Soil Carbon Sequestration in U.S. Rangelands

Issues Paper for Protocol Development

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Terms

AFOLU	Agriculture, Forest and Other Land Use
BAU	Business As Usual
CARB	California Air Resources Board
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CRP	Conservation Reserve Program
DNDC	DeNitrification-DeCarbonization (ecosystem model)
EC	Eddy Covariance
ESD	Ecological Site Description
EQIP	Environmental Quality Incentives Program
GIS	Geographical Information System
GPS	Geographical Positioning System
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
kg^{-1}	per kilogram
LIBS	Laser Induced Breakdown Spectroscopy
MIRS	Mid InfraRed Spectroscopy
MMV	Measurement, Monitoring and Verification
$MTCO_2e$	metric tons of carbon dioxide equivalent

N	**nitrogen**
N_2O	**nitrous oxide**
NIRS	**Near InfraRed Spectroscopy**
NOx	**nitrogen oxides**
NRCS	**Natural Resources Conservation Service**
REDD	**Reduction of Degradation and Deforestation**
SIC	**soil inorganic carbon**
SOC	**soil organic carbon**
SSURGO	**Soil Survey Geographic database**
STM	**State and Transition Model**
USDA	**United States Department of Agriculture**
WCI	**Western Climate Initiative**

The purpose of this paper is to identify and explore the issues relevant to the development of a greenhouse gas emissions reduction crediting protocol for soil carbon sequestration in U.S. rangelands.

Executive Summary

Rangelands are uncultivated lands that include grasslands, savannas, steppes, shrublands, deserts, and tundra. The native vegetation on rangelands is predominantly grasses, forbs or shrubs (Kothmann 1974). Rangelands cover 31% of the land surface area of the United States (Havstad et al. 2009), and up to half of the land surface area worldwide (Svejcar et al. 2008, Lund 2007). Most land areas that are not developed, not cultivated, not forested, and not solid rock or ice can be classified as rangelands. Because of their extent, a small change in soil carbon stocks across rangeland ecosystems would have a large impact on greenhouse gas accounts.

There are 761 million acres of rangelands in the U.S. (Havstad et al. 2009), half of which is public lands in the West (Follett et al. 2001). The primary activity focus on rangelands is grazing. Rangelands and grazing lands and are two broadly overlapping categories. U.S. grazing lands, including managed pasturelands, have the potential to remove an additional 198 million tons of carbon dioxide (CO_2) from the atmosphere per year for 30 years (Follett et al. 2001). This would offset 3.3 % of U.S. CO_2 emissions from fossil fuels (EIA 2008), and help protect rangeland soil quality for the future.

The past twenty years have seen a tremendous enhancement of the understanding of soil carbon, both its role in the global carbon cycle and the factors that influence its dynamics. Although soil organic carbon (SOC) has long been of interest to scientists, technical advisors and land managers as an indicator of soil health, the link between the carbon cycle and global climate change has provided increased impetus for quantification and ultimately, management.

Even if atmospheric concentrations of greenhouse gases were quickly stabilized, anthropogenic warming and sea levels would continue to rise for centuries (IPCC 2007a). Even the most drastic reductions in emissions of anthropogenic greenhouse gases may not do enough, on their own, to preserve current environmental integrity for future generations. If the effects of global warming are to be kept to a minimum, carbon already emitted to the atmosphere as a result of human activities must be sequestered into stable forms.

Various strategies have been proposed, including the use of untested technologies requiring vast expenditures of energy and financial resources. For example, while geologic and deep ocean sequestration schemes have been proven physically viable, the economic, environmental and social costs associated with these technologies remain uncertain. For the immediate future, sequestration via natural processes remains the most viable and ready to implement option, and one of the most cost-effective (Department of Energy 2009).

Soils hold over three times as much carbon as the atmosphere (Lehmann and Joseph 2009), more carbon than the Earth's vegetation and atmosphere combined, and have the capacity to hold much more (Lal 2004). Carbon stocks in terrestrial ecosystems have been greatly depleted since the beginning of the Industrial Revolution, with changes in land use and deforestation responsible for the emission of over 498 gigatons of CO_2 to the atmosphere (IPCC 2000), approximately half of which has been from soils (IPCC 2000, Lal 1999). Each ton of carbon stored in soils removes or retains 3.67 tons of CO_2 from the atmosphere.

Soil carbon comprises SOC and soil inorganic carbon (SIC). SOC is a complex and dynamic group of compounds formed from carbon originally harvested from the atmosphere by plants. During photosynthesis, plants transform atmospheric carbon into the forms useful for energy and growth (Schlesinger 1997). Organic carbon then cycles from the plant to the soil, where it becomes an important source of energy for the soil ecosystem, driving many other nutrient cycles. SIC is the result of mineral weathering and forms a small proportion of many productive soils. The focus of this paper is on SOC sequestration.

SOC makes up approximately 50% of all soil organic matter (SOM) (Wilke 2005, Nelson and Sommers 1982). SOM content is correlated with productivity and defines soil fertility and stability (Herrick and Wander 1998). SOC and SOM buffer soil temperature, water quality, pH and hydrology (Pattanayak et al. 2005, Evrendilek et al. 2004). Increases in SOC and SOM lead to greater pore spaces and surface area within the soil, which subsequently retains more water and nutrients (Tisdale et al. 1985, Greenhalgh and Sauer 2003). This factor is of critical importance in U.S. rangelands, most of which experience less than 600 mm precipitation per year. Higher soil carbon levels can reduce the impacts of drought and flood.

U.S. rangelands cover a vast area, comprise many different ecosystems, and experience a wide range of environmental conditions. Landowners and land managers will select project actions with the goal of maximizing productivity and carbon sequestration, according to local conditions. The ecological state of the landscape (Asner et al. 2003), its vegetation (Derner and Schuman 2007) and land use history all influence the effectiveness of different project actions.

Project actions for soil carbon sequestration, some of which require further research, include:

Changes in land use:

- conversion of abandoned and degraded cropland to grassland (Franzluebbers and Stuedemann 2009)
- avoided conversion of rangeland to cropland or urban development (Causarano et al. 2008)

Changes in land management:

- Extensive management (i.e., does not require infrastructure development)
  - adjustments in stocking rates (Schuman et al. 1999, Conant and Paustian 2002)
  - integrated nutrient management (FAO 2008, Franzluebbers and Stuedemann 2005, 2008)
  - introduction or reintroduction of grasses, legumes and shrubs on degraded lands (Schuman et al. 2001, Conant et al. 2001)
  - managing invasive species
- Intensive management (i.e., requires infrastructure development)
  - reseeding grassland species
  - addition of trees and shrubs for silvopastoralism (Sharrow 1997, Nair et al. 2009)
  - managing invasive shrubs and trees (Franzluebbers et al. 2002)
  - riparian zone restoration
  - introduction of black carbon (biochar) into soils (Lehmann and Joseph 2009)

There are two motivating factors likely to encourage landowners to adopt carbon sequestration practices. The first is the range of biophysical benefits. Soil carbon is positively correlated with productivity such that as soil carbon increases, long-term soil productivity can be expected to increase under proper management. The second factor is increased financial benefit. Landowners could benefit from revenues from the sale of what are termed *emissions reductions credits* that result from increased soil carbon sequestration. The existence of a comprehensive rangeland soil carbon protocol will allow increases in soil carbon storage to be converted to verified emissions reductions for use within an offset market, Cap and Trade system, or other regulatory frameworks or programs.

Environmental and financial benefit will result from carbon sequestration above that which would have occurred in the absence of the project. This additional sequestration will be achieved by the transition from one set of management practices to another, not by any set of management practices *per se*. New management practices will be selected with reference to those to be replaced.

The many co-benefits associated with increasing levels of soil carbon suggest the prospect of win-win scenarios for landowners, climate change mitigation, and ecosystem services. Optimizing uptake of sequestration activity depends on the design and implementation of the protocol, since it is here that incentives to implement changes in management practices will be generated.

When it comes to quantifying changes in soil carbon stocks, it is generally true that accuracy costs more, and that less expensive methods are less accurate. Neither extreme is desirable: extreme data coarseness would lead to low confidence in sequestration values and low market interest in credits generated; cost-prohibitive quantification costs would also lead to low uptake. Between these two extremes, a balanced methodology will optimize adoption rates and environmental benefit.

There are many methods available for assessing changes in rangeland soil carbon stocks. Rather than tie a protocol to the limitations of one particular method, it is logical to combine the strengths of different methods into a single combination methodology, which may be updated as economics and technical advances allow. A performance standard for field use that is supported by ecosystem modeling and site-specific measurements would represent a balanced solution at a viable cost, and provide the economic and social incentives for adoption of enhanced management.

Critical Terms Defined

For the purposes of this paper, a *methodology* is defined as the accredited means of scientifically quantifying changes in soil carbon stocks within a greenhouse gas emissions reduction *protocol*, which is the document that also includes all relevant rules, parameters and equations for the components of the credit accounting process—including any deductions that need to be made from gross sequestration values. The term *performance standard* implies a methodology that is based on a number of standard assumptions, as opposed to a project-specific quantification methodology. A performance standard is usually easier, faster and less accurate than project-specific quantification methodologies.

Soils are often *carbon sinks*, and sometimes *carbon sources*. A sink absorbs more carbon than it emits; a source emits more carbon than it absorbs.

There is a difference between *soil carbon sequestration* and *soil carbon storage*. *Soil carbon sequestration* is a process, whereby carbon is transferred from the atmosphere into soils. *Soil carbon storage* is the retention of sequestered carbon in the soil. (Storage of newly sequestered soil carbon must take place over the lifetime of the credit.)

