PRRC 06–03

Southwest Regional Partnership on Carbon Sequestration

Revised Semiannual Report

Reporting Period: April 1, 2005 – September 30, 2005

Principal Author*: Brian McPherson

Issue Date: April 2006

DE-PS26-03NT41983

Submitting Organization: New Mexico Institute of Mining and Technology
801 Leroy Place
Socorro, New Mexico 87801

*Other Contributing Authors:
Rick Allis, Utah Geological Survey, Barry Biediger, Utah Automated Geographical Reference Center, Joel Brown, U.S. Department of Agriculture, Jim Cappa, Colorado Geological Survey, George Guthrie, Los Alamos National Laboratory, Richard Hughes, University of Oklahoma, Eugene Kim, Texas Bureau of Economic Geology, Robert Lee, New Mexico Institute of Mining and Technology, Dennis Leppin, Gas Technology Institute, Charles Mankin, Oklahoma Geological Survey, Peter Kobos, Sandia National Laboratories, Rajesh Pawar, Los Alamos National Laboratory, Tarla Peterson, University of Utah, Steve Rauzi, Arizona Geological Survey, Jerry Stuth, Texas A&M University, Genevieve Young, Colorado Geological Survey, and many other partners in the Southwest Partnership

DISCLAIMER

ABSTRACT

The Southwest Partnership on Carbon Sequestration completed several more tasks during the period of April 1, 2005 – September 30, 2005. The main objective of the Southwest Partnership project is to evaluate and demonstrate the means for achieving an 18% reduction in carbon intensity by 2012. While Phase 2 planning is well under way, the content of this report focuses exclusively on Phase 1 objectives completed during this reporting period. Progress during this period was focused in the three areas: geological carbon storage capacity in New Mexico, terrestrial sequestration capacity for the project area, and the Integrated Assessment Model efforts.

The geologic storage capacity of New Mexico was analyzed and Blanco Mesaverde (which extends into Colorado) and Basin Dakota Pools were chosen as top two choices for the further analysis for CO_2 sequestration in the system dynamics model preliminary analysis.

Terrestrial sequestration capacity analysis showed that the four states analyzed thus far (Arizona, Colorado, New Mexico and Utah) have relatively limited potential to sequester carbon in terrestrial systems, mainly due to the aridity of these areas, but the large land area offered could make up for the limited capacity per hectare. Best opportunities were thought to be in eastern Colorado/New Mexico.

The Integrated Assessment team expanded the initial test case model to include all New Mexico sinks and sources in a new, revised prototype model in 2005. The allocation mechanism, or "String of Pearls" concept, utilizes potential pipeline routes as the links between all combinations of the source to various sinks. This technique lays the groundwork for future, additional "String of Pearls" analyses throughout the SW Partnership and other regions as well.

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

The primary progress achieved during April 2005 through September 2005 was to finish regional characterization and to refine plans for field validation testing. Progress during this period was focused in three areas: geological carbon storage capacity in New Mexico, terrestrial sequestration capacity for the project area, and the Integrated Assessment Model efforts.

In New Mexico, 507 Permian Basin pools, or reservoirs, and 80 San Juan Basin pools were identified as potential CO_2 sinks. Each of these pools was assigned a unique number, usually the state mandated, Oil Conservation Division (OCD) number, and entered into the modified GASIS database. Further, the names and exact locations of all these pools have been entered into a GIS database so that their spatial relationships to each other, the power plants, population centers, geographic grids, etc. can be portrayed in Arcview (a desktop GIS software package that is written and marketed by the Environmental Systems Research Institute, Inc). Several major sources of data were used to obtain the detailed information for the GASIS Database, whose search engine was modified to find pools that met or exceeded ten key criteria, including specified distance from power plants, thickness, porosity, cumulative production, and depth. Blanco Mesaverde (which extends into Colorado) and Basin Dakota Pools were chosen as top two choices for the further analysis for CO_2 sequestration in the system dynamics model preliminary analysis.

Terrestrial sequestration capacity analysis showed that the four states analyzed thus far (Arizona, Colorado, New Mexico and Utah) have relatively limited potential to sequester carbon in terrestrial systems, mainly due to the aridity of these areas. However, the vast amounts of land with small per hectare potential could result in a substantial amount of carbon sequestration if there is a broad-based effort to realize this potential. Better opportunities can be found in the eastern sections of Colorado and New Mexico, where rainfall is higher and soils more fertile.

The Integrated Assessment team developed a dynamic simulation computer model to help interested parties understand the potential screening criteria necessary to develop a carbon sequestration project. The screening criteria include geologic considerations for underground storage of carbon dioxide (CO_2), the relative size of the CO_2 flow from the source to the sink, and the associated economics with the system. The modeling team decided to focus on electricity production by utilities from coal and gas fired power plants as a point source for CO_2 emissions for the initial test case model framework. The test case region focused on the San Juan Basin in northwestern New Mexico and southeastern Colorado. Four power plants and seven geologic sinks were selected for the test case. The CO_2 sources and sinks selected for the model test case result in many combinations of potential sequestration actions, with associated sequestration rates and capital, operation and maintenance costs. These combinations provided the initial high-level "what if" analysis opportunities for sequestration in the test case area. The model calculated all of the illustrative cost and CO_2 flow combinations between the four power plants, and the seven geological sequestration sites, and ranked them from lowest to highest.

The Integrated Assessment team expanded the initial test case model to include all New Mexico sinks and sources in a new, revised prototype model in 2005. The model calculates the distance to transport CO_2 from the source to the closest sink to be utilized. An algorithm was developed to calculate a route of pipelines from the source of CO_2 (e.g., power plant) to each of the geologic sinks and then to calculate the total distance (and eventually cost) of the pipelines (Stephens, 1998). These sinks are used in such a way that as each one fills to capacity the transportation network extends to the next viable sink, and then to the next to eventually develop a pipeline network system. This allocation mechanism, or "String of Pearls" concept, is also

known as a minimal spanning tree approach. The links between all combinations of the source to various sinks are the potential pipeline routes. This technique serves as a linear proxy for pipeline length, and lays the groundwork for future, additional “String of Pearls” analysis throughout both the Southwestern Regional Partnership area in the United States, and other regions interested in carbon capture and sequestration analysis. With this technique, the model could address additional metrics (e.g. lowest overall cost, largest sink volume, etc.) for systems insight.

EXPERIMENTAL

No special experimental methods are being employed in this project. Materials and equipment used include only standard communication means and data management tools, including computerized databases and internet websites.

RESULTS AND DISCUSSION

The April 2005–September 2005 results of this project are described in this section. Interim summary reports of geological carbon storage capacity for New Mexico, terrestrial sequestration capacity, and the integrated assessment results comprise this section.

Section 1: Geological Carbon Storage Capacity Evaluation—New Mexico

Using cumulative production cutoffs of one million barrels of oil and/or ten billion cubic feet of gas, 507 Permian Basin (PB) Pools (reservoirs) and 80 San Juan Basin (SJB) Pools were identified as potential CO_2 sinks. Each of these pools was assigned a unique number, usually the state mandated, Oil Conservation Division (OCD) number, and entered into the modified GASIS database. In addition, the database also contains detailed information on four natural CO_2 pools and the West Pearl Queen Pool (PB), which was chosen as the field demonstration site for CO_2 sequestration in NM. The SJB list contains seven pools that did not quite meet the production criteria, but were in close proximity to the two power plants and were similar geologically to the top choices. The names and exact locations of all the pools have been entered into a GIS database so that their spatial relationships to each other, the power plants, population centers, geographic grids, etc. can be portrayed in Arcview (a desktop GIS software package that is written and marketed by the Environmental Systems Research Institute, Inc).

The following major sources of data were used to obtain the detailed information for the GASIS Database:

- The Roswell Geological Society Oil and Gas Fields of Southeastern New Mexico (1956, 1960, 1967, 1977, 1988, 1999).
- The Four Corners Geological Society Oil and Gas Fields of the Four Corners Area (1978, 1983).
- The Atlas of Major Rocky Mountain Gas Reservoirs (1993).
- State of New Mexico, Energy, Minerals, and Natural Resources Department, Oil Conservation Division Orders.
- The detailed well and pool data housed at the New Mexico Bureau of Geology's Petroleum Records Section.

The search engine in the GASIS (Access) Database was modified to find pools that met or exceeded ten key criteria; e.g. specified distance from power plants, thickness, porosity, cumulative production, and depth. From the list of 14 pools that were within 50 miles of the power plants, at least 3000 ft deep, and had produced at least 1.5 million barrels of oil and/or 10 BCF gas, Blanco Mesaverde and Basin Dakota Pools were chosen as top two choices for the further analysis for CO_2 sequestration in the system dynamics model preliminary analysis. Blanco Mesaverde Pool extends into Colorado, where it is known as Ignacio Blanco Mesaverde, and thus involves two state-regulatory agencies.

1. <u>Blanco Mesaverde (San Juan Basin)</u>:
   Advantages:

   - Majority of production (>90%) from the regressive Point Lookout Sandstone, a continuous marine reservoir.
   - The main reservoir is sealed by several hundred feet of shale and coal.
   - Cumulative production of more than 41million barrels of oil, 12 million barrels of water, and 10 trillion cubic feet of gas.
   - Reservoir at a depth of more than 4,500 ft.
   - Discovery well is within a 30 mile radius of the power plants.
   - Average reservoir thickness is 140 ft.
   - Calculated storage capacity of CO_2 is more than 750 million tonnes.
   - The Blanco Pictured Cliffs pool (728 bcfg) is 1,700 feet above. If CO_2 were to leak past the Mesaverde reservoirs, it could be trapped here (calculated storage capacity of about 50 million tonnes).
   - Sparsely populated area with few nearby population centers (e.g., Farmington, Bloomfield, and Aztec).
   - Large areal extent (more than 1 million acres) means that sequestered CO_2 could be injected at wide spacing.

   Issue(s) needing further evaluation:

- The Pictured Cliffs pool, which is 1700 feet above, is near the depth cutoff for supercritical CO_2 (800 m) and could possibility provide additional CO_2 storage from the same injector well.
- Regulatory issues related to pool's extension in two states.
- Located on private, state, BLM, and Indian land.

2. <u>Basin Dakota (San Juan Basin)</u>:
   Advantages:

   - Most of production is from marine beach and offshore bar sandstones, which means the reservoir is continuous.
   - The reservoir is sealed by several hundred feet of marine shale.
   - Cumulative production of more than 45 million barrels of oil, 14 million barrels of water, and 5 billion cubic feet of gas.
   - Reservoir at a depth of more than 7,000 ft.
   - Discovery well is within a 10 mile radius of the power plants.
   - Average reservoir thickness is 60 ft.
   - Calculated storage capacity of CO_2 is more than 550 million tonnes.
   - There are several reservoirs above, including the Mesaverde and Pictured Cliffs, that could trap any leaked CO_2.
   - Sparsely populated area with few nearby population centers (e.g., Farmington Bloomfield, and Aztec).
   - Large areal extent (more than 1 million acres) means that sequestered CO_2 could be injected at wide spacing.

   Issue(s) needing further evaluation:

   - Located on private, state, BLM, and Indian land.

In addition, we have supplied the Test Case Team with the eleven other top rated pools that are at varying distances from the power plants and produce from different depths to allow for variability in the test case analyses. We have reduced the key categories of geologic/geographic information from the two-three hundred in the GASIS database to fewer than 50 for the test case analyses.

The first CO_2-enhanced coal-bed methane production occurred in SJB in 1995. At Burlington Resources' Allison Unit more than 100,000 tons of CO_2 were injected over a three-year period to enhance production of coal-bed methane. The CO_2 was injected by four injector wells and is now sequestered in the coal at depths in excess of 3,000 ft. Critical factors for sequestration include coal seam continuity, cleat permeability, coal shrinkage/swelling, gas adsorption/desorption, and seal integrity. The SJB is one of the top ranked basins for CO_2 coal-bed sequestration because it has: 1) advantageous geology; 2) abundant anthropogenic CO_2; 3) low capital and operating costs; 4) well developed natural gas pipeline system; and 4) companies with CBM expertise. Selection of a potential coal-bed methane CO_2 sequestration sites in SJB is difficult and will require more detailed reservoir studies than are available in the literature because: 1) the coal seams are discontinuous; 2) the major coal-bearing formation in the San Juan Basin is generally too shallow to keep the CO_2 in super critical state; and 3) all coal-bed methane production from the Fruitland Formation in the SJB is now lumped together, making it difficult to know how much methane has been produced from a single reservoir.

