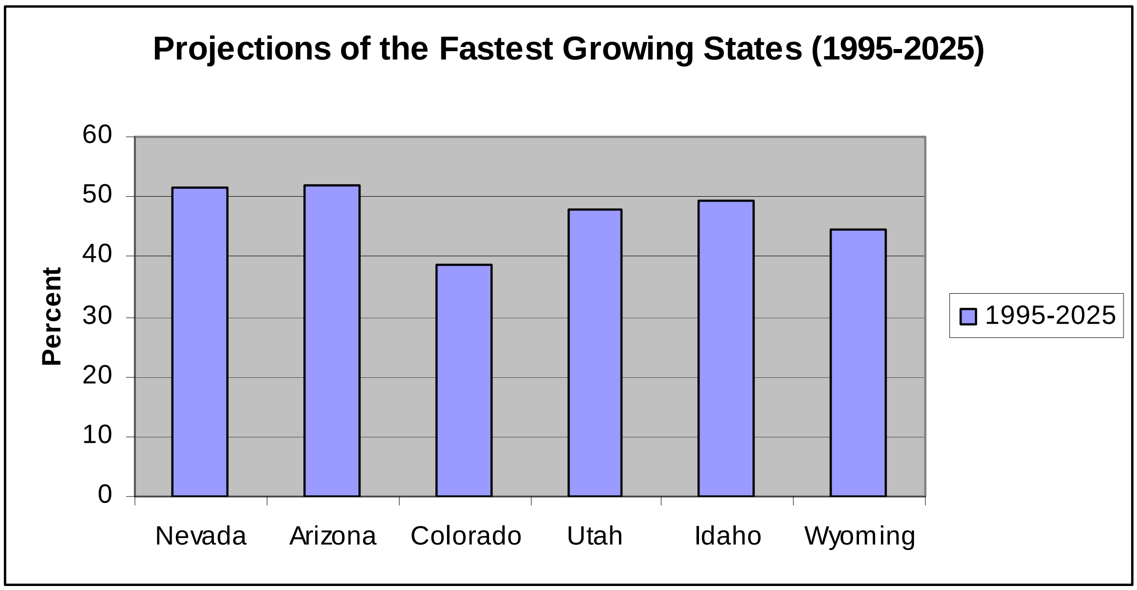


Figure 9. Projected fastest growing Western states from 1995–2025. [U.S. Census Bureau]

2.4 Energy Resource Availability

The Big Sky region contains abundant raw energy resources (i.e., water for hydropower, mineable coal, natural gas, wind, and geothermal resources) relative to the small population of the region. New energy resources (described below) are being planned to support the energy demands from population growth in the Big Sky region (e.g., Treasure Valley in Southwestern Idaho) as well as demands from expanding populations in the West. The Rocky Mountain States include Idaho, Montana, and Wyoming, as well as Colorado, Utah, and New Mexico.

COAL: According to the Organization for Economic Cooperation and Development (OECD), coal is expected to play a key role in the world energy mix, with demand projected to grow for steam coal, which is used for generating electricity and process heat, by 1.5% per year over the period of 2002–2030. The assumed 2008 generation capacity located within the Rocky Mountain States is 29,121 MW. The distribution of generation among the Rocky Mountain States is shown in Figure 10. [8]

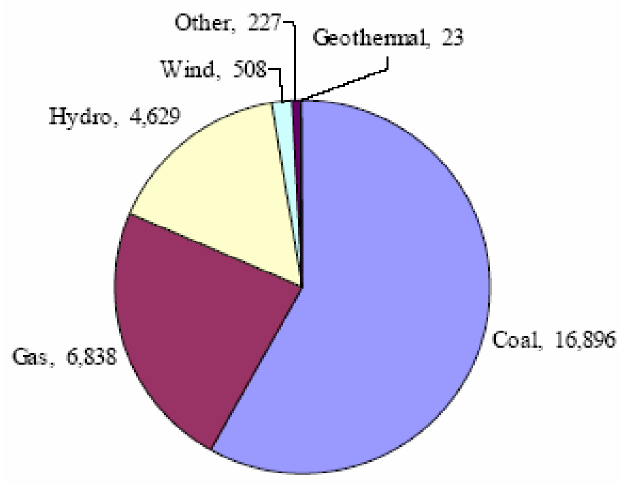


Figure 10. 2008 Rocky Mountain area total resources by type (MW) [OECD]

Significant reserves of coal are available in Wyoming and Montana. The Energy Information Agency (EIA) reports that Montana and Wyoming hold nearly 40% of the total U.S. coal reserves. Montana is ranked number one in reserves with 120.1 billion tons and Wyoming, ranked as number three, has 68.7 billion tons. In 2000, coal production in the Western Region (as well as in the entire United States) was dominated by Wyoming, which accounted for two thirds of the regional production and nearly one third of U.S. production of 1,073 million tons in 2000, as shown in Figure 11. Overall U.S. coal production in 2000 dropped 2.4 percent (26.8 million short tons) from 1999, but the Western region declined at a slower rate of only 0.3 percent. The decline in production was attributable to (1) a substantial draw down in total coal stocks, (2) a lack of excess production capacity at some mines, and (3) a reluctance on the part of some producers to expand production to meet increasing demands in the latter part of the year. Wyoming produced 338.9 million short tons of coal—only 7 percent less than the next three largest coal-producing states combined. In 2000, Wyoming continued an 8-year trend of increasing coal production, growing by 1.8 million short tons (0.5 percent). The continued penetration of the Powder River Basin coal into the eastern electric power markets has helped to drive Wyoming production to record levels for another year, although the level of growth dropped substantially in 2000. The slowdown in growth in Wyoming was a reflection of the decision by some producers to limit production expansion and by the constraints of the coal transportation (or railroad loadout) capacity in the Powder River Basin. [9,10]

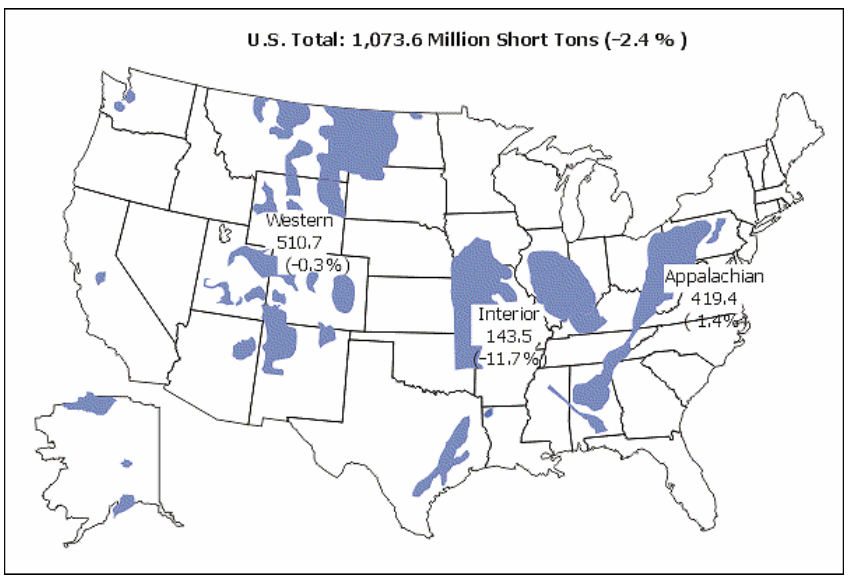


Figure 11. Coal Production by Coal Producing Region, 2000. [EIA]

WIND: Renewable energy from wind may also be tapped in the Big Sky region. Interest in wind power has grown considerably in the Big Sky region over the last several years. Several outstanding wind resource locations are available in Eastern Idaho, Montana, and Wyoming for large-scale wind development. The foothills of the Rocky Mountains are particularly attractive locations, as shown in Figure 12 by the brightly colored areas flowing from Northwest Montana diagonally traversing through Montana and across Wyoming. The region has excellent wind resources that could be tapped to support small- and large-scale wind turbine installations on farms, ranches and tribal lands. Wind is an intermittent seasonal resource, with the greatest production of wind electricity generated in the winter. The estimate used for annual energy output is a 35 percent capacity factor. The 35 percent factor means that a wind project with a nameplate capacity of 100 MW will produce and average of 35 MW over the course of a year.

Where the transmission grid is accessible, small-scale wind turbines can connect directly to existing power lines and provide economic benefits for rural landowners by allowing them to sell their extra power back to the utility. Larger-scale wind production will in some cases (e.g., Treasure Valley) require significant upgrades to the transmission paths. [11]

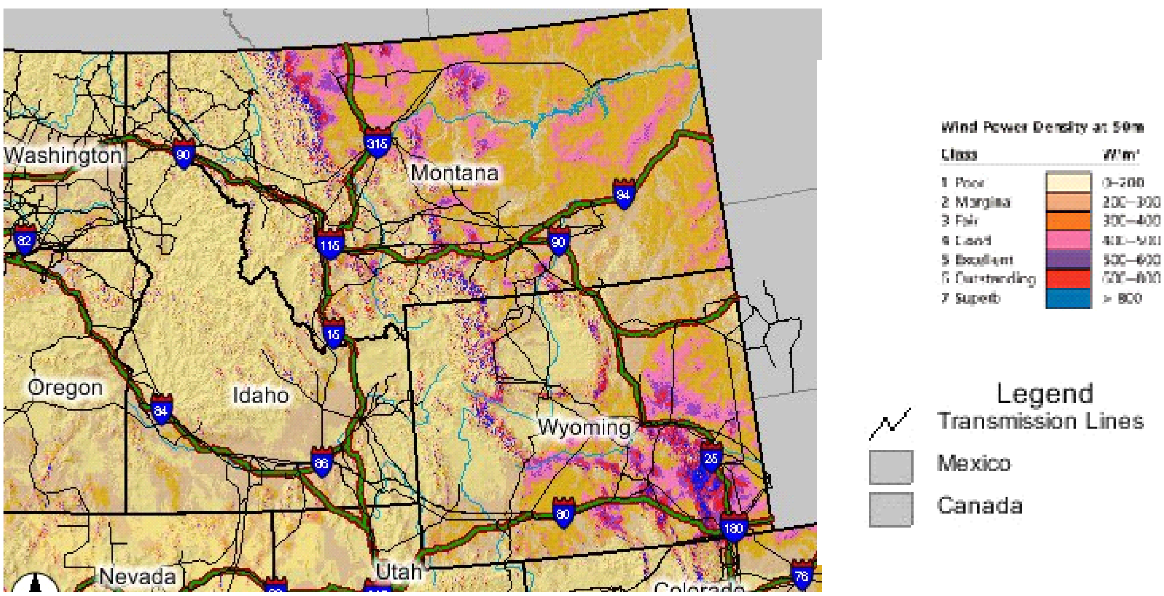


Figure 12. Wind power density in the Big Sky region. [Hewlett Foundation]

NATURAL GAS: Comparative supplies of domestic natural gas are significantly limited. Non-conventional reserves—coal-bed methane, tight gas and shale gas—mostly found in the Rocky Mountains could provide a major source of new supply. However, much of the gas is effectively stranded because of public access and environmental restrictions on drilling on federal lands. (Figure 13) About 5.5 Tcm are in the Rocky Mountains and mid-continent regions. [8,12]

Conclusions regarding energy resource availability: 1) the Big Sky region contains significant U.S. coal reserves which could be used to fuel thermoelectric power production in the region for many years, 2) the region also hosts regions with high potential to support wind generated power, 3) natural gas reserves may also be tapped in the future, if desired, and 4) abundant tracks of land are available to site new energy systems.

Source: IEA based on NPC (2003).

Figure 13. North American and Rocky Mountain growth of natural gas supplies. [OECD]

2.5 Energy Transmission Infrastructure

There are tradeoffs between shipping coal from mines to power plants versus shipping the electricity (wheeling the power) from a mine-mouth power plant to regional markets. Coal is commonly shipped by rail to power plants located near population centers, and then the electricity is transferred through the electric transmission and distribution system to end consumers. The railroad infrastructure has supported transport of coal from mines in Montana and Wyoming to coal power plants throughout the U.S. Some coal transportation capacity constraints have been associated with the Powder River Basin in Wyoming and Montana. [13]

The existing electricity transmission system in the Big Sky region is currently limited for new capacity growth. However, bottlenecks are known and solutions available to increase regional capacity and expand transmission corridors to surrounding Western markets. Plans have been drawn up in the Integrated Resource Plans of utilities in the West to expand capacity in selected bottlenecks to enable higher energy throughput in the region. The Rocky Mountain Area Transmission Study (RMATS) has developed two recommendations to expand energy transmission. Recommendation 1 includes three projects involving upgrades to the Montana system (tan oval), Bridger expansion (green oval), and Wyoming to Colorado Project (yellow oval) as shown in Figure 14. The expansion provided by these upgrades would provide for construction of 2,205 MW of wind power, and 1,884 MW of coal-fired generation capacity at the cost of $970 million. These upgrades would support new energy generation additions that are expected to meet expected load growth in the Rocky Mountain region for the 2013 timeframe. [13]

In addition to the export projects in Recommendation 1, Recommendation 2 provides expansions that extend beyond the Big Sky region that will substantially enable exports of generation. This longer-term proposal would 1) include the additional generation defined in Recommendation 1; 2) provide for construction of 3,900 MW of coal generation and remote wind generation; and, 3) build export paths to the West Coast, Nevada, and Arizona markets. This expansion would provide 7,800 total MW at the cost of $4.3 billion. Figure 15 shows the transmission expansion extending beyond the Big Sky region. Figure 16 shows the assumed generation additions provided by this upgrade. Figure 17 shows load centers and projected peak growth with existing transmission capacity, 1999 and 2010.

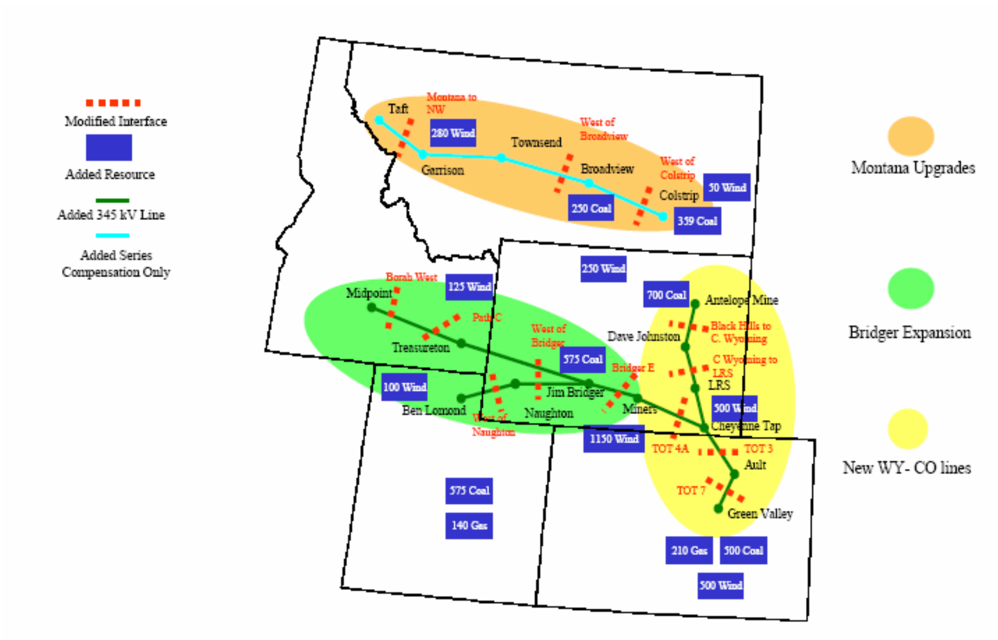


Figure 14. Recommended distribution upgrade projects in RMATS Recommendation 1. [RMATS]

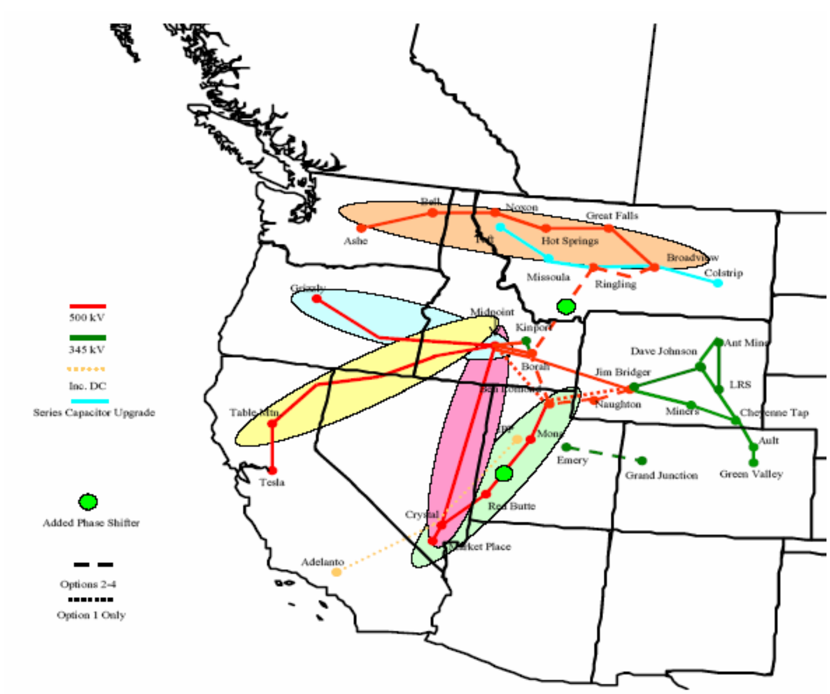


Figure 15. Transmission expansion extending beyond the Big Sky region. [RMATS]

Added transmission capacity acts as a “hedge” against the risk of upward swings in the forward price of power from natural gas and any other fuel source. The construction of new transmission capacity allows customers to pay a known amount now to lessen or lower the risk later of high dependency on a single fuel source, whose future price is vulnerable to fluctuations in regional and global market conditions.

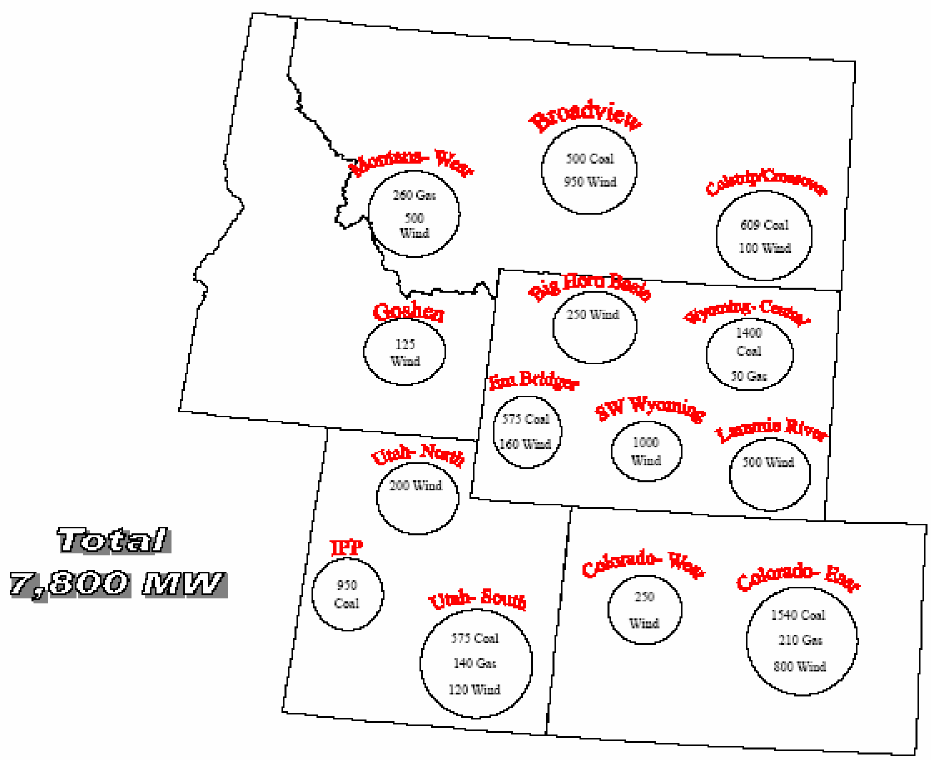


Figure 16. Generation additions assumed in Recommendation 2. [RMATS]

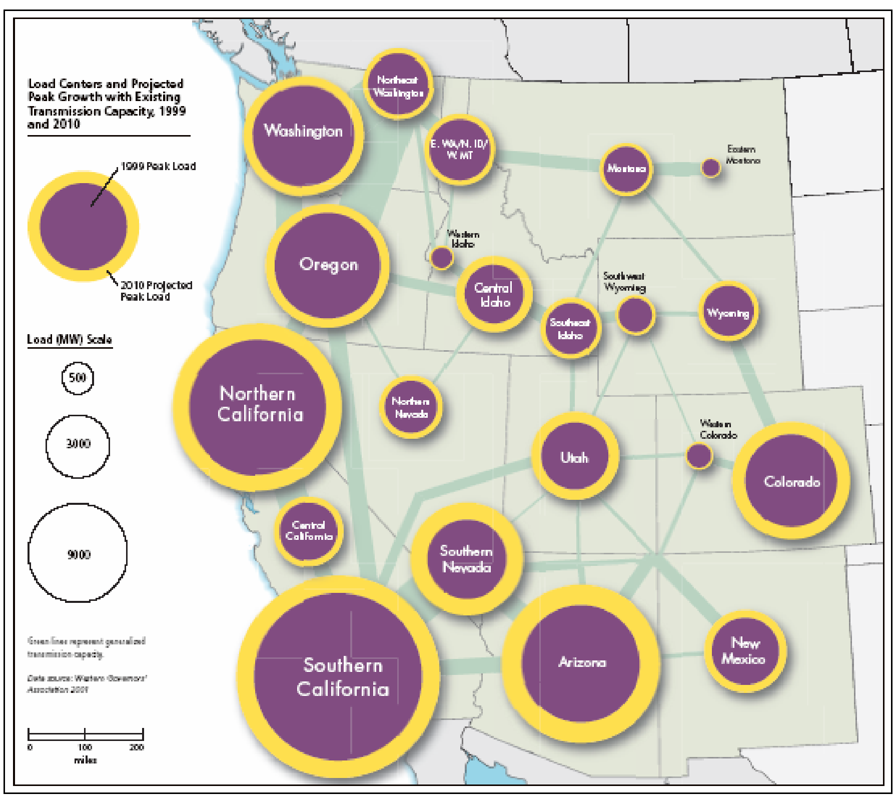


Figure 17. Load centers and projected peak growth with existing transmission capacity, 1999 and 2010. [Hewlett Foundation]

Open transmission access has facilitated the transfer of power within the West, but has also increased the competition for transmission resources. Since 1996, Idaho Power has been providing transmission service to qualified wholesale customers under its Open Access Transmission Tariff. Because of the geographic location of the Big Sky region, there are many requests to transport power between the Pacific Northwest and the desert U.S. Southwest. Idaho Power cannot deny service to qualified wholesale customers when there is sufficient transmission capacity available to satisfy the customer's request. The Open Access Transmission Tariff policy also provides that additional transmission facilities will be constructed if the party seeking the increased capacity pays the cost of adding the capacity.

Additionally, transmission-planning reserves have been increased as a hedge against unexpected loss due to natural or man-caused events. Natural events include low water years when peak-hour deficiencies are being met by energy purchases from the Pacific Northwest at the same time that system is delivering power to local users. Man-caused events include terrorist strikes to the national energy infrastructure, which could result in planning reserves to be widened, demands for increased system redundancy, and demands for additional power plants.

Conclusions regarding energy resource availability: 1) rail infrastructure is in place to transport coal to markets across the U.S., 2) increasing competition for electrical transmission compounds current bottlenecks within the system, and 3) transmission reserves may be widened to support contingencies for low water years and natural and man-caused disruptions.

2.6 Land Availability

Land is required to support the siting of new power plants and upgrades and additions to energy transmission. Transmission upgrade projects will, in some cases, require limited siting requirements (e.g., upgrades to existing substations sites). Alternatively, acquisition of sufficient land for substations and new transmission corridors are more serious issues. Land availability and transmission corridors will be important to implement large capacity upgrades. Land may also be required to obtain the water rights needed for power plant cooling water. Additionally, large tracks of lands would be required to support renewable sources like wind or solar power.

The Big Sky region is located geographically central to the West coast, the Rocky Mountains, and the Southwestern energy markets. The Big Sky region has large tracks of privately owned agricultural and range lands that could be reclassified for commercial uses, as has historically happened near population centers. However, a large percentage of the Big Sky region consists of federal lands, which historically have been challenging to secure the necessary easements for transmission corridors.

Conclusions on land availability: 1) suitable lands are necessary for energy production and transmission, and 2) lands are available in the Big Sky region but may require access to public lands.

2.7 Regional Energy Market Demands

Load forecasts are developed by the power companies to provide the most probable projection of service territory load growth during a planning period (generally 10 years). The forecast for the total load growth is determined by summing the load forecasts for residential, commercial, irrigation, industrial, and additional firm load growth. The projections of energy growth from selected Western Integrated Resource Plans (IRPs) as of July 2004 are shown in Figure 18. The projected annual growth rate ranges from 1.0% to over 3.5%. The expected load growth forecast for the Idaho Power service territory is 2.2% per year over the ten-year planning period. The peak loads for the West range from around 1,000 MW for Avista Corporation and NorthWestern Energy Corporation to as high as 9,000 MW for Pacificorp. [13, 16]

Energy suppliers are seeking a balance between renewable resources, demand-side measures, and thermal generation. In the recent past, fast growing energy markets have been meeting base load demand with low capital cost gas plants.

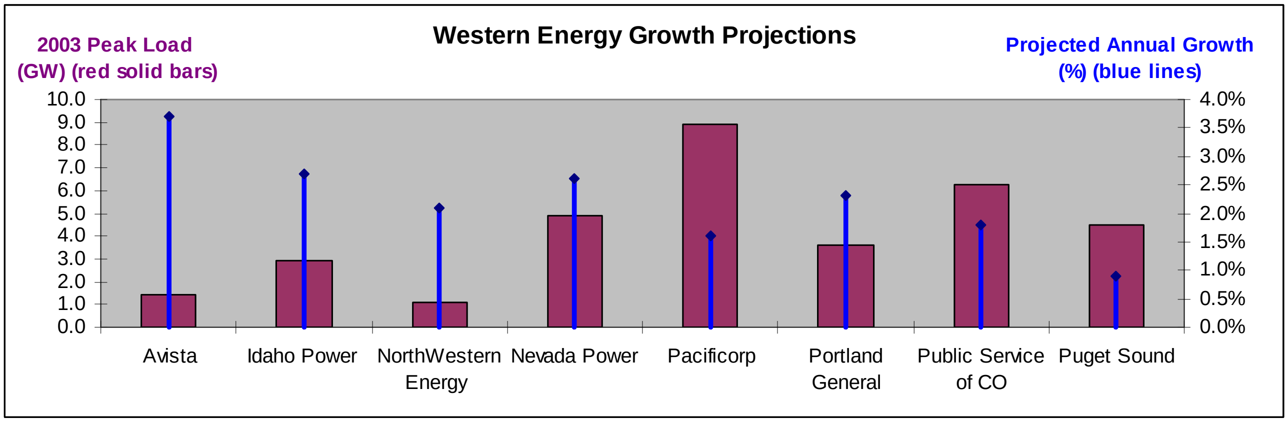


Figure 18. Growth projections for selected Western energy companies. [Western Governors Association]

Consequently, natural gas sets the price of electricity in the Western states more than 70% of the time. More than 90% of the interconnection is becoming increasingly dependent on gas-fired generation. But recent price spikes of natural gas (over $6/Mcf), which have been driven by increased demand, have cooled the interest in gas. Gas and oil, heavily imported from the middle-east, have seen historical price swings. Electricity costs over the past thirty years have shown increases in-step with the costs of imported oil and natural gas. The price stability of coal vs. the volatility of natural gas will be a factor in the selection of fuels for new power plants. By diversifying fuels, generators can mitigate gas price risks. Coal (lowest black line) has historically has been the lowest cost of energy on an equivalent cost of energy basis, as shown in Figure 19. Long-term coal resources in the Big Sky region are available to support long-term base load capacity. [17, 20]

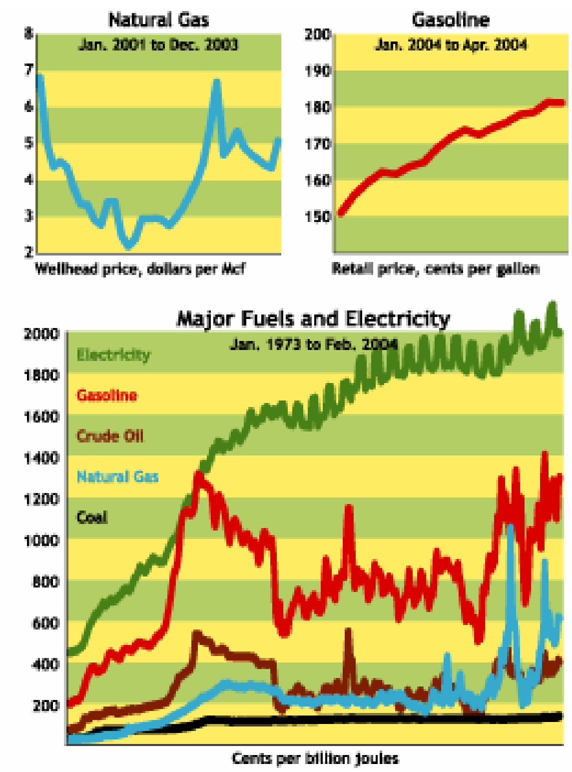


Figure 19. Comparison of Major Fuels and Electricity. [Power & Energy]

Conclusions regarding regional energy market demands: 1) the West has created a dependency on gas-fired generation to support peaking loads, 2) the price stability of coal vs. the volatility of natural gas will be a factor in the selection of fuels for new power plants, and 3) diversification of energy sources and expansion of transmission capacity can help reduce price spikes.

2.8 Environmental/Regulatory Constraints

There are increasing restrictions associated with the emissions from fossil power plants in Washington State and Oregon. Examples include:

• In the State of Washington, House Bill 3141 (signed in March 2004) requires that fossil fueled power plants with a generating capacity of 25 MW or more to mitigate 20% of the carbon dioxide emissions the plant produces over 30 years. This requirement also applies to new power plants seeking site certification and existing plants that increase production of carbon dioxide by 15%. [14]

• In 1997, the Oregon legislature gave the Energy Facility Siting Council authority to set carbon dioxide emissions standards for new energy facilities. The standard requires new power plants to emit 17% less carbon dioxide than the most energy-efficient plant available. The standard can be met by offsetting emissions through energy efficiency or carbon sequestration projects. Energy facility operators may implement offset projects directly, or by payment to the Climate Trust, which encourages and funds projects to reduce or offset CO2. New energy facilities can meet the standard in four ways: 1) building high-efficiency plants; 2) cogeneration projects; 3) invest directly in CO2 offset projects; 4) pay a fee (raised in October 2001 from $.57 per ton to $.85 per ton) for excess CO2 emissions. Plants constructed or planned since passage of the standard will double the generating capacity within Oregon. [15]

There is reasonable likelihood that carbon emissions will be regulated within the operational timeframe of any power plant built in the future. The other Western states could adopt carbon emission restrictions similar to Washington State and Oregon, or federal laws could be passed that restrict carbon emissions or require mandated cap and trade programs. Current regulations in the Big Sky region are not restrictive on carbon emissions. Fossil energy produced in the Big Sky may become more competitive as further emission restrictions are placed on other energy producers in the region. Longer term, the regulation of carbon capture, transportation, and geologic sequestration is another area of uncertainty. Future regulations may decide if geologically stored carbon dioxide is classified as a product or waste.

Conclusions regarding environmental/ regulatory constraints: 1) the Big Sky region currently allows unrestricted carbon emissions, 2) carbon restrictions within the West may provide a short-term competitive advantage for electricity produced in the Big Sky region, and 3) the regulatory issues associated with geologic sequestration are important to future fossil energy development in carbon constrained environments.

2.9 Energy Technology Resources

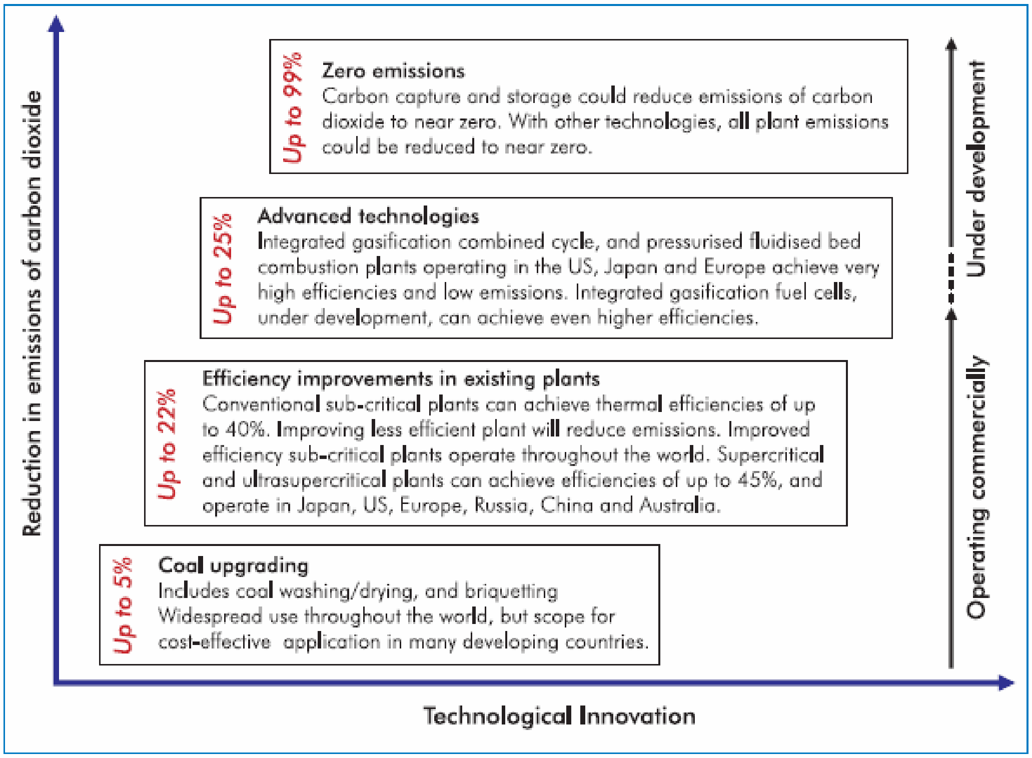
Implementation of clean coal technologies, which would improve the thermal efficiency of coal production and use and reduce emissions, could minimize investment risk and give a major boost to prospects for coal demand. New techniques have been developed for coal mining and the preparation of coal for use in power stations, as well as for coal combustion, emissions-control and the disposal of solid waste. Technologies on the horizon such as carbon capture and storage could achieve near-zero emissions of all pollutants from coal-fired power plants. Technology innovations are expected to reduce the emissions of carbon dioxide as shown in Figure 20. [8]

Future energy concepts, including FutureGen, would include the production of hydrogen and sequestration of carbon dioxide. Siting of these future power plants would need to consider market opportunities for hydrogen and new fossil energy products (e.g., syngas), and sequestration locations for storage of carbon emissions.

The Big Sky region has several unique characteristics relative to the production and storage of carbon. First, the region is very near zero-net carbon emissions resulting from a small but growing industrial base, low populations, and large areas of forest and agricultural lands which hold the capacity to store carbon. [19]

The Big Sky region has diverse geologic formations, as shown in Figure 21, which could take carbon captured from power plants and permanently store it in geologic reservoirs in a solid carbonate form.

Carbon offsets could be also achieved through terrestrial sequestration in the rich agricultural and forested areas of the Big Sky region. Processes are being developed to increase soil organic carbon and store carbon in biomass. The Big Sky region has diverse agricultural, timber, and grasslands that could be used to store carbon, as shown in Figure 22.



Source: Based on World Coal Institute (2003).

Figure 20. Reductions in emissions of CO2 through technology innovation. [OECD, World Coal Institute]

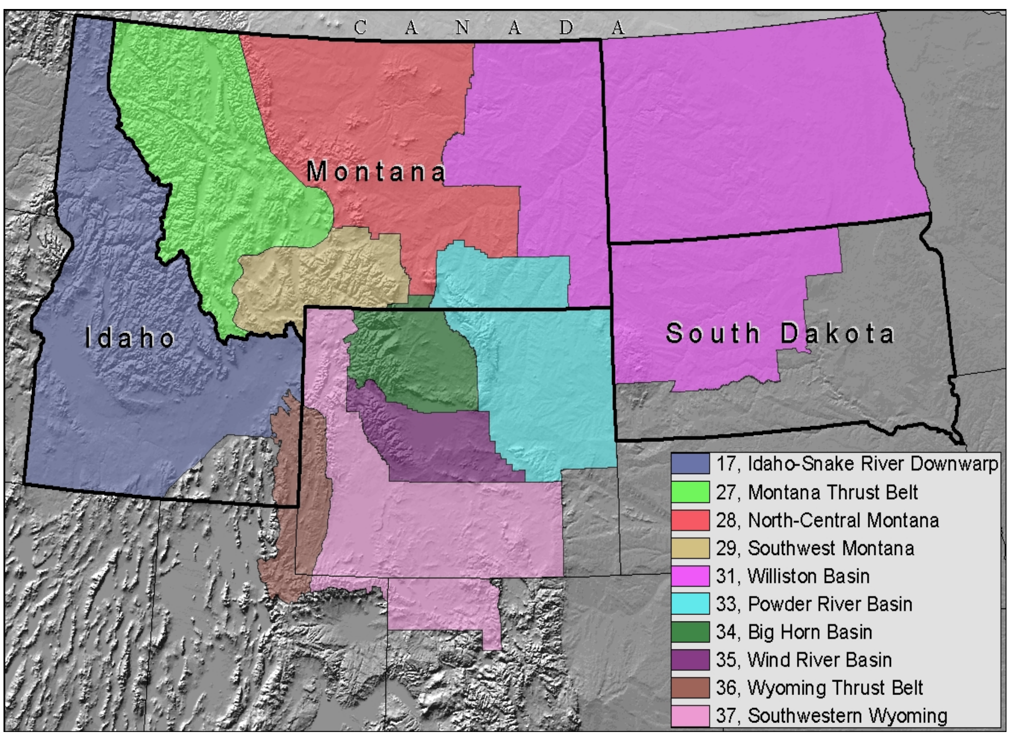


Figure 21. Diversity of geologic sequestration locations in the Big Sky region. [Big Sky Regional Carbon Sequestration Partnership]

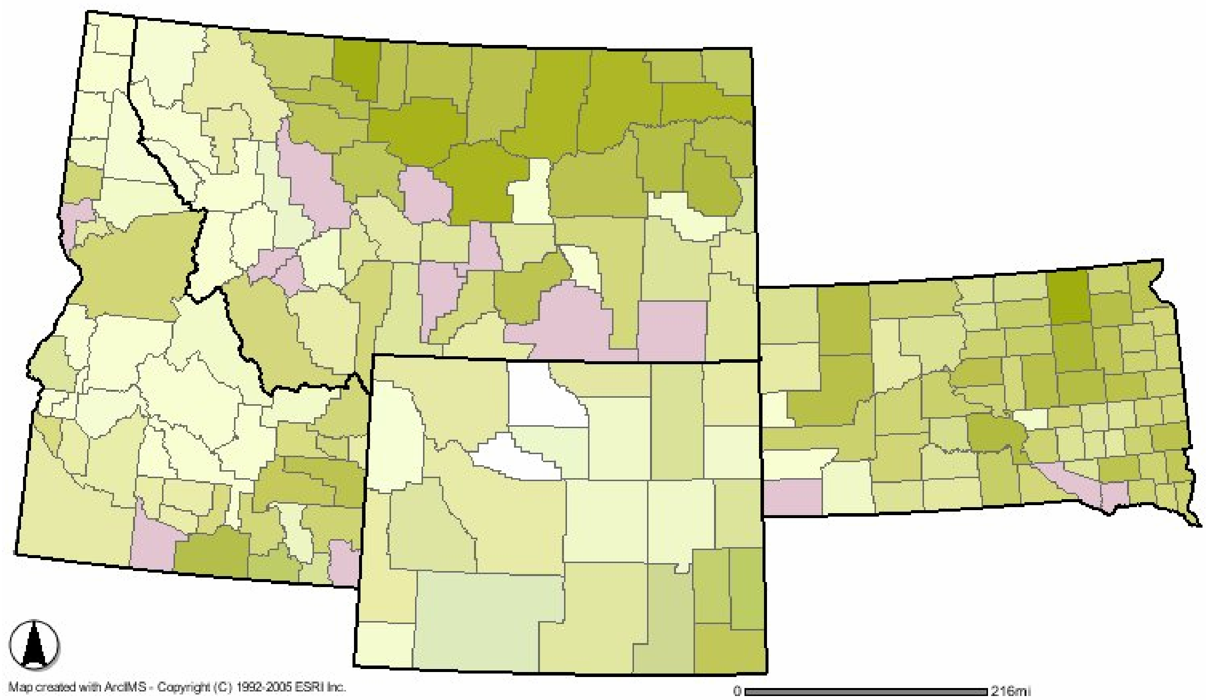


Figure 22. Diversity of terrestrial sequestration locations in the Big Sky region [Big Sky Regional Carbon Sequestration Partnership]

Conclusions regarding energy technology innovation and the Big Sky carbon sequestration resources: 1) clean coal technologies would improve the thermal efficiency of coal production and use, reduce emissions, minimize investment risk, and would give a major boost to prospects for coal demand; 2), the region offers diverse terrestrial and geologic sequestration opportunities; and 3) the Big Sky region currently has very low carbon emissions that are substantially offset by agriculture and forestry carbon storage; and 4) new energy products derived from hydrogen and carbon dioxide streams could be sold in regional markets.

3. Conclusions

Evaluating future energy growth in the Big Sky region is a complex undertaking that must account for many dynamic conditions. One emerging condition that has the potential to impact energy growth is climate change. The Big Sky region is well positioned to be the location for future energy development due to the wealth of energy resources, including both renewable and nonrenewable assets, and access to growing energy markets. The Big Sky region has the capacity to increase its energy production and provide a wealth of carbon sinks for carbon dioxide produced through energy production. The Big Sky Regional Carbon Sequestration Partnership is examining regional carbon sequestration resources that could be used to reduce or offset the carbon emissions from fossil power energy production and other industrials. This study will be used by the Big Sky Partnership to gain insight into the issues impacting regional energy demand and facilitate the development of a regional infrastructure that can support future energy development with carbon sequestration resources. The methodologies created through this partnership are intended to be applicable to other regional applications.

Acknowledgements

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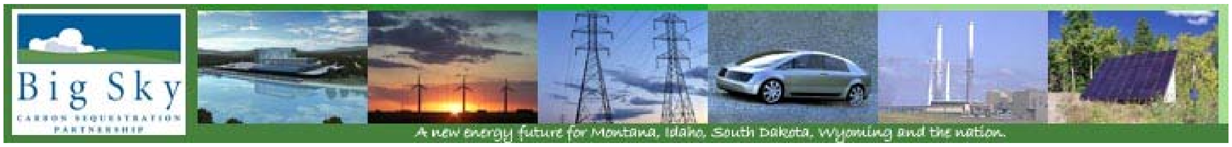

Big Sky Carbon Sequestration Partnership – Phase I

Deliverable 2 and Deliverable 3: Report on Technology Needs and Report and Action Plan on the Evaluation of Geologic Sinks and Pilot Project Deployment.

