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Improving Estimates of Rangeland Carbon Sequestration Potential in the US Southwest

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Abstract

Rangelands make an important contribution to carbon dynamics of terrestrial ecosystems. We used a readily accessible interface (COMET VR) to a simulation model (CENTURY) to predict changes in soil carbon in response to management changes commonly associated with conservation programs. We also used a subroutine of the model to calculate an estimate of uncertainty of the model output based on the similarity between climate, soil, and management history inputs and those used previously to parameterize the model for common land use (cropland to perennial grassland) and management (stocking rate reductions and legume addition) changes to test the validity of the approach across the southwestern United States. The conversion of small grain cropland to perennial cover was simulated acceptably ($<$ 20% uncertainty) by the model for soil, climate, and management history attributes representative of 32% of land area currently in small grain production, while the simulation of small grain cropland to perennial cover + legumes was acceptable on 73% of current small grain production area. The model performed poorly on arid and semiarid rangelands for both management (reduced stocking) and restoration (legume addition) practices. Only 66% of land area currently used as rangeland had climate, soil, and management attributes that resulted in acceptable uncertainty. Based on our results, it will be difficult to credibly predict changes to soil carbon resulting from common land use and management practices, both at fine and coarse scales. To overcome these limitations, we propose an integrated system of spatially explicit direct measurement of soil carbon at locations with well-documented management histories and climatic records to better parameterize the model for rangeland applications. Further, because the drivers of soil carbon fluxes on rangelands are dominated by climate rather than management, the interface should be redesigned to simulate soil carbon changes based on ecological state rather than practice application.

Resumen

Los pastizales naturales contribuyen de modo importante a la dinámica de carbono de los ecosistemas terrestres. Utilizamos una interface fácilmente accesible (COMET VR) de un modelo de simulación (CENTURY) para predecir los cambios de carbono orgánico que ocurren a raíz de cambios en el manejo de pastizales comúnmente asociados con programas de conservación. Asimismo utilizamos una subrutina para estimar el grado de certeza de las salidas del modelo basados en la similitud entre inputs de clima, suelo, e historia de manejo con aquellos utilizados anteriormente en la configuración del modelo para simular cambios comunes en el uso de la tierra (de cultivos a pasturas perennes) y el manejo (reducciones de la carga animal y agregado de leguminosas) a fin de probar la validez de este enfoque para pastizales del sudoeste de Estados Unidos. La simulación de conversión de tierras de cultivo de grano fino a pasturas permanentes fue aceptable ($<$ 20% de incertidumbre) para situaciones que representan los atributos del suelo, clima, y manejo del 32% del área actualmente utilizada para granos finos, mientras que la simulación de la conversión de cultivos de grano fino a pasturas permanentes +leguminosas produjo salidas aceptables para el 73% del área actualmente cultivada con cereales de grano fino. El comportamiento del modelo fue pobre en situaciones de pastizales naturales de zonas áridas y semiáridas para prácticas de manejo (reducción de la carga animal) y restauración (incorporación de leguminosas). Sólo un 66% del área de pastizales naturales poseía atributos de clima, suelo, y manejo que resultaron en niveles de incertidumbre aceptables. Sobre la base de estos resultados, creemos que resultará difícil predecir de modo creíble los cambios en el carbono orgánico en el suelo que resulten como consecuencia de prácticas de manejo comunes, tanto a escalas finas como gruesas. Para superar estas limitantes, proponemos un sistema integrado de medición espacialmente explícita de carbono en el suelo en lugares que posean historias de manejo bien documentadas y buenas series de datos climáticos que permitirían mejorar la configuración del modelo a fin de simular pastizales naturales. Más aun, dado que los flujos de carbono del suelo en pastizales naturales están controlados en gran medida por el clima más que por el manejo, la interface utilizada debería ser rediseñada para simular cambios en el carbono del suelo sobre la base del estado ecológico más que por la aplicación de prácticas de manejo.

Key Words: CENTURY model, Conservation Reserve Program, greenhouse gas management, land use change

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INTRODUCTION

Terrestrial carbon sequestration is an important component of a comprehensive greenhouse gas (GHG) management strategy (Rice 2006). Because carbon stocks in soils and vegetation respond to changes in land use and management, realizing the potential of terrestrial sequestration is an attractive means of reducing GHG levels in the near term (< 20 yr; Conant et al. 2001; Thomson et al. 2008). Carbon sequestration through land use and management change has an inherent competitive advantage compared to geologic (deep burial in stable formations) and oceanic (fertilization of shallow, nutrient-poor waters or burial in deep oceans) sequestration in that 1) results can be achieved quickly, 2) technologies for enhanced sequestration can be implemented without major economic impact and are generally associated with improved management of resources and more efficient production systems, and 3) delivery infrastructure (land management programs in extension and federal agencies) is in place, proven, and relatively well funded (Brown and Sampson 2009).