Publicly available information on deep saline aquifers in New Mexico is fragmented and scattered in the geologic and hydrologic literature. The Texas Bureau of Economic Geology (BEG) has compiled data on the Morrison Formation of the San Juan Basin in its study of "Optimal Geological Environments for CO_2 Disposal in Brine Formations (Saline Aquifers) in the United States." They noted (p.32) that "… the same attributes that make saline water-bearing formations desirable as disposal sites (isolation, low potential for economic use, and few well penetrations) are those for which we have little direct information." (Hovorka, 2001)

Section 2: Terrestrial Sequestration

Terrestrial carbon sequestration is an important component of a comprehensive greenhouse gas (GHG) management strategy in the southwest. The ability to transfer and store atmospheric C in soils and vegetation by manipulating the rate and magnitude of naturally occurring processes, such as photosynthesis, humification and aggregation by changing land management is an attractive alternative to reduce GHG levels because 1) results can be achieved quickly 2) technologies for enhanced sequestration can be implemented without major economic impact and are generally associated with improved management of resources and more efficient production systems and 3) delivery infrastructure (land management programs in extension and federal agencies) is in place, proven and relatively well-funded. However, the design and implementation of policies and programs to accelerate and realize the potential of terrestrial sequestration requires analyses that examine regional land use patterns, human activity systems and economic development objectives and how they affect ecological processes.

Within the Southwest Regional Partnership area, the range in ownership and land management patterns require that outreach and education activities must be broad-based, flexible and integrated with a wide variety of federal, state and local programs. Land cover varies considerably within the partnership region, ranging from deciduous forests at the easternmost extreme to desert shrublands in the lower elevation west and coniferous forests in higher elevations. Each soil/vegetation/land management combination has a unique potential to capture and store carbon that can only be assessed within an economic and social, as well as biophysical context.

The complex combination of land use, land management and natural conditions in the Southwest Regional Partnership area offers an opportunity to examine policy, program and operational alternatives to optimize terrestrial sequestration against a background of competing land use objectives. Meeting the challenge of integrating sequestration as another land management objective into agriculture and forestry production systems will require an analytical approach that draws upon existing expertise and information as well as a combination of analytical tools.

Methods

The Southwest Regional Partnership encompasses the states of Arizona, Colorado, Oklahoma, New Mexico, Utah, and portions of Kansas, Nebraska, Texas, and Wyoming (Fig. 1). To assess the regional sequestration potential of land areas within the partnership, a framework was developed that had two distinct phases (Fig. 2). The first phase involved the use of climate, soil, land tenure, land cover, and major land resource area spatial coverages that could be incorporated into a geographic information system (GIS) in order to define areas having greatest potential for implementing carbon sequestration programs in the region. Once these areas were identified, a second phase was initiated that used the COMET VR model to assess the amount of carbon that would be sequestered under land management and conservation programs available for the region.

GIS Phase

For these analyses, the various data layers were acquired from online data sources and the datasets were classified into categories of potential to allow for spatial indexing. The data layers acquired included: 1) long-term precipitation, 2) land tenure; 3) soils, 4) land cover, 5) major land resource areas, and 5) administrative boundaries. Long-term precipitation was used to define climatic potential and was defined as precipitation amounts that would be of sufficient quantity to allow for suitable plant growth or success in revegetation. To assess climate potential, the long term average precipitation (1971-2000; Spatial Climate Analysis Service, Oregon State University, http://www.ocs.oregonstate.edu/prism/) was classified as follows: No Potential (0 to13 cm), Low Potential (13 to 23 cm), Moderate Potential (23 to 46 cm) and High Potential (>46 cm).

Land tenure was used to delineate private/non-federal, federal, and Indian reservation lands. This spatial coverage was acquired from the national atlas website (www.nationalatlas.gov). This allowed separation of land areas where carbon sequestration programs could be targeted for private/non-federal land and Indian reservations, since incentive programs will not be implemented on federal lands.

Soils data were classified based on three characteristics that influence soil carbon. These were Soil Organic Carbon (SOC), Calcium Carbonate ($CaCO_3$), and the Wind Erodibility Index (WEI). The data layers used were acquired from the Natural Resources Conservation Services (NRCS) Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) soil databases. The SSURGO data (higher resolution) were used where available. STATSGO was used to fill in areas not covered by SSURGO. SOC was classified for indexing as follows: Low (0 to 0.75%), Moderate (0.75 to 1.75%), High (1.76 to 10%) and Very High (>10%). $CaCO_3$ content was classified as follows: Low (0 to 15%), Moderate (15 to 30%) and High (>30%). The WEI was indexed as follows: Low (0 to 100 t/ha/yr), Moderate (100 to 200 t/ha/yr) and High (> 200 t/ha/yr).

The climate, land tenure, and soil data layers were intersected in the GIS to create a coverage that would allow spatial queries based on these attributes. Boundaries of interest—major land resource areas (MLRA), and counties—were also included in the GIS to allow aggregation. We identified sites where management could reliably increase soil carbon by first identifying locations with high or moderate baseline levels and then focusing on sites that have lost, through tillage practices or land conversion, a portion of that carbon. It is unlikely that we can increase soil carbon beyond that identified by soil and climate limitations, but changes in land use or management can restore soil carbon to baseline levels. These target areas were then cross indexed with the National Land Cover Data (NLCD, http://landcover.usgs.gov) to determine land cover. NLCD is a 21-class land cover classification scheme applied consistently over the US. The data were reclassified into four major classes to reflect land cover types where government programs could be implemented: Grazing Lands, Row Crops, Small Grains, and Forests. Spatial queries were then conducted to acquire the data needed by the COMET-VR model. These included acreages of each land cover category, soil textures, county, and MLRA.

COMET VR Phase

COMET-VR, an on-line interface to the Century model, was used to assess baseline carbon and management induced carbon changes in areas identified as having high to moderate potential for carbon sequestration. The COMET-VR interface allows a user to select a location (state and county), soil texture, land use history, and a proposed 10-year future management alternative.   Based on these choices, COMET-VR accesses information on climate and land use from database sources and runs the Century model. The results are calculated and presented as 10-year annual averages of soil carbon sequestration or emissions with associated statistical uncertainty values.

Areas identified during the GIS Phase that had sufficient acreage in either grazing lands, small grains, or row crops were modeled. For grazing lands, three practices were compared: continuous grazing (heavy or moderate), seasonal reduced grazing, and CRP (Conservation Reserve Program; a cropland retirement program)-grass-legume mixture (no grazing). For row crops and small grains five practices were compared: intensive tillage, reduced tillage, no-till tillage, CRP-100% grass, and CRP-grass-legume mixture. Weighted averages for carbon capture were calculated for each MLRA in order to identify MLRAs with higher sequestration potentials that could be targeted for government incentive programs.

To date, we have completed analysis for Arizona, Colorado, New Mexico and Utah. The results and interpretations for those states are discussed in the following section.

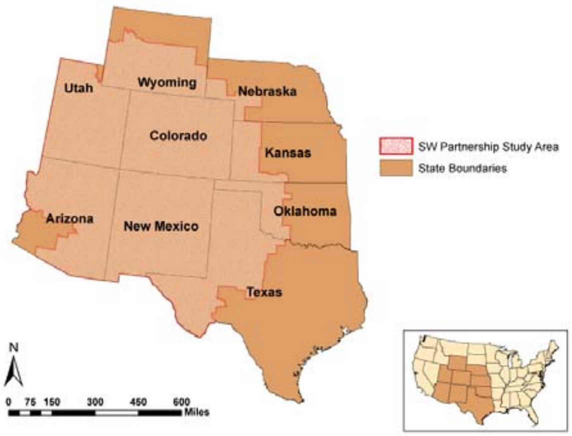

Fig. 1. Study area for assessing carbon sequestration potential in the Southwest Carbon Sequestration Partnership region.

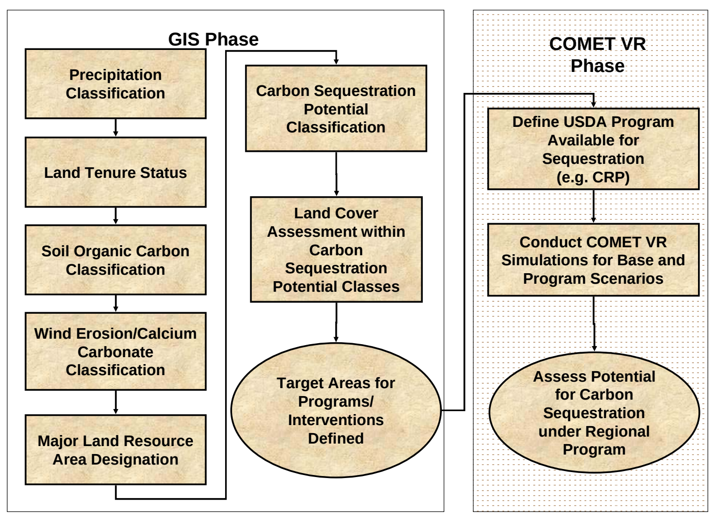

Fig. 2. Flow chart describing analysis in Phase I.

Preliminary Results

The results are presented on a state-by-state basis and are aggregations of Major Land Resource Area (MLRA) and County level information. MLRAs are geographic associations of land based on climate, topography, land use, water, soils and potential natural vegetation (http://soils.usda.gov/survey/geography/mlra/mlra_definitions.html).

Because of the unique nature of many land management decisions and their interactions with government programs, activities at the county level may restrict the amount of incentive funding that can be used influence land owners' decisions. Whenever county level limits on land use change or management are important in determining the potential for state level carbon sequestration activities, it will be noted.

Arizona

There were 2, 197, 869 hectares subjected to analysis for the potential to increase carbon storage. No county level constraints on land use change under federal programs were identified, so results will be presented at the MLRA level. The spatial distribution of MLRA is shown in Fig. 3.

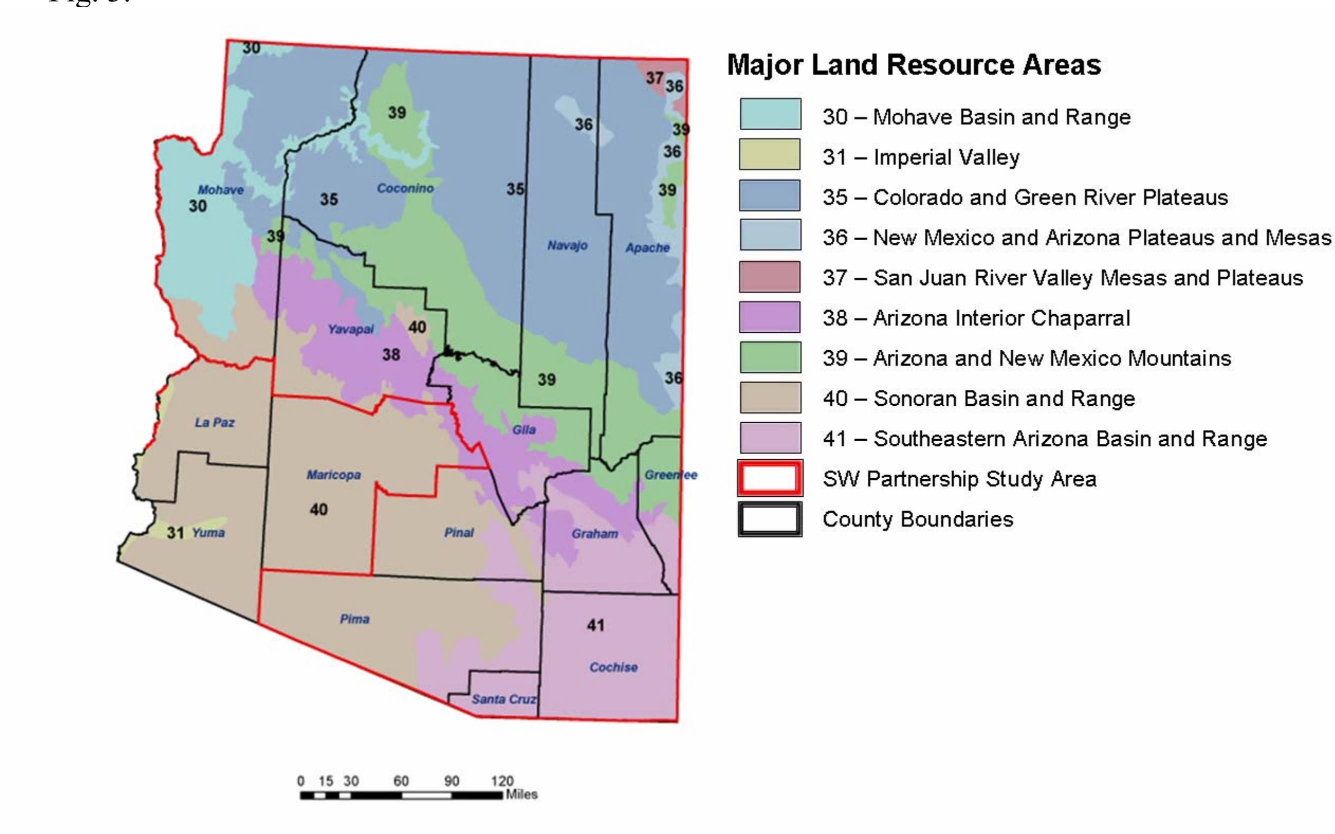

Fig. 3. Distribution of major land resource areas in Arizona.