July 2005

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Susan M. Capalbo
Big Sky Principal Investigator
207 Montana Hall
Montana State University-Bozeman
Bozeman, MT 59717-2460
scapalbo@montana.edu
http://www.bigskyco2.org/
Phone: (406) 994-5619
Fax: (406) 994-2893

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CO_2 Sequestration Potential of Sedimentary Basins in the Big Sky Region

Nathan Erickson, University of Idaho
Travis L. McLing, Idaho National Laboratory

Presented in this section is an annotated description of the (carbon dioxide) CO_2 sequestration capacity of the large sedimentary basins contained within the Big Sky region. A master's thesis by Nathan Erickson at the University of Idaho, Idaho Falls campus contains a more complete description of the data and methodology. Mr. Erickson is expected to complete his thesis in December 2005.

Introduction

The region encompassed by the Big Sky Partnership hosts a number of large sedimentary basins including the Powder River, Williston, and the Green River and associated basins (Figure 1). Together these basins cover more than 400,000 km^2 of Wyoming, South Dakota, and Montana. These basins range from 1,500 to 3,000 meters thick and are comprised of bedded sandstones, shales, thick coal beds, dolomites and limestone. The same geologic conditions (i.e. basins depth, structure, and permeability), that have made these basins productive coal and hydrocarbon producers also make them attractive targets for large scale CO_2 sequestration. In addition to representing large storage potential, the basins also posses desirable mineral characteristics. These minerals, when exposed to CO_2 and water, can rapidly convert to stable secondary minerals phases, effectively sequestering CO_2 indefinitely. Also contributing to CO_2 sequestration suitability are thick deposits of unminable sub bituminous coal, located deep within many of the basins. These thick coalbeds can adsorb CO_2 onto the internal surfaces of its microporous structure releasing methane that can then be captured and used. Preliminary empirical data shows that the sub bituminous coal found in the Wyoming and Montana sections of the Powder River basin (Figure 1) is superior to other higher ranked coals for CO_2 storage.

The importance of evaluating the sequestration potential of these basins is self evident when considering the growing power demands of the west and the vast resources and energy producing potential of this region. It is clear that the resources of these basins will be used for energy production well into the future. Therefore, a full characterization of sequestration capacity will be beneficial for locating future power plants built to meet the energy demands of a growing population in the western U.S.

Because of the wealth of natural resources associated with the basins in the Big Sky region they represent significant targets for future energy exploitation and CO_2 sequestration. During the performance period of Phase I, the Big Sky Partnership geology team has developed techniques to evaluate the sequestration potential of these basins. As a result of the Phase I assessment, a capacity and location catalog of sedimentary target reservoirs has been developed.

Discussion

Because of the vast amounts of oil, natural gas and coal associated with the Powder River, Williston, and the Green River basins, a large volume of data has been collected on them, much of it from the public domain. The states of Wyoming and Montana have organized the collected data from their respective states into publicly accessible databases. The assessment of the volume of CO_2 that can be sequestered in these reservoirs was evaluated at a sub-basin scale. For convenience, these basins were broken into manageable parcels of like geology. These parcels are known throughout the oil and natural gas industries as plays[1] which are defined as geologic units comprised of a potential hydrocarbon source, reservoir rock, and cap. In order to maintain uniformity with the other six regional partnerships, the Big Sky Partnership geology team based its play location and boundaries on the 1995 National Assessment of United States Oil and Gas Resources conducted by the United States Geological Survey (USGS 1995). The National Assessment identified 10 provinces (Figure 2) and 107 plays (Figure 3a, 3b) in the Big Sky region. Of the 107 plays, 80 are conventional (Figure 3a) or plays with oil and natural gas deposits that can be extracted using traditional methods. The remaining 27 are unconventional plays (Figure 3b)which are generally characterized as continuous geologic formations that because of rock type, geologic timing, or seal failure do not contain hydrocarbons. The Big Sky Partnership's geologic team has utilized the copious volume of data available from the 107 plays to calculate the sequestration potential of the large sedimentary basins occurring in its region.

Each play has one or more geologic formations that were identified; the needed properties for each formation were collected based on availability. Wyoming's data is typically available at the well level, while Montana's depth to formations is recorded at the well level, and all other properties are only available for each oil or natural gas field. South Dakota does not have a unified database for the collections of oil and natural gas field properties; as a result, an assessment of sequestration potential has not been made. Generally, a great deal of data is available for plays that have produced or are thought to be capable of producing hydrocarbons, as there is an economic driver for collecting the data. The States of Montana and Wyoming have gone to great lengths to collect the available data into state managed databases which are available to the general public.

Evaluation Parameters

The evaluation of sequestration potential for sedimentary basins requires the collection of specific parameters for each play (Table 1). The parameters of interest for each play include the properties that describe the rock chemistry, brine chemistry, hydraulic conditions, depth to play, etc. In most cases this data is easily obtainable as the parameters are typically collected to determine hydrocarbon production. Oil, natural gas, and coal data for Montana and Wyoming are recorded differently in each state; Wyoming has an advanced system of collecting and recording all data for each well to a single source. The Wyoming Oil and Gas Conservation Commission maintains a web site that contains all oil and natural gas wells, their corresponding well logs and/or other properties measured for each well. Montana's data system is not as advanced and requires the use of several different sources; 1) Montana Board of Oil & Gas Conservation which has the well locations and depth to each formation that is maintained on a their website, and 2) Montana Geological Society, which identifies the reservoir properties of each oil and natural gas field, in book form, for all of Montana. Each of these sources provides important information that will be used to calculate the amount of CO_2 a reservoir will contain. Table 2 shows a list of important properties and the source from which they are collected. The data is used in calculations to determine the amount of CO_2 that can be contained in each reservoir. All information is collected into a Microsoft Access database and converted into a GIS format for the assessment.

CO_2 capacity is calculated for all of the 107 identified plays. Properties listed in Table 1 are used to make the calculations with the assumption that 50 percent of the reservoir pore space is available to

[1] The fundamental geologic unit used in the 1995 National Oil and Gas Assessment was the 'play', which is defined as a set of known or postulated oil and or gas accumulations sharing similar geologic, geographic, and temporal properties, such as source rock, migration pathways, timing, trapping mechanism, and hydrocarbon type

store CO_2. Using the reservoir specific data, a series of calculations (appendix A) determine the sequestration volume. These calculations are extremely sensitive to: temperature, pressure, salinity, reservoir thickness, reservoir area, porosity, and water saturation. Subtle changes in these values could result in a significant change of calculated reservoir capacity.

Wyoming Data

Wyoming's data is available from the Wyoming Oil & Gas Conservation Commission website (http://wogcc.state.wy.us/), with information on 117,304 wells and 351,823 formations available for download. Some wells are recorded in multiple oil and natural gas fields; therefore, a query is used to exclude duplicate records. Formation names are sorted and normalized for consistency in naming, this avoids duplication of records in the database. The water analysis data for each formation in Wyoming also is downloadable and includes sample date, ion concentrations, total dissolved solids, pressure temperature, and pH. The same database also contains formation parameters including depth interval, temperature, water resistivity, and shut in pressure. In addition, records for porosity, grain density, oil content, and water saturation are available for all formations with a core analysis record. Average values for each formation are calculated and entered into a Microsoft Excel spread sheet and later used to determine the porosity and water saturation for each play.

Montana Data

The data for Montana's wells and the depth to each formation are obtainable from the Montana Board of Oil and Gas Conservation website (http://bogc.dnrc.state.mt.us/). The formation properties are available from the Montana Geological Society, which in 1985, produced two books containing information on all of Montana's oil and natural gas fields (Tonnsen and others, 1985). The Montana Oil and Gas Fields Symposium books report properties for each formation within each field, including porosity, water saturation, lithology, salinity, and other properties. This data is entered into Microsoft Excel manually and quality control checks eliminate errors. Data from a total of 253 oil and natural gas fields and 489 formations were downloaded.

Sequestration Potential

The assessment of each plays capacity to sequester CO_2 shows the enormous volume of CO_2 that could be sequestered in each play, an from the Lakota formation is shown in Figure 4). The volumes for each play are the sum of all formations in that play and do not take into account formation ranking. According to the Energy Information Administration, (www.cia.doe.gov), the total CO_2 emissions for the United States year are 5.8 billion metric tons, while many of the saline aquifer capacities in the Big Sky region are in the 10,000 to 100,000 million metric tons range. Total sequestration volumes for the Wyoming, Montana, and South Dakota sedimentary basins have been organized by reservoir type: saline aquifer, oil and natural gas reservoir, and coal seams. These capacities range from .1 to 10^6 million metric tones of CO_2. In general, non oil producing saline aquifers represent the most volumetrically significant target for sequestration with some of these formations reaching nearly 1,000,000 million metric tones of capacity. An example of how this information can be use is shown in Figure 4. In this example, the Lakota formation contained within the Power River Basin is present in terms of its sequestration potential as a function of depth. Also presented is the formations proximity to cities, wells, pipelines, power plants, and state boundaries. Although this approach represents an inherently conservative estimate for CO_2 sequestration capacity, it does provide the appropriate information needed to determine if a given location is suitable for further investigation. Overall, every sedimentary formation investigated in the region has the potential to sequester large amounts of CO_2. Many other formations are lacking sufficient data to conclude upon their ability to sequester CO_2. As information is made available, these formations will be evaluated and may also prove to be favorable carbon sequestration targets.

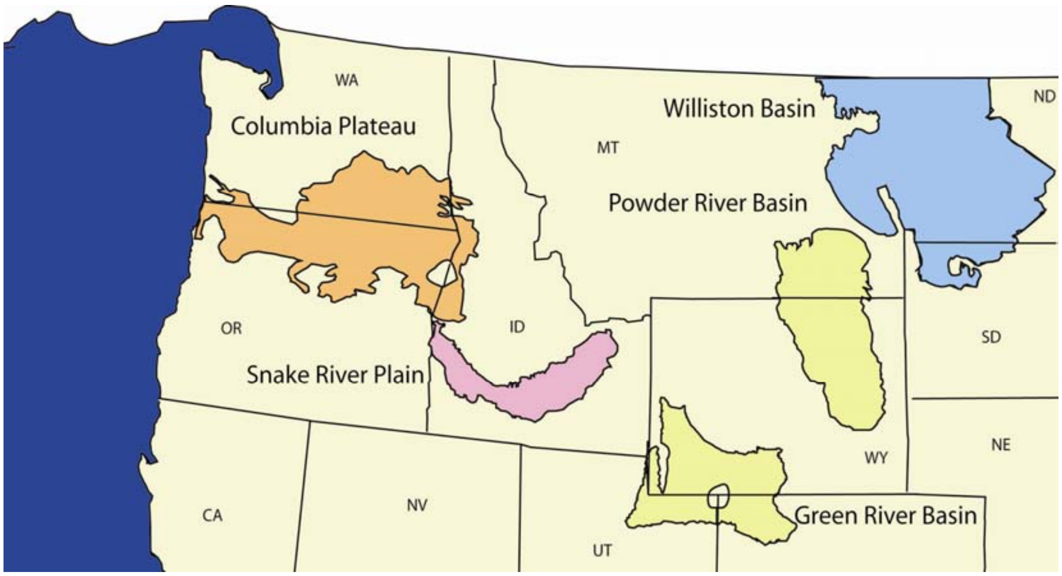


Figure 1. Major sedimentary and volcanic basins within the Big Sky Partnership.

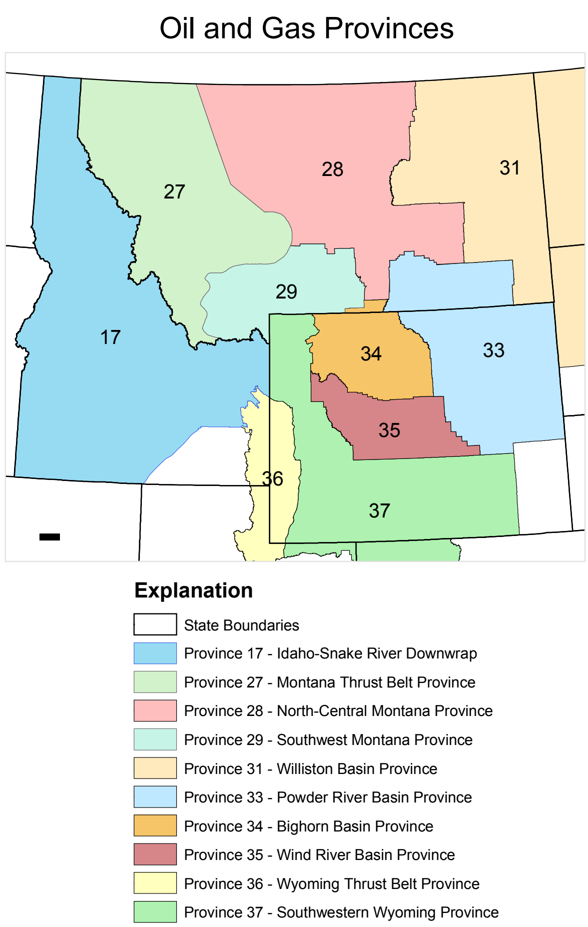


Figure 2: Oil and gas provinces located within the Big Sky Carbon Sequestration Partnership.

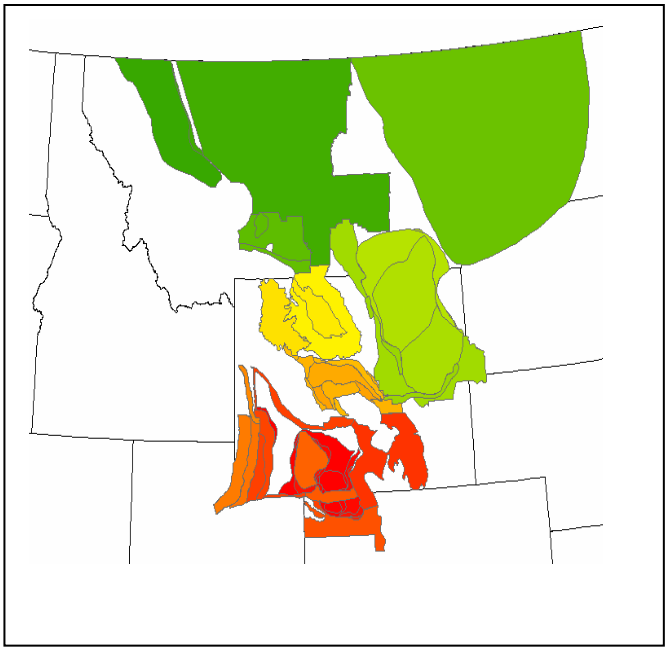


Figure 3a Known sedimentary plays

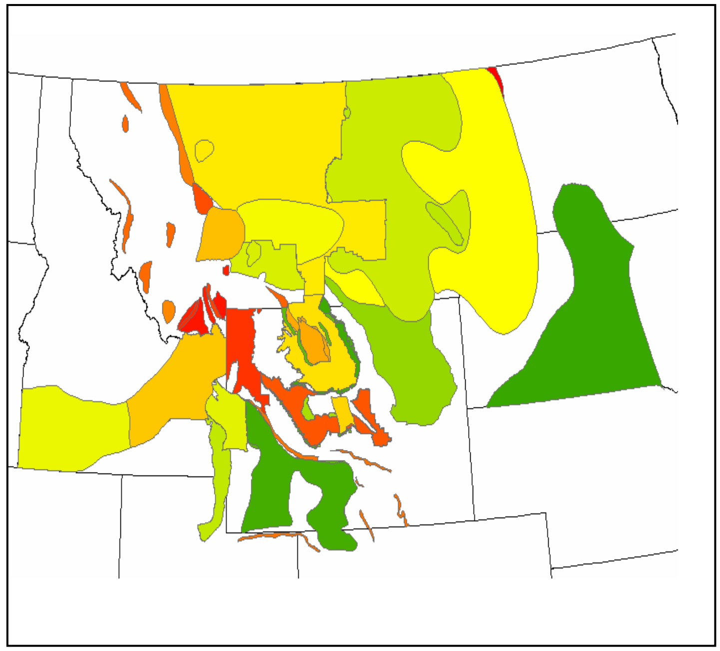


Fig 3b unconventional Plays

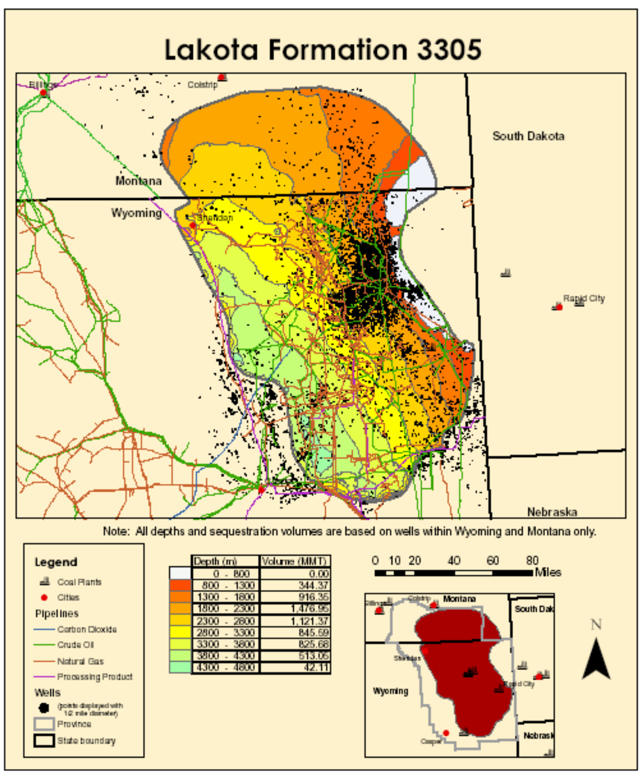


Figure 4. Sequestration and infrastructure information for Lakota formation in Play 3305

	Evaluation Properties
1	Porosity
2	Depth
3	Pressure
4	Temperature
5	Lateral extent
6	Thickness
7	Water saturation
8	Gas content of coal
9	Salinity
10	Rock type
11	Cap rock
12	pH
13	Fluid properties
14	Permeability
15	Faults
16	System integrity
17	Whole rock chemistry

Table 1: Required properties needed to calculate CO_2 sequestration potential.

	Wyoming Data Sources				Montana Data Sources	
	Lithology & Location	Pressure &Temp	Water Chemistry	Cores	BOGC Web Page	Symposium Book
Api (Identification #)	X	X	X	X	X	
Formation	X	X	X	X	X	X
Latitude	X				X	
Longitude	X				X	
Field	X				X	X
Elevation	X				X	
Well Class (oil, gas…)	X				X	
Depth	X				X	
Temp		X				X
Pressure		X				X
RW		X				X
Chemistry			X			
Salinity			X			X
pH			X			
Porosity				X		X
Perm.				X		X
Saturation				X		X
Unit Thickness						X
Cap Rock						X
Rock Type						X

Table 2. List of all characteristics and sources for which data was available in Montana and Wyoming.

Appendix A

Oil and Natural Gas Reservoir Calculations

Once all properties are in a usable format, applications to facilitate calculations are explored. ArcMap 9.0 has an application called Model Builder which allows users to combine multiple processes or calculations in the same application. The calculations for oil and natural gas reserves and saline aquifers are combined in the same model. The complete model has a total of 26 steps. The following information provides the equation for each step, any assumptions, and explanations.

1 - Calculate pressure in psia. To calculate a pressure for the entire area of interest an equation that uses the depth to calculate pressure was used (McDonald, 2003).

(Equation 1) $P(psia) = .433 * Depth$

2 – Calculate pressure bar. Pressure was converted from psia to bar. A value of 1×10^{-15} was added for future calculations that required there be no zero values.

(Equation 2) $P(bar) = (P(psia) * .0689475729) + 1 \times 10^{-15}$

3 – Calculate pressure mpa. Pressure was converted from bar to mpa.

(Equation 3) $P(mpa) = P(bar) * .101325$

4 – Calculate temperature in Fahrenheit. To calculate a temperature for the entire area of interest on equation that relates temperature to depth was used (McDonald, 2003).

(Equation 4) $T(f) = 61 + (.007 * Depth)$

5 – Calculate temperature in Kelvin. Temperature was converted from Fahrenheit to Kelvin. A value of 1×10^{-15} was added for future calculations that required there be no zero values.

(Equation 5) $T(K) = (((T(f) – 32) * 5/9) + 273.15) + 1 \times 10^{-15}$

6 – Calculate the reference Henry's constant or H_{CO2}. Based on experimental data a relationship using temperature (K) to calculate H_{CO2} was developed (Bachu and Adams, 2003).

(Equation 6) $H_{CO2} = -5032.99 + 30.741113T – 0.052667T^2 + 2.630218 \times 10^{-5}T^3$

7 – Calculate the molar volume of CO2 at infinite dilution or v_{CO2}. Based on experimental data, a relationship using temperature (K) to calculate v_{CO2} was developed (59).

(Equation 7) $v_{CO2} = 1799.36 – 17.8218T + 0.0659297T^2 – 1.05786 \times 10^{-4}T^3 + 6.200275 \times 10^{-8}T^4$

8 – Calculate constant a_{CO2}. Based on the Redlich-Kwong parameters, a relationship was developed to calculate the a_{CO2} constant (Spycher and others, 2003).

(Equation 8) $a_{CO2} = 7.54 \times 10^7 – (4.13 \times 10^4 * T(K))$

9 – Calculate CO_2 volume. The input values of pressure, temperature, and the a_{CO2} constant were converted from a raster to ascII files for use in this calculation. The volume of the compressed gas phase is computed by recasting the Redlich-Kwong equation as a general cubic equation in terms of volume. For this step it was necessary to develop a script in visual basic that would loop through the equation until the desired tolerance was met (Appendix A). A starting volume was calculated using the ideal gas law:

(Equation 9) $V = 83.145 * T / P$

The starting volume was substituted in to the cubic equation:

(Equation 10) $V^3 – V^2(RT/P) – V(RTb/P – a_{CO2}/PT^{0.5} + b^2) – (ab/PT^{0.5}) = 0$

where:

$b = 27.80$ cm^3/mol

The derivative of equation 10 was calculated.

(Equation 11) $3V^2 – 2V(RT/P) – ((RTb/P) – (A/(PT^{0.5})) + b^2 = 0$

The tolerance for the equation was set at .0001, if the first guess for the equation did not equal .0001 or less then a second guess was calculated using Newton's method (Hornbeck, 1975). Iterations of guess

volumes were continued until the tolerance was meet, these calculations occurred for each 500m x 500m cell.
10 – Convert asscII file to Raster. This step required a change of file format for use in GIS.
11 – Calculate fugacity coefficient. The fugacity coefficient was calculated from standard mixing rules using the Ridlich-Kwong equation (Spycher and others, 2003).

(Equation 12) $\ln(\Phi_k) = \ln(V/(V - b_{mix})) + (b_k/(V - b_{mix})) - (2a_{CO2}/(RT^{1.5}b_{mix})) \ln((V + b_{mix})/V) + (a_{mix}b_k/(RT^{1.5}b_{mix}^2)) [\ln((V+b)/V) - (b_{mix}/(V + b_{mix}))] - \ln(PV/RT)$

where:
b_{mix} = 27.80 cm^3/mol
b_k = 27.80 cm^3/mol
$a_{mix} = a_{CO2}$

12 – Calculate fugacity. Fugacity was calculated from the fugacity coefficient, and converted from bars to mpa (Spycher and others, 2003).

(Equation 13) $f_{CO2} = e^{(\Phi k)} * P * .101325$

13 to 15 – Calculate mole fraction. The calculation of mole fraction took place in several steps because the model had problems making the calculation as a whole. Step 13 uses the pressure (mpa), H_{CO2}, v_{CO2}, and fugacity to calculate the part of the mole fraction within the parentheses (Bachu and Adams, 2003). Step 14 introduces the negative to the equation. And step 15 takes the inverse of the natural log of the equation to calculate the mole fraction of CO_2.

(Equation 14) $\ln x_{CO2} = -(\ln HCO_2 + v_{CO2}P/RT - \ln f_{CO2})$

16 – Calculate mass fraction.

(Equation 15) $X_{CO2} = (x_{CO2} * 44) / ((1-x_{CO2}) * 18)$

17 – Calculate the total dissolved solids (TDS). This step uses the depth raster as a template for applying the TDS, a depth raster is brought in and all values are made zero, then the value for TDS is added. The purpose of this step was to help in automating the entry of TDS. The TDS value is also converted from ppm to wt.% by dividing by 10,000.

(Equation 16) S = Depth * 0 + (TDS/10,000)

18 – Calculate mass fraction of solubility.

(Equation 17) $Xs_{CO2} = X_{CO2}(1.0 - 4.893414 \times 10^{-2}S + 1.302838 \times 10^{-3}S^2 + 1.871199 \times 10^{-5}S^3)$

19 – Convert units of solubility. This step converts the units from g/cm3 to scf/bbl water (McDonald, 2003).

(Equation 18) $Xs_{CO2} = Xs_{CO2} * .00220462262 * 28316.8466 * 5.61458 * 8.615$

20 – Calculate aquifer sequestration volume. This calculates the volume of CO_2 that can be sequestered in the saline aquifer based on water saturation, porosity, reservoir area, thickness, and CO_2 solubility (McDonald, 2003).

(Equation 19) $Q = ((7758 * sw * \phi * a * h * CO_2s)/1000)/18.95$

where:
Q = sequestration volume (metric tons)
7758 = convert everything to ft^3
sw = water saturation
ϕ = porosity
a = reservoir area (acres).
h = thickness (feet).
CO_2s = CO_2 solubility (scf/bbl water)
18.95 = conversion factor from mcf to metric tons

21 – Convert saline aquifer sequestration volume to an integer. This was necessary for the next step.
22 – Convert integer raster to points. This allowed the total sequestration volume for the play to be summed. Each point represented the same amount of area 500m.

23 – Calculate density. This calculated the density based on mass and volume, and then converted the units to lb/acre-ft.

(Equation 20) $d = (44/V) * (.0022046/.0000353) * 43560$

24 – Calculate oil and gas reservoir sequestration volume. This calculates the volume of CO_2 that can be sequestered in the oil and gas reservoirs based on water saturation, porosity, reservoir area, thickness, and CO_2 density (McDonald, 2003).

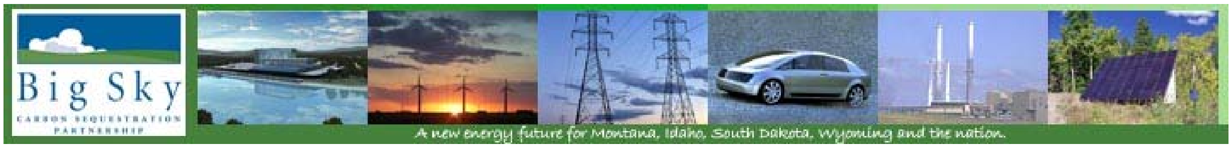
(Equation 21) $Q = \rho_{co2} * h * a * \phi * (1-Sw)/2200$

where:
Q = sequestration volume (metric tons)
ρ_{co2} = CO2 density (lbs/acre-ft)
h = net thickness (feet)
a = area (acres)
ϕ = porosity (percent)
Sw = Water saturation (percent)
2200 (lbs) = 1 metric ton

25 – Convert oil and gas reservoir sequestration volume to an integer. This was necessary for the next step.

26 – Convert integer raster to points. This allowed the total sequestration volume for the play to be summed. Each point represented the same amount of area 500m.

The raster and point files created by the model were saved for each of the calculations. The sum of sequestration volume for oil and natural gas reservoirs and saline aquifers was recorded in a Microsoft Excel spreadsheet for the area of each play that had data.



Big Sky Carbon Sequestration Partnership – Phase I

Deliverable 8: Report on Evaluation of Terrestrial Sinks

Attachment A: Evaluation of Cropland Terrestrial Sinks for the Big Sky Region

Attachment B: Rangeland Terrestrial Sinks Forestry

(see separate file for PDF document)

Attachment C: Forest and Agroforestry Opportunities for Carbon Sequestration in the Big Sky

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Susan M. Capalbo
Big Sky Principal Investigator
207 Montana Hall
Montana State University-Bozeman
Bozeman, MT 59717-2460
scapalbo@montana.edu
http://www.bigskyco2.org/
Phone: (406) 994-5619
Fax: (406) 994-2893

Deliverable 8 – Attachment A
Evaluation of Cropland Terrestrial Sinks for Big Sky Region

This report summarizes efforts to date on assessing the terrestrial sinks for the Big Sky region. The assessments are done in terms of both technical potential and economic potential. Technical potential provides the most optimistic estimate of the size of the terrestrial sinks, assuming that all land use management was changes to the management regime that sequestered the maximum amount of soil carbon. The economic potential examines the amount of carbon that would be sequestered from land use changes taking into account the "cost' of changing the existing land use management to a management regime that would sequester larger amounts of carbon. In theory, the economic assessment is a realistic means of capturing both the potential size of the sinks and the opportunity cost of sequestering carbon. This research is supported by the DOE/NETL/Partnership grant and through the USDA/CASMGS grant.

PART I: Technical Assessment, Methods, and Results

GIS components of the terrestrial sink evaluation were represented aerially as continuous surfaces summarized by county; these include climate, soil, and land use databases.

One hundred and eight years of climate data from National Climate Data Center station records were averaged for each of up to 10 climate zones in each state so as to produce zone-average files. In addition, zone-specific statistical data on climate variability were used to simulate climate after 2003.

Soil texture grids derived from SSURGO or STATSGO soil databases were developed for eachstate, then statistically aggregated to approximately 20 representative soil texture classes. Land management data were extracted from the 1997 Census of Agriculture and from the Conservation Technology Information Center. These data were compiled on a county-level basis and are summarized in Table 1.

Table 1. Agricultural land areas, in km^2.

State	***Crop-Conv Till***	***Crop-No till***	***Grazing***	***CRP***	***Total***
Wyoming	8,881	142	127,357	1,134	137,514
Idaho	19,479	1,087	23,325	3,244	47,135
Montana	39,801	4,226	141,882	10,884	196,793
South Dakota	51,986	14,664	105,440	5,752	177,842

The CENTURY Model

Terrestrial sequestration technical potential was estimated by applying results of the CENTURY model, a point-based protocol for predicting carbon stock changes, over counties in accord with alternative land management scenarios. Initially, the sets of point-based predictions are generated based on unique combinations between different management scenarios, climatic zones and soil texture classes. These results are then applied across individual counties, respective to the relevant climatic zone and to the extent of within-county management class areas as estimated in proportion to areas of within-county soil texture classes. To obtain the county-level estimated annual soil carbon flux rates, predicted carbon stock changes were then summed across all management classes within each county (Figure 1).

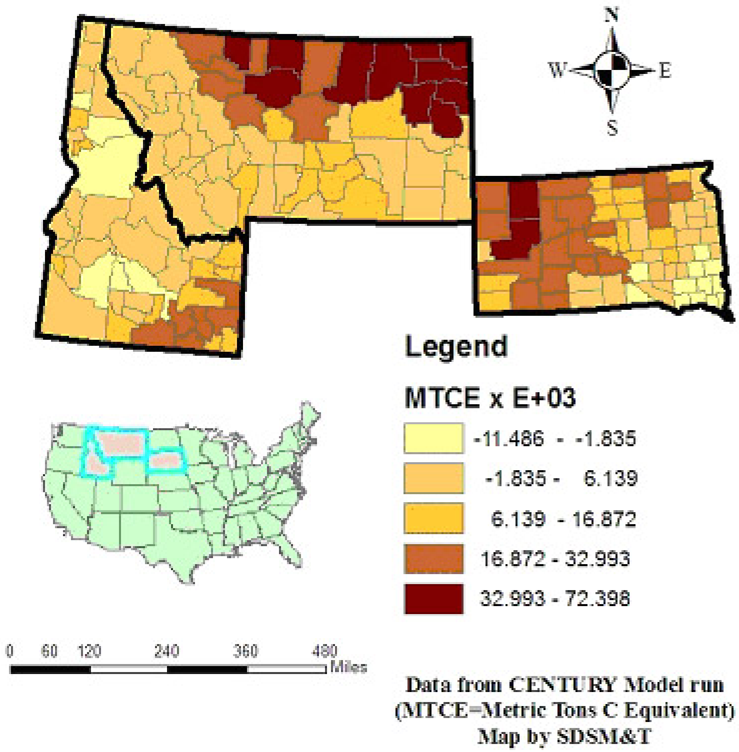

Figure 1. Current estimated annual soil carbon fluxes in Big Sky states (ID, MT, and SD).

GIS-based modeling has enabled the iterative exploration of effects from changes to the status quo in land use/management such as altered rates of no-till adoption or CRP enrollment. The CENTURY model has already afforded significant insights into the spatially-variable prospects for terrestrial sequestration; as one general example, results have confirmed that South Dakota (the state with by far the largest area of harvested cropland) offers the largest potential for terrestrial sink enhancement due to improved agricultural land management, particularly through conversion to no-till. Estimates of sequestration potential for a limited suite of scenarios are currently included in the GIS database of the Big Sky Carbon Warehouse.

Results

Montana has the largest agricultural land base, but South Dakota has by far the largest area of harvested cropland (Table 1). As a result, South Dakota offers the largest technical potential for terrestrial sink enhancement due to cropland management, but Wyoming and Montana may provide greater potential benefits due to improved rangeland management.

Statewide simulation preliminary results for current and potential agricultural management scenarios are summarized in Table 2. Increasing CRP areas by 25% at the expense of conventionally tilled lands enhances agricultural sinks by 4-9% over 40 years of simulation. An increase in no-till area appears to offer the greatest potential for enhancing agricultural sinks in South Dakota, which has more cropland than the other states. The much lower gains resulting from increased no-till in Montana, Idaho and Wyoming are due in part to the very small areas currently classified as no-till. On the other hand, Wyoming and South Dakota realize the largest gains from a hypothetical 50% reduction in grazing pressure across all grazing lands. It is not clear why Montana, with a larger rangeland area than SD, does not realize at least a comparable benefit. Literature indicates that forage condition responds in a complex way to the interaction of grazing pressure and climate (under wetter conditions pasturelands can sustain more intensive grazing without losing productivity); however, it is unlikely that Century is capable of simulating this interaction effectively, therefore grazing results should be treated as preliminary.

Table 2. Predicted 40-year average annual C stock change (MTCE) for different scenarios. Percent change from current in parentheses.

State	***Current***	***+25% CRP[1]***	***-50% Grazing[2]***	***+25% No-Till[3]***
Idaho	287,124	312,968 (9%)	283,087(-1%)	289,071 (1%)
Montana	788,544	818,251 (4%)	883,797 (12%)	801,317 (2%)
South Dakota	706,193	748,105 (6%)	846,748 (20%)	931,406 (32%)
Wyoming	43,050	46,742 (9%)	104,093 (142%)	43,323 (1%)

1. 25% increase in current CRP area, deducted from current conv till land.
2. Grazing intensity reduced by about 50% on all grazing land.
25% increase based on *current* no-till area, deducted from current conv. till land (i.e. 0% current no-till resulted in 0% increase).

Table 3. Role of agriculture in state GHG budgets.

	Idaho	***Montana***	***South Dakota***	***Wyoming****
	State Annual Estimates for 2000 in MMTCE			
Fossil/Industrial Emissions	15.93	13.1	11.37	21.46
Forest LUC	-3.26	-8.41	0.59	-0.04
Agriculture – Soil C	-0.29	-0.79	-0.66	-0.04
Agriculture – Net	1.87	1.32	3.04	0.64
TOTAL NET	12.39	3.9	11.26	21.37
*Preliminary data				

Note that in SD the LULUCF offset reduces gross emissions by about 1%, due entirely to agricultural soils; in MT there is a 70% offset due almost entirely to forest growth; in ID there is a 22% offset. largely due to forest growth, and in WY there is almost no LULUCF offset against an emissions load attributable in large part to utility emissions and energy production (Table 3).

PART II: __Economic Methods and results__

In a market for greenhouse gases, the competitiveness of US agricultural producers as suppliers of carbon-credits depends on the marginal costs and quantities of soil carbon (C) that can be sequestered. Economic and ecosystem models can be used together to estimate the marginal costs of soil C sequestration and the quantity of C-credits that can be sequestered within a given region.

__Approach.__ The economic approach to the analysis of the potential to sequester soil C links biophysical data and models with economic data and models on a site-specific basis. In this way, the analysis can account for the spatial heterogeneity of biophysical conditions (soil C sequestration rates) and economic decisions (land use) and how these conditions interact to determine the marginal cost of sequestering C in soil. We apply an integrated assessment approach to quantify the costs of sequestering C from changes in land use and management practices in the dryland grain production systems of the Northern Plains region of the United States which encompasses the Big Sky region. In this region, changes in land use such as conversion of crop land to permanent grass, and changes in management practices such as use of reduced fallow, may be economically feasible where afforestation—the conversion of non-forest land to forest—is not. We compare the relative efficiency of sequestering soil C for two alternative policies relevant to the Northern Plains region: one that provides producers with payments for converting crop land to permanent grass (similar to the Conservation Reserve

Program in the United States), and one that provides payments to farmers to switch from a crop-fallow rotation or permanent grass to a continuous cropping system. These policies are similar to ones proposed in recent U.S. legislation. Our analysis shows that the economic efficiency of C sequestration and the size of the sinks depends on site-specific opportunity costs of changing practices, the rates of soil C sequestration associated with changing practices, and the policy design.

Assuming that agricultural producers are initially utilizing those land use and management practices that yield the highest economic return, it follows that producers will adopt different practices that increase soil C if and only if there is a perceived economic incentive to do so. While there are many possible ways to design policies to sequester soil C, we have adopted the basic structure of a soil C contract program, where soil C can be purchased by either the government or a private entity. Within a given region, let a contract pay the farmer g^{is} dollars per hectare per year for T years to change from management practice *i* to management practice *s* that sequesters additional soil C. Letting the total increase in soil C over the time period t = 0 to T from switching from *i* to *s* be $\Delta c^{is} = c_T^{\,s} - c_0^{\,i}$, the average increase is $\Delta c^{is}/T = c^{is}$ (metric tons per hectare per year). Although the time path for the increase in the stock of soil C in response to the adoption of improved practices is non-linear, the path is often approximated linearly with the annual average rate of soil C increase (e.g., see the soil C rates discussed in Watson et al.). Furthermore, because it is not practical to measure soil C rates accurately on an annual basis, we assume that these average annual rates are what would be actually measured and used in soil C contracts.

The per hectare capitalized value of the contract to the farmer to switch from *i* to *s* is

$$(1) \qquad \sum_{t=1}^{T} g^{is} (1+r)^{-t} = g^{is} D(r,T),$$

where D(r,T) denotes the present value of $1 at interest rate r for T periods. The value of a C contract to the government or other purchaser of carbon depends on the soil C rate parameter c^{is} and the time period over which the practices are adopted. If the buyer of the carbon can sell the C for *p* dollars per metric ton, it follows that the value of the contract to the buyer is

$$(2) \qquad \sum_{t=1}^{T} p\, c^{is}(1+r)^{-t} = p\, c^{is} D(r, T).$$

The equivalence of (1) and (2) implies that $g^{is} = pc^{is}$. If a program pays farmers g^{is} dollars per hectare per year for soil C sequestration, then the implicit price per metric ton being paid by the government or any other buyer of soil C is equal to g^{is}/c^{is} . Under the assumption of static price expectations for carbon, the payment per hectare per year to the farmer is equal to the value of the C sequestered per hectare per year. More generally, if prices are constant but the rate of increase in soil C varies with time, then it follows that $pk = g^{is}$, where $k = \sum_t c_t^{\,is} (1+r)^{-t}/D(r,T)$.

Producers will switch production practices if and only if the profits per hectare of their profit-maximizing practices are less than the alternative practices plus the payment per hectare. Let the total amount of agricultural land in a region be *A* hectares, and let the share of land in a given region that is entered into C contracts for switches from i to s be $z^{is}(g)$, where we have assumed that $g^{is} = g$ for all *i*, *s* that result in a positive amount of soil C accumulation and $g^{is} = 0$ otherwise. This region would sequester $C(g) = T \sum_i \sum_s c^{is} z^{is}(g) A$ metric tons of C, or $C(g)/T$

metric tons of C per year. The region's marginal cost function for sequestering soil C, $M(C)$, can then be defined as the correspondence between p and $C(g)$.

When a producer switches to alternative practices as part of the program the reduction in profitability, net of the payment, is the opportunity cost of entering into the contract. Given site-specific data on net returns, the opportunity costs differ across regions and thus an economic production model of land-use choices is needed to determine the share of land that would be entered into a specific type of contract as payment levels increase. An upward-sloping marginal cost curve for soil C in a region reflects the fact that different land units have different opportunity costs.

Given $M(C)$, the corresponding total cost can be calculated by integrating under the marginal cost curve adding any fixed transactions costs. Revenue generated by producers selling C contracts is equal to $R = pC(g)$ and the net benefit to producers is the usual producer surplus measure. In the case of a government payment program that pays farmers \$$g$ per hectare the total cost to the government is revenue R.

The integrated assessment approach to assess the cost of agricultural soil C sequestration involves linking the output of two disciplinary models—an econometric-process simulation model and a crop ecosystem model—to quantify the responses of farmers to economic incentives to sequester soil C. The econometric-process model, which is discussed below, simulates expected returns to alternative production systems on a site-specific basis, in response to incentives provided through a policy that pays farmers to change land use or management practices. These expected returns are used to simulate the farmer's choice of production system for a given land unit. This simulation model utilizes the stochastic properties of the economic production models and sample data, so its output can be interpreted as providing a statistical representation of the population of land units in a given region. The crop ecosystem model provides estimates of the levels of soil C and productivity (yields) associated with each production system. Following the marginal cost presentation, simulated changes in production systems are combined with simulated changes in soil C to compute the implied marginal costs, government costs, and producer surplus associated with policies in given regions. Thus, the integrated assessment model provides answers to policy questions about the effects of different payment schemes on the quantity of carbon sequestered and the marginal cost of sequestering soil C, and how the costs vary spatially. This approach also provides a basis for estimating the value of using government-based carbon payments as a part of the policy options to offset greenhouse gas emissions.

Econometric-Process Model of Production System Choice

In previous work, an econometric-process model was developed to model a producer's intensive- and extensive-margin production decisions. The motivation for the development of the econometric-process approach was the need to link economic analysis of production systems to site-specific bio-physical simulation models to assess the economic and environmental impacts of changes in policies, technologies, or biophysical conditions (Antle et al. 1999; Antle and Capalbo 2001a). Site-specific data are used to estimate the economic production models which are then incorporated into a simulation model that represents the decision making process of the farmer as a sequence of discrete and continuous land use and input use decisions. This discrete/continuous structure of the econometric-process model is able to simulate decision making both within and outside the range of observed data in a way that is consistent with economic theory and with site-specific biophysical constraints and processes.

The economic model is specified as follows: the production process of activity i at site j in period t is defined by a non-joint production function $q_{ijt} = f(\mathbf{v}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$ where $\mathbf{v}$ is a vector of variable inputs, $\mathbf{z}$ is a vector of allocatable quasi-fixed factors of production and other fixed effects, and $\mathbf{e}$ is a vector of bio-physical characteristics of the site (soils, topography, climate, etc.) (random terms are suppressed here for notational convenience). For expected output price p_{ijt}, the profit function is $\pi_{ijt} = \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$. If a crop is not grown, the land is in a conserving use with a return of π_{hjt}. Define $\delta_{ijt} = 1$ if the i^{th} crop is grown at j at time t and zero otherwise. The land-use decision on site j at time t is

$$(3) \qquad \max_{(\delta_{i1t}, \ldots, \delta_{int})} \sum_{i=1}^{n} \delta_{ijt}\, \pi_i(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it}) + (1 - \sum_{i=1}^{n} \delta_{ijt})\, \pi_{hjt}.$$

The solution takes the form of a discrete step function

$$(4) \qquad \delta^*_{ijt} = \delta i(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{hjt}),$$

where $\mathbf{p}_{jt}$ is a vector of the p_{ijt} and likewise for the other vectors. Using Hotelling's lemma, the quantity of the i^{th} output on the j^{th} land unit is given by

$$(5) \qquad q_{ijt} = \delta^*_{ijt}\, \partial\pi_i(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})/\partial p_{ijt} = q_{ijt}(\mathbf{p}_{jt}, \mathbf{w}_{jt}, \mathbf{z}_{jt}, \mathbf{e}_{jt}, \pi_{hjt}).$$

Variable input demands are likewise given by

$$(6) \qquad \mathbf{v}^*_{ijt} = -\,\delta^*_{ijt}\, \partial\pi_i(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})/\partial \mathbf{w}_{ijt} = v_{ijt}(\mathbf{p}_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{ijt}, \pi_{hjt}).$$

The econometric process approach combines the econometric production model represented by the supply and demand functions given in (5) and (6) with the process-based representation of the discrete land-use decision represented by (3) and (4). The model simulates the producer's crop choice, and the related output and costs of production at the field scale over time and space. This simulation structure utilizes the stochastic properties of the econometric models and the sample data, so its output is interpreted as providing a statistical representation of the population of land units in the region.

