Climatic Change (2011) 108:301–331
DOI 10.1007/s10584-010-0009-1

An analysis of cropland carbon sequestration estimates for North Central Monana

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Received: 9 March 2009 / Accepted: 4 November 2010 / Published online: 5 February 2011

Abstract A pilot cropland carbon sequestration program within north central Montana has allowed farmers to receive carbon credit for management adjustments associated with changing from tillage-based agricultural systems to no-till. Carbon credit can also be obtained by adopting conservation reserve, where cropland is planted into perennial vegetation. Summer fallowing is also considered within the crediting process as credit is not given in years that a field is left un-vegetated. The carbon sequestration program has been advocated as a means to mitigate climate change while providing an added source of income for Montana farmers. There is lack of data, however, pertaining to the percentage of lands within this region that have not converted to no-till management, lands under certain crop intensities (e.g. those that are cropped every growing season vs. those that use a fallow-crop-fallow system), or cropland that have converted to perennial vegetation outside of the popular Conservation Reserve Program. Data is also sparse concerning the amount of soil organic carbon that might be sequestered given a conversion to no-till or conservation reserve. This study established regional percentage estimates of cropland under no-till, various degrees of crop intensity, and conservation reserve within north central Montana. Literature-based carbon sequestration estimates were used to generate carbon gain data associated with the conversation to no-till and to conservation reserve. These estimates were then applied to the area-based cropland statistics to estimate potential regional carbon sequestration associated with these management changes.

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1 Introduction

Increased carbon mitigation efforts have arisen in response to global climate change. Terrestrial-based mitigation presents a practical and more immediate approach to carbon (C) capture and storage, given the existing limitations to geologic-based sequestration (Schrag 2007; Bachu 2008; Figueroa et al. 2008). Terrestrial sequestration utilizes plant photosynthesisto remove existing carbon dioxide (CO_2) from the atmosphere and to store the captured C within plant molecules. Afforestation and management changes within existing forests and rangeland have been advocated as possible options for increased C storage (Turner et al. 1995; Schuman et al. 2002). Cropland soils have also received considerable attention, influenced by its large global expanse (recently estimated at 1.53 billion-ha by Biradar et al. 2009) and documented losses in soil C due to cultivation (Lal et al. 1995). The potential for increased C storage within cropland soils has been proposed, primarily through changes in tillage management, cropping intensity, and the conversion of croplands to perennial vegetation (Lal et al. 1998; Post and Kwon 2000; West and Post 2002).

1.1 Cropland C sequestration potential

Soils have long been recognized as important C sinks (Schlesinger 1977). The global soil pool is estimated to hold 2,500 Gt C (1 Gt = 1 billion tonnes), 3.3 times the amount of atmospheric C (Lal 2004). Cropland soils within the United States are reported to hold 2.7 Gt C (Houghton et al. 1999; Houghton and Hackler 2000), an estimate reflecting cropland C loss after years of tillage and summer fallowing. Tillage practices incorporate mechanical disturbance for surface residue management, weed control, and to prepare the soil for planting. Summer fallow refers to the practice of leaving a field unvegetated during a growing season (weed and volunteer crop growth is controlled through tillage and herbicide application within traditional systems, while herbicide is solely used in no-till systems) and has traditionally been implemented in non-irrigated croplands to build up soil moisture in the root zone for the subsequent crop.

The soil organic C (SOC) cycle is a complex system of input, storage, and release. Sequestration potential is largely controlled by climate, soil organisms, parent material, topography, and time (Schimel et al. 1994; Post et al. 2004). Land management also influences SOC flux. Cropland management techniques that facilitate the input of organic materials into the soil and/or reduce decomposition rates serve to increase SOC. Recent increases in cropland C storage have been attributed to management changes associated with the conversion from traditional, more intensive, tillage systems to conservation tillage practices such as no-till (NT) and the conversion of cropland into perennial plant cover (Eve et al. 2002). Increased crop intensity, or the reduction of fallow, has also been advocated as a management change that could result in added soil C (Halvorson et al. 2002; Sherrod et al. 2003).

NT systems seed directly into the previous crop stubble and can disturb no more than 15% (pre-2008 definitions have allowed for up to 25% disturbance) of the soil surface (NRCS 2008). Crop intensity is the inverse proportion of growing seasons that a field is summer fallowed instead of under live vegetation (cropped).

Incentives to convert cropland into perennial grass within the United States have been provided primarily by the Conservation Reserve Program (CRP). The CRP program is administered by the US Natural Resource Conservation Service (NRCS) and provides monetary support to farmers who voluntarily convert degraded cropland fields into perennial vegetative cover. Fields are required to remain within the CRP for ten to 15 years; managed grazing is allowed only once every three or five years, depending on local CRP guidelines, and managed haying might also be permitted as deemed appropriate by state-level administration (USDA-FSA 2007, 2009). Incentives for the conversion of cropland to perennial grass outside of the CRP might exist but have not been addressed within published literature. For the purposes of this study, we refer to croplands having been converted, for *any* reason, to perennial vegetation (mainly grass and grass/legume in north central Montana) as being under Conservation Reserve (CR), as distinguished from the more narrow CRP. We include the term “reserve” as these lands might at some point be converted back to cropland after a period of rest from cultivation.