The term *soil carbon stocks* refers to how much carbon is stored in the soil at a particular time. Changes in carbon stocks, as a result of project activity, are calculated as the difference between stocks before and after project activity. Pre-project carbon stocks are referred to as the *baseline*. There is a second definition of *baseline*, which is the forward-looking conditions or soil carbon levels *as they would have been in the absence of the project*, under Business As Usual (BAU). We refer to the former as the *pre-project (soil carbon) baseline* and the latter as the *forward-looking baseline.*

Additionality refers to the concept that carbon sequestration, or emissions reductions, achieved by project activity must be over and above any that would have occurred in the absence of the project, i.e. beyond BAU. Additionality must be proved for credits to be countable. Different ways of establishing additionality are discussed.

Leakage is the concept that activity to reduce greenhouse gas emissions within project boundaries in some cases may force increased emissions outside project boundaries, thereby eliminating some of the achieved emissions reductions. For example, although converting usable cropland to rangeland may lead to increased carbon sequestration within project boundaries, it could force displaced crops to be grown elsewhere, resulting in leakage.

Permanence is the concept that carbon sequestration achieved as a result of project activity must be secured over the lifetime of the credit.

Strategies to address leakage and permanence are discussed below.

Within the context of this paper, successful project activity will lead to net reductions in greenhouse gas emissions, on a project, regional and national basis. For this reason soil carbon credits are henceforth referred to as *greenhouse gas emissions reductions credits*, or simply *emissions reductions credits*.

One credit represents one metric ton of emissions reductions, in carbon dioxide equivalent, achieved as a result of project activity, once verified according to the mechanisms specified in the relevant protocol and then issued by the registry in question.

A registry is an agency such as the Chicago Climate Exchange, the Voluntary Carbon Standard or the Climate Action Reserve that oversees the development and management of protocols designed to lead to net emissions in greenhouse gases, either through direct emissions reductions or the sequestration of greenhouse gases into non-atmospheric states.

For the purposes of this discussion, all emissions reductions credits will be generated by soil carbon sequestration, although it is very important to recognize that rangeland ecosystems and management systems have significant potential for additional woody biomass sequestration and reductions in the emissions of greenhouse gases other than CO_2.

Greenhouse gases emissions that may potentially be affected by changes in management in rangeland ecosystems are CO_2, nitrous oxide (N_2O) and methane (CH_4). Over 100 years, the Global Warming Potential (GWP) of CO_2 is 1, of methane is 25, and of nitrous oxide is 298 (IPCC 2001a, 2007b). GWP values allow the net effect of changes in greenhouse gas budgets across different gases to be calculated, and for different scenarios to be compared. The resulting figures are given in MTCO2e, or metric tons of carbon dioxide equivalent. (1 MMTCO2e = one million metric tons of CO_2 equivalent.)

Introduction

Rangelands represent “a broad category of land…characterized by native plant communities, which are often associated with grazing, and are managed by ecological, rather than agronomic methods. The term ‘range’ can also include forestlands that have grazing resources, or seeded lands that are managed like rangeland. Range resources are not limited to the grazable forage, but may include wildlife, water and many other benefits.” (Society for Range Management 2009) Rangelands include grasslands, savannas, shrublands, deserts, and tundra. Most areas in the world that are uncultivated, not forested and not solid rock or ice can be classified as rangelands.

Pastureland is distinguished from rangeland by the fact that periodic cultivation may be used to maintain introduced forage species; agronomic inputs such as irrigation, fertilization and weed control are also practiced.

Dynamics of Soil Carbon Sequestration

SOC is a dynamic group of compounds that have their origin in the photosynthetic activity of plants—trees, grasses, shrubs, forbs and legumes. The carbon in these compounds cycles through solid forms back to the atmosphere, at different rates, with turnover times ranging from months to hundreds of years (Davidson and Janssens 2006, Six and Jastrow 2002).

During photosynthesis, plants reduce carbon from its oxidized form to the organic forms useful for growth and energy storage (Schlesinger 1997). Some of this carbon that has been fixed from the atmosphere in time becomes soil carbon through the processes of above- and belowground decomposition, root die-off, and the release of sap exudates from plant roots into the soil (exudates contain carbohydrates). Photosynthesis also provides the raw materials for indirect imports of carbon-rich material onto and into the soil, for example animal manure and compost.

Soil carbon includes SIC in the form of carbonates. SIC is the result of mineral weathering, and is less responsive to management than SOC, turning over much more slowly (Izaurralde 2005). SIC content is low in many productive soils. Soil microbial biomass carbon forms 1-3% of total soil carbon.

SOC forms 48-58% of SOM (Wilke 2005). SOM defines soil fertility and stability (Herrick and Wander 1998). Most SOC is found in the top of the soil profile, due to the presence and influence of biotic processes there, with approximately 64% of soil carbon in the top 50cm (Conant et al. 2001). Around 90% of carbon in rangeland systems is located in the soil (Schuman et al. 2001), as opposed to above-ground biomass.

SOC accumulation is positively correlated with precipitation and negatively correlated with temperature (Jones 2007). The rate of soil organic carbon accumulation is highest in cool, wet conditions (Schlesinger 1997) and lowest in deserts. The SOC content of rangeland soils varies from under 1% to over 10%—even in drylands (Janzen 2001). Soil carbon stocks are positively correlated with the presence of clay and iron, and negatively correlated with the bulk density of soil. (This factor also reflects the negative effect of compaction on productivity.)

The rate of carbon sequestration is determined by the net balance between carbon inputs and carbon outputs. Carbon inputs and outputs are affected by management and by two biotic processes—production of organic matter in the soil and decomposition of organic matter by soil organisms. The biotic processes are strongly controlled by physical, chemical, and biological factors including biome, climate, soil moisture, nutrient availability, plant growth, and erosion (Derner and Schuman 2007, Jones 2007, Post et al. 2001, Svejcar et al. 2008, Ingram et al. 2008).

Soil CO_2 is the main end product of the decay of SOC. Under aerobic conditions CO_2 is produced by respiration of bacteria and protozoa in the guts of insects, and bacteria and fungi in the soil (Singer and Munns 1987). Soil CO_2 production accelerates with temperature and with exposure of SOM to air in pore spaces and on the surface of the soil. When decomposition and soil CO_2 production can be slowed, the net rate of soil carbon accumulation and storage may be increased.

There are three ways in which SOC and SOM can be protected from microbial metabolization or decomposition (Jastrow and Miller 1998)**:** Biochemical recalcitrance occurs due to the chemical characteristics of carbon substrates, and because as substrates are consumed by microbes, remaining un-decayed compounds become progressively less decomposable. Chemical stabilization occurs with the bonding of negatively charged cations associated with SOC to positively charged iron and clay anions. Physical protection of SOM occurs within soil aggregates, held together by 'aggregate glues' such as glomalin, a sticky substance produced by soil fungi that is 30-40% carbon by weight (Comis 2002)**.** SOC lower in the profile tends to be protected from microbial decomposition due to chemical stabilization. Physical protection can vary by depth and soil type (Del Galdo et al. 2003).

Carbon Pools and Carbon Fractions

Researchers employ the concept of carbon pools to distinguish carbon that cycles at different rates in the ecosystem. Carbon in each pool has a different turnover time or Mean Residence Time (MRT). Carbon pools are not distinct groups of carbon compounds, which are called *fractions*. There are two soil fractions, the light fraction and the heavy fraction, which are further classified and range from the *free light fraction* to the *heavy occluded fraction*.

Light fractions are composed of fresh plant materials that are subject to rapid decomposition, with turnover from a few months to a few years. Early changes in SOC due to management often occur in the small light fraction, which is known for its spatial and temporal variability. Because most of the turnover of SOM is in the light fractions, it is important to include this fraction within any chosen methodology (Post et al. 2001). Accumulations of light fraction carbon can be quite large in permanently vegetated soils—forests and grasslands.

Carbon in the heavy occluded fraction has a MRT from hundreds to over a thousand years. SOC and SOM in this fraction are less susceptible to decomposition than in the light fraction. The heavy fraction is composed of polysaccharides (sugars) and humic materials often stabilized in complexes with clay minerals and silt-sized particles (Schlesinger 1997). One very chemically recalcitrant portion of the heavy fraction has turnover times of 1,500 to 3,500 years (Post et al. 2001).

The Effects of Management on Soil Carbon Dynamics

Soil carbon levels at a regional scale generally depend upon rainfall and year-to-year variability. Historic soil fertility is an important driver of soil carbon dynamics. Soils with relatively high levels of available nutrients (phosphorus, nitrogen, potassium, etc.) will typically experience higher levels of plant productivity when water is readily available for plant uptake. Few, if any, rangelands receive regular additions of artificial fertilizer; thus soil fertility, along with water availability, is a key factor in predicting plant productivity and soil carbon levels.

Management is an important contributor to carbon dynamics on rangelands. While croplands and forests are managed to optimize the harvest of plant material directly, rangeland managers typically rely on the use of domestic herbivores to harvest and convert plant material to useable products. The presence of grazing animals complicates the job of predicting carbon dynamics.

