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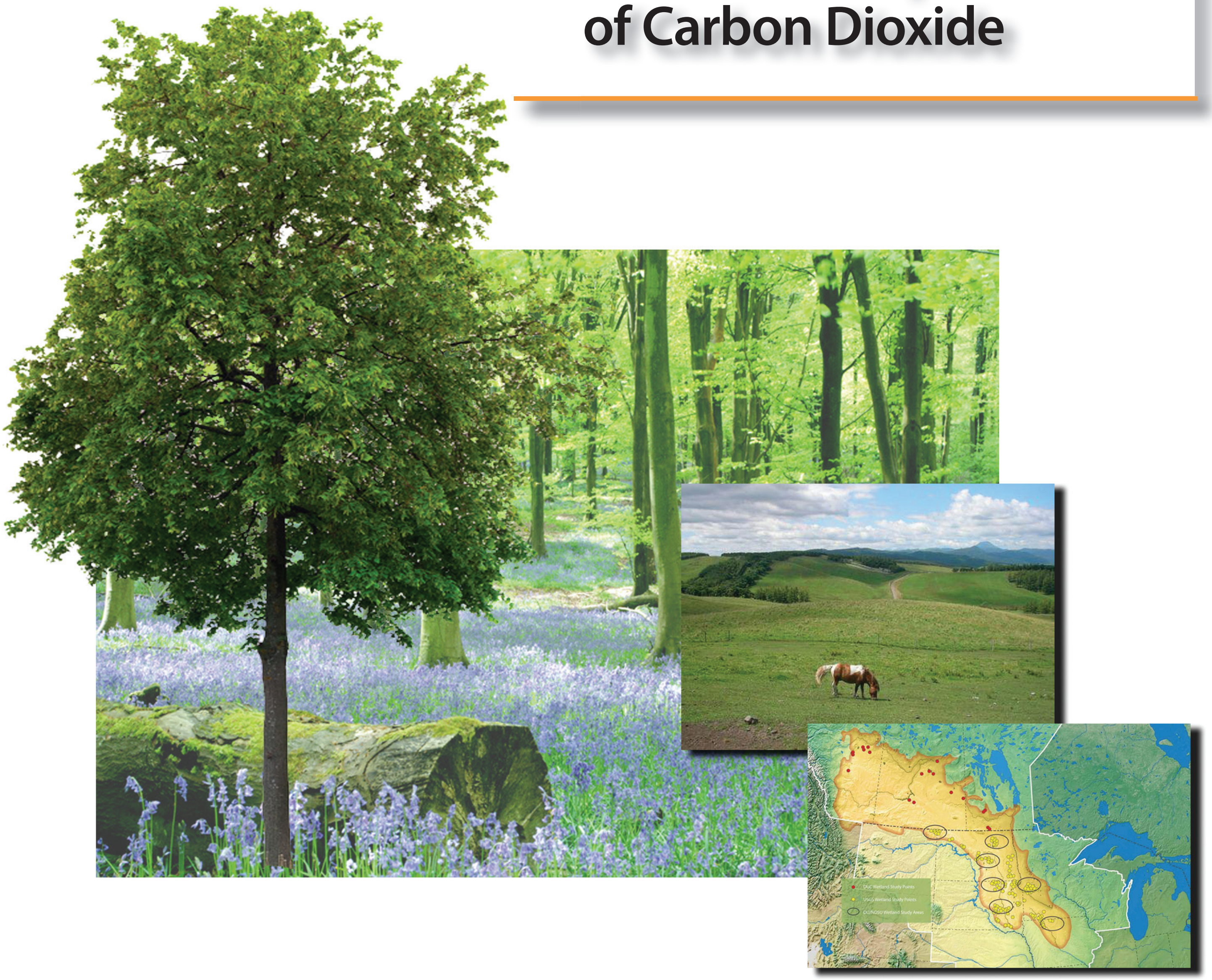
BEST PRACTICES for:

Terrestrial Sequestration of Carbon Dioxide



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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

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Terrestrial Sequestration of Carbon Dioxide

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List of Acronyms/Abbreviations

Acronym/Abbreviation	Definition
^{14}C	Radiocarbon
APEX	Agricultural Policy/Environmental eXtender
Big Sky	Big Sky Regional Carbon Sequestration Partnership
BLM	Bureau of Land Management
C	Carbon
CCS	Carbon Capture and Storage
CCX	Chicago Climate Exchange
CCX-CFI	Chicago Climate Exchange Carbon Financial Instrument
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DOE	Department of Energy
ECBM	Enhanced coal bed methane
ECD	Electron Capture Detector
EU ETS	European Union Emission Trading Scheme
FID	Flame Ionization Detector
GHG	Greenhouse Gas
Gt	gigatonnes
ha	hectare
IET	International Emissions Trading
INS	Inelastic Neutron Scattering
IR	Infrared spectroscopy
JI	Joint Implementation
LIBS	Laser Induced Breakdown Spectroscopy
LOI	Loss-on-Ignition
MGSC	Midwest Geological Sequestration Consortium
MIR	Mid-infrared
MLRA	Major Land Resource Areas
MODIS	Moderate Resolution Imaging Spectroradiometer
MRCSP	Midwest Regional Carbon Sequestration Partnership
Mt	megatonnes
MVA	Monitoring, Verification, and Accounting
NO_3	.Nitrate
NASA	National Aeronautics and Space Administration
NH_4	Ammonium
NIR	Near-infrared
PCOR	Plains CO2 Reduction Partnership
PPM	Parts Per Million
PPR	Prairie Pothole Region
RCSP	Regional Carbon Sequestration Partnership
RGGI	Regional Greenhouse Gas Initiative
RO	Reverse Osmosis
RSAPG	Rangeland Sequestration Assessment Potential Group
SECARB	Southeast Regional Carbon Sequestration Partnership
SF_6	Sulfur Hexafluoride

SIC	Soil Inorganic Content
SMCRA	Surface Mining Control and Reclamation Act of 1977
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SWP	Southwest Regional Partnership on Carbon Sequestration
TLS	Terrestrial Laser Scanner
TM	Thermatic Mapper
TNC	Thermal Neutron Capture
TOC	Total Organic Content
UNFCCC	United Nations Framework Convention on Climate Change
VisNIR	Visible and Near-Infrared spectroscopy
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WFPS	Water-filled Pore Space

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Terrestrial Sequestration of Carbon Dioxide

1.0 Introduction

Carbon (C) is an essential element for sustaining life. It can be found naturally in organic and inorganic forms with a very small exchange rate between them. At about 18 percent (about 50 percent on a dry basis), the concentration of C in living matter is almost 100 times greater than the average concentration in the earth (0.19 percent). Thus, for life to continue, carbon must be recycled. This is accomplished primarily by photoautotrophs that use light energy from the sun to convert carbon dioxide (CO_2) in the atmosphere to organic matter by photosynthesis. This carbon is returned to the atmosphere as CO_2 by respiration, combustion, and decay.

For thousands of years, this cycle remained in balance, and the CO_2 concentration in the atmosphere remained fairly constant. However, in the last 100 years or so, combustion of fossil fuels, deforestation, changes is tillage practices, and other factors have perturbed this balance, resulting in an increase in atmospheric CO_2. There is growing concern that increasing levels of greenhouse gases (GHGs) in the atmosphere, particularly CO_2, are contributing to global climate change (IPCC, 2007). Atmospheric levels of CO_2 have risen significantly from preindustrial levels of 280 parts per million (ppm) to present levels of 384 ppm (Tans, 2008). Evidence suggests that elevated atmospheric CO_2 concentrations are the result of a combination expanded use of fossil fuels for energy production and transportation, land use conversion (deforestation), and soil cultivation. Predictions of increased global fossil energy use imply a continued increase in carbon emissions (EIA, 2007) and a corresponding rise in the CO_2 level in the atmosphere unless a major change is made in the way energy is produced and used—in particular, how carbon is managed (Socolow et al., 2004; Greenblatt and Sarmiento, 2004).

Carbon dioxide circulates through, and accumulates in, the atmosphere, the oceans, and the land; these CO_2 pools are a natural part of the carbon cycle. Unfortunately, the natural land and ocean pools are unable to absorb all of the anthropogenic CO_2 currently being emitted; as a result, residual carbon is accumulating in the atmosphere at a rate of about 3.2 gigatonnes (Gt) of carbon per year (NASA, 2009). This has led to efforts to enhance natural pools and to provide artificial ones. One option that is receiving considerable attention is the capture of CO_2 from large point sources and subsequent injection into deep geologic formations for permanent storage, generally referred to as carbon capture and storage (CCS). Although showing considerable promise, CCS cannot recover CO_2 from non-point sources, such as vehicles and home heating. However, vegetation is able, through photosynthesis, to remove CO_2 from the atmosphere and convert it to carbohydrates. Some of this carbon returns to the atmosphere through decay or burning, but much of it can remain in the soil or in plant tissues for many years. By improved management practices, the amount of carbon stored in soils and plants can be increased. Storing carbon in this way is referred to as terrestrial sequestration. In addition to being able to remove CO_2 from the air, terrestrial sequestration has the advantage that it can be quickly instituted; generally does not require a permit; and usually has ancillary benefits, such as better water retention, increased crop yields, and improved wildlife habitat.

There are a variety of options for terrestrial sequestration, including restoring mined lands, aforestation, reforestation, rangeland improvement, improved tillage practices, and wetlands restoration. Since forests contain more carbon per hectare (ha) than grasslands, planting trees instead of grass when restoring mined areas or planting trees on cleared areas can significantly increase carbon sequestration over time. Because terrestrial sequestration projects can be implemented rather quickly, the Department of Energy's Sequestration Program had an active effort to promote terrestrial carbon sequestration as an early entry approach to reducing atmospheric GHG levels, with particular interest in restoring mine lands (Litynski et al., 2006); however, there is currently no active program.

For every terrestrial CO_2 storage project, monitoring, verification, and accounting (MVA) of the stored CO_2 will be an important activity. MVA for terrestrial carbon sequestration refers to monitoring the growth of plant species and the buildup of carbon in the soil, verifying that the carbon buildup is stable, and accounting for the amount of carbon that has been stored. It will not be possible to obtain credit for the carbon stored in terrestrial carbon storage projects without robust MVA protocols to verify the amount of carbon that is being sequestered.

This manual covers land types and management methods that can maximize carbon storage in vegetation and soil. It also covers the analytical techniques necessary to monitor, verify, and account for terrestrially stored carbon, which is required for this carbon to be traded. The status of GHG trading and the institutions involved are also covered. Finally, results from the Regional Carbon Sequestration Partnerships (RCSPs) terrestrial field trials are discussed as examples of what can be done. This manual is aimed at individuals and organizations considering terrestrial sequestration projects and those considering regulations/legislation governing carbon emissions caps.

2.0 Terrestrial Carbon

Terrestrial carbon refers to carbon, both organic and inorganic, stored in soils and carbon in the vegetation supported by the soil and includes both living and dead forms of biomass. There are many different land forms and soil types. The objective of this manual is to indicate the best management practices to enhance carbon content and to maintain it at the maximum practical level for a given area.

2.1 Natural and Anthropogenic Sources of CO_2

Carbon enters the atmosphere from a variety of sources, both natural and anthropogenic. Natural sources include decay of animal and plant life, volcanoes, natural brush and forest fires, respiration of plants and animals, methane from the digestive systems of ruminants, and methane from natural seeps and thawing permafrost. Anthropogenic sources include vehicles (cars, trucks, trains, and planes), home heating, power plants, cement plants, ethanol plants, steel mills, and other industrial plants.

2.2 Place of Terrestrial Carbon in the Global Carbon Cycle

There are three major carbon pools—the land, the oceans, and the atmosphere—and it is the interchange of carbon among these pools that constitutes the carbon cycle (Figure 1). The amount of carbon in these pools is very large (see Table 1) (U. Mich, 2008), but the interchange between pools is the main interest.

Table 1: Amount of Carbon Stored in Various Pools

Location	Amount (approximate) Gt of Carbon
Minerals (limestone, dolomite, etc.)	65,000,000
Oceans	39,000
Soils	1,580
Terrestrial Vegetation	610
Atmosphere	775

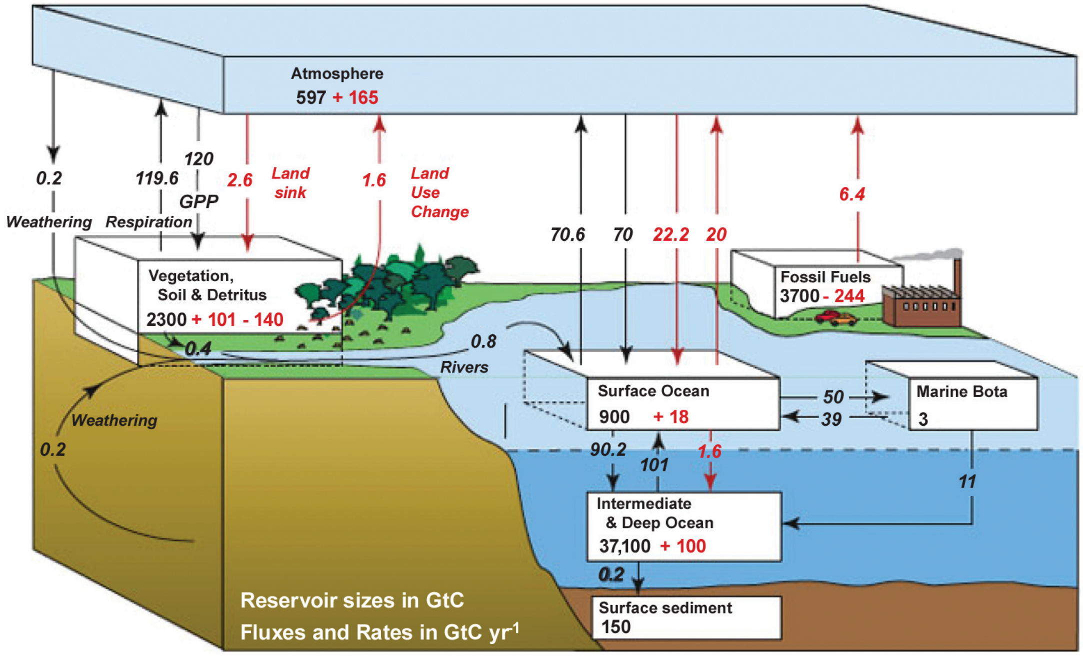


Figure 1: The Carbon Cycle. Carbon cycles constantly between land, oceans, and the atmosphere. Black arrows in this image show natural fluxes and red arrows show anthropogenic contributions. The residence time of carbon varies widely among different reservoirs. On average a carbon atom spends about 5 years in the atmosphere, 10 years in terrestrial vegetation, and 380 years in intermediate and deep ocean waters (IPCC, 2007).

Through photosynthesis, vegetation is able to extract CO_2 from the atmosphere and convert it to carbohydrates, but through respiration and decay, plants also contribute CO_2 to the atmosphere. The oceans both absorb and emit CO_2. Many oceanic organisms use dissolved CO_2 to form shells consisting primarily of calcium carbonate ($CaCO_3$); most of these shells settle to the bottom of the ocean when the organisms die. In addition to the natural CO_2 emissions to the atmosphere from the land and oceans, human activities contribute CO_2 to the atmosphere. The major anthropogenic emissions result from combustion of fossil fuels and changes in land use.

The values of all these fluxes are not known with precision, and estimates differ slightly from authority to authority. Furthermore, due to lack of precise data, there is a slight discrepancy when a carbon mass balance is calculated. The inputs to the atmosphere minus the removals from the atmosphere amount to approximately 5.2 Gt/y of carbon. However, measurement of the CO_2 concentration in the atmosphere indicates a buildup of only 3.2 Gt/y of carbon, leaving 2.0 Gt/y unaccounted for (see Table 2) (U. Mich., 2008). Terrestrial ecosystems appear to be the most likely repository for this unaccounted carbon.

2.3 Historic Loss of Terrestrial Carbon

Table 2: Atmospheric Carbon Balance

Source	Inputs, Gt/y	Removals, Gt/y
Fossil Fuel Combustion	6.3	
Land Use Changes	1.6	
Plant & Soil Respiration/Decay	110	
Photosynthesis		111.4
Oceans	90	91.7
Total	207.9	203.1
Calculated Accumulation	5.2	
Measured Accumulation	3.2	
Discrepancy	2.0	

U.S. soils have been degraded of carbon by a variety of causes. One problem is erosion. Croplands and steep lands are subject to accelerated erosion. It is estimated that 44 megahectares (Mha) of cropland (about 28 percent of all cropland) and 51 Mha of grazing land (about 15 percent of all grazing land) are subject to accelerated erosion. In addition to these soils, about 4 Mha are severely disturbed due to mining, resulting in erosion and other forms of carbon loss (see Section 3.1). Accelerated erosion decreases soil organic carbon (SOC) by breaking up aggregates, increasing preferential removal of carbon in runoff or dust, and increasing mineralization. However, carbon that is deposited and buried and does not reach the atmosphere can be considered to be in long term storage. The SOC pool for eroded soil, relative to the original SOC, may be reduced by as much as 70 percent compared to 40 percent for non-eroded soil. Cultivated soils not prone to erosion generally achieve a stable SOC level within 30–50 years. Organic soils, especially those that have been drained and cultivated, are prone to decomposition of organic matter and subsidence. Deforestation is another activity that can lead to loss of SOC (Lal et al., 2003).

2.4 Potential for Terrestrial Carbon Storage in the United States

Conversion of forests to agricultural uses, cultivation of grasslands, draining of wetlands, mining, erosion, fires, and other causes have significantly reduced (20-50 percent lower) the SOC in the U.S. from its original level. This means that there is significant potential for terrestrial carbon storage by increasing SOC to its original level. Table 3 lists potential terrestrial storage capability by land use (Lal et al., 2003).

Table 3: Terrestrial Carbon Storage Potential in the United States

Land Use	Carbon Storage Potential, Mt/y
Cropland	45-98
Grazing land	13-70
Forestland	25-102
Land conversion	21-77
Land restoration	25-60
Other	15-25
Total	**144-432**

Based on these values, an average of 288 Mt/y of carbon (1,056 Mt/y of CO_2) could be sequestered in terrestrial systems, a rate that could be sustained for perhaps as long as 30 years. In 2008, CO_2 emissions from electric power production amounted to 2.36 Gt. Terrestrial sequestration could handle about 12% of these emissions.

3.0 Land Use/Land Cover in the United States

Terrestrial carbon sequestration occurs when the uptake of carbon by plants exceeds carbon losses through soil respiration, plant respiration, and biomass removal. This balance is affected by many factors, such as type, age, and condition of vegetation; climate; soil type and wetness; previous history of the site; crop harvesting; fire; plant pests and disease; etc. (Anderson et al., 2008). A critical factor is land use and type of cover. Some land uses have much higher potentials for carbon uptake than others. A rapidly growing forest has a much higher rate of carbon sequestration than either a mature forest or grassland. Thus, the potential for terrestrial sequestration in the United States depends upon the distribution of land uses. Table 4 lists major land uses in the United States (Lubowski et al., 2006).

3.1. Mined Lands

Surface mining results in elimination of existing surface vegetation and severely disturbed soil that can accentuate CO_2 emissions through mineralization, erosion, leaching, changes in soil moisture and temperature, and reduction in the amount of biomass returned to the soil (Shrestha and Lal, 2006). About 3.2 Mha of land have been disturbed by coal mining in the United States of which only about 2 percent is reclaimed and bond released. Because the SOC of mined lands tends to be low, such lands offer significant potential for terrestrial sequestration of carbon. Shrestha and Lal (2006) estimate that reclaimed mine lands have the potential to store carbon at the rate of 0.5-1 tonne of carbon per ha per year for a total storage capacity of 1.6-3.2 Mt of carbon per year, offsetting the emission of 5.8-11.7 Mt of CO_2 per year.

3.2 Forests

On a per hactare basis, forests can store more carbon than grasslands. Mature pine plantations in the southeast can accumulate about 250 tonnes of carbon per ha after 90 years, or roughly 2.5 tonnes per ha per year (Birdsy, 1996). Carbon storage in a forest is split between carbon in vegetation and carbon in the soil. Although soil carbon may be similar between grassland and forest, carbon in vegetation is much higher for forestland.

Table 4: Land use in the United States

Land Use	Area, million acres	Percent of total
Cropland used for crops	340	15.0
Idle cropland	40	1.8
Cropland used only for pasture	62	2.7
Grassland pasture and range	587	25.9
Farmsteads, farm roads	11	0.5
Forestland grazed	134	5.9
Forestland not grazed	517	22.8
Transportation uses	27	1.2
Recreation and wildlife areas	242	10.7
National defense areas	17	0.8
Urban land	60	2.6
Miscellaneous other land	228	10.1
Total	**1,091**	**100.0**

Source: USDA, Major Uses of Land in the United States, 2002. Economic Information Bulletin 14.

3.2.1 Forests with High Fire Risk

Managing forests to prevent high-intensity fires that release large amounts of CO_2 is important if high stored carbon levels are to be maintained. As an example, historically, the surface fuel layer of low-elevation, ponderosa pine forest was dry during the summer fire season, resulting in frequent, low-intensity surface fires. More recently, fire suppression activities have disturbed this historical fire regime, resulting in the build-up of ladder fuels at intermediate heights that can carry surface fires into the crown, which can lead to large, catastrophic fires. Mixed-intensity fire regimes occur mostly at mid-elevations in mixed conifer forest stands defined by a mixture of tree species and densities. The frequency, severity, and size of fires in these forests are affected by fuel accumulation and climate. The impact of suppression practices on fuel loads in these forests varies depending on the composition of the forest stand.

3.3 Rangelands

Rangelands are lands on which the indigenous vegetation is predominantly grasses, grass-like plants, forbs, or shrubs and that are managed as a natural ecosystem. Rangelands include grasslands, savannas, shrublands, deserts, tundra, marshes, and meadows. Over one third of the land area in the United States (770 million acres) is classified as rangeland. Increases in invasive species, both introduced and native, can drastically reduce the productivity of rangeland by using limited resources, such as water, nutrients, and sunlight. Over time, shrubs have tended to displace grasses on many rangelands. Rangelands store large quantities of carbon in soil and vegetation, and it is estimated that they can store 26–72 million tonnes/y (SRM, 2010). However, for this to occur, they must be managed to increase productivity. Management will have to be at a regional scale, not just at an individual ranch level.

Rangelands must be managed to avoid catastrophic changes. In general, arid and semi-arid rangelands do not have a unique condition to which they return after disturbance, so degradation must be assumed to be permanent, at least on a human time scale (SRM, 2010). Unfortunately, the need to maintain economic performance acts as a driver for keeping usage levels during poor climatic conditions the same as those during good climatic conditions, thus leading to rangeland degradation. Managing rangelands in the face of global climate change will require an emphasis on the restoration and enhancement of ecosystem resilience, that is, the ability of an ecosystem to withstand stress and disturbance and return to its original condition.

3.4 Grasslands

Grasslands are areas where the vegetation is predominantly grasses and other herbaceous plants with few or no trees and shrubs. Grasslands typically grow in regions with an annual rainfall of 50–90 cm. Grasslands dominated by unsown wild-plant communities (unimproved grasslands) can be classified as either natural or semi-natural. The majority of temperate grasslands are semi-natural. Although their plant communities are natural, their management depends on anthropogenic activities, such as grazing and mowing. To a large extent, native plant grasslands have been replaced by sown monocultures of cultivated varieties of grasses and clovers.

In the past, the grasslands in the Midwest of North America supported huge herds of American bison. Thus, these grasslands developed in parallel with grazers, and proper management may depend upon simulating the behavior of the large bison herds. These herds would heavily browse and trample an area and then move en masse to a new area. The effect of the grazers is to break soil crusts and trample seeds and plant materials into the soil, helping seeds to germinate. Also, trampled vegetation acts like mulch that protects the soil and retains moisture, and the grazers' manure acts as a fertilizer.

The situation before the arrival of European settlers can be simulated by confining cattle to a relatively small area and allowing them to graze heavily for a short time before moving them to a new area and allowing the grazed plot to recover for a long time before again instituting grazing (Keppel, 2002). In this way, carbon stocks in the grassland can be increased. However, some of this carbon buildup is offset by methane emissions from the grazing domestic ruminants.

3.5 Agricultural Lands

Agricultural land is land modified by human activity specifically to grow crops or livestock for human consumption or use. Agricultural land includes cropland, pasture, orchards, groves, vineyards, nurseries, ornamental horticulture areas, and confined feeding areas. Agricultural lands are among the nation's most important land. However, because of intensive tillage, most agricultural lands contain significantly less carbon than they did prior to being converted to agricultural use, thus representing a major potential for terrestrial storage of carbon. Lal (2002) estimates that most soils in the Midwestern United States have lost 30-50 percent of their original carbon pool, a loss of 25-40 tonnes of C per ha. Sixty to seventy percent of the lost carbon can be restored by improved crop and soil management practices, such as conversion to no till, manuring, growing winter cover crops, crop rotation, and integrated nutrient management. All other factors being equal, pasture soils have more SOC than cropland soils because of low soil disturbance due to lack of plowing, more root biomass and residue returned to the soil, and return of manure to the soil (Lal, 2002).

One strategy for increasing carbon in soils is agricultural intensification; that is, the use of prime soils for cultivation using the best management practices for optimum sustained yield, while maintaining marginal lands in a land bank (Lal, 2002). Such an approach can increase SOC, improve soil quality and productivity, and enhance water quality, while removing CO_2 from the air. It is estimated that the world's croplands have the potential to sequester 0.7–0.9 billion tonnes of carbon per year for the next 25 to 50 years (Lal and Bruce, 1999).

3.5.1 Agricultural Land Used for Growing Biofuels

Interest is growing in producing biofuels as a way to mitigate CO_2 emissions from combustion of fossil fuels (Lal, 2005; Lal, 2008). There are two options: relative to growing biofuels on land: (1) diverting food crops, such as corn or soybeans, to energy production, and (2) growing a crop, such as switchgrass or fast-growing aspens, whose main use is as a fuel. For the first case, management practices should be the same for energy production as for food production. However, for the second case, management may be considerably different.