The amount of SOC that might be sequestered through changes in tillage, crop intensity, and the adoption of CR, varies greatly and can be area-specific. Estimated sequestration rates for the conversion from traditional tillage to conservation tillage management (mulch till, ridge till, NT, etc.) have ranged from 300–600 kg C ha^{-1} year^{-1} within the US Great Plains (Follett and McConkey 2000) to 100–300 kg C ha^{-1} year^{-1} in the Canadian prairies (McConkey et al. 1999). Research has shown that C sequestration potential is often greater in soils with higher C depletion and that storage amounts are finite and will increase until reaching system equilibrium (West and Six 2007). A lower C sequestration potential might occur within cropping systems converting from more minimal forms of tillage to NT than in systems with a prior history of traditional, high disturbance, tillage. Minimum-tillage (MT) systems are not well defined but are generally considered to fall somewhere between traditional tillage and NT systems in the amount of surface disturbance and crop residue existing within the system. Implements used within MT systems might include tandem disks, chisel plows, and field cultivators, but exclude moldboard plows. Sequestration rates for systems converting from MT to NT have not been well established within published literature.

Increased crop intensity reduces the amount of time that a field is under fallow during the growing season. Active vegetation provides essential, C-rich, organic residues into the soil system that offset C loss due to microbial activity and erosion (Potter et al. 1997; Staben et al. 1997; Paustian et al. 2000; Halvorson et al. 2002; Jarecki and Lal 2003). Residue inputs are trivial (i.e., weeds or volunteer crop) during fallow periods and a net system loss of SOC might result if the C accumulated during alternate cropped years is not substantial enough to mitigate for C losses. The degree of crop intensity incorporated within dryland settings is largely dependent on annual precipitation. Farmers in areas of low precipitation might be hesitant to plant crops in two subsequent years as the soil moisture content might not be adequate for supporting an economical harvest in the second year.

C accumulation following the conversion to grassland-based CR is often variable and has ranged from 0 to >400 kg ha^{-1} year^{-1} (Uri 2001; McLauchlan 2006). Higher reported sequestration rates have been attributed to soil moisture availability (Uri 2001) and adequate nitrogen levels (Baer et al. 2000). The establishment of legumes in systems converted to perennial vegetation can help to increase soil nitrogen and subsequent SOC. One Wyoming study reported that levels of nitrogen and labile SOC more rapidly increased in CRP fields where established legumes were present (Robles and Burke 1997). Alfalfa has been widely introduced into Montana perennial systems due to its recognized quality as wildlife and cattle forage. A review of CRP lands in eastern Montana reported alfalfa to be highly competitive with warm and cool season grasses within the region (Jacobs and Nadwornick 2008), and is frequently required as a component species.

1.2 C credits and regional sequestration potential

The US Department of Energy has established regional partnerships, including the Big Sky Carbon Sequestration Partnership (BSCSP), to investigate possible ways to offset anthropogenically produced CO_2. A BSCSP-sponsored program, in conjunction with the National Carbon Offset Coalition (NCOC 2008), has promoted the development of cropland-based C offset credits within north central Montana and adjacent states (Young 2003; Capalbo 2005). Land owners enrolled within the program are paid on a per-area basis for the implementation of practices such as NT and grassland-based CR, according to C sequestration standards established by the Chicago Climate Exchange (CCX 2008a). Each C credit resulting from the implementation of these practices represents the removal of 1 t CO_2 from the atmosphere (Bayon et al. 2007) and are considered to be a commodity that might be purchased directly from the source or traded within an exchange. C credits are not issued in years of summer fallowing or when residue management through burning or physical removal (haying) occurs. The system used by the CCX assigns C credits on a per-zone basis, using coarse regional approximations established by a soil C technical advisory committee comprised of “leading experts from the academic soils science community” (CCX 2008b, p. 4).

C credits ideally would be assigned according to localized C data. These data, however, are usually unavailable, making it necessary to apply broad-scale C rates in place of more location-specific sequestration estimates. The general lack of studies establishing region-specific C sequestration rates has been due largely to the great cost and time involved in measuring and monitoring soil C (Smith 2004). Many researchers have instead used C models for sequestration estimates (Melillo et al. 1995; Coleman and Jenkinson 1996; Parton et al. 2005; Bricklemyer et al. 2007), but it is often difficult to acquire adequate parameter data for large-area analyses. Some studies (Eve et al. 2002; Sperow et al. 2003) have avoided the use of regional C models by applying available C rate estimates to land use practice statistics. This type of an approach, applying generalized averages to regional land-use percentages, likely is ideal for C sequestration analyses within Montana, given the difficulty of obtaining the parameters needed for a model-based approach.