MLRA 30, Sonoran Basin and Range (15559 ha)

The primary limitation on the potential to sequester carbon in this area is low rainfall. The dominant land use is livestock grazing at light stocking rates, and maintaining that land use will result in stable carbon fluxes within the area. Improving species composition and net primary productivity by adding legumes to existing rangeland offers the potential to increase soil carbon storage by about 0.10 T C/ha/y over a 10 year period. However, the uncertainty associated with the model applications of this land management practice is extremely high.

MLRA 35, Colorado and Green River Plateaus (965, 035 ha)

Adding a legume to existing rangeland has the potential to increase carbon storage from 0.10 to 0.25 T C/ha/y. Sandy loam soils were identified as the soils with highest potential (0.17 to 0.25) while heavier textured soils (clays) were typically below 0.10 T C/ha/y. Silty soils and clay loam soils were intermediate.

MLRA 36, New Mexico and Arizona Plateaus and Mesas (21, 093 ha)

Legume addition to existing rangelands can increase carbon storage between 0.15 and 0.24 T C/ha/y depending on soil texture. Sandy loam soils have greater potential than heavier textured clay soils. The uncertainty associated with these potential gains is extremely high.

MLRA 38, Arizona Interior Chaparral (356, 987 ha)

Legume addition to existing rangeland has the potential to increase carbon storage between 0.10 and 0.65 T C/ha/y depending on soil texture. The range in potential is similar to other MLRAs (sandy loam>loam>clay>silt). The uncertainty associated with these estimates is extremely high.

MLRA 39, Arizona and New Mexico Mountains (171, 151 ha)

Legume addition to existing good condition or degraded rangeland should increase carbon storage from 0.13 to 0.64 T C/ha/y depending on soil texture (clay loam>loam>sandy loam). However, the uncertainty associated with model outputs for this practice in these areas is extremely high.

MLRA 40, Central Arizona Basin and Range (105, 417 ha)

Potential for increased carbon sequestration in soils ranged from negligible on arid loam soils to 0.60 T C/ha/y on sandy loam soils in more mesic areas. These areas are spatially limited in extent (< 9000 ha). The model results were associated with very high uncertainty.

MLRA 41 Southeastern Arizona Basin and Range (521, 091 ha)

Adding a legume to heavily and moderately grazed rangeland would result in an increase in soil carbon storage of up to 0.34 T C/ha/y in loamy textured soils in the wetter portions of this area (Cochise and Graham Counties). Again, model results had a high level of uncertainty associated with this practice.

There are very limited possibilities for increasing carbon sequestration in Arizona soils. This analysis identified only those rangelands having a favorable climate, soils and land use change, yet the vast majority of these areas were estimated to have the potential to sequester less than 0.10 T C/ha/y. Although there were some areas with relatively fertile soils and favorable rainfall, the practices required to achieve these estimates are unreliable and not yet proven. In addition, the uncertainty associated with the model estimates that exceeded 0.2 T C/ha/y were very high.

Colorado

There were 3, 871, 478 ha subjected to the analysis described in the methods to identify areas with high potential for carbon sequestration. The results are reported by MLRA (Fig. 4).

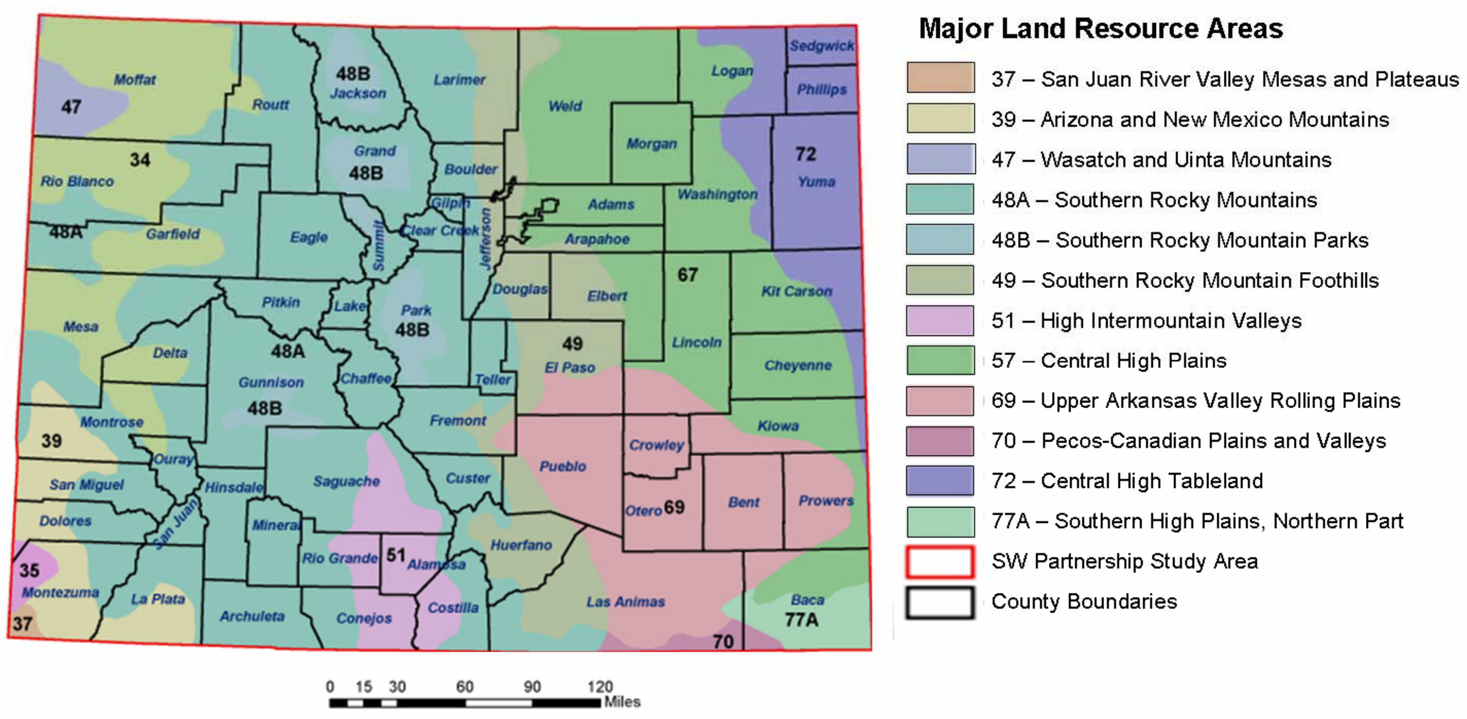

Fig. 4. Distribution of major land resource areas in Colorado.

MLRA 34 Central Desertic Basins, Mountains and Plateaus (152, 250 ha)

In general, the potential for sequestration is low throughout MLRA 34. Loamy soils in Rio Blanco and Moffat counties (108, 513 ha) have potential to sequester between 0.16 and 0.48 T C/ha/y when legumes are added to existing grazed rangelands.

MLRA 39 Arizona and New Mexico Mountains (15, 748 ha)

Sequestration potential is limited in this MLRA. Addition of legumes to existing rangelands has the potential to increase soil carbon storage 0.29 T C/ha/y on loam soils.

MLRA 48A Southern Rocky Mountains (498, 927 ha)

Rangelands on loam soils in San Miguel (23, 127 ha) and Rio Blanco (11, 112 ha) counties have the potential to increase carbon storage by 0.16 to 0.24 T C/ha/y with the addition of legumes to existing grazed rangelands. However, the uncertainty associated with these estimates is extremely high.

MLRA 48B Southern Rocky Mountain Parks (225, 868 ha)

Sequestration potential is very limited in this MLRA, typically less than 0.10 T C/ha/y. Sandy loam soils with rangeland cover in Jackson county (23843 ha) can increase carbon storage by up to 0.24 T C/ha/y with the addition of legumes to existing plant communities. This estimate of sequestration potential is highly uncertain.

MLRA 49 Southern Rocky Mountain Foothills (629, 804 ha)

There is substantial potential to increase soil carbon sequestration in MLRA 49, primarily due to the large proportion of the area in small grains. Converting small grain to perennial vegetative cover in Weld (7599 ha) and Elbert (4036 ha) counties can increase carbon storage between 1.30 and 1.60 T C/ha/y. Alternatively, adopting no-till tillage on those areas currently under conventional tillage could increase soil carbon between 0.23 and 0.66 T C/ha/y. Adopting reduced tillage would have little impact on soil carbon levels. The uncertainty associated with these estimates is relatively low (<15%). Adding legumes to currently grazed rangelands has the potential to increase soil carbon on much of the area in this MLRA by up to 0.25 T C/ha/y, but the uncertainty is extremely high.

MLRA 51 High Intermountain Valleys (32, 633 ha)

The potential for carbon sequestration is very limited in this MLRA, primarily due to the high elevation and short growing season. Addition of legumes to rangelands with loam soils could increase soil carbon levels by up to 0.14 T C/ha/y, but uncertainty is extremely high.

MLRA 67 Central High Plains (1, 568, 188 ha)

The 437,110 ha of small grains in the area offer substantial opportunity to increase carbon storage. Converting cropland to perennial cover (including legumes) in this area will increase soil carbon storage an average of 1.3 T C/ha/y. Converting to perennial grass cover without a legume would increase soil carbon uptake an average of 0.6 T C/ha/y. The uncertainty associated with these practices on these soils is relatively high, especially on silty and clay soils. Adopting no-till tillage on these acres would only slightly increase soil carbon uptake (generally <0.05 T C/ha/y). Adopting reduced tillage would not affect the soil carbon levels in this MLRA. Counties included in this MLRA are Adams, Arapahoe, Baca, Cheyenne, Elber, Kiowa, Kit Carson, Lincoln, Morgan, Prowers, Washington and Weld.

MLRA 69 Upper Arkansas Valley Rolling Plains (125, 887 ha)

Carbon sequestration potential is very limited in this area because of low annual precipitation. The greatest opportunity is in converting small grains in Lincoln County (1660 ha) to perennial cover with legumes (1.3 T C/ha/y). Adopting no-till tillage gains very little increase in carbon storage (<0.05 T C/ha/y)

MLRA 70 Pecos Canadian Plains and Valleys (19, 562 ha)

This is a relatively small area entirely within Las Animas County. Potential to increase carbon storage is limited by low annual precipitation and current land use patterns (current use is rangeland).

MLRA 72 Central High Tableland (659, 581 ha)

Converting small grain croplands to perennial vegetation cover with legumes offers the greatest potential to increase carbon storage in this area (1.1 to 1.35 T C/ha/y). There are currently 248, 149 ha of small grain cropland in Cheyenne, Kiowa, Kit Carson, Logan, Phillips, Sedgewick, Washington and Yuma counties included in this MLRA. Adopting no-till tillage offers only slight potential (<0.05 T C/ha/y). Adding legumes to existing rangelands (328, 806 ha) can increase soil carbon storage an average of 0.03 T C/ha/y, but the uncertainty is extremely high.