The production of ethanol from corn is the most common biofuel process in the United States. A major weakness of this technology is that only the corn kernel can be converted, meaning that the bulk of the corn plant cannot be converted to fuel. Research is underway to convert cellulose to ethanol, which would permit the entire corn plant to be used. However, a problem with this approach is that extensive energy is required (through the use of machinery and transportation) in removing the corn stover (the non-grain part of the corn) from the field, resulting in a negative impact on terrestrial carbon sequestration that at least partially negates the advantage of biofuel usage (Lal and Pimentel, 2007).

Switchgrass is a tall—up to 10 feet—grass with stems as thick and strong as a wooden pencil. It is fast growing and can flourish on poor soil. It is a persistent perennial, and can be harvested annually or semiannually for 10 or more years before requiring replanting. Yields as high as 13.5 tonnes per acre per year (dry weight) have been achieved. Switchgrass has deep roots and adds organic matter to the soil, rather than depleting the soil as many crops do. In addition, the root system prevents soil erosion, even in the winter. Switchgrass could prove to be a valuable crop from several points of view. For example, it can be used as a biomass crop for production of ethanol, fiber, electricity, and heat, and for biosequestration of atmospheric CO_2. It may also prove to be an alternative to merely letting ground lie fallow.

Another plant that has been extensively studied as a potential biofuel feedstock is the poplar tree, which can grow to a height of about 70 feet in five or six years. Much effort has gone into hybridization and genetic modification to further increase growth rate. Current yields are about 22 tonnes per hectare per year. The two main options for using this biomass are direct combustion and conversion of cellulose to sugars followed by fermentation to ethanol. However, there are still technical issues to overcome for this second option. With current technology, the efficiency for converting biomass to liquid fuels to replace petroleum is relatively low.

3.6 Deserts

Deserts are caused by extremely low rainfall over an area and cover about one fifth of the earth's land area. Although plant growth is typically limited due to lack of water, some arid ecosystems can be successfully rehabilitated and cultivated with halophytes (salt-tolerant plants). Total carbon sequestration by desert halophytes is potentially comparable to that of temperate forest plantations. There are several types of desert, as described briefly below (SciLinks, 2009).

3.6.1 Arid Deserts

Arid deserts generally occur at low latitudes and can be found in North and South America, Africa, and Southern Asia. Seasons in the arid desert are generally dry and hot, with few occurrences of rain during the winter. Heat peaks to extremes during the daytime because there are no clouds to shield the earth from the sun's rays. When it does rain, it is not uncommon for the rain to evaporate before hitting the ground. The soil is usually either sandy or coarse and rocky. Such conditions limit vegetation to mainly shrubs and small trees whose leaves have evolved to retain water. Animal species are active mostly at night when it is cooler.

3.6.2 Semi-arid Deserts

Semi-arid deserts are found in North America, Europe, Russia, and Northern Asia. Seasons are generally more defined than in the arid desert, with low rainfalls during the winter. Even if the rainfall is at a bare minimum, several species of animals and plants thrive in this climate; animals, while generally nocturnal, can be found during the day, mostly in the shade of various trees and plants.

3.6.3 Coastal Deserts

Coastal deserts are found in areas that are moderately warm to cool, such as the Neotropic and Nearctic realm. The winters are usually cool and short, while the summers are long and warm.

The soil is mostly sandy with a high alkaline content; it is also very porous, allowing rain to seep quite rapidly into the ground. Most of the flora in coastal deserts features thick foliage with good water retention and roots close to the surface of the ground to absorb enough water before it drains into the soil. Animals of the coastal desert include rough skinned amphibians, birds of prey, scavenger mammals, reptiles, and insects; most have adapted quite well to the climate and are largely nocturnal during the warmer months.

3.6.4 Cold Deserts

Perhaps the strangest of all desert biomes is the cold desert, as deserts are typically associated with the heat of the sun. In cold deserts, the soil is too heavy and alkaline to support most vegetation, even if there is a moderately high amount of snow and rainfall during wintertime,. Alluvial fans pull some of the salt through the porous soil, so plant life can survive, but the cold desert offers less than ideal conditions for sustaining delicate plants and animals. Most of the animals in the cold desert are burrowers. Deer and other large herbivores are found only during the winter, when the supply of grass is more abundant.

3.7 Wetlands/Estuaries

Wetlands include a wide range of habitats, and definitions for these habitats tend to vary between different agencies and individuals, depending on particular interests. The U.S. Fish and Wildlife Service defines wetlands as "lands transitional between terrestrial and aquatic systems, where the water table is at or near the land surface or the land is covered by shallow water. Wetlands must have one of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered with shallow water at some time during the growing season of each year."

The U.S. Environmental Protection Agency (EPA) defines wetlands as "those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas."

Wetlands serve many functions, including flood control, improved water quality, wildlife habitat, recreation, and carbon sequestration. Because organic matter tends to decompose more slowly under water, wetlands can accumulate considerable quantities of carbon. Peat bogs are an example of carbon accumulation in a wetland.

3.8 Tundra

Tundra is a biome characterized by hindered tree growth due to low temperatures and a short growing season. The tundra ecosystem is extremely sensitive to any type of disturbance. Disruption of vegetative cover causes permafrost to melt deeply, causing the ground to collapse and soil loss. Vehicle tracks can result in deep gullies that can persist for years. There is relatively little potential for significantly increasing carbon storage in tundra. There are two types of tundra: arctic and alpine.

3.8.1 Arctic Tundra

Arctic tundra, which surrounds the North Pole, is a vast area of stark landscape that is frozen much of the year. It is characterized by a layer of permafrost, soil that is permanently frozen (from 25 to 90 cm down). Since tree roots cannot penetrate the permafrost, tree growth is impossible. Vegetation is typically restricted to low growing plants, such as members of the heath family, mosses, and lichens. In the summer, the temperature rises above freezing, melting the top layer of soil and leaving the ground very soggy. The arctic tundra is covered by marshes, lakes, bogs, and streams during the summer. Precipitation is low, about 15 to 25 cm/y. Because of the harsh conditions, the arctic tundra has been little exploited, although that is changing as energy exploration and production in the arctic is increasing.

3.8.2 Alpine Tundra

Alpine tundra occurs in mountains worldwide. It is located on mountain peaks above the tree line, where conditions are too severe to support tree growth. Alpine tundra is distinguished from arctic tundra by the absence of permafrost. Alpine soils are typically better drained that arctic soils, and its flora is characterized by dwarf shrubs close to the ground. The cold climate of the alpine tundra is due to the low air pressure and is similar to the polar climate.

4.0 Management Practices

The ability of soils to store carbon and support vegetation is highly dependent on management practices. This is especially true of lands under intensive cultivation, heavy grazing or logging. Successful terrestrial carbon storage requires not only the retention of the existing carbon inventory but also its enhancement, which may result from increased soil carbon or increased plant growth or both. Practices which can be used to improve carbon uptake are discussed in the following sections.

4.1 Reclamation of Mine Lands

The low SOC of mined lands can be enhanced by: (1) proper reclamation, (2) adopting recommended management practices, (3) improving soil fertility using integrated nutrient management, (4) recycling nutrients by returning biomass to the soil, and (5) growing leguminous plants or trees for biological nitrogen fixation. Enhancing soil fertility is one of the major goals of mined lands reclamation. One method to achieve this is to add organic materials, such as peat, sewage sludge, paper mill sludge, etc., to the soil to stimulate microbial activity. Application of biosolids decreases soil bulk density, improves soil water holding capacity, increases soil organic matter and nitrogen content, and alters pH with an attendant increase in biomass production. Increased biomass production can be achieved by planting at the recommended density species adaptable to adverse conditions, mulching, and applying management practices to ensure that vegetative cover is established (Shrestha and Lal, 2006).

The addition of amendments, both organic, such as swine or poultry manure, sewage sludge, paper mill sludge, and sawdust, and inorganic, such as coal combustion by-products and flue gas desulfurization by-product, can ameliorate severely disturbed soils by improving the chemical and physical properties of the soil, improving fertility, increasing biomass production, and enhancing carbon storage in the soil. Although many readily available organic amendments are good sources of nutrients, they are not likely to be retained in the soil for long periods. However, when combined with more refractory amendments, such as lignin-rich paper mill sludge and woody wastes, microbial action produces refractory carbon species that add to SOC (Shrestha and Lal, 2006).

Another benefit of enhancing SOC of mined lands is the removal of toxic metals. Organic amendments can bind metals, such as nickel, lead, and cadmium, thus reducing their percolation into groundwater and decreasing plant uptake (Chu and Poon, 1999; Wong, 1995).

A practice that can be helpful in reclaiming mined lands is mulching, which protects the soil from wind and rain erosion and enhances revegetation. Suitable mulches include straw, hay, and wood residues. Mulching improves plant growth, biomass production, and nutrient uptake. Another approach that has been used to add organic matter to mined lands is the use of cattle. Livestock are concentrated on a small area for a short time and fed hay. The hoof action of the cattle incorporates organic matter into the soil, enhancing the reclamation of the mined lands, finally resulting in a self-sustaining ecosystem (Bengson, 1999).

A study by Amichev et al. (2008) of reforested mine lands in Midwestern and Appalachian coalfields showed that mined sites accumulated nearly as much C in the tree and litter C pools as nearby unmined sites. However, SOC stocks were consistently lower on mined sites, thus providing an opportunity to store more C on mine lands. It was estimate that over 60 years, additional SOC accumulation could amount to 25–100 tonnes/ha. During coal mining and the subsequent reclamation, native topsoil and the accompanying seed and microbe pools are largely destroyed. Consequently, the natural terrestrial C cycle is severely interrupted. Amichev et al. recommend reclamation methods that introduce, accumulate, and stabilize SOC; reestablish soil microbial communities; and prepare the site in ways that maximize the growth of planted trees and other plants.

Analyses of soil samples show that carbohydrates offer efficient building bridges between soil aggregates and facilitate development of better soil structure. In general, the greater the degree of humification, the greater the aromatic nature and degree of substitution, the greater the stabilization of SOC and, therefore, greater potential for SOC sequestration on reclaimed mine land. The disturbed soil that results from mining activities may not absorb rainfall as well as undisturbed sites, resulting in increased soil erosion. Planting grass/legumes on reclaimed mine sites, in addition to storing soil carbon, also reduces soil erosion. This erosion reduction benefits nearby streams, lakes, and other waterways that may contain fish and other wildlife. The results of the study may be applied to most of the thousands of hectares of land permitted for mining activities in regions where the predominant reclamation activity is planting grass/legumes.

The alternative is to restore the mine lands through planting trees. Establishing a forest on mined lands can be problematic. Public Law 95-87, the Surface Mining Control and Reclamation Act of 1977 mandates that surface mined land in the United States be returned to a condition capable of supporting its pre-mined use or a use of higher value. Since 1977, the majority of mined land has been reclaimed as hayland/pasture or wildlife habitat. The reasons for this are varied and include: economics (less expensive than forestation), limited technical knowledge for establishing forests, and convenience—it may be the easiest way to get performance bond release. As the result of a limited livestock industry and the fact that most wildlife lands are abandoned after bond release, there are now thousands of hectares of unproductive grasslands and scrublands throughout otherwise forested areas in the eastern United States. Since forest land stores more carbon per hectare than grassland, there is significant potential for increasing carbon storage by converting to forests land originally reclaimed to grass (Sullivan et al., 2006).

Factors to consider when reforesting a surface mined site include the following (Bagley, 1980; Limstrom, 1964):

- The species selected should be suitable for the planting site. Avoid species that are susceptible to insect damage or disease in the area.
- The seeds or seedlings should be from a source in an area with a similar climate, although seeding may not be effective on strip-mined land.
- The species should be suitable for the desired product—lumber, pulpwood, Christmas trees, or erosion control.
- Handling of the planting stock is important. Time between lifting and planting should be minimized, and roots should not be allowed to dry out. Proper planting time for the region should be chosen.
- Supervision of planting is important to ensure that the seedlings are planted correctly to maximize their survival. It may be necessary to clear a small area around the seedling if the existing vegetation is too high.
- Formed in 2003, the **Appalachian Regional Reforestation Initiative** (ARRI) is a coalition of groups, including citizens, industry, and government (including the Forest Service), dedicated to restoring forests on coal-mined lands in the Eastern United States. ARRI advocates a five-step forestry reclamation approach:
- Create a suitable rooting medium no less than 4 feet deep and made up of topsoil, weathered sandstone, and/or the best available material.
- Loosely grade the topsoil or topsoil substitute to create a noncompacted growth medium.
- Use ground covers that are compatible with growing trees.
- Plant two types of trees—early successional species for wildlife and soil stability and commercially valuable crop trees.
- Use proper tree planting techniques.

The specifics for each of these steps are available from the ARRI Web site under Forest Reclamation Advisories or at arri.osmre.gov/PDFs/FRA_No.2.pdf.

4.2 Forest Management

Carbon accumulation in forests eventually reaches a maximum, beyond which additional storage is no longer possible. This happens when trees reach senescence. To restart carbon storage, the trees must be harvested and the area reforested with seedlings. The harvested timber will be converted into a variety of products ranging from construction materials like plywood through furniture with lives of 15 to over 80 years. With timber harvest, most of the original soil remains in place; thus, the soil can be relatively fertile, and tree growth can be rapid.

Oregon has regulations requiring logged areas to be reforested. These regulations specify the number of trees of various sizes that must be planted per acre, how soon they must be planted after logging operations cease, and how soon they must be firmly established (ODF, 1994). The regulations promote the use of native species. The important issue here is to reforest the area as quickly as possible so that vigorous carbon storage can recommence. Weed control in the early years is important to prevent tree seedlings from being crowded out and growth stunted.

Over the last 100 years, largely as a result of the exclusion of fire and the buildup of hazardous fuels, the threat of wildfires in forests has increased. Fire has been identified as the single largest source of emissions from forestland in California (Pearson et al., 2009). In California an estimated 1.83 Mt CO_2e are emitted per year due to fires on forests and rangelands (Pearson et al., 2009). For Oregon the value is 1.03 Mt CO_2e/yr, for Washington 0.18 Mt CO_2e/yr, and for Arizona 0.47 Mt CO_2e/yr (Pearson et al., 2007).

The rate at which carbon accumulates during regrowth after a fire depends, in large part, on the fire's severity. A severe fire that burns through the entire canopy would likely have a slower rate of post-fire carbon accumulation than a less severe surface fire that leaves a majority of the older, larger trees intact. On the other hand, severe fires increase light and soil nutrients for regeneration, and reduce competition for water resources (but reduce the organic carbon base in the soil for regenerating seedlings). Severe fires may lead to an arrested succession, whereby a dominant understory species, such as Manzanita, prevents tree reestablishment or where soil conditions are altered so that the site is not immediately suitable for seedling establishment.

Some authorities see a need to reduce hazardous fuels in forests, particularly in those near population centers. Carbon emissions reduction projects are designed to achieve a decrease in emissions or an increase in sequestration relative to a reference case or baseline. A carbon emissions reduction project developer needs to estimate the emissions from fires that are likely to occur within defined project boundaries without implementation of the project and how much the implementation of the project would decrease emissions. Thus, the substantial challenge is to determine the risk of fire and the emissions associated with that risk, and to quantify how forest fuels treatments can diminish these emissions. A good deal of anecdotal evidence exists suggesting that fuels treatments in particular locations appear to have reduced the intensity, spread, or emissions from fires, and/or slowed the fire's progress enough to make suppression possible. The challenge is to move from anecdotal evidence to a rigorous scientific methodology, quantifying in a transparent and replicable way the GHG benefits attributable to forest fuels treatment.

By necessity, the reduction of forest fuels requires an initial decrease in the carbon pool, as live trees are removed from the forest, decreasing the biomass (hazardous fuel available in the event of a wildfire). The net change in carbon emissions is the difference in the selected carbon pool between a "baseline" case and a "project" case, with various fuel reduction treatments as project scenarios.

A baseline is used as a reference case to estimate changes in the emissions of GHGs attributable to changes in land use and management. Baseline scenarios are defined by projecting and quantifying carbon emissions from a "business as usual" approach to forest management (i.e., the emissions that would occur if current management practices were to continue into the future). In forest fire reduction, the baseline is related to the likelihood that a fire will occur at a given location and the net carbon, as CO_2 (and potentially other GHGs, such as methane and nitrous oxide), that would be emitted. A carbon baseline has three components: (1) a projection of the area of the forest that would burn over a given time frame, (2) the change in forest carbon stock and associated GHG emissions resulting from the fire, and (3) the pre-fire and post-fire rates of carbon accumulation in the forest.

Baseline emissions are essentially equal to the risk of a wildfire in the absence of the proposed project multiplied by the carbon emissions estimated to result from the burned area. Pre-fire carbon stocks exist in live and dead standing trees, understory vegetation, litter, and downed dead wood; all of these carbon stocks are potential fuel for a fire. Historically, in the mixed conifer forest type, fire would pass through the understory relatively quickly and consume downed dead wood, understory vegetation, and litter. One hundred years of fire suppression has led to a growth in the stock of all potential fuels. In particular, tree density has increased so that young trees (ladder fuels) can carry fires directly into the forest canopy, and understory vegetation and dead wood stocks have grown so that flame lengths can threaten the canopy.

Pre-fire carbon stocks have five potential endpoints during and after a fire—some carbon survives the fire to continue as live vegetation, some is volatilized during the fire and immediately released to the atmosphere, while the remaining carbon is divided between dead wood, soot and charcoal. Soot and charcoal are stable forms of carbon and can remain virtually unchanged for long time periods, while dead wood releases its stored carbon into the atmosphere as it gradually decays. The amount of carbon that transforms to these various forms during a fire depends upon a variety of factors, including the quantity of fuel (relative to the carbon stock in non-fuel tree vegetation), its moisture content, and the prevailing weather conditions.

An additional baseline consideration is the rate of carbon accumulation in the forest pre- and post-fire. Pre-fire rates are related to several factors, such as species mix, age, and management practices. Post-fire carbon accumulation rates are strongly influenced by factors such as fire intensity (heat of burning), fire severity (extent of burning), soil moisture condition, nutrient availability, and availability of seed sources.

The project case involves the net emission of carbon resulting from project implementation. In the case of fuels management, a project would involve treatments that reduce the quantity of hazardous fuels. Because the treated area may also experience a wildfire (although GHG emissions would be reduced), the project case must also incorporate the risk of fire, the change in carbon stocks resulting from that fire, and the pre- and post-fire rates of carbon accumulation. The difference between this project value and the baseline value is the carbon benefit. Net carbon emissions are likely to increase initially as a result of project implementation; but, in some scenarios, these emissions may be offset by the treatment effect.

The impact of fuel treatment on the carbon stock is relatively straightforward and must be accounted. Fuel treatment involves removal of live vegetation, including small trees that act as ladder fuel in a wildfire and larger trees if it is deemed necessary to thin the crown to reduce the potential spread of a wildfire. In some cases, larger trees may be removed as saw timber in order to produce revenue to cover the cost of the fuel treatment. These removals represent a loss of live carbon stock (carbon emissions). Emissions may not total 100 percent of the carbon removed, depending on how the biomass is utilized.

Other considerations are also part of the overall GHG balance or “carbon budget” of fuel treatments. These include:

- Indirect emissions, such as the GHG emissions from harvest and transport equipment.
- Differences in net GHG emissions when fuel is removed to a biomass energy facility instead of either burning in a fire or decomposing post-treatment in the forest. These differences include both the displacement of emissions from fossil fuel-derived electricity or fuels and differences in emissions of non-CO_2 GHGs during the controlled combustion of a biomass energy facility compared to the various stages of a wildfire.
- Since fuel treatments often involve some saw timber removal, it is necessary to consider the transfer of carbon into wood products and the associated emissions, both from conversion inefficiencies and the gradual retirement of long-lived wood products.

These considerations have both positive and negative effects on the overall GHG balance of fuel treatment activities.

Finding the best way to manage fire on forested lands may ultimately lead to lower CO_2 emissions, but the current state of forests is such that reducing emissions from fire in the long term requires increased emissions from removal of biomass in the short term. It may be desirable to return forests to a condition that more closely resembles pre-suppression forests. Such forests are likely to experience fewer high severity fires; and, therefore, release less CO_2 in the event of a wildfire. However, achieving these conditions will require the short term release of CO_2 currently stored as forest biomass and, thus, end up decreasing the amount of carbon sequestered. Therefore, it is not currently feasible to view this type of management as a carbon offset project type.

4.3 Grasslands/Rangelands

Grazing land is a vegetative land area that can be used for the feeding of domestic animals on growing grass, legumes, and other herbaceous plants. Grazing lands encompass a broad range of land types defined by climatic zone, terrain, vegetative cover, and primary land use. Lands used for grazing may include rangelands, grazed forest lands, native grasslands, naturalized and cultivated pasture, and crop and hay lands.

Field studies suggest that grazing lands can be managed to enhance forage productivity while preserving environmental quality. Practices undertaken as part of an improved grazing system include rotational grazing to allow grass rejuvenation; fencing to restrict livestock access to sensitive areas; watering facilities to keep livestock from riparian areas; windbreaks and shelterbelts to disperse herds; manure storage facilities for temporary confinement areas; filter strips to intercept runoff from heavy-use areas; improved grass and legume cultivars; improved nutrient management practices; and integrated pest management strategies.

Producer returns may also increase from improved grazing practices. Benefits include improved quantity and quality of forage, healthier livestock, lower veterinary costs, better monitoring of livestock resulting in earlier problem detection, higher weaning weights, and reduced problems with noxious weeds and other undesirable plant species.

4.3.1 Controlled Grazing

Efforts to increase efficiency, lower costs, and gain more profit from existing resources, while ecologically maintaining those resources, have led many progressive ranchers to controlled grazing. Controlled grazing is the management of forage with grazing animals. Since its introduction to North America in the 1970's, controlled grazing has proven itself a sound management practice. It limits access to grazing by subdividing pastures with permanent and temporary fences. When compared to controlled grazing practices, traditional grazing methods prove inefficient in terms of energy, production, and operation.

In addition to providing environmentally responsible grazing, controlled grazing results in increased amounts of forage harvested by animals, improved forage quality, extended grazing seasons, reduced fertilizer and herbicide applications, reduced labor and feed costs, and fewer weeds. Fencing plays a critical role in the success of controlled grazing. New fencing options and technology simplify controlled grazing and help improve results, such as forage quality, production, and environmental impact.

To implement controlled grazing successfully, enough livestock should be concentrated into an area so that the forage is grazed to the desired height before the grazed plants begin to regrow. Forage usage should be monitored daily. The smaller the paddock and the larger the number of animals, the more uniformly the paddock will be grazed. When the forage in the paddock is grazed to half its original height, the livestock is moved to a paddock that is ready to be grazed. Once animals are accustomed to controlled grazing, moving to new paddocks should only require a few minutes.

The ideal forage height to begin and end grazing is dependent on species and climate conditions. Forage plants should be grazed before they get too mature, but not so soon or so low that the crowns are damaged. When forage has recovered, move livestock back into the paddock. Growth rates vary widely during the grazing season. Available moisture is the key to the length of time for the forage to recover. The rule of thumb is "fast growth, fast moves; slow growth, slow moves."

4.4 Agricultural Lands

There are many factors that influence the amount of carbon stored in agricultural lands, as discussed in the following sections.

4.4.1 Cropland Tillage Practices

Tillage practices can have a major impact on SOC. When tilled by machinery, soil layers invert, air mixes in, and soil microbial activity dramatically increases over baseline levels. The result is that soil organic matter is broken down much more rapidly, and carbon is lost from the soil into the atmosphere. This, in addition to emissions from farm equipment, increases CO_2 emissions to the atmosphere.

No-till farming has the potential to increase soil carbon by storaging organic matter in those arable lands which are prone to accelerated erosion because of slope gradient (>2% slope), are subject to crusting, have low plant-available water storage, good internal drainage, and have large soil carbon sink capacity created by severe depletion of carbon pool due to historic land use and management practices.

Cropland soils are ideal for use for carbon storage, since they have been depleted of carbon in most areas. It is estimated that 78 billion tonnes of carbon that was trapped in the soil have been released because of tillage. Conventional farming practices that rely on tillage have removed carbon from the soil ecosystem by removing crop residues, such as leftover corn stalks, and by the addition of chemical fertilizers that reduce soil organic matter by promoting increased microbial activity. By eliminating tillage, so that crop residues decompose where they lie, and by growing winter cover crops, field carbon loss can be slowed and eventually reversed.

No-till requires some different skills in order to be successful. As with any production system, if no-till isn't done correctly, yields can drop. A combination of technique, equipment, pesticides, crop rotation, fertilization, and irrigation must be used, depending on local conditions. Cover crops are used occasionally in no-till to help control weeds and increase nutrients in the soil (by growing legumes). Farmers, experimenting with organic no-till, use cover crops instead of tillage for controlling weeds and are developing various methods to kill the cover crops (rollers, crimper, choppers, etc.) so that the newly planted crops can get enough light, water, nutrients, etc. With no-till, residue from the previous year's crops lie on the surface of the field, cooling it and increasing moisture. This can cause increases, decreases, or variations in the diseases that occur, but not necessarily at a higher or lower rate than conventional tillage.

Some farmers who prefer to pursue chemical-free management practices often rely on the use of normal, non-dyed, corrugated cardboard for use on seed-beds and vegetable areas. Used correctly, cardboard placed on a specific area can (1) keep important fungal hyphae and microorganisms in the soil intact, (2) prevent recurring weeds from popping up, (3) increase residual nitrogen and plant nutrients by top-composting plant residues, and (4) create valuable topsoil that is well suited for next year's seeds or transplants. The plant residues (leftover plant matter originating from cover crops, grass clippings, original plant life, etc.) will rot while underneath the cardboard so long as conditions remain sufficiently moist. This rotting attracts worms and beneficial microorganisms to the site of decomposition, and over a series of a few seasons (usually spring to fall or fall to spring) and up to a few years, will create a layer of rich topsoil. Plants can then be direct seeded into the soil during spring, or holes can be cut into the cardboard to allow for transplantation. Using this method in conjunction with other sustainable practices such as composting/vermicompost, cover crops and rotations are often considered beneficial to both land and those who remove crops from it.