1.3 Land use data for regional sequestration estimates

Statistics concerning the percentage of agricultural land within north central Montana under NT, CR falling outside of the CRP, and various crop intensity levels are lacking. The US Department of Agriculture census data are limited to 5-year intervals and have not included information regarding tillage management or crop intensity. The Conservation Technology Information Center (CTIC) currently relies on sporadic voluntary data to estimate the amount of land under different tillage practices. Data exist for CRP land under contract with the Montana Farm Service Agency (MFSA); these statistics, however, are typically not available for use outside the MFSA. The CRP data do not account for CR areas outside of CRP contract.

Cost-effective and timely options for the collection of regional tillage, crop intensity, and CR data must be considered as survey-based efforts are too expensive and time-intensive to facilitate the annual collection of cropland statistics. One alternative is satellite image analysis. Image analysis has been widely used in the characterization of land cover practices (Lefsky et al. 2002; Kerr and Ostrovsky 2003; Cohen and Goward 2004). Several studies have reported high classification accuracy in detecting CR vegetation (Price et al. 1997; Egbert et al. 1998, 2002; Watts et al. 2009) and crop and fallow parcels (Xie et al. 2007; Watts et al. 2009) through image classification. An object-based analysis might also be used, rather than the traditional per-pixel approach, as it allows for land cover classifications to be based on meaningful management units, such as agricultural fields (Watts et al. 2009), and can avoid problematic mixed classifications within single management zones (Benz et al. 2004).

Image-based analysis is also highly advantageous for land use assessments as it provides population data for a given landscape (Lachowski and Johnson 2001). Survey-based approaches only provide a population sample, from which inferences must be made concerning the population. The sole reliance on population sampling can be limiting, as they do not provide a fine-scale representation of spatial patterns within a landscape (Kerr and Ostrovsky 2003). Increased analytical strength comes from the incorporation of image-based population data with randomly-sampled, field-based data for which specific information has been obtained. Localized sample data representing field management types can be used within a supervised classification to create models that predict class types (e.g., fallowed or vegetated) for individual units across the population. This process often results in efficient (both cost and time-wise) across-scale landscape analyses (Barrett and Curtis 1999; Gallego 2004).

1.4 Assessing regional C sequestration potential

The objective of this study was to examine SOC storage potential within north central Montana through an approach similar to those used by Eve et al. (2002) and Sperow et al. (2003), specifically the application of available C-rate estimates to land use statistics. This was accomplished as a two-part process. Land use data were generated through a field survey and through Landsat image-based classifications to establish the percentage of cropland within north central Montana under tillage, NT and CR management in 2007. Lands under CR management, for purposes of this study, included CRP lands and "other grasslands" having vegetation and management practices similar to those within the CRP, but exclude managed pasture lands. A multi-year image analysis of crop and fallow practices was also conducted to determine four-year crop intensity patterns spanning from 2004–2007. The crop intensity values were assigned on a per-field basis and indicated the proportion of years that a field was classified as cropped, as opposed to summer fallow, over the observed time period.

The second step was to identify previously published SOC sequestration rates for systems having converted from tillage-based systems to NT and from cropland to grassland-based CR within north central Montana. We also attempted to identify SOC rates associated with the conversion to NT in conjunction with changes in crop intensity. Generalized estimates of regional C sequestration potential resulting from the conversion of these systems were then established by applying the sequestration rates to the regional land use information. Data were not available that specifically separated intensive tillage management from MT. Consequently three management scenarios were evaluated. The first assumed that all tillage in the region consisted of intensive tillage, the second assumed all tillage was MT, and the third assumed an even mix amongst intensive tillage and MT classes.

2 Methods

2.1 Study area description

This study was limited to cropland and CR lands within north central Montana (Fig. 1) and spanned ∼780,000 ha. This region is considered to be semi-arid steppe (NRCS 2007a); regional topography ranges from gently rolling hills to relatively flat prairie lands and soil type varies considerably (NRCS 2007b). Temperature and especially precipitation also vary strongly within the region. Annual average minimum temperatures have ranged from −0.7°C Havre to −0.9°C in Great Falls, with annual average maximum temperatures ranging from 12.7°C in Havre to 15.5°C in Fort Benton (NWS 2007). Mean annual precipitation (MAP) has ranged from 265 mm in Chester to 318 mm in Cut Bank and 373 mm in Great Falls (WRCC 2006).