Many Colorado counties are near or fully subscribed under existing USDA land conversion programs (Conservation Reserve Program). In the program regulations, 25% of existing cropland enrolled in CRP was established as an upper limit. Realizing the potential carbon sequestration associated with cropland conversion to perennial cover in counties that are currently over the limit would require a change in program rules. Those counties are: Baca, Bent, Cheyenne, Crowley, Dolores, Kiowa, Las Animas, Lincoln, Moffat, Morgan, Prowers, Pueblo, Washington and Weld.

New Mexico

In New Mexico, 3, 120, 965 ha were subjected to the analysis described in the Methods section. The land was located in MLRAs 36, 39, 70 and 77D (Figure 5). Curry, Harding, Lea and Roosevelt counties are at or near the limit.

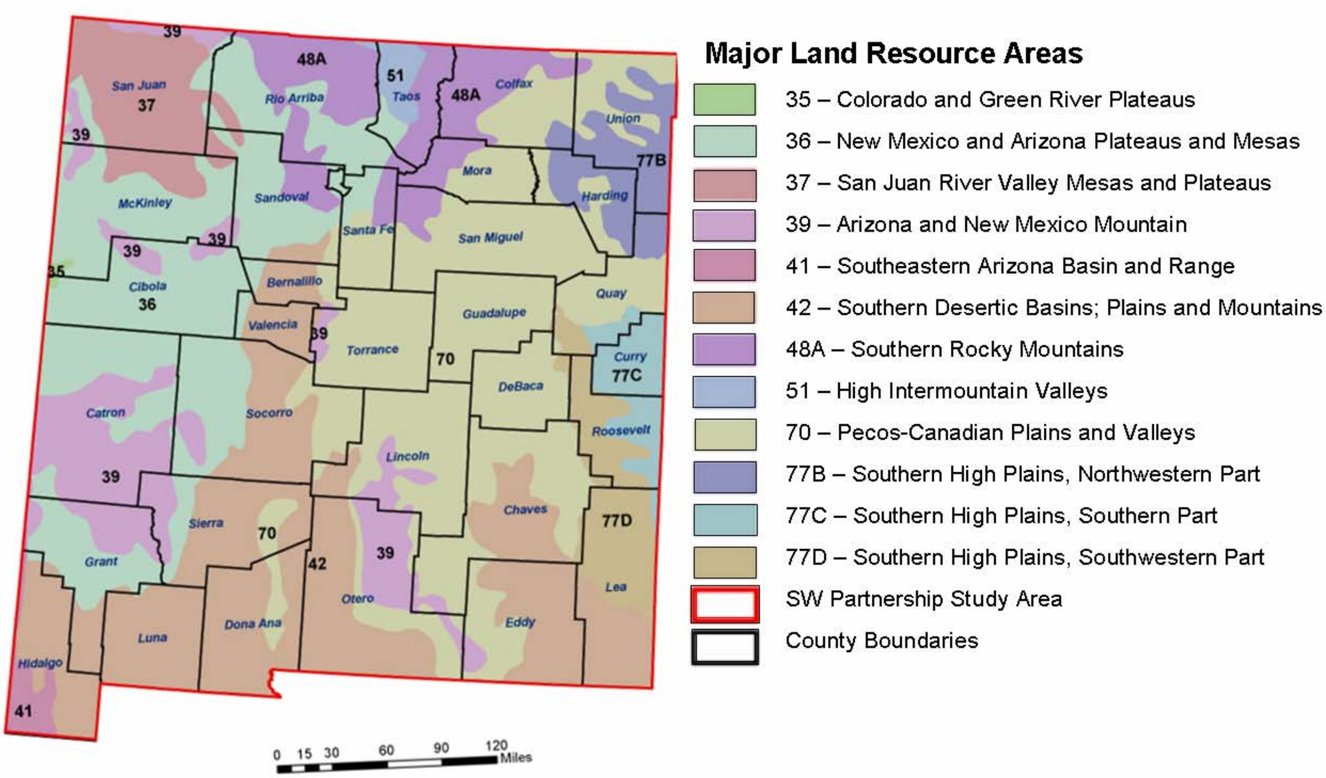

Fig. 5. Distribution of major land resource areas in New Mexico.

MLRA 36 New Mexico and Arizona Plateaus and Mesas (182, 799 ha)

Land use in this area is dominated by grazing on native rangeland. The opportunities for increasing soil carbon storage are limited. Adding legumes to existing rangeland plant communities may increase net primary productivity and soil carbon, but uncertainty is extremely high.

MLRA 39 Arizona and New Mexico Mountains (24, 140 ha)

Rangeland grazing is the dominant land use in this area and there is little potential to increase soil carbon because of the low annual precipitation.

MLRA 70 Pecos Canadian Plains and Valleys (2, 250, 308 ha)

Livestock grazing on native rangeland is the dominant land use in this area (2, 238, 157 ha) and there is little potential for increasing soil carbon due to low precipitation. Cropland with row crops, primarily irrigated corn (8677 ha) offers some potential to increase soil carbon by converting to perennial cover, but the majority of this land use is currently in corn:alfalfa rotations and only moderate increases in soil carbon (0.6 T C/ha/y) could be expected from the conversion. In addition, the majority of this land is in Quay County, which is already exceeding program limits within the Conservation Reserve Program. Adoption of reduced tillage offers little opportunity for increasing soil carbon.

Cropland with dryland small grains (3474 ha) also offers moderate potential to increase soil carbon. Converting to perennial grass cover with a legume would increase soil carbon 1.1 T C/ha/y; without legumes about half that. However, this option is currently limited because this land category is entirely within Quay Country, which is currently over the program limit for CRP. Because the crop rotation is primarily wheat:fallow, there is little opportunity to increase soil carbon by adoption of no-till tillage.

MLRA 77D Southern High Plains (663,718 ha)

Livestock grazing on rangeland is the dominant land use in this MLRA (599, 877 ha). The only land management option that consistently exceeded 0.10 T C/ha/y, although with very high uncertainty, was the addition of legumes to existing rangeland plant communities. Grazing management offered little opportunity to increase soil carbon storage.

Row crops (42, 019 ha) offer some opportunity to increase soil carbon storage, but will require changes in land use that is limited under current federal programs. Irrigated corn:alfalfa rotations (5446 ha) could be converted to perennial grass cover and increase soil carbon between 0.4 and 0.65 T C/ha/y depending on the use of legumes. Dryland cotton makes up the remainder of the row crop category (36, 573 ha). Increasing soil carbon on this land use can be achieved by conversion to perennial grass with or without legume (0.65 vs 0.4 T C/ha/y). The adoption of reduced tillage offers little opportunity to increase soil carbon on row crops in this area.

Small grain cropland (21, 823 ha), either wheat:fallow or wheat:grain sorghum rotations, have substantial potential to increase soil carbon, either through land use change or changes in tillage practices. Converting wheat:fallow rotations (10, 636 ha) to perennial grass cover with legumes could increase soil carbon by 1.1 T C/ha/y. Converting wheat:milo rotations would sequester about half that amount. Adopting no-till tillage on wheat:milo rotations could sequester 0.14 T C/ha/y, while no-till tillage on wheat:fallow rotations could increase soil carbon by 0.05 T C/ha/y.

A substantial barrier exists to achieving high rates of sequestration in the MLRA. All of the row crop and small grain cropland is located in Lea, Roosevelt and Quay counties. All of these counties are already at or near participation limits in the Conservation Reserve Program. A more effective strategy to reduce emissions might be to increase incentives to keep land with expiring CRP contracts (10 years in length) enrolled in the program. There are currently more than 3500 ha of land enrolled in CRP on which contracts will expire in 2005 or 2006.

Utah

Major Land Resource Areas within Utah (see Fig. 6) that were identified as having land with high carbon sequestration potential were:

25 Owyhee High Plateau (84, 123 ha)
28 Great Salt Lake Area (982, 805 ha)
34 Central Desertic Mountains, Basins and Plateaus (119, 357 ha)
35 Colorado and Green River Plateaus (28, 135 ha)
39 Arizona and New Mexico Mountains (64, 887 ha)
47 Wasatch and Uinta Mountains (423, 406 ha)
48 Southern Rocky Mountains (43, 609 ha).

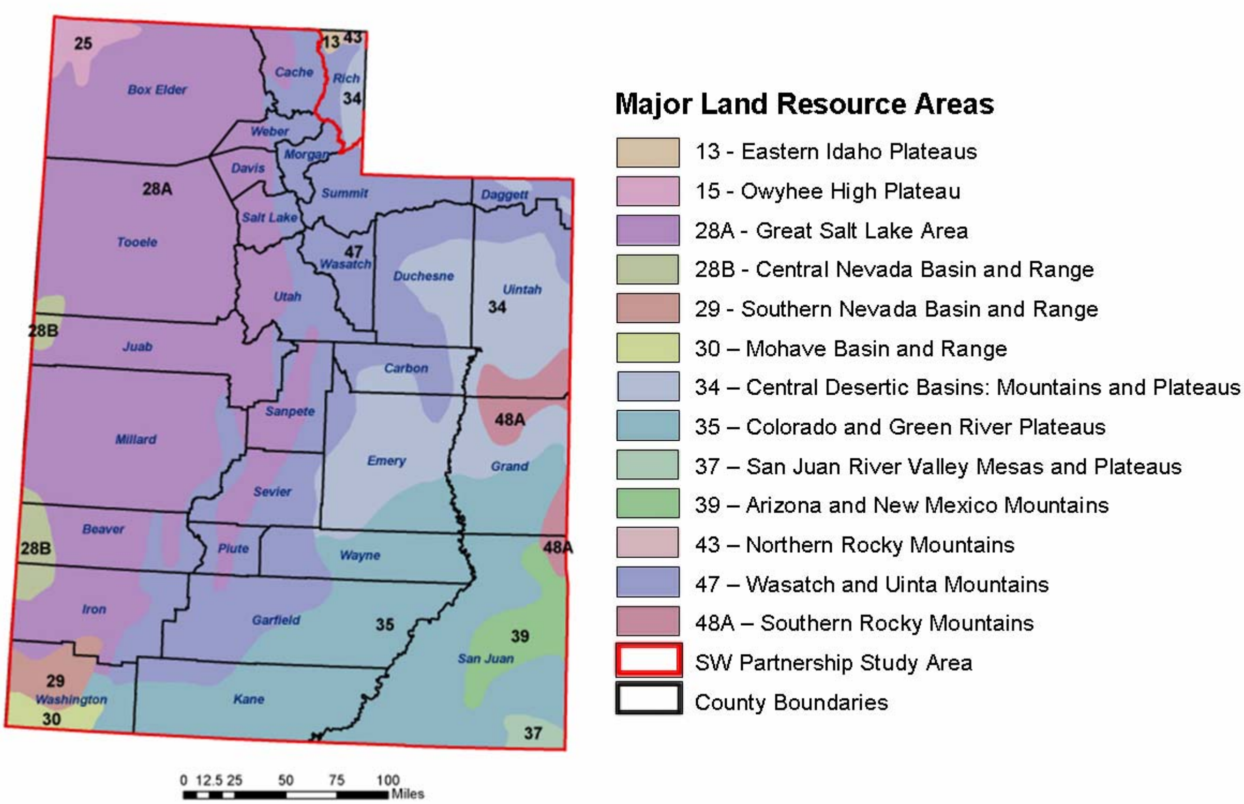

Fig. 6. Distribution of major land resource areas in Utah.

Regardless of soil and land form classification, the low annual precipitation was the overriding factor limiting response to management in all of the MLRAs. Only the addition of legumes to existing rangeland livestock grazing systems were identified has having a positive effect on soil carbon storage (generally 0.10 to 0.20 T C/ha/y). However, this practice is associated with very high uncertainty.