No-till dramatically reduces field erosion. While much less soil is displaced, any gullies that do form will get deeper each year instead of being smoothed out by regular plowing. This may necessitate sod drainways, waterways, permanent drainways, etc.

Residue retention as surface mulch is essential for soil carbon sequestration and soil quality improvement in no-till systems. Rates of soil carbon sequestration (250–1,000 kg C/ha/yr) depend on soil properties, crop rotations, residue management, soil fertility management, and the length of time since conversion from plow tillage to no-till. Residue removal adversely impacts soil quality. Residence time of carbon sequestered in soil depends on soil properties (more for clay than sandy soils), depth (longer for subsoil than surface soil), vegetative cover (longer for perennials than annuals), and management. The soil carbon pool will be maintained or enhanced as long as a no-till system and other best management practices are used and maintained; any disturbance can release a substantial amount of carbon.

4.5 Management of Arid Soils

In conjunction with the SWP's enhanced coal bed methane (ECBM) sequestration test, a terrestrial pilot test (Test Letter H in Table 7) is being conducted in the San Juan Basin. ECBM operations are notorious for producing huge volumes of water. This water source is being desalinated and used for irrigating a riparian restoration project, forming a combined ECBM–terrestrial sequestration project. Although the desalination process is an expensive one, the Bureau of Land Management (BLM) and ConocoPhillips are both interested in making beneficial and environmentally friendly use of the produced water.

Rangelands in the San Juan Basin of New Mexico could potentially store large quantities of carbon in plants and in soil. The challenges to achieving this potential terrestrial C storage are (1) limited moisture and (2) reduced capacity for recovery. Optimizing carbon storage in soils and vegetation while increasing the value of other ecosystem services requires a two-pronged strategy: enhancing existing and reintroducing woody plant species along riparian areas, and reestablishing native grasses and shrubs in upland areas. The limiting factor in both cases is water. A reliable source of water for agricultural irrigation, such as the water produced during ECBM production, could provide the necessary base for the reestablishment of native vegetation with a host of environmental benefits in addition to carbon sequestration.

4.6 Restoration of Wetlands

Lost tidal marsh can be restored using clean dredged material (see Section 6.3.3). Restored and natural marsh at the Blackwater National Wildlife Refuge is sequestering carbon at an above-average rate compared to the national average, based solely on a surface accumulation rate of about 3.4 tonnes of C/ha/yr. The rate of carbon sequestration will likely vary across the wetland types within a proposed restoration. This estimate is conservative because it only accounts for surficial carbon deposits. Unfortunately, a significant portion of the carbon sequestration benefit in marshes can be offset through methane emissions.

5.0 Monitoring, Verification, and Accounting for Terrestrial Carbon Sequestration

Since the 1860's, soil carbon has been measured in relation to soil fertility and agricultural production. However, in the current context of global climate change, the goal is to measure soil carbon as a pool to decrease CO_2 buildup in the atmosphere. This is an important distinction. Terrestrial carbon is present in several forms, all of which must be accounted for to obtain an accurate picture of the total amount of carbon stored at a particular site and how this amount changes with time and management practices. This information is critical for obtaining carbon credits for trading.

The major terrestrial carbon pools are: aboveground biomass, belowground biomass (mainly roots), litter (fallen leaves, dead grass, etc.), and soil carbon. The following sections discuss methods for assessing each of these carbon pools.

5.1 Accounting Protocols for Terrestrial Carbon

Accounting protocols are formalized procedures for estimating the amount of terrestrial carbon stored at a particular site. Several organizations have developed such protocols, which differ from organization to organization, depending on their objective, the characteristics of the site (forests vs. grasslands, for example), remote vs. ground data gathering, and other factors. Brief discussions of some of these protocols follow.

5.1.1 Winrock International

Winrock International has developed an accounting protocol for assessing terrestrial carbon. Winrock International's Forest Carbon Monitoring Program (MacDicken, 1997) was developed as a way to provide reliable results using accepted principles and practices of forest inventory, soil science, and ecological surveys. The system assesses changes in four main carbon pools (aboveground biomass, belowground biomass, soils, and standing litter crop) with the objective of evaluating the net change in each pool for project and non-project (or pre-project) areas over a specified time period. Carbon monitoring efforts require specialized equipment, methods, and trained personnel, which can be expensive for individual organizations. Since most monitoring activities are likely to be performed infrequently (once every two to five years), the system is designed to minimize costs through collaboration between an organization with specially trained personnel and local organizations at each project site. Winrock's system involves the following components:

- Baseline determination of pre-project carbon pools in biomass, soils, and standing litter crop
- Establishing permanent sample plots for periodic measurement of changes in carbon pools
- Plotless vegetation survey methods (*quarter point* and *quadrat* sampling) to measure carbon stored in non-project areas or areas with sparse vegetation
- Calculating the net difference in carbon accumulated in project and non-project land uses
- Using SPOT satellite images as gauges of land-use changes and as base maps for a microcomputer-based geographic information system
- Software for calculating minimum sample size, assigning sample unit locations (either in a systematic grid or randomly), determining the minimum spacing for plots, and optimizing site-specific monitoring plans
- Computer modeling of changes in carbon storage for periods between field measurements
- A database of biomass partitioning (roots, wood, and foliage) for selected species

See the references (MacDiken, 1997) for a link to the Winrock report.

5.1.1.1 American Carbon Registry

The American Carbon Registry (ACR) is an enterprise of Winrock International. The American Carbon Registry Standard provides specifications for the quantification, monitoring, and reporting of project-based GHG emissions reductions and removals, verification of project registration, and issuance of offsets. The ACR Standard sets the level of quality that every project must meet in order for ACR to make GHG emissions reductions and removals into tradable and fungible environmental assets for voluntary and emerging U.S. pre-compliance carbon markets (ACR, 2010). Requirements are provided for Afforestation/Reforestation, Improved Forest Management, and Reducing Emissions from Deforestation and Degradation projects. See the references (ACR, 2010) for a link to the report.

5.1.2 U.S. Forest Service

The U.S. Department of Agriculture's Forest Service has also been active in developing accounting protocols for terrestrial carbon. Carbon stored in aboveground vegetation can be estimated based on aerial or satellite surveys or measurements taken on the ground. The Forest Service has developed several techniques for estimating carbon in forests (Pearson et al., 2007; Smith et al., 2005), including:

- The Carbon Calculation Tool (CCT)—http://nrsfs.fed.us/pubs/2394
- The Carbon Online Estimator (COLE)—http://www.ncasi2.org/COLE/
- The Forest Vegetation Simulator (FVS)—http://www.fs.fed.us/fmsc/fvs

5.1.3 The Terrestrial Carbon Group

Another organization that addresses terrestrial carbon accounting is The Terrestrial Carbon Group at the Heinz Center. Their report (Havemann, 2009) provides a great deal of information on accounting for terrestrial carbon pools. See the references for a link to their report.

The Terrestrial Carbon Group is an international group of specialists from science, economics, and public policy with expertise in land management, climate change and markets. Its objective is for terrestrial carbon to be effectively included in the international response to climate change. The Terrestrial Carbon Group is working to determine, support and guide the actions that are required to show how the ultimate aim of a holistic approach to terrestrial carbon can be realized. Guiding principles for effective action on terrestrial carbon are:

1. Maximise long-term terrestrial carbon volumes
2. Maintain existing terrestrial carbon and create new terrestrial carbon

3. Include all types of terrestrial carbon (using a phased approach starting with carbon and CO_2 in peatlands, forest, and lands that can become secondary forest)
4. Use a mix of complementary approaches (market and non-market, public and private)
5. Take action on terrestrial carbon in addition to, not in substitution for, deep reductions in greenhouse gas emissions from all other sources across the world
6. Recognize sovereignty over land management
7. Build appropriate national and international institutions
8. Avoid perverse outcomes
9. Adapt to best available information

5.1.4 U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency has a protocol for quick assessment of terrestrial ecosystems (Mayer et al., 2008). This protocol has three appendices covering different ecosystems:

Appendix B—Forested land—
http://www.epa.gov/nrmrl/pubs/600r08061/600r08061appb.pdf

Appendix C—Nonforested land
(http://www.epa.gov/nrmrl/pubs/600r08061/600r08061appc.pdf)

Appendix D—Wetland (http://www.epa.gov/nrmrl/pubs/600r08061/600r08061appd.pdf)

5.1.5 Chicago Climate Exchange (CCX)

The CCX has developed two protocols defining general provisions, rules for estimating carbon in long-lived wood products, and guidelines for verification under the following two eligibility scenarios:

1. The protocol for crediting carbon in long-lived wood products for commercial forest product companies registered in CCX.
2. The protocol for crediting carbon in long-lived wood products for CCX forest offset providers/aggregators.

These protocols establish the conditions that a CCX member must meet to have carbon sequestered in long-lived wood products included in the calculation of CCX Carbon Financial Instruments (CFIs).

5.1.6 Clean Development Mechanism (CDM)

This United Nations Framework Convention on Climate Change (UNFCCC) website (http://cdm.unfccc.int/methodologies/ARmethodologies/index.html) provides access to approved methodologies and the methodological tools agreed by the Executive Board for afforestation and reforestation projects.

The Clean Development Mechanism (CDM) is one of the flexibility mechanisms defined in the Kyoto Protocol (IPCC, 2007). One objective is achieved by allowing the Annex I countries to meet part of their caps using Certified Emission Reductions from CDM emission reduction projects in developing countries. The CDM allows industrialized countries to invest in emission reductions wherever it is cheapest globally. Between 2001, which was the first year CDM projects could be registered, and 2012, the end of the Kyoto commitment period, the CDM is expected to produce some 1.5 billion tons of carbon dioxide equivalent (CO_2e) in emission reductions. Most of these reductions are through renewable energy, energy efficiency, and fuel switching.

An industrialized country that wishes to get credits from a CDM project must obtain the consent of the developing country hosting the project that the project will contribute to sustainable development. Then, using methodologies approved by the CDM Executive Board (EB), the applicant (the industrialized country) must make the case that the carbon project would not have happened anyway (establishing additionality), and must establish a baseline estimating the future emissions in absence of the registered project. The case is then validated by a third party agency, called a Designated Operational Entity (DOE), to ensure the project results in real, measurable, and long-term emission reductions. The EB then decides whether or not to register (approve) the project. If a project is registered and implemented, the EB issues credits, called Certified Emission Reductions (CERs, commonly known as carbon credits, where each unit is equivalent to the reduction of one metric tonne of CO_2e, e.g. CO_2 or its equivalent), to project participants based on the monitored difference between the baseline and the actual emissions, verified by the DOE.

5.1.7 Other Organizations

A number of other organizations are involved with terrestrial carbon accounting, including the North American Research Center, The Nature Conservancy (TNC), Ducks Unlimited, Inc. (DU), the carbon credit program, and the National Carbon Capture Center (NCCC), which developed accounting protocols for forested lands under the Big Sky Regional Carbon Sequestration Partnership. TNC has submitted protocols for projects to CDM.

A credible terrestrial sequestration MVA program will require close attention to integrating the direct measurement of carbon in soils and vegetation with the use of statistically valid scaling, models, and remote sensing.

5.2 Classical Methods for Measuring Soil Carbon

The world's soils contain a large, dynamic pool of C that plays a critical role in regulating the global carbon budget (Lal, 2004). Soils affect the global carbon-cycle through carbon storage; via photosynthesis and litter accumulation and decomposition; and contribute to GHG production, via respiration, combustion, and decay. Carbon is central to soil quality; it is the third most abundant element in the soil after oxygen and silicon. Assessing the C inventories and fluxes of soil has gained importance because the ability to measure stored C in soils and in aboveground biomass is critical to understanding C cycling in terrestrial ecosystems (Ellert et al., 2001). Also, trading of C credits for terrestrial storage will depend upon the existence of inexpensive methods for quantifying and verifying soil C content over large land areas.

Efforts to understand and address C management at the regional and global scales stimulated the development of more efficient methods for soil C determination (Bricklemyer et al., 2008; Greenland, 1998; McCarty and Reeves, 2001; National Research Council, 1999; Wielopolski et al., 2008). There is a need for rapid, accurate, inexpensive analyses that measure C content using standardized protocols and methods that overcome the limitations of the current approaches. Such improved analyses are essential to detect and quantify changes in the level of C present in ecosystems.

Soil is a dynamic system—a mix of living and dead plant matter, fungi, macro- and microfauna, plant exudates, and animal waste embedded in a matrix of solids, liquids, and gases—that is altered when it is removed from its location. Studying the component parts of soil presents a challenge because dissecting the soil changes the overall compositional dynamic (Johnston et al., 2004).

Carbon in soil is mainly associated with the soil organic matter (SOM). The fact that many methods have been developed for the determination of SOM indicates the importance of quantifying SOM. There is an extensive literature on both *ex situ* soil analysis (Rosell et al., 2001; Schumacher, 2002; Tan, 2005; Tiessen and Moir, 1993) and *in situ* analysis (Chattarjee et al., 2009; Gehl and Rice, 2007), however, the capabilities of these methods are limited, offering varying degrees of usefulness. Carbon in soil occurs in two general forms, organic and inorganic, that must be distinguished during analysis and reporting.

Traditionally, C concentration is reported as the mass of C per unit mass of soil (kg/kg) and is usually expressed as percent C. This unit of measurement is adequate when reporting local levels or changes in soil C, assuming that field conditions are unchanged. However, when calculating soil C pools or comparing results from different fields, the measure of carbon should be standardized to account for differences in the soil's bulk density and the sampling depth. Clearly, the C content in soil derived from two different depths will be dissimilar, as will the results from soils collected at the same depth but with different bulk densities. Thus, C stocks in the field are expressed on an area basis as the total mass of organic carbon (to a depth of 30 cm) per unit area (using one of the units, g C/cm^2, kg C/m^2, or tonnes C/ha).

For a total C inventory, it is customary to report concentrations to a depth of one meter. These calculations require data on the soil's bulk density (determined at known depth increments), together with information on its content of rocks and root fragments. This generates significant uncertainty in the calculations (Post and Kwon, 2000); in particular, determining total soil volume for a range of soils, including those with high gravel content, high organic-matter content, and high swell-shrink properties, produce doubts in estimating the soil's bulk density (Lal, 2006). These difficulties greatly confound the assessment of the soils' bulk density and C content on an area basis.

5.2.1 *Ex situ* Classical Methods and Current State-of-the-Art Approaches

Many analytical methods have been proposed for the determination of C in soils. However, these methods have some issues, and a generally satisfactory method has yet to be formulated. In most cases, the method used depends on the objectives of sampling and the type of soil. The two preferred *ex situ* methods are wet oxidation and dry combustion (Rosell et al., 2001). Wet oxidation involves, After proper sample preparation, dissolving the sample in dichromic acid and determining Cr^{+3} or the evolved CO_2. In dry combustion, the sample is oxidized at high temperature, and the CO_2 given off is measured either by the change in the mass (loss-on-ignition—LOI) or by collecting the evolved CO_2 with automated instruments (Table 5). In both methods the SOC is oxidized at a high temperature.

The LOI method entails heating the sample in a muffle furnace between 200-500 °C; dry oxidation is accomplished via an automated analyzer operating between 950-1150 °C. At high temperatures, carbonates decompose, giving a measure of total C, rather than only organic C. While the LOI method is a simple, rapid, and inexpensive method to determine SOC, a LOI-SOC regression equation must be derived for each soil type and sampling depth. The correlation between LOI and SOC is improved by including the percentage of clay in a bivariate regression equation. For good results, the ignition temperature, the exposure time, and the sample size must be consistent; this information should be included when reporting results (Heiri et al., 2001; Konen et al., 2002).

The results from dry combustion with automated analyzers offer higher precision than those from wet combustion, but the analysis costs more due to the expense of the analyzer (about $60,000). Operating costs also are slightly higher, because the analysis requires consumables and high purity gasses (He and O_2) and a significant amount of electricity to heat the furnace. Jimnez and Ladha (1993) estimated the cost for analyzing total soil carbon (TSC) using a Perkin-Elmer 2400 CHN analyzer as $3.80 and $6.50 per sample for running 100 samples versus 10 samples, respectively, in a single operation; today's costs are triple these values. The limitations and applicability of these methods are discussed in Tiessen and Moir (1993).

Besides carbonates, soils have carbonaceous components, such as coal and charcoal (Black C), which interfere with determining SOC. The presence of coal is a major concern in assessing the effect of reclamation measures on mine lands, while charcoal may be present in soils affected by fire. Coal-derived C can be measured quantitatively by its radiocarbon (^{14}C) activity; however, this method is very expensive, and few facilities are equipped to undertake this analysis (Rumpel et al., 2003). Alternatively, coal-derived C can be determined by diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy, in combination with multivariate statistical analysis; measurements by this method correspond well with ^{14}C values (Rumpel et al., 2001). Recently, Ussiri and Lal (2008) have developed a cost-effective chemo-thermal method for this assessment; it showed high recovery, comparable to ^{14}C measurements. Several approaches based on thermal and/or chemical oxidation can quantify charcoal C, but the extent of recovery varies widely because charcoal particles occur in a wide continuum of sizes, ranging from large pieces of slightly charred biomass (1-100 µm) to submicron soot particles (30-40 nm) (Hammes et al., 2007; Hedges et al., 2000; Masiello, 2004).

A comparison of *ex situ* methods indicates that no single method offers both high precision and low cost. Automated dry combustion analyses offer high precision, while the LOI method is inexpensive. The cost of assessing soil C can be lowered if a relationship is established between LOI and automated dry combustion for a particular soil type. However, it is rare to find a strong linear relationship between the two (Abella and Zimmer, 2007). Further, there is wide variation in the recovery of C in the Walkley and Black wet digestion method (Walkley and Black, 1934), and it does not strongly correlate with the findings from the automated dry combustion technique

(De Vos et al., 2007); furthermore, the disposal of chemicals is environmentally problematic. In general, automated dry combustion appears to be the more reliable, comprehensive method to determine soil C concentration, with the added benefit of simultaneously measuring N and S. If the budget is limited, the LOI method could suffice, rather than the automated technique; however, their correlation factor should be reported with the results. Chatterjee et al. (2009) reviewed *ex situ* methods (see Table 5).

The standard method for carbon analysis is sampling soil in the field, followed by automated dry combustion, However, the whole process is time-consuming, labor intensive, and expensive. The automated analysis of a prepared soil sample costs about $12. Moreover, without intensive sampling, it is hard to detect changes in soil C over large areas due to spatial heterogeneity (Freibauer et al., 2004). All laboratory analyses use a small quantity of homogenized sample, generally 0.1 to 1 g. These major limitations of *ex situ* methods instigated the development of alternative methods, particularly *in situ* methods, to achieve higher precision and faster results with lower costs.

Table 5: Features of ex situ soil C determination methods

Wet Combustion				
Combustion	Sample heated with K2Cr2O7-H2SO4-H3PO4 mixture in a CO_2-free air stream to convert OC to CO_2.	Gravimetric/	Measures total organic C (TOC) in absence of inorganic C/ Requires sample preparation and quantitation, requires careful analytical techniques, titrimetric is less precise	Schollenberger, 1927;
Van-Slyke-Neil apparatus	Sample heated with a K2Cr2O7-H2SO4-H3PO4 mixture in a combustion tube to convert OC to CO_2.	Titrimetric	Simple to conduct, no need to maintain a CO_2 free atmosphere/ Expensive apparatus, requires skill to operate, apparatus is easily damaged.	Nelson and Sommers, 1982;
Walkley-Black	Sample heated with K2Cr2O7-H2SO4-H3PO4 mixture; excess dichromate is back- titrated with ferrous ammonium sulfate.	Manometric	Simple, rapid, minimal equipment needs/ Oxidation factors are needed due to incomplete oxidation, generates hazardous byproducts, such as Cr.	Chatterjee et al., 2009.
Dry combustion				
Weight-loss-on-ignition	Sample heated to 430 °C in a muffle furnace over 24 hours.	Gravimetric	Ensures combustion of all C forms, measures TOC or total C at temperatures above 1350 °C, relatively fast and inexpensive/ Weight loss due to moisture and volatile organic compounds over- estimates the organic matter, requires no leak gas flow system.	Christensen and Malamros, 1982
Automated	Sample mixed with catalysts or accelerator and heated in resistance or induction furnace in O_2 stream to convert all C to CO_2.	Thermal conductivity, gravimetric, spectrophotometric	Method of choice, rapid, precise, no loss of C, measures C, N, H and S, can be connected to mass spectrometer/ expensive, slow release of contaminant CO_2 from alkaline earth carbonates with resistance furnace.	Smith and Tabatabai, 2004;

5.3 Determining Aboveground Carbon

It is necessary to estimate aboveground biomass (AGB) to study productivity, carbon cycles, nutrient allocation, and fuel accumulation in terrestrial ecosystems. It is also necessary to assess the growth of aboveground vegetation from baseline AGB to determine overall carbon uptake of a given terrestrial sequestration effort (for example, mine land reclamation or afforestation projects).

5.3.1 Determining Carbon in Aboveground Biomass

Temporal and spatial biomass production patterns in forests are a direct measure not only of productivity, but also of nutrient accumulation and distribution. Measurements to quantify the amount and distribution of biomass are important in understanding the structure and function of the ecosystem as well (Grove and Malajczuk, 1985). This in turn provides invaluable information for decision makers in afforestation and reforestation programs. When possible, aboveground biomass can simply be measured by clipping all the vegetation to the surface level, separating the live plant material from dead, and weighing the dry biomass. In forests this procedure is not practical; instead the biomass is estimated from allometric relations between the tree diameter at breast height (dbh) and tree biomass (Ter-Mikaelian et al., 1997; Tritton and Hornbeck, 1982; Zewdie et al., 2009). Various dendrometic variables are used in the regression analysis with dbh being the most common. Typical regressions lead to power relationships that are expressed in logarithmic form. Satellite observations can be obtained over large areas with high revalidation frequencies. These remote sensing techniques enable the examination of ecosystem properties and processes and their variability at multiple temporal and spatial scales. Remote sensing, in addition to satellites, can be obtained using airplanes, balloons, and high towers. Many studies have demonstrated that indices, such as spectral vegetation index (SVI), simple ratio (SR), normalized difference vegetation index (NDVI), and corrected normalized difference vegetation index (NDVIc) obtained from satellite data are useful predictors of leaf area index (LAI), biomass, and productivity in grasslands and forests (Zheng et al., 2004).

Remote sensing is mainly based on the behavior of the visible and near-visible part of the electromagnetic spectrum when interacting with materials and objects. The bulk of the radiation sensed is either reflected or emitted from the target, generally through air until it is detected by a sensor that responds to reflected intensity, spatial dependence, and spectral distribution. Major elements of a remote sensing system include: (1) an optical system of lenses, mirrors, apertures, modulators, and dispersion devices; (2) detectors that provide an electrical signal proportional to the irradiance on its active surface (may be wavelength dependent); and (3) a signal processor for the desired output data. The data from the scanned area is presented in the form of a pixilated image that reveals vegetation type and state (Figure 2). Through remote sensing it is possible to quantify on

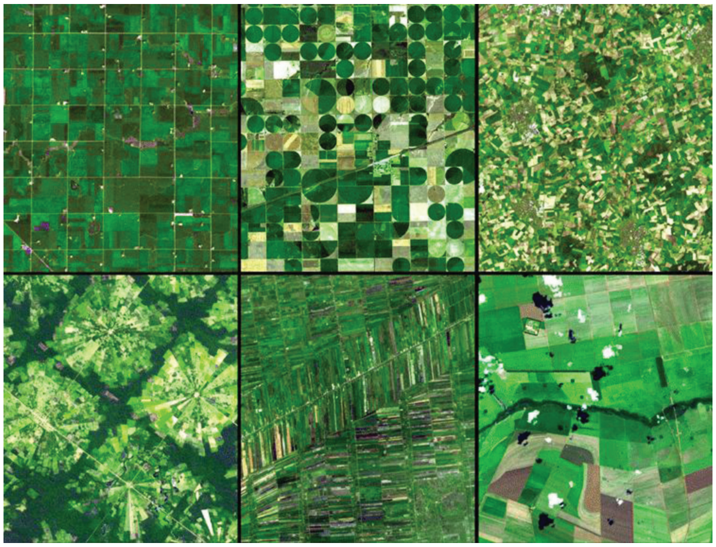


Figure 2: Satellite images of various crops and field patterns: upper left, Minnesota; upper center, Kansas; upper right, Northern Germany; lower left, Bolivia; lower center, Thailand; and lower right, Brazil (RST, 2003)

a global scale the total acreage dedicated to various crops at any time. Of particular importance is the use of space observations to accurately estimate (best case 90 percent) the expected yields of each crop, locally, regionally, or globally, thus estimating the aboveground biomass.

5.3.2 Carbon in Litter

Carbon measurements in downed and dead wood, forest floor, and mineral soil are identified as critical data gaps in the United States' assessment of carbon (Havemann, 2009). Litter is organic debris on the soil surface and is usually freshly fallen or slightly decomposed vegetation. The standing litter crop is the total weight per unit area of litter on the soil surface at the time of sampling. Measurement of the standing litter crop does not require monitoring of litter fall.

Changes in standing litter crop can be important, particularly when forest soils are converted to land uses that oxidize organic matter (e.g., crops that require intensive cultivation). It is easy to measure the standing litter crop, but it requires consistent adherence to pre-defined standards. Measure the standing litter crop by collecting all litter on the soil surface in each of the sampling frames used for measuring herbaceous vegetation. Samples can be bulked by plot. Samples should be weighed and subsamples collected in the same way as for herbaceous vegetation (see Appendix 5 in Winrock's report). Care should be exercised to ensure that the litter comes from the area of interest and was not blown in from an adjacent area.