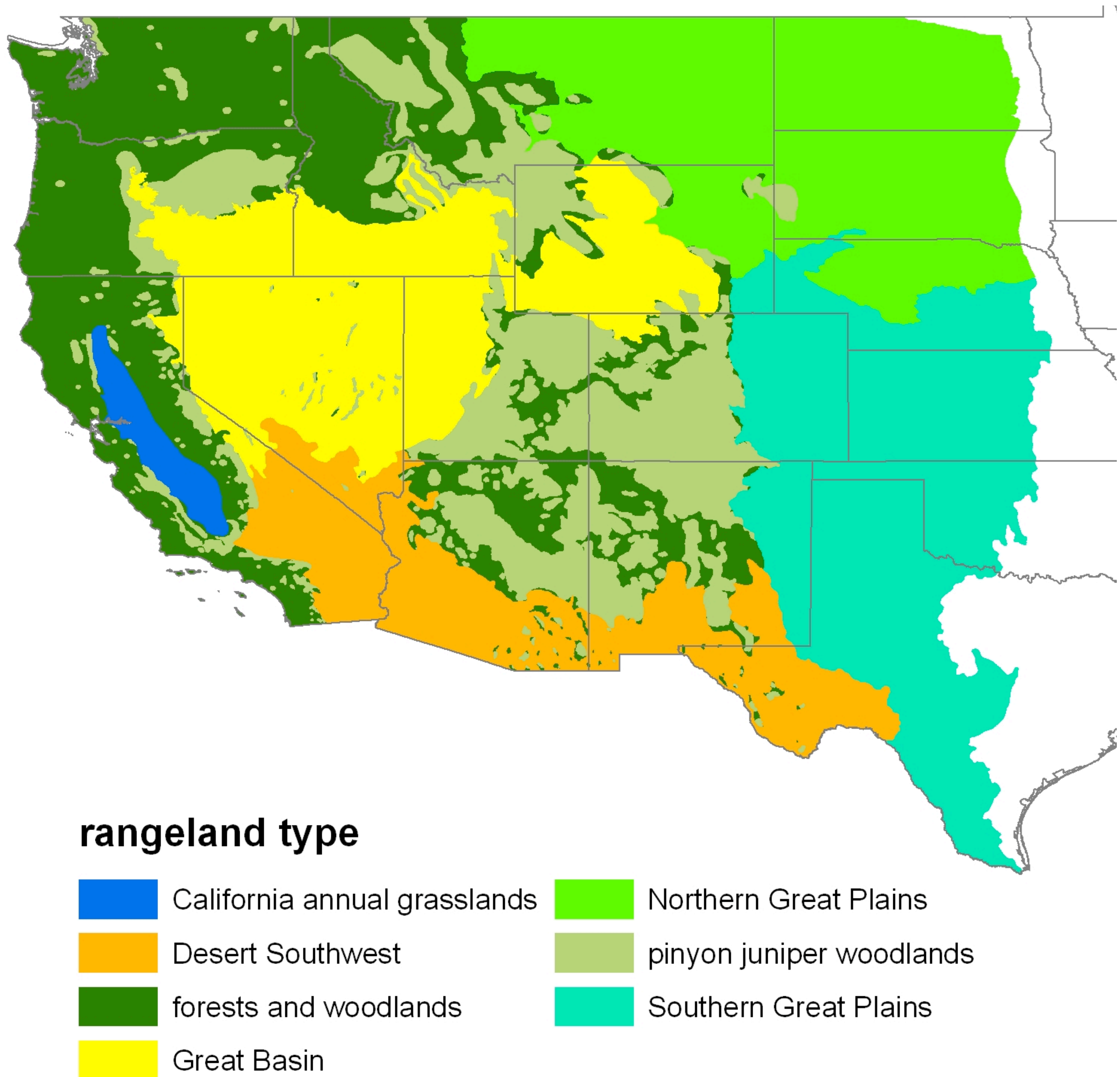
While management, however intensive, will not overcome the fundamental importance of climate and inherent soil fertility in controlling primary productivity and carbon dynamics, it is important to recognize that management can both increase and reduce rangeland productivity. Therefore the challenge is to define the range of management activities that optimize plant performance for a given ecosystem.

Rangelands in the Western United States

The following section was extracted by Joel Brown from:

Havstad, K., D. Peters, B. Allen-Diaz, J. Bartolome, B. Bestelmeyer, D. Briske, J. Brown, M. Brunson, J. Herrick, L. Huntsinger, P. Johnson, L. Joyce, R. Pieper, T. Svejcar, and J. Yao. 2009. The Western United States Rangelands: A Major Resource. pp.75-93. *In:* W.F. Wedin, and S.L. Fales [eds.]. Grasslands - Quietness and Strength for a New American Agriculture. Soil Science Society of America: Madison, WI, USA.

Figure 1: ***Rangeland types in the contiguous western United States.***



Rangeland types are aggregations of ecoregions within a type as delineated by the National Geographic Society as detailed at: <http://www.nationalgeographic.com/wildworld/terrestrial.html>.

The forests and woodlands type encompasses a multitude of interspersed areas of diverse forest and woodland species.

Rangeland is a type of land found predominantly in arid and semiarid regions, and managed as a natural ecosystem supporting vegetation of grasses, grass-like plants, forbs, or shrubs. This land type is characterized by three features: 1) limited by water and nutrients, primarily nitrogen, 2) low annual production characterized by tremendous temporal and spatial variability, and 3) a landscape mosaic of governmental ‘public lands’ and private ownership. In the United States, rangelands comprise about 31% of the total land area, around 761 million acres, which occur mostly in the western states. The rangeland region of the western U.S. is the most sparsely populated in the contiguous United States, and probably has been throughout the course of human habitation due to its rugged terrain, relatively low and highly variable productivity, and often-long distances between water sources. While these circumstances persist today, the region has experienced more rapid population growth than other parts of the U.S. in recent years. This growth is significantly impacting rangeland management and conservation.

Most rangelands in North America are in a region that experiences a continental climate (cold winters, warm wet spring and summer) with relatively uniform seasonal precipitation. This unique seasonal precipitation distribution governs the type and amount of plant production and carbon dynamics. Typically, soils gain carbon during periods of plant growth, while soils lose carbon during periods of dormancy. The length and severity (air temperatures) of dormant seasons can have an inordinate influence on carbon dynamics in Mediterranean systems compared to continental climates.

In the archetypical prairie rangelands of North America, soils are classified as Mollisols (high organic matter formed from basic parent material over long periods in Continental climates). These soils are relatively deep with high water holding capacity and high levels of fertility. Mediterranean climate rangelands, on the other hand, are typically associated with more shallow and poorly developed soils (Aridisols).

Major Rangeland Regions

The Great Plains

The physiography of the Great Plains consists of an enormous piedmont that flanks the eastern slope of the Rocky Mountains for a distance of several hundred miles. The climate is uniquely continental and is characterized by dominant north-south temperature and east-west precipitation gradients. These climatic gradients and physiographic features define the province and ecological attributes of these ecosystems. The Northern Great Plains are vast grasslands occupying most of the states of North Dakota and South Dakota and substantial areas of Montana, northeastern Colorado, and northern Nebraska. This region is generally flat to rolling, with features such as the Black Hills, badlands, and rivers providing sharp breaks in the gentle topography. The influence of glaciation is very evident in the northeastern portion of the Northern Great Plains where, during the Pleistocene, continental glaciers moved south as far as the Missouri River. When they receded, the glaciers left behind millions of shallow depressions that are now wetlands called prairie potholes. The Southern Plains are situated between the Rocky Mountains and the central lowlands and encompass portions of six states. Native vegetation is dominated by short and mid-height perennial grasses that evolved with natural disturbance regimes characterized by grazing, drought and fire.

Great Basin

The Great Basin has been defined in a variety of ways over the years. The two most common definitions are: 1) an area that is drained internally and has no outlet to the sea, or 2) a floristically-defined region that is characterized primarily by shrub-steppe (shrub/bunchgrass communities). The region designated as Great Basin includes the area, which is internally drained (hydrologic definition), but also includes additional areas of shrub steppe to the north and east.

Much of the Great Basin is in the Basin and Range Province, with isolated mountain ranges separated by valleys. The mountain ranges are a result of fault activity (the meeting of the Pacific and North American Plates), and generally have a north-south orientation. The Basin and Range geography results in rainshadows and steep elevation gradients, which create high temporal and spatial variability in both climate and vegetation.

Desert Southwest

The desert rangelands in the southwestern U.S. are the driest, hottest, and least productive rangelands in North America. Desert rangelands consist of three hot deserts: Chihuahuan, Sonoran, and Mojave.

Most of the Chihuahuan Desert—the largest desert in North America covering more than 193,000 square miles—lies in Mexico. In the U.S. it extends into parts of New Mexico, Texas, and sections of southeastern Arizona. The Sonoran Desert covers 120,000 square miles in southwestern Arizona and southeastern California. The Mojave Desert, the smallest of the three hot deserts, is located in southeastern California and portions of Nevada, Arizona and Utah, and occupies more than 25,000 square miles. These three desert rangelands share a number of characteristics related to climate, vegetation, and land-use dynamics related to human activities, yet differ in elevation, seasonality in rainfall, and plant species composition.

Woodlands and Forests

This region includes both the piñon-juniper woodlands and the widely dispersed forested lands of the western U.S. Woodland vegetation is widely distributed in the West and is distinguished from more classically described forested land by the reduced height of the tree layer (30–50 ft). Of the western U.S. states with piñon-juniper vegetation, New Mexico has the largest area, and Idaho the smallest.

Forested lands regarded as rangeland have often been synonymous with forest land that is grazed by livestock. These lands, at least periodically, produce sufficient understory vegetation suitable for forage that can be grazed without significantly impairing wood production and other forest values. These lands comprise nearly 20% of the total area grazed in the U.S. Reflecting the diversity of ecosystems and western topography, these forested rangelands are interspersed with meadows, high elevation grasslands, riparian ecosystems, and, often, with piñon-juniper woodlands at their lower elevation margins.