Summary

The four states analyzed thus far, Arizona, Colorado, New Mexico and Utah, have relatively limited potential to sequester carbon in terrestrial systems. The lack of precipitation in these arid areas was the primary limiting factor. However, the vast amounts of land with small per hectare potential could result in a substantial amount of carbon sequestration if there is a broad-based effort to realize this potential. By far, the most attractive opportunities can be found in the eastern sections of Colorado and New Mexico, where rainfall is higher and soils more fertile. The conversion of cropland and/or adoption of reduced tillage in these cropland systems should sequester carbon at a rate that is approaching the values (0.5 to 1.0 T C/ha/y) touted by private market developers.

The remainder of the analysis, in the more mesic eastern portion of the region, should yield much greater opportunities for all types of land management to improve carbon storage via land management.

Section 3: Integrated Assessment Initial Results[1]

Overview

The Integrated Assessment team developed a dynamic simulation computer model to help interested parties understand the potential screening criteria necessary to develop a carbon sequestration project. The screening criteria include geologic considerations for underground storage of carbon dioxide (CO_2), the relative size of the CO_2 flow from the source to the sink, and the associated economics with the system.

With these screening criteria, the test case model has successfully been used to bring together participants across the Southwest Regional Partnership (SRP). Workshops with the collective participation of the SRP provided feedback regarding the model's framework, and allowed for the multidisciplinary team to begin thinking about where the important aspects of such a project may lie (e.g., the geological science, the industry collaboration, the public involvement) and how the SRP could address these aspects in subsequent analytical efforts.

The methodological framework developed for the integrated assessment was first applied to four power plants in New Mexico and several geologic sinks in the San Juan Basin as a test case for the framework. Using this framework, the Integrated Assessment team then developed a

---

[1] Part 3 of the Fourth Semiannual Report draws from the following select SAND documents and meetings as part of the Southwest Regional Partnership on Carbon Sequestration Integrated Assessment efforts, and serves as the basis for future Integrated Assessment:

- Peter H. Kobos, David J. Borns, Len A. Malczynski and Orman H. Paananen. (2005). Southwest Regional Partnership on Carbon Sequestration: A Test Case Model in the San Juan Basin Sandia National Laboratories, Poster Presentation at the Fourth Annual Conference on Carbon Capture & Sequestration May 2–5, 2005 Alexandria, Virginia. SAND2005-2481C.
- Peter H. Kobos, David J. Borns, Leonard A. Malczynski, and Orman H. Paananen. (2005). The Southwest Regional Partnership on Carbon Sequestration: Employing the Integrated Assessment Model for Systems Insight. SAND2005-4902C and Proceedings of the 25thAnnual North American Conference of the USAEE/IAEE, September 19–21, 2005, Denver, CO.
- MIT Carbon Sequestration Forum VI: Taking Stock of CO_2 Capture & Storage. Royal Sonesta Hotel, Cambridge, MA, November 3–4, 2005.
- Coupling MMV to Models and Risk Assessment: Developing the Integrated Assessment Model Based on the Input from Experts. (2005). Discussions at MMV Workshop for SW Partnership, November 17, 2005, NMT Building, Albuquerque, NM.Peter H. Kobos, Leonard A. Malczynski and David J. Borns. (2005) The Integrated Assessment Overview. Southwest Regional Partnership on Carbon Sequestration Project Kick-off Meeting, New Mexico Institute of Mining and Technology Socorro, NM, December 15–16, 2005. SAND2005-7906P.

path forward towards characterizing the whole state of New Mexico, and laying the groundwork to cover additional regions both within the Partnership, and beyond where appropriate. The initial findings suggest that the capture costs at the power plant for CO_2 may comprise a large component of the systems costs, but Measurement, Monitoring and Verification (MMV) costs could change the overall system's cost balance depending upon the length of time the sinks are to be monitored.

The Integrated Assessment Model

The Southwest Regional Partnership on Carbon Sequestration Integrated Assessment Model is a high level, dynamic simulation model that is meant as a learning tool for policy makers and members of the public who would like to understand some of the implications for future energy demand and the potential corresponding stationary CO_2 sequestration options. Figure 7 illustrates that the majority of the stationary CO_2 emissions from a few states within the SRP were from utility (electricity generation) sources, while smaller amounts were from other non-utility sources.

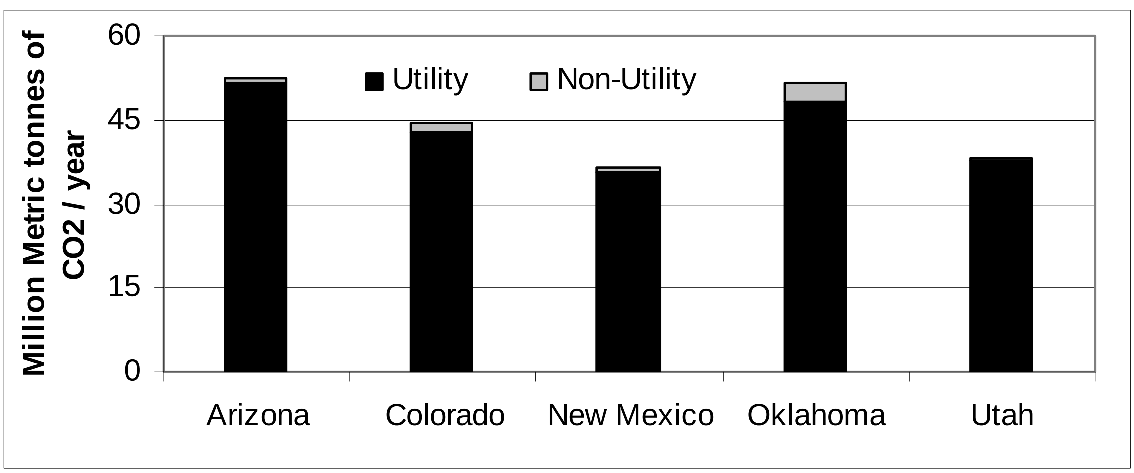

Fig. 7. Most of the carbon dioxide emissions in 2000 that occurred in the states shown were from electricity generation (EPA, 2005).

The modeling team decided to focus on electricity production by utilities from coal and gas fired power plants as a point source for CO_2 emissions for the initial test case model framework. The test case region focused on the San Juan Basin in northwestern New Mexico and southeastern Colorado.

The Integrated Assessment model team worked closely with the geologic sinks, physical infrastructure, and sources teams to characterize the power plants and geologic sinks, and the costs associated with sequestration options in the test case. Sources were characterized by accounting for their annual CO_2 emissions and other select attributes. Sink characterization included location, depth, volume, relative risk of leaks (based on geologic features), and other select features. The distances between sources and sinks were calculated using a great circle distance (GCD) formulation.

The model structure allows the user broad flexibility in changing key assumptions, and the base case assumptions were developed from the topical experts of the SRP and information drawn from the literature. The test case cost equations for CO_2 separation and capture at the source were developed using historical power plant data from the 2002 version of the Emissions and Generation Resource Integrated Database (eGRID), and the Integrated Environmental Control Model (IECM) (EPA, 2005; CMU, 2004).[i] The Integrated Assessment Model employs transport and injection equations for storage based on the relevant literature, and they were assessed by members of the physical infrastructure and sources team (Ogden, 2002, Williams, 2002, Hirl, 2004).[ii] The model develops prototype cost algorithms for the Integrated Assessment model from this information. Figure 8 depicts the overall structure of the modeling effort, and Fig. 9 illustrates the stages of the test case model.

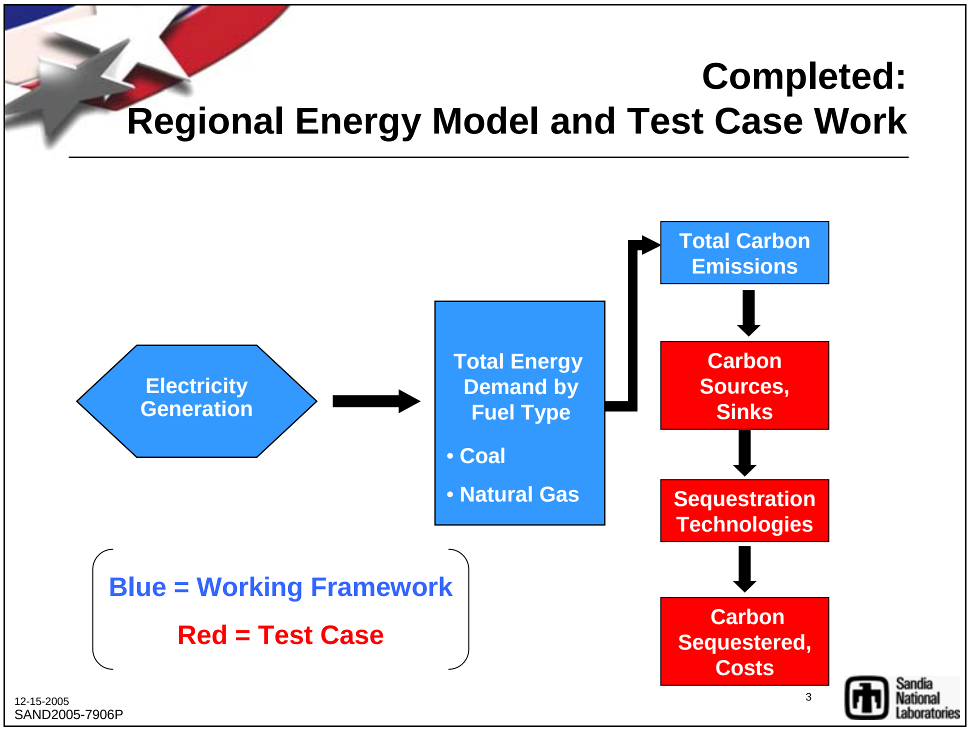

Fig. 8. Schematic of the Integrated Assessment Model's overall structure.

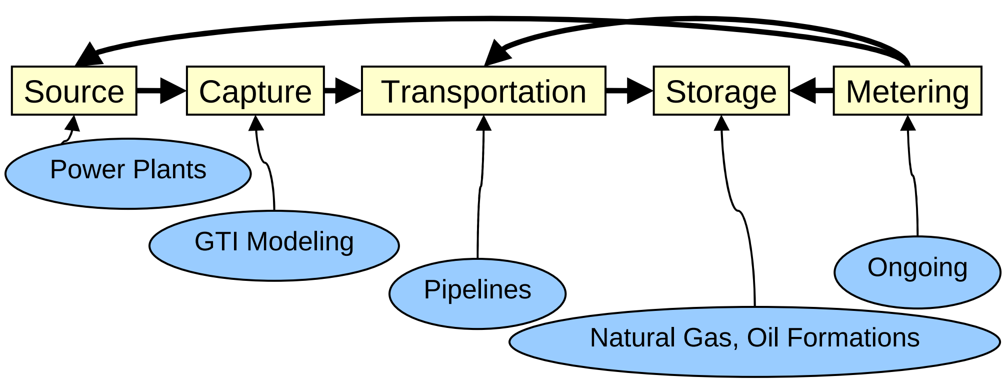

Fig. 9. Schematic of the CO_2 pathway in the Southwest Regional Partnership on Carbon Sequestration Integrated Assessment Model.

The basic framework allows interested parties to assess different regional sequestration options for CO_2 emissions sources, and to evaluate the total CO_2 emissions in the region. The model has an additional role to help the public gain insight to the tradeoffs between different sequestration strategies by providing opportunities to perform "what if" analyses of different approaches to CO_2 sequestration.

Four workshops/meetings and several web-based conferences have been held, involving individuals from the electric power industry and state regulatory agencies.[iii] Members of the Integrated Assessment team presented aspects of the test case model at the third and fourth annual Carbon Capture and Sequestration conferences, and attended the MIT Carbon Sequestration Forum VI to further expose the analysis for additional vetting and professional feedback (Paananen, 2004; Kobos et al., 2005a). The model's analytical capabilities and interface development process incorporated the feedback from the workshops and conferences to help guide the ongoing development of the Integrated Assessment Model.