5.4 Determining Carbon in Belowground Biomass

Even at moderate levels of precision, measuring root biomass is time consuming and expensive due to the wide variability in the way that roots are distributed in the soil. For many projects, the best approach may be to estimate root biomass using a conservative ratio for root/shoot biomass as the basis for claiming carbon credit. For example, if the lowest root/shoot ratio reported for species X is 5:1, a conservative estimate, without measuring roots, would be a calculation of root biomass as not less than 10 or 15 percent of above-ground biomass. However, for cases in which more accurate estimates of belowground biomass are required, Appendix 7 in Winrock's report (MacDiken, 1997) describes measurements using pit, auger/core sample, and pinboard monolith methods. Root/shoot ratios for some tree species are available in the literature. Based on 160 studies, Cairns et al. (1997) found a mean root/shoot ratio of 0.26 with a range of 0.18 to 0.30.

5.5 Determining Soil Bulk Density

The following material is adapted from Lal et al. (2006). Soil bulk density is defined as $\rho_b = M_s/V_t$, where M_s is the mass of soil and V_t is the total volume; ρ_b needs to be appropriately corrected for gravimetric moisture content: $\rho_b = \rho_b'/(1 + w)$, where ρ_b is the dry bulk density, ρ_b' is the moist bulk density, and w is the gravimetric moisture content. To obtain an accurate value of ρ_b, M_s, V_t, and w must be measured accurately. Accurate values of M_s and w can be obtained gravimetrically, but V_t is more challenging. Two methods of measuring V_t are the core method and the clod method. The core method is simpler but has some problems, such as difficulties with sandy or noncohesive soils, compression and distortions (especially in small cores), and incomplete core in gravelly soils or those with coarse roots.

The clod method is an alternative to the core method. In this method, a clod of known weight is coated with a water-repellant material, such as saran, paraffin, or wax. The volume is then determined by water displacement. The clod method is usable under field conditions.

In gravelly or noncohesive soils, where it is difficult to obtain either cores or clods, soil is excavated and weighed. The volume of the excavation is determined by the sand replacement method or the rubber balloon method. The accuracy of this method depends on the ability to measure accurately the amount of sand or air to completely fill the excavation.

Indirect methods, involving radiation, are also available. Most instruments involve γ-radiation from a ^{137}Cs source and are either the backscatter type or the transmission type. For *in situ* use, radiation instruments must be calibrated under site specific conditions. Calibration is affected by several factors, including soil chemical composition, gravel concentration, and horizonation. Calibration is also influenced by hydrogen, which is present both in water and soil organic matter.

Gravelly soils pose a major challenge in the measurement of soil bulk density. Neither radiation nor direct methods (e.g., core and clod) are applicable for gravelly soils. If the gravel or concretions are 2–10 mm in size, corrections for skeletal material are required. Corrections involve separate measurement of the mass and volume of the gravel fraction.

5.6 Determining Surface CO_2 Fluxes

Alternative, albeit indirect, methods of monitoring belowground activity and the status of carbon involve measuring surface CO_2 flux and aboveground growth. CO_2 flux monitoring at the soil-atmosphere interface entails direct and indirect methods, sometimes refered to as the net ecosystem exchange (NEE). The aboveground determination of carbon stock entails allometry, the study of the relationship between size and shape (Niklas, 1994), and remote sensing (Short, 2006). The eddy covariance (eddy correlation, eddy flux) technique is a prime method for measuring atmospheric CO_2 flux, thereby calculating vertical turbulent fluxes within atmospheric boundary layers (Munger and Loescher. 2010). Eddy covariance is a statistical method, used in meteorology and other applications, that analyzes high-frequency wind and scalar atmospheric data series to yield values of the fluxes. Such measurements are widely used to estimate momentum, heat, water, and CO_2 exchange, as well as the exchange of methane and other trace gases.

Figure 3: Eddy covariance system consisting of an ultrasonic anemometer and infrared gas analyzer (IRGA)

However, the eddy covariance method is mathematically complex, requiring significant care to set up and process the data. The method's main challenge is the complexity of system design, its implementation, and processing the large volume of data. One option is to incorporate a microclimate station containing an anemometer mounted on a tower (Figure 3). An eddy covariance tower provides information from a fixed point in space that must be extrapolated to the region. The footprint covered depends on the tower's height, the complexity of the terrain, and the type and size of vegetation.

An approach for near-surface gas monitoring is the accumulation chamber (AC) method for measuring soil CO_2 flux at discrete locations over an area of several square centimeters. In this technique, an AC with an open bottom is placed either directly on the soil's surface or on a collar installed on the soil's surface; the contained air is circulated through the AC and an infrared gas analyzer (IRGA). The rate of change of CO_2 concentration in the chamber is used to derive the flux of CO_2 across the soil's surface at the point of measurement (LBNL, 2004). LI-COR (4647 Superior Street, Lincoln, Nebraska) operates several sensitive ACs with different power consumptions. While this technique lacks the ability to measure CO_2 flux over a large area, data acquired can be extrapolated over an area with the same soil characteristics and under the same environmental influences.

5.7 Advances in Carbon Analyses for Terrestrial Carbon Sequestration

Estimates of terrestrial carbon accumulation rates are inherently uncertain. Spatial heterogeneities of topography, climate, vegetative cover, and soil type combine to make it very difficult to accurately "scale up" from a few site-specific measurements to regional estimates. However, to get a better understanding of the terrestrial role in the overall carbon cycle and the role of terrestrial sequestration on a global scale, new analytical techniques are needed which can cheaply evaluate large land areas in a short time.

Achieving this goal will require several developments, including:

- Rapid, low cost, in situ soil analyses that can be conducted in the field and cover large areas in a relatively short time.
- Improved tables of root/shoot ratios.
- Improved remote sensing to more accurately quantify aboveground biomass.
- Improved models to produce more accurate estimates of the carbon stored in various pools.

Promising additional technologies are being developed, through federal and private sector funding, to quantify soil carbon over large areas. Some promising analytical techniques for achieving this are described in Table 6.

6.0 Regional Carbon Sequestration Partnership Terrestrial Field Tests

The U.S. Department of Energy (DOE) selected seven partnerships, through its Regional Carbon Sequestration Partnership (RCSP) initiative, to determine the best approaches for capturing and permanently storing CO_2. The RCSPs are made up of state and local agencies, coal companies, oil and gas companies, electric utilities, universities, private companies, and nonprofit organizations. These partnerships form the core of a nationwide network helping to establish the most suitable technologies, regulations, and infrastructure needs for carbon sequestration. The partnerships include more than 400 organizations, spanning 43 states and four Canadian provinces. The RCSPs are developing the framework needed to validate and deploy carbon sequestration technologies. The RCSPs will determine which of the numerous geologic and terrestrial sequestration approaches are best suited

Table 6: Key features of advance (in situ) soil C determination techniques

Method	Principle	Penetration in soil (cm)	Sampled volume (cm^3)	Advantages/Disadvantages	References
Laser induced breakdown spectroscopy (LIBS)	Laser-ablated sample forms micro plasma that, upon cooling, emits light from the ionized atomic- and molecular- species	0.1	~10^{-2}	High spatial resolution, ~1 mm, minimal sample preparation/ Small mass, point measurement, presence of roots and rocks increases C signal variability, requires signal normalization	Cremers et al., 2001; Ebinger et al., 2003; Martin et al., 2003; Martin et al., 2010
Mid- and Near-infrared reflectance spectroscopy (MIRS/NIRS)	NIRS (0.4-2.5 µm) and MIR (2.5-25 µm) region utilized to quantify soil C; based on the absorption by the C-H, N-H and O-H bonds found in organic constituents	0.2-1	~10	Minimal sample preparation, chemical speciation, measures organic carbon/small mass, destructive, strong matrix interferences, isotopic and C specie sensitive, intensive spectral analysis	Reeves III, 2000; Reeves III, 2010; Shepherd and Walsh, 2007; McCarty et al., 2002; Madari et al., 2006
Inelastic neutron scattering (INS)	Based on spectroscopy of gamma rays induced by high, 14 MeV, and low energy neutrons	30	~10^5	Non-destructive, no sample preparation, multi-elemental, measures elemental total carbon, analyzes large mass, ~300 kg, scanning capability, provides true sequential measurements, has an ex[licit analytical expression for the response function/ Requires radiological permits for neutron generator	Wielopolski et al., 2004; Wielopolski et al., 2008; Wielopolski et al., 2010a; Wielopolski et al., 2010b; Wielopolski et al., 2010c

for their specific regions of the country and identify regulatory and infrastructure requirements that will be needed should policy and economics indicate that sequestration be deployed on a wide scale. Although the RCSPs are conducting both geologic storage and terrestrial storage field tests, only the terrestrial storage tests are discussed in this best-practices manual. Results and assessments from these efforts will assist commercialization efforts for future sequestration projects in North America.

The seven partnerships include:

- Big Sky Regional Carbon Sequestration Partnership (Big Sky)
- Plains CO2 Reduction Partnership (PCOR)
- Midwest Geological Sequestration Consortium (MGSC)
- Midwest Regional Carbon Sequestration Partnership (MRCSP)
- Southeast Regional Carbon Sequestration Partnership (SECARB)
- Southwest Regional Partnership on Carbon Sequestration (SWP)
- West Coast Regional Carbon Sequestration Partnership (WESTCARB)

6.1 RCSP Validation Phase

Terrestrial storage field tests are being conducted as part of the Validation Phase (the second phase of the three phase RCSP program), which focuses on validating the most promising regional opportunities to deploy CCS technologies. The RCSP's are conducting 11 terrestrial sequestration tests (Figure 4). The terrestrial Validation Phase tests focus on the uptake of atmospheric CO_2 into soils and vegetation through activities such as tree-plantings, no-till farming, wetlands restoration, land management (grasslands, grazing lands), fire management, forest preservation, employing effective MVA technologies, and implementing and understanding accounting protocols for trading markets (CCX). Table 7 summarizes the RCSP terrestrial field testing efforts.

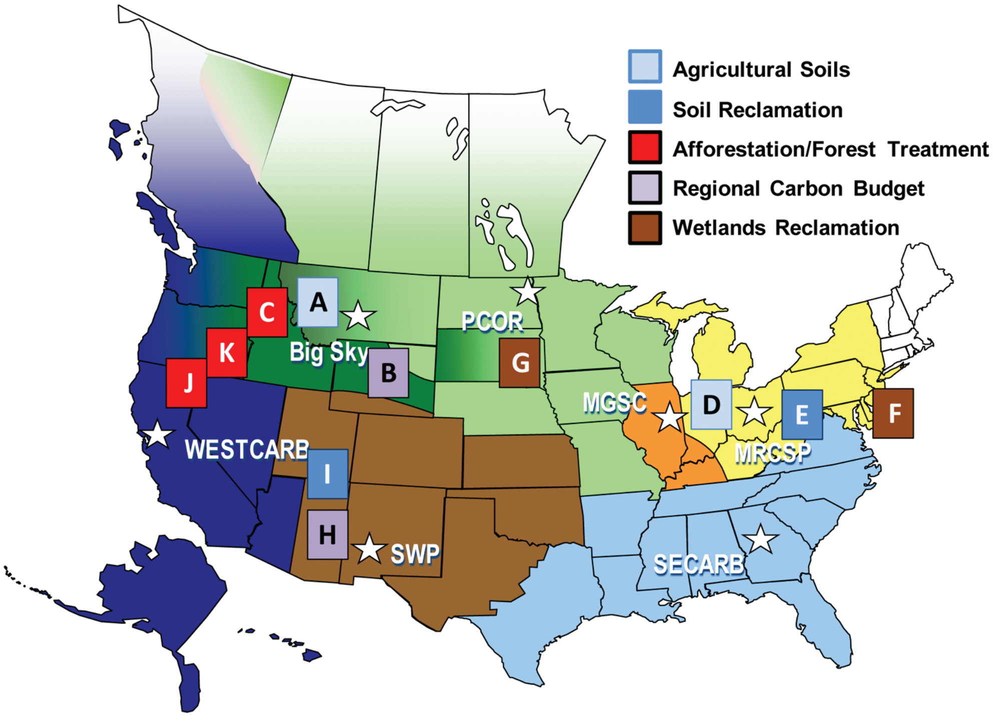


Figure 4: RCSP Validation Phase Terrestrial Field Test Locations and Type

Table 7: Summary of RCSP Validation Phase Terrestrial Field Tests

Test Letter	Partnership	Location	Estimated CO$_2$ Capacity, Mt*
A	Big Sky	North Central, MT	60 Mt over 20 years
B	Big Sky	Eastern, WY	30 Mt over 10 years
C	Big Sky	Region-Wide	640 – 1,040 Mt over 80 years
D	MRCSP	Region-Wide	25 Mt over 20 years
E	MRCSP	Region-Wide	100 Mt over 20 years
F	MRCSP	Cambridge, MD	TBD
G	PCOR	Great Plains – wetlands complex (PPR)	14.4 Mt
H	SWP	Region-Wide	TBD
I	SWP	San Juan Basin Coal Fairway (Navajo City, NM)	TBD
J	WESTCARB	Shasta County, CA	4,600 Mt over 80 years
K	WESTCARB	Lake County, OR	900 Mt over 80 years

The purpose of these terrestrial sequestration field tests is to reduce the amount of CO$_2$ in the atmosphere by enhancing the storage capability of soils, grazing and crop lands, and trees through changes in management practices. The RCSP Validation Phase terrestrial field tests are designed to test multiple terrestrial sequestration options across varying regional settings and determine best practices for terrestrial carbon sequestration.

The following sections summarize the RCSP terrestrial sequestration Validation Phase field tests, including a brief description of each test, an overview of the regional setting, testing procedures, and results and lessons learned.

6.2 Big Sky Carbon Sequestration Partnership

The Big Sky Partnership (Big Sky) region provides tremendous potential for GHG offsets through terrestrial carbon sequestration in forests, rangelands, and agricultural croplands. The Big Sky Region encompasses Montana, Wyoming, Idaho, South Dakota, and eastern Washington and Oregon; the overall land area includes considerable acreage of agricultural, range, and forest lands that can be managed for greater storage of soil carbon and carbon in biomass. Based on current land use practices, the Region can potentially sequester 6.7 million tonnes of CO$_2$ per year in agricultural lands (NETL, 2008). The partnership currently has a comprehensive terrestrial sequestration program. The Big Sky Partnership has designed cropland, rangeland, and forestland field validation tests to advance the partnership's Characterization Phase market-based carbon storage methods and verification protocols to demonstrate the viability of emerging pilot carbon markets. Big Sky has developed a market-based approach to carbon storage and verification protocols that includes: (1) establishing terrestrial pilots in cropland, forestland, and rangeland; (2) designing carbon portfolios in conjunction with industry, tribal members, and landowners; and (3) conducting a remote sensing study of management practices and adoption trends in north-central Montana.

6.2.1 Cropland Field Validation Test

The cropland field test (Test Letter A from Table7) is being conducted in north central Montana which consists of over two million hectares of cropland. Small grain agriculture is the most common land-use practice in the region. Since the early 1900's, the region has been under cultivation with soil management progressing from intensive moldboard plowing to less intensive cultivation to no-till or direct-seed management. The objectives of this test are to: (1) quantify and determine cropland management practices that optimize carbon sequestration in semi-arid Montana; (2) develop MVA protocols to evaluate carbon sequestration for farms enrolled in carbon trading; and (3) investigate satellite image analysis as an alternative to the on-site verification of National Carbon Offset Coalition carbon contract compliance and as a means to remotely obtain cropland data used in predicting farmland soil carbon sequestration.

6.2.1.1 Controlled Study

Existing field trials at six controlled benchmark sites address the first objective by testing the effects of tillage vs. no-tillage and fallow-wheat vs. pulse-wheat crop rotations. Standard carbon measurement was used for this study and involves employing dry combustion and modified pressure calcimeter analysis for total carbon and inorganic carbon, respectively. This practice is typically well respected and documented. This method relies on efficient sampling designs to measure SOC temporally and spatially. Big Sky's soil sampling will provide critical look at effects of management practices on SOC after six years, often regarded as the first checkpoint where changes in C can be reliably measured against background total organic content (TOC).

Results from this test suggest that increasing cropping intensity (i.e., fewer years of summer fallow) will be key to increasing SOC. No-till management showed no increase in measured and estimated biomass carbon inputs, and so any measured soil carbon change will be more likely related to an alteration of soil organic matter decomposition. However, the carbon budget illustrated that five of six annually cropped systems had significantly greater carbon inputs than the fallow-cropped system and averaged 1.4 Mg ha^{-1} greater carbon input across all six sites. Greater carbon inputs, coupled with a soil context less favorable to carbon loss, highlight the importance for annual cropping in increasing soil organic carbon. The creation of economic incentives that encourage greater cropping intensity could be beneficial to increasing SOC in the region.

6.2.1.2 Enrolled Site Proximal Soil Sensing MVA

MVA technologies and protocols will be developed and tested at eight enrolled sites to address the second objective. The goal of this component is to determine if remote sensing can be used to accurately identify agricultural practices specified in carbon contract agreements as set by the National Carbon Offset Coalition. This will include using remote sensing techniques to identify no-till, crop intensity, and conservation reserve lands. The MVA methods compared to estimate soil carbon content are: (1) lab-based and "on-the-go" visible and near-infrared (VisNIR) spectroscopy; (2) LIBS; and (3) conventional laboratory methods.

VisNIR spectral signatures of materials are defined by their reflectance, or absorbance, as a function of wavelength. These signatures are due to electronic transitions of atoms and vibrational stretching and bending of structural groups of atoms that form molecules and crystals. SOC and soil inorganic content (SIC) are both molecular components of soil and VisNIR has been shown to semi-quantitatively estimate SOC and SIC in soils. "On-the-go" VisNIR has the advantage of quickly collecting large amounts of spatial VisNIR data to map soil variability within fields.

LIBS is essentially an elemental analysis technique that involves directing a focused Nd:YAG (neodymium-doped yttrium aluminum garnet (used as a laser medium) onto the surface of the target material. The focused laser excites a small amount of surface material from creating a supersonically expanding plasma of electronically excited ions, atoms, and small molecules. These species emit light as they relax back to lower electronic states at wavelengths that identify the elements present in the sample. Some of this emission is directed into a dispersive spectrometer and the resulting spectrum is detected with a charge-coupled device (CCD) detector. Combining VisNIR and LIBS sensors could provide quantitative determination of SOC and SIC.

The completed study of proximal soil sensing using “on-the-go” VisNIR results show that lab-based spectroscopy provided more accurate predictions than “on-the-go” VisNIR. “On-the-go” VisNIR did show potential for mapping soil properties with some potential limitations. Findings suggest that “on-the-go” VisNIR may be best applied to mapping fields or regions with relatively high SOC and clay content variability. Initial simulations for *in situ* SOC measurements using LIBS have been completed by Big Sky. Results indicate that LIBS spectral data, collected on intact soil cores, can be calibrated to accurately estimate and differentiate between soil total and inorganic C concentrations using multivariate regression analysis. A lack of SOC variability limited the ability to evaluate LIBS SOC prediction capabilities. Calibrating LIBS models with soil datasets exhibiting greater SOC variation in conjunction with expanding the LIBS spectral range to capture emissions from a broader range of elements related to soil organic matter might improve SOC predictions. It is a more rapid approach and more cost effective than standard analyses.

6.2.1.3 Remote Sensing Study

The third objective is being addressed via a remote sensing study that relies primarily upon analysis of Landsat Thematic Mapper (TM) satellite imagery. Field locations for data collection were determined by applying a random point generator to the TM image set following an image masking process to remove non-agricultural areas. A file containing a road spatial area was then overlaid onto the imagery and all generated points located away from road structures were removed. As a result, about 500 semi-random field reference locations were generated (about 1/4 of these sites turned out to be rangeland sites), and site visits to each occurred in June 2007. A collection of cropping status (vegetated or fallow), crop type, and tillage management (till vs. no-till) was taken for each site. These locations included 220 fields under no-till management and 201 fields under conventional tillage management. 112 of these sites were fallowed and 309 were vegetated.

An image-object or object-oriented approach is being used to classify cropland. A raster-based satellite imagery approach is used that is ultimately segmented, generating vector-based data representative of cropland fields. The field-based spectral data associated with the field reference locations were incorporated into a Breiman Cutler Classification and Regression Tree-based model (presented as randomForest). The resulting imagery includes six Landsat Thematic Mapper paired scenes (39-26 and 39-27) and two Landsat Enhanced Thematic Mapper scenes. Image pre-processing efforts, which include geometric correction, cloud masking, conversion from scaled pixel values to top-of-atmosphere reflectance, and non-agricultural masking, have been completed for these image sets. The completed study and results indicate the separation of no-till from conservation tillage management through spectral and textural-based satellite mapping is unlikely with Landsat data alone, given the current technology and similarities in surface residue coverage. Attempts to build a classification model based on the acquired imagery resulted in poor class accuracies. Rangeland that was misclassified as cropland was a large source of error (30 percent misclassification rate). Within north central Montana, variability in the degree of soil disturbance associated with more moderate forms of tillage has made it difficult to separate fields characterized by minimum disturbance tillage from those under no-till, using available Landsat TM data. Fields thought to be under minimum tillage were often misclassified as “no-till” due to surface spectral similarities likely attributed to the presence of surface stubble (Figure 5).

Figure 5: A minimally tilled field in north central Montana (foreground) with surface stubble characteristics similar to that of the neighboring no-till field (background).

However, the incorporation of MODIS (Moderate Resolution Imaging Spectroradiometer), a satellite-based imaging tool deployed by the National Aeronautics and Space Administration (NASA) data is being investigated as a means of improving till vs. no-till accuracy.

A summary of the tools used for the cropland field validation (Section 6.2.1.1, 6.2.1.2, and 6.2.1.3) test is provided in Table 8.

6.2.2 Rangeland Sequestration Potential Assessment

Continuing a study that began in 1982, this field test (Test Letter B in Table 7) focuses on determining best management practices for carbon sequestration on rangelands. The Rangeland Sequestration Assessment Potential Group (RSAPG) is evaluating and quantifying carbon sequestration potentials of different rangeland practices in eastern Wyoming to determine overall carbon sequestration potential. Grazing rangelands can influence plant community structure, soil chemical and physical properties, and the distribution and cycling of nutrients within the plant-soil system. The spatial and temporal distribution of grazing patterns, as well as grazing intensity and other land management practices, can produce measurable differences in soil carbon content. Through proper rangeland management, opportunities may be available to partially mitigate CO_2 concentrations via sequestration of atmospheric CO_2 thorough storage in biomass and soil organic matter. This study is intended to investigate the effects of grazing intensity (none, light, heavy) on season long grazing and rotationally grazed pastures. The test includes soil and biomass sampling at two long-term rangeland sites in eastern Wyoming on a native northern mixed-grass prairie. An assessment of storage potential for these rangelands is being performed, including potential benefits to ranchers. Findings from this field test are expected to be relevant to rangelands in Montana and eastern Colorado.

Table 8: Overview of Monitoring Techniques and Applications for the Big Sky Partnership Cropland Field Validation Test

Measurement Technique	Measurement Parameters	Application
Controlled site benchmark sampling locations	Standard soil organic carbon (SOC) measurement (bi-annually): TC-IC=SOC, where TC = total carbon by dry combustion, IC = inorganic carbon by modified pressure calcimeter	Track temporal changes in SOC associated with tillage and cropping intensity
Visible and infrared imaging from satellite or planes	Spectral imaging of land surface	Document acres under current soil management types (e.g., tilled, direct-seed) Document crops and crop rotations
Visible and infrared ("on-the-go")	Spectral imaging of in situ surface soils	Mapping soil carbon and soil variability in agricultural surface soils
Visible and infrared (lab-based)	High resolution spectral imaging of soil samples in the lab and simulated in situ using intact soil cores. This is currently a semi-quantitative, molecular spectroscopic method.	Build predictive models using visible and near infrared reflectance spectra to estimate soil organic and inorganic carbon
Laser-induced breakdown spectroscopy	High resolution spectral imaging of soil samples in the lab and simulated in situ using intact soil cores. This is currently a semi-quantitative to quantitative elemental spectroscopic method.	Build predictive models using visible and near infrared reflectance spectra to estimate total soil carbon
Combined visible and infrared—laser-induced breakdown spectroscopy	High resolution spectral imaging of soil samples in the lab and simulated in situ using intact soil cores. This is theoretically a quantitative elemental and molecular spectroscopic technique.	Build predictive models using combined visible and near infrared reflectance and laser-induced breakdown spectra to quantitatively estimate soil organic and inorganic carbon

The grazing study includes two replicated pastures that each contain two sampling areas with 50-m transects from which long-term annual vegetation data has been collected. In addition, five soil sample sites have been located along each of these transects and were sampled in 1993 and 2003, and re-sampled in June 2006. Soil sample depth intervals include: 0–3.8 cm, 3.8–7.6 cm, 7.6–15 cm, 15–30 cm, and 30–60 cm. All samples were air dried and filtered through a sieve to eliminate rock fragments, surface plant litter, and coarse root material. Finer material (like roots and organic matter) were separated by sieve. Both the soil and root samples were ground to a fine powder and analyzed for total carbon and nitrogen by dry combustion. Inorganic carbon will also be determined on the soil samples using the procedure described in Sherrod et al. (2002). Soil organic carbon is calculated by subtracting inorganic carbon from total carbon. A summary of the MVA efforts for this study are provided in Table 9.

Table 9: Summary of the MVA tools used for the Big Sky rangeland sequestration project

Measurement Technique	Measurement Parameters	Application
Soil samples processed with the methods described above	Soil organic carbon, soil total carbon, nitrogen	Detection of carbon storage in soil profile and relation to nitrogen cycling
Root analyses	Organic carbon, total carbon, and nitrogen	Detection of carbon storage in soil profile and relation to nitrogen
ANOVA statistical analysis	Treatments/ collected data	Detection of best management practices and seasonality on carbon sequestration rates in rangeland ecosystems

Results indicate that grazing can significantly affect carbon dynamics and the plant community composition of rangeland ecosystems, and grazing at proper stocking rates enhances soil carbon and the potential for soil carbon sequestration. Study results indicated an increase of carbon in the soil carbon content at 0–30 cm depths with grazing treatments. Studies initiated in 1982 at the High Plains Grasslands Research Station near Cheyenne, Wyoming, have shown that after 12 years of continuous, season-long grazing at light and heavy grazing rates, the total carbon mass of the belowground plant-soil (0–60 cm) system was not affected when compared to a non-grazed treatment. However, sign increases in the mass of carbon in the primary root zone (0–30 cm) of the soil were evident in the grazed treatments (between 58.0 and 58.3 Mg carbon/ha, depending on stocking rates) compared to 47.9 Mg carbon/ha in the non-grazed areas.