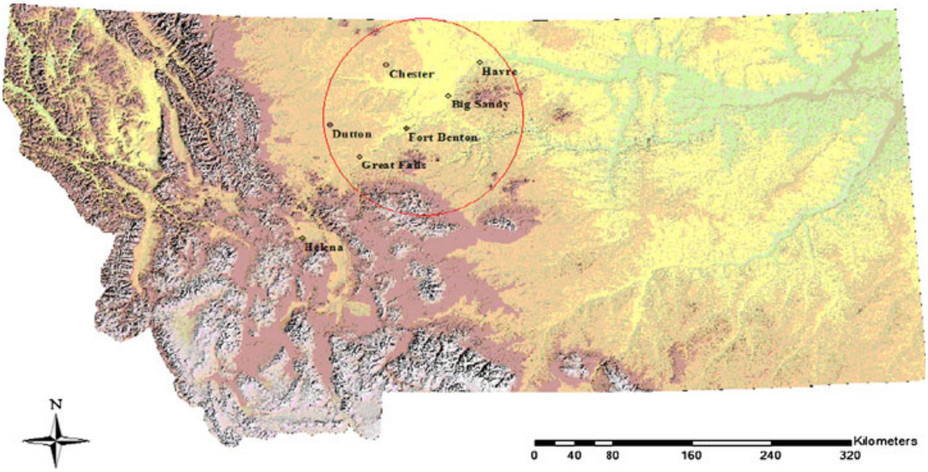

Fig. 1 Geographic location of the remote sensing cropland validation study (*within red circle*), Montana, USA

Dryland wheat is the primary crop (87%), followed by barley (11%), within north central Montana (USDA-FSA 2007); the decision to plant spring or winter crops is primarily driven by market price and soil moisture conditions. Other crops might occasionally be planted but have contributed to a minute proportion of total cropped hectares (CTIC 2004; USDA-NASS 2007). A fallow-crop rotation is common throughout the region.

Four regional subsets were identified for the image-based classification and analysis of crop and fallow patterns. This step was necessary to enable timely data management due to the computationally intensive, multi-step, process required to determine field crop intensity based on multi-year crop and fallow classifications.

The resulting geographic sub-regions were selected to represent four different precipitation zones existing within north central Montana. The inclusion of different precipitation zones was important as the ability of a dryland system to support a more temporally intensive cropping rotation (reduced summer fallow) is often dependent on annual precipitation amounts. Thus, a greater incorporation of fallow (lesser cropping intensity) might be expected in regions of lower precipitation.

The subsets were located near Dutton (18,500 ha), Chester (11,250 ha), Great Falls (13,014 ha), and between Big Sandy and Fort Benton (7,646 ha; Fig. 2). Chester represented a drier climate within the 2004–2007 period (~250 mm), Great Falls a relatively wetter climate (~390 mm) (HPRCC 2008), while Dutton and Big Sandy/Fort Benton areas were moderate (~290–320 mm).

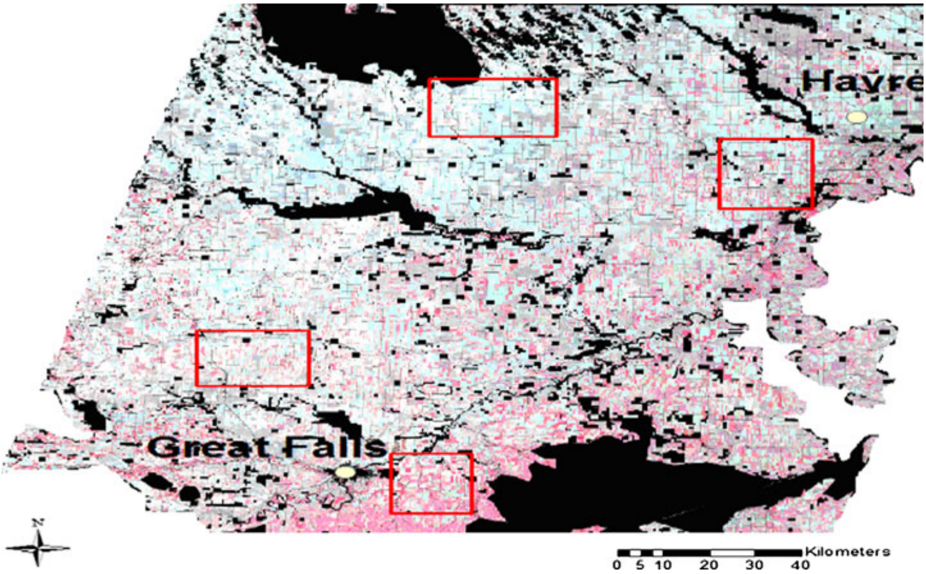

Fig. 2 A 2007 Landsat TM image scene displaying north central Montana cropland, with the cities of Havre and Great Falls (*yellow circles*) provided as spatial reference. Data subset locations (*outlined in red*) within representative regional precipitation gradients were used to identify crop and fallow practices from 2004–2007

2.2 Estimation of regional cropland land use management

2.2.1 Cropland survey

Field survey data were collected early June 2007. A GIS-based random point generator was used to determine data site locations within the study region. The final field locations were based on their proximity to public roadways to enable time-efficient site visits and to avoid land access issues. Collected information included vegetative status (cropped or fallow), crop type, and tillage management (tilled or NT). The determination of tillage management within a field included an examination of stubble (stubble in a NT field should generally be in a relatively upright position) and soil surface disturbance. Many fields classified as tillage had high levels of surface residue but also showed substantial surface disturbance.