While the potential for terrestrial sequestration to contribute to mitigation is substantially less than existing emission reduction technologies or developing geologic sequestration technologies, it is consistently identified as an important component of a comprehensive greenhouse gas management strategy. Pacala and Socolow (2004) identified terrestrial sequestration as two of the 14 "wedges" in a "stabilization triangle" proposed to stabilize atmospheric CO_2 at 500 ± 50 ppm by 2054. A wedge is defined as an activity that reduces emissions to the atmosphere that begins at zero and climbs to 1 GT $C \cdot yr^{-1}$ within 50 yr (GT = gigaton = 10^{15} g = 1000 million metric tons [MMT]). They propose 14 total wedges (including fuel-efficient vehicles and buildings, alternative fuels, and capture technologies). Two of those wedges are defined as "natural sinks"—forests and agricultural soils. Although not specifically identified by Pacala and Socolow (2004), rangeland management and restoration are generally considered within the agricultural soils management category and have been evaluated separately by several authors for their potential contribution (for review, see Thomson et al. 2008). Thomson et al. (2008) treated "pasturelands" as a separate sequestration category and estimated potential at peak rates of 0.15 GT $C \cdot yr^{-1}$ by 2100. Over the same period, they estimated that cropland management has the potential to sequester 0.21 GT $C \cdot yr^{-1}$ and reforestation 0.31 GT $C \cdot yr^{-1}$ with similar assumptions. By their own analysis, these estimates are conservative in both the rates of adoption of sequestering technologies and carbon storage. Even though rangeland sequestration has relatively low potential compared to other land use categories, the absolute amount and high cobenefits (e.g., potential for reduced erosion, improved water quality, and drought tolerance) makes it well worth pursuing (Conant et al. 2001).

In the United States, Follett et al. (2001) estimated improved grazing land management could increase soil carbon storage between 29.5 and 110.0 MMT $C \cdot yr^{-1}$, all achievable within the existing framework of land use and management decision making. Those potential gains included conversion of cropland to rangeland and restoration of degraded rangelands (17.6–45.7 MMT $C \cdot yr^{-1}$) and improved management on existing rangelands (5.4–16.0 MMT $C \cdot yr^{-1}$). Again, these rates and total amounts are relatively small compared to other source reduction and sink enhancement options but still represent a viable contribution to the overall reduction of atmospheric carbon if they can be exploited. In addition, the possibility of marketing carbon storage increases realized through deliberate management actions has potential for increasing total ranch-level income with minimal risk (du Stieger et al. 2008).

However, there are several barriers to successful implementation of sequestering technologies that must be overcome to ensure that carbon sequestration objectives are achieved and properly accounted. Terrestrial sinks in general and rangelands in particular are widely dispersed and highly variable in both time and space, making them difficult to accurately track. The relatively small annual rates of change per hectare (generally < 1.0 MT $C \cdot yr^{-1}$) are at the lower limits of detection using existing technology, such as eddy covariance and Bowen ratio methods (Svejcar et al. 2008) and, when combined with the costs of measurement, preclude these direct measurement technologies as a primary basis for monitoring and verification. Similarly, the slow rates of change and high spatiotemporal variability limit the effectiveness of a monitoring strategy based entirely on direct measurement of changes in soil carbon content (Smith 2004; Follett et al. 2005). The extensive spatial areas involved (10^6 km^2) and decadal time frames necessary to detect change with direct measurement (either flux rates or soil carbon change) dictate the use of predictive models as a basis for assessing the value of individual practices and developing realistic policy alternatives (Lokupitiya and Paustian 2006). Although a model-based approach may have the benefit of producing estimates of change for lower costs than field-based measurements, substantial effort is necessary to ensure credibility. Computer-based modeling approaches to predict changes in soil carbon over large areas and/or long time frames require commitment of time and resources to ensure that input information is current and processes are described correctly. Most models currently in use perform poorly in predicting soil carbon changes on arid lands in general and on rangelands in particular. This is, in part, due to a lack of adequate base information (soils, vegetation cover, and management practices) and uncertainty about the interactions among those driving variables (Martens et al. 2005).

Thus, the credibility of a systematic accounting of carbon change, regardless of the scale, depends on the development of consistent, accurate, and transparent modeling approaches. At the scale of individual or collections of ranches, relatively precise (site or soil map unit) estimates of carbon change in response to management are necessary to support participation in a private-sector market of ecosystem service trading. At state, regional, and national scales, credible and transparent estimation technologies are vital to accounting schemes that underlie program development, policy formation, and international treaty obligations. While credibility can be enhanced by ensuring a strong scientific basis for estimates, transparency depends on widespread access to and documentation of models. Thus, any system that meets these criteria will have to be accessible to scientists, policymakers, land managers, and technical advisers as well as an interested public.