A range of 27–30 percent of the SOC was lost from the heavily grazed treatment in the various soil depths when grazing versus no grazing treatments were sampled after 21 years of treatment. The heavily grazed treatment resulted in a shift in the plant community from one dominated by cool-season perennial grasses to one dominated by the warm-season blue grama grass, which represents 42 percent of the production in the heavy grazing compared to only 4 and 11 percent in the non-grazing and low grazing treatments, respectively. In 2003, SOC and nitrogen contents were significantly higher in the low grazing treatment compared to the high and non-grazing treatments.

6.2.3 Forestry Field Validation Test

This forestry field test (Test Letter C in Table 7) uses remote sensing with field surveys and forest stand growth modeling to predict rates of aboveground carbon sequestration in forested regions in the Northern Rocky Mountains. This remote sensing complements contractual, ground-based, random plot sampling and allometric measurements. The primary objective is to quantify sequestration potential in forests through understanding the effects of forest management on different carbon pools in forests. During the project, the Big Sky Partnership is (1) conducting baseline vegetation sampling, (2) collecting and analyzing data from a time-series of airborne lidar (light detection and ranging) remote sensing techniques, (3) calibrating remote sensing data to field data, and (4) using the results to parameterize a process-level forest growth model to extrapolate findings to other forested areas.

Big Sky has conducted analysis of multitemporal lidar data collected in 2003, 2007, and again in 2009 in order to make a preliminary assessment of whether the Big Sky forestry study methodology is likely to provide direct measurement of aboveground carbon sequestration into forests over a 4-year period. The study area, plot locations, forest stand delineations, and lidar data acquisition areas are denoted in Figure 6.

Forest metrics quantified in field between 2003 and 2008 indicate that (1) forest growth was quantifiable and (2) data could be used to obtain the annual increase in forest aboveground biomass generated. Results indicate that aboveground carbon sequestration is quantifiable over this timespan using a combination of both ground sampling data and lidar data. For example, forest metrics quantified in the field between 2003 and 2008 indicated that (1) forest growth was quantifiable (Figure 7) and (2) could be used to derive the annual increase in forest aboveground biomass during the period (Figure 8). These data confirm data from lidar-measured forest height, which also shows that height increases can be measured using lidar remote sensing data.

Big Sky commenced analysis of lidar data and field data collected in 2009 in order to (1) assess the 2009 aboveground carbon stocks and (2) to calculate the difference between 2009 carbon stocks and those that existed in 2003. This comparison allows for the calculation of the uptake rate of carbon on a 20 m grid-cell basis. Big Sky has completed labeling of the canopy lidar returns vs. ground lidar returns and has calculated a digital elevation model (DEM) with 1 m spatial resolution. Big Sky is using this information to generate landform shape and canopy height metrics that will be used as inputs in a plot-based statistical model that will serve as the basis to input aboveground canopy biomass on a successional basis.

Moscow Mountain Study Area

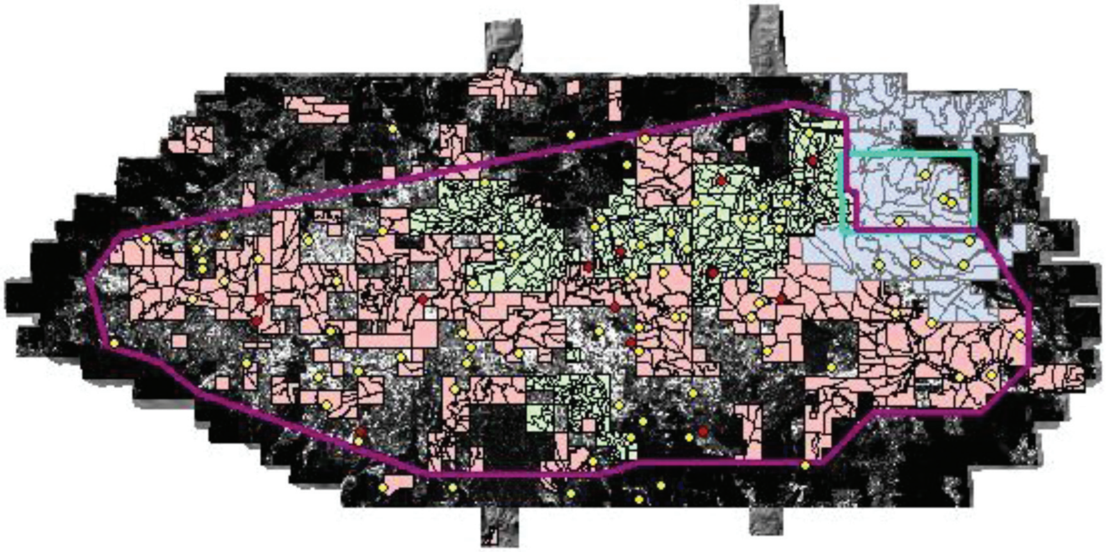


Figure 6: Moscow Mountain forestry study area. Red and yellow dots represent field plot locations sampled during the summer of 2009. Dark mapped areas denote the lidar acquisition of 2003, the green outline denotes the lidar acquisition area for 2007, and the magenta outline denotes the lidar acquisition for summer 2009. Salmon, green, and gray areas denote the various forest stands for use in the monitoring and validation effort. The East-West (horizontal) dimension of the acquisition area is approximately 30 kilometers.

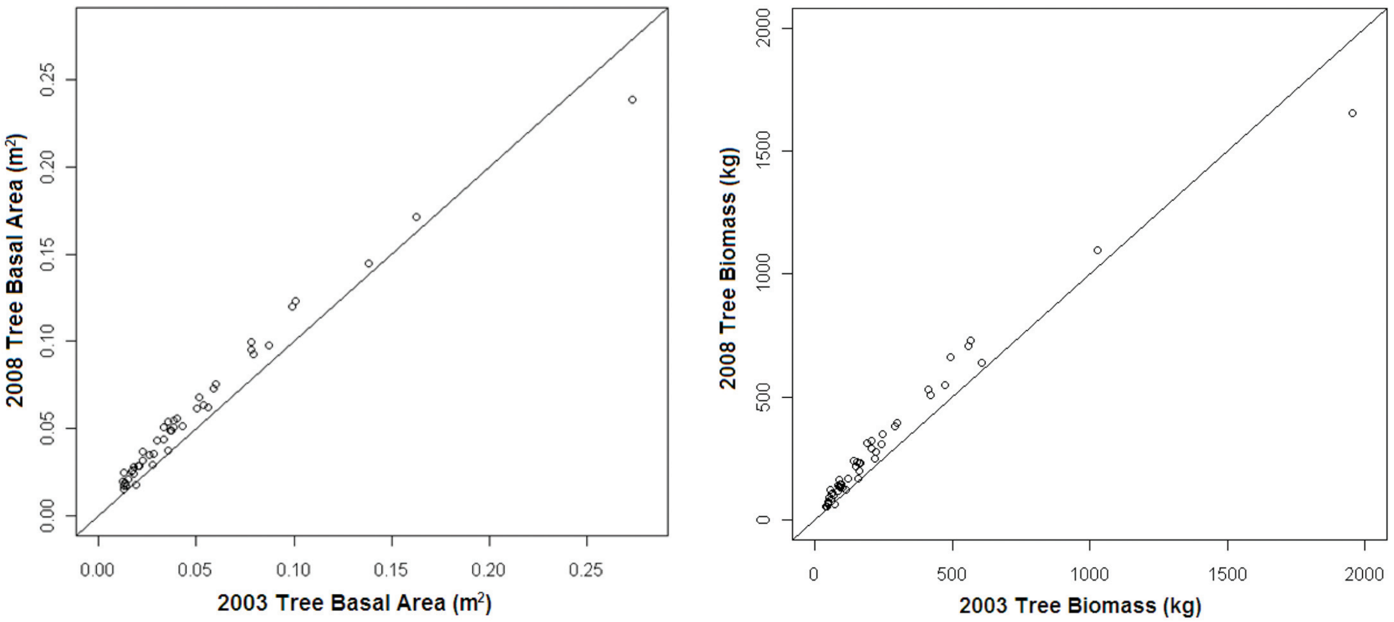


Figure 7: Field measurements of tree basal area (left) and tree biomass (right) of trees measured in 2003 and 2008.

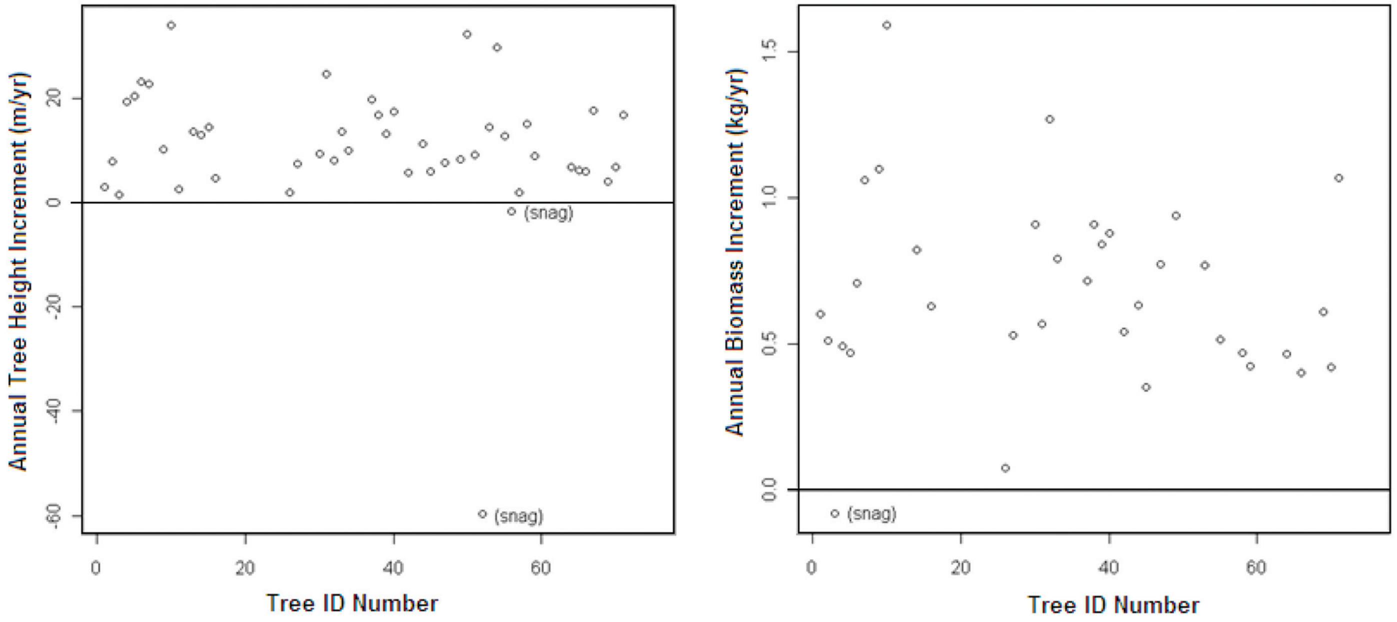


Figure 8: Derivations of the annual biomass increment (left) and the annual tree height increment (right) gained by trees measured in the field of 2003 and 2008.

Furthermore, Big Sky has collected supplemental field data using a terrestrial laser scanner (TLS) at a subset of the field site. Three full-radius scans were performed at a spatial resolution of less than 1 cm in order to assess any errors that may have occurred from airborne lidar acquisition (Figure 9). This comparison allows for the quantification of the amount of biomass that is underestimated due to an expected underestimate bias in tree height as derived from airborne.

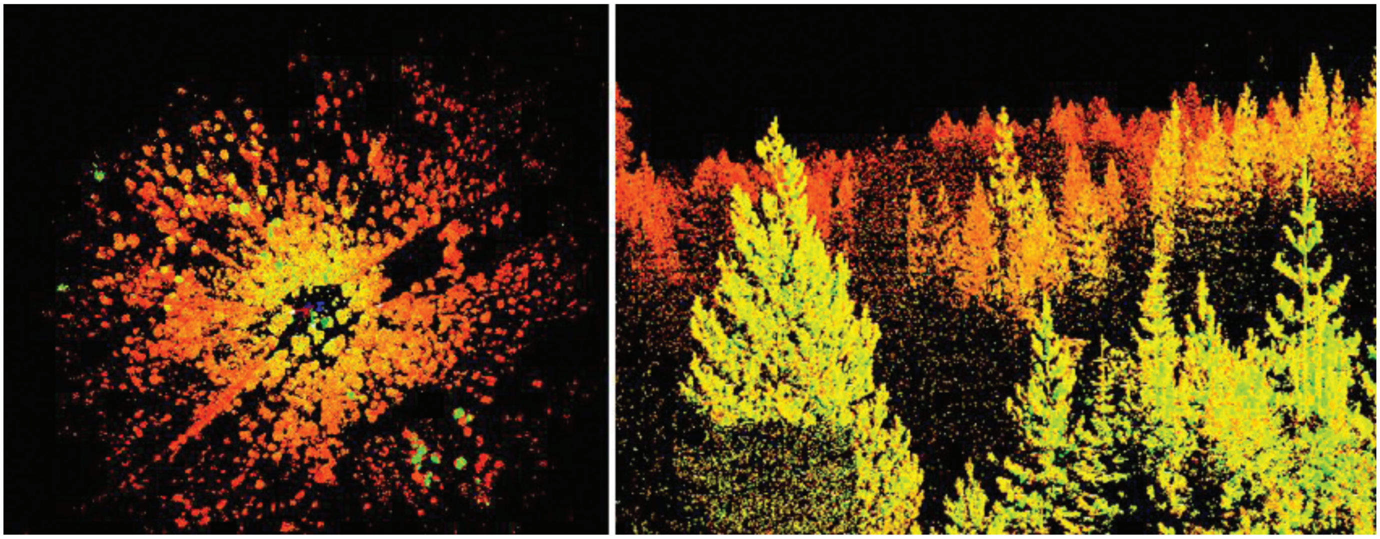


Figure 9: (Left) Plan view of the extent of one TLS scan. Each cluster of points represents one tree. (Right) Cross-sectional view of the forest canopy TLS data. Each point represents an (x, y, x) canopy location. The high detail shown is crucial for error assessment in forest height as well as in carbon storage estimates.

6.3 Midwest Regional Carbon Sequestration Partnership Field Tests

Terrestrial sequestration research conducted by the MRCSP is focused on five land use types: non-eroded prime croplands, eroded prime croplands, marginal lands, minelands, and wetlands. The total terrestrial sequestration potential of the region, encompassing the states of Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia, for these five land use classes is estimated to be 144 million tonnes (not including estimates in New York and New Jersey) of CO_2 per year, distributed among the five land use categories as follows:

- Non-eroded prime croplands – 14 million tonnes CO_2/year
- Eroded prime croplands – 11 million tonnes CO_2/year
- Marginal lands such as forest, pasture, and severely eroded croplands – 99 million tonnes CO_2/year
- Minelands – 6 million tonnes CO_2/year
- Wetlands – 14 million tonnes CO_2/year

Ancillary, non-climate benefits associated with terrestrial sequestration within the MRCSP region include improved soil quality, reduced erosion and sedimentation, bio-filtration of pollutants, and decreased rates of CO_2 emissions.

The MRCSP demonstrated soil carbon sequestration in three types of land: cropland, restored wetland and marshland, and reclaimed mineland. These land-use types were selected for advance research because of their prominence in the MRCSP region, the strong commercial interest in reusing these types of land, and the potential for large-scale emissions abatement. The following sections provide a summary of the three MRCSP terrestrial field tests, techniques used, and results.

6.3.1 Terrestrial Sequestration Field Test: Croplands

The MRCSP Croplands terrestrial sequestration test (Test Letter D in Table 7) focuses on MVA protocols and technologies across multiple cropland plots within different Major Land Resource Areas (MLRA's) in the MRCSP region, primarily Indiana, Kentucky, Michigan, Ohio, and Pennsylvania. MLRAs are identified based on similar soils, climate, vegetation or crop types, and predominant land use. The major soil orders represented by the different MLRAs in the MRCSP region include: Histosols, Spodosols, Alfisols,, Mollisols, Inceptisols, and Entisols. The mean annual temperature ranges from 6.4 to 12.0 °C and mean annual rainfall ranges from 800 to 1,400 mm.

Multiple test sites located within the various MLRAs were selected for soil sample collection and analysis to evaluate the rates and magnitude of soil carbon sequestration in relation to principal management systems widely adopted by the farmers in the MRCSP region (Figure 10). Critical factors for site selection were soil type, slope, and past management practices (e.g., cropping and fertilization histories). The objectives of this study included demonstrating carbon sink capacity for predominant land use systems, developing a credible measuring, monitoring, and modeling protocol to evaluate carbon sink capacity in biota and soil at different scales, and assessing the mechanism of carbon sequestration with regards to land use and soil management.

6.3.1.1 Modeling and MVA Efforts

The SOC concentrations and physical and other chemical soil properties (e.g., pH, cation exchange capacity, total nitrogen, bulk density, porosity, hydraulic conductivity, and water infiltration) under no-till and conventional tillage systems were determined within each MLRA. The effect of no-till and conventional tillage was extrapolated to larger scales under different soil types. More than 20 MLRAs were sampled for comparing different land use systems.

Soil cores were also taken on no-till sites converted from conventional tillage to assess the changes in SOC levels occurring after the change in cropland management. Soil samples were collected from plots under no-till and conventional tillage practices that were generally less than 20 years old. The major crop rotations in no-till and conventional tillage were corn (*Zea mays* L.), soybean (*Glycine max* L.), and continuous corn. In addition, soil cores were collected to compare the soil properties resulting from different crop residue treatments under both tillage systems. SOC levels under conservation tillage where crop residues are either incorporated or left on the surface depends on the amount, quality, and depth to which the residue is incorporated. Thus, soil cores were also collected at mulch and non-mulch treatments for monitoring the benefits of mulch (residues) on SOC sequestration under different land uses.

Soil samples were also collected from woodlots/forest areas in MLRAs to compare the soil properties under less disturbed land use with those in no-till and conventional tillage plots. Woodlots, no-till, and conventional tillage plots/fields were often located adjacent to each other and had similar slopes and soil types. The woodlot plots served as control in comparison to the effects of tillage treatments on soil properties. At woodlots, soil

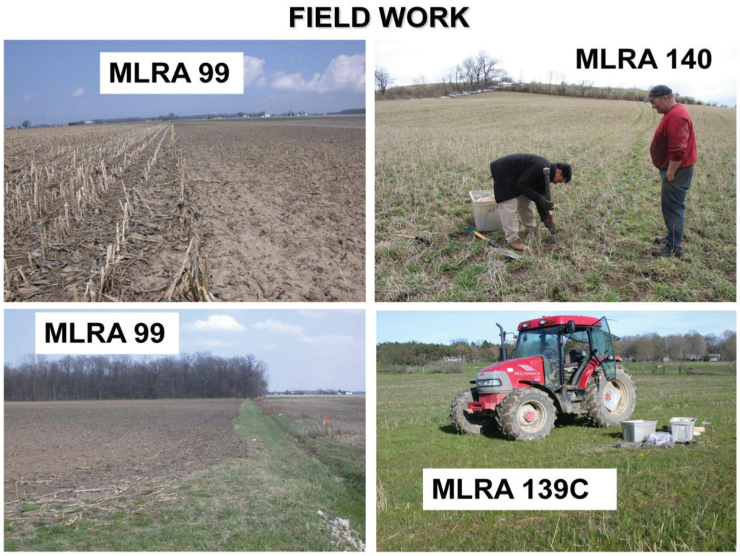


Figure 10: Field work on MLRA sites.

cores were obtained 10–20 cm distant from the tree trunk to avoid damage to the tree, in particular, the tree roots. Figure 11 shows soil sampling in cropland (rotational grazing) and woodlot plots in West Virginia.

Soil sampling at shallower depths may be insufficient to assess land use and soil management effects on the SOC pool. Thus, to evaluate impacts of different tillage systems and to improve estimates for the SOC pool, deeper profile sampling to about 1-m depth for various soil types, management scenarios, and cropping system was completed. The spatial distribution and number of samples required for obtaining valid comparisons among different treatments are very important. Field sampling generally requires 3–6 replications up to 50 or 60-cm depth in each treatment depending on the soil type. The soil sampling depths at the majority of locations were: 0–10, 10–20, 20–30, 30–40, 40–50, and greater than 50 cm. The most common sampling design used in the research areas was the complete randomized block design. This design has the least mean sum of squares due to higher degree of freedom of error as compared to other designs. However, variations in the soil parameters and landscape required occasional use of randomized block design.

SOC predictions at the state and regional scale were performed using different spatial interpolation methods, including ordinary kriging, multiple linear regression, regression kriging, and geographically weighted regression (GWR). The soil data served as a basis for validating models. In addition, the SOC data were also extracted from the National Cooperative Soil Survey Characterization Database or from soil characterization database from different US universities. Measurement techniques used at field test sites are provided in Table 10.

6.3.1.2 Research Findings to Date

The Validation Phase studies on terrestrial carbon sequestration in cropland have resulted in the following findings:

- Residue retention as surface mulch is essential for soil carbon sequestration and soil quality improvement in a no-till system.
- The no-till practices are very effective in enhancing SOC, but this effect depends on soil depth and duration of management practice.
- Rates of soil carbon sequestration (250–1,000 kg carbon/ha/yr) depend on soil properties, crop rotations, residue management, soil fertility management, and the time since conversion from plow tillage to no-till. Residual removal adversely impacts soil quality.

Figure 11: Sampling with a soil hammer in cropland (rotational grazing) and woodlot plots in West Virginia.

Table 10: Measurements Techniques used at Field Test Sites

Measurement Technique	Measurement Parameter	Application
Dry combustion method (900 °C) – CN analyzer	Total Organic Carbon (%) and Total Nitrogen (%)	Measure soil organic carbon and nitrogen content in all samples
Dry combustion and isotopic separation	Total carbon (%) and δ13C	Measure soil carbon and δ13C as well as plan residue carbon and δ13C
Core method	Bulk density	Determine the density of the bulk soil
Static hand core penetrometer	Cone index	Determine the resistance of the soil to cone penetration as a means to evaluate soil compaction
Crushing method	Tensile strength of aggregates	Determine the tensile strength of individual soil (5–8 mm, 2–5 mm, and less than 2 mm diameter) aggregates
Clod method	Aggregate density	Determine the density of discrete (5–8 and 2–5 mm diameter) aggregates
Tension table and pressure plate apparatus	Moisture retention of aggregates	Determine the capacity of aggregates (5–8 mm, 2–5 mm, and less than 2 mm diameter) to retain water
Wet-sieving method	Aggregate stability	Quantify the percentage and mean weight diameter of water-stable aggregates
Hydrometer method	Soil texture	Determine the particle size distribution

- Residence time of carbon sequestered in soil depends on soil properties (more for clayey than sandy soils), depth (longer for sub-soil than surface soil), land use (longer for perennials than annuals), and management. The soil carbon pool is maintained or enhanced as long as no-till systems and other best management practices are used.
- The soil carbon pool stored in deeper layers (greater than 30 cm) is the most important fraction for long-term SOC sequestration as it is stabilized in association with the soil mineral phase resulting in long carbon mean residence time. This must be taken into account while conducting research trials in the MRCSP region.

The potential benefit of adopting no-till or reduced tillage practices over a 20-year period could result in an estimated 200 to 270 million tonnes of additional CO_2 sequestered. The stored carbon may be sold as CO_2 offset credits, which would provide additional profits to landowners in the region. Converting cropland to no-till and reducing tillage practices also yields benefits of placing land use into more sustainable agricultural practice, while reducing emissions from fossil fuel consumption used for plowing and other farm operations.

6.3.1.3 Storage Opportunities and Benefits

The potential benefit over a 20 year period could result in an estimated 250 million tonnes of additional CO_2 sequestered. The stored carbon may be sold as CO_2 offset credits, which would provide additional profits to the landowners in the region.

6.3.2 Terrestrial Sequestration Field Test: Minelands

Surface mining operations alter existing landscape patterns and adversely affecting soil quality. The original upper-soil horizons are destroyed by pre-mining removal and mixing and post-mining replacement leads to soil erosion, enhanced SOC mineralization, and nutrient leaching. However, with proper reclamation and sufficient time, these degraded soils have the potential to return to functioning soils, primarily by increasing the SOC content. The costs to landowners to achieve these carbon sequestration rates depends upon the specific costs to re-contour, vegetate, fertilize, etc., which varies by region, species planted, and planting density. Planting grass/legumes on reclaimed mine sites, in addition to storing soil carbon, also reduces soil erosion. This erosion reduction benefits nearby streams, lakes, and other waterways that may contain fish and other wildlife. Soil samples from five mine sites reclaimed to grass and legumes in Monongalia County, West Virginia (Test Letter E in Table 7), were collected and analyzed to assess soil carbon accumulation (Table 11). Mine sites were selected that had known pre-mining land use, coal seam, overburden geology and mining and reclamation practices, and where the mine operator or landowner permitted access to the sites. The Waynesburg coal seams for all five mine sites were contour mined beginning as early as 1982 and as late as 2007 using front end loaders. Overburden material placed on the disturbed land consisted of 70 to 80 percent sandstone, with shale comprising the remaining 20 to 30 percent. Mining operations ceased at different times for each of the sites (1990, 1998, 2000, 2005, and 2007), which allowed comparison across reclaimed mine sites over time. Soil sample collection began in 2006 and continued annually through 2008 to assess the changes in soil carbon accumulation over time. In addition to measuring soil carbon stocks on reclaimed mine lands, the project performed economic analyses to assess the trade-offs between existing land management activities and those that enhance carbon sequestration. The analysis involves estimating the difference in soil carbon accumulation rates in soils on sites reclaimed to grass/legumes and forest, which capture carbon in above ground (biomass) and below ground (soil) systems. The objective is to assess the economic viability of using the carbon accumulation on reclaimed mine sites as a GHG mitigation activity.