Verbal communication with local farmers confirmed that MT, where only a light tillage is incorporated for residue management purposes and weed control, is often used throughout the region. This level of disturbance might be relatively minimal compared to a more intensive management but would still be considered “tillage” under US Natural Resource Conservation Service (NRCS) definitions (NRCS 2008). MT-related disturbances also violate guidelines specified within C-offset programs (NCOC 2008). Consequently we did not separate tillage class type beyond the NCOC-based binary split of NT or tillage.

Data for CR lands were obtained by randomly selecting samples from CRP data provided by the Montana Farm Service Agency (MFSA). Vegetation on these sites consisted primarily of grass, and mixed grass-alfalfa. Data were not available for lands converted from cropland to dryland perennial vegetation outside of the CRP, and for lands previously within the CRP. The collected CRP data were thought to adequately represent the spectral and textural surface characteristics of CR grasslands for the purpose of developing image-based classification models used to classify cropland from CR lands within north central Montana.

The resulting 2007 survey-based cropland data set included information for 78 NT-fallow, 138 NT-cropped, 48 tilled-fallow, and 148 tilled-cropped sites. The MFSA-based random sample included 127 CR field sites.

2.2.2 Satellite-based analyses

Regional, site-specific, land use statistics for CR and crop intensity were established through satellite image classifications. Particular care was taken to exclude non-agricultural lands (non-cropland and non-CRP) from the regional analysis through a series of data masking procedures (Watts et al. 2009). Special attention was also given to the removal of areas not associated with cropland systems, including managed pasture lands and grasslands along roadways, railways, power lines, and riparian buffer strips (Watts et al. 2009) using data obtained from the MFSA and the State-based Natural Resource Information Service. Data provided by the MFSA for CRP parcels, and classification results generated from the Crop vs. CR model (Table 1), were also used to remove CR lands from the cropland data set.

Classification models (Watts et al. 2009) were developed for CR and crop intensity management using data collected through the 2007 cropland field survey (Table 1). Image-based classifications were also attempted for tillage and NT, but the resulting

Table 1 Image-derived land use classification accuracies, from Watts et al. (2009)

Model	Overall accuracy	Classification matrix[a]			Producer's[b]	User's[c]
Crop & CR			Crop	CR		
May 2007	97%	Crop	304	0	100%	96%
		CR	12	115	91%	100%
Crop & Fallow			Crop	Fallow		
Aug. 2007	91%	Crop	178	10	95%	93%
		Fallow	12	55	82%	84%
Sept. 2006	96%	Crop	80	5	94%	95%
		Fallow	4	122	96%	96%
Sept. 2005	93%	Crop	68	5	93%	93%
		Fallow	5	65	92%	92%
July 2004	93%	Crop	103	8	93%	93%
		Fallow	7	105	93%	93%

[a] The classification matrix describes the resulting model-based assignments for each class (ex. 304 fields out of 304 total cropped fields were classified as Crop)

[b] Producer's accuracy is the percentage of fields within a class type that were correctly classified into that class (ex. 115/127 CR = 91%; the model failed to correctly classify (omitted) 9% of CR fields)

[c] User's accuracy provides an indication of the errors of commission for each class type (e.g. 0 of the 115 fields classified as CR were actually Crop, resulting in a 100% probability that a field classified as CR actually belongs to that class)

statistics were not used due to poor accuracy within the tillage class (Watts et al. 2009). Classification models were applied to all fields within the study area (Watts et al. 2009) to predict CR status and crop intensity on a field-by-filed basis. Crop intensity values were assigned to each field based on a per year (2004–2007) analysis of crop and fallow classifications for each field. The crop intensity value was determined, per field, by dividing the number of years that a particular field object was classified as crop by the total number of years evaluated (e.g., 3 years cropped/4 total = 0.75 crop intensity).

2.2.3 Survey-based tillage management estimates

The 2007 survey data were used to estimate the percentage of land-use area under NT and tillage due to the high degree of error within the image-based tillage classifications. This error was attributed to residue-related surface spectral similarities between fields having more minimum tillage management and those under NT (Watts et al. 2009). Confidence intervals (95%) were applied to each percentage estimate according to standard procedures for the statistical analysis of sample proportions (Moore 2004). It was assumed that these data were unbiased as they were collected randomly. The elimination of sites not accessible from roads was not expected to induce bias with respect to any management practices. The resulting percentages were then multiplied by the total cropped hectares analyzed within the image-based cropland classifications following the exclusion of cropland parcels classified as CR (those occurring outside of documented CRP contracts for 2007) to obtain land-area estimates for tillage and NT. The survey-based estimates did not separate fields under MT practices from those under a more intensive tillage.