In this article, we describe a test of the regional application of a commonly used soil carbon model, CENTURY (Parton et al.

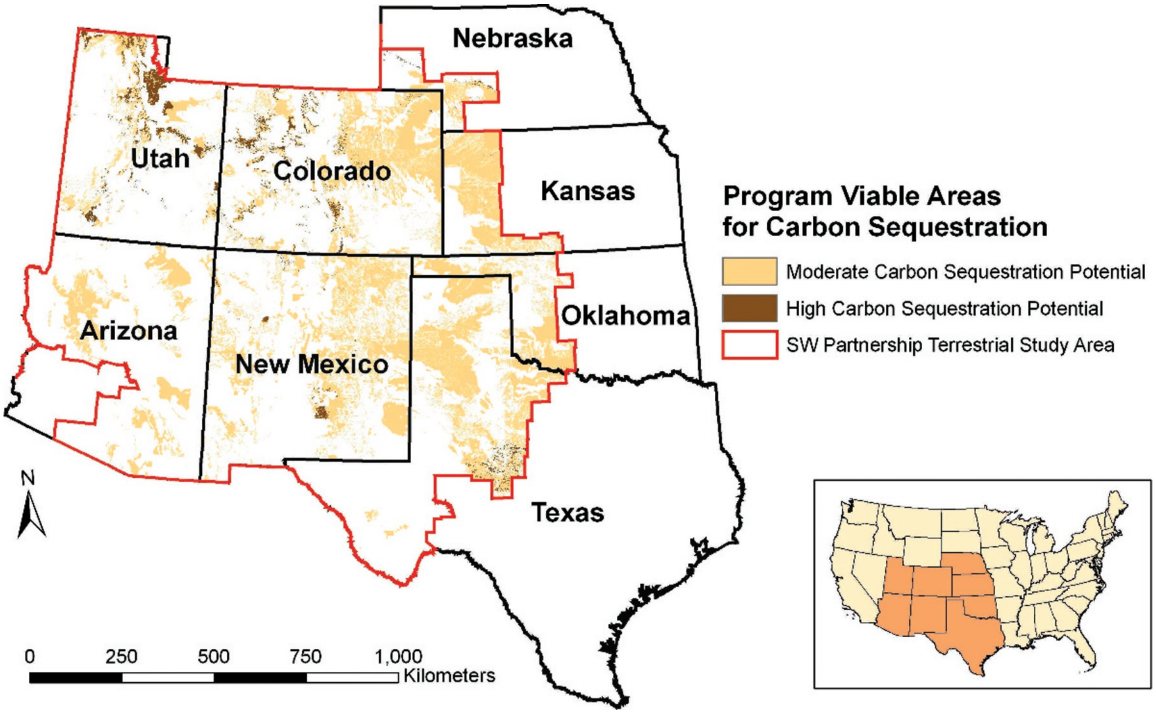

Figure 1. Study area for assessing carbon sequestration potential in the Southwest Sequestration Partnership region.

1987) and COMET VR (US Department of Agriculture [USDA] 2007), an interactive decision support tool, to determine the potential for land use and management change to affect soil carbon levels, identify common conservation practices that could increase soil carbon, and define the strategic elements of a plan to reduce uncertainties of the approach. Even though the CENTURY model is widely accepted as the standard for modeling soil carbon and nitrogen change in response to climate and management, it is poorly parameterized for rangelands in general and arid rangelands in particular. Specifically, we test the current parameterization of the model against attributes commonly associated with land use and management changes in the southwestern United States as a means of assessing uncertainty. Our goal is to use the information in this analysis to develop a systematic approach for estimating soil carbon change that can inform policy, programs, and management that is widely available and accepted. Meeting the challenge of integrating sequestration as an additional land management objective into agriculture and forestry production systems will require an analytical approach that draws on existing expertise and information as well as a combination of analytical tools.

It is not our intent in this article to verify the CENTURY model output with actual soil carbon levels under different climatic and management regimes. While this task is certainly important, it must be approached as a distinct component of the overall goal of developing a model-based soil carbon prediction system. A failure to systematically test the individual components that contribute to the development of a credible system would very likely result in only marginal improvement and would certainly be an ineffective use of public resources.