6.3.2.1 Modeling and MVA Efforts

In 2006, soil samples were located to encompass the maximum variability expected at each site. Carbon data from the 2006 samples were used to characterize the spatial variability and to optimize a grid for soil sample collection on irregular field sites in 2007 and 2008. Soil samples were collected at two depths (0–6 cm and 6–12 cm) in late summer/early fall of 2006, 2007, and 2008 (Table 12). The

Table 11: Site Characteristics of the Chronosequence Identified in 2006

Site Name	Mylan Park	WVSK	Dent's Run	New Hill	WV01
Mining begins	1982	1996	1999	2003	2004
Mining ends	1985	1998(1)	2000	2005	2006
Mine soil age in 2006	21	8(1)	6	1	0
Pre-mine land use	Mixed pasture and forest				
Coal seam	Waynesburg				
Method of mining	Contour mining, front end loaders				
Overburden type	70—80% sandstone, remainder shale				
Reclamation method	Backfilled, 7.6 cm topsoil, grass, and legumes				

(1) After soil sampling in 2006, it was discovered that this site had been recontoured in 2003 and thus was actually only 3 years old.

Table 12: Total Number of Soil Samples Collected at Each Site, for Each Depth, and Each Year from all Sampled Mine Sites

Year	Depth (cm)	Site					Total
		WV01	New Hill	WVSK	Dent's Run(1)	Mylan Park	
2006	0–6	X	60	30	60	60	210
	6–12	X	60	30	55	56	201
2007	0–6	64	79	83	X	74	300
	6–12	10	12	13	X	12	47
2008	0–6	64	79	83	X	74	300
	6–12	10	12	13	X	12	47
Total	**148**	**302**	**252**	**115**	**288**	**1,105**	

(1) After soil sampling in 2006, the property owner stopped allowing access to the site.

Table 13: Sample analysis techniques for mine lands test site

Measurement Technique	Measurement Parameters	Application
Dry combustion—LECO	Total Organic Carbon (%) Total Nitrogen (%)	Measure soil carbon and nitrogen content
Dry combustion—Loss on Ignition	Total Organic Matter (%)	Measure soil organic matter that is then adjusted by the soil bulk density to estimate soil organic carbon content
Flow Injection Analysis	Extractable nitrate and ammonia	Measure soil nitrate and ammonia content to assess availability for biomass production

samples were analyzed for concentrations of total organic carbon, total nitrogen, total organic matter, and extractable nitrate and ammonia (Table 13).

6.3.2.3 Research Findings to Date

The results of the study may be applied to most of the 576,000 hectares of land permitted for mining activities in the MRCSP region where the predominant reclamation activity is grass/legumes (approximately 95 percent). Research findings included the following:

- The results of the SOC analyses indicate that carbon does accumulate in mined land reclaimed to pasture/grass, but the variability of SOC accumulation across sites is significant. One key finding of the analysis is that the number of soil samples required to adequately characterize SOC accumulation in the heterogenic soils found on reclaimed mine land is high. This heterogeneity of soil characteristics increases the cost of soil sampling and would make verification under a carbon trading scheme more costly. (Alternative non-intrusive methods for measuring soil carbon content that do not require physically removing soil samples are under development by various corporations and government agencies, but these are not yet on the market.)
- Whether reclaimed mine land soils could be used for carbon trading requires more research, but early indications are that carbon accumulates on reclaimed mine land nearly as rapidly as other land uses, and due to limited other uses for the land, it could be a part of a suite of solutions.
- Reclaimed mine land planted to forest could store 2.6–5.5 Tg CO_2 yr^{-1} over the CO_2 accumulation in pasture soils when the carbon accumulation in aboveground biomass, litter layer, and soils are included. This represents the marketable portion of the stored CO_2 that could be used as offset credits by landowners that plant forest on reclaimed mine sites. The economic analysis also demonstrated that the reclamation costs in some regions are lower for forest than for pasture as the reclamation activity.

6.3.2.4 Storage Opportunities and Benefits

The potential benefit over a 20-year period could result in an estimated 40–81 million tonnes of CO_2 sequestered. The results of the study may be applied to most of the 576,000 hectares of land permitted for mining activities in the MRCSP region where the predominant reclamation activity is grass/legumes (approximately 95 percent). The stored carbon may be sold as CO_2 offset credits, which would provide additional profits to the landowners in the region.

6.3.3 Terrestrial Sequestration Field Test: Wetlands

This project (Test Letter F in Table 7), with major funding from the Maryland Department of Natural Resources Power Plant Research Program, monitored the carbon sequestration rates in tidal marshes at the Blackwater National Wildlife Refuge. Considered a wetland of international importance, the Blackwater National Wildlife Refuge has been identified as one of six priority wetland areas by the North American Waterfowl Management Plan and is called one of the “Last

Great Places" by The Nature Conservancy. An estimated 3,200 hectares of tidal marsh have been lost since the 1930s at Blackwater due to sea-level rise, subsidence, erosion, salt water intrusion, and herbivory by invasive species. Current tidal marsh loss rates are estimated at 60-160 hectares per year. The project area is near Cambridge, Maryland, where it has been proposed to restore up to 8,000 hectares of lost tidal marsh using clean dredged material.

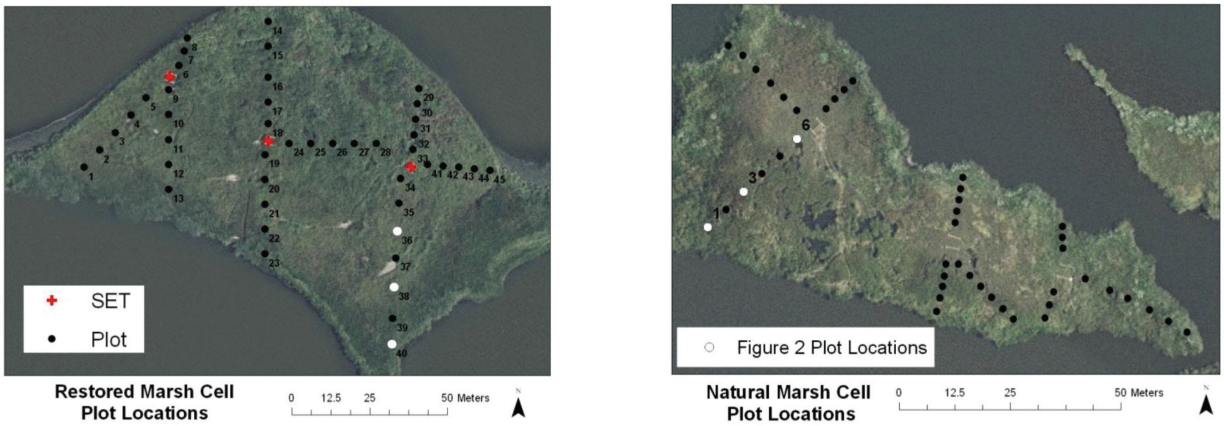
Marsh systems have among the highest carbon sequestration rates found in terrestrial systems due to high net primary productivity, low decomposition rates, and accretion in response to sea-level rise. The results of this study are being used to estimate carbon sequestration rates in restored marshes over time, evaluate the extent to which various management practices influence this process, and develop a sampling protocol for CO_2 validation in restored marshes.

6.3.3.1 Modeling and MVA Efforts

The study was conducted on one restored tidal marsh cell created in 2003 and one natural marsh cell (Figure 12). Within each cell, 45 plots were laid out for annual soil core and vegetation data collection. Feldspar markers were used to mark initial surfaces, in subsequent years samples were collected above and below the initial marked surface. Upon collection, soils were divided into horizons and analyzed for bulk density and carbon. In 2008, methane emissions were monitored monthly throughout the growing season at three sites per cell.

6.3.3.3 Research Findings to Date

- The Validation Phase studies on terrestrial carbon sequestration in watersheds have resulted in the following findings:
- The restored and natural marshes at the Blackwater National Wildlife Refuge are sequestering carbon at an above-average rate versus the national average based solely on surficial accumulation, which is probably an underestimate of total carbon sequestration.
- Based on the differences in surfical carbon sampling between 2006 and 2008, the rates of surficial carbon sequestration were estimated at the restored site of 3.4 Mg carbon ha^{-1} yr^{1}, with a range of 0.8 to 5.9 Mg carbon ha^{-1} yr^{1} at individual sites. At the rate of 3.4 Mg carbon ha^{-1} yr^{1} of surficial carbon sequestration, the proposed 8,000 ha restoration would sequester about 27,000 tonnes carbon/yr (equivalent to 99,000 tonnes CO_2/yr).
- At the natural site, the estimated rate was 4.4 Mg carbon ha^{-1} yr^{1}, with a range of 3.4 to 5.7 Mg carbon ha^{-1} yr^{1}. Variability of surfical carbon sequestration was significantly greater at the restored site than at the natural site, indicating that a greater number of samples may be required for precise estimates in restored sites versus natural sites. This variability was primarily due to variation in the organic matter accumulation rates.
- Thus far, it has not been possible to quantify subsurface carbon changes. Difficulties in



Restored Marsh Cell Plot Locations

Natural Marsh Cell Plot Locations

Figure 12: Surface elevation table (SET) and plot locations for the restored and natural (reference) marshes at Blackwater National Wildlife Refuge.

finding the original and post-restoration surfaces highlight the problems associated with evaluating carbon sequestration in restored systems without knowledge of conditions prior to restoration.

- The use of feldspar markers was not a successful method to establish a reference plane for future sampling. The earth anchor method appears to be a viable method to perform carbon accounting deeper into the soil profile.
- A significant portion of the carbon sequestration benefit in these marshes is offset through methane emissions. Restoring marshes with higher salinity or other conditions that reduce methane generation would be preferable to improve the net greenhouse gas balance.

6.3.3.4 Storage Opportunities and Benefits

Current proposals include estimates of up to 8,000 hectares of marsh restoration in the mid-Chesapeake Bay region. Modeling work has estimated that the carbon sequestration rates in these marshes may range from 2.5 to 5.7 Mg carbon ha^{-1} yr^{-1}. These estimates are approximate and highly dependent on rates of organic matter accumulation and sea-level rise. At these values, the full restoration would sequester 20,000 to 45,600 Mg carbon yr^{-1}.

6.4 Plains CO_2 Reduction Partnership Field Test

The PCOR Partnership region is home to a variety of land-use options that present opportunities for carbon sequestration. Many of the region's important and highly productive ecosystems have been altered by agricultural and commercial development. Terrestrial carbon sequestration on these diminished lands can be enhanced by implementing practices such as introducing cover crops on fallow land, the conversion from conventional tillage to conservation tillage, and the restoration and/or preservation of grasslands and seasonal wetlands. Landowners adopting these practices can generate a new source of income while at the same time revitalizing a suite of ecosystem functions that were either nonexistent or greatly reduced.

The PCOR region includes a unique landscape called the Prairie Pothole Region (PPR). The PPR covers about 347,490 mi^2 (900,000 km^2) (one quarter of the PCOR region). Specifically, the PPR covers portions of Iowa, Minnesota, Montana, North Dakota, and South Dakota in the United States and Alberta, Saskatchewan, and Manitoba in Canada. During Phase I (2004–2005) of the PCOR Partnership, it was estimated that the PPR included up to 4,944,000 ha (12.2 million acres) of potentially restorable wetlands (i.e., cropland wetlands) and that if restored, these wetlands alone could potentially sequester 111,216,000 Mg (122.6 million tons) of SOC (Euliss et al., 2006; Gleason et al., 2005).

A major portion of the PCOR Partnership team effort was focused around a multiyear wetland/grassland complex restoration project (fall of 2006 to fall of 2009) located in north central South Dakota. The test was initiated to develop the technical capacity to systematically identify, develop, and apply alternate land-use management practices to the Prairie Pothole ecosystem (at both local and regional scale) that results in net GHG reductions and marketable carbon offsets. The project implemented land management practices that will restore wetland and grassland areas to pre-settlement characteristics and promote the replacement of the soil carbon lost during tillage since European settlement. As part of the terrestrial field validation test, PCOR partners measured and determined the site landscape, along with the monitoring of erosion, runoff, habitat quality, and needs for chemical inputs, as well as developing materials and capabilities to help landowners undertake successful carbon sequestration activities.

This project also demonstrated optimal practices for terrestrially sequestering CO_2 in grasslands and croplands at multiple sites located across the northern Great Plains (Table 7 test G). Terrestrial CO_2 storage potential for wetland restoration in the PPR is outlined in Figure 13.

The goal of this project was to identify methods for monetizing terrestrial carbon credits in grasslands and wetlands. Through the Ducks Unlimited, Inc. (DU), carbon credit program, the monetization of carbon credits for grasslands has been realized, and it is anticipated that with the results of this project, methodologies will be developed in the near future for wetlands.

Soil and gas samples were collected from various age cohorts of restored grasslands, native prairie, cropland, and wetlands throughout Montana, North and South Dakota, Minnesota, and Iowa. In addition to carbon

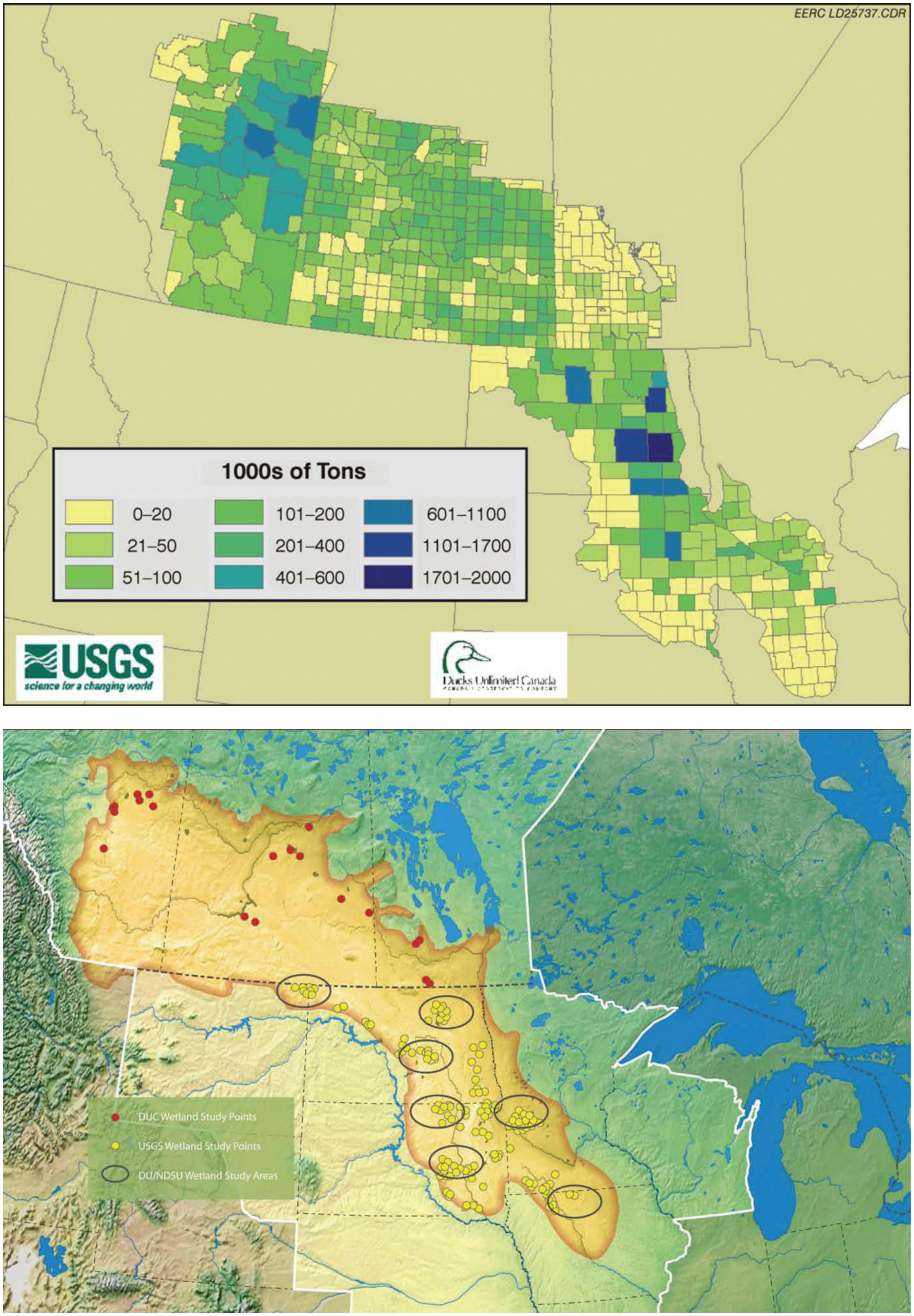


Figure 13: Carbon sequestration potential in restored wetlands in the PPR (top) and terrestrial sampling locations (bottom). Red dots indicate Ducks Unlimited Canada sampling locations and yellow dots indicate U.S. Geological Survey and North Dakota State University (NDSU) sampling locations.

Table 14: Summary of the MVA Techniques for the PCOR Terrestrial Field Test

Static Chamber Approach	• Measurement of fluxes: • N_2O • CH_4 • CO_2	Gas exchange measurements
Various Meters/Probes and Laboratory Sampling	• Volumetric water content (θ) • Total soil porosity (Pt) • Soil temperature • Precipitation • Climate and soil properties	Determine influences on gas flux and carbon storage
Core Sampling (soil probe)	• Soil bulk density • Soil moisture • Soil carbon analysis	Measurement of carbon in soil

uptake and storage measurements, methane (CH_4) and nitrous oxide (N_2O) gas fluxes were also measured to estimate the net GHG flux of each management practice. These data have been instrumental in advancing terrestrial carbon credits from the PCOR partnership region into the marketplace. A summary of the MVA effort for this project is outlined in Table 14. Terrestrial sequestration projects create carbon credits that can be transacted in voluntary or mandatory regional, national, or international carbon markets. Under a mandatory GHG reduction program, these credits provide entities with alternative compliance options, in addition to direct reductions, to reduce GHG emissions while new less carbon-intensive fuels and technologies are developed.

6.4.1 Measurement of Gas Fluxes

Fluxes of N_2O, CH_4, and CO_2 were measured on a biweekly basis during the growing season (approximately May–September) using a static (non-steady-state) chamber approach. In each catchment, eight (five wetland and three upland) monitoring locations were established along a transect extending from the wetland center to the catchment boundary. Five monitoring locations were established in the wetland zone by placing one chamber in the wetland center, one in the wetland–upland transition zone, and three at equal-distance intervals between the wetland center and wetland–upland transition zone. The placement of eight chambers along transects covered a range of soil moisture conditions (i.e., soil water-filled pore space [WFPS]) that influences emission of gases; studies suggested that the relative contribution of nitrification and denitrification to N_2O and dinitrogen (N_2) emissions varies with WFPS (Davidson et al., 2000). WFPS ranged from field capacity (60 percent WFPS) at the wetland–upland transition zone to saturated (100 percent) near the wetland center. Changes in WFPS along transects were gradual rather than abrupt because of low relief associated with depressional wetlands. Hence, soil moisture did vary more than 10 percent (e.g., 60 percent, 70 percent, 80 percent, 90percent, 100 percent) between chambers along transects.

Gas flux measurements were initiated by sealing chambers at the base dry sites, and floating chambers were deployed at wet sites. Gases were allowed to accumulate in the chamber headspace for a minimum of 30 minutes after deployment. Headspace gas samples were withdrawn from the chamber through a septum port by syringe. Samples of the initial gas concentration were obtained by drawing ambient atmosphere into a syringe at the start of the flux measurement. All syringe gas samples were immediately transferred to and stored overpressurized in 10-mL preevacuated (less than 10 torr) crimp-top serum bottles fitted with thick gas-impermeable septa/stoppers. Laboratory tests showed that N_2O, CH_4, and CO_2 concentrations remained stable within the overpressurized serum bottles for at least 3 weeks.

Gas samples were analyzed by gas chromatography within 1 week of sampling. A gas chromatograph equipped with electron capture detector (ECD) and flame ionization detectors (FID) and two 10-port valves was used to measure N_2O, CH_4, and CO_2 with a single injection of sample. The instrument configuration and operating conditions provide minimum detection levels of less than 3 ppbv N_2O (ECD), less than 10 ppbv CH_4 (FID), and less than 1 ppmv CO_2 (ECD and FID). Coefficients of variation for detection of the three target gases within ambient air were less than 2 percent (UWSP Dissolved Gas Laboratory). The gas chromatograph was calibrated with commercial N_2O, CH_4, and CO_2 air blends verified against a reference standard from the National Oceanic and Atmospheric Administration.

6.4.2 Measurement of Co-variables Known to Influence Gas Fluxes

Water-Filled Pore Space (WFPS): Along a moisture gradient from the upland zone to the center of each wetland, WFPS was expected to exert important control over trace gas production in the soil. The formation of N_2O as a by-product of nitrification and denitrification reactions peaks at about 60 percent WFPS (Davidson et al., 2000). Below 60 percent WFPS, nitric oxide (NO) becomes an increasingly dominant gaseous by-product of nitrification relative to N_2O, while above 80 percent, N_2O tends to be converted to N_2 gas. The formation of CH_4 as a product of anaerobic soil respiration becomes increasingly favored as WFPS approaches 100 percent. Soil WFPS is expressed as the ratio of volumetric water content (θ) and total soil porosity (P_t):

$$\%\text{WFPS} = (\theta/P_t) \bullet 100$$

During each biweekly sampling event, θ was measured in the top 15 cm of the soil near each gas chamber along each transect using a TH_2O soil moisture meter. Total porosity in the top 15 cm of soil was determined from bulk density (ρ_b) and particle density (ρ_s) according to:

$$P_t = 1 - \rho_b/\rho_s$$

Soil densities were mapped on a one-time basis along each transect using the core (ρ_b) and pycnometer (ρ_s) methods (Klute, 1986), respectively. Soil densities were assumed to be constant during the study period.

***Soil Temperature*:** Microbially mediated nitrification and denitrification processes are influenced by soil temperature. During each biweekly sampling event, temperature (°C) was measured in the top 15 cm of the soil near each gas chamber along each transect using a soil thermometer. Additionally, temperature data loggers were buried in the center of each wetland to provide a continuous (e.g., hourly) record of soil temperature fluctuations.

Precipitation and Climate: A rain gauge was installed at each wetland. Precipitation was monitored weekly and after major or unusual precipitation events.

Soil samples were collected to a depth of 15 cm near monitoring locations and submitted for determination of the following: extractable nitrate (NO_3) and ammonium (NH_4), total nitrogen, total carbon, organic carbon, inorganic carbon, extractable phosphorus (P), bulk density (g/cm^3), and soil texture.

Nutrient loading and groundwater flows are influenced by catchment morphometry. A topographic field survey was conducted on all catchments. Wetland catchments were surveyed using a global positioning system total station. Using the program ForeSight version 1.3 (Tripod Data Systems, Inc., Corvallis, Oregon), estimations of wetland and upland areas (ha), maximum depth (m), and wetland volume (ha-m) were made, and the average grade (percent) and length (m) of the upland slopes were estimated.

6.4.3 Research Findings to Date

- Gas emissions were collected from 17 wetlands in north-central South Dakota on a biweekly basis (11,625 individual gas flux samples collected).
- Soil samples were collected on 14,250 acres of native grassland, restored grassland, and cropland (2,850 soil samples collected). Sample sites are located in North and South Dakota, Montana, Iowa, and Minnesota.
- An Oracle software-based carbon-tracking database was officially launched for use in May 2008. This database provides carbon transaction information complete with serial numbers for unique carbon units and tons and includes business requirements generated for calculating, inventorying, and tracking offsets. These reports were used in a recent grassland carbon credit transaction.

- Project results have supported the accreditation of an Avoided Grassland Conversion project with Climate, Community, and Biodiversity Standard (CCBA, 2008). This project was the first to be certified by the standard in the United States and is the first Avoided Grassland Conversion project in the world.
- Business models/processes for aggregating and transacting carbon offsets in a voluntary market as well as the necessary legal documents for easements (including carbon rights) have been developed.
- An economic model was constructed to examine land units affected by various wetland restoration actions. This model, along with another that predicts the probability that a parcel of land will remain in a particular land use (with varying commodity prices and subsidy and conservation payments), was used in a “price point” and/or “willingness to sell/convert” analysis on private lands in the PCOR Partnership region.