By operating at the field scale with site-specific data, the simulation can represent spatial and temporal differences in land use and management, such as crop rotations, that give rise to different economic outcomes across space and time in the region. Moreover, because of the detailed representation of the production system, the econometric-process model can be linked directly to the corresponding simulations of the crop ecosystem model to estimate the impacts of production system choice on soil C. Each field in the sample is described by area, location, and a set of location-specific prices paid and received by producers, and quantities of inputs. Using sample distributions estimated from the data, draws are made with respect to expected output prices, input prices, and any other site-specific management factors (e.g., previous land use). The econometric production models are simulated to estimate expected output, costs of production, and expected returns. The land-use decision for each site is made by comparing expected returns for each production activity. These spatially and temporally explicit land-use decisions are combined with simulated outputs of the crop ecosystem model to assess changes in soil C.

Biophysical Process Model

The crop ecosystem model known as Century is utilized to represent the processes controlling crop growth, water, nutrient, and organic matter dynamics that determine the productivity of agricultural ecosystems (Parton et al. 1994; Paustian, Elliott, and Hahn, 1999). Century is a generalized biogeochemical ecosystem model which simulates C (i.e., biomass), nitrogen and other nutrient dynamics. It includes submodels for soil biogeochemistry, growth and yield submodels for crop, grass, forest and savanna vegetation and simple water and heat balance. For use in agricultural and grassland ecosystems, the model incorporates a large suite of management options including crop type and rotation, fertilization, tillage, irrigation, drainage, manuring, grazing, and burning. The model employs a monthly time step and the main input requirements (in addition to management variables) include monthly precipitation and temperature, soil physical properties (e.g., texture, soil depth) and atmospheric nitrogen.

For the current application, soils and climate data for each of the sub-MLRAs are used as Century model inputs in addition to management variables such as crop type and rotation, fertilization and tillage practices. The Parameter_elevation Regressions on Independent Slopes Model (PRISM) data set was used to determine weather-related data. Information on current management systems is from the 1995 survey of Montana producers, augmented with the USDA National Agricultural Statistics Service (NASS) database, the National Resources Inventory (NRI) database, and county_level databases of the National Association of Conservation Districts (NACD). Soil characteristics are determined using the Advanced Very High Resolution Radiometer (AVHRR) database (USGS_Earth Resources Observation System (EROS) Data Center), the State Soil Geographic Database (STATSGO) and the NRI database. Baseline projections of soil C are made using historical climate and land-use records. These projections are compared to NASS records of county-level crop yields and changes in soil C derived from the Century database of native and cultivated soils. The initial land-use allocation from the 1995 Montana survey was used to calculate base C levels for each sub-MLRA.

The variability in the levels of soil C predicted by the Century model across the six major crop producing sub-MLRAs and production systems in Montana is shown in Figure 2. Simulations of the crop-fallow, continuous cropping, and permanent grass production systems with the Century model show that the equilibrium levels of soil C under a crop-fallow rotation range from 3–7 MT per hectare less than continuous grass over a twenty year horizon, and that soil C levels under permanent grass range from 1–5 MT per hectare less than under continuous cropping depending upon sub-MLRA. In sub-MLRA 52-low, soil C levels under permanent grass compare favorably with soil C levels under a continuous cropping system. The variability across sub-MLRAs reflects the heterogeneity in biophysical and climatic conditions, which translates into different equilibrium levels of soil C for the production systems.

Simulation of Soil C Levels and Costs

The economic simulation model selects the land use that maximizes expected returns for each sample field for each policy scenario that is investigated. When using this model to address soil C sequestration analysis, the net returns are augmented by the per hectare payment, *g,* to switch to management and land uses that would sequester additional carbon. The economic simulation is executed over a time horizon (approximately 20 years) sufficient to reach an equilibrium for each policy setting *g*. The land-use patterns are then summarized for each sub-MLRA for each policy setting in the form of proportions $z^{is}(g)$ of land reallocated from activity i to activity s. The Century model is used to simulate the soil C levels and annual averate rates for each land use in each sub-MLRA over a given time horizon. Given the land-use changes within each sub-MLRA based on maximizing expected returns, we calculate the levels of soil C sequestered and the resulting C sequestration costs using the procedures discussed earlier.

Simulation Results: Land-use Changes, Soil C Levels, and C Sequestration Costs

We present the empirical results for changes in land use, changes in soil C levels, and the costs of sequestering soil C for two policy scenarios: a policy for conversion of crop-land to permanent grass (PG) which gives producers a fixed annual per hectare payment; and a policy that pays producers on a per-hectare basis for fields switched to continuous cropping (CC). A precedent exists for using compensation schemes to enhance the environmental benefits from use of agricultural land. Existing agricultural policies, such as the Conservation Reserve Program (CRP), provide producers with per-acre payments in return for changes in land use and management that provide environmental benefits. The proposed revisions to the Food Security Act of 1995 would offer farmers the option of participating in a voluntary, incentive-based conservation program in exchange for compensation. Alternative policy designs for sequestering carbon, such as per ton payment schemes, are discussed in Antle et al. (2001).

Under the PG policy scenario, the producer could choose to enter a field into permanent grass and receive a payment above and beyond the payment for land in CRP. The level of the CRP payments used in the simulation model is set at the average level of CRP payments in Montana in the mid 1990s ($37.50 per acre or $93.75 per hectare). The PG policy is simulated for *additional* payments ranging from zero (the base case) to $125 per hectare by increments of $12.50 per hectare. Land is enrolled for a period of twenty years, and all cropland and pasture land is eligible for payment. This policy scenario reflects a payment design that is similar to other land retirement programs such as the CRP that are currently being used in agriculture and is comparable to payments schemes utilized in other studies of C sequestration (Plantinga, Mauldin, and Miller, 1999; Stavins, 1982).

The CC policy provides per hectare payments for switching from a crop-fallow or permanent grass system to a continuous cropping system. Producers are offered payments that range from a low of $5 per hectare per year and increase by $5 increments to $50 per hectare per year. Clearly, only land that is switched from crop-fallow or grass to continuous cropping results in an increase in soil C that is attributable to the policy. However, if the policy pays only farmers who switch from crop-fallow or grass to continuous cropping and does not include payments to farmers who already use continuous cropping, it creates an incentive for those farmers to switch temporarily to crop-fallow and then back to continuous cropping. Thus, two variations on the CC scenario could be considered: all fields continuously cropped could be eligible for payments, regardless of their previous cropping history (*nontargeted CC payments*); or only fields with a history of crop-fallow or grass could be eligible for continuous cropping payments (*targeted CC payments*). Both the targeted and nontargeted policies would result in the same *net* increase in soil C, and the same changes in land use and opportunity costs of sequestering C, but the costs of the policy borne by the government and the resulting producer surplus would be greater under the non-targeted program as a result of the additional fields eligible for payments. A simulation of the model with the payments set equal to zero generates a baseline estimate of the land use and soil C levels for each sub-MLRA for both policies. The economic simulation model was executed for each field in the data set using observed initial conditions for land use and prices set at mean levels to reflect long-run averages over the past decade. The land-use alternatives simulated in the model were winter wheat, spring wheat, and barley in either a continuous cropping or crop-fallow rotation, and permanent grass. The baseline land-use patterns indicate that permanent grass is a more attractive alternative relative to continuous cropping in sub-MLRAs 58A-high, 58A-low, and 53A-high. These areas in the eastern and southeastern part of the state have lower levels of moisture relative to the more productive areas sub-MLRAs 52-high and 52-low. In these latter two areas, continuous cropping accounts for approximately 50% more land acreage than permanent grass.

Simulated Changes in Land Use and Soil C Levels

Figure 3 shows the changes in land use under each policy for each sub-MLRA as payment levels increase. For the PG policy, as payment levels increase the *additional* share of land in permanent grass increases from less than 20% to approximately 25 to 45% within each sub-MLRA (Figure 3a). The baseline shares of land in permanent grass range from a high of 33 to 35% in sub-MLRA 58A-high and 58A-low to under 7% in sub-MLRA 53A-high. The differences in land use in permanent grass across the sub-MLRAs reflect the effects of spatial heterogeneity on the opportunity cost of grain production.

Recall that the crop-fallow and continuous systems yield similar net returns on average; thus the baseline allocation of land in crops is about evenly divided between the two in the sample. This implies that a relatively small payment could induce farmers to switch land from crop-fallow to continuous cropping. Baseline shares of total acreage in continuous cropping ranges from 13% in sub-MLRAs 58A-high to approximately 18% in the other four areas. Figure 2b shows the response of land-use changes to payment levels under the CC policy. All sub-MLRAs exhibit a similar pattern of land-use change under the CC policy, reflecting the fact that the opportunity cost of switching from crop-fallow or grass to a continuous cropping system is fairly similar across the sub-MLRAs.

The effects of these changes in land use on the changes in the equilibrium levels of soil C after 20 years are shown in Figure 4 for each sub-MLRA for each payment level. The amount of soil C sequestered varies depending upon the land area, land use, and the relative productivity of each cropping system to sequester soil C. Under both policies, the largest change in soil C sequestered in response to changes in payment levels occurs within sub-MLRAs 52-high and 52-low which comprise an average of 50% more acreage than the other areas. Comparing across policies, a greater amount of soil C is sequestered under the CC policy relative to the PG policy within each sub-MLRA. The increases in soil C become smaller as payment levels increase, reflecting the diminishing rates of land-use changes shown in Figure 2.

On a *per hectare basis*, the average amount of carbon sequestered under the highest PG policy payment is fairly constant across the sub-MLRAs at about 0.4MT/hectare. For the CC policy, the highest payment level results in average levels of C sequestration per hectare per sub-MLRA that range from 0.8 to 1.1 MT/hectare. Over the six sub-MLRAs considered, the total C sequestered ranges from 1.75 to 4.84 MMT under the PG policy, and from 4.80 MMT to 17.7 MMT under the CC policy.

Costs of Sequestering Soil C

To compare the relative efficiency of the two policies, the marginal cost curves for each sub-MLRA are constructed as discussed above. The per hectare payment levels are divided by the area-specific and activity-specific carbon sequestration rates to obtain the implicit price per metric ton of carbon. This is arrayed with the amount of carbon sequestered over the twenty-year time period, where the amount of carbon sequestered is a function of the opportunity cost and site-specific land-use decisions. Alternative ways of displaying the marginal costs would be to array the costs per metric ton and the *annual* carbon sequestration or to use a *discounted* carbon quantity. Use of annual carbon sequestration quantities could be misleading because there is an upper bound on the total amount of carbon that can be sequestered in each sub-MLRA (saturation), and thus the resulting annual amounts would depend upon how many years one wants to consider. Likewise, discounting the carbon levels assumes that we know the relevant social rate of discount and time horizon. Moreover, for comparisons of our results to the biophysical estimates of soil C potential in the literature cited above it is necessary to use undiscounted measures of soil C.

The simulated marginal cost curves for the both the PG and CC policies embody the combined effects of site-specific land-use changes, soil C productivity differences, and differences in the payment levels (Figure 5). For the PG policy, the spatial differences in land area, opportunity cost of alternative land uses, and carbon sequestration rates cause a corresponding heterogeneity among the marginal cost curves. For the CC policy, the relative homogeneity of changes in land-use patterns shown in Figure 3 means that the observed differences in marginal costs of C sequestration are explained largely by the spatial differences in the productivity of the soils to produce soil C and by the size of the sub-MLRA.

The relative efficiency of the PG and CC policies can be seen by comparing the marginal cost of producing a given level of soil C. As an example, to sequester an additional .75 MMT of C in each sub-MLRA under a PG policy, the marginal costs start at $150/MT and increase to over $500/MT of C. Under the CC policy, .75 MMT of C could be sequestered for less than $50/MT even in the less efficient production areas. In general, our results show that for each sub-MLRA and for all C levels, the PG policy is far less efficient than the CC policy. Furthermore, the patterns of land-use change under the CC policy mean that the marginal cost curves under the CC policy are more elastic relative to the PG cost curves. Above $150/MT, these CC marginal cost curves turn steeply upward in response to the limitations on the quantity of soil C that can be sequestered when all acreage is in continuous cropping.

Table 4 presents a comparison of the quantity of soil C sequestered over the twenty year time horizon and undiscounted government costs and estimates of producer surplus, aggregated across all sub-MLRAs. In order to sequester approximately 7 MMT of C (more precisely 6.76 MMT in the PG scenario and 7.61 MMT in the CC scenario), the PG policy would involve government outlays that are more than ten-fold larger than the CC policy, and total costs that are nearly twice as high. From taxpayers' point of view the CC policy is far superior to the PG policy, providing much more soil C sequestered for a given government cost. From producers' point of view, the PG policy provides much larger income transfers to them per metric ton of soil C sequestered. These differences in the efficiency of the two policies can be measured at either the aggregate level or on a sub-MLRA basis. Over all sub-MLRAs, the efficiency gains associated with sequestering approximately 7 MMT of C using the CC policy rather than the PG policy amounts to over $430/MT of C at the margin.

The effects of spatial heterogeneity on government costs and benefits to producers are illustrated in Table 5 which compares similar data for sub-MLRAs 52-high and 58A-low. Within the payment levels considered in the simulation model, the CC policy always sequesters more C than the PG policy and the marginal costs per MT of C are lower. As payment levels are raised beyond the $125/hectare under the PG policy, the increases in soil C are minimal, as less productive land is switched into grass at a decreasing rate. Such an intensive switch to permanent grass may actually cause a decline in the overall soil C levels if the acreage is taken from the land that was continuously cropped. For the CC policy, payments in excess of $50/hectare do not add appreciably more soil C because the share of land in continuous cropping at payment levels of $50/hectare is at least 90% of the cropland acreage.

Conclusions

Previous published studies of C sequestration have considered the conversion of agricultural land to forests. There are important reasons to consider the economic feasibility of using crop land to sequester C: first, there are large areas of agriculture with substantial technical potential to sequester C in soil that are not suitable for afforestation; second, changing agricultural practices to sequester soil C is likely to bring subsidiary environmental benefits associated with reduced soil erosion and enhanced productivity; and third, changing agricultural practices does not have the potentially large, and often negative, regional economic impacts that are associated with land retirement programs.

We developed a conceptual framework for analysis of the economic potential for C sequestration in agricultural soils which shows that the economic efficiency of soil C sequestration depends on site-specific opportunity costs of changing practices and on the rates of soil C sequestration associated with changing practices. Our analysis of dryland grain production systems in the Northern Plains shows how site-specific land-use decisions change in response to policy incentives, and how this induces changes in soil C within a given region. The analysis shows that a policy providing payments for converting crop land to permanent grass is a relatively inefficient means to increase soil C, with marginal costs per MT of C ranging from $50/MT to over $500/MT. In contrast, payments to adopt continuous cropping were found to produce increases in soil C at a marginal cost ranging from $12 to $140 per MT of C even in the less productive regions of the northern Great Plains. For this policy, the average costs do not exceed $50 per MT of C.

Several caveats should be mentioned in concluding which may affect the costs of soil C. First, if the duration of contracts for soil C sequestration were extended beyond the time period T needed to reach the saturation of soil C, the estimated costs would increase. Second, in this analysis the entire opportunity cost associated with changing agricultural practices was attributed to a single environmental benefit—sequestering C. In many cases, changes in land use and management practices produce multiple environmental benefits, such as reduced soil erosion, improved water quality and wildlife habitat, and visual amenities. If additional environmental benefits were incorporated into an analysis of soil C, the relative economic efficiency of alternative land use and management options could be different, and other options to sequester soil C may become more competitive with non-agricultural reductions in GHG emissions.

Finally, it is important to note that agriculture is both a sink for C as well as a major emitter of CO_2 and two other potent greenhouse gases, nitrous oxide and methane (McCarl and Schneider; Robertson, Paul, and Harwood). Ideally policies to mitigate GHG emissions would reward sinks and tax sources according to their global warming potential (GWP), wherein methane is estimated to be about 21 times more potent than a unit of CO_2, and nitrous oxide is estimated to be about 310 times more potent (IPCC). Both methane and nitrous oxide are also likely to be influenced by land use and other management practices. An efficient GHG policy would provide incentives according to GWP that accounted for the total mixture of emission and sequestration fluxes of GHG caused by a farmer's altered land use and management practices. To do so one could replace the C rate in our analytical framework with a measure of GWP, and introduce a policy that would provide a positive payment for a reduction in GWP and a tax on actions that increase GWP. While this generalization is straightforward in principle, implementing it poses formidable measurement problems because methods and models to quantify nitrous oxide and methane emissions are not as well developed as those for C. Nevertheless this does appear to be the direction that policy will move as the needed science and data are developed.

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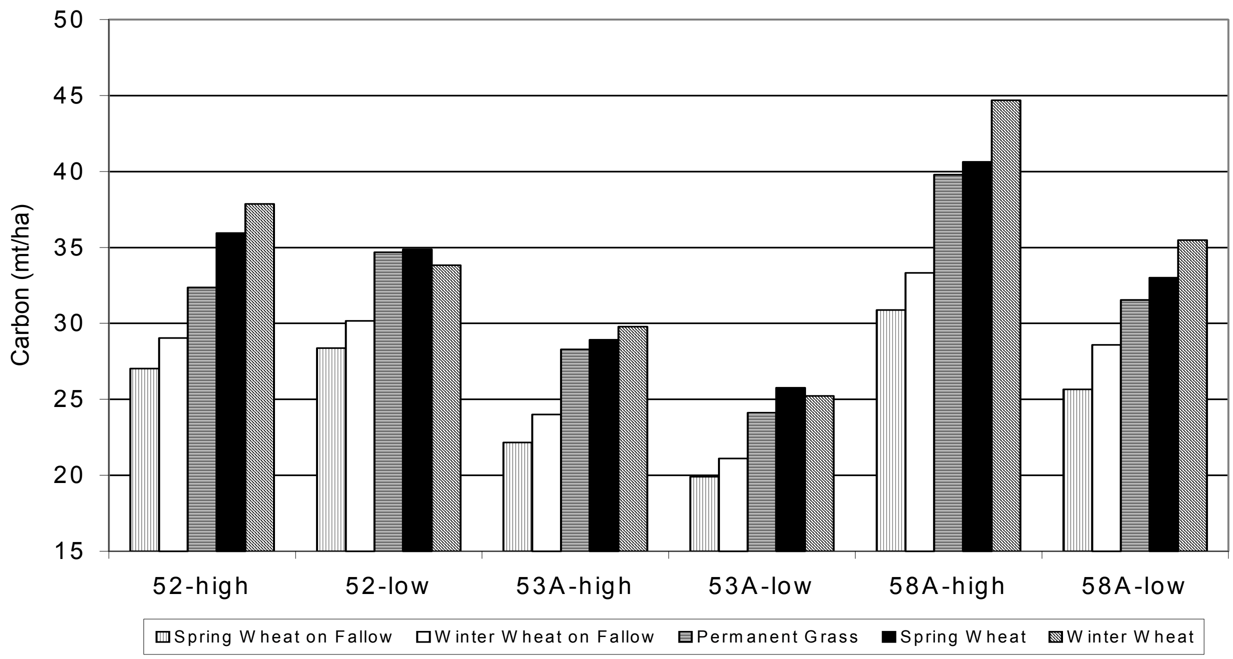
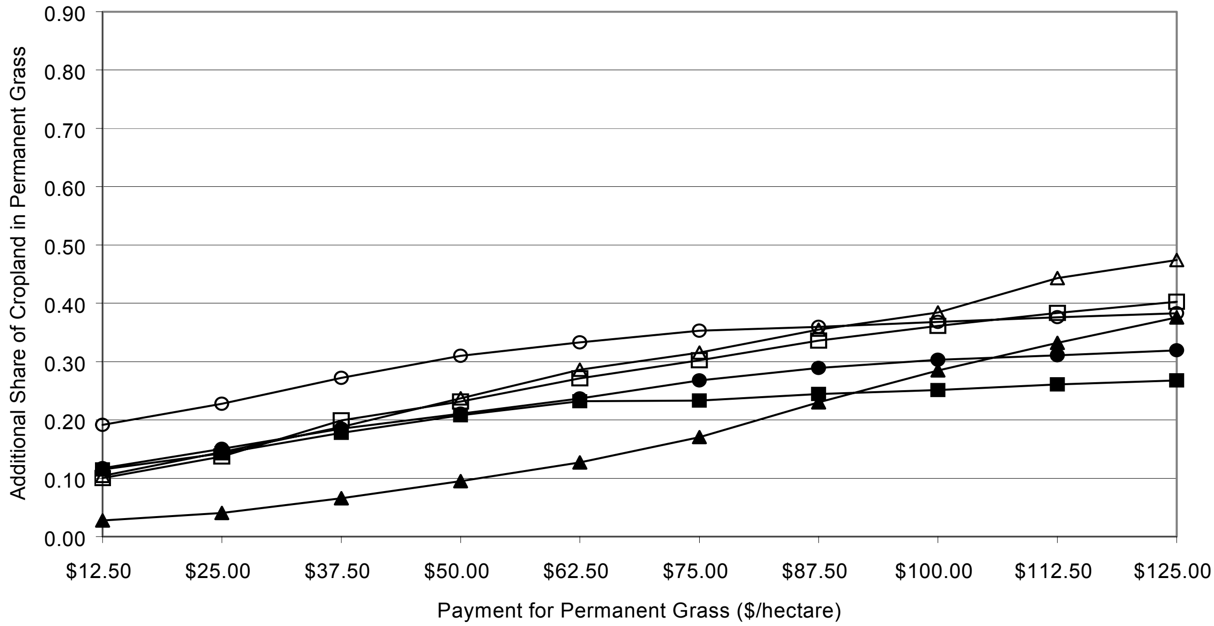
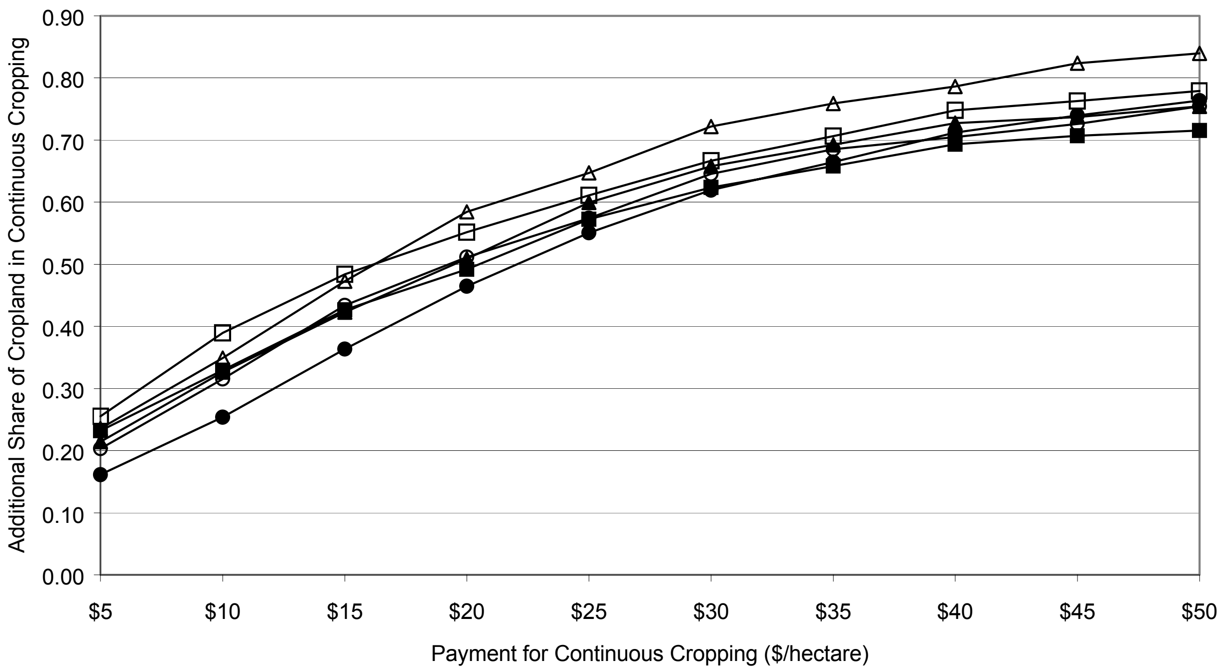


Note: Soil C levels for barley are the same as spring wheat.

Figure 2. Soil C levels predicted by Century model for cropping systems in Montana



(a) Permanent Grass Payment Policy



(b) Continuous Cropping Payment Policy

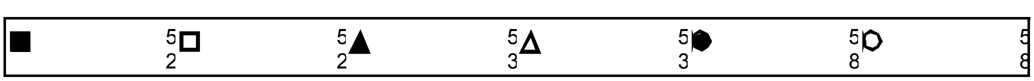
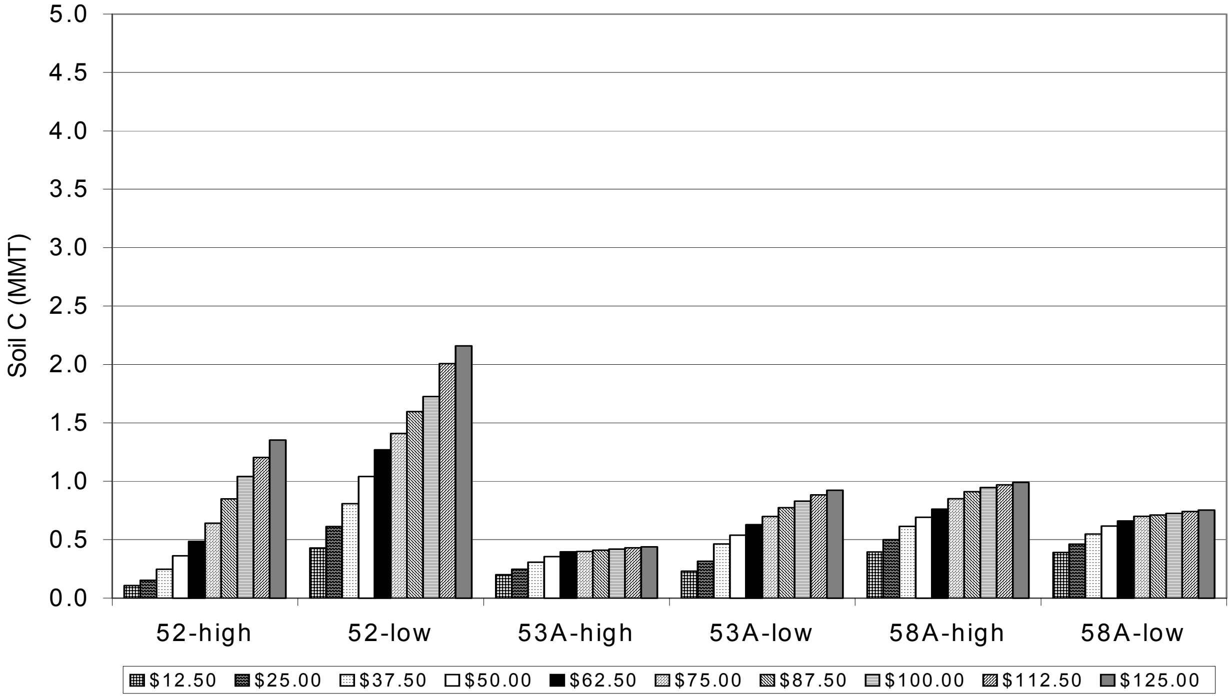
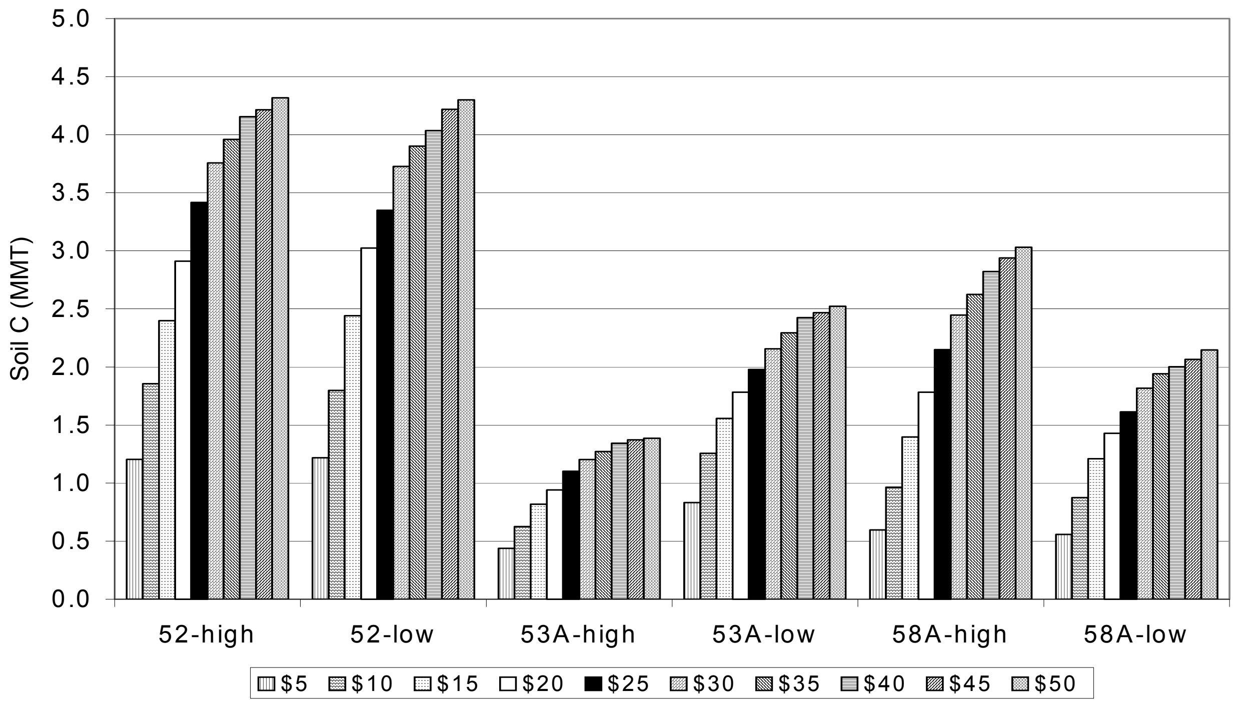


Figure 3. Changes in land-use shares by sub-MLRA and policy scenario

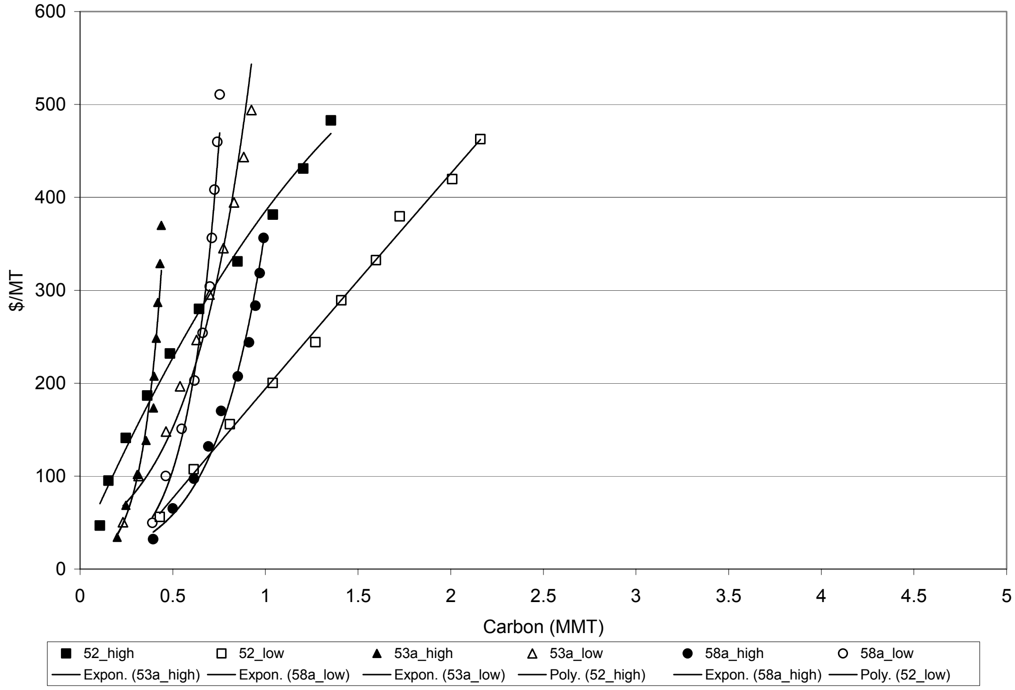


(a) Permanent Grass Payment Policy

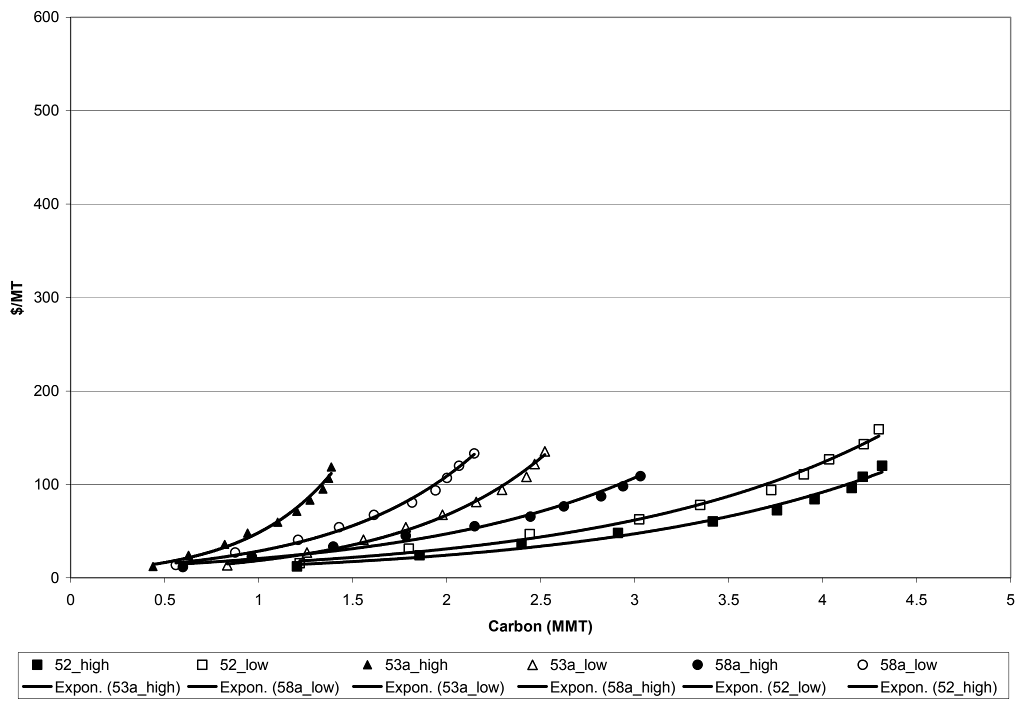


(b) Continuous Cropping Payment Policy

Figure 4. Changes in soil C by sub-MLRA and policy scenario



(a) Permanent Grass Payment Policy



(b) Continuous Cropping Payment Policy

Figure 5. Marginal cost for soil C by sub-MLRA and policy scenario

Table 4. Levels of Carbon Sequestered, Costs to Government, and Producer Surplus, by Policy Scenario for All Sub-MLRAs

A. Permanent Grass Payment Policy

Payment Level ($/hectare/year)	Quantity of Soil C Sequestered (MMT)	Cost to Government (Million $)	Producer Surplus (Million $)
$25	2.37	216.9	81.3
$50	3.71	670.2	325.1
$75	4.82	1305.3	673.0
$100	5.82	2121.5	1135.4
$125	6.76	3084.0	1674.4

B. Continuous Cropping Payment Policy

Payment Level ($/hectare/year)	Quantity of Soil C Sequestered (MMT)	Cost to Government (Million $)	Producer Surplus (Million $)
$10	7.61	201.7	66.4
$20	12.22	647.1	303.4
$30	15.54	1226.3	639.6
$40	17.28	1818.6	1063.5
$50	18.25	2404.9	1531.2

Table 5. Simulation of Land-use Changes, Carbon Sequestration Levels, and Costs for Sub-MLRAs 52-high and 58a-low

A. Permanent Grass Payment Policy*

Area	Payment Level ($/hectare/year)	Change in Share of Land in Permanent Grass	Quantity of Soil C Sequestrated (MMT)	Marginal Cost of Carbon Sequestrated ($/MT)	Average Cost of Carbon Sequestrated ($/MT)	Government Costs (million $)	Producer Surplus (million $)
MLRA 52-high	$25	0.04	0.15	95	67	14.6	4.2
	$50	0.10	0.37	186	123	67.6	22.9
	$75	0.17	0.64	279	185	179.7	60.7
	$100	0.28	1.04	381	247	396.7	138.8
	$125	0.37	1.35	482	294	653.4	255.4
MLRA 58A-low	$25	0.23	0.46	100	55	46.2	20.4
	$50	0.31	0.62	203	76	125.3	78.0
	$75	0.35	0.70	304	95	213.0	146.2
	$100	0.37	0.73	408	105	296.3	219.4
	$125	0.38	0.75	510	117	384.7	294.8

B. Continuous Cropping Payment Policy**

Area	Payment Level ($/hectare/year)	Change in Share of Land in Continuous Cropping	Quantity of Soil C Sequestrated (MMT)	Marginal Cost of Carbon Sequestrated ($/MT)	Average Cost of Carbon Sequestrated ($/MT)	Government Costs (million $)	Producer Surplus (million $)
MLRA 52-high	$10	0.33	1.86	24	16	44.7	14.3
	$20	0.51	2.91	48	24	139.6	67.0
	$30	0.66	3.76	72	34	271.0	143.1
	$40	0.73	4.15	96	40	399.3	235.5
	$50	0.75	4.32	120	42	518.1	337.6
MLRA 58A-low	$10	0.32	0.88	27	18	23.7	7.2
	$20	0.51	1.43	54	28	77.2	37.0
	$30	0.65	1.82	81	39	146.4	74.7
	$40	0.70	2.00	107	44	213.8	124.9
	$50	0.75	2.15	133	50	285.9	177.8

*Baseline share of land in permanent grass: MLRA 52-high=0.07, MLRA 58A-low= 0.36
**Baseline share of land in continuous cropping: MLRA 52-high=0.15, MLRA 58A-low=0.13 Total hectares: MLRA 52-high=0.68 million, MLRA 58A-low=0.36 million

Forest and Agroforestry Opportunities for Carbon Sequestration in the Big Sky

A contribution to

The Big Sky Carbon Sequestration Partnership

by

R. Neil Sampson
Matt Kamp
The Sampson Group, Inc.
February 10, 2005

Contents

Executive Summary

The Big Sky Carbon Sequestration Project is attempting to characterize the carbon sequestration potential in the agricultural and forest areas of the 4-state region, comprising Idaho, Montana, South Dakota and Wyoming. This study addresses the portion of that potential related to agroforestry practices and biomass production on agricultural lands, as well as afforestation of marginal agricultural soils and changing the management of existing private forests. None of these opportunities are overwhelmingly large, as one would expect in a region characterized by a high proportion of federal land, vast areas of arid and semi-arid ecosystems, and widely scattered production areas. But they could be important contributors to state, regional, and national efforts to mitigate greenhouse gas emissions in the near term, as these management practices are available immediately, with mature technologies that are widely known to landowners and technical agents in the region. In the event that carbon sequestration were to gain some market value, these opportunities could become a badly-needed supplement to income in a region dependent on agriculture and forestry for much of its rural economy.

Table 1 illustrates the estimates produced by the study. These estimates have a high degree of uncertainty, in that while most of the practices are well established, the policies and incentives to implement them are not. An example is found in the agroforestry practice of field windbreaks. The values of field windbreaks for soil erosion reduction, soil moisture retention, fuel use reduction, and farm yield protection have been known for decades, and there have been federal cost-sharing incentives since the 1930's. But there are still thousands of acres where windbreak protection would be beneficial, but remains undone. Farmers have resisted the existing incentives, and it is not yet clear how an added incentive tied to carbon sequestration would make a significant difference.

Table 1 contains estimates that reflect the total physical area in the region that is suitable for each practice. While these lands are available in the physical sense, they do not reflect actual implementation. The "potential area" is an author's estimate of what is most likely to be realized over the next 5-10 years unless much additional work is done to produce the policy, economic, and institutional support needed to assure increased success.

Table 1. Summary of carbon sequestration potential in agroforestry, biomass, and forestry, Big Sky Region.

Practice	Available Area (1,000 Ac)	Potential Area (1,000 Ac)	Potential Mitigation ($TgCO_2e/yr$)*
Afforestation	34,000	3,400	4 – 6
Forest Management	10,900	6,200	1.5 – 2
Field Windbreaks	594	300	1.0 – 1.5
Riparian Forest Planting	1,500	750	2.0 – 2.5
Biomass for co-firing	10,500	330	0.25 – 3

* Tg = terragrams = million metric tonnes

Table 1 suggests a total agroforestry, biomass, and forest opportunity in the range of 9 – 15 $TgCO_2e$ per year on the non-federal lands of the region. In comparison, USDA currently estimates that the forests of the region (including federal forests) are sequestering around 41 $TgCO_2e$ per year (Table 8). Thus, while 9-15 will not represent a huge national or global impact, it would mean that activities on private lands could increase regional sequestration by 25 to 35 percent. That, accompanied by the many other environmental values associated with improved carbon sequestration practices, would seem substantial.

Background of the Study

The Sampson Group, Inc. is a contributor to the Big Sky Carbon Sequestration Partnership, working together with other institutions and organizations under sponsorship of the U.S. Department of Energy to coordinate a study of the carbon sequestration opportunities in the region encompassing the states of Idaho, Montana, and South Dakota (www.bigskyco2.org). Wyoming has recently joined the partnership, as well, thus data for Wyoming have been included in this study.

This study is designed to contribute to the task of evaluating the terrestrial sequestration potential in regional ecosystems through forestry, agroforestry, and bioenergy opportunities.