2.3 C sequestration rate estimates

Relevant research was reviewed for reported C sequestration rates pertaining to the conversion from tillage to NT, tillage to NT as influenced by crop intensity, and the conversion from cropland to CR. C gains associated with the conversion from MT to NT were also evaluated due to concerns that these systems might sequester less C following NT adoption than those previously under more intensive tillage, and therefore should be considered separately. The review primarily included sequestration data based on physical measurements (hereafter referred to as the literature-based data), with the exception of values derived from a C-gain model (McConkey et al. 1999) due to the lack of studies examining C sequestration rates specifically associated with the conversion from MT to NT systems. The C-gain model was also used to estimate C sequestration rates associated with changes in crop intensity as the literature-based studies mainly focused on systems converting from a 0.5 (crop-fallow) to a 1.0 (continuous crop) intensity. In addition, the rates used by the CCX for C-crediting were evaluated to verify the adequate representation of sequestration potential for lands in north central Montana under C contract.

2.3.1 Literature-based data

The literature-based C sequestration data utilized within this study were constrained to those most representative of climatic regimes within north central Montana, with exception given to CR data that reflected areas under higher annual precipitation as climatically similar CR studies were not identified. Selected data were primarily taken from studies that established sequestration rates by comparing baseline SOC data with C measurements taken after management conversion. Post-hoc rates based on side-by-side comparatives, where one location was kept under tillage while a neighboring location had switched to NT management, were also included only if they provided information directly relevant to the study area.

The final selection included eight studies associated with the conversion from intensive tillage to NT (Table 2), one study that dealt with the conversion from MT to NT (Table 2), and three studies that established SOC sequestration rates resulting from the conversion from cropland to grassland-based CR (Table 3). Prior cropland management within the tillage studies included some degree of summer fallowing. Implements used for cultivation purposes in “tilled” treatments within these studies reportedly included tandem disk cultivator; sweeps and rod weeder; chisel plough and mounted harrow.

The literature-based data often represented C measurements at variable depths. C data used within this study were constrained within the ∼0–20 cm soil depth for the tillage studies and 0–15 cm for the CR studies, as most of the studies evaluated sampled within these ranges. Measurements taken from the 0–20 cm depth likely provide an adequate representation of management-influenced SOC accumulation (Kay and VandenBygaart 2002) as tillage disturbances in dryland settings, and hence the greatest amount of C depletion, typically occur within the top 0–15 cm of soil. The conversion from weight-based to area-based estimates (e.g., multiplying g C by soil bulk density) was necessary for one study and incorporated soil bulk density measurements specified within the study text. Studies sometimes presented sequestration rate estimates across fertilizer rate treatments; in these cases the

Table 2 C sequestration rates for NT

Study	Location	Mean annual precip. (cm)	Mean annual temp. (°C)	Climate[a]	Soil texture[b]	Management comparison	Years since mgmt. change	Sampling depth (cm)	Total SOC Seq. (g/m^2)	~ Rate (g/m^2/years)
NT										
Black and Tanaka (1997)	South Central North Dakota	40	5	CT	SiL	Till to NT-SW/F[c]	7	0–15.2	~ –304[e]	–43.4
						Till to NT-SW/WW/SF[d]			~91[e]	13.0
Bricklemyer et al. (2007),	North Central	26	5	CS	SL	Till vs. NT-W/F	7	0–10	186	Avg. 26.5 (15.7–47.1)
Bricklemyer (2003)	Montana	36	7.5		CL, C	Till vs. NT-W/F	6		371	Avg. 61.8 (36.6–96.6)
Campbell et al. (2001)	Saskatchewan	42	2	CT	C	Till to NT-W/F	10	0–15	393	39.3
						Till to NT- F/W/W			521	52.1
						Till to NT-W/W/W			195	19.5
Halvorson et al. (2002)	South Central North Dakota	41	12	CT	SiL	Till to NT-SW/WW/SF	13	0–15.2	140	10.8
					SiL	Till to NT-SW/F			–190	–14.6
McConkey et al. (2003)	Saskatchewan	33	3.3	CS	SL	MT vs. NT-W/W,W/F	11	0–15	200	18.2
					SiL	MT vs. NT-W/W,W/F	12		80	6.7
					C	MT vs. NT-W/W,W/F	11		250	22.7
Sainju et al. (2007)	North East Montana	36	~6	CS	SL	FST-SW/SW vs. NT-SW/SW	21	0–21	170	8.1
						ST-SW/F vs. NT-SW/SW			840	40.0
West and Six (2007), Aase and Pikul (1995), Black (1973)	North East Montana	36	~6	CS	SL	Till to NT-SW/B	9	0–9	–	37.5–45.0

Rates reflect the conversion of tillage-based cropland to NT as influenced by crop intensity (the key follows Table 3). Study cropland management prior to treatment initiation included some degree of summer fallowing (most often a 0.5 crop intensity)