METHODS

This analysis is a part of the Southwest Regional Sequestration Partnership (SWRP) and the Regional Sequestration Partnership Program of the US Department of Energy (http://www.fossil.energy.gov/sequestration/partnerships/index.html). The program is intended to identify, in each of seven regions, greenhouse gas emission sources and potential carbon sinks and to develop strategies and technologies to support commercially viable carbon sequestration projects, including capture, transport, and storage (geologic, oceanic, and terrestrial). The SWRP (http://www.southwestcarbonpartnership.org) encom-

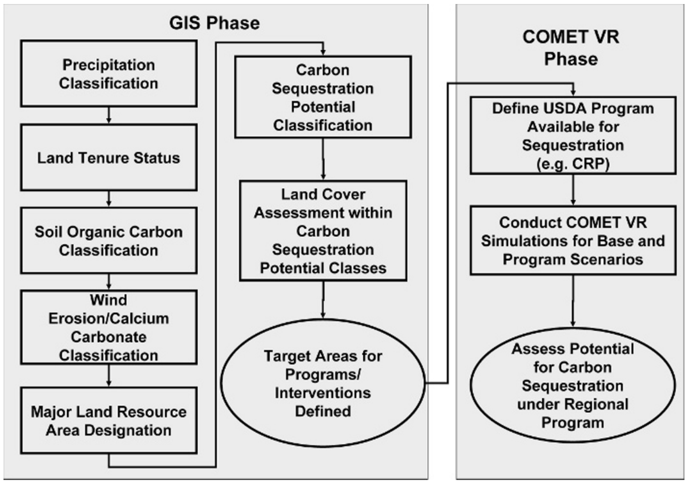

Figure 2. General framework for assessing carbon sequestration potential in the Southwest region.

passes the states of Arizona, Colorado, New Mexico, and Utah and portions of Kansas, Nebraska, Oklahoma, and Texas (Fig. 1).

To assess the sequestration potential of land areas within the partnership, a framework was developed with two distinct phases (Fig. 2). The first phase involved the use of climate, soil, land tenure, land cover, and major land resource area spatial coverages incorporated into a geographic information system (GIS) to define areas having greatest potential for implementing carbon sequestration programs in the region. Once these areas were identified, a second phase was initiated that used the CENTURY model and COMET VR tool (described later) to assess the amount of carbon that could be sequestered under land management systems and conservation programs available for the region.

For these analyses, the various data layers were acquired from online data sources, and the data sets were classified into categories of potential to allow for spatial indexing. The data layers included 1) long-term precipitation, 2) land tenure, 3) soils, 4) land cover, 5) major land resource area, and 5) administrative boundaries (state and county lines). Long-term precipitation was used to define climatic potential and was defined as precipitation amounts that would be of sufficient quantity to allow for suitable plant growth or success in revegetation. To assess climate potential, the long-term average annual precipitation based on the output of the PRISM model (8-km resolution) for the period 1971–2000 (PRISM Climate Group 2004) was classified as no potential (0–13 cm), low potential (13–23 cm), moderate potential (23–46 cm), or high potential ($>$ 46 cm).

Land tenure was used to delineate private/nonfederal, federal, and Indian reservation lands (http://www.nationalatlas.gov). This allowed separation of land areas where carbon sequestration programs could be targeted for private/nonfederal land and Indian reservations since incentive programs will not be implemented on federal lands. Soils data were classified based on three characteristics that influence soil carbon. These were soil organic carbon (SOC), calcium carbonate ($CaCO_3$), and the Wind Erodibility Index (WEI). The data layers used were acquired from the Natural Resources Conservation Services Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) soil databases (Soil Survey Staff 2005, 2007). The SSURGO data (higher resolution) were used where available. STATSGO was used to fill in areas not covered by SSURGO. SOC in the upper 20 cm was classified for indexing as low (0–0.75%), moderate (0.75–1.75%), high (1.76–10%), or very high ($>$ 10%). $CaCO_3$ content was classified as low (0–15%), moderate (15–30%), or high ($>$ 30%). The WEI was indexed as low ($0–100\ t \cdot ha^{-1} \cdot yr^{-1}$), moderate ($100–200\ t \cdot ha^{-1} \cdot yr^{-1}$), or high ($> 200\ t \cdot ha^{-1} \cdot yr^{-1}$).

The climate, land tenure, and soil data layers were intersected in the GIS to create a coverage that would allow spatial queries based on the above defined attributes. Boundaries of interest (Major Land Resource Areas [MLRA] and counties) were also included in the GIS to allow options for aggregating at multiple spatial scales. A spatial query was conducted on private/nonfederal lands and Indian reservations to identify sites having moderate to high climatic potential, moderate to very high SOC, low $CaCO_3$, and low WEI. The land areas identified through this query were designated as target areas for carbon sequestration programs/interventions. These target areas were then cross indexed with the 2001 National Land Cover Data (NLCD; http://landcover.usgs.gov) to determine land cover. NLCD is a 21-class land cover classification scheme applied consistently over the United States. The data were reclassified into three major classes to reflect land cover types where government programs for terrestrial sequestration could be implemented: rangelands (including shrublands and grasslands), row crops, and small grains. Spatial queries were then conducted to acquire the data needed by the COMET VR interface. These included spatial extent of each land cover category, soil texture, county, and MLRA.