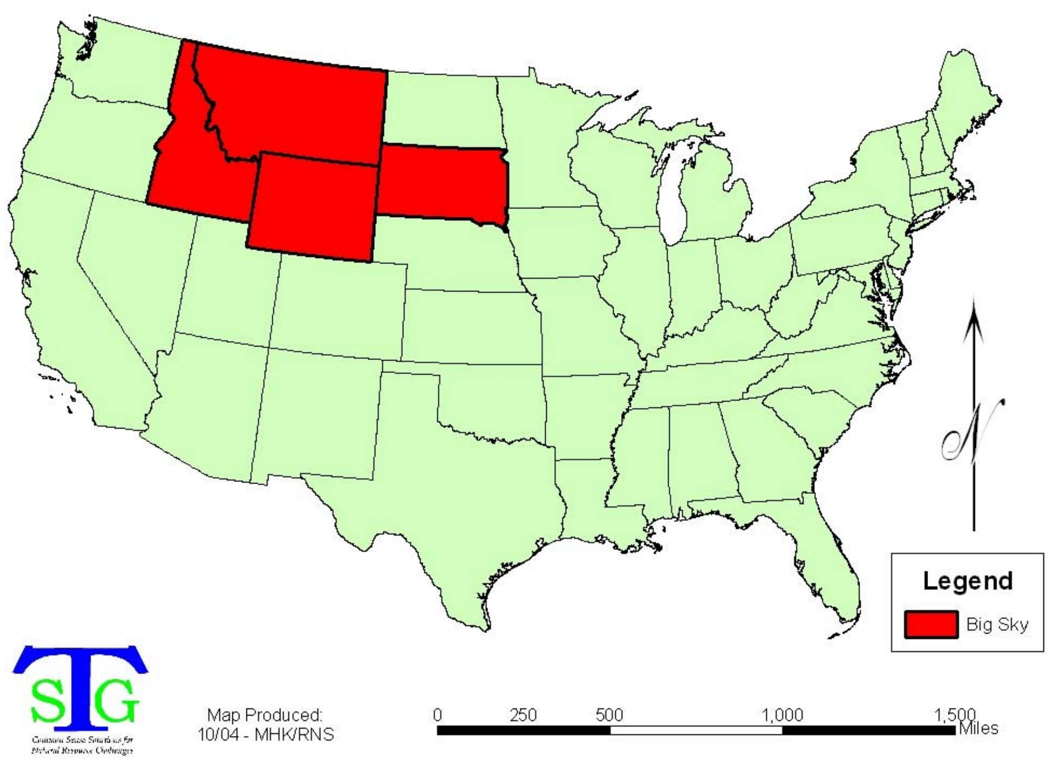


Figure 1. The Big Sky Region covers the states of Idaho, Montana, South Dakota, and Wyoming.

The Big Sky Land Base

The Big Sky region, for the purposes of this paper, consists of the states of Idaho, Montana, South Dakota, and Wyoming (Figure 1). Large areas of arid and semi-arid grazing and croplands are common on the eastern and southern sides of the region, while forested mountainous areas characterize the west. Average annual precipitation rates are highly variable (Figure 2), and even more locally variable in mountainous forest areas where topography and micro-climatic change significantly affect growing conditions.

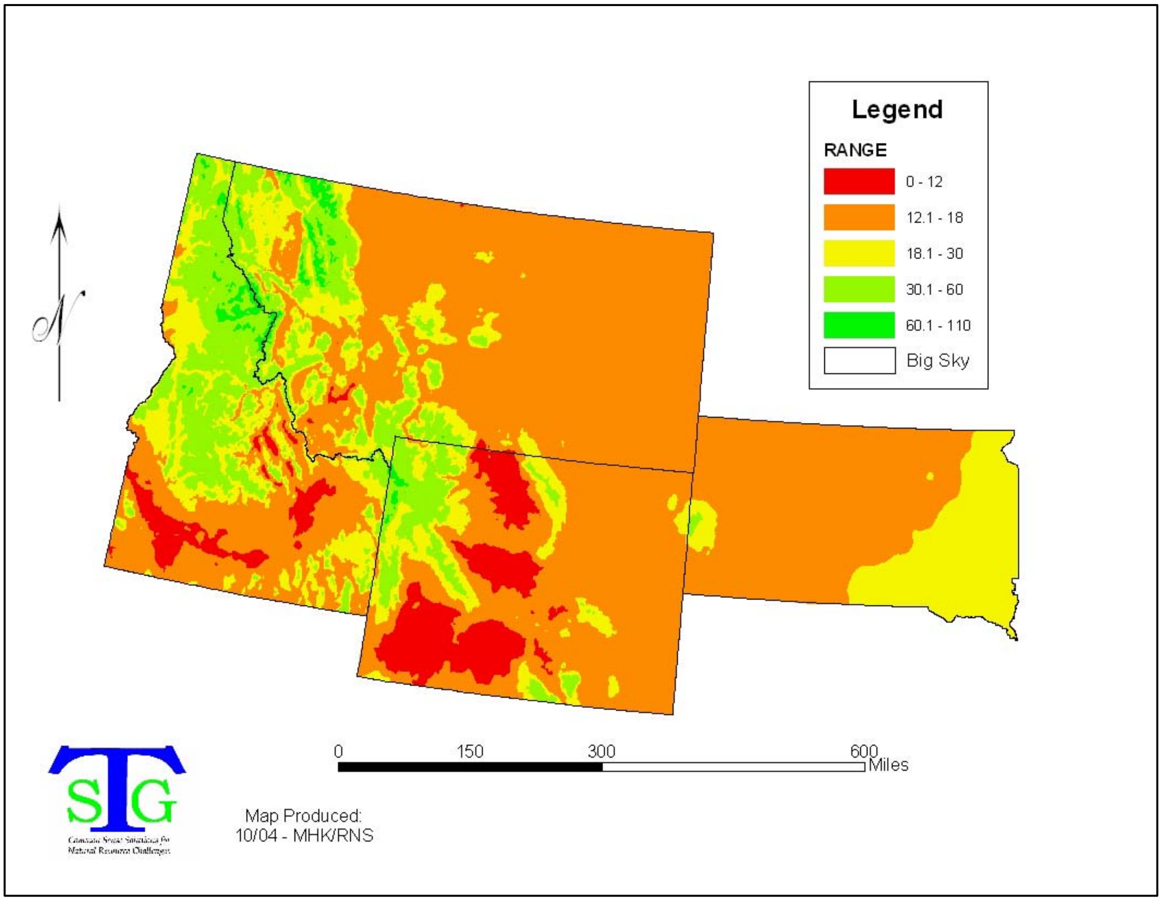


Figure 2. Average annual precipitation, in inches, Big Sky Region. Source: PRISM

The region is 40% federal land (Table 2; Figure 3). These lands are included in the federal Greenhouse Gas Inventory (USDA 2004) that is outlined below (Tables 7 & 8), but are excluded from the estimates of potential opportunity for the creation of additional GHG reductions through state or market programs for carbon sequestration. The exception to this was in the analysis of potential for biomass fuels, where the federal forest land was included as a potential source of woody biomass.

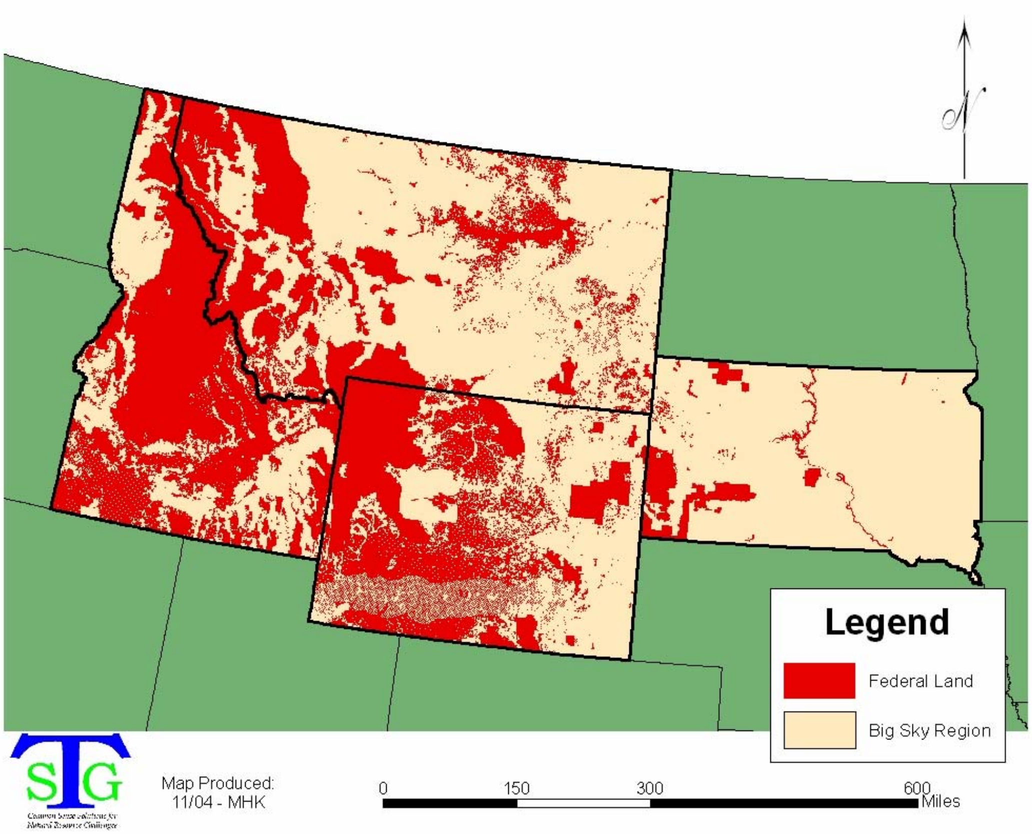


Figure 3. Federal land in the Big Sky Region.

This analysis focuses on the 161 million acres of rural, non-federal land in the region, estimating the potential for increasing carbon sequestration through forestry, agroforestry, and bioenergy strategies.

Table 2. Surface area of nonfederal and federal land and water areas, by state, 1992

				Nonfederal Land		Total
State	Federal Land	Water	Developed	Rural	Total	Surface area
	------------------------------- 1,000 acres --					
Idaho	33,480.9	552.2	690.0	18,764.4	19,454.4	53,487.5
Montana	27,089.7	1,052.5	758.6	65,209.2	65,967.8	94,110.0
South Dakota	3,107.9	874.4	957.9	44,417.8	45,375.7	49,358.0
Wyoming	28,748.0	430.9	662.8	32,761.1	33,423.9	62,602.8
Total Big Sky	92,426.5	2,910.0	3,069.3	161,152.5	164,221.8	259,558.3

Source: USDA-NRCS 2000; 1997 NRI, Table 1, National Summary.

The current (1992) use of non-federal rural land is indicated in Table 3. We used the 1992 NRI data (as corrected in 1997) (USDA-NRCS 2000) for this analysis since the only available land use/land cover geographic data was developed in 1992 (USGS 1998). The NRI data provides an independent source against which to test the GIS-derived estimates of potential land use change for improving carbon sequestration. The GIS-derived estimates were derived by identifying areas of non-forested land as shown by the 1992 National Land Cover Data (NLCD) (USGS 1998) that occurred on general soil types that supported native forest cover, as shown by the STATSGO general soil map (USDA-NRCS 2004). For a fuller explanation of how the potential land use change estimates were derived, see Appendix A. Both the NRI and NLCD for 2002 are in development, and the analysis could be fairly easily updated when both become available for use.

Table 3. Land use of non-federal land, 1992, by state.

State	Cropland	CRP	Pasture	Range	Forest	Other rural land	Total rural land
				(1,000 acres)			
Idaho	5,600.0	823.7	1,299.0	6,517.2	4,019.9	533.2	18,793.0
Montana	15,035.0	2,781.3	3,406.6	36,982.0	5,413.6	1,404.5	65,023.0
South Dakota	16,436.7	1,756.8	2,199.7	22,078.9	524.1	1,477.3	44,473.5
Wyoming	2,271.9	251.7	935.3	27,312.1	1,030.2	1,006.1	32,807.3
Big Sky Total	39,343.6	5,613.5	7,840.6	92,890.2	10,987.8	4,421.1	161,096.8

Source: USDA-NRCS 2000; 1997 NRI, Table 2, National Summary.

Much of the cropland (19%) in the region is irrigated (Table 4). The opportunities identified in this paper for converting marginal crop and pasture land to forest are limited to non-irrigated cultivated cropland where soils and climate conditions could support forest growth. Irrigation is too expensive to be used for growing forest (with the possible exception of fast-growing hybrids), and this land would be too arid for trees if the irrigation was discontinued, so irrigated cropland was not considered an opportunity for conversion. Non-cultivated cropland is largely meadow hayland, hayland, vineyards, or orchards, so was also not considered a high opportunity for conversion. While the non-irrigated cropland area is large, only a portion lies in climate zones where trees are adapted. The GIS analysis used to identify those climate zones is described in Appendix A.

Table 4. Cropland use, by state, 1992

State	Cultivated Cropland			Non-cultivated Cropland			Total
	Irrigated	Non-irrigated	Total	Irrigated	Non-irrigated	Total	
				(1,000 Acres)			
Idaho	2,862.2	1,793.0	4,655.2	633.0	311.8	944.8	5,600.0
Montana	884.4	11,597.9	12,482.3	1,193.0	1,359.7	2,552.7	15,035.0
South Dakota	420.9	13,983.7	14,404.6	61.4	1,970.7	2,032.1	16,436.7
Wyoming	456.5	518.5	975.0	962.9	334.0	1,296.9	2,271.9
Big Sky Total	4,624.0	27,893.1	32,517.1	2,850.3	3,976.2	6,826.5	39,343.6

Source: USDA-NRCS 2000; 1997 NRI, Table 3, National Summary.

Land use change has not been a major factor in the region since 1982, as illustrated in Table 5. Virtually all of the Conservation Reserve land that has been established has come from cropland, and this land retirement was the main factor in a cropland reduction of about 3.5 million acres (8.2%) over the past 15 years. Both the total area (~ 11 million acres) and the individual sample plots on nonfederal forest land have been essentially unchanged since 1982 (the margin of error in the 1982 and 1997 total estimates is around 500,000 acres, so the changes shown are not statistically significant).

Implementation of the most recent signup in the CRP program has resulted primarily in the conversion of cropland to grassland, as shown in Table 6. Even in the counties where conversion to trees looks biologically possible, the amount of CRP land planted to trees has been very low. These factors suggest that conversion of marginal cropland to trees is a difficult "sell" in this region, even in those counties where trees are a logical option. This is not a recent phenomenon, nor is it limited to this region. Esseks et al. (1992) found that farmers outside the Southeast, where forest production is a common practice on private lands, were generally unwilling to commit to the permanence of forest cover and opted, instead, for the land use flexibility of planting a grass cover.

One possibility, largely unused to date, is the potential for the Conservation Reserve Enhanced Program (CREP) for establishing riparian forests as a means of enhancing water quality.

Table 5. Land Cover/Land Use Change, 1982-1997, Big Sky Region.

	Land Cover/Use in 1997								
Land Cover/Use in 1982	**Cropland**	**Pasture-land**	**Range-land**	**Forest Land**	**CRP Land**	**Other Rural Land**	**Devel-oped Land**	**Water & Federal Land**	**Total in 1982**
					(1,000 Acres)				
Cropland	**35,609**	1,599	218	9	5,066	219	221	182	43,122
Pastureland	1,682	**5,618**	162	19	153	54	93	46	7,825
Rangeland	2,037	625	**91,373**	159	207	134	202	320	95,055
Forest Land	13	19	176	**10,458**	0	18	86	201	10,972
CRP Land	0	0	0	0	**0**	0	0	0	0
Other Rural Land	77	83	86	41	12	**3,925**	21	16	4,261
Developed Land	13	5	23	6	0	2	**2,768**	0	2,816
Water & Federal Land	169	65	393	209	0	27	0	**94,643**	95,507
Total in 1997	39,600	8,011	92,430	10,901	5,438	4,380	3,391	95,408	259,558

Source: NRCS 2000 (1997 NRI). Note: Acreage in bold is unchanged from 1982 to 1997.

Table 6. Conservation Reserve Program Acres, Big Sky States, by Cover Type, Signup #26, 2003

State	Total CRP	Grass		Trees	
	Acres		*Percent*	*Acres*	*Percent*
Big Sky Region	129,985	127,847	98.4%	2,138	1.6%
Idaho	53,750	51,829	96.4%	1,921	3.6%
Montana	50,255	50,242	100.0%	13	0.0%
South Dakota	25,980	25,776	99.2%	204	0.8%
Wyoming	0				

• Greenhouse Gas Emission Inventory

The U.S. Department of Agriculture has conducted a comprehensive assessment of greenhouse gas emissions and sinks in U.S. agriculture and forests (USDA 2004). Estimates are provided at State, regional, and national scales, categorized by management practices where possible. The estimates are consistent with those published by EPA in the official Inventory of U.S. Greenhouse Gas Emissions and Sinks that was submitted to the United Nations Framework Convention on Climate Change in April 2003. For the Big Sky Region, cropland soils were estimated to be an annual sink of 5.4 TgCO_2e (Table 7), while forests (not counting soils or forest products) were estimated to be a sink of 40.8 TgCO_2e per year (Table 8). (Tg stands for teragrams, or million metric tons.)

Table 7. State estimates of soil carbon changes in cropland and grazing land in 1997 by major activity categories.

State	Plowout of grassland to Annual cropland[1]	Cropland manage-Ment	Other Crop-land[2]	Cropland converted to hayland[3]	Hayland manage-ment	Cropland converted to grazing land[3]	Grazing land man-agement	CRP	Manure applica-tion	Cultiva-tion of organic soils	Net soil carbon Emissions[4]
						Tg CO_2e					
Idaho	1.1	-0.07	0	-1.03	-0.04	-0.26	-0.04	-0.59	-0.34	0.07	-1.19
Montana	1.91	-0.59	0	-1.28	-0.07	-0.48	0	-1.8	-0.08	0.11	-2.28
South Dakota	4.07	-0.18	0	-2.9	-0.04	-0.44	0.07	-1.39	-0.31	0.07	-1.04
Wyoming	0.51	-0.07	0	-0.62	-0.04	-0.29	0	-0.37	-0.04	0	-0.92
Big Sky Totals	7.59	-0.91	0	-5.83	-0.19	-1.47	0.03	-4.15	-0.77	0.25	-5.43

Negative numbers indicate net sequestration.

[1] Losses from annual cropping systems due to plow-out of pastures, rangeland, hayland, set-aside lands, and perennial/horticultural cropland (annual cropping systems on mineral soils, e.g., corn, soybean, cotton, and wheat).

[2] Perennial/horticultural cropland and rice cultivation.

[3] Gains in soil carbon sequestration due to land conversions from annual cropland into hay or grazing land.

[4] Total does not include change in soil organic carbon storage on federal lands, including those that were previously under private ownership, and does not include carbon storage due to sewage sludge applications.

Source: Appendix Table B-11, USDA 2004.

Tg = terragrams = million metric tonnes

Table 8. State summaries of forest area, total area, forest non-soil stocks (2002), forest non-soil stock change (2001), and forest products stock change (2001).

State	Forest Area	Total Area	Forest non-soil stocks	Forest non-soil stock change	Products stock change
	1,000 ha		*Tg CO_2 e*	*Tg CO_2 e/yr*	
Idaho	8,760.0	21,646.0	4,145.0	-12.1	-3.4
Montana	9,426.0	23,291.6	3,938.0	-21.5	-2.3
South Dakota	655.0	1,618.5	192.0	0.6	-0.2
Wyoming	4,449.0	10,993.5	1,897.0	-7.8	-0.2
Big Sky Totals	23,290.0	57,549.6	10,172.0	-40.8	-6.1

Source: Appendix Table C-1, USDA 2004

• Forestry Opportunities for Carbon Sequestration in the Big Sky

• *Afforestation*

We define the biological opportunity for afforestation as all non-federal, non-forest land (primarily cropland and grassland) identified in the 1992 NLCD data in areas where the STATSGO soil survey (USDA-NRCS 2004) identifies woodland as being the native vegetation (Figure 4). See Appendix A (Tables A-1 and A-2 for the classifications used.) That estimate may overstate the real biological opportunity, since some of those sites have been degraded by soil erosion to the point where an ecological type change has occurred that may prevent successful re-establishment of trees. That overestimation has been taken into account by discounting the estimates of feasible afforestation from the estimate of total suitable land. The amount of discount was based on the current land use and the forest type suitability (Appendix Table A-6).

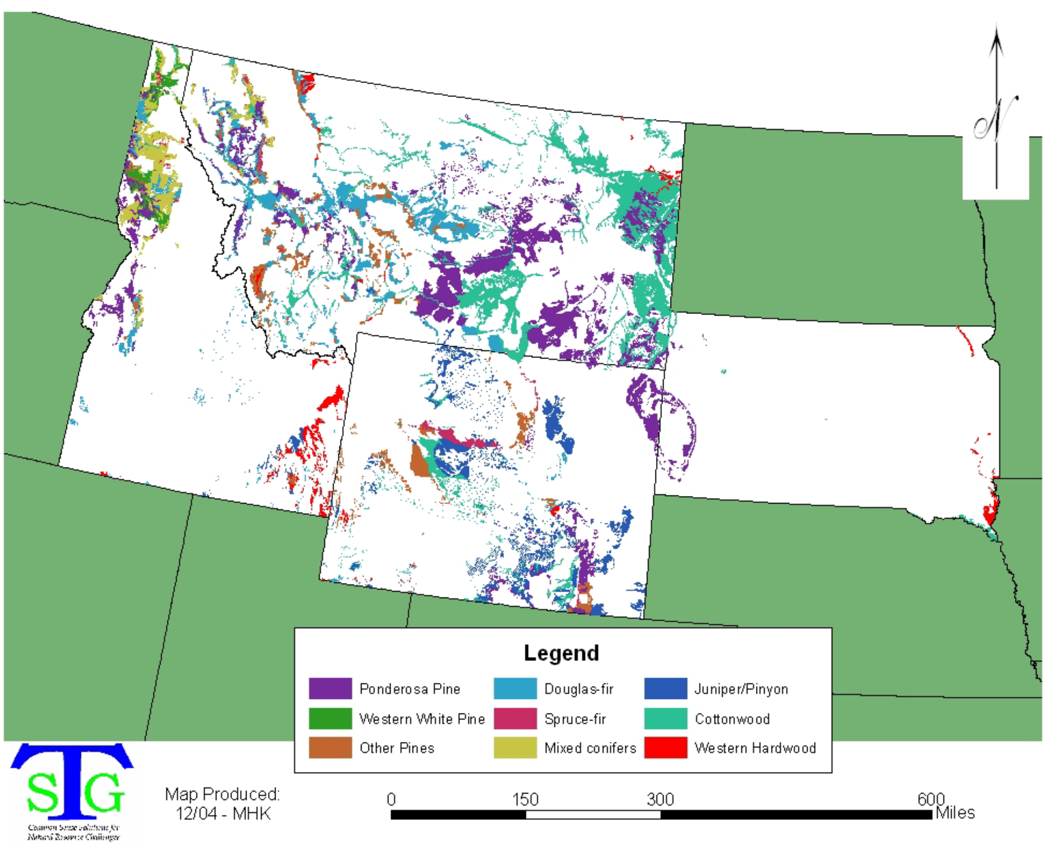


Figure 4. Potential forest types on non-federal lands, as indicated by general soil type (STATSGO).

To develop estimates of the impact of afforestation, tables were developed by state indicating the current non-forest area that coincided with a native forest type. These were then combined in a regional table (Appendix Table A-3). See Appendix A for a description of the analytic methods used. Average annual forest growth estimates were developed from Birdsey (1996) (Appendix Table A-4). Estimates of potential timber volume growth were developed by multiplying the acreage of land available to be afforested times the average annual growth rate of the appropriate forest type.

The estimates of potential timber volume growth were converted to carbon dioxide equivalents by the factors published by Birdsey (1992, 1996). When the specific factors are applied to the species in the region, they range from 88 to 127 lbs CO_2e per ft^3 of timber grown.

The resulting biological opportunity is around 44.6 TgCO_2e per year (Appendix Table A-5) on the region's non-federal lands. This estimates the upper limit of potential afforestation impact. This would represent a significant impact, more than doubling the amount of sequestration currently occurring in the forests of the region (Table 8). If the estimate of available, suitable acres (34.3 million) is reasonable, however, the estimated sequestration rate is about 1.3 tCO_2e per acre per year. That is conservative, as there are existing default factors, such as those used by the Chicago Climate Exchange, that run in the range of 1.4 to 1.5 tCO_2e per year.

Since it is anticipated that only a small portion of the potential will be realized (and that it will be realized at a different rate for different existing land uses and timber types, see Table A-6), a final table (Table A-7) was constructed based on an author's estimate of the potential for conversion, based on experience in the region. These factors can be debated by experts in the region and changed to reflect other opinions. The impact of this calculation was to reduce the biological potential estimate by nearly 90%. In other words, we think it reasonable for the region to seek a goal of sequestering about 10% of the total biological opportunity available for afforestation (Table A-7).

On this basis, we estimate that the potential for additional carbon sequestration from an effective afforestation program in the 4-state Big Sky Region is in the range of 5 TgCO_2e per year. The range of uncertainty in the estimate is significant, running from near zero to an upper estimate of some 15-20 TgCO_2e per year. That would suggest an increase in the range of 10 to 50% compared to what is currently sequestered in all the region's forests (Table 8). Given that Table 8 includes millions of acres of federal forestlands, such a potential increase from the limited amount of non-federal forests is fairly significant. An economic supply curve could be constructed that would estimate the prices that might be required to realize the quantities within this range, but that is beyond the scope of this paper.

- ***Forest Management***

The analysis for forest management opportunity is based on data from the 1997 National Resources Inventory (NRI) that, for the first time, included an attribute for woodland species on the non-federal lands (USDA-NRCS 2000). Here, the land that was forest in 1997 was tabulated by forest type. There are no data on forest age or condition, how intensively these forests are currently being managed, or what opportunities might exist to improve that management through practices like enrichment planting (to fill understocked stands), thinning to improve health and growth in overstocked stands, or fertilization. The carbon dynamics in these forests can also be changed by lengthening the growing rotation on managed forests to provide larger trees, and larger wood products that last longer in use (Row 1996).

Table 9 contains 1997 estimates of non-federal forest by species groups as one basis for understanding the potential for carbon sequestration through improved forest management.

Table 9. Forest species groups on non-federal land, by state, 1997.

Group	Species	Idaho	Montana	S Dakota	Wyoming	Total
				1,000 acres		
1	Ponderosa Pine	462.0	1,116.7	346.5	660.7	2,585.9
2	Lodgepole Pine	47.0	662.7		49.3	759.0
3	Douglas Fir	1,272.5	2,335.0		23.8	3,631.3
4	Fir; Spruce	122.0	439.6		98.2	659.8
4	Hemlock; Sitka Spruce	658.0	-			658.0
4	Spruce; Fir		8.2			8.2
5	Larch	946.1	296.1			1,242.2
5	Western White Pine	60.7	16.2			76.9
6	Pinyon; Juniper	5.4	-			5.4

7	Elm; Ash; Cottonwood		40.6	89.4	3.2	133.2
8	Aspen; Birch		54.4	10.1	15.9	80.4
8	Oak; Pine			40.1	10.7	50.8
8	Western hardwoods	248.4	192.6	26.6	107.4	575.0
9	Noncommercial	3.6	90.5	5.0	32.9	132.0
9	Non-stocked	122.1	178.2	0.6	2.0	302.9
	Total non-federal forest	3,947.8	5,430.8	518.3	1,004.1	10,901.0

Source: 1997 NRI (USDA-NRCS 2000)

The next question that arises is the extent to which the existing forests can be managed differently to increase carbon sequestration. Not knowing the level of current management intensity, we applied general factors across the area, recognizing that on any one forest, the departures from average will likely be significant.

There are some forest types that are more likely to be managed for improved growth and productivity than others. One example would be ponderosa pine versus pinyon pine. Ponderosa is widely managed for timber and other forest values, while pinyon is generally a scattered forest across broad areas that are primarily used for grazing land by private landowners. Thus, pinyon/juniper is one forest type that is unlikely to be managed to increase carbon sequestration. Most of the western hardwoods in the Big Sky Region probably fall into this category, as well. Based on these factors, the forest types were divided into three classes on the probability that state or regional carbon sequestration programs would be likely to impact forest management (Table 10).

As a general rule, the average annual carbon sequestration impact from changing forest management is quite low (Table 10). Lengthening harvest rotations, thinning and weeding for improved species adaptation and forest health, inter-planting to achieve optimum stand density, and fertilization all can change forest growth dynamics, but the region's forest types are fairly slow-growing, and changing management does not impact the annual change in standing biomass rapidly. The result is fairly low estimates of potential annual impact from forest management. The large area involved, almost 10 million acres in the "high" and "medium" categories, result in fairly significant estimates of potential impact. The bottom line of 1.5 to 2 $TgCO_2e$/yr, would represent a change of some 3-5 percent in the region's currently estimated annual forest sequestration (Table 8).

- **Table 10. Non-federal forest land, Big Sky Region, with estimates of the management opportunities for increasing carbon sequestration**.

		Management Opportunity*		
Species Group	1000 Acres	High	Medium	Low
Ponderosa Pine	2,585.9	2,585.9		
Other Pines	759.0		759.0	
Douglas-fir	3,631.3	3,631.3		
Fir-spruce	1,326.0		1,326.0	
Mixed conifers	1,319.1		1,319.1	
Pinyon/juniper	5.4			5.4
Cottonwood	133.2			133.2
Western Hardwood	706.2			706.2
Non-stocked	434.9			434.9
Total	10,901.0	6,217.2	3,404.1	1,279.7
* Rated by authors on the basis of the likelihood that landowners will manage them for long-term timber or carbon sequestration goals.				
tCO_2e/acre/year		0.25	0.1	0
Sequestration Opportunity		1,554.3	340.4	-
Total Annual Sequestration Opportunity (1000 tCO_2e)				1,894.7

• Agroforestry Opportunities

• *Field Windbreaks*

The analysis for field windbreak needs and opportunities is based on data from the 1997 NRI (USDA-NRCS 2000). We used the NRI to identify all non-irrigated cropland with an erosion index (EI) of 5 or higher that did not have windbreaks or cross-wind stripcropping established in 1997 (Table 11). These lands may have other erosion control practices such as conservation tillage, vegetative soil traps, or other herbaceous wind barriers, but there is a good indication that windbreaks would be a helpful addition to the wind erosion control strategy on many of them, and the carbon sequestration impacts would be an added benefit to the landowners and the environment. (Soils with EI values over 5 are erodible, and USDA classifies those with EI values over 8 as highly erodible (USDA-NRCS 2000)).

For those erodible dry croplands, we estimated that field windbreaks occupying 5% of the cultivated surface area would be a realistic goal for the establishment of needed windbreaks (Brandle et al., 1992a). At an average one-row windbreak width of 16½ feet, such a windbreak would occupy 2 acres per mile. At 8 to 10-foot spacing between trees, there would be 530 to 660 trees per mile. The carbon sequestration rate was estimated at 3 tCO_2e per acre per year (Table 11, see Table 12 for representative species). No credit was given for the emissions reductions inherent in the soil conservation effect of windbreaks, or the reduction in cultivated area and associated fuel and fertilizer use, etc. What is clear, however, is that field windbreaks offer significant ancillary environmental benefits in addition to their impact on carbon sequestration (Brandle et al., 1992b). Work is currently underway at the University of Nebraska to develop more definitive tables of sequestration in windbreaks, and could become available for use in the near future (Table 12, Zhou and Brandle, unpub.).

• **Table 11. Croplands with a wind erosion index (EI) greater than 5, and annual carbon sequestration from establishing windbreaks on 5 percent of those that lacked stripcropping or windbreaks in the 1997 NRI.**

Category	Idaho	Montana	South Dakota	Wyoming	Big Sky
			1,000 acres		
Cultivated Cropland, Wind EI > 5	2,823.1	12,350.9	3,584.9	870.1	19,629.0
Dry Cultivated (DC) Cropland, EI > 5	172.8	11,534.1	3,535.0	467.0	15,708.9
DC Cropland, EI > 5, with no Stripcropping	164.6	8,711.1	3,452.9	217.9	12,546.5
DC Cropland, EI > 5, with no Stripcropping or Windbreaks	164.6	8,682.9	2,818.3	217.9	11,883.7
Windbreaks on 5%	8.2	434.1	140.9	10.9	594.2
tCO_2e/acre/year	3.0	3.0	3.0	3.0	3.0
$TgCO_2e$/year	0.025	1.3	0.42	0.033	1.78

Table 12. Estimated sequestration rates for 3 common windbreak species.

Species	KgC/tree/yr	Lb/tree/yr	Trees/acre	tC/ac/yr	tCO_2e/ac/yr
Green Ash	5	11.02	264	1.32	4.85
Austrian Pine	4	8.82	264	1.06	3.88
Eastern Redcedar	1.5	3.31	330	0.50	1.82

After Zhou and Brandle, unpub.

- ***Riparian Forest Establishment***

Many of the private lands with soils adapted to forest establishment are in riparian areas, particularly in the drier areas of the region. A close inspection of the forest-growing soils (Figure 4) shows many linear patterns, particularly with the western hardwood types. These patterns outline stream valleys for the most part, and the forest opportunities there are significant. The ancillary environmental benefits to water quality and wildlife habitat are also important in these riparian areas. Table A-3 indicates 1.5 million acres of western hardwood sites in the region, which is one indicator of the riparian forest opportunity. Yields will respond in these areas due to favorable soil and moisture conditions, leading to an estimated carbon sequestration gain of 2 – 2.5 $TgCO_2e$ per year if one-half of these lands were planted to species such as cottonwood, willow, and other adapted local species with yields of around 3 tCO_2e per acre per year.

• Biomass Energy Opportunities

The use of biomass as a substitute for fossil fuel (primarily coal) is an excellent opportunity to replace fossil carbon emissions with renewable fuels that grow and sequester carbon in the same general time as the emissions occur. Thus, the use of biomass is often referred to as an offset for fossil emissions (Klass 1998; Sampson et al. 1992).

Biomass for fuel can be harvested from existing forests, particularly those that are overstocked and need thinning. Thinning that removes small trees and ladder fuels can be a major contributor to helping these forests become less susceptible to uncharacteristic wildfires, improving forest health, and opening up overcrowded forests for additional biological diversity (Sampson et al. 2001).

While it is possible to build power plants that rely solely on biomass fuels, another opportunity lies in co-firing biomass in existing coal-burning power plants. Research indicates that firing with up to 10 percent biomass is technically feasible and provides reductions in pollution emissions, including carbon dioxide emissions (Payette and Tillman 2004). Biomass, while having several environmental advantages, can also be used effectively in co-firing despite supply variations due to things like annual weather or harvest conditions. The coal plant is not dependent on the biomass, so if a yield shortfall occurs, the plant is not forced to cut back on production.

One of the key economic limitations in biomass energy production is the transportation costs involved in moving heavy, low-value fuels large distances. For that reason, many authors suggest that a radius of about 50 miles is reasonable in calculating the region that can feasibly supply biomass fuel to an existing power plant (Klass 1998).

Figure 5 shows the existing coal-fired power plants in the Big Sky Region, according to the 2002 version of the eGRID database produced by the Environmental Protection Agency (USEPA 2003). A GIS analysis estimated the 1992 land cover/land use within a 50-mile radius of each plant. This analysis included federal lands, because federal lands in the region are in serious need of thinning to restore forest health and fire adaptability (Sampson et al. 2001).

Growing short-rotation crops like hybrid poplar or willow on agricultural land produces biomass yields in the range of 4-10 dry tons per acre per year (Tuscan 2000). Switchgrass should produce about 4 dry tons per acre per year on dry croplands in eastern South Dakota (Graham et al. 1996). Limited rainfall will preclude its growth west of there, according to the ORNL data (Graham et al. 1996). Thinning overcrowded forests produces one-time biomass yields of around 15 tons per acre

(Sampson et al. 2001). Although heat values vary considerably with the moisture content of biomass fuel, we assumed that 1 bone dry ton (BDT) of biomass would produce 1 MWH of electricity. Thus, around 8,700 BDT of biomass is needed to produce 1MWH for a year.

There is a significant difference in these biomass sources, however. Farm-produced biomass (switchgrass or short-rotation woody crops such as hybrid poplar) should yield around 4 tons per acre per year on a sustained basis. Thinning overcrowded forests is largely a one-time biomass removal, since converting the forests to a more sustainable condition will result in fewer small and uneconomic stems in the future (Sampson et al. 2001). There will be future production that may need removal by mechanical means, but the average per-year production rate will be slow. Thus, a power plant dependent on forest thinning needs an available acreage that is some 25-30 times larger than what is needed for its annual consumption.

Table 12. Estimates of land required, land available, and proportion needed to provide biomass sufficient for co-firing to replace 10% of the current MWh produced by coal-burning power plants in the Big Sky Region.

Plant No.	State	Name	2000 annual coal net generation (MWh)	Biomass to replace 10% of MWh[1] (BDT)	Land Required		Land Available		Proportion Needed	
					Crop-land[2]	Forest[3]	Cropland[4]	Forest[5]	Crop-land	Forest
1	ID	AMALGAMATED SUGAR CO LLC NAMPA FACTORY	42,436.9	4,244	1,061	283	403,505	317,587	0%	0%
2	ID	THE AMALGAMATED SUGAR CO LLC	28,238.3	2,824	706	188	897,829	22,657	0%	1%
3	MT	COLSTRIP + COLSTRIP ENERGY LP	14,715,206.9	1,471,521	367,880	98,101	318,606	538,893	115%	18%
4	MT	CORETTE	1,161,874.8	116,187	29,047	7,746	1,134,961	393,154	3%	2%
5	MT	LEWIS & CLARK	323,757.0	32,376	8,094	2,158	1,810,108	25,179	0%	9%
6	SD	BEN FRENCH	166,314.0	16,631	4,158	1,109	320,936	1,104,604	1%	0%
7	SD	BIG STONE	3,504,262.0	350,426	87,607	23,362	1,171,048	513	7%	4554%
8	WY	DAVE JOHNSTON	5,661,946.0	566,195	141,549	37,746	10,206	117,212	1387%	32%
9	WY	GENERAL CHEMICAL + JIM BRIDGER	16,380,196.4	1,638,020	409,505	109,201	7,671	13,848	5338%	789%
10	WY	OSAGE	245,439.0	24,544	6,136	1,636	48,978	349,676	13%	0%
11	WY	LARAMIE RIVER 1 + LARAMIE RIVER 2 & 3	12,440,471.0	1,244,047	311,012	82,936	495,047	222,950	63%	37%
12	WY	NAUGHTON	5,311,532.0	531,153	132,788	35,410	26,470	241,123	502%	15%
13	WY	NEIL SIMPSON + NEIL SIMPSON II + WYODAK	3,534,324.0	353,432	88,358	23,562	64,957	71,524	136%	33%

1 Estimated on the basis of 1 BDT yielding 1 MWH of power.
2 Estimated sustainable yields of 4 BDT biomass per acre per year with grass or woody crops
3 Estimated one-time yield of 15 BDT per acre of otherwise non-merchantable wood during thinning.
4 Total row crops, small grains, and fallow from NCLD within 50 miles of plant.
5 Total evergreen forest within 50 miles of plant. (Omits deciduous and mixed forests as unlikely sources.)

This analysis suggests that there are significant differences between locations as to the possibility of co-firing biomass from agricultural or forest sources. Some (i.e. 1 and 2) are located in the midst of irrigated agricultural areas where production costs might be too high to support biomass production. Forest resources are plentiful within 50 miles, and may be a better opportunity. Some plants (i.e. 3,8,9,11,12, and 13) would clearly be too large to be considered for agricultural inputs since they are so large in comparison with the available cropland nearby. Others (3,7,8,9,11,12, and 13) would overwhelm surrounding forest resources because of their size. Some of the smaller plants (i.e. 1,2,4,5,6, and 10) may be potentials for consideration as a co-firing opportunity.

Those six plants were responsible for annual emissions of 2.5 $TgCO_2e$ in 2000, according to the eGRID data, so if co-firing were feasible on all of them, a reduction of some 0.25 $TgCO_2e$ per year may be realized. While it is unlikely that all of this could be realized by co-firing, the estimate could also under-estimate the future opportunities if the current trend toward building new fossil-fired power plants were to include biomass co-firing as part of initial design, or if new technologies or economic conditions make construction of dedicated biomass plants feasible.

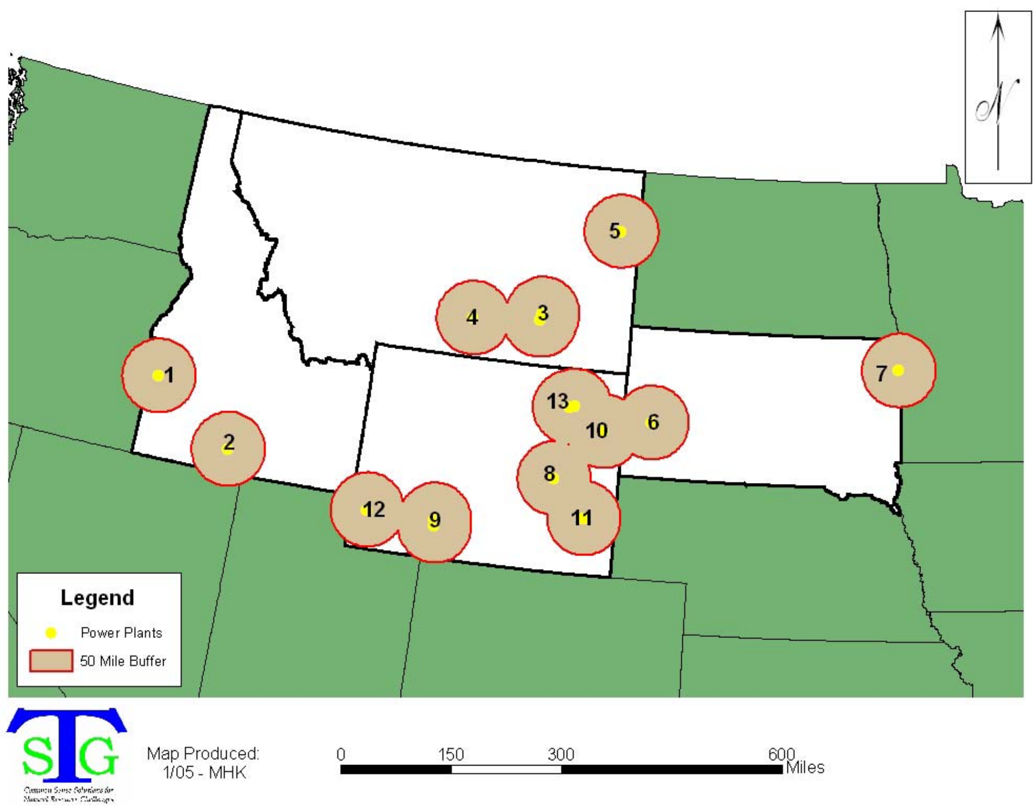


Figure 5. Existing coal-fired power plants, with 50-mile radius indicated.

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Appendix A. The Geographic Information System (GIS) Analysis for Afforestation Opportunity

Data Sources

Three primary data sources were used in this analysis. This included a vector layer containing the location of Federal lands, the U.S. Geological Survey National Land Cover Data (NLCD) raster coverages and State Soil Geographic (STATSGO) vector data. These layers were downloaded via the Internet from federal sources. Each layer was in the same projection system and measurement units (Albers Conical Equal Area, meters).

To obtain the location of Federal lands within the scope of the project, the *Federal Lands and Indian Reservations* vector file was downloaded from www.nationalatlas.gov. This is a federal website supported by the United States Department of the Interior that provides a platform to download federally produced GIS data sets. This layer contains polygons of the federally owned or administered lands throughout the United States. For the purposes of this study it was determined that federal lands were not eligible for afforestation, but Indian reservations could be. Therefore, the Indian Reservations were removed from this layer before it was used as a filter to remove Federal land.

The USGS National Land Cover Data (NLCD) was downloaded by state from *http://www.usgs.gov*. This data was derived from Landsat satellite TM imagery (circa 1992) and is provided in a Geo-TIFF format with a 30-meter resolution. Each cell contains a numeric value that represents a certain land cover based upon the NLCD Classification System.

State Soil Geographic (STATSGO) data were downloaded by state from http://www.nrcs.usda.gov. This vector layer and its related tabular data provide locations of current and potential forests by forest type based on soil types and descriptions. Use of this layer helps identify areas containing soils suitable for growing trees.