California Annual Grasslands

The California Annual Grasslands occupy about 13.6 million acres, primarily in the foothills of the Central Valley and in coastal valleys. This region has three major subtypes: inland Valley Grassland, Coastal Prairie and the Coast Range grassland.

The original dominants of the California grassland were perennial grasses interspersed with native annual grasses and perennial herbs, probably with a higher proportion of annuals in drier areas. Conversion of this grassland to an ecosystem dominated by exotic annuals began with the introduction of livestock, cultivation, and seed dispersal of Mediterranean-origin annual plants in the late 18^{th} century. This introduction expanded dramatically with a series of severe droughts in the late 1800s. Plants from the Mediterranean Region, mainly annual grasses, now dominate the Valley Grassland. The Coastal Prairie grassland retains a greater proportion of native species but has also been invaded by both perennial and annual plants from the Old World. The Coast Range grassland is characterized by some native perennials mixed with native and introduced annuals. The grasslands have been valued as a source of sustenance and homesteading, for livestock forage, as real estate, and increasingly for a diverse array of tangible and intangible services.

Measurement, Monitoring, and Verification (MMV)

Changes in ecosystem carbon can be assessed either by measuring carbon stocks at different times, or by quantifying the net rate of carbon flux into the system. **Direct methods** measure soil carbon directly from a soil sample, either onsite or in the laboratory. **Indirect methods** are based on relationships between other predictor variables and carbon content, and require calibrations and modeling. Most if not all methods rely on some form of extrapolation of information from a small set of samples to the project-, or regional-scale. All methods are ultimately based on data from samples.

Figure 2. ***Direct methods of quantifying changes in soil carbon stocks***

		Pros	Cons	Can be used
Soil core samples + dry combustion	Combustion and analysis occurs in the lab	Established and reliable method	Cost-prohibitive on per-project basis	In combination with other methods To provide model input data To provide data for a performance standard
LIBS (Laser Induced Breakdown Spectroscopy)	On site analysis Uses laser	Analysis occurs onsite Can provide chemical analysis	Cost-prohibitive on per-project basis	In combination with other methods To provide model input data To provide data for a performance standard
MIRS (Mid Infrared Spectroscopy)	Analyzes core samples on site	Analysis occurs onsite Can differentiate SOC and SIC More accurate than NIRS	Cost-prohibitive on per-project basis	In combination with other methods To provide model input data To provide data for a performance standard
NIRS (Near InfraRed Spectroscopy)	On site analysis	Considered a good, rapid, low-cost method	Less accurate than MIRS	In combination with other methods To provide model input data To provide data for a performance standard
Eddy Covariance	Measures ecosystem carbon flux from stationary towers above landscape	Increasingly robust method	Issues of error sensitivity and cost-effectiveness remain	In combination with other methods To provide model input data To provide data for a performance standard

Post et al. 2001, McCarty et al. 2002, Izaurralde 2005, Izaurralde et al. 1998

Direct Methods of Quantifying Changes in Soil Carbon Stocks

Soil Core Samples

The most established form of direct measurement is to extract and analyze soil core samples. The sample is combusted in the laboratory and analyzed for carbon content. This process does not differentiate between SOC and SIC. When measurements of SOC only are needed, SIC must be excluded from the sample prior to analysis, by digestion with acid. Alternatively the Sherrod et al. (2002) method can be used to determine SIC and total soil carbon; deducting SIC from total carbon provides a quantification of SOC. Dry combustion is a very accurate and widely used technique, whereas wet combustion is older, less reliable and now rarely used.

When considered alone, direct determination of SOC by dry combustion is generally expensive in relation to the required number of samples and expected revenues from carbon credits. Costs have two components: sampling and sample handling, and laboratory analysis. Cost of laboratory analysis ranges from $15 to $35 per sample. Cost of obtaining and handling the samples can vary widely, depending on site remoteness and accessibility, and on who performs the sampling.

Sampling costs can be reduced by stratification. **Stratification** is a means of improving the efficiency of sampling by subdividing the area to be measured into regions (strata) that are relatively homogeneous in the characteristics that are being measured, in this case, characteristics that affect stocks and fluxes of carbon. Stratification attempts to maximize variation among strata and minimize variation within strata, because only the variation within strata contributes to the variance for the whole population estimates (Thompson 1992). Stratification allows optimal allocation of sampling effort to the different strata to minimize the cost for a given level of precision. In general, more samples are allocated to strata that are more variable, larger, and more cheaply sampled.

Spectral analysis technologies (**LIBS**, **MIRS** and **NIRS**) are non-destructive, require no reagents, and are easily adaptable to automated and in situ measurements (Izaurralde 2005). All spectral measurements require field calibrations requiring sampling and analyses using established methods, such as dry combustion (Chatterjee et al. 2009).

LIBS (Laser Induced Breakdown Spectroscopy) uses a high-energy laser to create a plasma of the ionized elements in the sample. The light from the plasma is resolved spectrographically and integrated to give concentrations of each element in the sample. Currently carbon from SOC and SIC is not directly discernible, but methods are being developed to create this capability. LIBS allows for the simultaneous analysis of many elements, not just carbon. LIBS has a detection limit of 300 mg carbon kg^{-1} with precision of 4% to 5%, and an accuracy ranging from 3% to 14% (Izaurralde 2005).

MIRS (Mid InfraRed Spectroscopy) is a stationary device that analyzes core samples on site, and was originally developed to measure protein content in forages. MIRS can differentiate between SOC and SIC, and is best applied with other methodological tools. McCarty et al. (2002) found that MIRS yielded better spectral information than NIRS and was a better predictor of total carbon and carbonate.

NIRS (Near InfraRed Spectroscopy) is a simple, rapid way to assess SOC, widely used to characterize chemical compounds. Less accurate than MIRS, it was originally found to underpredict SOM concentrations at the high end of the scale (McCarty et al. 2002).

Eddy Covariance Flux Measurements

The eddy flux or eddy covariance (EC) method performs practically continuous measurements of net CO2 fluxes between the ecosystem and the atmosphere. Multiple micrometeorological variables are measured simultaneously. Fluxes are integrated over time to obtain yearly estimates of net change in carbon. The method has the advantage that it provides abundant information for modeling of carbon fluxes on the basis of weather and vegetation measurements. An eddy covariance system, usually referred to as "tower", measures fluxes representative of an area of approximately 1 ha.

The EC method has disadvantages. It only measures CO_2 flux and thus it would not detect other potential additions or losses of carbon such as erosion and exportation/importation of crops, residues and sol amendments. Moreover, the method is not stock-specific and is sensitive to changes in non-creditable stocks such as standing herbage mass. EC systems are labor intensive and tend to give poor measurements when the air is still. Data require lots of processing. This method is not applicable at a project level, but can be used as a basis for regional measurements to create and back up a performance standard.

Indirect Methods of Quantifying Changes in Soil Carbon Stocks

Indirect methods can be subdivided into two types. First, carbon stocks can be predicted by using models. These models are given the sequence of values of factors that affect carbon stocks, such as weather, vegetation type, and grazing regime, and they provide predictions or estimations of carbon stocks. Second, carbon stocks and changes can be estimated by using statistical relationships “calibrated” with previously obtained data. These relationships or equations use values of variables that are more easily or cheaply measured than carbon to estimate carbon. Input variables can be quantitative, such as amount of radiation reflected by soils and vegetation in each of several spectral bands, or qualitative, such as soil series.

Models

Ecosystem models used to quantify soil carbon stocks or changes therein are known as *process-based* or *mechanistic models*. These use an understanding of ecological processes and the factors influencing these processes to either forecast or enhance past datasets under different management and environmental regimes. Such process-based models also have a critical role in translating data to project-scale landscapes (Post et al. 2001). Such models are needed to quantify changes in rangeland carbon stocks because they provide estimates of changes in ecosystem carbon storage under varying management regimes and over different time periods.

Models include CENTURY, DNDC, COMET-VR, DAYCENT and EPIC. CENTURY appears quite popular for research purposes, and has been in use for three decades. DNDC is a well-known greenhouse gas model that also models soil carbon. COMET-VR and DAYCENT are variants of CENTURY. Of the three models in the CENTURY family, only COMET-VR can model greenhouse gases other than CO_2. DNDC and COMET-VR can predict CH_4 and N_2O fluxes.

Figure 3. ***Comparison of ecosystem models***

		Pros	Cons
CENTURY	Widely used for over 30 years	Provides very detailed information	Cannot model other greenhouse gases
DNDC	DeNitrification DeCarbonization greenhouse gas model	Can model N_2O and CH_4 fluxes	May not be ideal for rangeland landscape scale
COMET-VR	Modified version of Century Runs on a monthly timestep	Can model N_2O and CH_4 fluxes Has a web-based interface	
DAYCENT	Modified version of Century Runs on a daily timestep	Daily timestep not required for carbon sequestration projects	Cannot model other greenhouse gases

Li et al. 2003, Conant et al. 2005, Paustian et al. 2009, Parton et al. 2005, Adler et al. 2007

DNDC (DeNitrification DeCarbonization) is a process-oriented simulation model of soil carbon and nitrogen biogeochemistry that models greenhouse gases. At the core of DNDC is a soil biogeochemistry model describing carbon and nitrogen transport and transformation as driven by a series of soil environment factors such as temperature, moisture, redox potential, pH, and substrate concentration gradients (Li et al. 2003). The model recognizes four major SOC pools: plant residue or litter, microbial biomass, humads (active humus), and passive humus. DNDC also contains submodels for soil climate, decomposition, nitrification, denitrification and fermentation (Li et al. 2003).