Results from this project have provided the science and business processes framework (Figure 14) needed for project developers and investors to

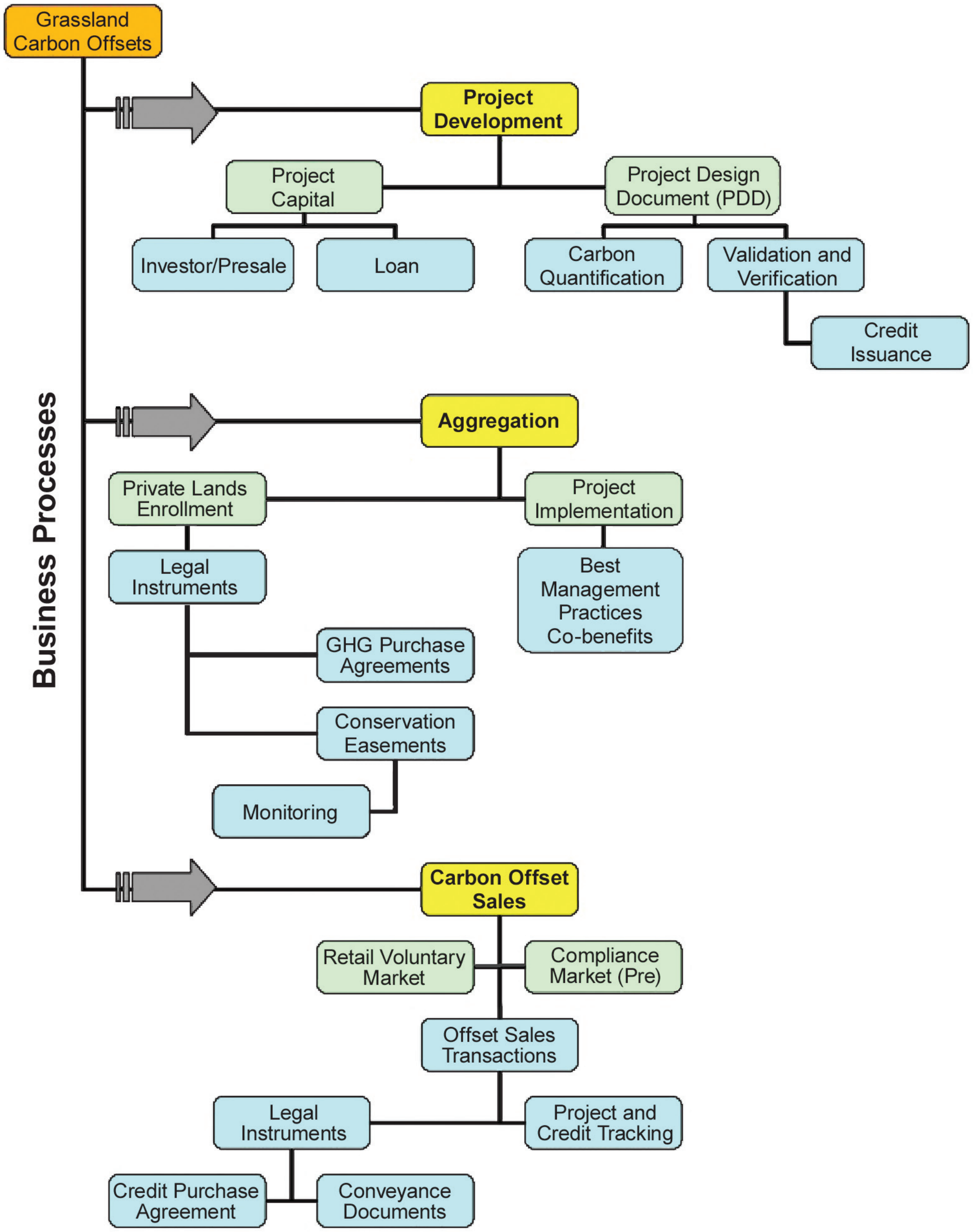


Figure 14: The PCOR Partnership science and business processes framework to advance emission reduction targets through terrestrial carbon sequestration efforts.

advance emission reduction targets as well as achieve financial returns in this rapidly emerging market. With the launch of the Ducks Unlimited Carbon Credit Program, landowners are provided with a revenue stream novel to the agricultural economy of the plains, sequestered carbon.

6.5 Southwest Carbon Sequestration Partnership

Terrestrial carbon capacity in the Southwest region is limited by low average annual precipitation and yearly variability in precipitation. The Southwest Regional Partnership on Carbon Sequestration (SWP) encompasses New Mexico, Arizona, Colorado, Oklahoma, Utah, and portions of Kansas, Nevada, Texas, and Wyoming. Even in systems managed for carbon storage, wet years followed by a series of dry years may result in a net carbon flux out of the system. There is limited opportunity to increase carbon storage on rangelands because most areas are at a relatively stable equilibrium given land use history and management. Much of the desert grassland and shrub land areas with less than 12 inches of annual precipitation are subject to loss of cover and exposure to wind and water erosion. Retaining soil carbon levels in these ecosystems requires active restoration practices that are challenging, given current technologies. There are two demonstration projects.

6.5.1 Southwest Regional Terrestrial Pilot Analysis

In conjunction with the SWP's ECBM sequestration test, a terrestrial pilot test (Test Letter H in Table 7) is being conducted in the San Juan Basin. ECBM operations are notorious for producing huge volumes of water. This water source is being desalinated and used for irrigating a riparian restoration project, forming a combined ECBM–terrestrial sequestration project. Though the desalination process is an expensive one, the BLM and ConocoPhillips are both interested in making beneficial and environmentally-friendly use of the produced water.

Rangelands in the San Juan Basin of New Mexico could potentially store large quantities of carbon in plants and in soil, in addition to their value as recreational lands. The challenges to achieving rangelands' potential terrestrial CO_2 storage options is primarily in (1) the limited growing conditions and (2) reduced capacity for recovery. Optimizing carbon storage in soils and vegetation while increasing the value of other ecosystem services requires a two-pronged strategy: enhancing existing and reintroducing woody plant species along riparian areas, and reestablishing native grasses and shrubs in upland areas. The limiting factor in both cases is water. A reliable source of water for agricultural irrigation, such as the water produced during ECBM production, could provide the necessary base for the reestablishment of native vegetation with a host of environmental benefits, as well as carbon sequestration. The San Juan Basin ECBM project is also the location of one of the terrestrial sequestration pilot tests. Produced water from the ECBM project and other wells is being desalinated and applied to a drought-stressed riparian area—the interface between land and a flowing surface water body—where carbon storage is being monitored and evaluated.

SWP activities for this terrestrial test include surface measurement of soil carbon, remote sensing classification protocols, ecological process modeling efforts, conducting a regional carbon inventory, and riparian restoration in the San Juan basin. The SWP terrestrial pilot analysis has resulted in a carbon reporting and monitoring system that functions consistently across hierarchical scales and is compatible with the existing technology underlying the DOE's Energy Information Administration Voluntary Reporting of Greenhouse Gases (1605b) Program. Within this system, the project will achieve the following: (1) develop improved technologies and systems for direct measurement of soil and vegetation carbon at reference sites selected within the region; (2) develop remote sensing (LIBS and NIRS both used) and classification protocols to improve mesoscale (km^2) soil and vegetation carbon estimates; and the (3) integration of available information at a sub-Major Land Resource Regional scale into a regional inventory system. The regional inventory can be used to estimate carbon changes at small scales using existing models and can also be used to make program and policy decisions. The value-added products of the test will be new carbon credits and increased land productivity.

Soil sampling using LIBS and NIRS occurred in 300 samples in the Chihuahuan Desert in New Mexico, 120 samples in the La Manga Canyon roads, well pads, and surrounding vegetated areas, and over 200 samples from Santa Rita Experimental Range (Arizona) and Fort Bliss. Results from conventional soil samples and results using LIBS and NIRS showed a strong correspondence.

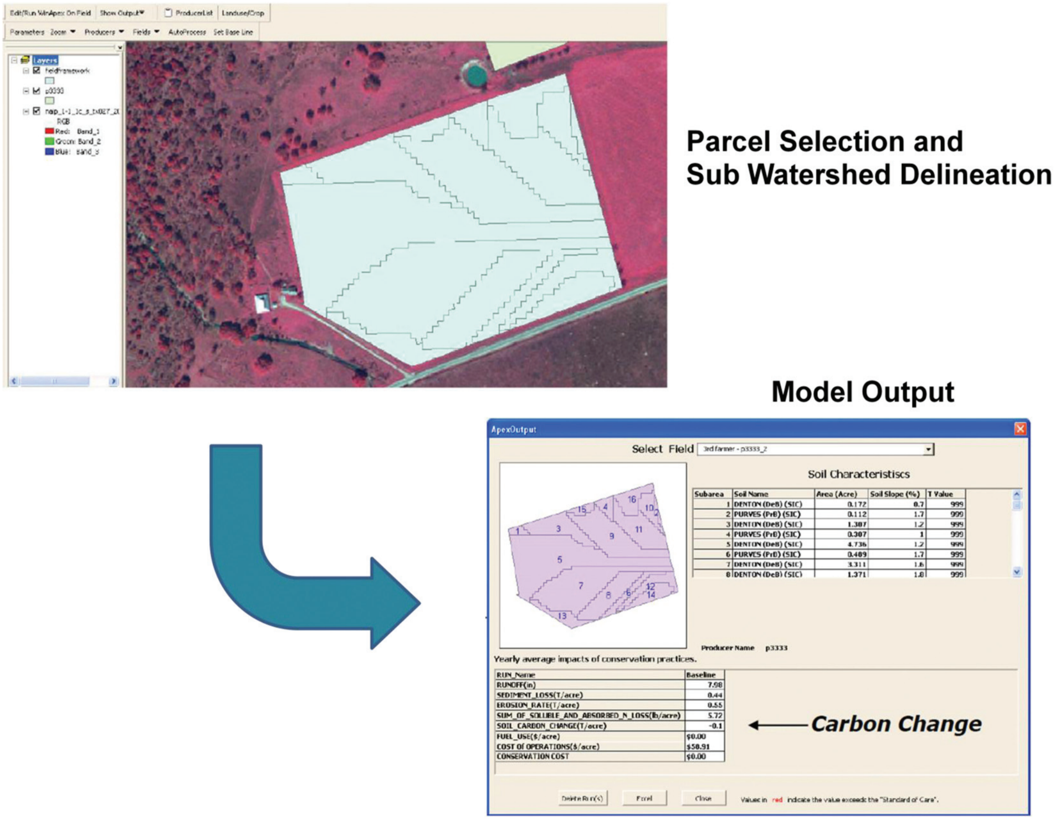
6.5.1.1 Carbon Decision Support Tool Development

SWP has developed a core model referred to as the Agricultural Policy/Environmental eXtender (APEX) model. This tool offers the ability to simulate production and terrestrial carbon sequestration over large landscapes. APEX accounts for transfers of nutrients, water, and animal movement between landforms or sub-watersheds and uses Century Model algorithms for carbon modeling. It allows examination of carbon sequestration in association with ecosystem services such as water quality. Example results from APEX are located in Figure 15.

Rangeland carbon modeling in APEX is being improved through the addition of a selective grazing component for multiple kinds and classes of grazers, and an improvement to the management scenario building for rangelands.

6.5.2 Local Terrestrial Arid Land Rehabilitation and Concomitant Sequestration Project

In this local terrestrial sequestration pilot (Test Letter I in Table7), SWP is currently integrating the soil, vegetation ,and road/well-pad spatiotemporal information into a watershed scale model (WinAPEX) to determine the criteria for evaluating the efficacy of applying produced water from an ECBM project to restore hydrologic function within the landscape. This project examined the decadal changes in land use and management in LaManga Canyon, located within the San Juan Basin Coal Fairway near Navajo City, New Mexico, as a



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Soil Characteristiscs

Subarea	Soil Name	Area (Acre)	Soil Slope (%)	T Value
1	DENTON (DeB) (SIC)	0.172	0.7	999
2	PURVES (PrB) (SIC)	0.112	1.7	999
3	DENTON (DeB) (SIC)	1.307	1.2	999
4	PURVES (PrB) (SIC)	0.307	1	999
5	DENTON (DeB) (SIC)	4.736	1.2	999
6	PURVES (PrB) (SIC)	0.489	1.7	999
7	DENTON (DeB) (SIC)	3.311	1.6	999
8	DENTON (DeB) (SIC)	1.371	1.8	999

Producer Name p3333

Yearly average impacts of conservation practices.

RUN_Name	Baseline
RUNOFF(in)	7.98
SEDIMENT_LOSS(T/acre)	0.44
EROSION_RATE(T/acre)	0.55
SUM_OF_SOLUBLE_AND_ABSORBED_N_LOSS(lb/acre)	5.72
SOIL_CARBON_CHANGE(T/acre)	-0.1
FUEL_USE($/acre)	$0.00
COST Of OPERATIONS($/acre)	$50.91
CONSERVATION COST	$0.00

Values in red indicate the value exceeds the "Standard of Care".

Figure 15: Example of the APEX model and corresponding output screen.

means to estimate carbon fluxes and to determine the potential for increases in carbon storage via ecological restoration. The project also evaluated the use of filtration technology to provide produced water for small-scale site restoration.

SWP has constructed a 50+ year history of the dynamics of the extent and distribution of the road and well pad networks in the San Juan Basin. The purpose of this analysis has been to examine the temporal changes in vegetation, energy infrastructure, and hydrology in relation to the geomorphology over time and to quantify the local, small-scale impact of the construction of roads on soil and vegetation attributes. Roads and well-pads serve as conduits for focusing run-off. Most erosion occurs down slope of well-pads; however due to higher total area of the roads the net effect of roads and well-pads are about even (Matherne, 2006). Figure 16 represents time-lapse aerial images of a well-pad evolution (from drilling, to production, to abandonment) in the San Juan Basin and how the impacted ground area overtime decreases. Well-pad areas no longer being impacted, depending on the stage of well-pad evolution, can be targeted for terrestrial sequestration opportunities through re-vegetation of the area.

Applied produced water from the ECBM project that had been treated to soils representative of the region to determine the impact on soil and vegetation. SWP has employed a zeolite-based reverse osmosis (RO) membrane for produced water purification. The zeolite RO has advantages of organic solvent resistance and can separate salt and organics from produced water simultaneously.

6.6 West Coast Regional Carbon Sequestration Partnership

Major terrestrial sequestration opportunities in the WESTCARB region include afforestation of rangelands and agricultural lands, changes in forest management to increase carbon stocks, improved management of forest fuels to reduce emissions from wildfires, and (where practical) the use of these fuels in biomass energy facilities in the western United States. Results of WESTCARB characterization studies to date show excellent carbon sequestration potential throughout the region for both geologic and terrestrial sequestration (Figure 17). WESTCARB researchers evaluated afforestation of rangelands for California, Oregon, and Washington over 20-, 40-, and 80-year time periods. On a dollar per tonne of CO_2-equivalent basis, costs are lowest for the longer timespans because the planted trees have more time in their prime growing years, and

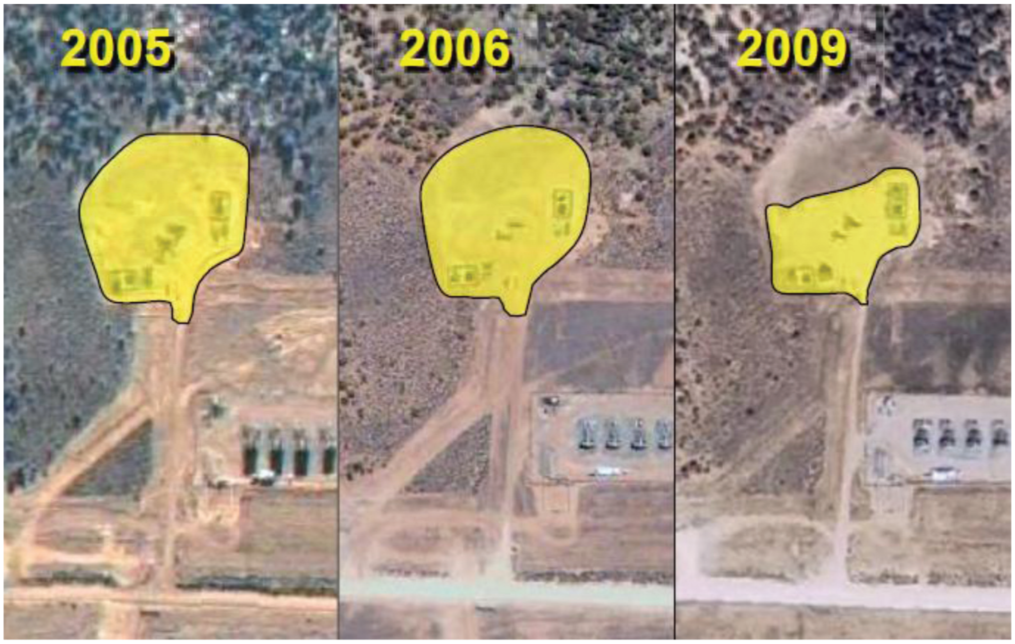

Figure 16: Impacted area of a well-pad site in the San Juan Basin over time from 2005 to 2009. The yellow area indicates the overall land area being used at that stage in time. Previously impacted areas no longer being used can be target for terrestrial sequestration options.

the initial costs of land preparation and planting are amortized over a larger quantity of sequestered carbon. Successful project development entails analysis of forest suitability of candidate lands; a thorough understanding of total costs, including opportunity, conversion, maintenance, measurement, and monitoring costs; gauging the potential variability in sapling survival and tree growth rates; and the aggregate area and geographic distribution of potentially afforested lands (NETL, 2008).

WESTCARB's terrestrial carbon sequestration pilot projects were implemented in Shasta County, California, and Lake County, Oregon. In Shasta County, afforestation activities entail restoring native conifer and oak forests on rangelands and fire-damaged forest lands on 12 pilot projects ranging from 10 to 100 acres each. In Lake County, researchers studied the feasibility of establishing plantations of fast-growing hybrid poplar trees on suitable agricultural or grazing land, which could be harvested on short rotations to fuel biomass

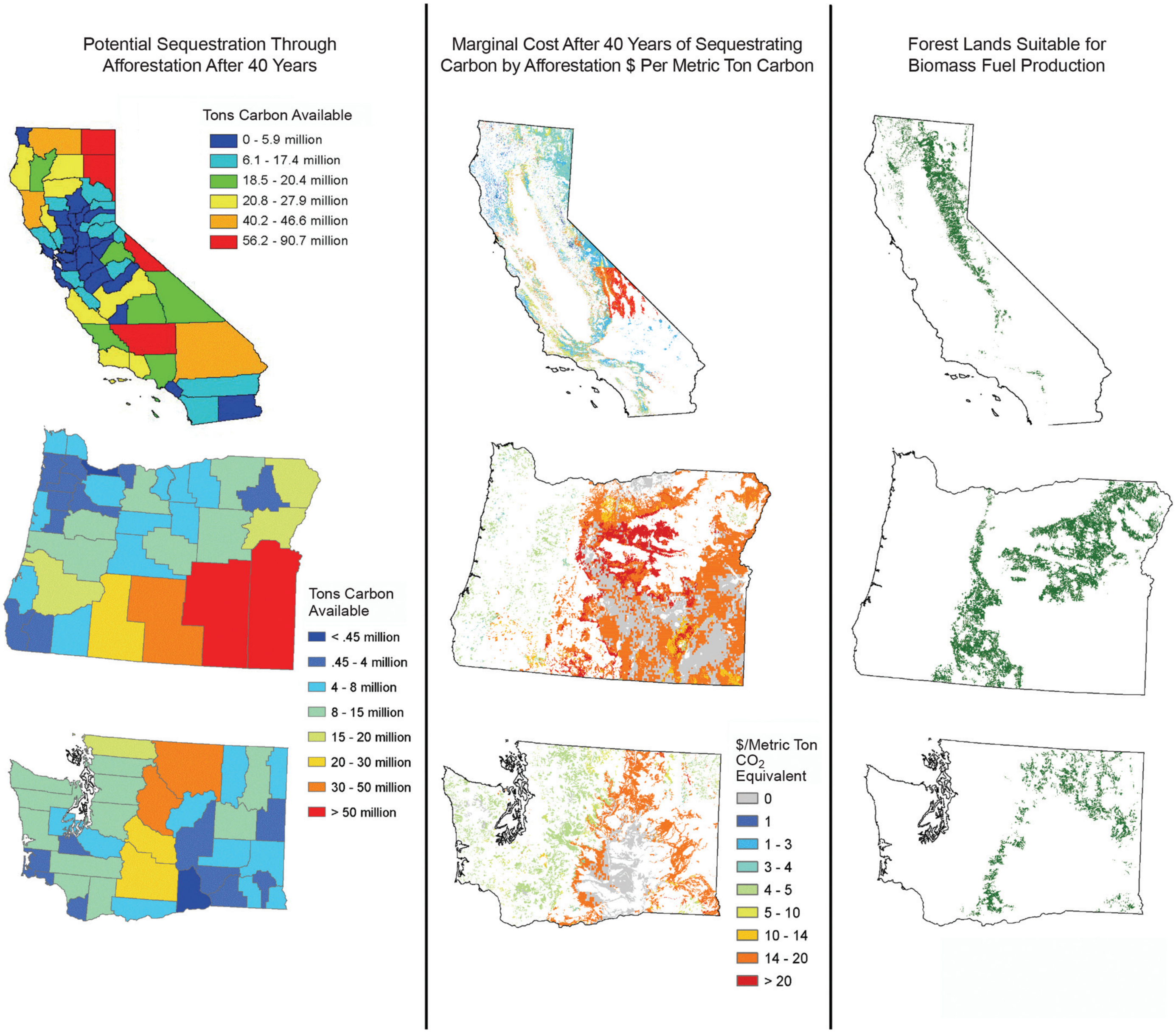

Figure 17: Summary of terrestrial CO_2 sequestration benefits in the California, Oregon, and Washington (NETL, 2008)

power plants. Both the California and Oregon pilots also involved research into carbon sequestration coupled with fire risk management through forest fuel reduction. Fire-prone forests were treated to restore forest health by removing understory trees, brush, and other fuels that could contribute to catastrophic wildfires and the associated large GHG emissions. Where feasible, the removed fuel in Shasta County was transported to a local biomass power plant to generate electricity, which can offset power demand that may otherwise be met by fossil fuel combustion.

6.6.1 Shasta County Terrestrial Sequestration Project

The Shasta County, California, terrestrial pilot (Test Letter J in Table7) included afforestation of marginal lands, conservation-based forest management where a conservation group and timber company worked together to restore and maintain high-quality forest habitats and test the practicality and effectiveness of forest carbon accounting protocols, and fuel reduction/biomass energy activities to reduce GHG emissions from catastrophic wildfires. For afforestation, native conifer and oak species were restored on shrublands and fire-damaged forest lands, with 12 pilot projects implemented, ranging from about 10 to 100 acres each.

Figure 18: Ponderosa Pine seedlings at the end of summer 2008 at the Hendrix site. Approximately 90 percent of all seedlings planted in March 2008 survived the entire summer.

Afforestation costs ranged from $350 to $1,880 per acre depending on the project site, specific site preparation efforts, and species being planted. Baseline conditions varied from recent burns with no existing vegetation and therefore no carbon stocks to old growth Manzanita that represented as much as 34 tons of carbon per acre. Ponderosa pine (*Pinus ponderosa*) was planted on 6 of the 12 study sites (Figure 18), mixed conifer on 4 sites, oak and pine 1 site, and oak woodland on another. Over a 100-year project lifetime, WESTCARB anticipates significant CO_2 sequestration from project sites planted to pine or mixed conifer, whereas sites planted to native oak are expected to sequester much less carbon per acre. Figure 19 shows the projected increase in tons of CO_2 per acre for average WESTCARB plantings, not accounting for baseline stocks. Table 15 provides a summary of each project, its cost, baseline carbon stocks, species planted, and projected net carbon stocks sequestered after 100 years.

Finally, for conservation-based forest management, through a partnership between a conservation group and a timber company, forest management practices on a large parcel were changed to reduce the level of timber harvested and increase rotation length, and the impacts of these changes on forest carbon stocks were analyzed. This pilot also tested the practicality and effectiveness of existing forest carbon accounting protocols. The project was set in a mixed conifer forest including ponderosa pine, sugar pine, incense cedar, white fir and black oak, with a density of 10 MBF/acre. The forest is managed for commercial timber production, similar to other nearby commercial properties. WESTCARB is measured initial existing carbon stocks and calculated anticipated emissions reductions by comparing baseline activity projection to project activity projection (100 years). Baseline activity includes existing timber production efforts under regulatory standards like the California Forest Practice Rules, Endangered Species Act.

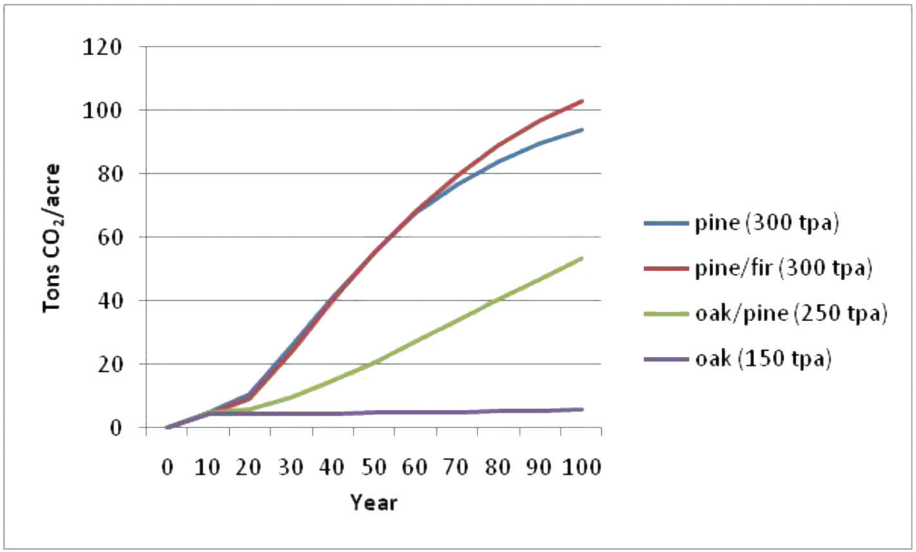

Figure 19: General growth projections from WESTCARB's Shasta County, California terrestrial sequestration field test. The pilot plantings varied in terms of species and number of trees planted, site quality, and survival rates. Shown here are plantings on moderate quality sites, with high survival rates, planted to ponderosa pine at 300 trees per acre (tpa); ponderosa pine and red fir at 300 tpa, native oak and ponderosa pine at 250 tpa, and native oak at 150 tpa. Projections shown here do not take into account the baseline condition, which may decrease the overall CO_2 per acre.