Scale/Accuracy

Data accuracy is always a concern when performing spatial analyses using multiple data layers from multiple sources. Data accuracy and scale of each layer was considered before the analysis was performed.

According to the metadata of the Federal Lands data, it was produced for analysis "at scales appropriate for 1:2,000,000-scale data." This is a small scale, so accuracy would be a concern if this data were used in analyses conducted at much larger scale. However, this analysis was conducted at the state level and, given the large size of the western states within the scope of our project, the use of this federal lands layer was considered appropriate.

The NLCD layers were produced with a 30 by 30 meter cell-size (or resolution). Therefore, each cell represents 900 square meters or 0.222 acres. These data were produced with the highest level of detail of any data used in this analysis and were appropriate for our state-level analysis.

According to its metadata, STATSGO data was "designed primarily for regional, multistate, river basin, state, and multi-county planning, managing and monitoring," so was considered appropriate for this analysis.

Procedures

The GIS analysis was conducted in several steps. The first step determined existing areas on non-federal lands that would be available for afforestation on the basis of current use (mainly cropland or pasture). The second step determined soil and climate situations suitable for afforestation based on the STATSGO data. The third step combined the outputs of the first two steps to compute a *Final Suitability* layer. Finally, the tabular data were converted from acres of potential forest into estimates of sequestration by primary forest groups, based on projected average annual yields of timber converted into its equivalent carbon dioxide sequestration impact.

Step 1- NLCD land cover on non-federal lands

The Federal Lands layer was first clipped to the Big Sky states within the scope of the project: Idaho, Montana, Wyoming and South Dakota. The polygons associated with the Indian Reservations and null values were then removed from the resulting federal land layers, since the Indian Reservations are considered potential cooperating lands for the purposes of this study. Each state-clipped federal land layer was converted to a raster grid with the same resolution (30m) and extent of the NLCD layer associated with each particular state. The resulting grids were then reclassified, so that the cells containing federal land held a value of zero and all other cells contained a value of one.

A raster calculation within each state multiplied the reclassified federal lands grids and the NLCD grids. The resulting grids contained a value of zero where federal lands exist and the previous value of the NLCD classification in all other areas.

Not all NLCD classes are available for afforestation (Table A-1). Areas already classified as forests, and areas such as urban, wetlands, etc., were excluded from the analysis. In order to isolate the suitable areas, the non-federal NLCD grids were reclassified to remove the cells that contained unsuitable values. The result provided maps and area estimates of the non-federal land within each state that is potentially available for afforestation based on NLCD classifications (Figure 4). (Note: this map contains areas unsuited for forests due to soil and climate conditions.)

Table A-1. NLCD classes identified as suitable/non-suitable for afforestation on the basis of 1992 land use or cover.

Suitable				Non-Suitable	
Code	Description	Comments		Code	Description
33	Transition Areas	Poss. Clearcuts		11	Water
51	Shrubland	good on suitable soils		12	Perennial Ice/Snow
61	Orchards/Vineyards/Other			21	Low Intensity Residentail
71	Grasslands/Herbaceous	good on suitable soils		22	High Intensity Residentail
81	Pasture/Hay			23	Commercial/Industrial/Transporation
82	Row Crops			31	Bare Rock/Sand/Clay
83	Small Grains			32	Quarries/Strip Mines/ Gravel Pits
84	Fallow			41	Deciduous Forest
				42	Evergreen Forest
				43	Mixed Forest
				85	Urban/Recreational Grasses
				91	Woody Wetlands
				92	Emergent Herbaceous Wetlands

Step 2- STATSGO suitability

For step two, the STATSGO data layers and their associated tabular data were analyzed for each state. To determine areas that are suitable for growing trees the 'woodland' table was joined to the base STATSGO layers. By doing so, the attributes identify polygons with soil and climate characteristics appropriate for growing trees. Only these areas in each state were included in further analysis.

The 'woodland' table also provides a native forest type based upon the soil and climate features. To simplify our analysis, we grouped the STATSGO forest types into nine groups (Table A-2). The federal lands were then removed, by clipping the forest group polygons to the non-federal lands layer created from the original Federal lands data. The resulting layer contained the areas of non-federal land that are suitable for afforestation based upon the STATSGO data (Figure 4).

Table A-2. Grouping of primary species in STATSGO soils data into major forest type groups.

Code	Group	Species included in Group
1	Ponderosa Pine	Ponderosa pine
2	Western White Pine	Western White Pine
3	Other Pines	Lodgepole pine, limber pine
4	Douglas-fir	Douglas-fir
5	Spruce-fir	Engelmann spruce, subalpine fir, white spruce, mountain hemlock
6	Mixed conifers	Grand fir, western larch, western redcedar
7	Pinyon/juniper	Utah juniper, oneseed juniper, pinyon, singleleaf pinyon
8	Cottonwood	Black cottonwood, narrowleaf cottonwood, plains cottonwood, eastern cottonwood
9	Western Hardwood	Bur oak, white oak, quaking aspen, silver maple

Step 3- Final Suitability

The final map layer identified areas available for afforestation by the NLCD (current cover is not forest) and potentially suited to forests according to STATSGO. These layers were combined by converting the STATSGO suitability layers to grids with the same resolution (30m) and extent of the NLCD suitability layers associated with each particular state. Each cell of the new STATSGO grids contained the forest type code (created in step 2) for the potential forest spatially associated with each particular cell.

This forest-type grid was then reclassified so that all cells containing a forest-type were given a value of 1 and all other cells contained a value of zero. A raster calculation was then performed between this reclassified grid and the NLCD suitability grid. This created a new layer that contained the NLCD codes in the areas determined suitable for growing trees by the STATSGO data.

In order to determine area estimates of potential afforestation by forest types, the original forest type grid values need to be incorporated with the NLCD values. This gives the area of potential afforestation by 1992 land cover and potential forest type. Another raster calculation is done between the suitable soil forest types and the original NLCD grid that contained the non-forest values.

Unfortunately, these grid values could not be simply added together, because the results would contain integers with potentially non-unique or overlapping values. In order to maintain the integrity of both the NLCD values and the forest group values, NLCD values were multiplied by 100 and then the forest type values were added to that number. The result was a grid with each cell identified by a four-digit number. The first two digits referred to the NLCD code associated with that cell, the third number was a zero (meaning nothing, but a place holder or separator) and the fourth number contained the forest type code associated with that cell. (Thus, a grid cell with an attribute of 7101 indicated an area of current grassland with the soil and climate potential to grow ponderosa pine.)

Step 4. Developing afforestation and carbon sequestration estimates

The final suitability grid was entered into a spreadsheet model and analyzed for potential afforestation acreage estimates within each state. Since each grid represents 900 m^2, multiplying the number of grids by 900 and dividing the result by 4047 converted the area to acres. A cross-tabulation produced a table showing current cover and potential forest type. These estimates were developed for each state and rounded to 1,000 acres to avoid the appearance of high precision. Table A-3 gives the results for the 4-state Big Sky Region – an estimate of some 34.3 million non-federal acres that are not now in forest, but that are biologically capable of supporting forest growth.

Table A-3. Area potential for afforestation, Big Sky Region

Potential Forest → / Current Cover ↓	Ponderosa Pine	Western White Pine	Other Pines	Douglas-fir	High Elev. Conifers	Other Conifers	Pinyon/ Juniper	Cotton-wood	Western Hardwood	Total
					1,000 acres					
Transition Areas	11.0	19.5	4.4	28.9	7.0	131.7	0.0	1.1	0.0	**203.6**
Shrubland	1,372.8	64.2	610.6	819.4	152.6	206.0	2,477.4	1,607.5	524.3	**7,834.8**
Orchards/Vineyards/Other	-	0.3	-	2.5	-	0.0	-	-	-	**2.8**
Grasslands/Herbaceous	6,807.4	72.6	1,641.9	2,233.8	312.8	165.3	1,627.7	5,130.3	466.7	**18,458.4**
Pasture/Hay	378.2	36.7	74.8	130.0	1.8	68.8	212.7	685.0	217.6	**1,805.6**
Row Crops	17.8	0.2	3.9	5.8	0.2	0.1	89.2	184.8	210.8	**512.8**
Small Grains/Fallow	1,379.9	108.5	104.4	480.5	0.8	198.6	98.9	3,007.9	118.6	**5,498.2**
TOTAL	**9,967.0**	**302.0**	**2,440.0**	**3,701.0**	**475.3**	**770.5**	**4,505.9**	**10,616.6**	**1,538.1**	**34,316.3**

Table A-4. Estimated average yields for major forest types, Big Sky Region.

Code	Group	Average Yield	Notes	lbs. total CO_2e per ft^3 timber*
		ft^3/acre/year		
1	Ponderosa Pine	25	Birdsey Table 32	100.4
2	Western White Pine	25	Birdsey Table 32	100.4
3	Lodgepole pine	27	Birdsey Table 34	111
4	Douglas-fir	29	Birdsey Table 31	88.4
5	Fir-spruce	39	Birdsey Table 33	92.5
6	Mixed conifers	29	Birdsey Table 31	92.5
7	Pinyon/juniper	10	Author's estimate	111
8	Cottonwood	30	Birdsey Table 25	126.9
9	Western Hardwood	50	Birdsey Table 26	126.9

*Factors for lbs. C per cubic foot and multiplier to total tree C taken from Birdsey (1996). Multiplied by 3.67 to produce CO_2e.

The final steps in the calculation were to estimate forest yields in terms of carbon sequestration. Yield estimates (in average ft^3 of timber per acre per year for a 50-year growing period) were taken from Birdsey (1996) where available, and estimated by the authors for species not covered in Birdsey (Table A-4). If improved local data are found, they can be readily substituted into the spreadsheet model for updating.

The estimated yields were then multiplied times the areas estimated in Table A-3 (in thousands of acres), and the product multiplied by the pounds of total CO2e (Table A-4), then divided by 2204 to convert to thousands of tonnes, and divided again by 1000 to convert to million metric tonnes of CO_2e ($TgCO_2$e). The results were the biological estimates. (Table A-5).

Table A-5. Estimated annual biological carbon sequestration from afforestation opportunities, Big Sky Region.

Potential Forest → / Current Cover ↓	Ponderosa Pine	Western White Pine	Other Pines	Douglas-fir	High Elev. Conifers	Other Conifers	Pinyon/ Juniper	Cotton-wood	Western Hardwood	Total
					$TgCO_2e$ per year					
Transition Areas	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2
Shrubland	1.6	0.1	0.8	1.0	0.2	0.3	1.2	1.9	1.1	8.1
Orchards/Vineyards/Other	-	0.0	-	0.0	-	0.0	-	-	-	0.0
Grasslands/Herbaceous	7.7	0.1	2.2	2.6	0.5	0.2	0.8	8.9	1.3	24.4
Pasture/Hay	0.4	0.0	0.1	0.2	0.0	0.1	0.1	1.2	0.6	2.7
Row Crops	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.6	1.0
Small Grains/Fallow	1.6	0.1	0.1	0.6	0.0	0.2	0.0	5.2	0.3	8.2
TOTAL	11.3	0.3	3.3	4.3	0.8	0.9	2.3	17.4	4.0	44.6

Note: All estimates smaller than 0.05 Tg rounded off to zero.

Table A-6 estimates the impacts of an afforestation program based on current cover and potential forest. These reductions were made as an author's estimate, and could be changed on the basis of regional expert review and comment or further studies such as a supply curve related to possible future carbon credit prices. Such a study was beyond the scope of this paper.

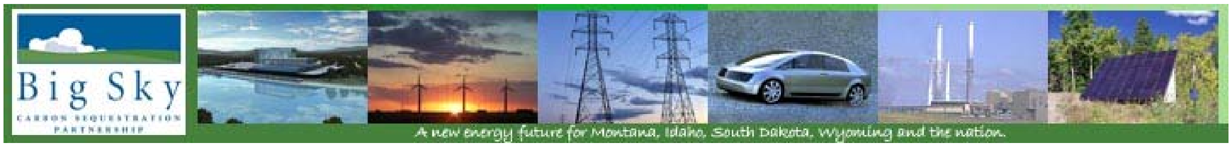
Table A-6. Estimated potential for conversion, as a percent of suitable land.

Potential Forest → / Current Cover ↓	Ponderosa Pine	Western White Pine	Other Pines	Douglas-fir	High Elev. Conifers	Other Conifers	Pinyon/ Juniper	Cotton-wood	Western Hardwood
					percent				
Transition Areas	10%	10%	10%	10%	0%	10%	0%	10%	10%
Shrubland	10%	10%	10%	10%	0%	10%	0%	10%	10%
Orchards/Vineyards/Other	2%	2%	2%	2%	0%	2%	0%	2%	2%
Grasslands/Herbaceous	10%	10%	10%	10%	10%	10%	0%	10%	10%
Pasture/Hay	10%	10%	10%	10%	10%	10%	0%	10%	10%
Row Crops	10%	10%	10%	10%	0%	10%	0%	10%	10%
Small Grains/Fallow	20%	20%	20%	20%	0%	20%	0%	20%	20%

The final estimate (Table A-7) was derived by multiplying the area suitable for conversion (Table A-3) times the percentage factors in Table A-6. The result was an estimate of potential annual carbon sequestration in the range of 5 $TgCO_2e$ per year in the Big Sky Region.

Table A-7. Estimated average annual carbon sequestration from afforestation opportunities, Big Sky Region

Potential Forest → / Current Cover ↓	Ponderosa Pine	Western White Pine	Other Pines	Douglas-fir	High Elev. Conifers	Other Conifers	Pinyon/ Juniper	Cotton-wood	Western Hardwood	Total
	$TgCO_2e$ per year									
Transition Areas	0.0	0.0	0.0	0.0	-	0.0	-	0.0	0.0	0.0
Shrubland	0.2	0.0	0.1	0.1	-	0.0	-	0.2	0.1	0.7
Orchards/Vineyards/Other	-	0.0	-	0.0	-	0.0	-	-	-	0.0
Grasslands/Herbaceous	0.8	0.0	0.2	0.3	0.1	0.0	-	0.9	0.1	2.4
Pasture/Hay	0.0	0.0	0.0	0.0	0.0	0.0	-	0.1	0.1	0.3
Row Crops	0.0	0.0	0.0	0.0	-	0.0	-	0.0	0.1	0.1
Small Grains/Fallow	0.3	0.0	0.0	0.1	-	0.0	-	1.0	0.1	1.6
TOTAL	1.3	0.0	0.3	0.5	0.1	0.1	-	2.3	0.4	5.0



Big Sky Carbon Sequestration Partnership – Phase I

Deliverable 8: Report on Evaluation of Terrestrial Sinks

Attachment B: Rangeland Terrestrial Sinks Forestry

July 2005

U.S. Department of Energy (DOE)
National Energy Technology Laboratory (NETL)
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Susan M. Capalbo
Big Sky Principal Investigator
207 Montana Hall
Montana State University-Bozeman
Bozeman, MT 59717-2460
scapalbo@montana.edu
http://www.bigskyco2.org/
Phone: (406) 994-5619
Fax: (406) 994-2893

Big Sky Partnership
The Northern Rockies and Great Plains Regional Carbon Sequestration Partnership_MLRAs
Appendix 1

Summary of MLRA Attributes for Montana, Idaho, and South Dakota

% of region	MLRA	NAME	Area km^2	Area mi^2	States
	10	Upper Snake River Lava Plains and Hills (10A proposed)	44,870	17,330	Idaho and Oregon
	11	Snake River Plains (11A and 11B proposed)	35,250	13,610	Idaho and Oregon
	12	Lost River Valleys and Mountains	16,380	6,320	Idaho
	13	Eastern Idaho Plateaus	21,010	8,110	Idaho
	43	Northern Rocky Mountains	282,650	109,130	Idaho, Montana, Oregon, Washington, and Wyoming
	44	Northern Rocky Mountain Valleys	32,320	12,480	Idaho, Montana, and Washington
1/2 north	46	Northern Rocky Mountain Foothills	52,070	20,110	Montana and Wyoming
	52	Brown Glaciated Plain	52,110	20,120	Montana
2/3 west	53 A	Northern Dark Brown Glaciated Plains	30,740	11,870	Montana and North Dakota
1/3 south	53 B	Central Dark Brown Glaciated Plains	44,980	17,370	North Dakota and South Dakota
	53 C	Southern Dark Brown Glaciated Plains	13,870	5,350	South Dakota
1/3 south	54	Rolling Soft Shale Plain	58,100	22,430	Montana, North Dakota, and South Dakota
	55 C	Southern Black Glaciated Plains	20,240	7,810	South Dakota
	58 A	Northern Rolling High Plains; Northern Part	105,620	40,780	Montana and Wyoming
1/2 south	58 D	Northern Rolling High Plains; Eastern Part	10,000	3,860	North Dakota and South Dakota
	60 A	Pierre Shale Plains and Badlands	23,600	9,110	Nebraska, South Dakota, and Wyoming
	60 B	Pierre Shale Plains; Northern Part	5,600	2160	Montana
	61	Black Hills Foot Slopes	8,400	3,240	South Dakota and Wyoming
	62	Black Hills (home of Rocky Racoon)	9,200	3,550	South Dakota and Wyoming
	63 A	Northern Rolling Pierre Shale Plains	29,610	11,430	South Dakota
1/2 north	64	Mixed Sandy and Silty Tableland	28,400	10,970	Nebraska, South Dakota, and Wyoming
1/3 north	66	Dakota-Nebraska Eroded Tableland	12,400	4,800	Nebraska and South Dakota
1/2 west	102 A	Rolling Till Prairie	38,600	14,900	Minnesota and South Dakota
	102 B	Till Plains	43,790	16,910	Iowa, Minnesota, South Dakota, and Nebraska

Land use

3/5 federal, 90% range, 5% (along streams) irrigated for potatoes, small grains, pasture
1/2 federal - mostly range,   annual grasses have invaded much of the rangeland, 1/4 irrigated potatoes
mostly all federal, high mountain slopes are forested, grass - shrubs on slopes and valleys are grazed
1/4 federal, 1/2 range, 1/4 dryfarm - wheat, ~10% irrigated -alfalfa, ~10% forested mt. slopes
Nearly all this area is federally owned, less than 2% cropped, Mostly forest -lumbering and mining
farms and ranches.1/2-1/3 native range (grass-shrub) , 1/3 irrigated - Potatoes, sugar beets, and peas
1/5 federal, 1/2 range of short and mid grass, 1/5 dryfarm (northeast side) wheat
Most of the land in the east is in range/ one-half of the total area is cropped (west) spring wheat
1/2+ dryland farm mostly spring wheat / sloping soils are in native grass range
1/2+ is dryfarmed -.winter wheat chief cash crop. Corn, grain, sorghum, oats, and alfalfa also grown sloping soils are in range.
2/3 dryland Spring wheat is the chief crop / flax, oats, barley, and alfalfa also grown / more sloping soil in native grass range
1/3 dry frarmed wheat/ 3/5 native grass and shrub grazed /
70% dryland farm.- Corn, small grains, and alfalfa main crops / 1/4 native range and tame pasture alone steeper slopes
Most in native grasses and shrubs grazed by cattle and sheep / rest dryland farming in wheat / sugar beets, alfalfa along river
4/5 ranches in native grasses and shrubs grazed by cattle and sheep 10-15% dryland wheat and alfalfa
Most of it is in native grasses and is used for grazing livestock / Badlands National Monument is a large tourist attraction.
Most of it is rangeland used for grazing livestock
Native grass is used mainly for livestock grazing. / the less sloping parts are farmed mainly to alfalfa and small grains
Black Hills National Forest used for mining, recreation, and hunting./Some timber / summer grazing
area is used mainly for livestock production and cash-grain farming / Dry-farming soils not suited to cultivation is destroying the native grassland
3/5 rangeland cattle / 1/3 crop cash grain and winter wheat / corn and sugar beets are irragated crops
Most of this area is in native grasses that are grazed by cattle
70 % is cropland Corn, soybeans, alfalfa, flax, spring wheat, and oats are the principal crops /
70% cropland Corn, soybeans, grain sorghum, alfalfa, and oats are the principal crops./ Urban development is expanding

Elevation	Precipitation	Temperature	Freeze free days
400 to 2,000 m	250 to 500 mm.	4 to 13 C	60 to 165 days
600 to 1,700 m	175 to 325 mm	5 to 11 C	90 to 170
1,400 m valleys to 3,100 m mt.crests.	175 to 275 mm valleys 625 mm mountains	3 to 7 C valleys	80 to 110 days valleys
1,400 to 2, 000 m plains and plateaus	300 to 625 mm	4 to 7 C	50 to 120
400 to 2,400 m	625 to 1,525 mm	2 to 7 C	45 to 120 days
600 to as much as 2,100 m	300 to 400 mm in most of the area	4 to 8 C	100 to 120 days
1,100 to 1,800 m in north	300 to 500 mm	6 to 7 C	90 to 125 days
600 to 1,400 m	250 to 375 mm	3 to 7 C	100 to 130
600 to 900 m	300 to 350 mm	3 to 5 C	110 to 125 days
400 to 700 m	425 to 475 mm	7 to 9 C	130 to 150 days
500 to 600 m	350 to 425 mm	1 to 7 C	110 to 130 days
500 to 1100 east to west	325 to 450	4 to 7 C	110 to 135
400 to 600	50 to 525 mm	7 to 9 C	l30 to 155 days
900 to 1,800 m east to west	300 to 500 mm	4 to 7 C.	120 to 140 days
700 to 1,000 m east to west	325 to 375 mm	4 to 7 C	120 to 130 days.
800 to 1,100 m	300 to 400 mm	7 to 9 C	130 to 150 days
900 to 1,000 m on uplands	300 to 350 mm	4 to 7 C.	110 to 125 days
900 to 1,200 m	375 to 450 mm	6 to 9 C	110 to 140 days
1,100 to 2,000 m	450 to 650 mm	3 to 7 C	80 to 130 days
400 to 500 m bottom 500 to 900 m upland	375 to 475 mm	7 to 9 C	130 to 160 days
900 to 1,200 m	375 to 450 mm	7 to 9 C	~140 days.
600 to 900 m	450 to 550 mm	8 to 10 C	130 to 160 days
300 to 400 m lowlands 400 to 500 m uplands	500 to 600 mm	6 to 9 C	120 to 140 days
300 to 400 m bottpm 400 to 500 m uplands	500 to 650 mm	9 to 11 C	135 to 165 days

Water

supplies small mostly untapped - low to moderate precipitation is adequate for dryfarming
Ground water is plentiful around major rivers - scarce on sites far from the major rivers
moderate precipitation for grass/shrubs on slopes, valleys depend on the streamflow
limited amount precip. for dryfarming and grazing
Moderate precipitation and many perennial streams and lakes provide ample water
Perennial streams principle source.
Presipitation too low for crops in some parts/ adequate for grain and forage in others
Most of the area depends on precipitation for water for range and crop
mostly moisture is inadequate for good crop production /
Most years, moisture is inadequate for maximum crop production.
most years moisture is inadequate for maximum crop production
most years moisture is inadequate for maximum crop production
most years precipitation is inadequate for maximum crop production
low and erratic precipitation is the principal source of water for agriculture.
low and erratic precipitation is the principal source of water for agriculture
limited precipitation, production of cultivated crops is marginal.
limited precipitation, the growing of cultivated crops is marginal
Most of the soils suitable for cultivation are dry during much of the growing season.
Precipitation, perennial streams, springs, and shallow wells provide adequate water for domestic use
In most years precipitation is inadequate for maximum plant growth
Most of the area depends on the rather low and erratic precipitation for water
limited precipitation makes farming a risk
In many years precipitation is inadequate for maximum production
Precipitation is the principal source of moisture for crops some year it is inadequate

Irrigation

Streams provide enough irrigation water along the major valleys
ground water around major rivers is used extensively for irrigation
about 1% mostly for hay and pasture
Ground water is scarce except near the large streams
Streams and reservoirs supply water to adjoining MLRA's for irrigation
Ground water is abundant some used for irrigation
1-2% irrigated (valleys) major rivers provide most water for irrigation
The Milk River provides irrigation water to its flood plains
only a small acreage is irrigated by the Missouri river
irrigated cropland is mostly along a narrow band of the Missouri river
only a small acreage is irrigated around the Missouri river
irrigation is available in quantity only from the Missouri River
Water from reservoirs on the Missouri River is used for irrigation
Strips along the Yellowstone River and main tributaries are irrigated.
no irrigation some wells provide water for stock
Few places have shallow-water wells for domestic use.
Water for livestock comes mainly from runoff that flows into dams
Domestic wate mostly from f streams, shallow wells, and springs.
moisture is adequate for normal plant growth. No irrigation
reservoirs on the Missouri River are on the eastern border
Ground water is scarce and of poor quality in most of the area
The Niobrara River is the only perennial stream.
Shallow wells iand small ponds principle water supply for for livestock
irrigation is increasingly along major rivers

Dominat soil	Vegetation type
Xerolls and Argids moderately fine textured to fine textured	shrub-grass association
Orthids, Argids, and Orthen	shrub-grass vegetation
Orthids, Orthents, Aquolls, and Xerolls (valleys)	desert shrub, shrub-grass, and forest vegetation
Xerolls and Borolls	grass-shrub vegetation
Ochrepts and Andepts	conifer forests
Orthids, Borolls, and Argids medium to fine textured	conifer forests and grassland vegetation
Borolls, Orthents, and Fluvents medium to fine textured	grass valleys/foothills, forest higher elevations
Borolls, Orthents, Argids, and Fluvents medium to fine textured	grass land vegetation
Borolls. deep, well drained, and medium textured	natural prairie vegetation
Ustolls. They are deep, well drained, and medium textured	natural prairie vegetation
Borolls. They are deep, well drained, and medium textured	natural prairie vegetation
Borolls. moderately deep - deep, loamy and clayey	natural prairie vegetation
Ustolls. deep, well to moderately well drained, sandy to clayey.	natural prairie vegetation
Orthents, Orthids, Argids, Borolls, and Fluvents. medium to fine textured, shallow to deep	grassland vegetation
Orthents, Orthids, Argids, and Borolls. They are medium to fine textured and well drained	mixed prairie vegetation
Orthids. They are moderately deep and deep and fine textured	natural mixed prairie vegetation
Orthids and Orthents. They are moderately deep and deep and fine textured	natural mixed prairie vegetation
Orthents. They are deep to shallow and fine textured to medium textured	open grassland, forest, and savanna vegetation
Boralfs. They have a frigid or cryic temperature regime	open to dense forest vegetation
Ustolls and Orthents fine textured and very fine textured	transition between mixed and true prairie vegetation.
Ustolls. They are medium textured and formed in loess or in alluvium	mixture of short, mid, and tall grasses
Ustolls. moderately and deep, medium and moderately coarse textured	mixed prairie vegetation
Borolls. They are deep and loamy and silty	true prairie vegetation
Ustolls. They are deep and silty and loa	true prairie vegetation

Potential Vegetation

Big sagebrush and bluebench wheatgrass are dominant on moderate to deep soils

Big sagebrush, winterfat, shadscale, Indian ricegrass, needleandthread, Thurber needlegrass, and Sandberg bluegrass grow on the lower Snake River Plains

Indian ricegrass, needleandthread, shadscale, gardner saltbush, and scarlet globemallow are major species in the valleys

Bluebunch wheatgrass and big sagebrush are dominant.

western white pine, ponderosa pine, lodgepole pine, western redcedar, western larch, hemlock, Douglas-fir, subalpine fir, and spruce are common

Bluebunch wheatgrass, rough fescue, Idaho fescue, and bearded wheatgrass are the major species of the grassland

Bluebunch wheatgrass, rough fescue, Idaho fescue, and western wheatgrass are the major grass species /Ponderosa pine, Rocky Mountain juniper higher up

Bluebunch wheatgrass, needleandthread, western wheatgrass, green needlegrass, and basin wildrye are dominant species.

western wheatgrass, needleandthread, green needlegrass, and blue grama. Little bluestem / important species on sloping and thin soils

Western wheatgrass, blue grama, needleandthread, and green needlegrass are dominant species

western wheatgrass, needleandthread, green needlegrass, and blue grama   Little bluestem important on sloping thin soils

Western wheatgrass, blue grama, needleandthread, and green needlegrass are dominant species / Prairie sandreed and little bluestem on shallow soils

western wheatgrass, green needlegrass, needleandthread, and porcupinegrass. Big bluestem is an important species on soil with restricted drainage

Western wheatgrass, bluebunch wheatgrass, green needlegrass, and needleandthread are dominant species /in east littlebluestem replaces bluebunch wheatgrass

western wheatgrass, green needlegrass, blue grama, and buffalograss /Little bluestem and sideoats grama grow on shallow soils

western wheatgrass, green needlegrass, blue grama, and buffalograss /Little bluestem and sideoats grama grow on shallow soils

western wheatgrass, green needlegrass, and blue grama. Little bluestem and sideoats grama grow on shallow soils.

little and big bluestem, green needlegrass, western wheatgrass, and needleandthread / Bur oak grows throughout the area

Black Hills spruce grows at higher elevations // Kentucky bluegrass, poverty oatgrass, Richardson needlegrass, and Canada wildrye are common under story grasses

Green needlegrass, western wheatgrass, needleandthread, porcupinegrass, little bluestem, and big bluestem are the major species

Blue grama, western wheatgrass, threadleaf sedge, sideoats grama, little bluestem, prairie sandreed, switchgrass, sand bluestem, and needleandthread are the major species

Little bluestem, prairie sandreed, green needlegrass, and needleandthread are dominant species / Sideoats grama and plains muhly are important on shallow soils.

big and little bluestem, porcupinegrass and green needlegrass / Needleandthread and prairie dropseed are important species on the steeper soils

big and little bluestem, indiangrass, porcupinegrass, and green needlegrass. Needleandthread and prairie dropseed are important species on the steeper soils

Appendix II. List of locations, sample numbers, laboratories, and contributing scientists for samples used in the first general carbon equation.

Location	No. Samples	Labs	Scientist
Akron, CO	12	USDA, Lincoln NE	Brian Wienhold
Argentina	14	Texas A&M Univ.	Wylie Harris
Blackland Prairies, TX	24	Texas A&M Univ.	R. Blaisdell
Brookings, SD	11	USDA, Lincoln NE	Brian Wienhold
Bushland, TX	22	USDA, Lincoln NE	Brian Wienhold
Fargo, ND	13	USDA, Lincoln NE	Brian Wienhold
Las Cruces, NM	24	USDA, Las Cruces, NM	Jeff Herrick
Mandan, ND	17	USDA, Lincoln NE	Brian Wienhold
Mead, NE	32	USDA, Lincoln NE	Brian Wienhold
Nebraska	138	Univ. Nebraska Lincoln	Achim Doberman
Ohio	37	Ohio State Univ.	Warren Dick
Sidney, MT	3	USDA, Lincoln NE	Brian Wienhold
Swift Current, Canada	21	USDA, Lincoln NE	Brian Wienhold
Throckmorton, TX	104	Univ. Nebraska	R. Blaisdell
Throckmorton, TX	64	Colorado State Univ.	Richard Teague and Cindy Cambardella
Vernon, TX	59	Colorado State Univ.	Richard Teague and Cindy Cambardella
Wyoming	66	Univ. of Wyoming	Jerry Schuman
Total	661	7	8

Appendix III. Soils database – listing collection locations, labs, constituents of interest and collaborators.

Location	n	Lab	Constituents of Interest	Collaborators
Big Brown Mine Fairfield, Texas	170	Univ. Delaware (FAME)	FAME	Allen Peach David Zuberer
Blackland Prairie, Central Texas	269	Texas A&M Univ. Univ. Delaware	OC,TN, IN, FAME (n=40)	Robert Blaisdell Steve Whisenant David Zuberer
Utah	26	USDA Lincoln, NE	Glomalin	Jayne Belnap
Ohio	200	Univ. Ohio	OC, enzymes	Warren Dick
Nebraska	147	Univ. Nebraska	OC, TN	Achim Doberman
Oklahoma	261	Oklahoma State Univ.	NO3, P, K OC	Sam Fuhlendorf
Argentina	16	Texas A&M Univ.	OC, TN, C13, N15	Wylie Harris
Las Cruces New Mexico	36	USDA Beltsville USDA Las Cruces	Glomalin OC, TN	Jeff Herrick
Kansas - Colorado	33	Colorado State Univ.	OC, TN, FAME	Rebecca McCulley
Wyoming	108	Univ. Wyoming	OC, TN	Jerry Schuman
Vernon, Texas	71	Colorado State Univ.	OC, IC, TN, POM	Richard Teague Cindy Cambardella
Bushland, Texas	24	USDA Lincoln, NE	OC (whole soil) glomalin (particle size)	Brian Wienhold
Fargo, North Dakota	24	USDA Lincoln, NE	OC (whole soil) glomalin (particle size	Brian Wienhold
Mead, Kansas	44	USDA Lincoln, NE	OC (whole soil) glomalin (particle size	Brian Wienhold
Swift Current, Canada	36	USDA Lincoln, NE	OC (whole soil) glomalin (particle size)	Brian Wienhold
Bushland, Texas	17	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Fargo, North Dakota	20	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Mandan, North Dakota	25	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Mead, Nebraska	28	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Sidney, Montana	22	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Swift Current, Canada	18	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Akron, Colorado	12	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Brookings, South Dakota	18	USDA Lincoln, NE	OC,TN, POM	Brian Wienhold
Throckmorton, TX	460	Univ. Nebraska (n =132) 328 predicted by NIRS	OC, IC, TN	Robert Blaisdell Jerry Stuth
Manhattan, Kansas Konza	~390	Kansas State Univ.	OC, TN	Chuck Rice Mickey Ransom Kevin Price Matt Ramspott
sum	2085	10		18

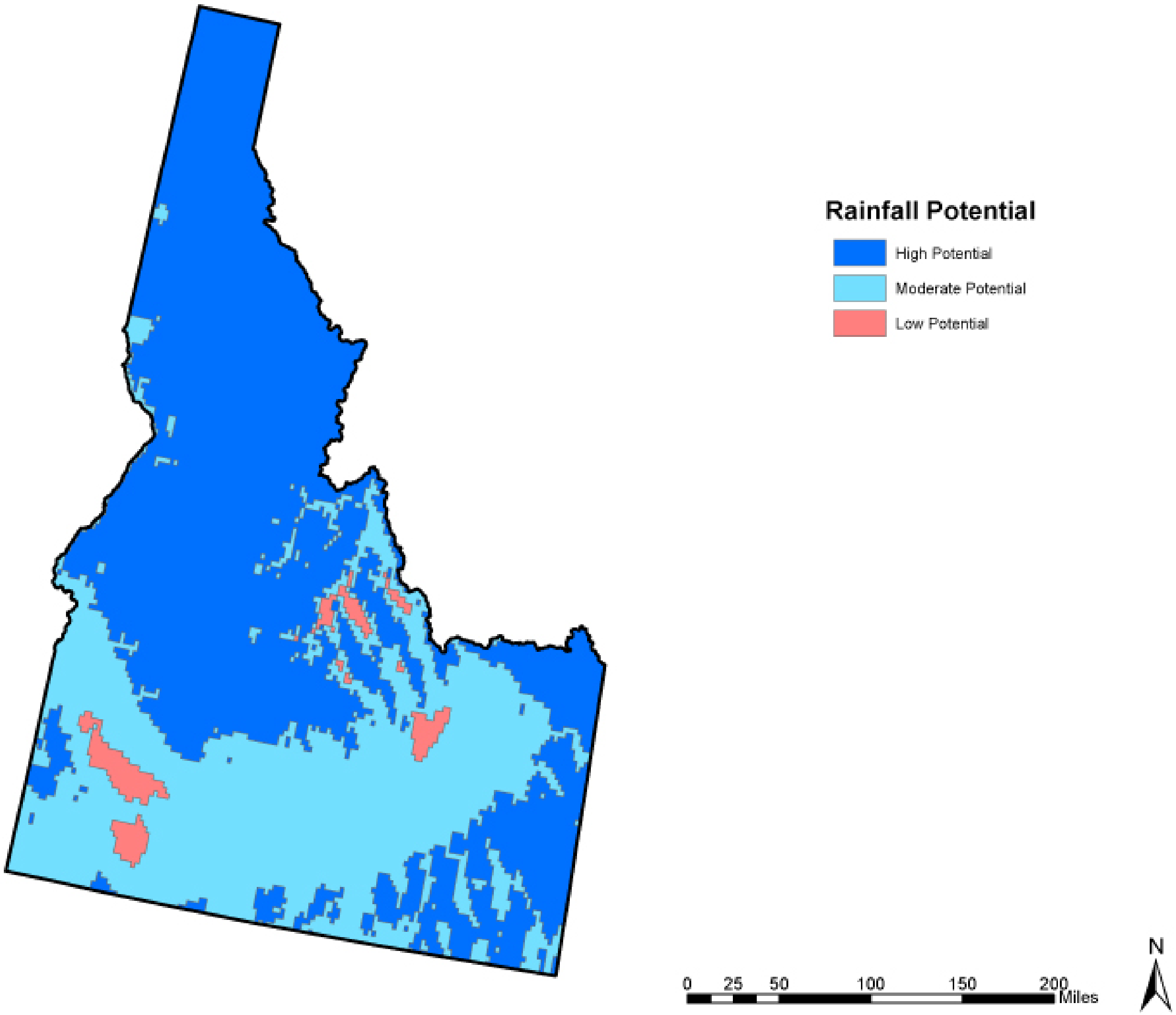


Figure 1. Spatial classification of climatic potential for Idaho. Areas classified as High Potential have greater than 460mm of precipitation per year. Areas classified as Moderate Potential have between 230 and 460 mm of precipitation per year. Areas classified as Low Potential have between 130 and 230 mm of precipitation per year.

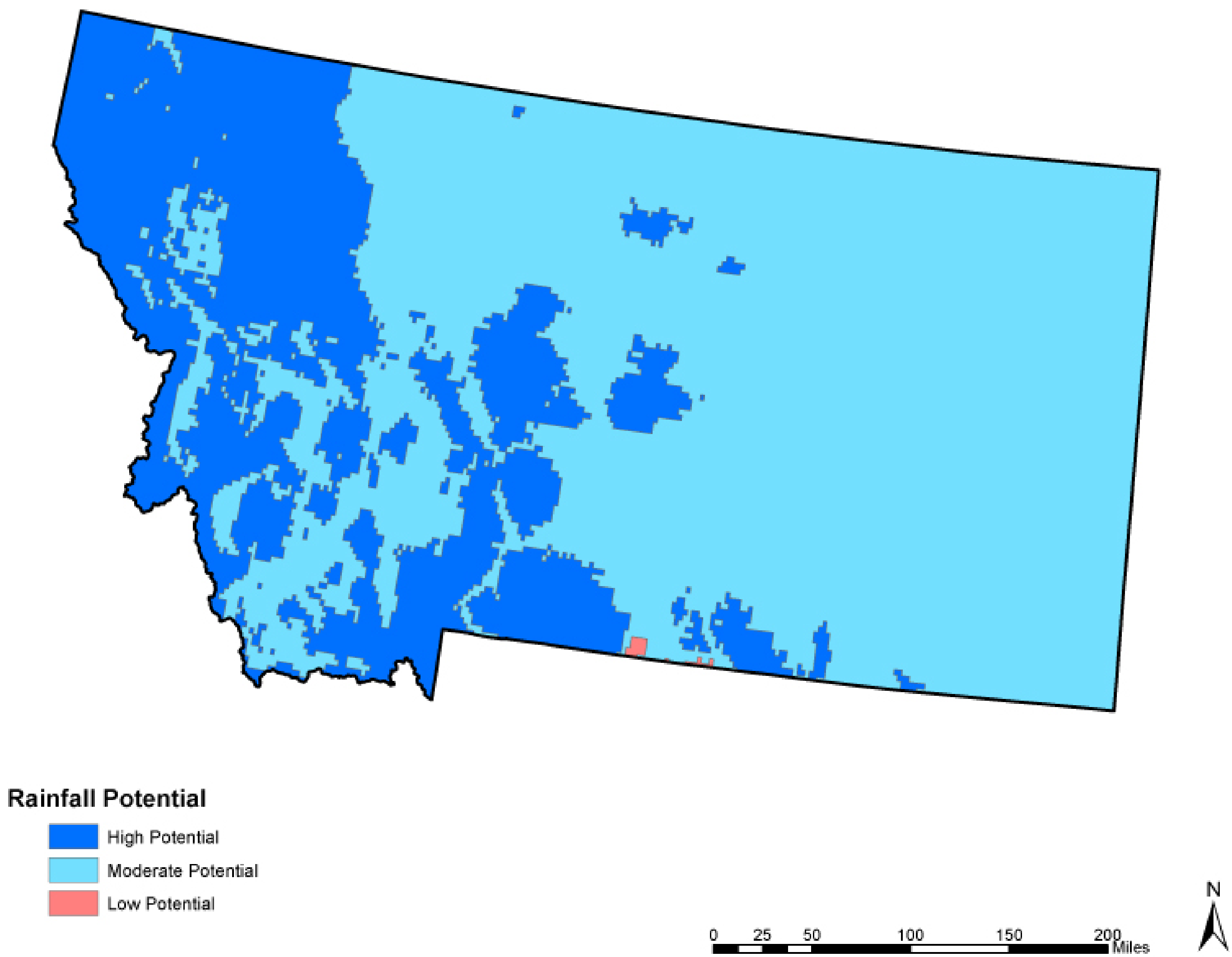


Figure 2. Spatial classification of climatic potential for Montana. Areas classified as High Potential have greater than 460mm of precipitation per year. Areas classified as Moderate Potential have between 230 and 460 mm of precipitation per year. Areas classified as Low Potential have between 130 and 230 mm of precipitation per year.

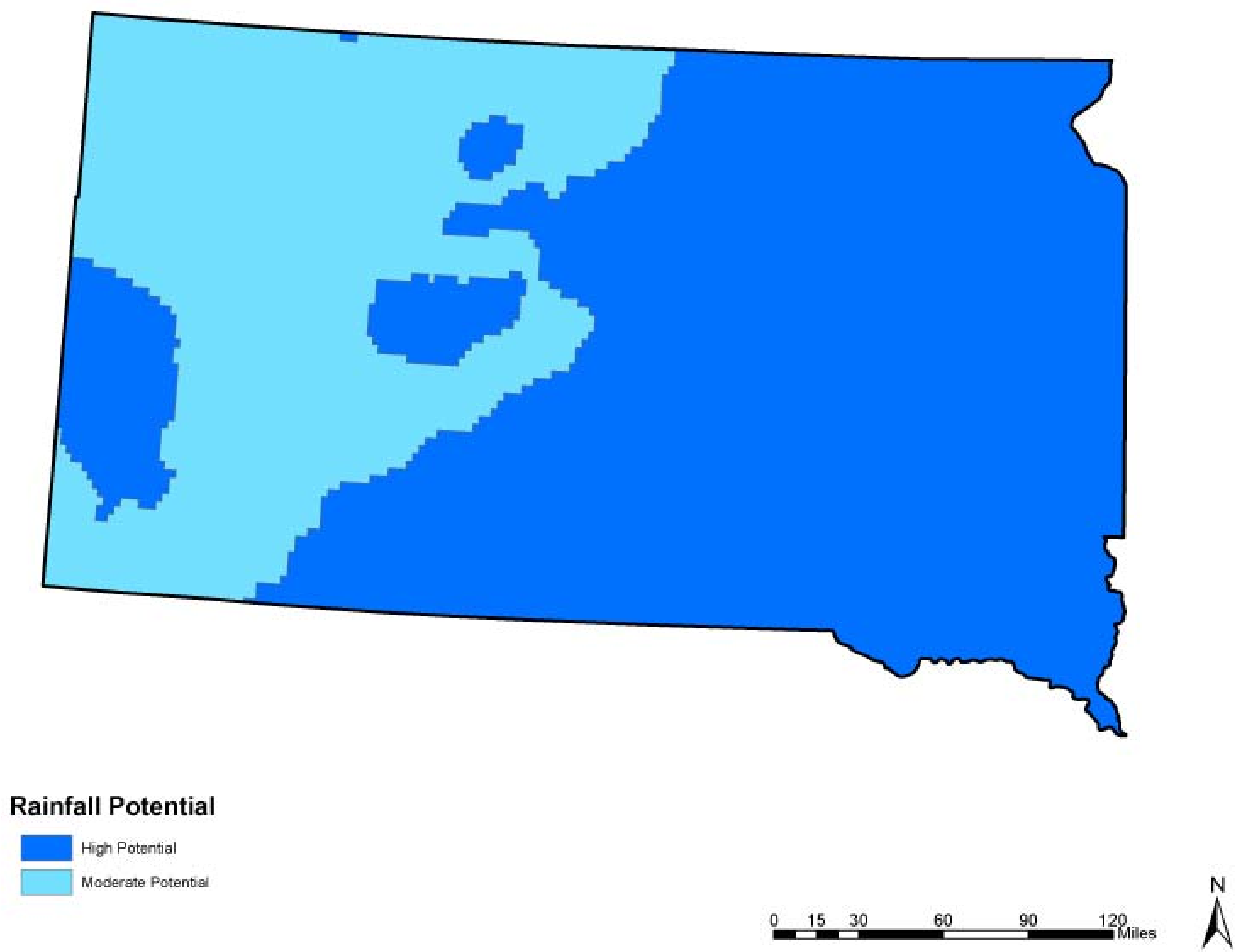


Figure 3. Spatial classification of climatic potential for South Dakota. Areas classified as High Potential have greater than 460mm of precipitation per year. Areas classified as Moderate Potential have between 230 and 460 mm of precipitation per year.