The CENTURY model is a general model of plant–soil nutrient cycling used to simulate carbon and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests, and savannas (Natural Resource Ecology Laboratory 2000). The model requires these driving variables as inputs: monthly average maximum and minimum air temperature; monthly precipitation; soil texture; plant nitrogen, phosphorus, and sulfur content; lignin content of plant material; atmospheric and soil nitrogen inputs; initial soil carbon; and nitrogen. These variables are available for most natural and agricultural ecosystems. CENTURY contains two plant production submodels: a grassland/crop submodel and a forest production submodel. Monthly maximum plant production is controlled by moisture and temperature, and maximum plant production rates are decreased if there are insufficient nutrient supplies.

COMET VR (USDA 2007), an online interface to the CENTURY model, was used to assess baseline carbon and management-induced carbon changes in areas identified as having high to moderate potential for carbon sequestration (Fig. 1). The COMET VR interface allows a user to select a location (state and county), soil texture, land use history, and a proposed 10-yr future management alternative defined by individual practices. Based on these choices, COMET VR accesses information on climate and land use from database sources and runs the CENTURY model. The results are calculated and presented as 10-yr annual averages of soil carbon sequestration or emissions with associated statistical uncertainty values expressed as a percentage (see Ogle et al. 2003, 2007). The uncertainty estimator was developed specifically to communicate to model users a level of confidence in the model output for a specific land unit (soil properties, climate, land use history, and future management) compared to the current parameterization of the model. The uncertainty estimator was developed as a statistical analysis (as opposed to a probability function such as Monte Carlo analysis) using a linear mixed model approach that compared model outputs to the measured results of 47 experiments (Ogle et al. 2007). These authors found that the CENTURY model could be used to reliably predict changes in soil carbon in response to management. However, there were significant shortcomings in the model for specific land use and management combinations. Thus, the uncertainty values generated by this technique can be used to asses the reliability of this modeling approach as a basis for policy, program, and management decisions.

In this analysis, we focus on the spatial distribution of uncertainty. While the absolute values of potential sequestration are important, given the ubiquitous nature of uncertainty associated with rangeland management practices, the issue of

Table 1. Percent of total land area for each uncertainty class by land management change. Uncertainty class category is described in the text. Conservation Reserve Program (CRP) represents the establishment of perennial native grasses on existing cropland (row crop or small grains). Legume addition is the addition of legumes to existing rangeland vegetation.

	Area					
	Row crops		Small grains		Rangeland management	
Uncertainty class (%)	CRP	CRP + legumes	CRP	CRP + legumes	Reduced stocking	Legume addition
0–20	19.6	37.0	31.8	73.0	66.7	0.2
21–40	18.5	0.2	40.0	0.0	0.0	0.4
41–60	0.0	0.0	0.0	0.0	0.0	1.0
61–80	0.0	0.0	0.0	0.0	0.0	7.1
81–100	0.0	0.0	0.0	0.0	0.0	3.4
Unknown	61.9	62.9	28.2	27.0	33.3	87.9

resolving uncertainty becomes paramount. For the model output, we classified uncertainty as 0–20% (acceptable), 20–40%, 40–60%, 60–80%, and 80–100% and displayed the distribution of that uncertainty on maps where each point represents a 30 × 30 m area. There was also a category, labeled "unknown," in which the model was unable to calculate an uncertainty value based on inputs and current model parameterization.

For the purposes of this analysis, land areas identified as potential target areas for carbon sequestration programs/interventions during the GIS phase that had sufficient area ($>$ 10 000 ha) in either rangeland, small grains, or row crops were modeled with COMET VR. For land conversion, two options were considered: conversion from either small grains or row crops to perennial grass or conversion to perennial grass + legume. These practices simulate those applied in federally funded conservation programs such as the Conservation Reserve Program. For rangelands, two management practices were compared: improved grazing management (conversion from heavy to moderate stocking rates) and grazing removal with the addition of a legume species to the plant community.

The COMET VR model was run for each unique combination of soil texture, land use history, future management scenario, county, and MLRA. Since many of the SSURGO and STATSGO map units can represent more than one soil series, weighted averaging of the COMET VR results was conducted using the component percentage for each series in the soil map unit as the weighting factor, thus providing a weighted average carbon and uncertainty value for each map unit. The values were then joined back to the spatial coverage of areas having high to medium sequestration potential to allow a spatial representation of data. A mask was derived for each of the land cover class and intersected with the map unit coverage to provide spatially explicit uncertainty values for the specific carbon management practice that could be implemented for that land cover class. For example, a specific map unit's uncertainty value for the sequestration practice of converting small grains to grassland was assigned to only those land areas identified in the map unit as having small grain land cover.