Table 15: Summary of WESTCARB Afforestation Pilot Projects in Shasta County, CA

Project	Acres	Cost/Acre	Baseline		Afforestation		Net Carbon stocks after 100 Years (t/acre)
			Cover Species	Carbon Stocks (t/acre)	Species	Trees/Acre Planted	
Red River Forests Partnership	98	$832	Manzanita	17	Ponderosa Pine	300	77
Brooks Walker	7	$1,265	Manzanita	2	Ponderosa Pine and Red Fir	300	101
Hendrix-Phillips Tree Farm	20	$1,223	Manzanita	6	Ponderosa Pine	300	85
Goose Valley Ranch	60	$1,033	Whitethorn	17	Ponderosa Pine, Red Fir, and Incense Cedar	290	88
Lammers	50	$858	Greenleaf, Deerbrush, and Whitethorn	12	Ponderosa Pine and Red Fir	249	81
Frase	43	$600	None	0	Ponderosa Pine	282	85
Kloeppel	51	$899	Greenleaf and Deerbrush	8	Ponderosa Pine and Red Fir	314	111
Sividas	46	$778	Manzanita	34	Ponderosa Pine	197	53
Eilers	20	$354	None	0	Ponderosa Pine (18 acres)	208	64
					Ponderosa Pine and Blue Oak (2 acres)	258	53
Wilson	14	$1,300	Manzanita	26	Ponderosa Pine	274	65
Lakey	60	$482	None	0	Ponderosa Pine	177	69
BLM	7	$1,880	None	0	Oak	143	6

Examples of required practices under the baseline activities include minimum rotation length for even-aged management (e.g. 60 year rotation for Site II lands), and State-mandated stream buffer widths. Project activity includes practices to conserve easement restrictions, including:

- Harvest 80 percent of growth until 25 MBF/acre stocking achieved
- Stream buffers extended
- Retention standards

WESTCARB anticipates approximately 1 million tonnes of CO_2-equivalent to be stored in the forest feedstocks under the project scenario over the long-term (approximately 100 years), whereas carbon storage potential in forest feedstocks under the existing baseline activity, that includes clearcut harvests, is far less and varies with timber production stage.

6.6.2 Lake County Terrestrial Sequestration Project

The Lake County, Oregon, terrestrial pilot includes fuel reduction/biomass energy activities to reduce GHG emissions from catastrophic wildfires and analysis of the feasibility of afforestation. In Lake County, WESTCARB is studying the feasibility of establishing plantations of fast-growing trees—hybrid poplars—on suitable agricultural or grazing land, which could be harvested on short rotations to fuel biomass power plants. Like the Shasta pilot, this pilot is testing forest management activities to reduce the potential for large GHG releases from catastrophic wildfires, applying new methodologies for rigorous area and emissions baselines, quantifying expected emissions with-treatment versus baseline, and conducting measurement and monitoring activities. The two terrestrial pilot projects combined provide insight into the transferability of fire risk reduction as a CO_2 emission mitigation strategy across forests of the WESTCARB region, as well as producing documentation on establishing baselines and carbon benefits measurements.

6.6.3 Hazardous Fuel Reduction

In both Shasta and Lake Counties, WESTCARB tested forest management activities to reduce the potential for large GHG releases from catastrophic wildfires. Carbon “loss” from conducting fuel treatments is an occasional investment designed to avoid the “problem fire” for multiple ignitions in 1 year and for multiple years. Building on existing fire models, project researchers examined the potential for new methodologies for rigorous area and emissions baselines, quantifying expected emissions with-treatment versus baseline, and conducting measurement and monitoring activities.

A conceptual framework was developed to determine the net impact hazardous fuel treatment activities have on the total quantity of greenhouse gases in the atmosphere? This framework incorporated the critical elements of fuel treatments and wildfire as they relate to net CO_2 emissions:

1. Annual Fire Risk
2. Emissions as a Result of Treatment
3. Emissions as a Result of Fire
4. Removals from forest Growth/Regrowth
5. Retreatment
6. Shadow Effect

The following framework was used to estimate losses and gains in stored carbon with and without treatments (“project” and “baseline” scenarios) and fire:

- **Gain** from *decreased* intensity or spread of fire due to fuel treatment * annual fire probability
- **Loss** from biomass removed during treatment
- **Gain** /**Loss** from substitution of fuels for energy generation
- **Gain** from long term storage as wood products from removed biomass during fuels treatment

- **Loss** from decomposition of additional dead wood stocks created through fuels treatment
- **Gain** /**Loss** from growth differences between with and without treatment and with and without fire
- **Loss** from fires occurring in with project case (with treatment) * annual fire probability
- **Loss** from retreating stands through time

A positive net result indicates increased carbon storage as a result of the without-treatment project, while a negative net result (compared to baseline) indicates a net loss in carbon storage and increased emissions as a result of the with-treatment project, unless CCS from biomass power is considered.

The individual elements of this framework were quantified to determine their overall impact on net emissions/removal, and on-the-ground projects were implemented to test the overall validity of the framework. Fire-prone forests were treated by the landowners/managers to restore forest health by removing suppressed understory trees, brush, and other fuels. Where feasible, biomass fuel was transported to a local biomass power plant to generate electricity that can offset power demand that may have otherwise been met by fossil fuel combustion.

The reality is that fire risk in any given location on the landscape in Shasta and Lake Counties is relatively low (less than 0.76 percent per year), and consequently baseline emissions in untreated stands are low. This reality must be balanced with the mental perception of high emissions that occur when a catastrophic fire occurs. While emissions from fire in the baseline scenario are relatively low, emissions from fuel treatment in the project scenario are not insignificant in that they occur across a relatively broad area in order to intersect with an unknown future fire location.

Substantial emissions occur in the event of a wildfire but significant greenhouse gas emissions still occur on treated sites. In addition regrowth of a healthy forest means that sites have to be retreated with accompanying emissions on a regular schedule (likely at intervals of 20 year or less). The impact of growth is complex but in the absence of wildfire growth projections showed that treated stands sequester less carbon than untreated stands—the opposite is true in the event of a wildfire but such a fire is a low probability event.

Overall findings show that the emissions from fuel treatment greatly exceed the emissions avoided through decreased fire extent and intensity, principally due to the relatively low risk of fire in any given location in a given year. This finding does not decrease the critical importance of fuel treatment activities, it merely shows that the carbon offset market will not be a source of income for fuel treatments.

Additional results from all of the WESTCARB pilot projects will be available in forthcoming Public Interest Energy Research (PIER) reports, which will be posted on the website of the California Energy Commission: http://www.energy.ca.gov/research/index.html.

7.0 Trading of Terrestrially Sequestered Carbon

Emissions trading, also known as cap-and-trade, is an administrative approach used to control pollution by providing economic incentives for achieving reductions in the emission of pollutants. The cap-and-trade approach to air pollution abatement was first implemented in the 'offset-mechanism" taken up in the Clean Air Act of 1977 and the launching of a first emissions trading system as part of the US Acid Rain Program in Title IV of the 1990 Clean Air Act. The sulfur dioxide trading market led to the reduction of emissions in the United States by over 40 percent between 1990 and 2007, meeting the 2010 target three years early and at a quarter of the cost originally predicted. The application of emissions trading has branched out from the US clean air policy to global climate change policy, including to the European Union and, with the expectation of an emerging global carbon market, to regional and private trading markets.

There are active trading programs in several air pollutants. For GHGs, the largest is the European Union Emission Trading Scheme (EU ETS), the world's first functioning GHG emissions trading system which issues 2.1 billion allowances covering over 11,500 emission sources (de Perthuis, 2008). In the United States, there is a national market to trade acid rain pollutants and several regional markets trading carbon allowances (e.g., the Regional Greenhouse Gas Initiative [RGGI]). Currently, there are several private exchanges trading in carbon allowances, including the Chicago Climate Exchange, the European Climate Exchange, Nord Pool, Euronext, European Energy Exchange, and CantorCO_2e. Many companies now engage in emissions abatement, offsetting, and sequestration programs to generate credits that can be sold on one of the exchanges.

7.1 Current Status

The global carbon market experienced strong growth between 2007 and 2008 due to the expansion of allowance markets. A number of national and sub-regional carbon market initiatives, including in the EU and the U.S., are either already underway, seriously under discussion, or actively being revised. Emissions trading systems are already operating or planned in over 35 countries in the developed world (Lazarowicz, 2009). In 2008, the estimated value of the carbon market doubled to $126 billion (Table 16). It is believed that the carbon market will grow significantly beyond 2012, due to the EU's initiative to build worldwide carbon trading mechanisms, the potential US federal

Table 16: Carbon Market at a Glance, Volumes and Values in 2007-2008. Source: World Bank (2009)

Year	**2007**		**2008**	
	Volume, $MtCO_2e$	**Value, MUS$**	**Volume, $MtCO_2e$**	**Value, MUS$**
Project Based Transactions				
Primary CDM	552	7,433	389	6,519
JI	41	499	20	294
Voluntary market	43	263	54	397
Subtotal	636	8,195	463	7,210
Secondary CDM				
Subtotal	240	5,451	1,072	26,277
Allowances Markets				
EU ETS	2,060	49,665	3,093	91,910
New South Wales	25	224	31	183
Chicago Climate Exchange	23	72	69	309
RGGI	na	na	65	246
AAUs	na	na	18	211
Subtotal	**2,108**	**49,361**	**3,276**	**92,859**
Total	**2,984**	**63,007**	**4,811**	**126,345**

cap-and-trade program, and the strong emergence of other regional market trading mechanisms (GlobalData, 2010). By 2020 the carbon market could be worth $2-3 trillion per year (Lazarowicz, 2009).

The term “carbon offset” is often used generically to refer to 1 tonne of CO_2 equivalent (CO_2e). An offset negates the effects of carbon emitted in one place by avoiding the release of a tonne of carbon elsewhere or absorbing/sequestering a tonne of CO_2e that would have otherwise remained in the atmosphere. As a unit of measurement, CO_2e is used as the internationally recognized unit for GHG emissions, since CO_2 is the most abundant GHG. An equivalency measure creates a standard metric, allowing for the conversion of other GHGs, such as methane and hydrofluorocarbons, into a common unit of global warming potential.

For trading purposes, one CO_2e allowance is considered equivalent to 1 tonne (international) or one short ton (RGGI) of CO_2 emissions. These allowances can be sold privately or in the international market at the prevailing market price. In Kyoto countries, these allowances trade and settle internationally and enable allowances to be transferred between countries. Under RGGI, allowances can be transferred across the 10 covered states. International transfers are validated by the United Nations Framework Convention on Climate Change UNFCCC. Each transfer of ownership within the EU is additionally validated by the European Commission.

Climate exchanges have been established to provide a spot market in allowances, as well as futures and options markets, to provide a market price and maintain liquidity. Carbon prices are normally quoted in Euros per tonne of CO_2 or its equivalent (CO_2e). These features reduce the financial impact of a quota on business, while ensuring that the quotas are met at a national and international level.

Emission reductions or GHG mitigation results, achieved by an unregulated outside party, that are transferred to an entity that purchases and/or reports the results, are termed offsets. A tonne of CO_2e can be created, certified, or transacted in several different ways. A combination of factors determine the terminology used to designate a carbon offset credit: Voluntary Carbon Unit (VCU), Climate Reserve Tonne (CRT), Verified Emission Reduction (VER), Certified Emissions Reduction (CER), Certified Financial Instrument, or Assigned Amount Unit (AAU).

Under the Kyoto-driven EU ETS, as stipulated by the UNFCCC, a cap is set on emissions. Allowances are provided, either through allocation or purchase, to emitters covered by the cap. These emitters are required to submit allowances equal to the amount of CO_2e emitted over a predetermined period. The difference between emissions and the cap creates a price for the allowances. Emitters who can reduce emissions for less than the price of an allowance will do so. If, however, abatement costs more than the price of an allowance, an emitter will purchase the allowance. The transfer of allowances is the ‘trade’ in cap-and-trade. Thus, the relative difficulty of abatement and the scarcity of allowances set the price. In theory, those that can reduce emissions most cheaply will do so, achieving the reduction at the lowest possible cost.

Kyoto Annex I countries can make use of three carbon market mechanisms to comply with their obligations under the Kyoto Protocol. These are (1) international emissions trading (often referred to as IET), (2) the Clean Development Mechanism (CDM), and (3) Joint Implementation (JI). With these three carbon market mechanisms in place, Kyoto countries have a wide range of carbon units (including AAUs, Certified Emissions Reductions, and Emissions Reduction Units), each equivalent to one tonne of CO_2e, that they can use for compliance. In addition, carbon can be removed from the atmosphere through land use and forestry management activities; to cover this, an additional type of carbon credit has been created, called a Removal Unit (RMU).

Trading of AAUs between Kyoto Annex I countries covers about one-quarter of world GHG emissions trading. This mechanism is top-down, since it was established by an overarching global convention, the UNFCCC, and involves government-to-government trading. The first commitment period of international emissions trading only started in 2008, so it is still too early to draw any conclusions.

A CDM allows Annex I countries capped under Kyoto to fund carbon reduction projects in non-Annex I countries and earn carbon credits against a pre-defined baseline. These carbon credits, CERs, are equivalent to 1 tonne of CO_2e abated through a CDM project. CERs can be used for compliance instead of AAUs, which means that AAUs and CERs are interchangeable (i.e., fungible). CERs do not result in additional emissions reductions, as they are purchased by Annex I countries to offset against an increase in emissions beyond the cap. They are also used, within limits, by companies to meet their compliance obligations in regional cap-and-trade systems (EU ETS and RGGI). Currently, the CDM is the mechanism used to link developing countries to existing carbon markets.

Finally, a JI allows Annex I countries capped under Kyoto to implement emissions reduction projects in other Annex I countries. Carbon credits generated through JI projects, called Emissions Reduction Units (ERUs), and converted from AAUs are equivalent to one tonne of CO_2e and can be used for compliance. In a similar way to the CDM, JI projects do not result in additional emissions reductions beyond the level of the national target. JI has made slow progress, with only around 200 projects registered to date (75 Mt of CO_2e), and most of these are taking place in Russia.

A terrestrial project carries out specific activities on an identified tract of agricultural or forest land that will sequester carbon in soil, wood, or wood products. The sequestered carbon amount is measured, converted into an equivalent CO_2 emission reduction, and the amount reported or registered under the guidelines. It is also recognized that an aggregator organization can assemble a group of projects and either report the offsets or transfer them to a reporting entity. In addition to the accounting protocols, there are other requirements for rigor, transparency, and certainty of carbon storage for projects to qualify for either a voluntary registry or a trading system.

The EU, U.S., and other countries and regions are seriously engaged in executing and developing markets in carbon credits. However, the numerous proposed emissions trading policies, standards, and processes are too complex and require greater simplicity, comparability of targets, and transparency of underlying assumptions. In addition to the CDM, there are now over a dozen carbon certification standards that compete with each other for market acceptance. Competition is good for the market, but accepted standards could reduce complexity and provide closer linkage across the carbon markets.

7.2 Carbon Trading Markets and Registries

A carbon market can be implemented nationally or regionally by setting emission caps consistent with international or regional rules and pushing the liability down to the emitter level. This means that emissions from selected industries (e.g., power generators) are capped, and individual companies can trade allowances on a carbon market to ensure that they have sufficient allowances to match their actual emissions. This enables each company to determine whether to emit and purchase allowances or to reduce emissions.

In 2003, the European Union agreed to create the EU ETS, bringing together all EU countries within one carbon market. The creation of the EU ETS was driven by the Kyoto Protocol. Since 2005, the EU ETS has developed measuring, reporting, and verification guidelines to produce accurate emissions data; established national registries (which contain accounts of where units are held in the name of the government or in the name of legal entities authorized by the government to hold and trade units); and encouraged businesses to factor carbon trading into business operations by taking part in the ETS.

EU ETS continued to dominate the global carbon market in 2008, with transactions valued at US$92 billion (€63 billion), representing 87 percent year-to-year growth. In 2008, over 3 billion EUA spot, future, and option contracts traded for a variety of purposes, including compliance, risk management, arbitrage, and profit-taking (World Bank, 2009). Economic slowdown in Europe and elsewhere led to lower demand for housing and cement, automobiles and steel, etc. As demand and commodity prices collapsed, emissions were lower as was the need to purchase EUAs, because emitters were granted free allocations prior to Phase II, when the economy was healthy, global demand for commodities was strong, and emissions were higher.

Verified emissions from the EU ETS decreased by around 3 percent in 2008, in part attributed to the economic downturn (New Carbon Finance, 2009). The decrease in emissions led to a fall in EU ETS allowance (EUA) prices in early 2009, which indicates that the market mechanisms of supply and demand are operating (Figure 20). In addition, because caps will be tighter in Phase III and businesses can bank surplus EUAs for future use, EUA prices have held up despite strong downward pressures. The EU ETS continues to

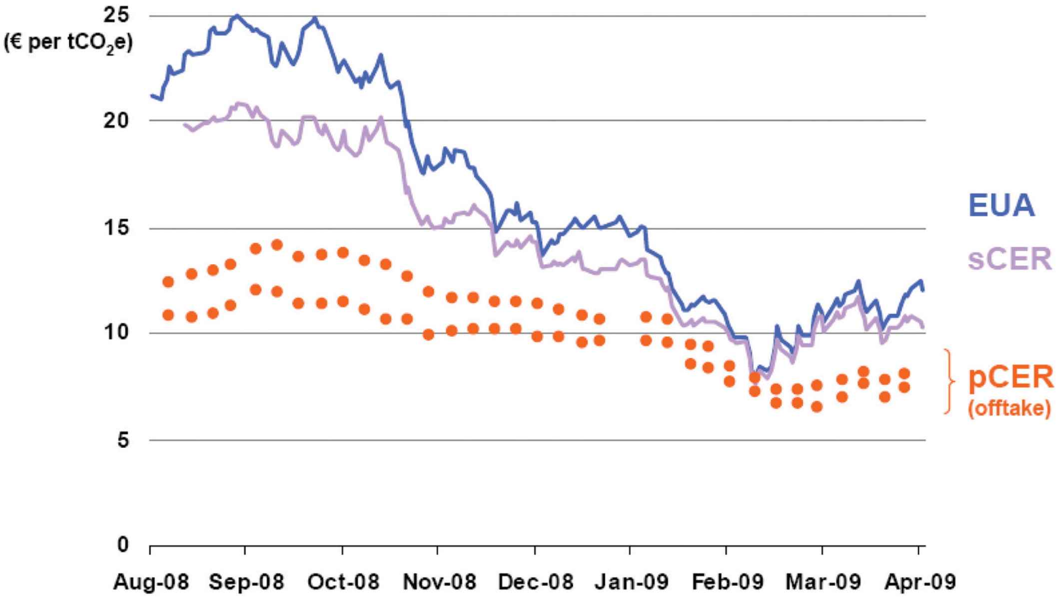

Figure 20: Market prices of EUA's and CER's. Source: World Bank (2009, Figure 1).

insist on its intent to exclude CDM credits from land use, land use change, and forestry (LULUCF) projects, citing concerns with non-permanence, monitoring and reporting requirements, and potential price impact (World Bank, 2009).

In the United States, a regional ETS has been operating since 2008; RGGI caps emissions in 10 northeastern and mid-Atlantic states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont) and plans to reduce CO_2 emissions from the power sector by 10 percent by 2018 (RGGI, 2010a). States sell nearly all emission allowances through auctions and invest the proceeds in consumer benefits—energy efficiency, renewable energy, and other clean energy technologies. The majority of CO_2 allowances issued by each participating state are distributed through quarterly auctions. Each RGGI state offering CO_2 allowances for sale in a CO_2 Allowance Auction retains the authority to make its own regulatory determinations in conducting the auction.

Under RGGI rules, a CO_2 allowance represents a limited authorization to emit one short ton of CO_2, as issued by a respective participating state (RGGI, 2010a). A regulated power plant (250 MW or larger) must hold CO_2 allowances equal to its emissions to demonstrate compliance at the end of each three-year control period. The first control period for fossil fuel-fired electric generators under each state's CO_2 Budget Trading Program took effect on January 1, 2009, and extends through December 31, 2011.

Allowances for the first (2009–2011) control period may be used to meet current compliance obligations or may be banked for use in future control periods. CO_2 allowances for the second (2012–2014) control period can only be used to meet compliance obligations beginning in 2012. CO_2 allowances issued by any participating state are usable across all state programs; thus, the 10 individual state CO_2 Budget Trading Programs, in aggregate, form one regional compliance market for CO_2 emissions. In the latest auction (March 12, 2010), all of the 40,612,408 CO_2 allowances for the first 3-year control period (2009-2011) sold at a price of $2.07 per allowance. A total of 2,091,000 of the 2,137,992 CO_2 allowances for the second control period (2012-2014) sold at a price of $1.86 per allowance (RGGI, 2010b).

The RGGI participating states also allow offset allowances in five project categories, each of which is designed to reduce or store emissions of CO_2, methane, or sulfur hexafluoride (SF_6) within the 10-state region. RGGI has been a useful testing ground for developing new monitoring, reporting, and verification standards; computer systems, such as registries; and, more generally, for bringing business to the business of carbon trading.

One of the first voluntary efforts was the National Voluntary Reporting of Greenhouse Gases Program (Section 1605(b) of the Energy Policy Act of 1992, P.L. 102-486) that required the Secretary of Energy, through the Energy Information Administration, to establish a voluntary reporting program and database on emissions of GHGs, reductions of those gases, and carbon sequestration. In response to the Act, DOE established the GHG Registry, widely known as the 1605(b) program, and has been operating and updating it since 1995.

The California Climate Action Registry (CCAR) is a nonprofit voluntary registry for GHG emissions, which allows members to document GHG emissions. California law (SB812) requires the CCAR to create a protocol to encourage carbon storage activities by creating an incentive for forest owners to undertake forest conservation, conservation-based management, and reforestation projects. The first forestry protocols were released in late 2004; the Registry encourages feedback on how to improve and update these protocols.

Under the forestry sector protocol, any entity with at least 100 acres of trees is eligible to report their GHG emissions. The registry requires them to report net emissions from both biological (e.g., sequestration gains and harvest losses) and non-biological (e.g., emissions from forestry management and harvesting operations). Guidelines for reporting non-biological emissions are included in the registry's General Reporting Protocol, and guidelines for reporting biological emissions are detailed in the Forest Sector Protocol. For the first three years of reporting, a forest entity is required to record only entity-level carbon stocks and CO_2 emissions. From the fourth year onwards, they are required to report any of the other five GHGs mentioned in the Kyoto Protocol that are relevant to the forestry sector.

The California Registry is transitioning to The Climate Registry. The Climate Registry is a nonprofit collaboration among North American states, provinces, territories, and Native Sovereign Nations that sets consistent and transparent standards to calculate, verify, and publicly report greenhouse gas emissions as a single registry.

The CCX is a self-regulating exchange that administers a voluntary, legally-binding pilot GHG emission reduction and trading program for North America. It began active on-line trading of GHG emission allowances in 2003. CCX members include major corporations, trading firms, non-governmental organizations, and public institutions, such as cities and universities. Reductions achieved through CCX are through a legally binding compliance regime providing independent, third party verification by the Financial Industry Regulatory Authority (FINRA, formerly NASD).

CCX has established eligibility and technical criteria for a variety of Offset Project categories (CCX, 2009). Currently, the following terrestrial mitigation activities have prescriptive eligibility, evaluation, and verification requirements:

- Agricultural Best Management Practices
    - Continuous Conservation Tillage
    - Grassland Conversion Soil Carbon Sequestration
    - Sustainable Rangeland Soil Carbon Sequestration
- Forest Carbon Sequestration
    - Afforestation and Reforestation
    - Sustainable Forest Management

The Chicago Climate Exchange Carbon Financial Instrument (CCX-CFI) skirted above US$7 per tonne CO_2e in early May 2008 before plunging to less than US$2 by September 2008, when it became clear that the Lieberman-Warner bill would not become law. The CCX-CFI traded in the US$1-2 price band through 2009, and prices have collapsed to US$0.10 per tonne as the supply of credits exceeds demand and the market perceives that any U.S. federal regulation is a long way off and will likely not recognize the value of CCX-CFIs.

8.0 Conclusions

There is growing concern that the buildup of CO_2 in the atmosphere is contributing to global climate change, and efforts are underway to reduce CO_2 emissions through the use of techniques such as CCS, but such approaches do nothing to remove CO_2 that is already in the air. However, there is an approach that can accomplish this by using the photosynthetic process, which is part of the natural carbon cycle, to create organic matter that is stored in vegetation and soils. Because many of the world's soils have been seriously degraded due to deforestation, poor farming practices, overgrazing, and wetlands destruction, there is considerable potential for restoring carbon stocks to their former levels through terrestrial carbon sequestration. Such efforts not only have the benefit of decreasing atmospheric CO_2 levels, but also increase the productivity of the land. Best practices include no-till farming, restoring mine lands to forest, managed grazing, and restoring wetlands. Field trials by the RCSPs are making a significant contribution to understanding the dynamics of carbon accumulation in soils.

To make terrestrial sequestration more attractive, some climate exchanges are allowing credits. For this to be possible, strict accounting protocols are needed, which in turn require robust and inexpensive analytical techniques. Several such techniques are under development and look very promising.

The overall conclusion of this report is that there is considerable opportunity and growing technical sophistication for terrestrial carbon sequestration, that analytical techniques are under development to allow terrestrially stored carbon to generate credits, and that a healthy carbon trading market is developing in spite of recent setbacks in the United States.

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Contacts

If you have any questions, comments, or would like more information about DOE's Carbon Sequestration Program, please contact the following persons:

Dawn Deel
Sequestration Project Manager
Strategic Center for Coal
304-285-4133
dawn.deel@netl.doe.gov

John Litynski
Sequestration Technology Manager
Strategic Center for Coal
412-386-4922
john.litynski@netl.doe.gov

Prepared by
Coordinating Lead Authors
Rameshwar Srivastava, Ph.D.—KeyLogic Systems
Howard McIlvried, Ph.D.—KeyLogic Systems

Contributing Authors
Derek Vikara, P.E.—KeyLogic Systems
Timothy Carr, Ph.D.—West Virginia University/KeyLogic Systems
Lucian Wielopolski, Ph.D.—Brookhaven National Laboratory
Katherine Goslee—Winrock International

Review Editor
Rattan Lal, Ph.D.—The Ohio State University

Quality Assurance/Control
Andrea Ware—KeyLogic Systems
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NATIONAL ENERGY TECHNOLOGY LABORATORY

1450 Queen Avenue SW
Albany, OR 97321-2198
541-967-5892

2175 University Avenue South,
Suite 201
Fairbanks, AK 99709
907-452-2559

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

13131 Dairy Ashford,
Suite 225
Sugar Land, TX 77478
281-494-2516

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