The following three models are closely related and can serve different purposes.

CENTURY simulates dynamics of carbon, nitrogen and phosphorus in grassland, forest, savanna and crop systems (Metherell et al. 1993; Parton et al. 1993) CENTURY has submodels for plant production, nutrient cycling, water flow, and SOM (Parton et al. 2005). The major input variables include soil texture, bulk density, soil hydric status, soil depth, soil field capacity, wilting point, location and climate data. CENTURY's plant production and water flow models use monthly time steps; the nutrient cycling and SOM submodels use weekly time steps (Parton et al. 2005).

DAYCENT is a modified version of CENTURY running on a daily timestep (Parton et al. 2005). DAYCENT simulates crop production, soil organic-matter changes, and carbon, nitrogen, nitrous oxides NOx, and methane fluxes from weather, soil-texture class, and land-use inputs (Parton et al. 2005).

COMET-VR runs a on a monthly timestep and has a graphical user interface. COMET-VR provides some estimation of energy use and nitrous oxide emissions, the former from direct-measurement data and the latter from DAYCENT model output; and generates an estimate of uncertainty based on published data on the practices in question (Paustian et al. 2009).

Model Calibration

Models must be tested prior to implementation since they need to be calibrated to each site for which they are used. A preliminary run produces output data that are checked against data obtained from an alternate source; typically the modeled dataset is compared to an actual dataset derived from field measurements. Discrepancies allow the model to be corrected and refined. When the model produces output that is within an acceptable margin of error, the model is considered calibrated and can be reliably used under the conditions or geographic region for which it was tested.

Models are not static, but and are regularly recalibrated and improved. As information of the site improves and technology advances the model can become more robust. Each model has strengths and weaknesses under particular circumstances, such as: physical and biological conditions of the region under study, the amount of experimental experience incorporated within the models, richness of climate, and land use and geographical information available for the analysis (Post et al. 2001).

Other Indirect Methods

There are other indirect methods available in addition to ecosystem models.

Remote sensing uses satellite or airborne sensors to gather data. These sensors measure reflected radiation in a few bands of wavelength. These measurements can then be calibrated to various characteristics of the landscape by using direct carbon measurements. Due to the repetitive nature of image acquisition, remote sensing provides information on landscape and vegetation changes through time (Post et al. 2001).

Land use history and databases are valuable in allowing the placement of current soil carbon levels within a historical trajectory of declining or increasing stocks. In addition, databases can allow the correlation of land use history with enduring ‘signatures’ that remain, for example, within the composition of microbial communities and the balance of various isotopes. Understanding these correlations can strengthen and refine models. Various databases, such as SSURGO (Soil Survey Geographic), are available through the USDA-NRCS, and local agencies. Land use and land cover databases can also be developed from remotely sensed data (Post et al. 2001).

Developing a Performance Standard

Each existing quantification method has its strengths and weaknesses, in terms of factors such as cost, ease of use and suitability for a national emissions trading platform. Different methods tend to perform better at one scale (plot, field, landscape or region) than at others. Instead of being tied to the constraints of one method, a rangeland soil carbon protocol methodology may harness several methods in combination, with the goals of reducing transaction costs and achieving a balance between ease of use and scientific acceptability.

Methodologies, existing or potential, may be placed along a conceptual spectrum, with extreme ease of use (and data coarseness) at one end, and higher confidence levels (and expense) at the other. A methodology too close to either end of the spectrum will not be popular among landowners or credit purchasers. A successful methodology lies somewhere between the two poles.

Using a performance standard, whereby standard metrics replace at least some project-specific measurement, is simpler than quantifying soil carbon in every parcel of land, which is impractical for reasons of cost and expediency. Any performance standard must be based on sound scientific correlations between changes in carbon stocks and surrogate variables or states that are easier to measure or document. An original performance standard may be developed to meet these needs, or an existing quantification system may be adapted. Whichever methodology or performance standard is developed, it should benefit from future improvements in the accuracy and availability of data.

Whatever protocol is created, it should include a mechanism through which published literature could be used to help generate estimates of creditable tons of net emissions reductions. Participating rangelands may be classified according to variables such as geographical region, ecosystem type, land use history, BAU practices, and so on, in an attempt to match project lands as closely as possible to those represented in the scientific literature. This matching will reduce the costs associated with site-specific quantification.

The more closely that the set of project-specific variables can be correlated to data in the literature, the lower the transaction costs will be, for two reasons: site-specific quantification costs will be reduced, and deductions from gross sequestration values to compensate for uncertainty (*conservatism*) will also be reduced.

A decision must also be made as to the number of variables to include within the performance standard. Having too few variables would have a negative effect on compensation rates, due to the need for a high degree of conservatism in project accounting, to buffer uncertainty; whereas having too many variables would make the protocol overly complex and would instill neither confidence among markets nor strong interest among landowners.

Careful thought should be given to the number of project actions to include within the protocol. Too few would represent missed opportunities to drive mitigation and adoption rates; too many would render the protocol unwieldy. It is not possible to accurately predict the effectiveness of a performance standard prior to its implementation (although public sector programs may come with more predictability). This factor highlights how important it is that participants in the protocol development process have a balanced understanding of the conceptual elements discussed in this paper.

Compensating for Changes in Management or for Changes in Carbon Stocks

Compensation for carbon sequestration could be based on verified changes in rangeland management practices (using a performance standard) or on estimated changes in carbon stocks that are based on local measurements. There are pros and cons associated with each option.

Providing compensation for changes in carbon stocks would allow for more project-specific accounting; yet this may not be desirable in every scenario, due to increased transaction costs. Compensating for changes in carbon stocks could spur innovation among landowners and project developers, who would have some freedom to innovate. One perceived risk is that without a pre-defined list of project actions, transaction costs could escalate if each of project action needs to be assessed, and if there are significant costs associated with such assessment.

Conversely, activity based measures would allow landowners to know they would be compensated for changes in activities from a fixed set. This could be a critical factor in reducing transaction costs and increasing landowners' willingness to participate in programs. The drawbacks of this approach are in the issues of possible error and permanence. Errors can be estimated using modeling/measurement techniques; permanence is discussed below.

Compensating for changes in practice would make it straightforward to restrict the number of project actions and contain the complexity of the protocol or program. However credit purchasers pay for emissions reductions, not changes in management. This discrepancy can be resolved primarily through a solid scientific basis for the assumptions embedded within the protocol, and secondarily through financial means including the use of brokers, risk management tools and insurance.

Potential systems to compensate for soil carbon sequestration are not limited to the private sector. Funding could also come through state or federal programs, such as the Conservation Reserve Program (CRP) or NRCS Environmental Quality Incentives Program (EQIP) grants. Emissions reductions in the agricultural sector may fit better into existing public sector programs, or offshoots thereof. A public sector program could further reduce transaction costs and increase financial yield to the landowner, leading to higher adoption rates and thus greater climate change mitigation.

The development of performance standards for rangeland carbon sequestration should consider all variables that are easy to measure and that can serve as predictors of changes in carbon stocks due to changes in activities. Those variables include all typical characteristics of rangeland operations such as location, land area, topography, weather and climate, digital-elevation map, management history, stocking rate, grazing method, soils map and profile descriptions from the USDA database, history of rangeland improvements and weed/brush control, fencing and stock water networks, rangeland site description and condition, indicators of BAU conditions, etc. All of these variables could be input into an online automated expert system that could give an immediate preliminary assessment to the landowner or manager. The assessment would contain a list of the potentially creditable activities, their spatial extension and the potential value of the changes in terms of carbon and money at current and projected prices.

Predicting Soil Carbon Dynamics for Decision-Making

Implementing management decisions to increase soil carbon relies on accessible, accurate information. While there is general agreement that traditionally defined 'good management practices' for grazing such as proper stocking rate, proper distribution and drought response will result in increased carbon sequestration, variations in soils, climate and the application of practices can dramatically alter the amount of carbon sequestered.

Most studies assessing the effects of management on rangeland soil carbon have found large variation across experimental sites or units. There is a tendency to focus on the average result of all units that receive a given management or treatment. However for carbon accounting the distribution of results is more important. Instead of thinking that a given area will achieve the average result, we should consider that—unless measured directly for the specific project boundaries—there is a certain probability that the actual sequestration can be any value within a range, including negative values. Therefore when employing a performance-based approach, particular care should be taken in the way in which published statistics and data are treated.

Ecological Site Descriptions (ESDs) are designed to display options for land management decisions in a graphic and text format (Bestelmeyer et al. 2003). ESDs are the most fine-grained (site-specific) information available to land managers, but they require specific management objectives and local knowledge to be used correctly. An important underlying assumption of the use of ESDs is that they reflect the dynamics of nonequilibrium (in terms of management) rangelands and the application of local practices, which can result in different outcomes depending on initial conditions. Thus, the outcome of practice implementation to sequester carbon can vary not only in space, but can differ depending on the time of application.

A key component of ESDs is the State and Transition Model (STM). An STM attempts to depict different system (site) conditions (states), including ecosystem patterns (such as plant community structure) and processes (including carbon fluxes), and the factors driving transitions between those states. Changes in system processes (such as carbon fluxes) can result from changes in vegetation (shrub vs. grass; cool season vs. warm season; bunchgrass vs. sod-forming; annual vs. perennial) resulting from changes in other systems processes (such as fire or grazing regime, or drought).