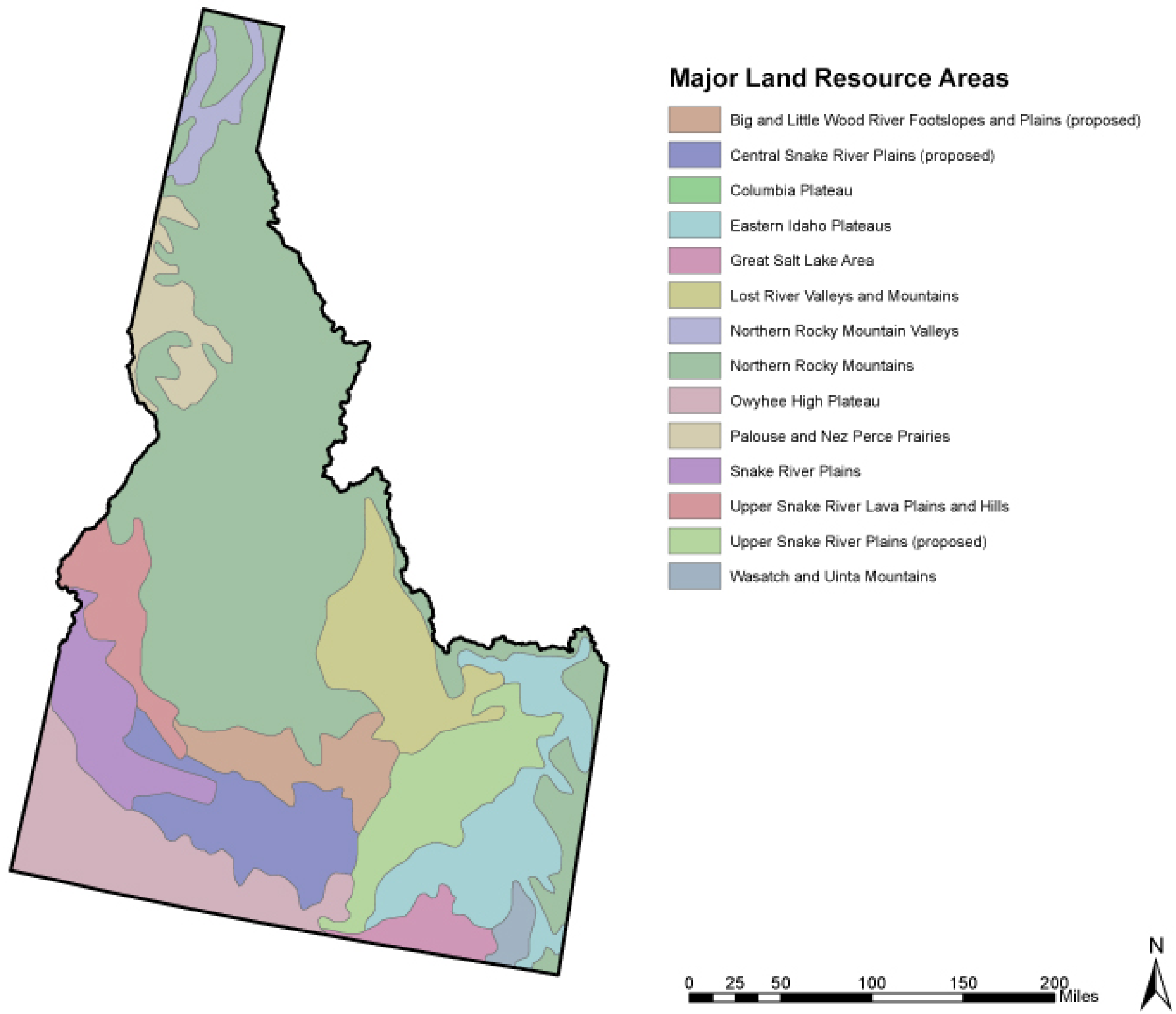


Figure 4. Major land resource areas (MLRAs) within the state of Idaho.

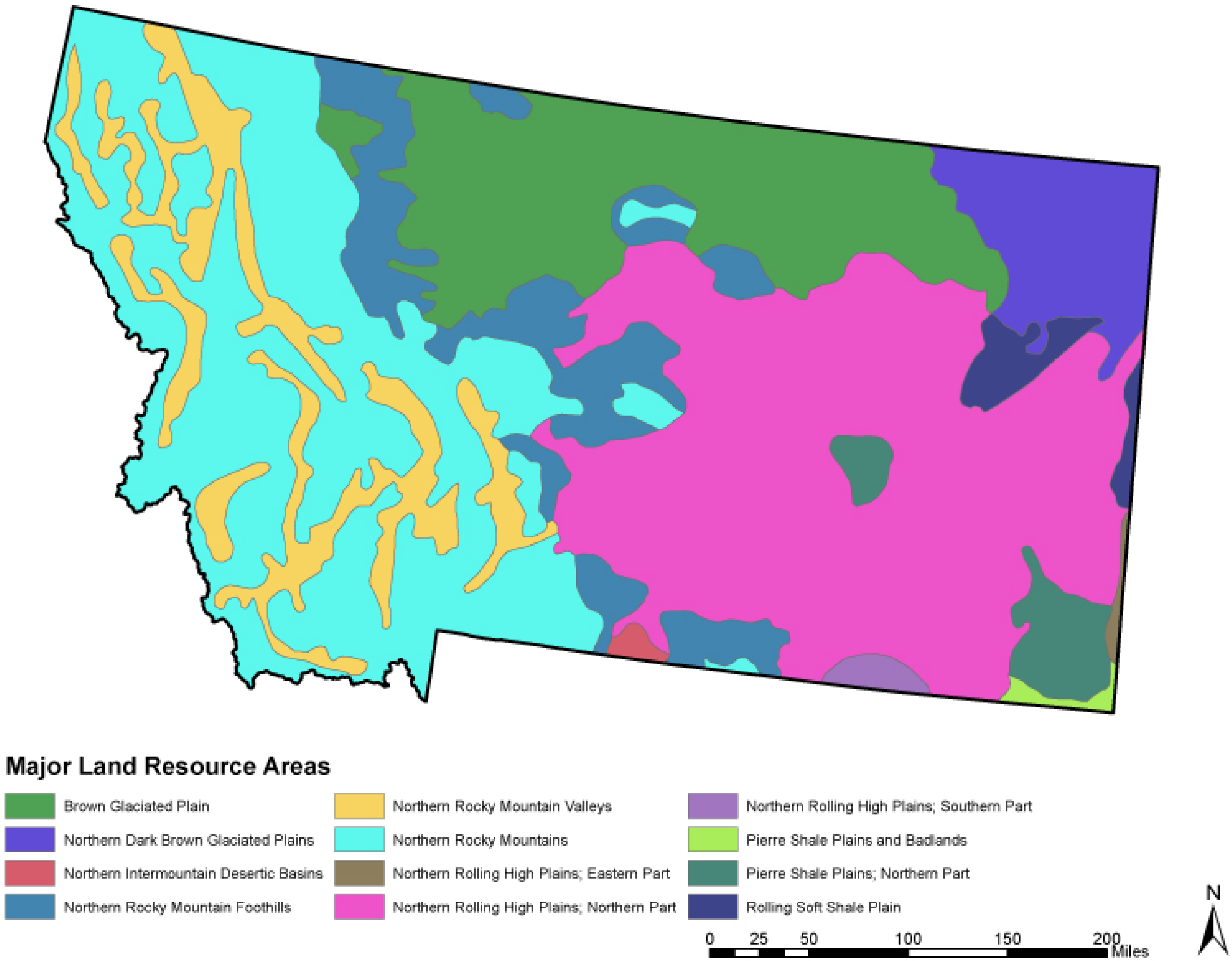


Figure 5. Major land resource areas (MLRAs) within the state of Montana.

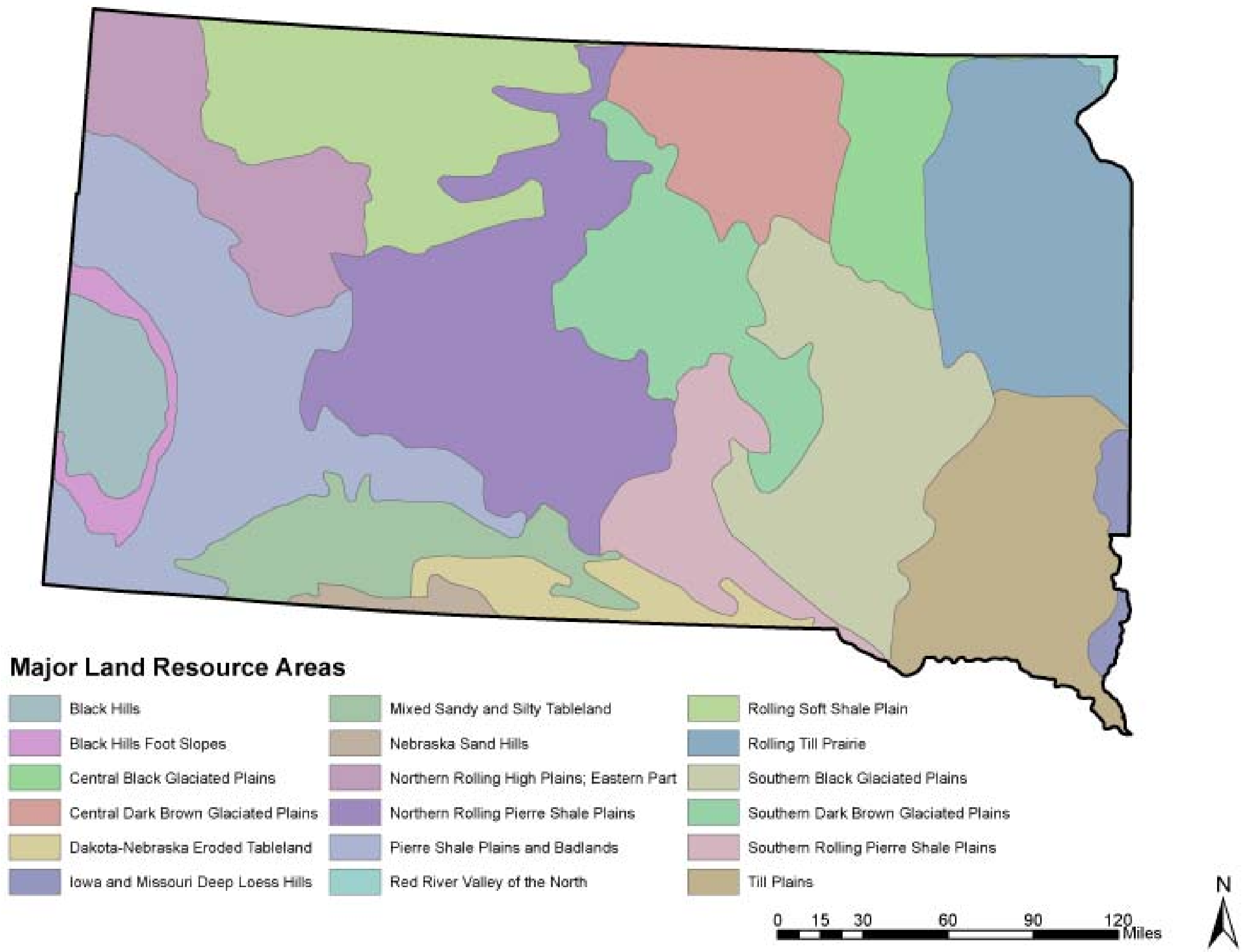


Figure 6. Major land resource areas (MLRAs) within the state of South Dakota

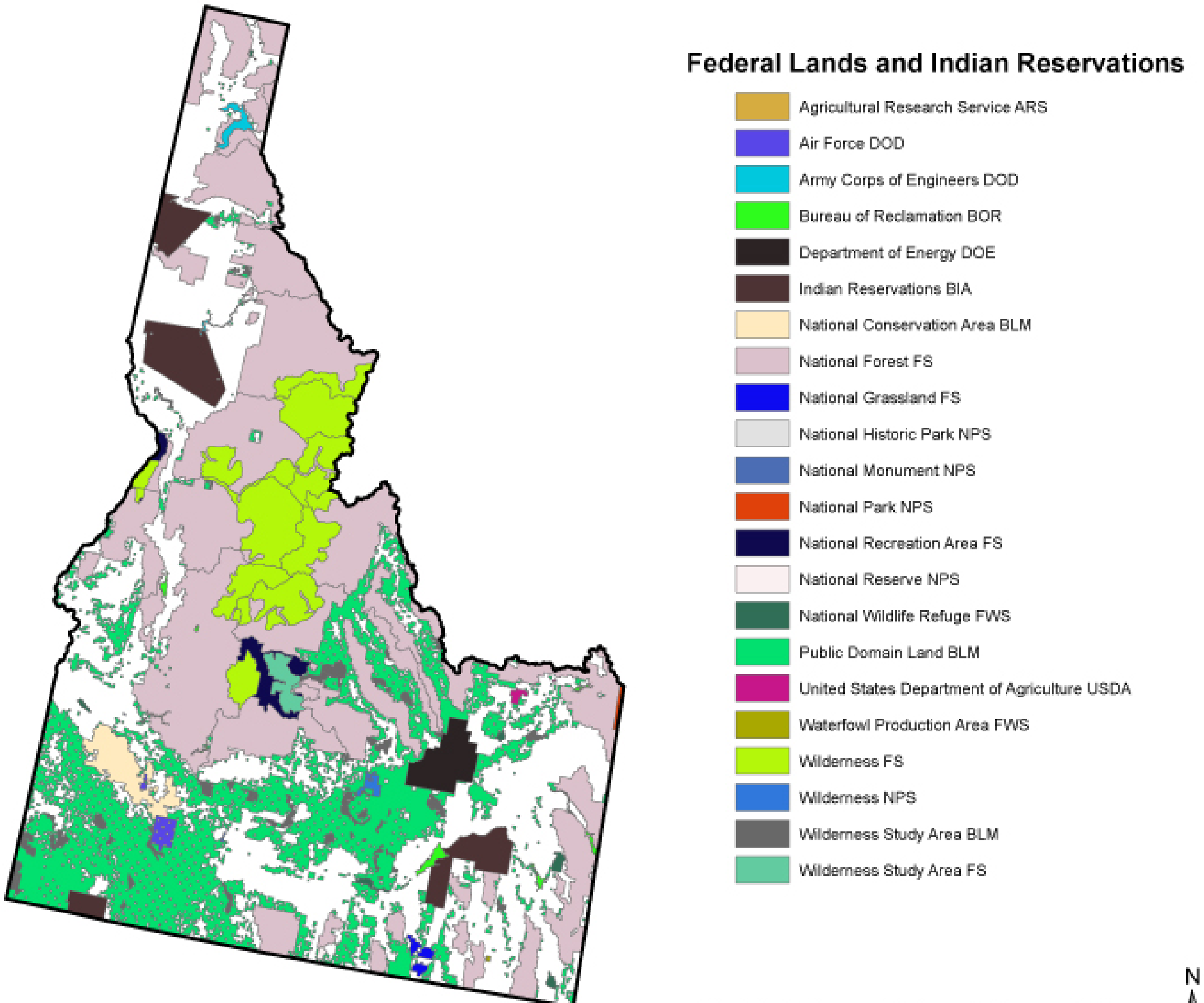


Figure 7. Federal lands and Indian reservations within the state of Idaho.

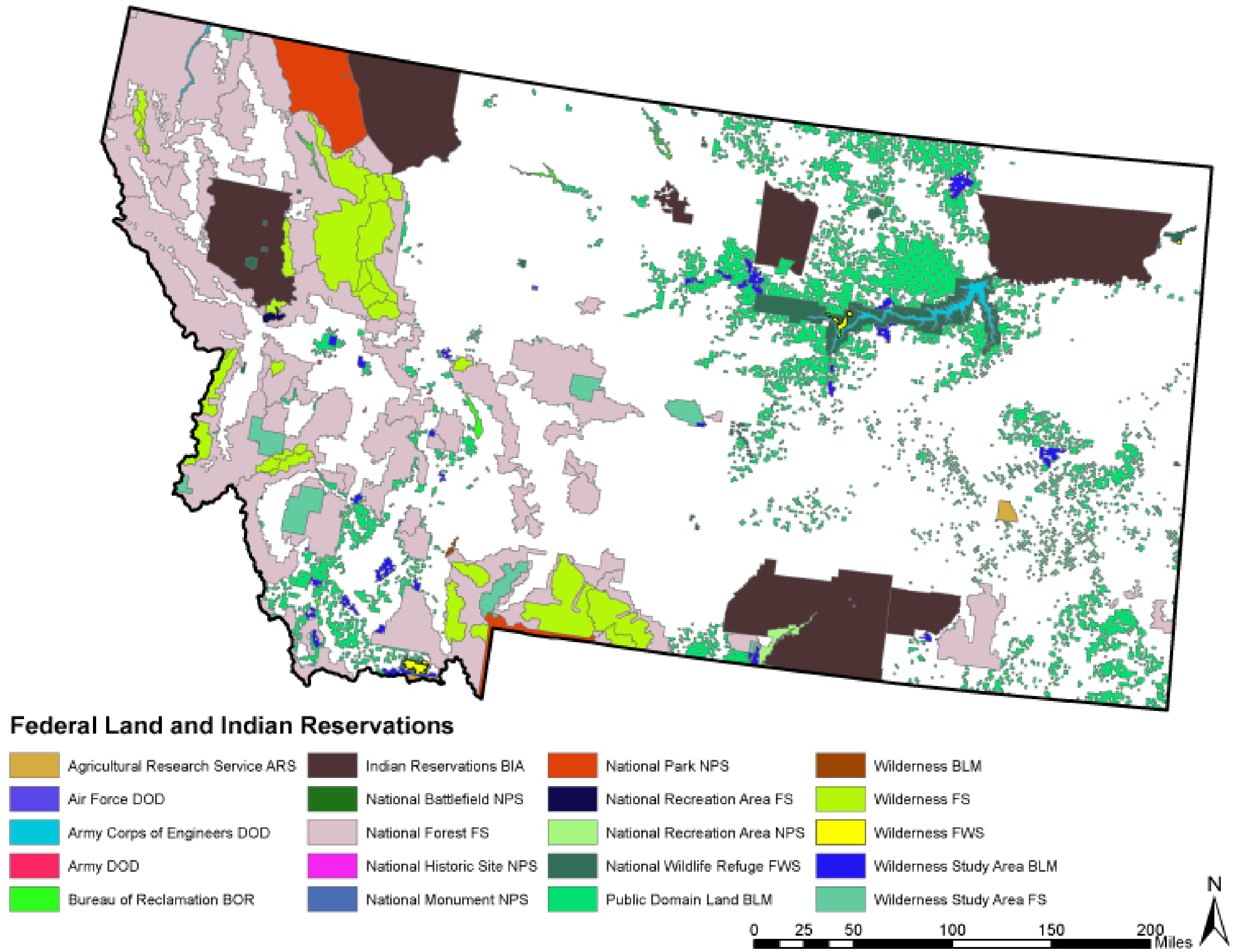


Figure 8. Federal lands and Indian reservations within the state of Montana.

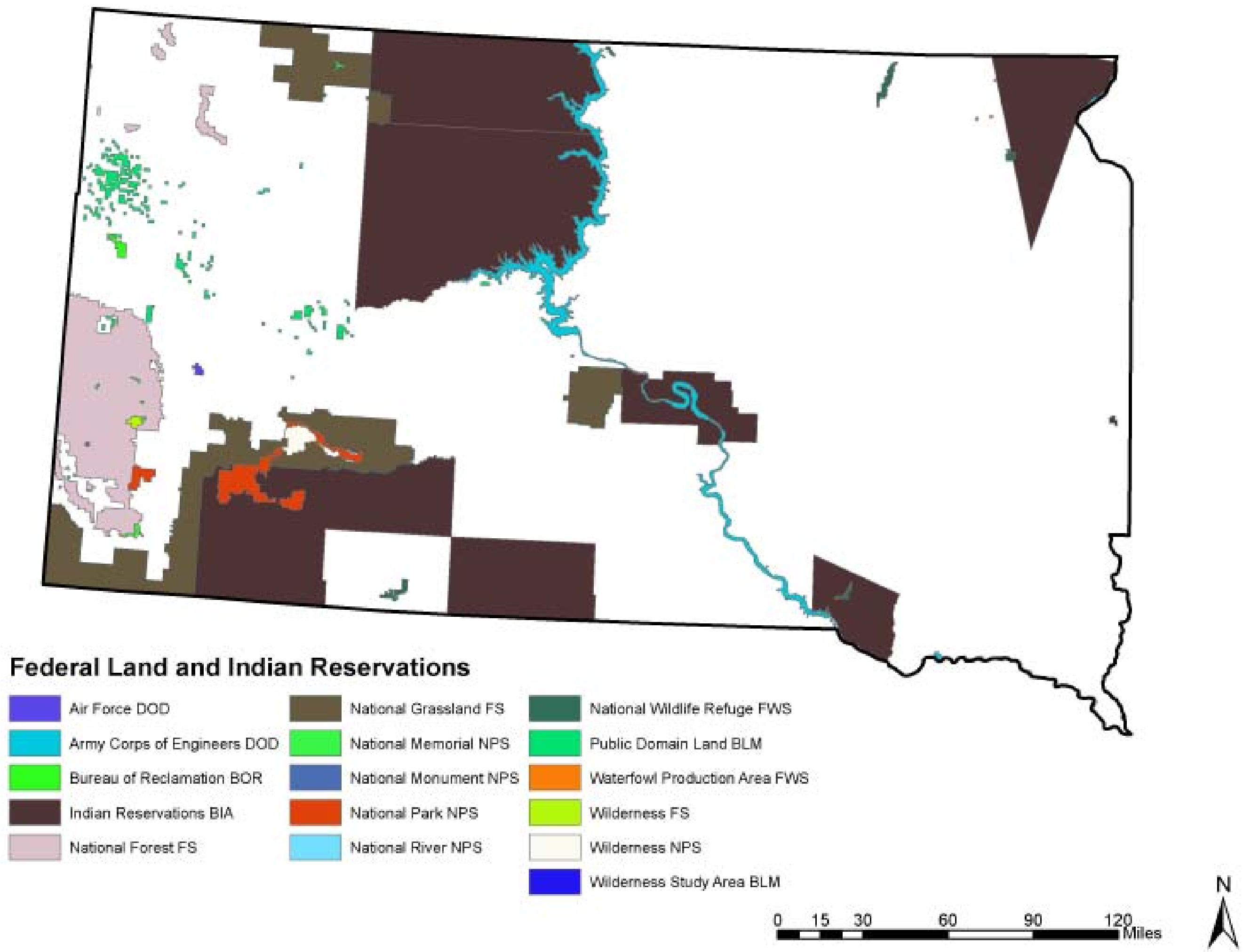


Figure 9. Federal lands and Indian reservations within the state of South Dakota

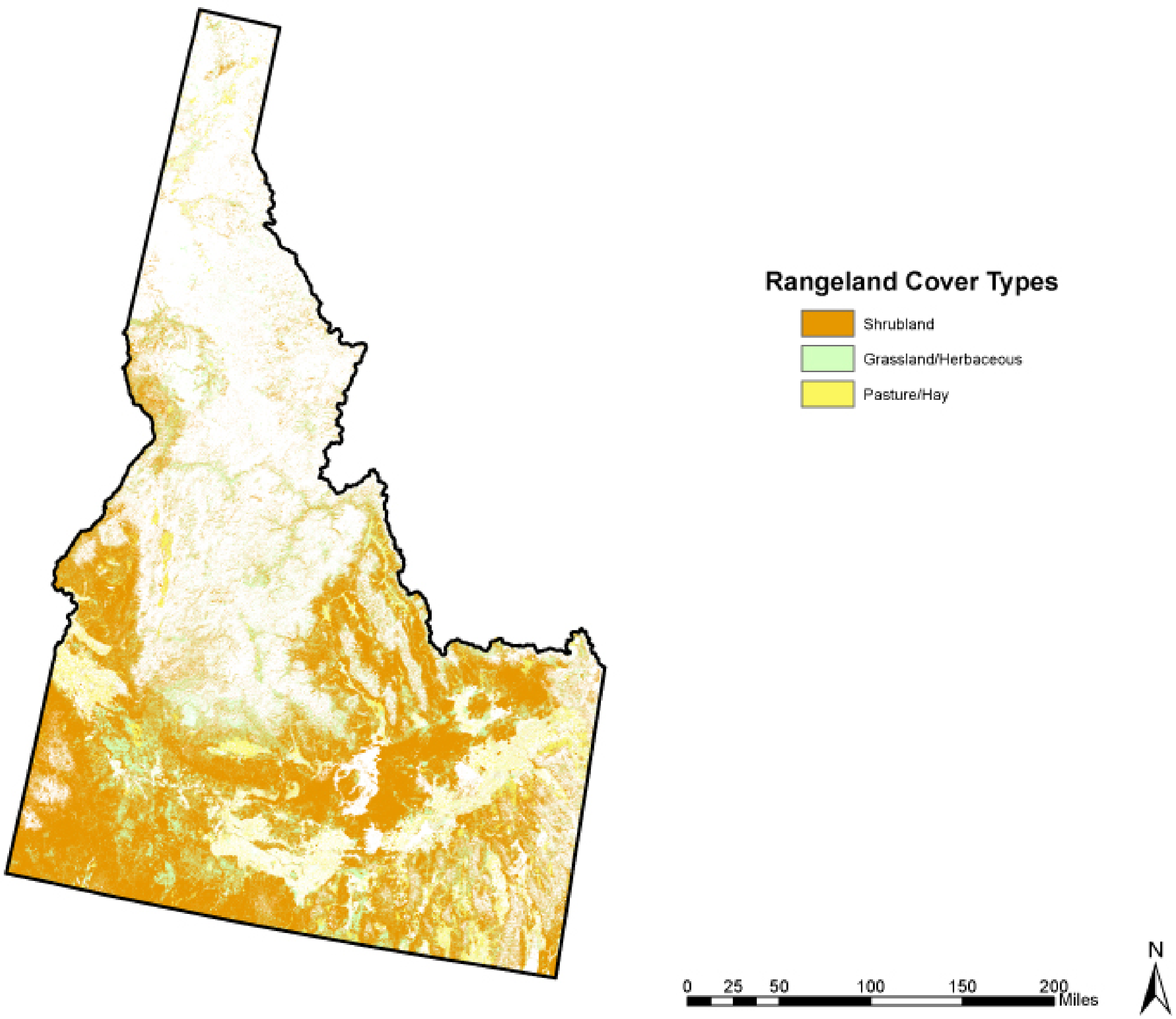


Figure10. Rangeland cover types for the state of Idaho as classified by the National Land Cover Database.

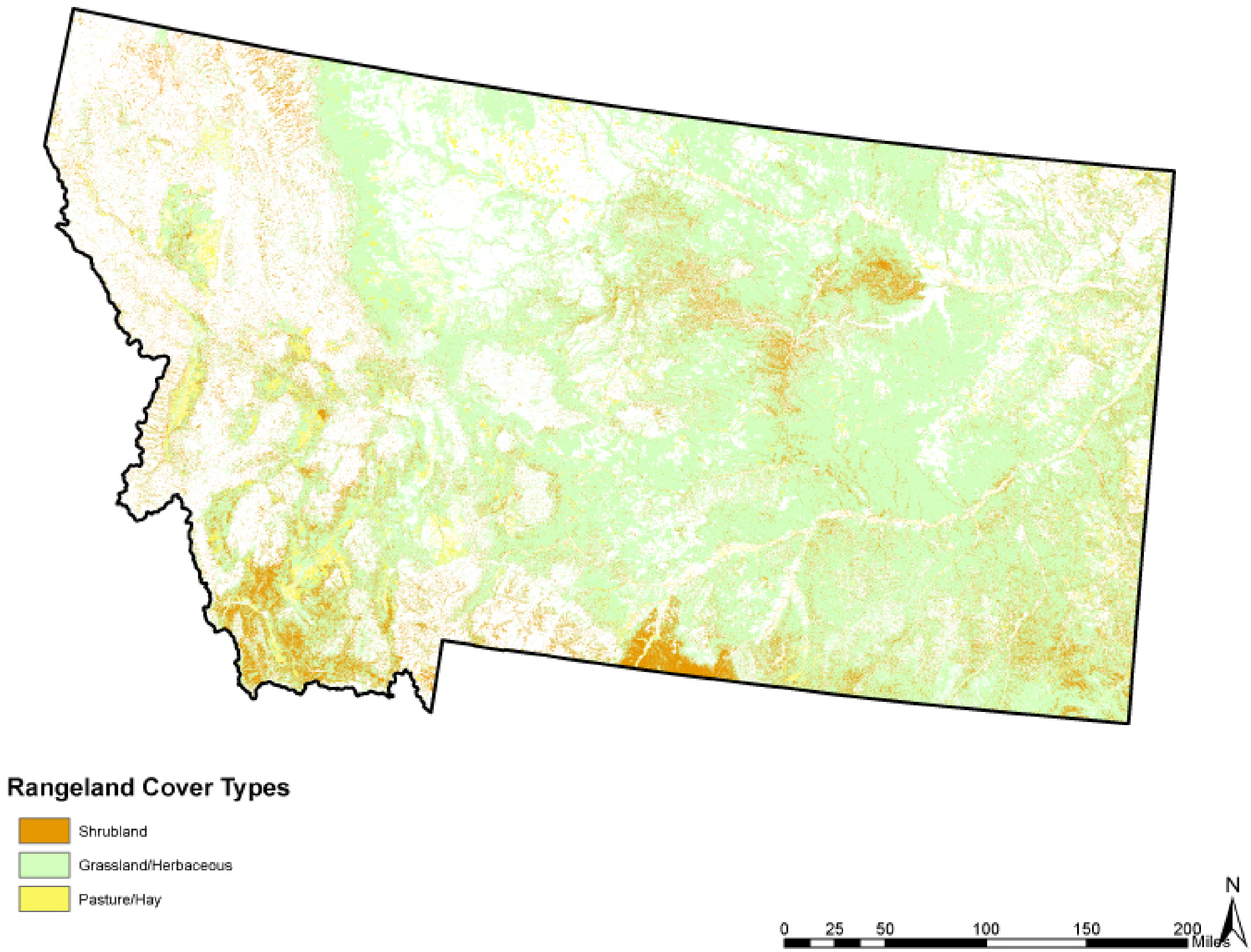


Figure 11. Rangeland cover types for the state of Montana as classified by the National Land Cover Database.

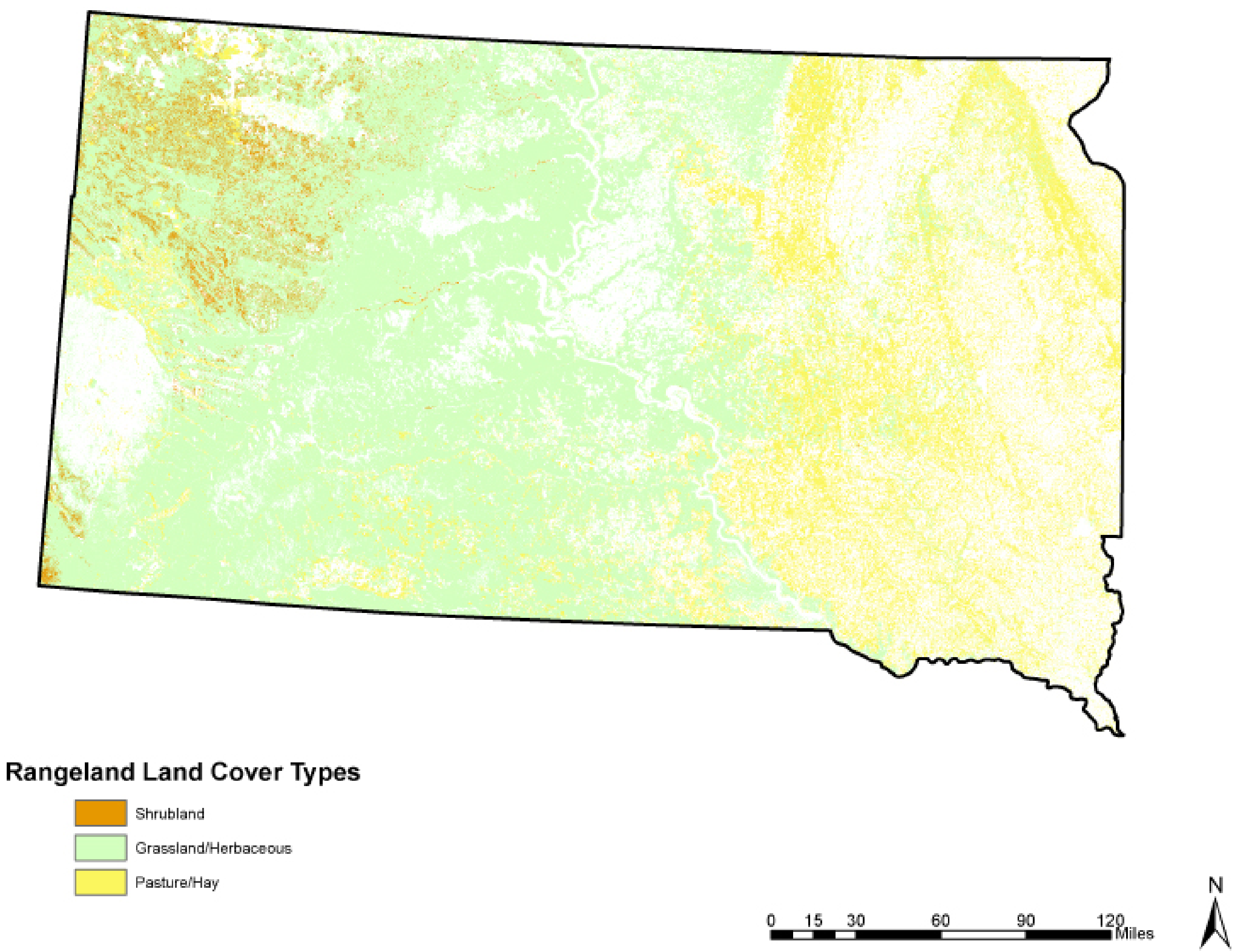


Figure 12. Rangeland cover types for the state of South Dakota as classified by the National Land Cover Database.

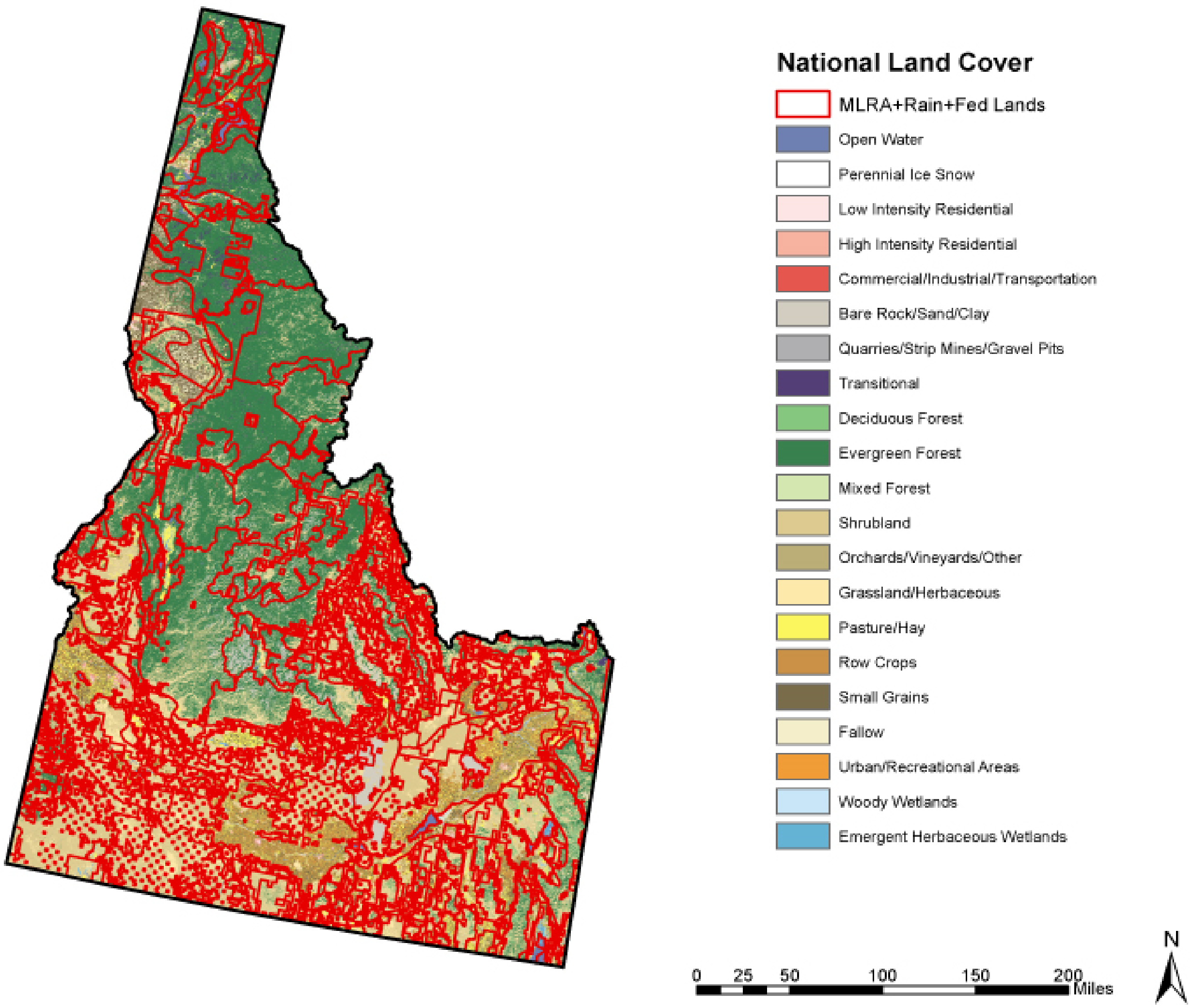


Figure 13. Sampling units (red lines) used in the spatial cross tabulation for the state of Idaho. The sampling units represent the intersection of the Major Land Resource Areas, climatic potential, and Federal Lands and Indian Reservations map coverage that were used in the spatial cross-tabulation analysis of the National Land Cover Database to determine area coverage of rangeland land cover classes (shrublands, grassland/herbaceous, and pasture/hay).

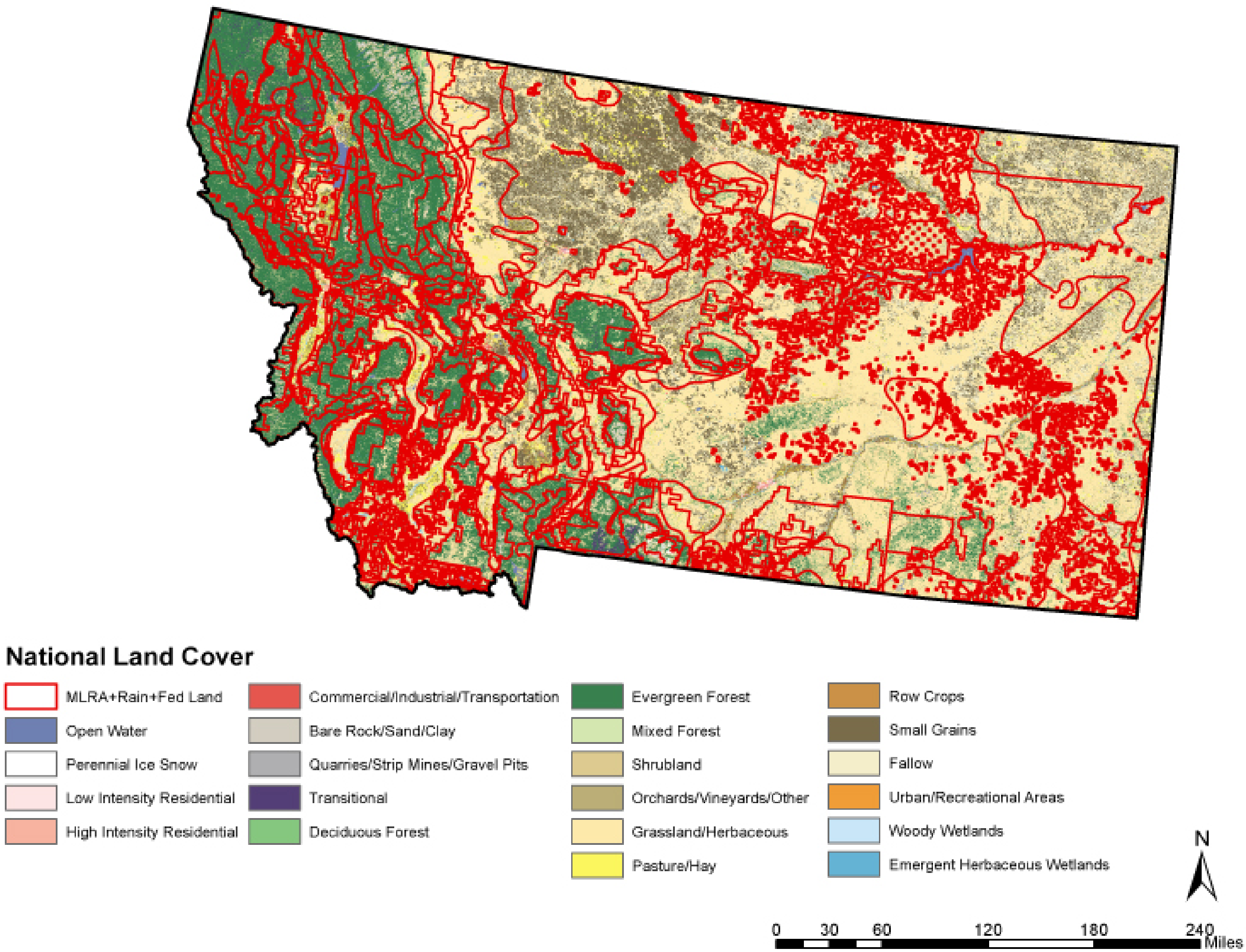


Figure 14. Sampling units (red lines) used in the spatial cross tabulation for the state of Montana. The sampling units represent the intersection of the Major Land Resource Areas, climatic potential, and Federal Lands and Indian Reservations map coverage that were used in the spatial cross-tabulation analysis of the National Land Cover Database to determine area coverage of rangeland land cover classes (shrublands, grassland/herbaceous, and pasture/hay).