CT cool, temperate; *CS* cool, semi-arid; *SiL* silt loam; *SL* sandy loam; *CL* clay loam; *C* clay; *NT* no-till; *SW* spring wheat; *WW* winter wheat; *W* wheat (type undefined); *SF* sunflower; *B* barley

[a] Climate type is defined by the Köppen classification system, according to annual precipitation and temperature data provided within each study

[b] Soil texture is described according to information provided within each study

[c] SOC rate for 0 kg/N treatment

[d] SOC rate for 34 kg/N treatment

[e] Bulk densities obtained within the specified study were used to calculate area-based SOC

Table 3 C sequestration rates for CR

Study	Location	Mean annual precip. (cm)	Mean annual temp. (°C)	Climate[a]	Soil texture[b]	Comparison type	Land characteristics	Years since mgmt. change	Sampling depth (cm)	Total SOC Seq. (g/m^2)	~ Rate (g/m^2/years)
CR											
Burke et al. (1995)	North East Colorado	36	16	CT	SiL, SiCL	Till to CR	Blue Grama dominant. Some grazing. non-CRP	53	0–10	82–200	3.1
Gebhart et al. (1994)	Kansas	53	12	CT	SiL	Till To CR	Bluestem, Grama, Switchgrass. CRP	5	0–15[c]	47	9
Post and Kwon (2000), White et al. (1976)	North Central South Dakota	~58	~15	CT	No data	Till to CR	Russian Wildrye, Crested Wheatgrass, Brome/Wheatgrass/ Alfalfa. Some grazing. non-CRP	8	0–7	148	6.86
											18.87
											14.01[d]
											34.15[e]

Rates reflect the conversion from cropland to grassland-based CR

CT cool, temperate; *SiL* silt loam; *SiCL* silt clay loam

[a] Climate type is defined by the Köppen classification system, according to annual precipitation and temperature data provided within each study

[b] Soil texture is described according to information provided within each study

[c] Rates were adjusted to reflect depth measurements common across the studies evaluated

[d] Brome/Wheatgrass /Alfalfa with full season grazing

[e] Brome/Wheatgrass/Alfalfa with short season grazing

rate estimates reflecting optimal sequestration were used within our analyses. C sequestration rates were then averaged according to management and rotation type.

2.3.2 C-gain model data

Data generated from the C-gain model were used primarily to provide an estimate for C sequestration in fields having changed from MT to NT, and for crop intensity changes within intensive tillage-to-NT and MT-to-NT systems. A sequestration rate associated with a conversion from intensive tillage to NT was also derived from the C-gain model for purposes of comparison with the only literature-based estimate.

The C-gain model was developed by McConkey et al. (1999) as a simple method to estimate C gains for tillage systems (both traditional tillage and MT) adopting NT and/or higher cropping intensities. Intensive, "traditional," tillage was defined for the model as a system where both fall and spring tillage occurred, each resulting in 100% surface disturbance (McConkey et al. 1999). MT was described as a system using both spring tillage and herbicides for weed control, in a manner that allowed for most surface residues to be retained (McConkey et al. 1999).

The model includes a C-gain equation (Eq. 1) and a corresponding table of C-gain rate fractions existing for various system adjustments including the adoption of NT in fields previously under tillage management (C_{tillage}), for years that fallow is eliminated from a system (C_{crop}), and for adjustments in fertilization (C_{fert}) (McConkey et al. 1999). Tabulated C-gain rate fractions are provided for three soil texture categories corresponding to four soil climatic zones. An optional landscape component is also provided to account for soil C movement due to erosion.

$$\text{Cgain} = \left(C_{\text{tillage}} + C_{\text{crop}} + C_{\text{fert}}\right)_{\text{zone/texture}} \times \text{landscape} \tag{1}$$

The tabulated rate fraction values for the C-gain model were established based on study findings (McConkey et al. 1999) for long-term tillage conversion experiments within the Canadian prairies. Only the provided rates corresponding to the "Brown and Dark Brown" zone were used for this study as it was most climatically similar to north central Montana (Padbury et al. 2002). A medium soil texture was assumed for the C-gain calculations, as was suggested by McConkey et al. (1999) to provide a balance between the higher sequestration that might occur in areas of fine-textured soil and a lower sequestration in more coarse soils. C-gain equation adjustments for changes in fertilizer rate were not included into the calculations. The landscape factor was also excluded from the C-gain calculations as it was deemed inappropriate to our study scale.

The C-gain model was also used to provide SOC estimates for changes in crop intensity. Estimates were calculated for tillage-to-NT systems and for MT-to-NT systems having crop intensity changes of 0.75 (3 of 4 years cropped as opposed to fallow) to 1.0 (continuous crop). Estimates were also made for tillage-to-NT and MT-to-NT systems converting from a 0.5 (2 of 4 years cropped) to 1.0 intensity for comparative purposes. An empirical correction (a 0.5 discount) was given to the C-gain predictions for use in this study, as a consistent degree of inflation was observed compared to the regionally-representative rates.