RESULTS

Land Conversion

The conversion of row crop (primarily grain sorghum, corn, and cotton) cropland to perennial grassland cover is a common practice in some portions of the region and relatively uncommon in other areas, and the modeling approach we used in this analysis reflected that range of experiences and data. Conversion from row crops to perennial grass cover had inconsistent and highly variable model performance ($>$ 60% unknown uncertainty; Table 1). Although this land use change had reasonably high certainty (generally $<$ 20% uncertainty) in

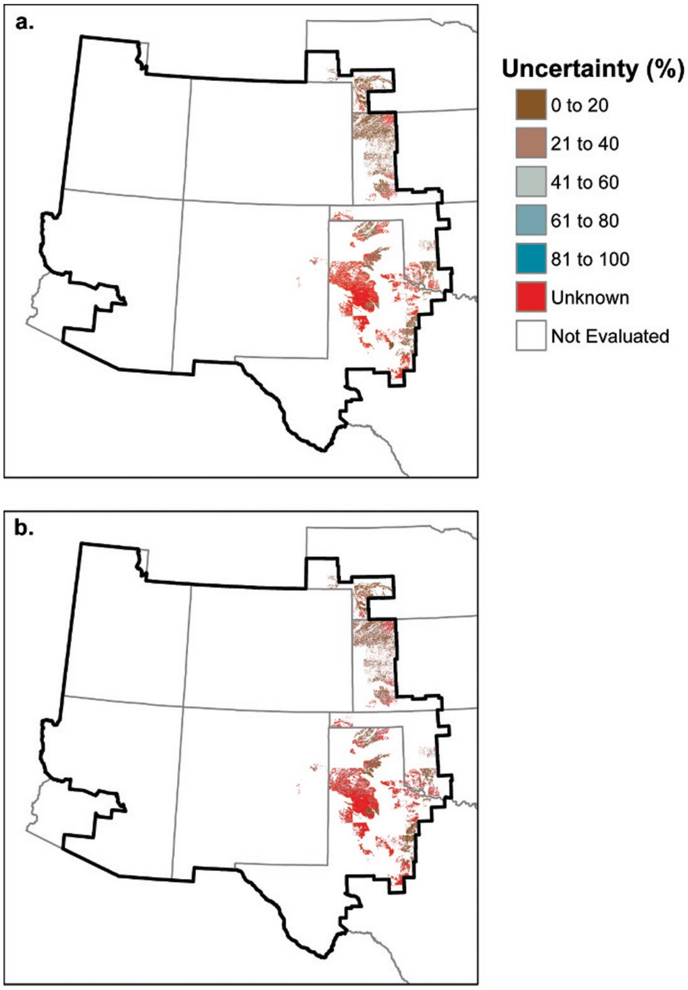

Figure 3. Spatial distribution of uncertainty associated with CENTURY model estimates of carbon sequestration potential in the southwestern US region for (**a**) conversion of row crops to perennial grass cover and (**b**) conversion of row crops to perennial grass + legume cover.

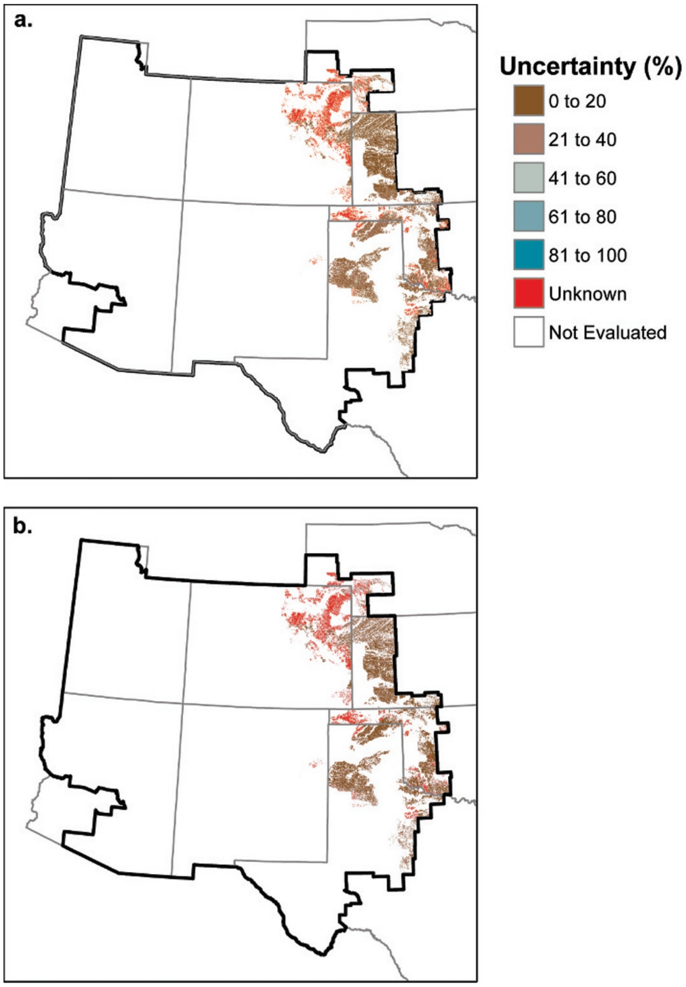

Figure 4. Spatial distribution of uncertainty associated with CENTURY model estimates of carbon sequestration potential in the southwestern US region for (**a**) conversion of small grains to perennial grass cover and (**b**) conversion of small grains to perennial grass + legume cover.