Extensive field research has demonstrated that different vegetation on the same or similar soils can result in different carbon dynamics (Derner and Schuman 2007). Different plant species use available resources (sunlight, soil moisture, nutrients) differently and can differ in their effect on the amount and distribution of carbon within the soil profile. They can also respond differently to different kinds of disturbance (fire, grazing, drought). These common disturbances are affected, either directly or indirectly, by the practices deployed by management and vice versa.

Thus, predicting soil carbon dynamics requires not only a general knowledge of carbon sequestration processes, but also a site-specific knowledge of the effects of common management practices within the range of predictable climatic variability. That site-specific knowledge would have to include an accurate assessment of the current ecological state to reasonably predict outcomes of management initiatives.

Project Boundaries

There are two kinds of project boundaries: physical boundaries and greenhouse gas boundaries. Physical project boundaries are defined as the area of land on which project activity occurs. This must be clearly delineated, preferably with GIS or GPS coordinates. Physical boundaries will also help determine the precise extent of greenhouse gas boundaries, since all changes in greenhouse gas fluxes occurring within physical boundaries will fall within greenhouse gas boundaries. Special care must be taken in the case of aggregated project activity if overlapping ownership by different parties occurs within the project's physical boundaries. Landowner responsibilities fall to the aggregator in such cases. Assessments of baseline and additionality must match this area on a *wall-to-wall* basis.

Greenhouse gas boundaries include all fluxes of all greenhouse gases affected by project activity, including leakage. Net credit quantification will include gross carbon sequestration in soils, avoided emissions from the ecosystem, project associated emissions, and any other significant project-driven greenhouse gas emissions reductions.

Complex greenhouse gas interactions can occur within rangeland ecosystems, with or without the presence of project activity. Regional modeling and/or surveying the available scientific literature may help provide emissions factors in this regard.

Baseline, Additionality, Leakage and Permanence

Baseline

The term *baseline* has two related meanings. Firstly, baseline is a quantified value of carbon stocks before any changes in management, or environmental conditions, occur. Secondly, within the context of project credit accounting, baseline is an extrapolated value for carbon levels *as they would have been* in the absence of project activity, under Business As Usual. We refer to the first as *pre-project baseline* and to the second as *forward-looking baseline*. Both are key metrics. The first helps in the calculation of the second. The second metric is used to quantify additionality and net emissions reductions generated by project activity.

To accurately reflect the mitigation effect of project activity, the forward-looking baseline should be quantified over the lifetime of the associated credits. Where data and modeling reveal positive net greenhouse gas emissions (source activity) under BAU, additionality may be achieved by implementing practices that decrease or eliminate source activity, or turn the source into a sink.

It is important to consider that when BAU shows a declining carbon stock, projects that stop the decline (i.e. maintain the current stocks) can be credited for the otherwise expected loss. This is known in the forestry carbon arena as Reduction of Degradation and Deforestation (REDD) projects, which are relatively new. The concept of REDD is significant because it can be applicable to rangelands that are subject to destruction or disappearance due to development and urbanization. The net carbon effects of preserving rangelands against urban development are not well known and should be studied further.

U.S. rangelands contain a very high degree of spatial and temporal variation. Baseline should therefore be established regionally according to the best available resources, including USDA-NRCS databases (such as SSURGO), local land use history, ecosystem modeling, soil archives, remotely sensed imagery and associated data processing, and where necessary, discrete soil sample measurements.

For the purposes of establishing baseline—and relevant to other areas of protocol development—boundaries between different regions must be defined. These will be determined using environmental criteria, data availability factors and economic factors around quantification. The availability of data gathering technologies, techniques and databases will also be relevant. For example, remote sensing technologies may reduce costs of mapping the different regions; but natural biome and ecosystem boundaries will strongly influence the extent of each region and suggest natural boundaries.

Additionality

The term *additionality*, like that of baseline, has two related definitions. The *concept* of additionality is that in order to attract compensation, emissions reductions must be in addition to what would have occurred under BAU. The *quantification* of additionality represents the credits that have been generated by project activity that can be transacted. Additionality is calculated against the forward-looking baseline. The concept and method of quantifying additionality are closely related to the concept and method of quantifying baseline.

Additionality is calculated as post-project carbon stocks less the forward-looking baseline, less deductions for leakage and *risk of reversal* (the permanence factor), less project-generated (non-ecosystem) greenhouse gas emissions.

There are two broad approaches to establishing additionality: project-based additionality testing and use of a performance standard. Project-based testing evaluates projects on a case-by-case basis. Commonly used project-based tests include (Stockholm Environment Institute):

- Legal and Regulatory Additionality Test: the project activity must not be legally mandated within a compliance system.
- Financial Test: the project is only viable if it is not profitable without revenue from emissions reductions.
- Barriers Test: the project is only additional if there are barriers that would prevent its implementation under BAU, regardless of profitability.
- Common Practice Test: the project is only viable if it employs practices not already in common use.

In the context of land use emissions reduction, *legal and regulatory additionality* is the approach usually discussed.

Under most performance standards, determination of baseline and additionality is generally not sought on a project-specific basis. Instead regional or ecosystem benchmarks are established, based on approximate or aggregated data (Stockholm Environment Institute 2009). Benchmarks bring simplicity but the risk of inaccuracy. Ensuring purchaser confidence and real emissions reductions are critical factors. One option is for a protocol or performance standard to mix the use of benchmarks with project-specific quantification, once more seeking to achieve the desired balance between accuracy and viable transaction costs.

When landowners and project developers select management practices, they are typically guided by economic factors. Practices that offer the greatest net financial return will be the most attractive. The gross revenue generated through carbon credits will be principally determined by the degree of additionality that each project action, or combined suite of actions, represents. The degree of additionality represented by various project actions will be determined by factors specific to project activity, factors relating to baseline, and the influence of local environmental factors, such as precipitation, soil type and land use.

Rules and the way they are applied must lead to accurate quantitative (metric) and qualitative (subjective) assessment of mitigation benefits as a result of project activity. The main challenge associated with quantifying additionality comes in determining what would occur in the absence of the project. How is this to be accurately assessed? The additionality rules of various emissions trading platforms have attracted criticism for lack of clarity, over-reliance on subjective assessment of what would have occurred in the absence of the project, and an apparent incompatibility with market dynamics. Such subjectivity however may be inescapable if a balance is to be achieved between the integrity of credits and not deterring investment with unworkable rules (Meyers 1999).

Additionality poses a significant problem, particularly for rangelands, because it does not reward good land stewards that in spite of greater costs or simply because of more altruistic objectives for land management, already have saturated their carbon stocks. Seen from a slightly different perspective, because of additionality, operations that depleted their soil carbon stocks prior to the trading system start date would be rewarded for their unsustainable practices because it would be easier for them to pass the additionality test and to sequester more carbon above the baseline.

Therefore, relevant to the concept of additionality is the idea of rewarding early adopters, parties who have acted as voluntary pioneers, often losing money in the process. In theory such action could also be used to promote best practices and encourage future innovation. Options here include payments to offset losses, bonus credits provided by a buffer pool and non-financial rewards. The active engagement of stakeholders over such issues will ultimately ensure a higher level of industry participation.

Leakage

Leakage occurs when “a carbon sequestration activity on one piece of land inadvertently, directly, or indirectly, triggers an activity which counteracts the carbon effects of the initial activity.” (IPCC 2001b) Most instances of leakage have a negative effect on the assessment of project benefit. Positive leakage occurs when management practices promote *reductions* in greenhouse gas emissions beyond project boundaries (Murray and Sohngen 2004).

Negative leakage is further categorized as either *market leakage* or *activity-shifting leakage*. Market leakage refers to increased greenhouse gas emissions outside project boundaries resulting from substitution of goods lost as a result of project activity, when an established carbon market is impacted. Activity-shifting leakage occurs when activities that would occur within project boundaries under BAU are displaced beyond the project boundaries.

Landowners and project developers seek to minimize lost revenue resulting from leakage, but up to a certain threshold these emissions may feasibly go uncounted. Rangeland soil carbon projects may encounter less leakage than a proportion of afforestation/reforestation projects—because the land remains in production—provided that services provided by the rangelands in question are maintained or increased as a result of project activity (FAO 2009).

For rangeland soil carbon projects, leakage potential exists from land that is set aside for project activity. Most of the research into soil carbon leakage has analyzed not rangelands but cropping systems, assessing changes associated with tillage and fertilizer practices, and land retirement. This research therefore helps inform the following discussion. In addition, several strategies to assess and mitigate leakage have been developed for afforestation/reforestation projects that may be applicable for rangeland soil carbon projects (FAO 2009).

Leakage from Conservation Projects

Leakage can occur if under project activity lands used for grazing are no longer used for grazing. Much of the research on leakage has focused on converting cropland or forests, not open range, to habitat preserves (although grazing can have a positive effect on habitat and biodiversity). For example, such studies suggest that leakage (measured in tons of CO_2e) associated with carbon sequestration in agricultural soils would range from less than 10% for working lands to 20% for retired land; whereas leakage associated with forest conservation could reach as high as 90% (Congressional Budget Office 2007).

The Conservation Reserve Program (CRP) is a federal program that retires highly erodible land from production, whether cropping or grazing. A study of cropland retired in the central United States under CRP found that for each 100 acres retired, 20 acres of non-cropland were converted to cropland in the same region (Wu 2000), representing a secondary loss of land of 20%. It should be noted that lands retired from cropland to rangeland use tend to be marginally productive, and so have a lesser effect on commodity supply and leakage than more productive lands.

Wu (2000) did not examine carbon leakage directly. Carbon leakage is not proportional to secondary loss of land because the land entering or leaving the production base has differing potential to sequester carbon (Murray and Sohngen 2004). While the research discussed above may provide some evidence of activity shifting in the agricultural sector, little empirical work has been conducted to estimate carbon leakage from NRCS programs (Murray et al. 2007).