Test Case: Initial Integrated Assessment Model Framework

Four CO_2 emissions sources—all electric power plants—were selected from the Emissions and Generation Resource Integrated Database (eGRID) for the test case.[iv] Power plant capacity ranges from approximately 13 megawatts (MW) to 2300 MW. Seven geologic sinks have been identified in the test area by the Geologic Sinks Team. The variable inputs to this dynamic simulation model (largely an illustrative tool) include the percentage of CO_2 captured from the four power plants. The Integrated Assessment aligns the CO_2 emissions from the four power plants with the seven sinks to calculate sink lifetime given these conditions. The criteria for test case sink selection included those that are ≥ 3000 feet deep, have desirable geological characteristics (e.g., low chance of CO_2 escaping into surrounding strata or the surface), and are within varying distances from the power plant(s) used in the test case analysis.[v]

The CO_2 sources and sinks selected for the model test case result in many combinations of potential sequestration actions, with associated sequestration rates and capital, operation and maintenance costs. These combinations provided the initial high-level "what if" analysis opportunities for sequestration in the test case area. Figure 10 shows the locations of the power plants and the geologic sinks in the test case area.

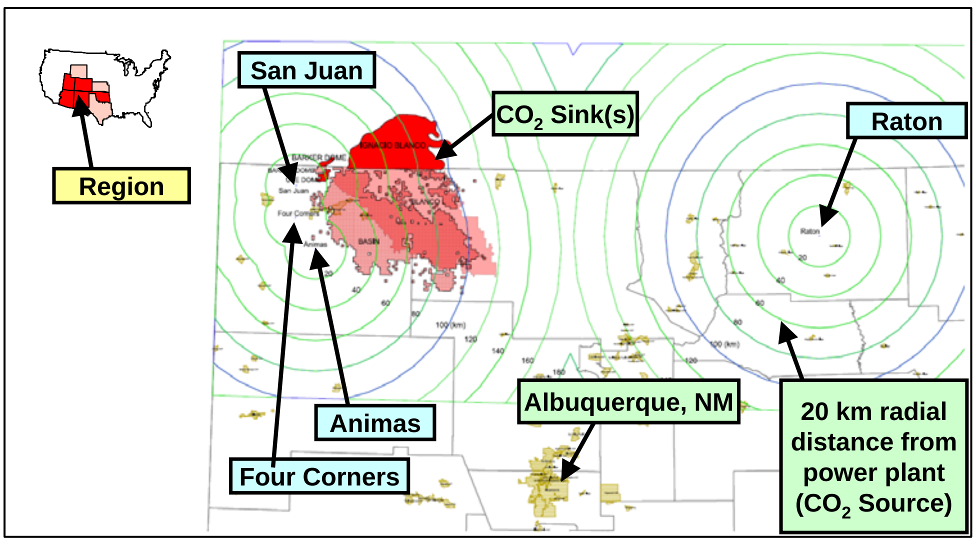

Fig. 10. Test Case Region for the Southwest Regional Partnership on Carbon Sequestration Integrated Assessment Model.

Figure 11 illustrates the summary screen model interface for the test case's base case results.[vi] The summary screen offers the base case scenario results that include the lowest total capture, pipeline transport and well-associated costs (upper left-hand graph), the kilometers (km) to the sink used for the base case within the test case region (upper right-hand graph), the overall lifetime of the sink selected (lower left-hand graph), and the annual amount of CO_2 captured at each plant (lower right-hand graph).

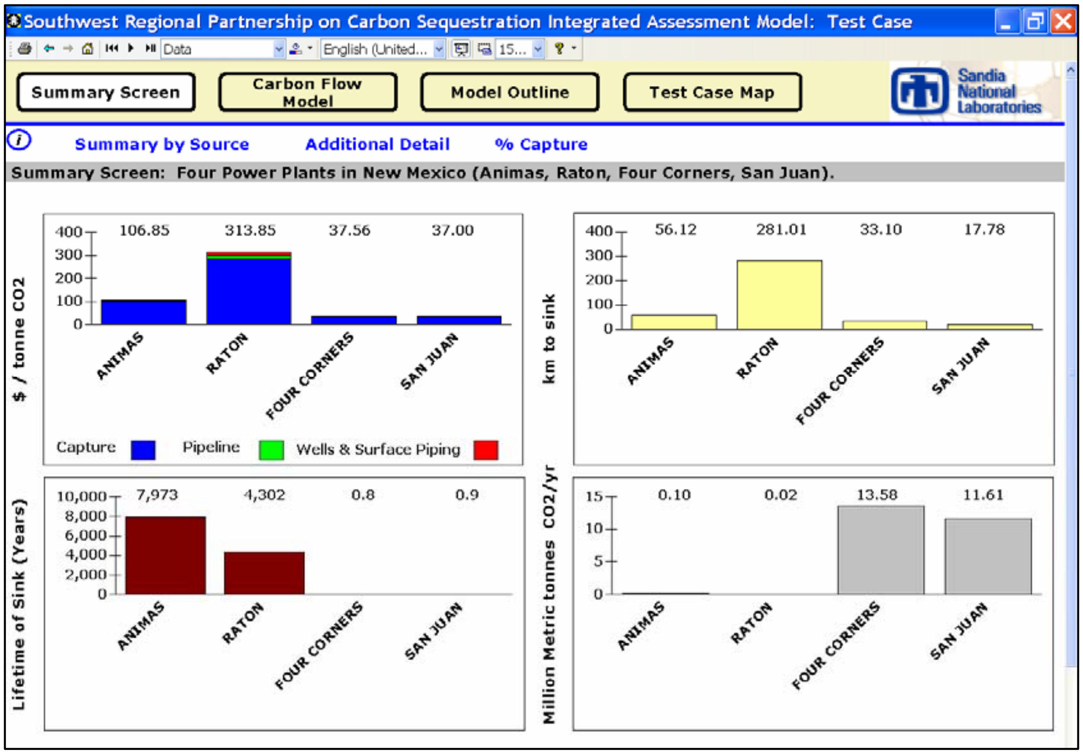

Fig. 11. Base Case results, Integrated Model summary screen interface.

The capture costs for CO_2 at the Animas, Raton, Four Corners and San Juan power plant sites represents 94, 91, 93 and 95 percent of the total capture, transport and injection cost total for each of the base case systems, respectively.[vii] The model calculates all of the illustrative cost and CO_2 flow combinations between the four power plants, and the seven geological sequestration sites, and ranks them from lowest to highest.

Discussion

This section discusses the test case model's sensitivities and provides several examples of additional work both underway and to be completed as appropriate for the larger analysis. The initial observations are listed below.

Model Results are Sensitive to Carbon Capture Percentage

The model results are sensitive to the percentage of CO_2 captured from the power plants. Based on the results of the IEGM model, several levels of percent CO_2 captured illustrate the affects on the dollars per tonne of CO_2 ($/t$CO_2$) and annual amount of CO_2 captured. The cost to capture additional CO_2 increases as the percentage captured at the plant decreases. The costs for the overall systems, driven largely by the capture costs under the current working results, are high because the test case uses existing plants to calculate capture costs from the IECM. A recent study reports carbon capture costs may range from approximately 15 $/t$CO_2$ for integrated gas combined cycle plants to 30 $/t$CO_2$ for pulverized coal facilities (DOE/EPRI, 2000).

Amount of Carbon Dioxide Accounted for in the Test Case is Small Relative to the Total for the Region

To add perspective to the regional aspects of the project, Fig. 12 illustrates the total CO_2 stationary source emissions for the Southwestern Region of the U.S., the state of New Mexico, and the four initial test case power plants. The four power plant-based test case analysis represents only 11 percent of the region's total, and 69 percent of those from New Mexico (EPA, 2005).

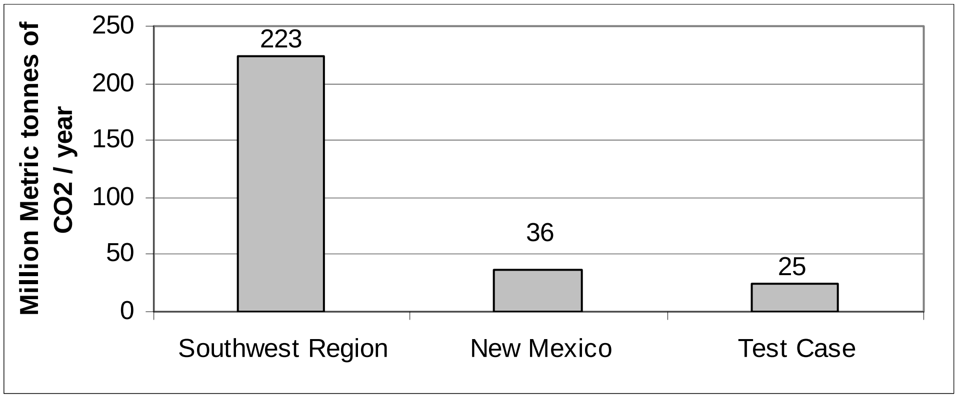

Fig. 12. Stationary CO_2 emissions in 2000 for the Southwest Region, New Mexico, and the Base Case of the Integrated Assessment Test Case Model. (Note: "Southwest Region" is the sum of Arizona, Colorado, New Mexico, Oklahoma and Utah, (EPA, 2005)).

Additionally, several states within the SRP have net exports of electricity. The states of Arizona, New Mexico, Oklahoma and Utah, for example, exported approximately 26, 41, 3 and 30 percent of their electricity outside of the state's borders in 2000, respectively (EIA, 2005).[viii] This poses both a modeling, and more importantly policy challenge as to how and who will be held responsible for CO_2 emissions in a carbon-constrained world; the electricity producers or the users. Figures 13 and 14 illustrate the installed megawatts and the corresponding CO_2 emissions within the selected Southwestern states.

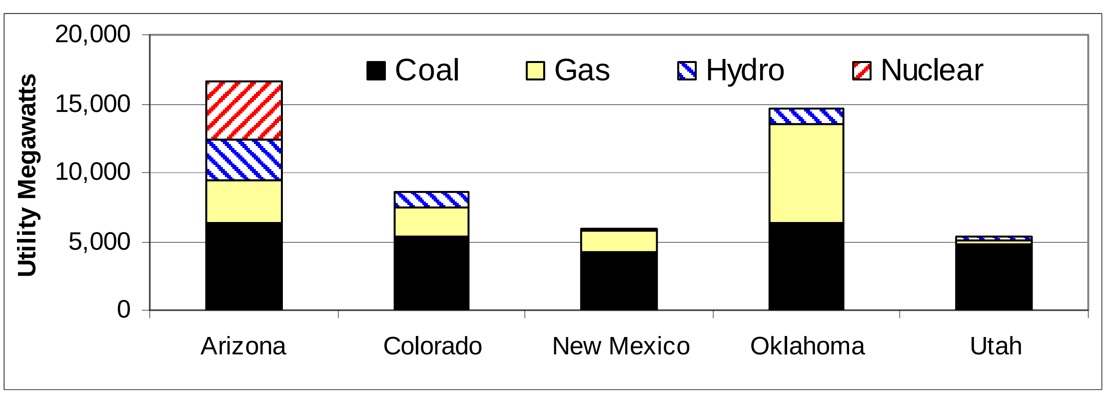

Fig. 13. Utility-based installed megawatts in the southwestern United States in 2000 (Note: oil-based and other fuels represented 2% or less of the total installed MW) (EPA, 2005).

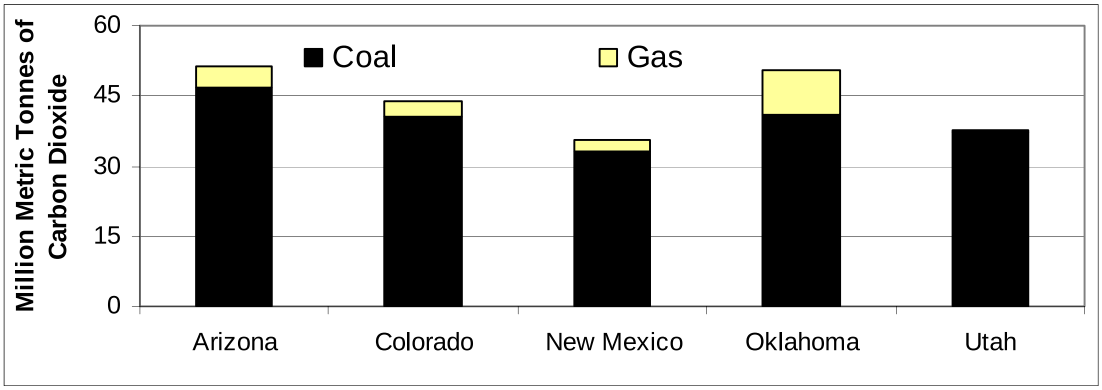

Fig. 14. Million metric tonnes of CO_2 emissions from utilities in the southwestern United States in 2000 (Note: oil-based and other fuels represented 1% or less of the total CO_2 emissions) (EPA, 2005).