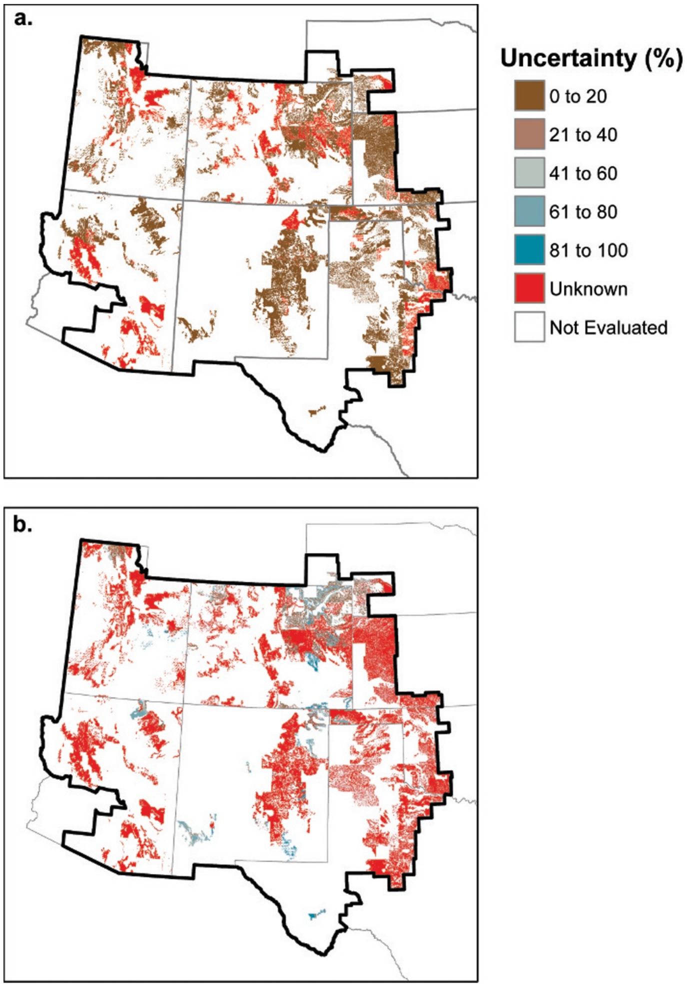

Figure 5. Spatial distribution of uncertainty associated with CENTURY model estimates of carbon sequestration potential in the southwestern US region for (**a**) reducing stocking rate from heavy to moderate and (**b**) removal of grazing + legume cover.

the High Plains region, roughly analogous to Land Resource Region G (USDA 2006; Figs. 3a and 3b; generally < 20% uncertainty), the exceptions were in western Texas for the conversion of row crops to perennial cover and conversion of row crops to perennial cover + legume. The dominant row crops in that region are cotton and grain sorghum and for the most part have been poorly investigated with regard to carbon dynamics (Martens et al. 2005). The factors contributing most to the high levels of uncertainty were lack of information about tillage practices associated with cotton culture and the influence of coarse-textured soils on carbon dynamics.

Conversion of small grains to perennial cover had relatively high levels of certainty associated with model predictions (Table 1; Figs. 4a and 4b). Conditions on almost three-quarters of the land area were within the lowest two uncertainty categories (< 40%), indicating a high level of model performance (Table 1). Less than 30% of the small grains cropland area was associated with attributes that resulted in uncertainty levels that could not be calculated. The primary exceptions were croplands in northeastern Colorado. Although there has been substantial work on the effects of crop rotations and tillage in this region, investigation of the conversion to perennial cover has been limited in both time (< 10 yr) and extent (Ogle et al. 2007). In general, the modeling approach that we tested performed relatively well (low uncertainty) for the conversion of land on which common crops are produced to perennial vegetation cover dominated by grasses.