Estimating local leakage separately could assist project designers to mitigate it, since local leakage is more likely to be within their control than distant leakage. The state of the art method in market leakage estimation uses aggregated data (regional and national) either in statistical or simulation models. There are many models and datasets available that factor in market phenomena, policy impacts, and leakage analysis at the county, regional or national level. However, separating market leakage into local and distant varieties is challenging because it is difficult to identify how changes in one parcel affect the management of neighboring parcels. National and transboundary leakage quantification may be addressed through monitoring key indicators and using standard risk coefficients (Watson 2000).

Recent advances in statistical techniques, such as spatial econometrics, may allow leakage to be estimated at a fairly disaggregated level. Such estimations, however, often require a large amount of primary data, which it may be impractical to collect in the case of many rangeland soil carbon projects. Local leakage may be best handled through project and contract design, by extending the carbon accounting boundary beyond the boundaries of the project. This will allow any localized shifting of activity in response to the project to be covered in the project accounting system and not generate unaccounted leakage locally (Murray and Sohngen 2004).

Permanence

Permanence refers to the net carbon sequestered remaining sequestered for the duration of the project contract. Usually the period is 100 years. This means that if a credited ton of CO_2 is released back to the atmosphere before this period is complete, the credit loses all or part of its value.

Securing achieved mitigation benefits in terrestrial ecosystems requires addressing the risk of reversal. This is because land use projects are thought to be more susceptible to natural disaster, and to changes in land ownership or management practices. Any of these may affect the permanence of carbon stored in soils. The risk of non-permanence is much lower when adoption of soil carbon sequestration practices also leads to more sustainable or profitable farming systems (FAO 2009), or is embedded within system-wide greenhouse gas emissions reductions transitions.

Carbon crediting policy must include a mechanism for handling permanence to ensure that payments for carbon sequestration are not under- or overvalued. If a program makes per-ton payments equal to the value of permanent sequestration, overpayments would occur if changes in land use or management practices re-released carbon back to the atmosphere, unless payments are adjusted for these releases (Lewandrowski et al. 2004).

Several methods have been proposed to address permanence, but a single solution has yet to receive general acceptance (Rose 2008). Suggestions include having projects run in perpetuity, debits for all releases, project replacement, and partial or initially delayed credits. Permanence may also be addressed through various internal and external risk reduction approaches including good practice management systems, project diversification, self-insurance reserves, standard insurance services, involvement of local stakeholders, and regional carbon pools (Watson 2000).

The mechanisms that have received most attention include creating a buffer, comprehensive accounting, *ex ante* discounting, and temporary crediting/leasing:

1) Create a buffer

The Voluntary Carbon Standard aims to remove the risk to permanence by using a *buffer pool*. Every project undergoes a risk assessment to determine how many credits from the project will be contributed to the buffer pool account. The intention is to ensure that credits are fungible, so that in case the project collapses, the buffer account can fill the credit gap; and the credit can be traded interchangeably with any other Voluntary Carbon Standard credit. Remaining questions around this approach include the necessary size of the account and how it would actually work in practice (Rose 2008). The Climate Action Reserve also uses a buffer pool within its Forestry Protocol 3.0 (Climate Action Reserve 2009).

2) Comprehensive accounting

This method balances debits and credits as they occur over time, and is consistent with national greenhouse gas accounting practices as currently used by Annex 1 countries (IPCC 1996b). It can be based on changes in carbon stocks or average storage over a specific time. Carbon stocks are measured at regular time intervals and credits are quantified accordingly. Given the frequency with which credits and debits may be exchanged, an average storage approach has been suggested to credit the average amount of carbon stored by a project over an extended period of time, smoothing out temporary stock fluctuations (Schroeder 1992). One of the downsides of comprehensive accounting is the high amount of MMV required (Murray et al. 2007).

3) *Ex ante* discounting

This approach accounts for the possibility of loss by reducing the number of credits from the outset, based on the expectation of reversal. If it is expected that sequestered carbon may be released in the future, the expected amount and timing of this release is estimated and values adjusted accordingly. Standard financial discounting methods are used to calculate the equivalence of any delayed releases in proportion to the permanent emissions reductions for which they are being traded (Murray et al. 2007). Net carbon sequestration values are based on assumptions of the permanence of storage, rather than observed outcomes. This simple formula allows for easy implementation of this approach; the tradeoff is a potential lack of accuracy.

4) Temporary crediting/leasing

Based on the idea that practices may only yield temporary reductions in atmospheric CO_2, this approach places a finite life on the credit. Reversal risk is addressed by treating the credit as if it must be redeemed in the future. Credits could carry expiration dates, at which time they would have to be regenerated by continuing the sequestration project, establishing a new project, or otherwise achieving a permanent reduction in emissions. A high amount of MMV is needed, but this approach would allow for up front payments and may encourage uptake by landowners. Temporary credit leasing is not a popular option with some project developers however, who consider it unrealistic and not suited to real market dynamics.

Increased productivity provided by more sustainably managed rangelands also provides certain disincentives to reversal, although this will vary case by case.

Ownership

Ownership of credits usually resides with the landowner, unless otherwise specified in the project design and contract. In the case of soil carbon sequestration and other greenhouse gas emissions reduction activities on rangelands, varying land and livestock ownership and management scenarios could create different credit ownership scenarios. The permutations include the following:

- Land and livestock ownership are the same.
- Land and livestock have different private ownership.
- Land ownership by a land trust and private livestock ownership.
- Private land with easement (e.g. land trust) with private livestock ownership.
- Public land agency permits ranching on state or federal lands (livestock are privately owned, but the land is publicly owned and maintained by the rancher).
- Livestock have access to both private and public land.
- Public funds are used for management practices that yield carbon benefits.
- Changes in ownership of the land and/or the livestock over time.
- An agency seeks to reclaim mineral rights on privately owned land.

A rangeland protocol should specify which party will own the credits. In case of controversy, there are ways to prevent and resolve potential disputes, including: establishing a contract with interested parties; including relevant information within the documentation when buying, selling, or leasing land; or involving a third party verifier to facilitate the process. Ownership of credits on leased land should be subject to private contracts between the landowner and rancher.

Only private land ownership is considered within the scope of this paper. A host of other issues and potential solutions arise for project activity on federal, state, and other publicly owned lands. These will be important to address if the 262 million acres of publicly owned grazing lands in the west become available for carbon sequestration project activity.

Environmental Co-Benefits

Sequestering carbon in rangeland soils brings about a number of positive environmental outcomes, or co-benefits, beyond offsetting greenhouse gas emissions, including its effects on soil quality—a term used to describe the fitness of soils to perform particular ecosystem functions by Weil and Magdoff (2004). SOC is a critical macronutrient in soils that supports a host of ecosystem functions. Increasing SOM content improves aeration, and soil tilth; and decreases bulk density by increasing soil porosity. SOM plays an important role in determining soil chemical properties including pH, nutrient availability and cycling, cation exchange capacity and buffer capacity (Tisdale et al. 1985, Evrendilek et al. 2004). Soil aggregation and aggregate stability are also improved by increased SOM accumulation (Gollany et al. 1992, Tisdall 1994).

Changes in agricultural practices that increase carbon sequestration can also improve water quality (Greenhalgh and Sauer 2003, Pattanayak et al. 2005). Increased SOM content improves water infiltration and water holding capacity of soils (Tisdale et al. 1985, Greenhalgh and Sauer 2003). Water quality is further enhanced by an associated reduction in soil erosion and sedimentation (Zebarth et al. 1999, Celik 2005). Increasing SOM is an effective method for increasing drought resistance in arid areas (Overstreet and DeJong-Huges 2009), by increasing the soil's ability to retain water that falls on it and passes through it. This is of critical importance in a changing climate, and where the economic viability of ranching operations may already be in question.

Improvements in soil water quality and availability can increase productivity (Mader et al. 2002, Huston and Marland 2003). There is also a strong correlation between the size of the SOC pool and both soil physical fertility and forage production (Mader et al. 2002, Blair et al. 2006). Soil management affects biodiversity and ecosystem functioning (Huston and Marland 2003). Soils with higher organic matter can support a more diverse array of soil microorganisms (Lal et al. 2007, Evrendilek et al. 2004).

Soil management methods that increase carbon inputs to the soil, such as manuring, are often observed to enhance microbial biomass, populations and activities (Acea and Carballas 1999, Ritz et al. 1997, Witter et al. 1993). The long-term use of manure also supplies large amounts of readily available carbon, resulting in a more diverse and dynamic microbial system compared to inorganically fertilized soil (Peacock et al. 2001). Biodiversity of soil fauna and flora are strongly correlated with soil quality and its functions (Bohlen et al. 1995, Huston and Marland 2003).

Management practices to increase soil carbon sequestration may in some cases have a negative environmental impact. For example the addition of animal manure to the soil can alter plant community composition by modifying competitive interactions between plant species. In addition, uncomposted manure may introduce seeds of invasive species or have a detrimental effect on water quality, depending on factors such as manure concentration and type, application method, location and timing, and precipitation patterns.

Methods used to sequester carbon in soils include increasing carbon inputs to the soil through changes in production or allocation by fertilization, irrigation, sowing legumes or more productive grass species, or by improving grazing management (Paustian et al. 1997; Conant et al. 2001). Practices such as N fertilization could lead to leaching, and potential increases in N_2O emissions that offset the benefits of carbon sequestration (Conant et al. 2005).