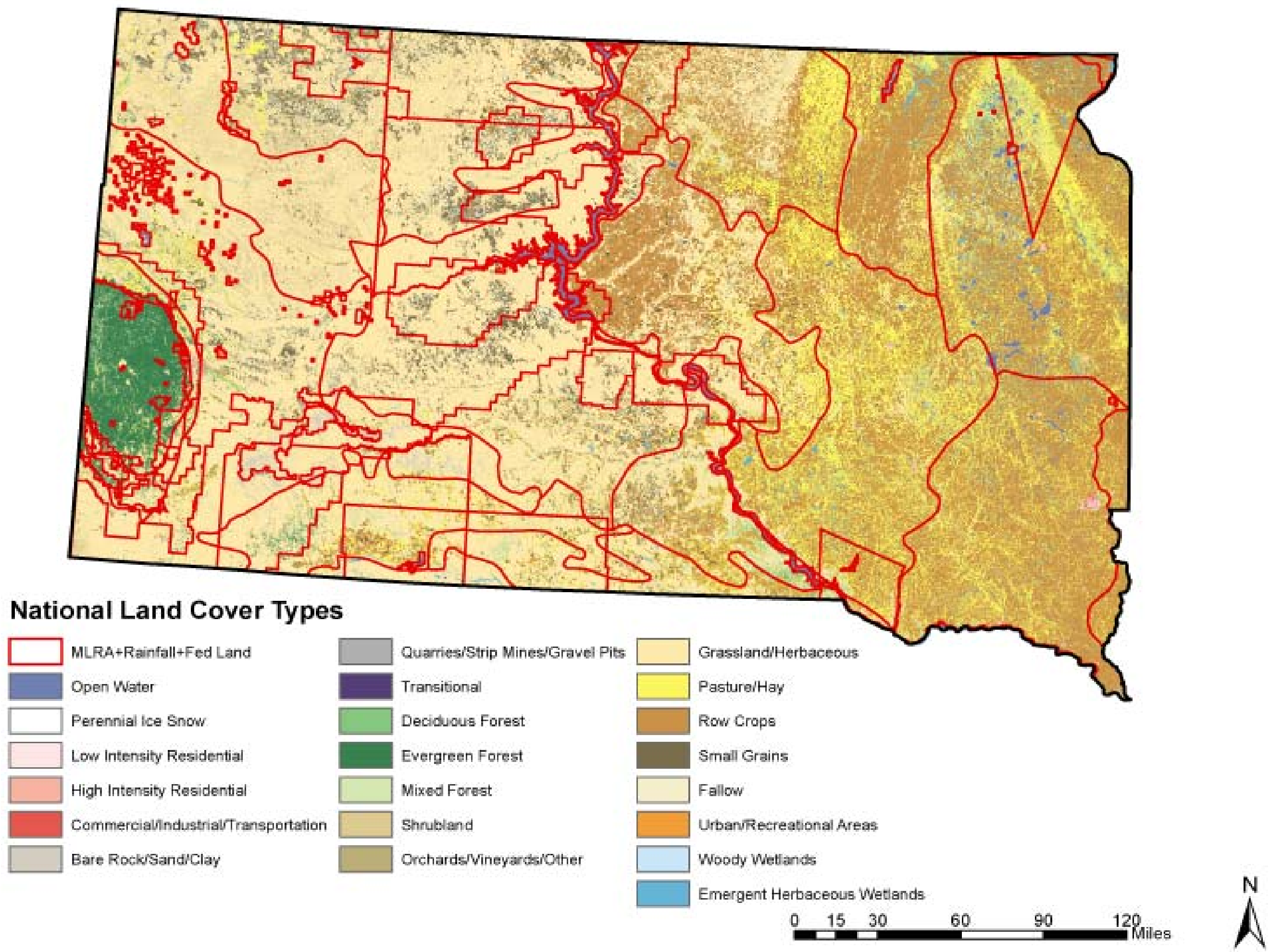


Figure 15. Sampling units (red lines) used in the spatial cross tabulation for the state of South Dakota. The sampling units represent the intersection of the Major Land Resource Areas, climatic potential, and Federal Lands and Indian Reservations map coverage that were used in the spatial cross-tabulation analysis of the National Land Cover Database to determine area coverage of rangeland land cover classes (shrublands, grassland/herbaceous, and pasture/hay).

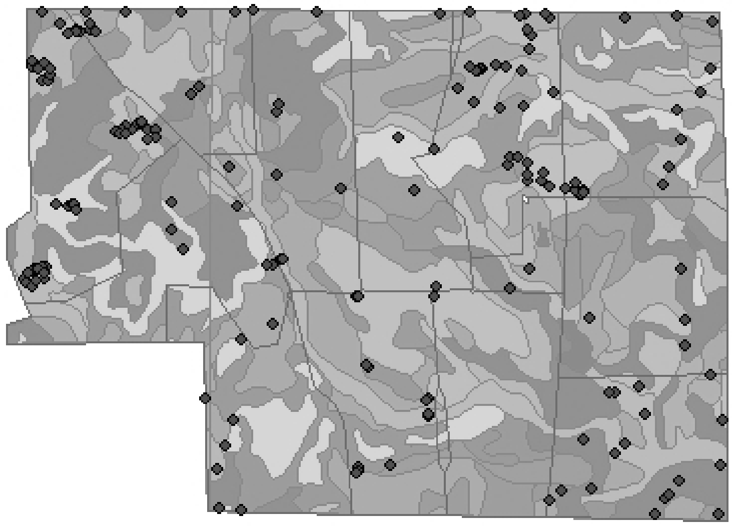


Figure 16. Distribution of sample points for Throckmorton Ranch placed over soil map and pasture boundaries.

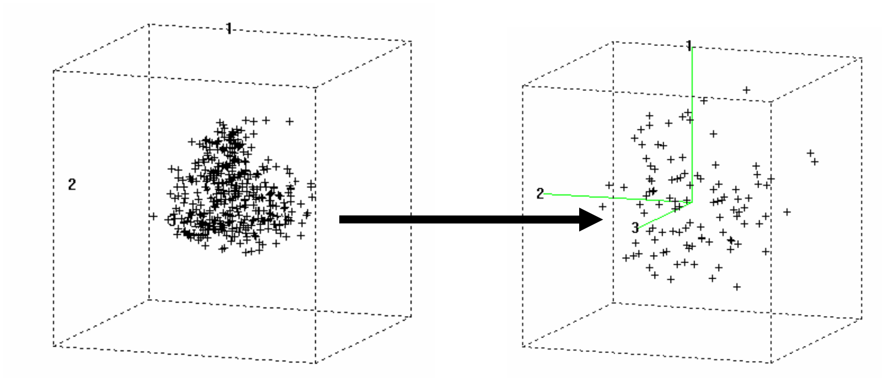


Figure 17. Selection of spectrally unique samples used to reduce laboratory costs and to choose samples that represent the range of population variance for equation development. From a total of 460 samples (left box) this procedure identified 107 spectrally unique samples (right box).

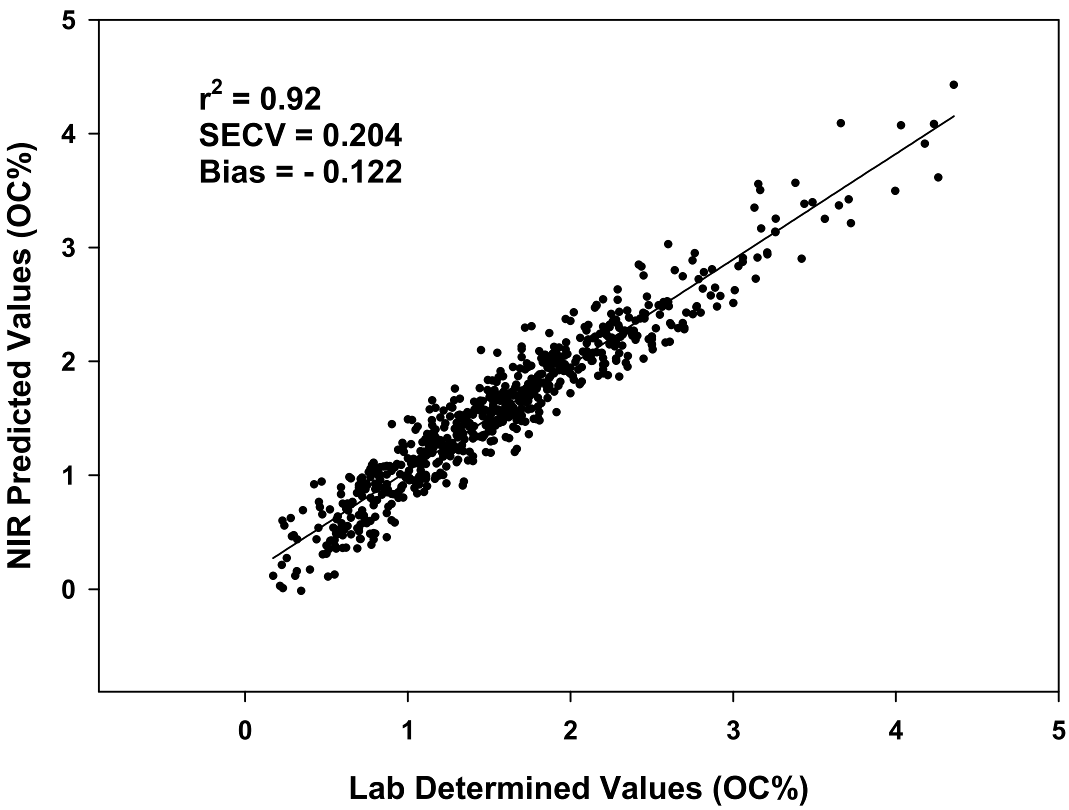


Figure 18. NIR cross validation prediction results for organic carbon using soils from diverse locations. (n = 661)

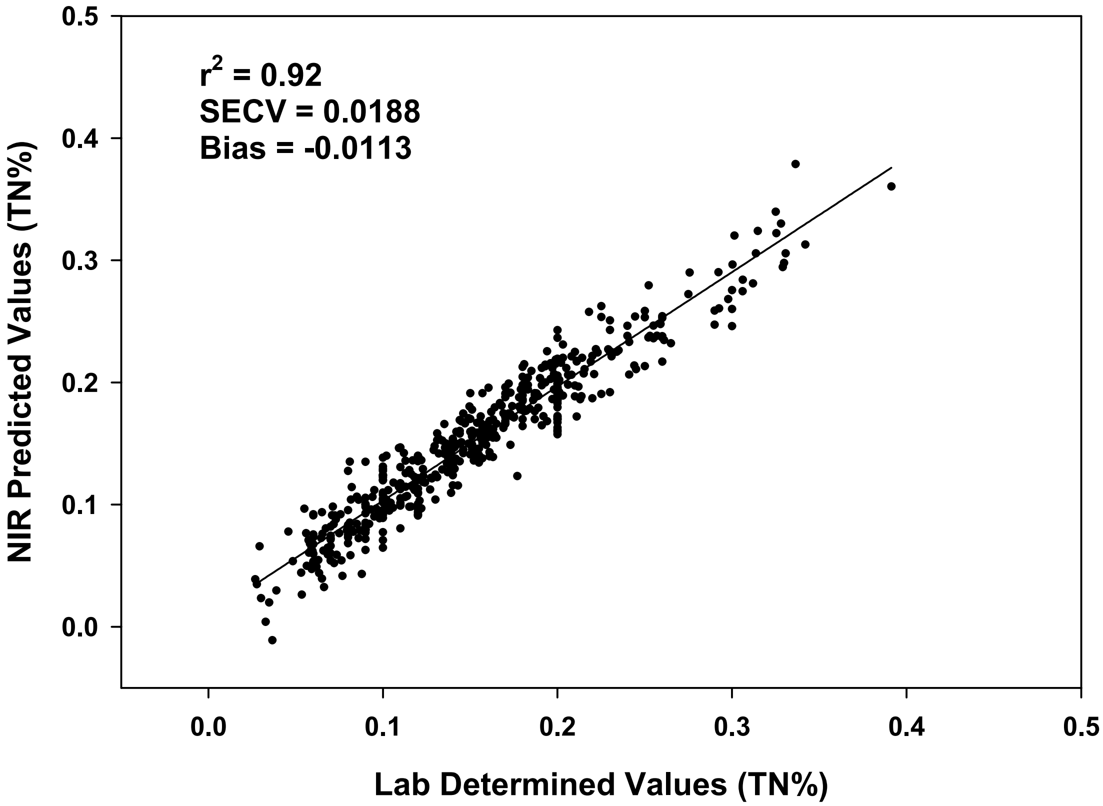


Figure 19. NIR cross validation prediction results for total nitrogen using soils from diverse locations (n = 502)

Table 1. Rangeland (ha) by land cover class and sums of the classes for Major Land Resource Area (MLRA) and land tenure class grouped according to Climatic Potential for carbon sequestration in Idaho. Percent of total reflects the percent of total rangeland occupied by the MLRA and Land Tenure class within the climatic potential grouping.

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/ Hay	Rangeland Totals	Percent of Total
High Climatic Potential (>460 mm)						
Big and Little Wood River Footslopes and Plains (proposed)	Federal	56,622	29,421	757	86,799	2.0
	Private or Non-Federal	27,243	15,017	92	42,352	1.0
Central Snake River Plains (proposed)	Federal	4,557	949	1	5,507	0.1
	Private or Non-Federal	829	336	41	1,207	0.0
Eastern Idaho Plateaus	Federal	193,563	63,495	3,173	260,231	6.0
	Indian Reservations	57,725	15,120	2,216	75,061	1.7
	Private or Non-Federal	314,950	105,948	75,772	496,670	11.4
Great Salt Lake Area	Federal	86,118	24,887	2,657	113,663	2.6
	Private or Non-Federal	44,230	20,983	23,323	88,536	2.0
Lost River Valleys and Mountains	Federal	164,767	82,669	261	247,697	5.7
	Private or Non-Federal	5,438	2,154	204	7,796	0.2
Northern Rocky Mountain Valleys	Federal	1,056	1,293	1,664	4,013	0.1
	Indian Reservations	0	0	0	0	0.0
	Private or Non-Federal	12,363	14,279	22,716	49,358	1.1
Northern Rocky Mountains	Federal	859,135	708,934	8,928	1,576,996	36.1
	Indian Reservations	18,552	16,882	3,180	38,614	0.9
	Private or Non-Federal	163,864	89,391	57,616	310,872	7.1
Owyhee High Plateau	Federal	136,813	21,248	85	158,146	3.6
	Indian Reservations	8,475	1,437	1	9,914	0.2
	Private or Non-Federal	68,598	7,731	665	76,994	1.8
Palouse and Nez Perce Prairies	Federal	2,418	1,595	6	4,019	0.1
	Indian Reservations	27,561	29,561	1,422	58,544	1.3
	Private or Non-Federal	27,529	21,288	1,764	50,581	1.2
Snake River Plains	Federal	3,687	68	0	3,756	0.1
	Private or Non-Federal	3,157	92	0	3,249	0.1
Upper Snake River Lava Plains and Hills	Federal	157,056	38,725	662	196,443	4.5
	Private or Non-Federal	226,480	47,414	13,631	287,525	6.6
	Federal	6,396	963	106	7,465	0.2
Upper Snake River Plains (proposed)	Indian Reservations	766	203	267	1,236	0.0
	Private or Non-Federal	7,107	2,884	4,075	14,066	0.3
Wasatch and Uinta Mountains	Federal	34,583	13,187	61	47,831	1.1
	Private or Non-Federal	25,893	8,698	5,444	40,035	0.9
	Sub Total	**2,747,530**	**1,386,853**	**230,791**	**4,365,174**	

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/ Hay	Rangeland Totals	Percent of Total
Moderate Climatic Potential (230 to 460 mm)						
Big and Little Wood River Footslopes and Plains (proposed)	Federal	360,770	39,236	1,796	401,803	6.3
	Private or Non-Federal	102,483	43,547	41,038	187,068	3.0
Central Snake River Plains (proposed)	Federal	454,674	173,426	5,770	633,870	10.0
	Private or Non-Federal	123,744	90,003	120,472	334,219	5.3
Columbia Plateau	Private or Non-Federal	254	161	0	415	0.0
Eastern Idaho Plateaus	Federal	51,017	9,328	2,619	62,963	1.0
	Indian Reservations	37,630	12,363	4,195	54,189	0.9
	Private or Non-Federal	140,491	57,646	79,381	277,519	4.4
Great Salt Lake Area	Federal	51,368	23,305	1,955	76,627	1.2
	Private or Non-Federal	22,751	14,359	28,563	65,674	1.0
Lost River Valleys and Mountains	Federal	447,226	100,518	6,059	553,802	8.7
	Private or Non-Federal	83,993	42,639	37,332	163,964	2.6
Northern Rocky Mountains	Federal	157,023	82,342	3,006	242,371	3.8
	Indian Reservations	173	23	0	195	0.0
	Private or Non-Federal	56,930	22,603	8,798	88,331	1.4
Owyhee High Plateau	Federal	1,032,573	160,837	3,007	1,196,417	18.9
	Indian Reservations	35,668	7,698	1,398	44,764	0.7
	Private or Non-Federal	194,881	33,059	13,933	241,873	3.8
Palouse and Nez Perce Prairies	Federal	1,780	624	0	2,404	0.0
	Indian Reservations	5,851	5,000	0	10,852	0.2
	Private or Non-Federal	22,538	10,783	0	33,321	0.5
Snake River Plains	Federal	250,264	95,717	3,502	349,483	5.5
	Private or Non-Federal	93,020	33,739	93,506	220,265	3.5
Upper Snake River Lava Plains and Hills	Federal	38,711	10,245	326	49,283	0.8
	Private or Non-Federal	115,130	26,065	11,503	152,698	2.4
Upper Snake River Plains (proposed)	Federal	394,244	82,842	2,973	480,059	7.6
	Indian Reservations	17,718	9,136	6,485	33,339	0.5
	Private or Non-Federal	162,794	85,580	122,121	370,495	5.8
Wasatch and Uinta Mountains	Federal	1,237	295	86	1,619	0.0
	Private or Non-Federal	5,737	2,328	3,317	11,382	0.2
	Sub Total	**4,462,675**	**1,275,446**	**603,141**	**6,341,262**	
Low Climatic Potential (130 to 230 mm)						
Central Snake River Plains (proposed)	Federal	8,437	2,317	6	10,759	2.3
	Private or Non-Federal	1,269	401	33	1,703	0.4
Lost River Valleys and	Federal	94,558	24,520	2,340	121,418	26.2

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/ Hay	Rangeland Totals	Percent of Total
Mountains	Private or Non-Federal	15,689	10,758	17,262	43,708	9.4
Northern Rocky Mountains	Federal	6,229	2,053	217	8,498	1.8
	Private or Non-Federal	1,129	506	395	2,030	0.4
Owyhee High Plateau	Federal	68,142	21,819	84	90,044	19.4
	Private or Non-Federal	3,705	1,029	1	4,735	1.0
Snake River Plains	Federal	81,218	46,044	3,122	130,384	28.1
	Private or Non-Federal	13,744	10,617	6,208	30,569	6.6
Upper Snake River Plains (proposed)	Federal	18,605	748	1	19,355	4.2
	Sub Total	**312,724**	**120,809**	**29,670**	**463,203**	
	Grand Total	**7,522,930**	**2,783,108**	**863,602**	**11,169,640**	

Table 2. Total hectares of rangeland cover types identified in Major Land Resource Areas (MLRA) in Idaho.

MLRA NAME	Rangeland (ha)
Northern Rocky Mountains	2267908
Owyhee High Plateau	1822887
Eastern Idaho Plateaus	1226633
Lost River Valleys and Mountains	1138385
Central Snake River Plains (proposed)	987265
Upper Snake River Plains (proposed)	926014
Snake River Plains	737706
Big and Little Wood River Footslopes and Plains (proposed)	718021
Upper Snake River Lava Plains and Hills	685948
Great Salt Lake Area	344500
Palouse and Nez Perce Prairies	159720
Wasatch and Uinta Mountains	100866
Northern Rocky Mountain Valleys	53371
Columbia Plateau	415

Table 3. Rangeland (ha) by land cover class and sums of the classes for Major Land Resource Area (MLRA) and land tenure class grouped according to Climatic Potential for carbon sequestration in Montana. Percent of total reflects the percent of total rangeland occupied by the MLRA and Land Tenure class within the climatic potential grouping.

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/Hay	Rangeland Totals	Percent of Total
High Climatic Potential (>460 mm)						
Brown Glaciated Plain	Indian Reservations	1,044	47,497	383	48,924	1.3
	Private or Non-Federal	154	6,993	59	7,206	0.2
Northern Intermountain Desertic Basins	Federal	1,798	2,606	0	4,404	0.1
	Private or Non-Federal	1,639	1,934	0	3,573	0.1
Northern Rocky Mountain Foothills	Federal	11,102	42,284	39	53,425	1.5
	Indian Reservations	30,045	138,512	5,937	174,495	4.8
	Private or Non-Federal	51,449	464,005	15,309	530,763	14.6
Northern Rocky Mountain Valleys	Federal	47,410	53,485	3,318	104,213	2.9
	Indian Reservations	3,492	15,622	2,129	21,243	0.6
	Private or Non-Federal	65,074	185,917	47,999	298,990	8.2
Northern Rocky Mountains	Federal	574,907	776,050	4,591	1,355,548	37.4
	Indian Reservations	30,912	107,895	6,724	145,531	4.0
	Private or Non-Federal	166,339	567,570	15,946	749,855	20.7
Northern Rolling High Plains; Northern Part	Federal	147	323	0	469	0.0
	Indian Reservations	11,539	72,612	1,957	86,108	2.4
	Private or Non-Federal	3,139	17,532	1,053	21,724	0.6
Northern Rolling High Plains; Southern Part	Federal	171	2,228	12	2,411	0.1
	Private or Non-Federal	1,359	15,404	299	17,062	0.5
	Sub Total	**1,001,720**	**2,518,468**	**105,755**	**3,625,943**	
Moderate Climatic Potential (230 to 460 mm)						
Brown Glaciated Plain	Federal	43,303	649,228	3,950	696,481	4.0
	Indian Reservations	16,450	374,909	7,319	398,679	2.3
	Private or Non-Federal	90,151	1,533,435	125,049	1,748,636	9.9
Northern Dark Brown Glaciated Plains	Federal	3,284	11,916	175	15,375	0.1
	Indian Reservations	32,783	173,152	3,429	209,364	1.2
	Private or Non-Federal	103,209	389,768	37,846	530,823	3.0
Northern Intermountain Desertic Basins	Federal	20,040	3,574	0	23,614	0.1
	Private or Non-Federal	24,763	6,049	1,423	32,235	0.2
Northern Rocky Mountain Foothills	Federal	31,919	57,980	172	90,071	0.5
	Indian Reservations	26,924	210,946	5,485	243,355	1.4
	Private or Non-Federal	72,222	983,168	58,110	1,113,500	6.3
Northern Rocky Mountain Valleys	Federal	51,065	84,188	4,337	139,590	0.8
	Indian Reservations	8,313	53,955	30,467	92,735	0.5
	Private or Non-Federal	177,486	728,161	222,278	1,127,925	6.4
Northern Rocky Mountains	Federal	146,928	189,265	2,490	338,683	1.9
	Indian Reservations	15,034	39,315	10,493	64,841	0.4

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/Hay	Rangeland Totals	Percent of Total
	Private or Non-Federal	199,634	654,437	54,658	908,728	5.2
Northern Rolling High Plains; Eastern Part	Federal	4,620	10,355	52	15,027	0.1
	Private or Non-Federal	11,434	35,177	2,490	49,102	0.3
Northern Rolling High Plains; Northern Part	Federal	310,851	1,340,477	3,688	1,655,017	9.4
	Indian Reservations	54,433	436,462	15,263	506,158	2.9
	Private or Non-Federal	648,515	5,506,180	145,777	6,300,471	35.8
Northern Rolling High Plains; Southern Part	Federal	2,479	10,565	45	13,090	0.1
	Indian Reservations	501	2,426	0	2,927	0.0
	Private or Non-Federal	25,141	104,513	1,723	131,377	0.7
Pierre Shale Plains and Badland	Federal	9,238	25,657	107	35,002	0.2
	Private or Non-Federal	6,909	65,461	2,117	74,487	0.4
Pierre Shale Plains; Northern Part	Federal	50,877	149,794	724	201,395	1.1
	Private or Non-Federal	86,067	449,058	10,616	545,740	3.1
Rolling Soft Shale Plain	Federal	227	2,763	138	3,128	0.0
	Private or Non-Federal	34,437	224,796	24,914	284,147	1.6
	Sub Total	**2,309,237**	**14,507,129**	**775,335**	**17,591,700**	
Low Climatic Potential (130 to 230 mm)						
Northern Intermountain Desertic Basins	Federal	9,260	535	20	9,815	33.5
	Private or Non-Federal	8,516	1,594	1,047	11,156	38.0
Northern Rocky Mountain Foothills	Federal	5,554	185	40	5,778	19.7
	Private or Non-Federal	471	7	0	478	1.6
Northern Rocky Mountains	Federal	1,780	254	0	2,034	6.9
	Indian Reservations	72	6	0	77	0.3
	Sub Total	**25,652**	**2,581**	**1,106**	**29,339**	
	Grand Total	**3,336,609**	**17,028,178**	**882,196**	**21,246,983**	

Table 4. Total hectares of rangeland cover types identified in Major Land Resource Areas (MLRA) in Montana.

MLRA NAME	Rangeland
Northern Rolling High Plains; Northern Part	8,569,948
Northern Rocky Mountains	3,565,297
Brown Glaciated Plain	2,899,925
Northern Rocky Mountain Foothills	2,211,864
Northern Rocky Mountain Valleys	1,784,696
Northern Dark Brown Glaciated Plains	755,562
Pierre Shale Plains; Northern Part	747,135
Rolling Soft Shale Plain	287,276
Northern Rolling High Plains; Southern Part	166,867
Pierre Shale Plains and Badlands	109,489
Northern Intermountain Desertic Basins	84,797
Northern Rolling High Plains; Eastern Part	64,128

Table 5. Rangeland (ha) by land cover class and sums of the classes for Major Land Resource Area (MLRA) and land tenure class grouped according to Climatic Potential for carbon sequestration in South Dakota. Percent of total reflects the percent of total rangeland occupied by the MLRA and Land Tenure class within the Climatic Potential grouping.

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/Hay	Rangeland Totals	Percent of Total
High Climatic Potential (>460 mm)						
Black Hills	Federal	126	63,784	11,469	75,379	1.1
	Private or Non-Federal	60	19,915	1,942	21,917	0.3
Black Hills Foot Slopes	Federal	19	10,776	689	11,483	0.2
	Private or Non-Federal	713	64,476	25,848	91,037	1.4
Central Black Glaciated Plains	Federal	0	278	1,638	1,916	0.0
	Indian Reservations	0	177	1,575	1,751	0.0
	Private or Non-Federal	45	40,388	171,125	211,558	3.2
Central Dark Brown Glaciated Plains	Private or Non-Federal	1,424	319,620	237,937	558,981	8.3
Dakota-Nebraska Eroded Tableland	Indian Reservations	0	152,108	19,518	171,626	2.6
	Private or Non-Federal	0	132,641	46,360	179,002	2.7
Iowa and Missouri Deep Loess Hills	Private or Non-Federal	1	1,618	31,220	32,839	0.5
Mixed Sandy and Silty Tableland	Federal	0	1,489	1,546	3,036	0.0
	Indian Reservations	0	264,652	44,531	309,184	4.6
	Private or Non-Federal	0	181,193	47,756	228,949	3.4
Nebraska Sand Hills	Federal	0	368	0	368	0.0
	Indian Reservations	0	43,193	1,426	44,618	0.7
	Private or Non-Federal	0	69,855	897	70,751	1.1
Northern Rolling Pierre Shale Plains	Federal	97	85,743	1,456	87,295	1.3
	Indian Reservations	1,556	235,250	1,848	238,655	3.6
	Private or Non-Federal	1,176	758,973	41,274	801,423	11.9
Pierre Shale Plains and Badlands	Federal	8	2,085	437	2,530	0.0
	Indian Reservations	0	77,028	8,188	85,216	1.3
	Private or Non-Federal	1,151	139,081	17,957	158,189	2.4
Red River Valley of the North	Federal	0	11	17	28	0.0
	Indian Reservations	0	3	1,620	1,624	0.0
	Private or Non-Federal	0	0	190	190	0.0
Rolling Soft Shale Plain	Indian Reservations	286	98,987	2,147	101,420	1.5
	Private or Non-Federal	0	796	416	1,213	0.0
Rolling Till Prairie	Federal	0	382	1,218	1,600	0.0
	Indian Reservations	1	21,170	113,190	134,360	2.0
	Private or Non-Federal	89	60,265	510,783	571,137	8.5
Southern Black Glaciated Plains	Federal	0	1,212	496	1,709	0.0
	Indian Reservations	0	15,080	54,100	69,180	1.0
	Private or Non-Federal	466	151,138	733,494	885,098	13.2
Southern Dark Brown Glaciated Plains	Federal	0	785	14	799	0.0
	Indian Reservations	30	15,325	161	15,516	0.2
	Private or Non-Federal	399	429,966	150,230	580,595	8.6

NRCS Major Land Resource Area	Land Tenure	Shrubland	Grasslands/ Herbaceous	Pasture/Hay	Rangeland Totals	Percent of Total
Southern Rolling Pierre Shale Plains	Federal	27	4,694	1,024	5,745	0.1
	Indian Reservations	75	86,247	11,763	98,085	1.5
	Private or Non-Federal	27	286,624	87,998	374,649	5.6
Till Plains	Federal	0	1,018	1,482	2,501	0.0
	Indian Reservations	0	371	822	1,193	0.0
	Private or Non-Federal	11	33,390	448,383	481,784	7.2
	Sub Total	**7,788**	**3,872,157**	**2,836,184**	**6,716,129**	
Moderate Climatic Potential (230 to 460 mm)						
Black Hills	Federal	303	2,524	53	2,881	0.1
	Private or Non-Federal	631	4,036	46	4,713	0.1
Black Hills Foot Slopes	Federal	878	34,954	686	36,518	0.7
	Private or Non-Federal	3,594	39,465	1,743	44,802	0.8
Central Dark Brown Glaciated Plains	Federal	0	17	0	17	0.0
	Private or Non-Federal	137	64,316	7,275	71,728	1.3
Mixed Sandy and Silty Tableland	Federal	0	10,346	64	10,410	0.2
	Indian Reservations	0	183,648	5,698	189,345	3.5
	Private or Non-Federal	0	9	5	15	0.0
Northern Rolling High Plains; Eastern Part	Federal	6,582	14,982	461	22,026	0.4
	Indian Reservations	399	13,283	0	13,681	0.3
	Private or Non-Federal	207,120	802,760	16,546	1,026,425	18.8
Northern Rolling Pierre Shale Plains	Federal	296	57,655	1,690	59,641	1.1
	Indian Reservations	3,225	383,905	833	387,962	7.1
	Private or Non-Federal	739	557,318	4,603	562,659	10.3
Pierre Shale Plains and Badlands	Federal	24,426	531,493	12,968	568,887	10.4
	Indian Reservations	0	154,950	3,880	158,830	2.9
	Private or Non-Federal	105,203	935,981	68,558	1,109,742	20.4
Rolling Soft Shale Plain	Federal	21,382	121,743	3,273	146,399	2.7
	Indian Reservations	27,392	653,331	6,522	687,244	12.6
	Private or Non-Federal	69,753	210,147	31,554	311,454	5.7
Southern Dark Brown Glaciated Plains	Federal	2	3,114	107	3,223	0.1
	Private or Non-Federal	10	27,258	2,694	29,962	0.5
	Sub Total	**472,070**	**4,807,234**	**169,260**	**5,448,564**	
	Grand Total	**479,858**	**8,679,391**	**3,005,444**	**12,164,693**	

Table 6. Total hectares of rangeland cover types identified in Major Land Resource Areas (MLRA) in South Dakota.

MLRA NAME	Rangeland
Northern Rolling Pierre Shale Plains	2,137,636
Pierre Shale Plains and Badlands	2,083,394
Rolling Soft Shale Plain	1,247,729
Northern Rolling High Plains; Eastern Part	1,062,133
Southern Black Glaciated Plains	955,986
Mixed Sandy and Silty Tableland	740,938
Rolling Till Prairie	707,097
Central Dark Brown Glaciated Plains	630,725
Southern Dark Brown Glaciated Plains	630,095
Till Plains	485,477
Southern Rolling Pierre Shale Plains	478,480
Dakota-Nebraska Eroded Tableland	350,628
Central Black Glaciated Plains	215,226
Black Hills Foot Slopes	183,841
Nebraska Sand Hills	115,738
Black Hills	104,890
Iowa and Missouri Deep Loess Hills	32,839
Red River Valley of the North	1,842

Table 7. Rangeland (ha) for each state in the Big Sky Project by climatic potential (annual precipitation) and land tenure class. Federal lands are not included since they will most likely not be included in carbon sequestration programs.

Land Tenure Class	Idaho	Montana	South Dakota	Big Sky Region Totals
High Climatic Potential (>460 mm)				
Indian Reservations	183,369	476,300	1,272,428	1,932,096
Private or Other Non-Federal	1,469,240	1,629,173	5,249,313	8,347,725
Moderate Climatic Potential (230 to 460 mm)				
Indian Reservations	143,339	1,518,059	1,437,063	3,098,461
Private or Other Non-Federal	2,147,225	12,847,170	3,161,500	18,155,895
Low Climatic Potential (130 to 230 mm)				
Indian Reservations	0	77	0	77
Private or Other Non-Federal	82,745	11,635	0	94,380
Totals	**3,943,172**	**16,470,702**	**11,120,304**	**31,534,178**

Table 8. Prediction statistics for the independent validation set predicted from the equation derived from the 107 analyzed samples and cross validation results obtained from combining the validation set with the calibration set. Values are percentages.

	Independent Validation				Cross Validation Combined Set				
Property	n	RSQ	SEP	BIAS	n	Mean	SD	SECV	RSQ
Inorganic Carbon	25	0.966	0.211	-0.060	120	1.85	2.11	0.279	0.98
Total Carbon	25	0.918	0.329	-0.016	120	3.46	1.90	0.313	0.97
Organic Carbon	25	0.859	0.278	0.090	120	1.63	0.73	0.266	0.87
Total Nitrogen	25	0.945	0.018	0.006	118	0.17	0.012	0.016	0.94

Table 9. Cross Validation Results for Final NIR Throckmorton Equation.

Property	n	Mean	SD	SECV	RSQ
IC	186	1.71	1.83	0.297	0.97
TC	188	3.32	1.75	0.323	0.97
OC	185	1.56	0.64	0.251	0.85
TN	118	0.17	0.012	0.016	0.94

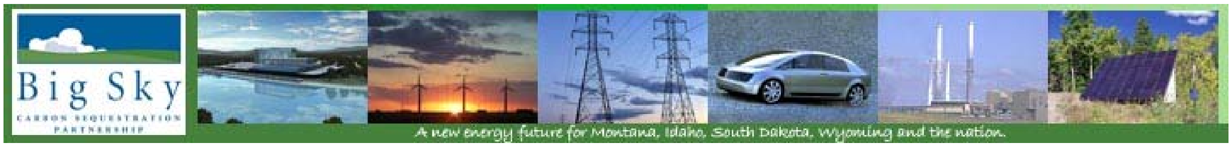
Table 10. Cross Validation Results for Second General Organic Carbon and Total Nitrogen Equation

Property	n	Mean	SD	SECV	RSQ
Organic Carbon	1110	2.10	1.10	0.36	0.89
Total Nitrogen	951	0.20	0.093	0.034	0.86

Table 11. Cross validation predictions of selected carbon fractions.

Property	n	Mean*	SD	SECV	RSQ	Bias
Glomalin	111	0.51	0.36	0.122	0.89	-0.07
POM	142	0.95	1.02	0.556	0.71	-0.33
Amino sugar	131	201.54	71.26	33.26	0.78	19.96
B -glucosaminidase	138	26.32	18.61	10.73	0.67	-6.44
B- glucosidase	130	75.94	46.76	29.10	0.61	-17.46

*units for glomalin and POM are mg g^{-1} and μg g^{-1} for amino sugar, B -glucosaminidase and B- glucosidase.



Big Sky Carbon Sequestration Partnership – Phase I

Deliverable 14:
Report on the Feasibility of Mineralization Trapping in the Snake River Plain Basin

Attachment A –
"Advanced Concepts for Geologic Sequestration of CO_2: Assessing Mineralization Trapping Potential for Mafic Rocks"

July 2005

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Susan M. Capalbo
Big Sky Principal Investigator
207 Montana Hall
Montana State University-Bozeman
Bozeman, MT 59717-2460
scapalbo@montana.edu
http://www.bigskyco2.org/
Phone: (406) 994-5619
Fax: (406) 994-2893

Advanced Concepts for Geologic Sequestration of CO_2:
Assessing Mineralization Trapping Potential of Mafic Rocks

Robert W. Smith[1], Travis L. McLing[2], Warren Barrash[3], William P. Clement[3], Nathan P. Erickson[1]
Big Sky Carbon Sequestration Partnership

[1]University of Idaho, 1776 Science Center Drive, Idaho Falls, ID 83402
[2]Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415
[3]Boise State University, 1910 University Drive, Boise, Idaho 83725

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Introduction

Carbon sequestration is one approach to stabilize or reduce the levels of greenhouse gases in the Earth's atmosphere. Geologic sequestration is the storage or entombment of carbon dioxide (CO_2) in subsurface geologic formations. Potential geologic formations in our region that may be conducive to sequestration include: deep saline reservoirs, depleted oil/natural gas reservoirs, deep unmineable coal beds, and mafic/ultramafic rocks. Because many of these natural reservoirs are known to have stored fossil fuels and other fluids over geologic time frames, they can be expected to have high potential for the long-term sequestration of CO_2.

Geologic sequestration occurs via three interrelated processes. The first is hydrodynamic trapping where CO_2 is physically isolated by trapping beneath impermeable geological barriers, such as a shale bed. This is the primary sequestering process in the short-term and is largely a function of the storage capacity of the deep system and its degree of isolation from the Earth's surface. The second process is solubility trapping in which CO_2 dissolves in subsurface fluids such as brines or petroleum. Solubility trapping is slower than hydrodynamic trapping and depends on the CO_2 dissolution rate in the fluid of interest. The third process is trapping due to mineralization in which CO_2 is entombed by increased weathering of the geochemically reactive base cations (primarily Ca^{2+}, Mg^{2+}, and Fe^{2+}) in subsurface minerals. The weathering reactions result in the conversion of CO_2 into carbonate alkalinity and ultimately carbonate minerals. Because existing groundwaters are often saturated with carbonate phases, carbonate minerals formed from anthropogenic CO_2 will be permanently entombed in the subsurface. The time frame for mineralization trapping is primarily a function of the weathering rate and is much slower than the other two trapping processes. Mineral trapping will be most pronounced in rocks that have high concentration of base cations and rapid reactions rates such as mafic volcanic rock. The permanence of sequestration by the three trapping processes is the inverse of their trapping time scale. Mineralization trapping offers the most permanent sequestration, hydrodynamic trapping the least. In an ideal sequestration site, CO_2 would be permanently stored through the presence of multiple trapping processes.

The Big Sky Carbon Sequestration Partnership is one of the U.S. Department of Energy's seven regional partnerships. The Partnership includes Montana, Idaho and South Dakota, as well as contiguous parts of neighboring states and Canada. The Partnership is developing a framework to reduce carbon dioxide emissions that contribute to climate change and is working with stakeholders to create the vision for a new, sustainable energy future that cleanly meets the region's energy needs. Because energy is not an optional commodity, carbon sequestration plays an important role.

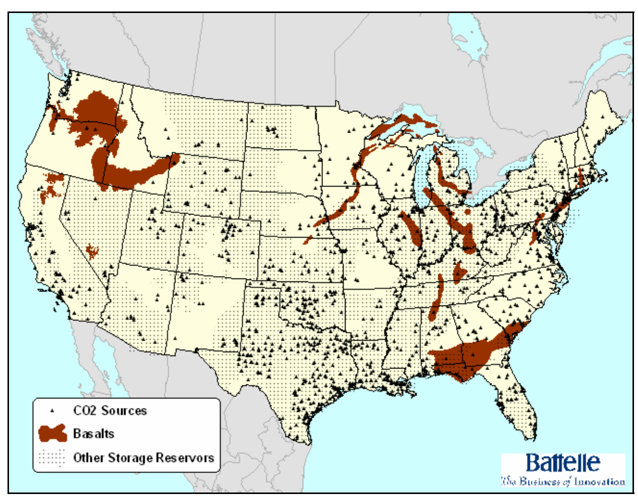

Figure 1. Map of U.S. Basalts, large CO_2 sources, and other candidate storage reservoirs.

The Big Sky Partnership has evaluated the geologic sequestration potential of the 64,700 km^2 basalt bearing Snake River Plain volcanic basins in Idaho and will, in Phase II, evaluate the potential for similar rock types of the 163,700 km^2 Columbia River Basalt Group in western Idaho and eastern Oregon and Washington. In addition to the formations located in the Partnership's region and as shown in Figure 1, other mafic rock provinces exist within large parts of the United States. Specifically considered in this report, and an example of the potential of mafic volcanic rocks, is an evaluation of sequestration in a mixed volcanic sedimentary section in southern Idaho. Given that the types of deep subsurface characterization data that is widely available for sedimentary basins containing energy resources are not available for the volcanic basins of Idaho, a preliminary evaluation of sequestration potential that relies solely upon average characteristics and literature results is considered here.

Assessment Approach

Geologic sequestration involves the injection of CO_2 captured from point sources into geologic formations as a supercritical fluid. The amount of CO_2 injected will exceed (in the short term) its solubility in the formation fluids (e.g., water) and will form a separate fluid-phase. Over time, the CO_2 will dissolve forming carbonic acid (H_2CO_3) that will be neutralized by weathering or corroding subsurface minerals to produce carbonate and bicarbonate ions (alkalinity) and/or mineral carbonates. Of particular importance are weathering reactions of silicate minerals rich in Ca, Mg and Fe. For example, the weathering of the calcic component of plagioclase feldspar (a common rock forming mineral) to calcite and a clay mineral can be written as:

Plagioclase($CaAl_2Si_2O_8$) + $2H_2O$ + CO_2 → Calcite($CaCO_3$) + Clay($Al_2Si_2O_5(OH)_4$) (1)

Consideration of the thermodynamics of this reaction indicates that for any CO_2 pressure important for sequestration, the reaction will proceed as written, entombing the introduced CO_2 as solid calcium carbonate. Mineralization potential will be highest in rocks with abundant Ca-, Mg-, and Fe-silicates (e.g., basalt) and lowest in rocks poor in these phases (e.g., sandstone). The time frame and extent of mineralization for a given subsurface environment is a function of the silicate weathering rate and the abundance of appropriate silicate phases. The quantitative assessment of reaction (1) requires an understanding of the reaction rates and the abundance of the reactive phases. To address reaction rates, a generalized kinetic expression for mineral dissolution reactions that accounts for changes in pH was developed from results presented by Lasaga et al. (1994) and Drever (1997)

$$R = k_+ \cdot A \cdot \left(a_{H^+}^{0.5} + 10^{-3} + 10^{-5} \cdot a_{H^+}^{-0.25}\right)\left[1 - \frac{Q}{K}\right] \qquad (2)$$

R = Reaction Rate
k_+ = Forward Rate Constant
A = Reactive Surface Area
a_{H+} = Aqueous hydrogen ion activity (pH)
Q = Ion Activity Quotient
K = Equilibrium Constant

Published kinetic information that can be used to derive k_+ is available for a limited set of minerals (e.g., Lasaga et al. 1994). Reactive surface area required in equation (2) can be estimated from geometric considerations or surface areas measured for whole rocks. The effects of pH on the relative value of R are shown in Figure 2. As may be seen, at lower pH values, reaction rates are more rapid than at higher pH values. The ion activity quotient can be calculated from water compositions. Equilibrium constants for a large number of minerals are available in published data bases (e.g., Bethke 2002).