The "String of Pearls" pipeline network tool in the Integrated Assessment Model

The Integrated Assessment team expanded the initial test case model to include all New Mexico sinks and sources in a new, revised prototype model in the latter half of 2005. The model calculates the distance to transport CO_2 from the source to the closest sink to be utilized. An algorithm was developed to calculate a route of pipelines from the source of CO_2 (e.g., power plant) to each of the geologic sinks and then to calculate the total distance (and eventually cost) of the pipelines (Stephens, 1998). These sinks are used in such a way that as each one fills to capacity the transportation network extends to the next viable sink, and then to the next to eventually develop a pipeline network system. This allocation mechanism, or "String of Pearls" concept, is also known as a minimal spanning tree approach. The links between all combinations of the source to various sinks are the potential pipeline routes. This technique serves as a linear proxy for pipeline length, and lays the groundwork for future, additional "String of Pearls" analysis throughout both the Southwestern Regional Partnership area in the United States, and other regions interested in carbon capture and sequestration analysis. With this technique, the model could address additional metrics (e.g. lowest overall cost, largest sink volume, etc.) for systems insight. Figure 15 illustrates a prototype pipeline route within the Integrated Assessment Model.

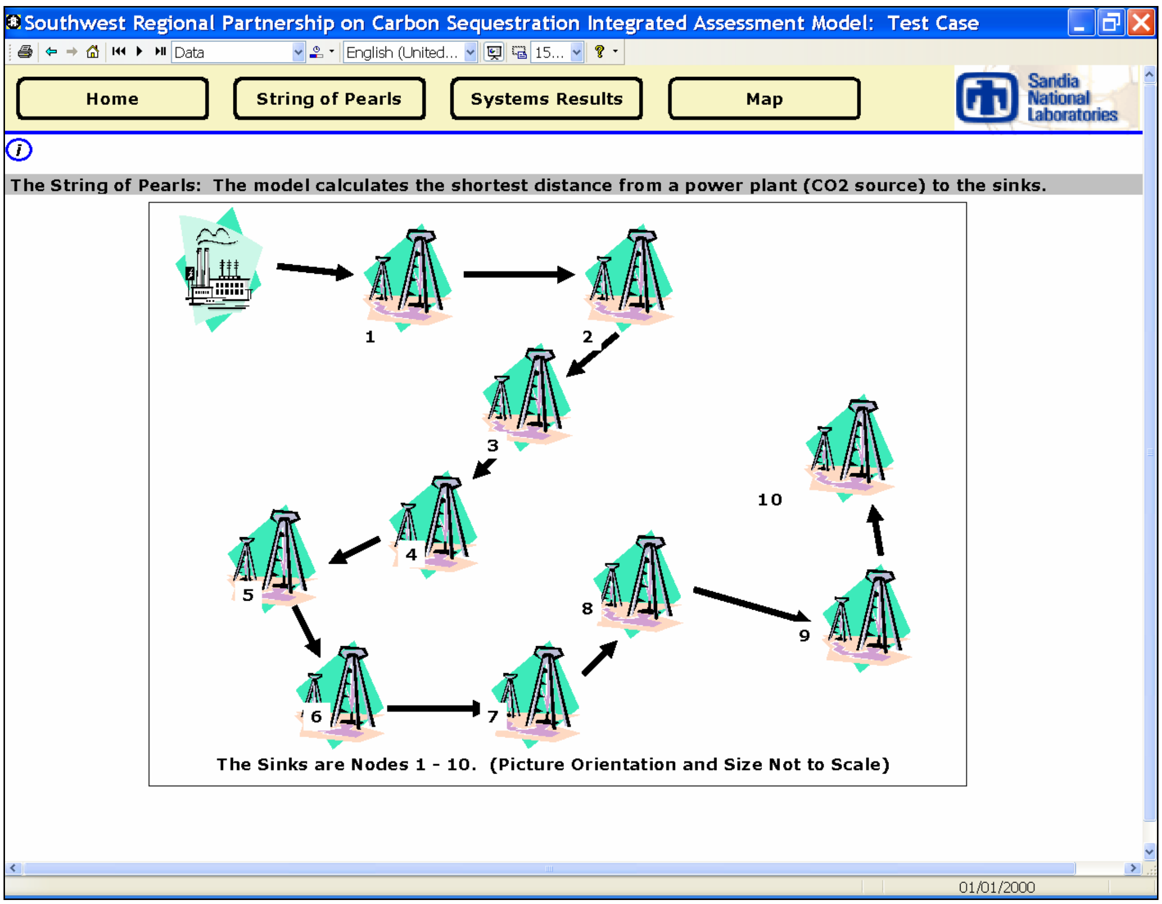

Fig. 15. Illustrative “String of Pearls” network showing the least distance solution to allocate CO_2 between sinks from a point source.

The “String of Pearls” model builds on the original test case model that involved four power plants and seven geological sinks in New Mexico. The larger “String of Pearls” model now includes four coal-fired power plants, six gas-fired power plants, and 29 geological sinks in New Mexico. The prototype “String of Pearls” model now can determine the source sink distances and associated economics (various components remain to be refined) for any of the source-sink combinations between these 10 power plants and the 29 geological sinks. The prototype model as of December 2005 can illustrate up to the top 10 closest sinks to any of the 10 power plants. Additionally, the model now includes high-level MMV costs based on Benson et al. (2004) of approximately \$0.16 to \$0.31 per tonne of CO_2 to begin assessing how these costs will affect the overall system's economics. Figure 16 illustrates the source and sink input options on the left and right of the graphic, respectively.

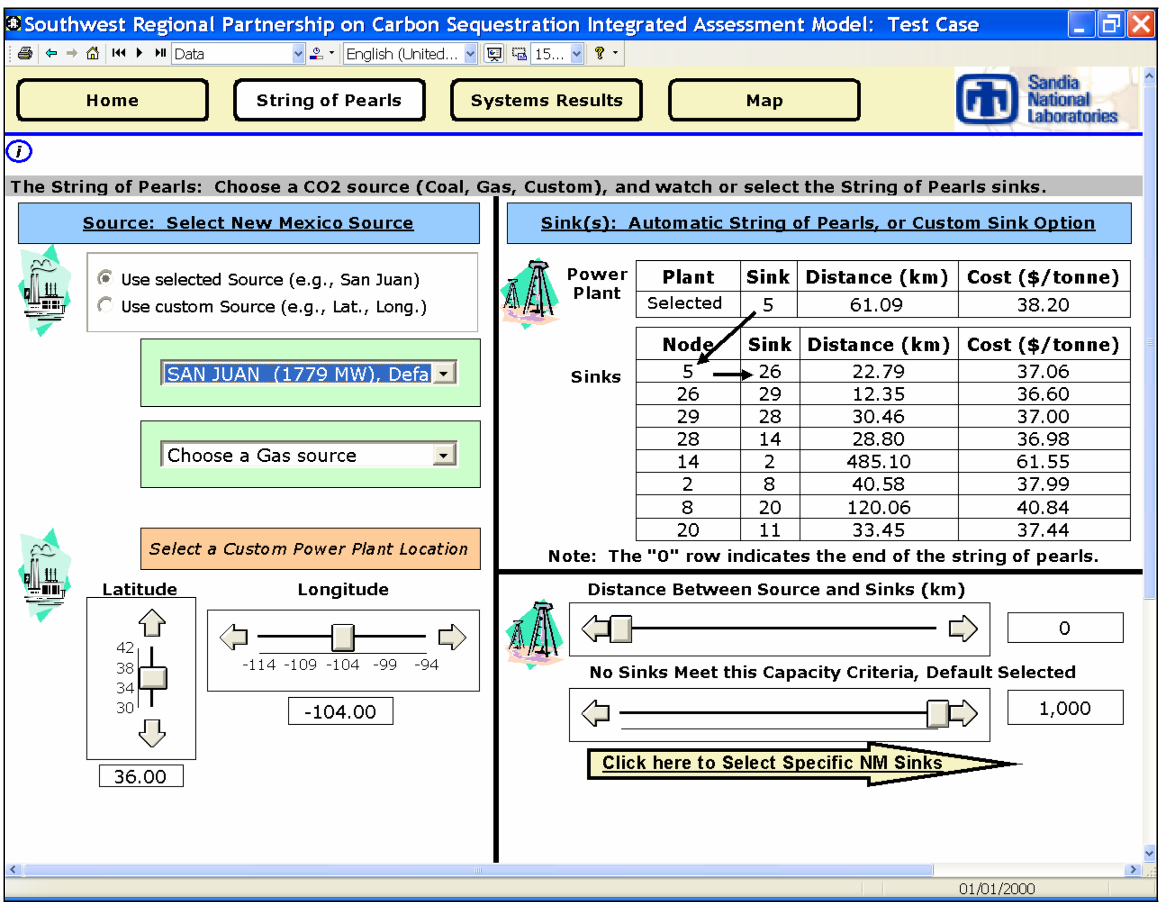

Fig. 16. Illustrative "String of Pearls" network showing the prototype least distance solution to allocate CO_2 between sinks from a point source.

The prototypic, illustrative results of Fig. 16 indicate that using the San Juan power plant, the "String of Pearls" algorithm determined that the sink categorized as number 5 is the closest to the power plant. The closest sink to sink number 5 amongst all the remaining 28 sinks is sink number 26, and so on. The user may also select sinks that are within a certain distance from the source, sinks that are of at least a certain capacity, or the specific sinks the "String of Pearls" algorithm should consider. Finally, the user is able to select a "custom" location for a power plant by specifying the latitude and longitude coordinates of the power plant. Figure 17 illustrates a map of the CO_2 sources and sinks considered in the "String of Pearls" prototype model for New Mexico.

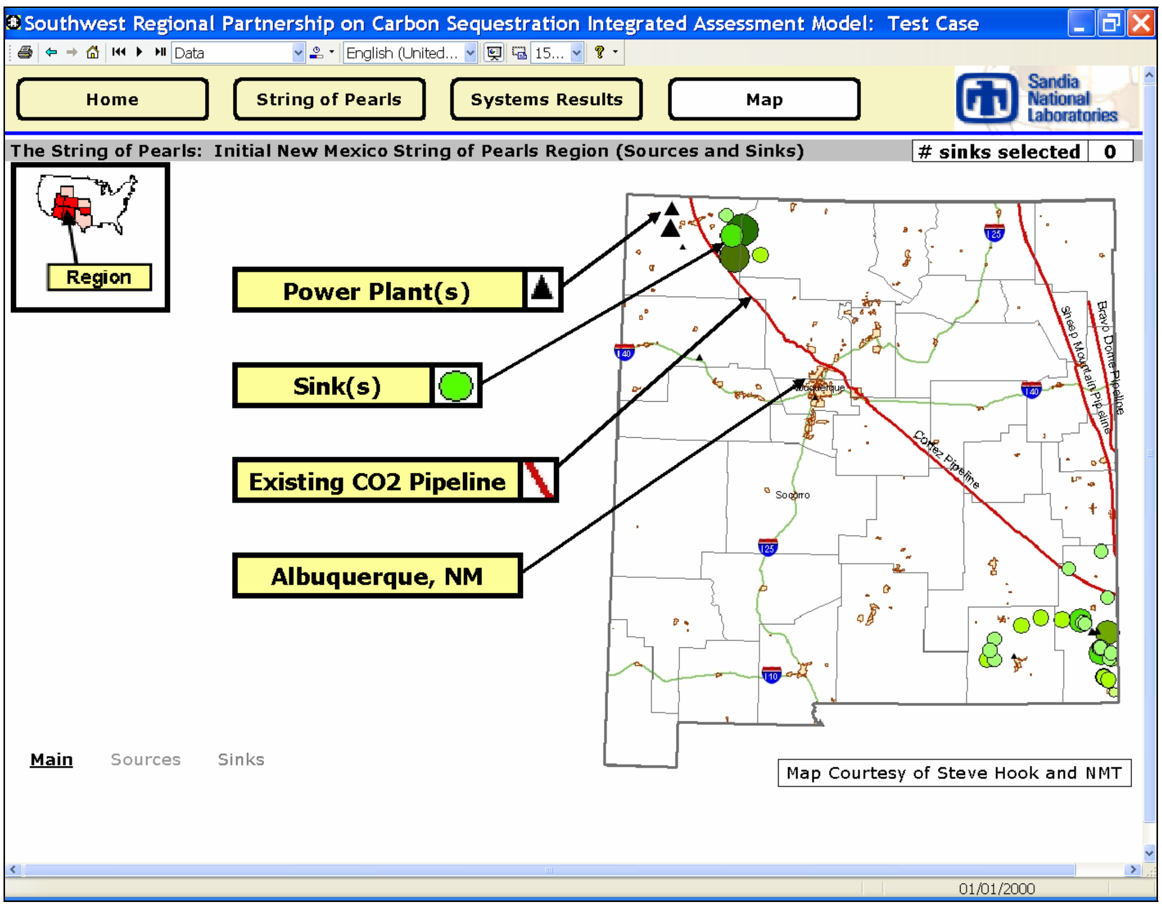

Fig. 17. Map of the CO_2 sources (power plants) and geological sinks considered in the "String of Pearls" prototype model for New Mexico.