Preservation and restoration of woodlands and trees at lower densities within rangeland landscapes can provide significant soil carbon benefits, and other benefits associated with those. Forage quality and quantity under California oaks have been found to be significantly greater than for areas where oaks have been removed (Dahlgren et al. 1997, Camping et al. 2002). Soil carbon levels under some California oak species can be higher per unit area than in the trees themselves (Gaman 2008). Grazing can deter invasive weeds, shrubs and trees (e.g. Franzluebbers et al. 2002), often with positive effects on avian habitat.

Because of the many functions performed by soil carbon and the degraded status of many soils, there is a high potential for positive environmental impacts as a result of the implementation of rangeland soil carbon projects. Most changes in rangeland management that are intended to increase carbon sequestration represent a shift toward sustainable land management practices. However, each practice needs to be assessed for any potential negative impacts.

Market Interest

A robust rangeland methodology should be cost effective, transparent and provide real benefits in the forms of greenhouse gas emissions reductions and more resilient rangeland ecosystems. The ultimate economics of this methodology however will not be known until actual development begins.

The Waxman-Markey ACES bill—the American Clean Energy and Security Act 2000—that has passed in Congress and has not, at the time of writing, passed in the Senate, is designed to reduce national greenhouse gas emissions by 80% against 2005 levels by 2050. The passage of such a bill, promoting a national Cap and Trade system, would increase demand for the development of land-based carbon sequestration and the necessary methodologies, spurring faster and greater increases in the prices for pre-compliance, and then compliance, emissions reductions credits. In Europe, the compliance market proved to be eight times the size of the pre-compliance market. In the U.S., the consensus in 2008 was that there were not enough quality credits available to meet demand even from voluntary and pre-compliance markets (Barbour and Philpott 2008).

'Carbon federalism' is in effect, which sees regions and states acting as laboratories for carbon regulation and creating momentum for federal legislation (Berendt 2008). Under California's Assembly Bill 32, among the country's leading climate change legislation, 85% of emissions will be capped. Under the Western Climate Initiative (WCI), comprising 11 partner and 14 observer states and provinces from Nova Scotia to Mexico, including California, up to 49% of reductions may initially be achieved through offsets (California Air Resources Board 2008).

It has been predicted that after the next major round of international climate change talks in Copenhagen in December 2009, prices for carbon (not CO_2) in the U.S. will reach $73 a ton (Point Carbon 2009). Investors acquainted with terrestrial carbon through forestry credits are becoming aware of soil carbon sequestration. The quality of these credits and actual potential of this opportunity depends upon the quality of the methodology associated with it and the confidence this attracts.

The term *slippage* is sometimes used to refer to deductions from revenue due to costs associated with a particular greenhouse gas emissions reductions typology. From the investor's or project developer's perspective, AFOLU (Agriculture, Forest and Other Land Use) typologies come with several drawbacks: lower returns, more slippage—due to buffers, leakage, verification costs and project costs—, low near-term yield, and the risk of liability with respect to permanence.

Therefore, activation on the open market of the mitigation potential represented by rangelands is likely to require price signals that are significantly higher than those that have been offered on the Chicago Climate Exchange, or alternatively through a public sector program.

Voluntary emissions reductions have traded via the Climate Action Reserve for over $10 (per ton of carbon dioxide equivalent).

Soil Carbon Research as the Basis for an Emissions Reductions Program

A correlation exists between productivity and soil carbon sequestration. Management practices to increase productivity can also positively impact soil carbon stocks. Current approaches for increasing productivity and SOM include ensuring that productive rangeland remains productive by using managed grazing as a tool, and restoring degraded rangeland to productivity. To date the only system that has compensated ranchers for changes in soil carbon stocks in the United States is the Chicago Climate Exchange's *Rangeland Soil Carbon* protocol. The Exchange provides compensation for the removal of 0.12 to 0.52 metric tons of CO_2 per acre per year for proscribed changes in management—primarily due to a shift to sustainable stocking rates and seasonal use—for a limited number of U.S. counties (Chicago Climate Exchange 2009).

Other management practices have the potential to increase productivity—for example, seeding annual legumes and fertilizing rangelands can lead to increased levels of SOC and SOM (Derner and Schuman 2007). While such practices can have a positive impact on productivity and revenue from traditional sources, their effect on soil carbon stocks remains to be quantified. The feasibility and ecological impacts of implementing different management practices must be taken into account. For example, application of fertilizer or legumes may be costly on large, untraversable tracts of land and may have impacts on water quality and availability. Any increased labor, machinery and fuel costs, and associated greenhouse gas emissions, will have to be defrayed from revenue from the sale of emissions reductions credits.

The use of an integrated approach to predict and track changes in agricultural soil carbon levels is critical in providing the basis for both private sector trading and public policy development and implementation (Follett et al. 2005). The integrated approach should include: direct measurement (eddy covariance, Bowen ratio, soil sampling) as part of statistically robust experiments; application of scaling functions to allow small plot measurements to extend to landscape and larger scales, and modeling to assist in making reliable policy and program decisions at regional and national scales. In addition, models should have sufficient precision to be useful to land managers at site specific scales to allow them to make cost-effective decisions compatible with other land use and management objectives (Brown and Sampson 2009).

Because of the importance of historical weather and management in determining response to future management changes, direct measurement experiments should occur at locations such as research stations where land use histories and site specific climatic records are available (e.g. Reeder et al. 2004, Derner et al. 2006). The effect on soil carbon of even decades old management practices dictates the need for complete characterization of soils, climate and management histories. Collection of soil carbon data at these locations should also be done with an emphasis on spatial patterning.

Quantifying the inherent spatial variability in soil carbon levels and the effects of within-site microtopography and vegetation patterns will be critical in designing monitoring and field verification schemes to further test and refine a modeling based system (Peters et al. 2006; Bestelmeyer et al. 2006). In addition, changes in land use and climate require annual updates to insure a level of accuracy necessary for credibility, regardless of the end user (Ogle et al. 2003).

Developing an integrated system to more reliably predict changes in rangeland soil carbon levels has little value unless it occurs within a framework that facilitates use by land managers, program designers and policy makers. Rangeland management and improvement practices lack the consistency of croplands. Carbon fluxes on rangelands are dominated by precipitation and temperature effects, and management influences are secondary (Haferkamp and MacNeil 2004). In addition, the effects of specific management practices—even when common and well understood (stocking rate changes, vegetation manipulation)—may have vastly different effects on a variety of ecosystem processes, including carbon sequestration, depending upon rangeland system state at the time of project initiation (Asner et al. 2003).

A practice driven interface, while appropriate for cropland use, will not necessarily be adequate or reliable for rangeland predictions. Thus, an integrated, model based system may be linked to the existing ESD and allow for the simulation of soil carbon change in response to state change (Herrick et al. 2006). Management and restoration practices can be used to maintain state attributes or to initiate state change, but soil carbon levels will be determined, and predicted, primarily by the ecological processes unique to a particular state.

Summary

If the effects of global warming are to be minimized, carbon already emitted to the atmosphere must be sequestered into stable forms. Soil carbon sequestration is one of the most cost-effective ways of achieving this. Rangelands cover 31% of the land surface area of the United States and grazing is the chief activity on these lands, with the potential to mitigate the equivalent of 3.3% of U.S. CO_2 emissions from the combustion of fossil fuels, every year for 30 years or more.

Project actions with the potential to increase soil carbon in rangelands include: conversion of abandoned and degraded cropland to grassland, avoided conversion of rangeland to cropland or urban development, adjustments in stocking rates, integrated nutrient management, introduction or reintroduction of grasses, legumes and shrubs on degraded lands, managing invasive species, reseeding grassland species, addition of trees and shrubs for silvopastoralism, managing invasive shrubs and trees, riparian zone restoration, and introduction of biochar into soils.

Soil organic carbon forms 50% of soil organic matter and is a critical macronutrient in soil ecosystems, driving many other nutrient cycles. Each new ton of soil carbon represents the removal of 3.67 tons of carbon dioxide from the atmosphere. Soils hold over three times as much carbon as the atmosphere and because of historic depletion have the capacity to store much more. The unique role of carbon in the soil system offers the potential for win-win scenarios for climate change mitigation, the environment, project developers and landowners. Activating this potential depends largely on the methodology or performance standard employed.

Within a protocol, an existing method of quantifying soil carbon may be used or several different methods may be harnessed into a combination methodology. Either way a balance must be achieved between ease of use and accuracy. A balanced methodology will lead to the optimization of the potential for additional soil carbon sequestration in U.S. rangelands. An understanding of ecosystem states and their differing ability to respond to the same changes in management will be critical to the development of an accurate and efficient performance standard.

Landowners will be compensated either for changes in management or for achieved net increases in soil carbon stocks. If changes in management are to be rewarded, close correlations must be established between those changes and the effect they have on carbon stocks. If changes in stocks are to be quantified, this may occur on a per-project basis or according to regional and ecosystem benchmarks.

Public sector programs are also an option, and may come with reduced transaction costs.

Permanence is a major issue to address. A variety of solutions have been proposed. Solutions to challenges regarding leakage, ownership and additionality may be learnt from existing land-use greenhouse protocols housed with the Climate Action Reserve and the Voluntary Carbon Standard.

Demand for high quality rangeland soil carbon credits is likely to be high within a compliance system such as federal Cap and Trade or other program, provided that risks to the private or public sector are addressed through measures such as conservative discounting and buffer pools.

The unique benefits to the environment and producers associated with increased soil carbon stocks should provide the necessary impetus to overcome any hurdles on the path to protocol development. Some solutions may only become apparent once the process has begun.

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