In our assessment approach, mineral precipitation reactions and reactions occurring in the water-rich fluid phase are assumed to be rapid when compared to dissolution reactions and are treated using equilibrium considerations. Reactions with the CO_2-rich fluid phase are ignored. The Geochemist's Workbench (v 4.03), a commercially available, mixed equilibrium-kinetics geochemical computer code (Bethke 2002), is used to model the weathering reactions that transform CO_2 to solid phase carbonate minerals.

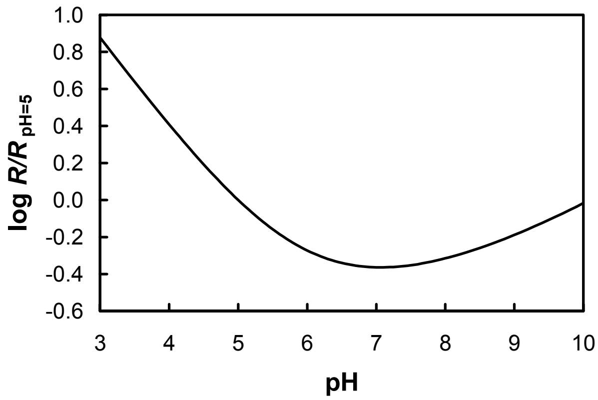

Figure 2. Relative reaction rate as estimated from Equation 2.

Subsurface geologic formations are composed of a multitude of site (or rock type) specific minerals. Because kinetic data are available for only a limited subset of the possible minerals, an approach that transforms actual rock mineralogy to an idealized set of minerals that can be modeled is required. The approach used here relies upon bulk whole rock chemical analyses for formation geomedia to calculate normative mineralogies (Lowenstern 2000). This approach provides a small, common-set of minerals that are independent of the site or formation being considered. For geochemical modeling, the normative mineralogy is simplified by removal of titanium and phosphorous containing phases. The use of normative mineralogies and geochemical modeling allows a uniform assessment of carbon sequestration potential for a variety of rock types. Although this approach does not accurately predict the capability for a given formation to sequester CO_2, site-specific kinetic data is not required, making it ideally suited for a regional survey of sequestration *potential* that includes a variety of rock types. The design of a sequestration system at a specific location should be guided by site specific models and mineralogoies.

Application of Assessment Methodology to Volcanic Rocks of the Snake River Plain, Idaho

The carbon sequestration potential of hypothetical hydrocarbon plays in the Idaho-Snake River Downwarp Province (USGS 1995) is part of the Partnership's regional assessment and evaluation. The direct injection of CO_2 into mafic-volcanic rocks is the scenario considered for this paper. This scenario has applicability to three of the four Idaho-Snake River Downwarp plays that contain or are bounded by volcanic rocks.

Geology

The Idaho-Snake River Downwarp plays considered include the Pliocene Lake Idaho sediments and Columbia River Basalts, Miocene Lake Bruneau sediments and basalts, and Pre-Miocene sedimentary and volcanic formations (Figure 3). Maximum thickness for the different plays range from 2,100 to 3,000 meters. These plays are located within the eastern and western provinces of the Snake River Plain (SRP) in southern Idaho. The Eastern Snake River Plain (ESRP) and the Western Snake River Plain (WSRP) have been differentiated based on their geologic history and their hydraulic attributes. Structural evolution leading to the development of the ESRP and the WSRP began ~17 million years ago as the North American Plate moved southwesterly over the Yellowstone Hotspot, resulting in a volcanic province that becomes thinner and younger to the northeast (Barrash and Venkatakrishnan 1982). The ESRP is generally younger than the WRSP and is composed of volcanic rock (primarily basalt with lesser amounts of rhyolite) and relatively thin layers or lenses of sedimentary material that tend to thin towards the center of the basin. The ESRP is host to an extremely productive aquifer that flows through the fractured basalts in a southwesterly direction. The

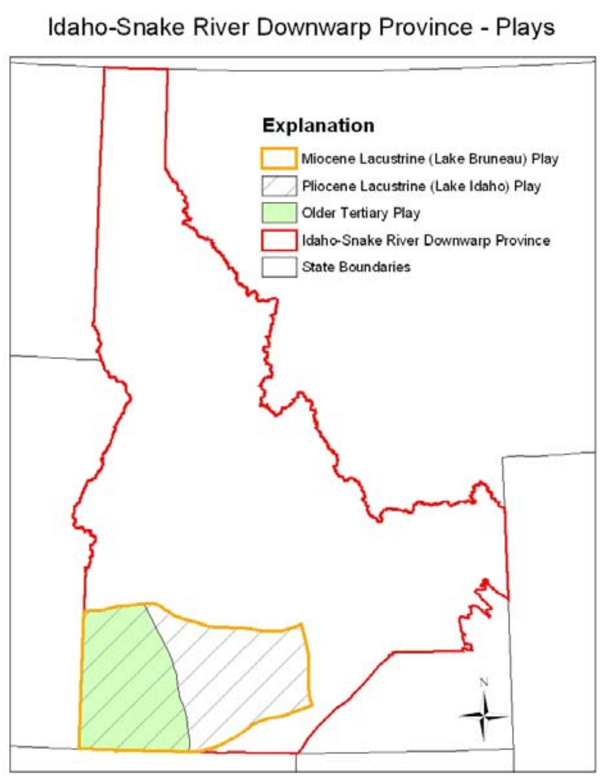

Figure 3. Map of Idaho showing locations of three plays (USGS 1995) with potential as carbon sequestration locations.

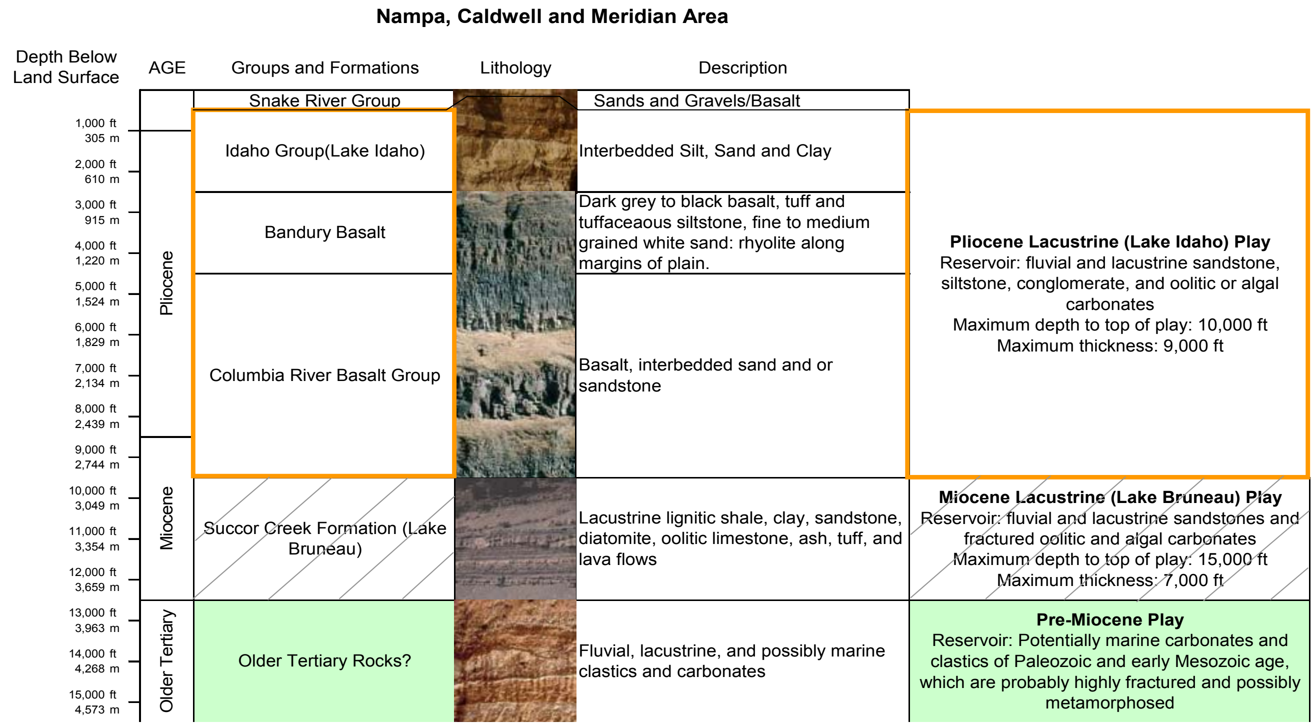

Figure 4. Generalized stratigraphic sections of Idaho plays with carbon sequestration potential.

WSRP is a structural downwarp that is believed to have been formed by crustal extension, beginning as early as 17 million years ago (Malde, 1991). Over these 17 million years, this structural depression has been filled with basalt flows separated by thick lacustrine sequences (Figure 4).

Basalts of the Snake River Plain are dominantly olivine tholeiites consisting of approximately 50-60 percent labradorite, 40 percent augite, less than 10 percent olivine, and 5 percent glass (Kuntz et al. 1992). Iron-titanium oxides (mostly magnetite) and minor apatite also occur. Of this assemblage, the most reactive phases are mafic glass followed by silicic glass, olivine, pyroxene, oxides, and labradorite (Morse and McCurry 2002). Reactive minerals in the sedimentary interbeds include K-spar, clays, calcite, dolomite, quartz, and volcanic glass (Rightmire and Lewis 1987).

Normative Media Properties

Average whole rock chemical composition for Snake River Plain basalts and the calculated normative mineralogy are given in Table 1. The normative mineralogy, comprised of end-member phases, are recast into solid solutions for the geochemical calculations. The required thermodynamic data for the new phases are estimated as a linear combination of the end-members and are included in the modeling database. Specific surface areas for basalt phases are also given in Table 1, are estimated from a total surface area calculated for the basalt, and are distributed among the normative mineral phases based on their volumetric abundances. The specific surface areas of the basalt is derived from geometric consideration with 1/3 of the porosity being attributed to one mm parallel fractures and 2/3 of the porosity attributed to intergranular porosity (assumed to be bundled capillary tubes with radius of 10.4 µm). A total porosity of 12.5 percent and median pore size of 10.4 µm is estimated from the averages of high pressure mercury injection tests conducted on 15 basalt samples.

Table 1. Average compositions of Snake River Plain Basalts (Kuntz et al. 1992), calculated normative mineralogy and specific surface areas.

Oxides	Wt %	Normalized Mineralogy	Wt %	Ti, P Free	Wt %	Surface Area $cm^2\ g^{-1}$
SiO_2	46.10					
TiO_2	2.60					
Al_2O_3	14.51	Orthoclase (Or)	5.51	K-Feldspar $KAlSi_3O_8$	5.51	123
Fe_2O_3	2.62	Albite (Ab)	20.89	Plagioclase $NaCaAl_3Si_5O_{16}$	46.66	115
FeO	10.57	Anorthite (An)	25.77			
MnO	0.20	Diopside (Di)	17.09	Clionpyroxene $Ca_3Mg_2FeSi_6O_{18}$	17.07	87
MgO	8.49	Hypersthene (Hy)	3.31	Orthopyroxene $Mg_2FeSi_3O_9$	3.31	87
CaO	10.34	Olivine (Ol)	16.64	Olivine $Mg_4Fe_2Si_3O_{12}$	16.64	84
Na_2O	2.47	Magnetite (Mt)	3.80	Magnetite Fe_3O_4	3.80	115
K_2O	0.93	Ilmenite (Il)	4.93			
P_2O_5	0.70	Apatite (Ap)	1.63			
Total	99.53	Total	99.55	Total	92.98	

Geochemical Modeling

The Geochemist's Workbench computer code is used to model the reaction of the normalized 'rock' from Table 1 and a representative Snake River Plain groundwater. The geochemical model is 'calibrated' by adjusting the surface area to yield an estimated basalt reaction rate of 150 mg L^{-1} yr^{-1} (Roback et al. 2001). Estimated specific surface areas are uniformly reduced by a factor of 100 to achieve calibration.

Using the calibrated model, a 500 year simulation for 200 bars CO_2 pressure and 40°C is conducted. In this simulation, 50 percent of the porosity is instantaneously flooded with supercritical liquid (SCL) CO_2 (with a density of 821 kg m^{-3}) to simulate the rapid injection phase. Under these P-T conditions a total of 15.4 kg m^{-3} of carbon is sequestered with hydrodynamic trapping accounting for approximately 14 kg m^{-3} of carbon and solubility trapping accounting for the remaining 1.4 kg m^{-3} of carbon. Because the simulation considered is for a single injection of CO_2, the total carbon sequestered is a constant 15.4 kg m^{-3} with time.

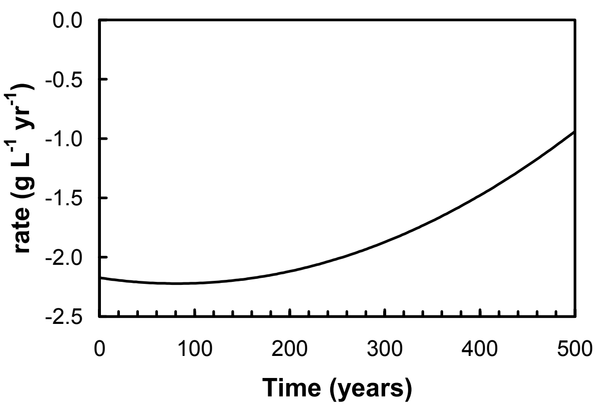

Figure 5. Dissolution Rate of primary basalt mineral as a function of time normalized to one liter of the aqueous phase.

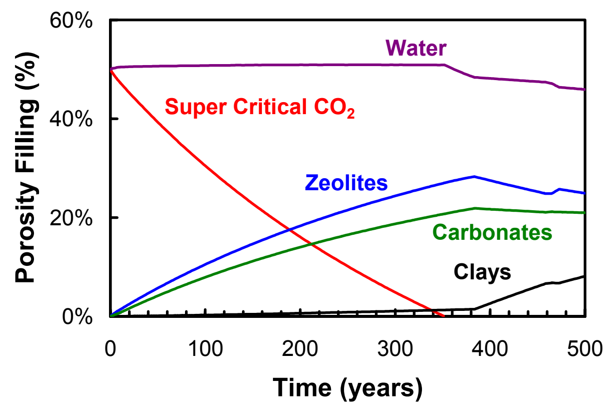

Figure 6. Relative filling of porosity (orignal porosity plus new porosity created by dissolution of primary minerals) as a function of time.

As a result of mineralization reactions, sequestered CO_2 dissolves the original minerals in the basalts (Figure 5) and precipitates secondary minerals (Figure 6). Within 350 years the SCL CO_2 phase disappears, ending the period in which hydrodynamic trapping contributes to sequestration. Initially, as may be seen in Figure 5, the rate[1] of dissolution is greater than 2 g L^{-1} yr^{-1}. Over time, the rate decreases reflecting the loss of the SCL CO_2 and an associated increase in pH. Figure 6 shows that during the period that SCL CO_2 is present (first 350 years), formed secondary minerals include zeolites and Ca, Fe, and mixed Ca-Mg carbonates. Following the loss of the SCL CO_2, dissolved aqueous CO_2 continues to react with the basalt for another 30 years. At approximately 380 years all the CO_2 is consumed, zeolites begin to dissolve, and clay minerals are formed.

Figure 7 shows that alteration reactions result in a steady decrease in porosity from 12.5 percent to 8.5 percent during the first 380 years. Following this period, the porosity remains essentially constant for the remainder of the simulation. Because the simulation considers only chemical interactions and does not include multiphase fluid flow, the full implications of porosity reduction on sequestration is not be evaluated. However, it is interesting to note that significant clay mineral formation does not occur until after the SCL CO_2 completely reacts. In addition, during early times (e.g. during injections) there is minimal porosity reductions suggesting that mineralization reactions are not important during the operation lifetime of an injection well. At later times, mineralization reactions with their associated reduction in porosity may serve to seal and isolate formation fluids. Figure 8 shows the relative importance of hydrodynamic, solubility, and mineral trapping over time of 1 m^3 of basalt geomedia. During early times, this potential is dominated by hydrodynamic (14 kg m^{-3} of carbon) and solubility (1.4 kg m^{-3} of carbon) trapping. Solubility trapping potential remains relatively constant as long as the SCL CO_2 fixed the activity of aqueous CO_2. With the loss of the SCL CO_2 phase at 350 years, solubility trapping decreases as aqueous CO_2 reacts with basalt silicates. Mineral trapping exceedes solubility trapping in about 160 years and accounts for 90 percent and 99 percent of the total carbon sequestered by 340 and 380 years, respectively.

Conclusions

The evaluations of potential geologic sequences for carbon sequestration need to consider the relative contributions of hydrodynamic, solubility, and mineralization trapping. The relative contribution to sequestration of these three processes will vary with rock type and time. In sequences that include basalts, such as those located in southern Idaho, all three processes contribute to sequestration, with hydrodynamic trapping important early and mineralization trapping dominating later. The specific potential of the Snake River Plain Basin is not determined in this report, but an preliminary assessment incidate that the Basin should be further studied.

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[1] The reaction rates as presented here are negative (the mass of primary minerals is decreasing) and are normalized to the volume of water in the system.

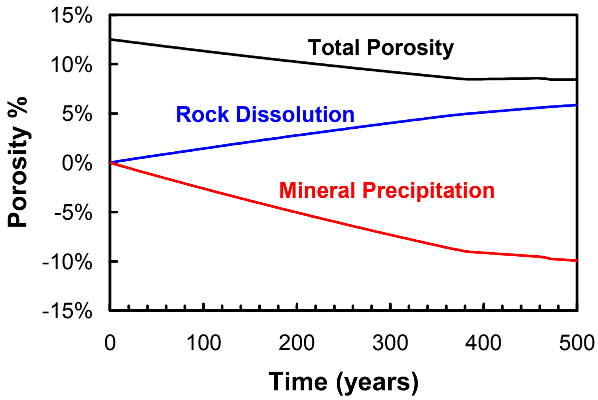

Figure 7. Changes in porosity as a function of time.

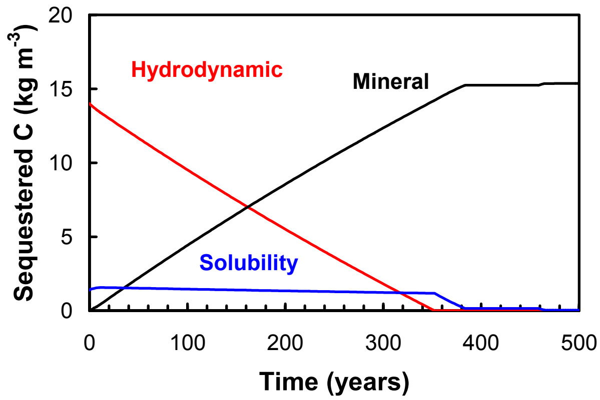

Figure 8. Caron sequestration potential of basalt by different mechanism as a function of time. The nature of the simulation fixed the total carbon sequestered at 15.4 kg m^{-3} (see text).

Acknowledgement

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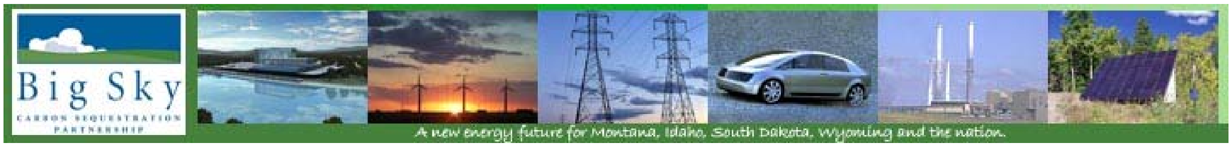

Big Sky Carbon Sequestration Partnership – Phase I

Deliverable 15:
Report on Results of Best Production Practice for Soil C Sequestration

Soil Carbon Sequestration and Best Production Practices: Some Preliminary Results for Montana

(Note: Analysis jointly supported by USDA/CASGMS and DOE Phase I efforts)

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U.S. Department of Energy (DOE)
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Susan M. Capalbo
Big Sky Principal Investigator
207 Montana Hall
Montana State University-Bozeman
Bozeman, MT 59717-2460
scapalbo@montana.edu
http://www.bigskyco2.org/
Phone: (406) 994-5619
Fax: (406) 994-2893

I. Farm Management Practices Can Affect Greenhouse Gases

The greenhouse effect is caused by heat from the sun that is trapped in the atmosphere by gases, much like the glass of a greenhouse traps the sun's warmth. Trapping the sun's heat allows fairly hospitable global temperatures and is essential to life. Without this natural greenhouse effect, Earth's average temperature would be below freezing and most life would be impossible.

But if the greenhouse effect becomes too intense, temperatures rise and have important environmental consequences. This is popularly known as "global warming," which scientists have stated is a leading global concern. Global warming is an increase in the earth's temperature caused by increased greenhouse gas concentrations in the atmosphere. As these gases increase, the 'greenhouse effect' intensifies, trapping more of the sun's heat.

Which Greenhouse Gases are Important to Agriculture? The primary greenhouse gases: water vapor, carbon dioxide, methane, and nitrous oxide, with water vapor being the most common. Carbon dioxide, methane, and nitrous oxide result mainly from human activities. Carbon dioxide is released mainly due to combustion of fossil fuels such as coal, gasoline, diesel, and natural gas, and is also produced when solid wastes, wood, and wood products are burned. Carbon dioxide concentrations have increased from 270 parts per million in the mid-1800s to 370 parts per million in 2004. These increases have been implicated in a gradual increase in the earth's temperature.

All atmospheric gases contribute to global warming, but some gases like nitrous oxide and methane are more powerful than carbon dioxide due to their long duration in the atmosphere and strong absorption of long-wave radiation. Scientists sometimes use the term global warming potential to compare the heat-trapping ability of other greenhouse gases to carbon dioxide. Carbon dioxide is used as the baseline greenhouse gas and assigned a value of 1. Methane has 21 times and nitrous oxide 310 times the global warming potential of carbon dioxide. Thus, every ton of methane has the global warming potential of 21 tons of carbon dioxide and every ton of nitrous oxide warms as much as 310 tons carbon dioxide. These values are referred to as carbon equivalents.

How can Agriculture Affect Climate Change? Agricultural activities serve as both sources and sinks for greenhouse gases, so specific agricultural practices could slow the pace of global warming. Methane dynamics are linked closely to livestock production practices and wetland agriculture, such as rice production. We focus on crop management in Great Plains agriculture in this note and so will ignore methane here. Carbon dioxide dynamics are related to energy use cycles on farms and more importantly, to soil management. Nitrous oxide dynamics are related to soil nitrogen management, including fertilizer nitrogen.

What is Soil Carbon Sequestration? Carbon sequestration refers to the removal of carbon dioxide from the atmosphere into a long-lived stable form that does not affect atmospheric chemistry. Currently, the only viable way to trap atmospheric carbon dioxide is via photosynthesis, where carbon dioxide is absorbed by plants and turned into carbon compounds for plant growth. Carbon is considered sequestered if it ends up in a stable form, such as wood or soil organic matter. Soil carbon sequestration is an important and immediate sink for removing atmospheric carbon dioxide and slowing global warming.

II. Management Practices that Sequester Soil Carbon

Practically, there are three areas of farm management that can affect soil carbon sequestration in the Great Plains: tillage, cropping intensity and fertilization.

Tillage and soil carbon are negatively related. The greater the tillage, the less soil carbon. No-till systems build soil organic matter, which is about 58 percent carbon. No reliable data exist in Montana regarding soil carbon accumulation rates due to no-till, but extensive research in nearby southwestern Saskatchewan shows that soils depleted of organic matter typically accumulate soil carbon at a rate of 0.1 tonne/ha/yr (~0.045 tons/ac/yr), but may vary from 0 to 0.2 t/ha/yr depending on soil type, soil management, local weather patterns and specific no-till systems.

Different no-till systems result in varying soil disturbance, but any system that reduces tillage substantially can increase soil carbon. Montana field research completed in 2001 showed carbon storage rate from no-till adoption similar to that in southwestern Saskatchewan, but with considerable farm-to-farm variability. That variability needs to be understood.

Cropping intensity and soil carbon are positively related. The more frequent the cropping and greater the biomass inputs, the more soil carbon. Summer fallow reduces cropping intensity. Reducing fallow typically increases soil carbon through greater annualized biomass inputs, but may be economically difficult. No Montana data exist on carbon storage rates due to cropping intensity, but data from southwestern Saskatchewan show average carbon storage rates of about 0.2 tonne/ha/yr (0.09 ton/ac/yr) when converting from 50:50 crop-fallow to continuous cropping. Field research began in 2003 in north central Montana to compare soil carbon accumulation due to no-till adoption and continuous cropping. We expect this research to provide important information about greenhouse gas emissions in the short term, and may serve as long term benchmark sites to support future carbon credit trading.

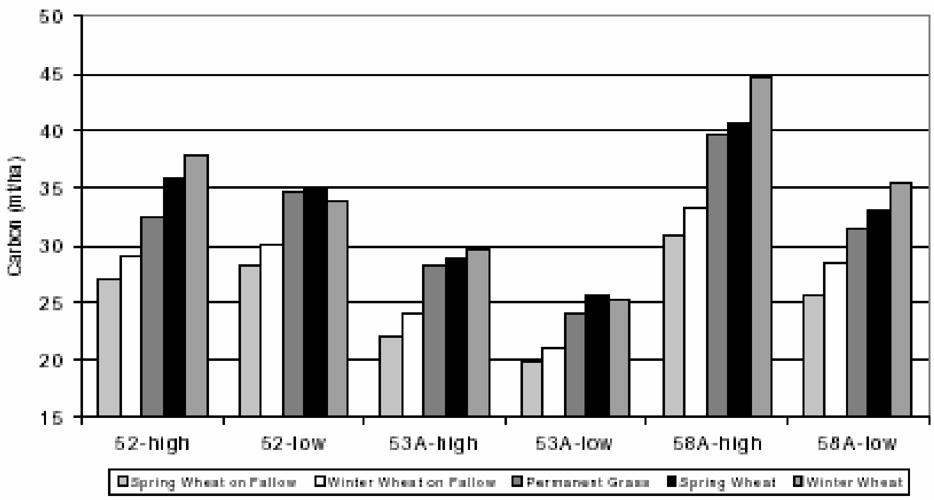
Fertilization affects soil carbon mainly through crop biomass. However the carbon:nitrogen ratio of soil organic matter results in stable organic matter typically within a range of about 8-10:1. If insufficient nitrogen is present to permit stable formation of soil organic matter via soil microbial degradation of crop residues, then little carbon may be sequestered.

<u>How are Soil Carbon and Nitrogen Related?</u> This 8-10:1 carbon:nitrogen ratio means that for every 8-10 lb of carbon sequestered in soil organic matter, 1 lb of nitrogen must accompany it. This tie-up of nitrogen reduces nitrogen for crops. For example, if a farmer adopted no-till that resulted in an increase of soil carbon of 0.45 ton/ac over 10 years, 0.045 t/ac (90 lb) of applied nitrogen would have been tied up in soil organic matter and would not have been available to his crops. Legume crops such as alfalfa, peas, lentils and chickpea could serve as alternative sources for nitrogen. Economic considerations of changing crop rotations should be considered carefully.

<u>Is Nitrous Oxide an Important GHG?</u> Nitrous oxide can be emitted from the soil during both nitrogen mineralization and immobilization processes and is linked to fertilizer nitrogen. The Intergovernmental Panel on Climate Change uses a default value of 1.25 percent of fertilizer nitrogen inputs are lost as nitrous oxide. Since nitrous oxide has a global warming potential equivalent 310 times that of carbon dioxide, a loss of even one pound of nitrous oxide has a large impact, potentially canceling out carbon credits due to carbon dioxide removal. Marked differences in such losses likely exist in different climates, and research is underway to measure such loss in semiarid cropping systems. Indications are that the 1.25 percent used by the IPC carbon is too large for semi-arid environments and may over-estimate nitrous oxide emissions from fertilizer applications in our region. Wet soils favor nitrous oxide losses. More intensive cropping by lowering fallow frequency, which reduces periods of high soil moisture, may minimize nitrous oxide emissions from soils.

III. Some Empirical Results on Changes in Soil Carbon Due to Changes in Management Practices in Montana.

IIIA Century Model results. The crop ecosystem model known as Century is utilized to represent the processes controlling crop growth, water, nutrient, and organic matter dynamics that determine the productivity of agricultural ecosystems (Parton et al 1994.; Paustian, Elliott, and Hahn 1999). Century is a generalized-biogeochemical ecosystem model which simulates C (i.e., biomass), nitrogen and other nutrient dynamics. It includes submodels for soil biogeochemistry, growth and yield submodels for crop, grass, forest and savanna vegetation and simple water and heat balance. For use in agricultural and grassland ecosystems, the model incorporates a large suite of management options including crop type and rotation, fertilization, tillage, irrigation, drainage, manuring, grazing, and burning. The model employs a monthly time step and the main input requirements (in addition to management variables) include monthly precipitation and temperature, soil physical properties (e.g., texture, soil depth) and atmospheric nitrogen. For the current application, soils and climate data for each of the sub-MLRAs are used as Century model inputs in addition to management variables such as crop type and rotation, fertilization and tillage practices. The Parameter-elevation Regressions on Independent Slopes Model (PRISM) data set was used to determine weather-related data. Information on current management systems is from the 1995 survey of Montana producers, augmented with the USDA National Agricultural Statistics Service (NASS) database, the National Resources Inventory (NRI) database, and county-level databases of the National Association of Conservation Districts (NACD). Soil characteristics are determined using the Advanced Very High Resolution Radiometer (AVHRR) database (USGS-Earth Resources Observation System (EROS) Data Center), the State Soil Geographic Database (STATSGO) and the NRI database. Baseline projections of soil C are made using historical climate and land-use records. These projections are compared to NASS records of county-level crop yields and changes in soil C derived from the Century database of native and cultivated soils. The initial land-use allocation from the 1995 Montana survey was used to calculate base C levels for each sub-MLRA. The variability in the levels of soil C predicted by the Century model across the six major crop producing sub-MLRAs and production systems in Montana is shown in Figure 1. Simulations of the crop-fallow, continuous cropping, and permanent grass production systems with the Century model show that the equilibrium levels of soil C under a crop-fallow rotation range from 3–7 MT per hectare less than continuous grass over a twenty year horizon, and that soil C levels under permanent grass range from 1–5 MT per hectare less than under continuous cropping depending upon sub-MLRA. In sub-MLRA 52-low, soil C levels under permanent grass compare favorably with soil C levels under a continuous cropping system. The variability across sub-MLRAs reflects the heterogeneity in biophysical and climatic conditions, which translates into different equilibrium levels of soil C for the production systems.



Note: Soil C levels for barley are the same as for spring wheat.

Figure 1. Soil C levels predicted by Century model for cropping systems in Montana

IIIB Field scale studies. To provide additional information about C sequestration rates in Montana cropland three studies were initiated. The first study, completed in 2003, used a predictive model (Century) to estimate historic gains in soil carbon 6 to 10 yr following conversion to no-till management at six farm fields in north central Montana. When field-specific soil textures were used the model predicted soil C gains within 10% of measured values with soil C sequestration rates ranging from 0.07 to 0.38 tons/acre/yr among the field sites. The second study, initiated in 2002, contrasts the effects of tillage system and cropping intensity on C sequestration in six farm fields in north central Montana. Scientific controls are more rigorous than the first study through the use of a common baseline, a single operator managing all cropping practices, and the field treatments are sufficiently large to be observed with remote sensing. Also, costs, returns and net GHG emissions are being closely monitored for each treatment and augmented with data collected from a survey instrument developed for this study. The third study was initiated in 2002, and compares C sequestration in 9 cropping systems within a replicated experimental plot design. The second and third studies are planned to run 10 years.

The objectives are to:

- Estimate direct and indirect changes in soil organic C and N_2O emissions as result of changes in tillage and cropping intensity.
- Compare alternative tillage systems and cropping intensity for full GHG accounting (energy-related and soil-sequestered C and N_2O) in dryland farm field settings.
- Estimate the potential for C sequestration as a result of adopting windbreaks and riparian plantings using different tree species in locations across the state.

Six paired farm fields in north central Montana were selected to compare conventional with no-till wheat cropping systems (Figure 2). Site selection was constrained by management history, soil characteristics and current crop growth, to enable valid inferential comparisons of these fields based on tillage management. Experimental design involved a randomized 30-m grid sampling approach (Nelson and Buol, 1990) of both tillage systems of adjacent fields within the soil type. Soil sampling was a stratified (depth varied systematically from 50 to 100 cm) protocol using a georeferenced 2x5 m grid approach (B. McConkey, K. Paustian, pers. comm., 2000). Fields were compared for soil organic C differences and sampling intensity was compared for cost efficiency. Measurements were compared with Century model predictions.

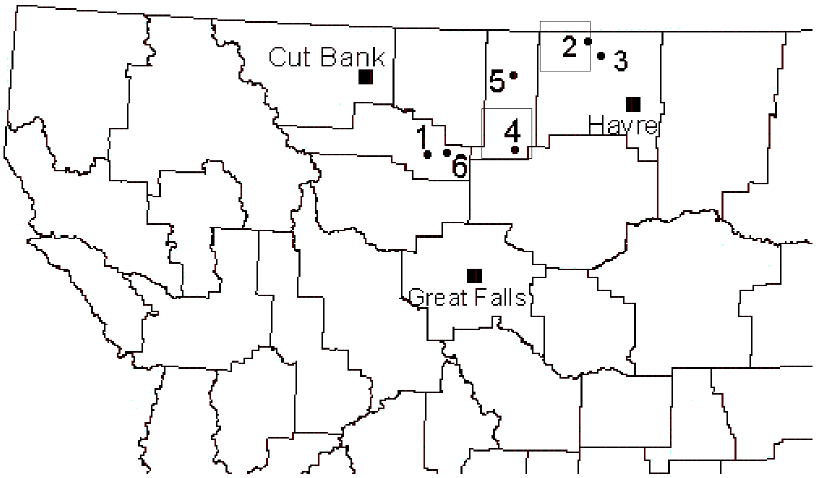


Figure 2. Locations of six farms in north central Montana for the On-farm Tillage Systems Comparison.

The use of agricultural best management practices, most notably the adoption of no-till systems, has become a potential technique to sequester (store) carbon in soils and help mitigate the effects of global warming. Efficient sampling designs and the use of process-based soil organic carbon (SOC) dynamics models are potential methods of monitoring and verifying soil carbon change. This research combined field-scale soil sampling and the use of the Century model to explore field-scale SOC variability and the effects of soil texture input data sources (STATSGO and SSURGO databases) on predicted SOC dynamics in north central Montana. Using soil-landscape associations for field stratification and sampling of microsites for paired management comparisons was an efficient design for measuring SOC (CV = 8-13%). An optimal sampling design of 4 microsites by 2 cores or 3 microsites by 3 cores provided reliable detection of a tillage effect on SOC, given the magnitude of differences (1.3 to 5.1 t C ha^{-1}) and degree of variability measured. Including the effects of soil clay content as a covariant may provide unbiased estimations of the effects of tillage on SOC among sites, particularly for coarse scale comparisons. The Century model accurately predicted SOC content at five sites using site-specific soils data (10% deviation from measured values). Neither the STATSGO (1:250,000 scale) nor SSURGO (1:24,000 scale) soil databases adequately predicted soil textures, nor supplied adequate soil textural information for use in the Century model and so introduced error to field-specific predictions. Century proved to be sensitive to the effects of clay content when predicting the amount of SOC in a particular field; however the model was insensitive to the effects of soil texture on C sequestration as a result of no-till management. The methods used to measure SOC and the Century model proved to be useful tools for determining carbon stored due to no-till management. Additional research is needed to determine if a consistent relationship exists between soil texture and the effect of tillage on SOC and thus determine if adjustments are needed to the Century model's treatment of soil texture.

These results support future measurement, prediction, and general understanding of soil organic carbon sequestration in semiarid dryland agricultural systems. Reliable measurement of soil organic carbon change associated with a shift in tillage management can be difficult, for SOC varies spatially and the degree of variability can be substantial. Confounding variables such as climate, topographic position, erosion potential, and soil texture also vary spatially and can greatly influence SOC change across small distances. A soil-landscape association method of field stratification addressed these confounding variables effectively and reduced SOC measurement variability; however, due to natural variation in soil texture, differences in soil texture still occurred between tillage treatments at some sites. Differences in soil textures may confound determination of the tillage effect, particularly at regional and larger areas. A measure of soil texture (i.e., % clay) was added as a covariant in statistical analyses. Including percent clay as a covariant provided estimates of SOC under no-till and tilled management adjusted for differences in clay content, and reliable determination of tillage effects.

The effect of soil textural variation at field-, 1:24,000 (SSURGO), and 1:250,000 (STATSGO) scales on the predictive capability of the Century model was explored. Both the SSURGO and STATSGO databases were limited in their accuracy of predicting soil textures at the sampled fields. Ranges in clay percentage reported by SSURGO included the measured values for three of 10 fields and STATSGO included five of 10. Due to the differences in scale, the width of the STATSGO ranges in clay % were two to seven times as wide as the SSURGO ranges. The shortcomings of these soils databases had a large effect on the accuracy of Century model predictions. Using field-scale soil textures and site-specific management data, Century accurately predicted soil organic carbon at five sites in north central Montana to within an average of 10% (range of -1 to +28%) of measured values.

Soil organic carbon estimates from Century for the management systems in this study were sensitive to the effect of clay content based on the range of modeled soil organic carbon values. Estimated SOC for the upper limit of reported clay content was 2.3 to 2.7 times greater than SOC estimates for the lower clay limit at the five sites modeled using STATSGO database ranges in clay content. Conversely, Century was largely insensitive to the effects of soil texture on the potential soil carbon change in response to the adoption of no-till. Century did not predict the amount of implied carbon change in response to the adoption of no-till at the five sites modeled in this study over a wide range in clay percentages. Model results for the five sites in Montana showed little difference in the amount of carbon stored in coarse-textured soils (5% clay) compared to fine-textured soils (35-40% clay), with the exception of the Ft. Benton site. The insensitivity of Century to a soil textural effect on C storage under no-till management assumes that a strong relationship exists between soil texture and the effect of tillage on soil organic carbon. This relationship is currently not well understood.

Additional analysis of the Century model's sensitivity to soil textural input variables is needed to determine if adjustments to the model would be necessary. This research was not an exhaustive look at the effects of soil texture on Century's predictive capabilities. Largely, it was shortcomings of the SSURGO and STATSGO soils databases that limited the effectiveness of Century. The model was sensitive to the effects of soil texture when predicting the amount of SOC in fields managed with and without tillage; however the model was not sensitive to the effects of soil texture on the ability of a particular soil texture to accumulate SOC over a 6-to-10-year period of no-till management. From a modeling standpoint, neither the SSURGO nor the STATSGO databases provided adequate soil textural information for use in the Century model, thus site-specific soil information is recommended for use with the Century model.

IV. Some empirical results for other parts of the Great Plains

In order to provide some additional information on how the best practices for sequestering soil carbon are spatially dependent, we report some preliminary results for grain and corn production in Nebraska, and compare no-till and reduced tillage practices to conventional tillage. The Century model provided estimates of carbon rate changes and crop yield changes.

Tillage options included conventional tillage (C), reduced tillage (R), and no-till (N). We also considered a CRP option within the tillage simulation scenario. Conventional tillage change to

CRP sequesters highest amount of carbon followed by reduced tillage to CRP and no-till to CRP for all dryland crop rotations. For irrigated crops, conventional to no-till change sequesters highest amount of carbon. Table 1 gives the carbon change estimates for selected rotations and selected tillage options.

Soil carbon change by MLRAs indicates that there is virtually no spatial variation for switching from conventional tillage practice to no-till. However, switching to CRP from conventional or no-till yields to higher rates of soil carbon in MLRA 75 and MLRA 106 compared to MLRA 73. This variability reflects the spatial heterogeneity in the biophysical and climate conditions across the survey transect.

Since switching to CRP sequesters 3 to 4 times as much carbon as opposed to switching to no-till, the economic simulation model is expected to yield higher degree of land use changes toward CRP for a given carbon price and CRP payment.

Table 1. Soil carbon change for consolidated rotations and tillage switch

	Carbon change due to tillage change (mt/acre/year)		
Rotations	***C to N***	***C to CRP***	***N to CRP***
Dryland Crops:			
Corn-soybean-sorghum	***0.12***	***0.48***	***0.36***
Wheat-corn-fallow	***0.10***	***0.54***	***0.44***
Fallow-wheat	***0.07***	***0.59***	***0.52***
Continuous wheat	***0.08***	***0.49***	***0.41***
MLRA 73			
Corn-soybean-sorghum	***0.13***	***0.43***	***0.31***
Wheat-corn-fallow	***0.10***	***0.49***	***0.39***
Fallow-wheat	***0.06***	***0.54***	***0.48***
Continuous wheat	***0.08***	***0.44***	***0.37***
MLRA 75			
Corn-soybean-sorghum	***0.12***	***0.49***	***0.37***
Wheat-corn-fallow	***0.10***	***0.56***	***0.46***
Fallow-wheat	***0.07***	***0.61***	***0.54***
Continuous wheat	***0.08***	***0.51***	***0.43***
MLRA 106			
Corn-soybean-sorghum	***0.12***	***0.50***	***0.38***
Wheat-corn-fallow	***0.10***	***0.57***	***0.47***
Fallow-wheat	***0.07***	***0.62***	***0.55***
Continuous wheat	***0.08***	***0.51***	***0.43***
Irrigated Crops:			
Corn-soybean	***0.19***	***-***	***-***
MLRA 73			
Corn-soybean	***0.19***	***-***	***-***
MLRA 75			
Corn-soybean	***0.19***	***-***	***-***

C = Conventional till; N = No-till; CRP = Conservation Reserve Program

Given the land use changes within each MLRA based on maximizing expected returns, the levels of soil carbon sequestered are calculated using the equilibrium average soil carbon rates for each field obtained from the Century model. The Century model preliminary results indicate that reduced tillage changes for the selected dryland crop-rotations enhance soil carbon levels. The average amount of carbon sequestered under these tillage scenarios for each MLRA and the total carbon sequestered over all three MLRAs are presented in Table 2.

Table 2. Average and total carbon sequestration by MLRAs

	Soil carbon (000 mt) over 20 years			
	C to N	***C to CRP***	***N to CRP***	***All Changes***
Average MLRA 73	***0.6***	***43.4***	***19.4***	***63.4***
Average MLRA 75	***3.7***	***16.5***	***5.6***	***25.9***
Average MLRA 106	***3.0***	***4.6***	***1.7***	***9.3***
Total for MLRAs in survey transect	***73.8***	***645.0***	***266.9***	***985.7***
Total for MLRAs in Nebraska State	***25,991.1***	***274,595.8***	***117,269.3***	***417,856.2***

Assuming identical crop productivity and soil carbon rates for the entire MLRA areas within the state of Nebraska, the model simulation is extrapolated for and entire MLRA areas and the total amount of soil carbon that could be sequestered for the entire MLRA areas is presented in the last row of Table 2. The total amount of carbon sequestered for the entire Nebraska MLRA areas range between 26 million metric ton for CN scenario and 275 million metric tons for the CCRP scenario over the 20 year period.

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