Potential Future Modeling Efforts

The Integrated Assessment Team will address the larger region covered by the Southwest Regional Partnership beyond the initial "String of Pearls" model for New Mexico. As the data develops for both the sources and the sinks from the Southwest Partnership's several thematic committees, the Integrated Assessment team will include it in the "String of Pearls" model. The model will also address additional developing Measurement, Monitoring and Verification (MMV) cost metrics, evolving system economics, and suggestions from the larger Southwest Partnership body of participants.

Additionally, the Southwest Regional Partnership on Carbon Sequestration has proposed a Phase 2 program that would carry out several field pilot tests to validate the most promising sequestration technologies and infrastructure concepts in the region. The Integrated Assessment Model may include metrics and information for these pilots as appropriate to continue to develop a "systems view" of the Southwest Regional Partnership's full analytical scope. The Integrated Assessment Model will continue to play an important role in the Southwest Regional Partnership outreach and education plans in Phase 2, with a focus on mediated modeling. Potential future meetings or web-based meetings are planned in order to demonstrate the working "String of Pearls" model to members of the Southwest Partnership, including the Phase II project kickoff meeting December 15–16 in Socorro. This will allow additional participants provide suggestions for model improvements and extensions, based on their interests and concerns about CO_2 sequestration, leading to an integrated model that is constructed collaboratively with the interested public. Finally, the Integrated Assessment Team will address risk issues as they relate to costs, MMV, and related topics. Specifically, the analysis will address levels of economic risk (e.g., what are the price thresholds for projects to move forwards and/or continue), performance risk (e.g., how might the plant (CO_2 source) life affect the CO_2 volumes captured and sequestered), and address what leak rates might be to integrate this information with MMV issues where appropriate.

Acknowledgements

The authors wish to thank the National Energy Technology Laboratory (NETL), Brian McPherson (New Mexico Institute of Mining and Technology), Stephen Hook (New Mexico Institute of Mining and Technology), Barry Biediger (Utah Automated Geographic Reference Center (AGRC)), Howard Meyer (Gas Technology Institute (GTI)), and collaborators from Los Alamos National Laboratory, the University of Utah, and other colleagues within the Southwest Regional Partnership on Carbon Sequestration.

---

[i] IECM calculations performed by Howard Meyer at the Gas Technology Institute (GTI).
[ii] Based on the Ogden (2002) model of CO_2 disposal costs for CO_2 sequestration, Williams (2002) develops the general framework where the cost of CO_2 disposal is a function of the cost of the pipeline transmission (C_{PT}) + the cost of disposal wells (C_{DW}) + the cost of surface piping near the disposal wells (C_{SP}).
[iii] 1st Workshop, March 25 – 26, 2004, Salt Lake City; CO_2 Sequestration Integrated Model Workshop, April 20 – 21, 2004; 2nd Workshop, June 8 – 9, 2004, Albuquerque, NM; 3rd Workshop, January 11 – 12, 2005, Albuquerque, NM; Web-based conferences, various, October – December, 2004; 4th Workshop/Phase II Kickoff meeting, December 15 – 16, 2005, Socorro, NM.
[iv] Emissions and Generation Resource Integrated Database (eGRID), EPA (2005).
[v] Members within the Carbon Dioxide (CO_2) Sources and Sinks thematic committee (notably Stephen Hook, Genevieve Young, and colleagues at Los Alamos National Laboratory) evaluated the sinks within New Mexico and Southern Colorado, and selected seven geological sites with sequestration potential for the illustrative test case model.
[vi] Model prototype version as of July, 2005.
[vii] The model can incorporate additional cost information beyond the working levelized costs as new information become available.
[viii] Colorado imported approximately 4% of its electricity in 2000 (EIA, 2005).

CONCLUSION

Progress during this period was focused in the three areas that were presented in the Results and Discussion section of this Semiannual Report: geological carbon storage capacity in New Mexico, terrestrial sequestration capacity for the project area, and the Integrated Assessment Model efforts.

In New Mexico, 507 Permian Basin pools, or reservoirs, and 80 San Juan Basin pools were identified as potential CO_2 sinks. Each of these pools was assigned a unique number, usually the state mandated Oil Conservation Division (OCD) number, and entered into the modified GASIS database. Further, the names and exact locations of all these pools have been entered into a GIS database so that their spatial relationships to each other, the power plants, population centers, geographic grids, etc. can be portrayed in Arcview (a desktop GIS software package that is written and marketed by the Environmental Systems Research Institute, Inc). Several major sources of data were used to obtain the detailed information for the GASIS Database, whose search engine was modified to find pools that met or exceeded ten key criteria, including specified distance from power plants, thickness, porosity, cumulative production, and depth. Blanco Mesaverde (which extends into Colorado) and Basin Dakota Pools were chosen as top two choices for the further analysis for CO_2 sequestration in the system dynamics model preliminary analysis.

Terrestrial sequestration capacity analysis showed that the four states analyzed thus far (Arizona, Colorado, New Mexico and Utah) have relatively limited potential to sequester carbon in terrestrial systems, mainly due to the aridity of these areas. However, the vast amounts of land with small per hectare potential could result in a substantial amount of carbon sequestration if there is a broad-based effort to realize this potential. Better opportunities can be found in the eastern sections of Colorado and New Mexico, where rainfall is higher and soils more fertile.

The Integrated Assessment team developed a dynamic simulation computer model to help interested parties understand the potential screening criteria necessary to develop a carbon sequestration project. The screening criteria include geologic considerations for underground storage of carbon dioxide (CO_2), the relative size of the CO_2 flow from the source to the sink, and the associated economics with the system. The modeling team decided to focus on electricity production by utilities from coal and gas fired power plants as a point source for CO_2 emissions for the initial test case model framework. The test case region focused on the San Juan Basin in northwestern New Mexico and southeastern Colorado. Four power plants and seven geologic sinks were selected for the test case. The CO_2 sources and sinks selected for the model test case result in many combinations of potential sequestration actions, with associated sequestration rates and capital, operation and maintenance costs. These combinations provided the initial high-level "what if" analysis opportunities for sequestration in the test case area. The model calculated all of the illustrative cost and CO_2 flow combinations between the four power plants, and the seven geological sequestration sites, and ranked them from lowest to highest.

The Integrated Assessment team expanded the initial test case model to include all New Mexico sinks and sources in a new, revised prototype model in 2005. The model calculates the distance to transport CO_2 from the source to the closest sink to be utilized. An algorithm was developed to calculate a route of pipelines from the source of CO_2 (e.g., power plant) to each of the geologic sinks and then to calculate the total distance (and eventually cost) of the pipelines (Stephens, 1998). These sinks are used in such a way that as each one fills to capacity the transportation network extends to the next viable sink, and then to the next to eventually develop a pipeline network system. This allocation mechanism, or "String of Pearls" concept, is also known as a minimal spanning tree approach. The links between all combinations of the source to various sinks are the potential pipeline routes. This technique serves as a linear proxy for pipeline length, and lays the groundwork for future, additional "String of Pearls" analysis throughout both the Southwestern Regional Partnership area in the United States, and other regions interested in carbon capture and sequestration analysis. With this technique, the model could address additional metrics (e.g. lowest overall cost, largest sink volume, etc.) for systems insight.

REFERENCES

Benson, S.M., Hoversten, M., Gasperikova, E., and M. Haines. (2004). Monitoring Protocols and Life-Cycle Costs for Geologic Storage of Carbon Dioxide. GHGT7 International Conference, Vancouver, B.C.

Carnegie Mellon University (CMU). (2004). The Integrated Environmental Control Model (IECM). IECM, Update version 4.0.4.1, September.

Drennen, T.E., Baker, A.B., Jones, S.A., Kamery, W.J., Lutz, A.E., Rosthal, J.E. (2004). The Hydrogen Futures Simulation Model (H2Sim) Technical Description. SAND2004-4937. October.

Environmental Protection Agency (EPA). (2005). Emissions & Generation Resource Integrated Database (eGRID), eGRID2002, Version 2.01. Year 2000 Data, 27, June 2005. http://www.epa.gov/cleanenergy/egrid/index.htm

Energy Information Administration (EIA). (2005). Individual State Data. 18, July, 2005. http://www.eia.doe.gov/emeu/states/_states.html

Hirl, M. (2004). CO_2 Sequestration Integrated Model Workshop, Personal Communication, April 20.

Hovorka, S.D., et al. (July 2001). Project Evaluation: Phase II: Optimal Geological Environments for Carbon Dioxide Disposal in Brine-Bearing Formations (Aquifers) in the United States, Final Contract Report prepared for U.S. Department of Energy, National Energy Technology Laboratory, under contract no. DE-AC26-98FT40417, Bureau of Economic Geology, the University of Texas at Austin, Austin, Texas.

Kobos, P.H., D.J. Borns, L.A. Malczynski and O.H. Paananen. (2005a). Southwest Regional Partnership on Carbon Sequestration: A Test Case Model in the San Juan Basin. Poster Presentation at the Fourth Annual Carbon Capture and Sequestration Conference, Alexandria, VA, May 2 – 5.

Kobos, P.H., Borns, D.J., Malczynski, L.A. and O.H. Paananen. (2005b). The Southwest Regional Partnership on Carbon Sequestration: Employing the Integrated Assessment Model for Systems Insight. SAND2005-4902C and Proceedings of the 25thAnnual North American Conference of the USAEE/IAEE, September 19 −21, 2005, Denver, CO.

McPherson, B. (2005a). Southwest Regional Partnership on Carbon Sequestration. 27, June 2005. www.southwestcarbonpartnership.org

Ogden, J.M. (2002). Modeling Infrastructure For a Fossil Hydrogen Energy System with CO_2 Sequestration. Sixth Greenhouse Gas Control Technologies Conference, Kyoto, Japan, September 30 – October 4.

Paananen, O. (2004). A Framework for Assessing Carbon Storage in the Southwestern United States. Presentation at the Third Annual Conference on Carbon Sequestration, Alexandria, VA, May 3 – 6.

Stephens, R. (1998). Ready-To-Run Visual Basic Algorithms, Second Edition. John

U.S. Department of Energy and Electric Power Research Institute (DOE/EPRI). (Dec. 2000). Evaluation of Innovative Fossil Fuel Power Plants. Interim Report 1000316.

Williams, R.H. (2002). Toward Zero Emissions for Transportation Using Fossil Fuels. In VII Biennial Asilomar Conference on Transportation, Energy, and Environmental Policy: Managing Transitions, K.S. Kurani and D. Sperling (eds.), Transportation Research Board: Washington, D.C. – forthcoming, and Prepared for Managing Transitions in the Transportation Sector: How fast and how far? VII Biannual Conference on Transportation, Energy & Environmental Policy, Monterey, CA. 11– 14, September, 2001, final draft revised 7.15.2002.