Rangeland Management

The uncertainty associated with model estimates of rangeland management practices was much greater across the region than that associated with land conversions (Table 1; Figs. 5a and 5b). Reduction of stocking rate from heavy (> 30% above recommended levels) to moderate and light is generally defined as the rangeland management practice that will have the greatest effect on soil carbon levels based on experimental evidence (Follett et al. 2001). The effects of that management change were relatively reliably predicted by our modeling approach, with more than 66% of the land area we evaluated having uncertainty levels below 20% (Table 1). However, parameterization of the model for this practice on more arid rangelands is lacking (Fig. 5b), limited to prairie vegetation/soil combinations (Ogle et al. 2007). For perhaps the most effective practice on rangelands to increase soil carbon, a decrease in grazing pressure, and the addition of legumes (Fig. 5b), there is a dearth of experimental information, and, as expected, the model performs poorly, with more than 87% of the land area evaluated having uncertainty levels that we were unable to calculate (Table 1).

DISCUSSION

The use of an integrated approach to predict and track changes in agricultural soil carbon levels is critical to provide 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, and soil sampling) as part of statistically designed 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).

In this article, we have reported the results of an experiment using the COMET VR interface with the CENTURY model to test its effectiveness in predicting soil carbon change in response to common management practices in arid and semiarid rangelands of the US Southwest. The approach worked relatively well in simulating changes to soil carbon when marginal cropland was converted to perennial grass cover. The uncertainty levels associated with these individual simulations were typically $< 20\%$, certainly acceptable for both large-scale and site-specific planning decisions and regional inventories. The model had less certainty when the conversion was to grass + legume, a viable but little-used option in popular federal conservation programs (Martens et al. 2005).

Simulations of changes in rangeland soil carbon levels had far higher levels of uncertainty. Uncertainty levels were acceptable ($< 20\%$) when reductions in stocking rate were simulated on shortgrass prairie soils and vegetation but were less reliable in more arid areas. Removal of grazing and addition of a legume, which could be interpreted as restoration, was much less reliable, and model simulations typically resulted in incalculable uncertainty estimates. In addition to the low certainty associated with simulating the effects of this practice, lack of proven technologies will make implementation on rangelands difficult.

The high levels of uncertainty associated with most rangeland applications in this region will make both credible regional inventories and participation in private-sector greenhouse gas offset trading schemes problematic. Improving the performance and reliability of this modeling approach will require a concerted effort to integrate direct measurement, refine the model, and improve communication with users to interpret results accurately. Our spatial analysis approach has allowed us to identify both specific locations and conditions (management history and future practices) that require additional direct measurement (flux rates and soil measurement) of soil carbon change to support improvements in modeling. 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 effects of even decades-old relatively common management practices on soil carbon dictate the need for complete characterization of soils, climate, and management histories. Collection of soil carbon data at these locations should also be done with a strong emphasis on spatial patterning (Conant and Pastian 2002). 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 (Bestelmeyer et al. 2006; Peters et al. 2006). In addition, changes in land use and climate require annual updates to ensure 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 policymakers. The COMET VR system has been designed primarily for use in croplands where practices such as tillage and crop rotation have reasonably consistent effects on carbon dynamics within a soil textural class. Unfortunately, rangeland management and improvement practices lack this level of consistency. 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 (stocking rate changes and vegetation manipulation) are highly variable depending on soil/vegetation state. The application of even common and well-understood management practices may have vastly different effects on a variety of ecosystem processes, including carbon sequestration, depending on the current state rather than the practice itself (Asner et al. 2003). A practice-driven interface, while appropriate for cropland use, will not be adequate or reliable for rangeland predictions. Thus, an integrated, model-based system should be linked to the existing Ecological Site Description system 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.

MANAGEMENT IMPLICATIONS

The results of this analysis demonstrate that the use of a model-based approach for estimating changes in soil carbon due to land use and management change in the southwestern United States requires improvement. If this modeling approach is to be used as the basis for government programs, international reporting, or private-sector market trades, the uncertainty associated with model estimates must be improved. The current level of uncertainty for specific practices and in specific areas is too great to generate the confidence necessary to make rangeland carbon sequestration offset projects viable. Given that the model works relatively well where sufficient experimental results are available to parameterize the model (i.e., High Plains region), it follows that the first step to improving model performance is to integrate the results of field experiments from geographic areas where the model currently performs poorly into the model and retest. Although spatial variability can complicate such field experiments, there have been several estimates of the numbers of samples necessary to achieve specified levels of statistical reliability at multiple spatial scales (see Conant and Paustian 2002).

Given the disparity between the value of carbon and the costs of direct sampling, the use of an integrated approach (experimental plot sampling, modeling, and project verification) is critical to credibly estimating changes in soil carbon in response to management. A clear path for improving each component will allow for the cost-effective improvement of a carbon change prediction system. Obviously, the level of uncertainty tolerable in a public policy or marketing application of this modeling approach will be determined by factors other than statistical analysis (carbon prices, international treaties, and so on). Regardless of the level of uncertainty regarded as tolerable by the public- or private-sector markets, we believe that this approach can be useful and can be the basis for sound decision making if those levels are agreed on and sufficient field studies are implemented to improve the performance of the model.

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