2.3.3 Regional C sequestration estimates

Regional C estimates associated with the conversion from tillage (intensive and MT) to NT, changes in cropping intensity coinciding with a conversion to NT, and the conversion of cropland to CR were obtained by multiplying sequestration rates (derived from either the literature or the C-gain model) for each category by the total estimated hectares that corresponded to that particular management adjustment. The sequestration rates supplied by the CCX (CCX 2008b, c) were also applied to generate current market-based estimates for tillage-to-NT and for cropland-to-CR conversions. The land-use area data used to estimate regional C sequestration associated with changes in tillage management were derived from the 2007 field survey; land-use areas for cropping intensity and the conversion to CR were derived from satellite-image analyses.

Three different land-use scenarios were reflected within the sequestration estimates for "tilled" systems converting to NT, due to lack of regional statistics specifically for MT management. These scenarios attempted to provide a range of possible regional sequestration potentials, based on the degrees of tillage management (intensive or minimum) that might exist prior to the adoption of NT.

The first management scenario assumed that all "tilled" lands were under a more traditional tillage system characterized by intensive soil disturbance. Two of the studies included within this scenario reported negative sequestration rates associated with the conversion from tillage to NT in spring wheat/fallow systems (Black and Tanaka 1997; Halvorson et al. 2002). These studies occurred within the same management area, and the resulting negative sequestration was attributed to diminished crop residues produced during the treatment periods (post-conversion to NT) compared to what had existed prior to treatment (Halvorson et al. 2002). The sequestration rates derived from the literature-based data for the categories specific to systems with no increase in crop rotation intensity (within a 0.5 crop intensity system), and systems averaged across crop intensities, were therefore divided into two groups. The first group represented "ideal" conversions to NT that were not confounded by reductions in SOC; the second group accounted for the possibility of decreased SOC that might occur in some systems resulting from some unbeknownst system-specific change that occurred coincidently or in conjunction with the adoption of NT. The second tillage management scenario was based on the assumption that all of the "tilled" lands within the region were under MT, instead of intensive tillage, and utilized rates primarily derived from the C-gain model (McConkey et al. 1999). The third scenario assumed that intensive tillage and MT occurred equally throughout the study region and used sequestration amounts that were averaged across the literature-based rates for intensive tillage and for MT.

3 Results

3.1 Land-use statistics

The satellite-based image classification analysis (Table 4) identified 24% of the study area as being under grassland-based CR management as opposed to cropland, a considerably higher percentage than the lands reported to be under CRP contract.

Table 4 2007 cropland tillage and grassland-based CR statistics

Image classifications			Field survey			
Management type	Hectares	%	%	95% CI	Hectares	95% CI
NT vs. Tillage						
NT	–	–	56	51–61	296,261	269,809–322,713
Tillage	–	–	44	40–49	232,776	118,504–259,228
Total land area	529,037[a]	100	100	–	529,037[a]	–
Crop intensity						
0.5	33,249	66	–	–	–	–
0.75	14,820	29	–	–	–	–
1.0	2,344	5	–	–	–	–
Total land area	50,413	100	–	–	–	–
Grassland-based CR						
Non-CRP	174,199[b]	92	–	–	–	–
CRP	14,350[c]	8	–	–	–	–
Total land area	188,549	100	–	–	–	–
Total land area for cropland and CR: 717,586 ha						

Land use data for tillage and NT derived from satellite-based image analyses and 2007 roadside survey results. Total land area within the CR analyses is the sum of total evaluated cropland and CRP hectare information provided by the MFSA

[a] This estimate was obtained following the exclusion of cropland parcels that were classified as CR (occurring outside of CRP contract)

[b] This estimate was derived by using the Crop vs. CR classification model (Table 1) to predict land-use type for parcels within the CRP program (2007) and for parcels considered to be under cropland. The spatial extent of cropland within the study area was determined through an evaluation of parcel land use information obtained from State-based Natural Resource Information Service (NRIS) GIS data

[c] CRP population statistics for the study area were provided by the Montana Farm Service Agency

The 2007 cropland field survey estimated that 56% of the evaluated region had practiced NT management in 2007, while 44% had incorporated some other tillage management.

Systems under a 0.5 crop intensity (from 2004–2007) included 66% of the analyzed cropland area (Table 4); 29% was under a 0.75 crop intensity, and 5% was under a 1.0 crop intensity. There appeared to be no connection between crop intensity and localized MAP within the regional subsets. It had previously been expected that areas having a greater MAP would be more likely to incorporate higher crop intensities, as soil moisture availability might constrain crop growth to a lesser degree than in areas with a lower MAP. Assuming that crop intensity percentages within the geographic sub-regions were adequately representative of the greater study area, the regional lands under a 0.5 crop intensity (Table 5) were estimated at 195,532 ha for NT and 153,632 ha for tillage. Lands under a 0.75 intensity were estimated to be 85,916 ha (NT) and 67,505 ha (Tillage), and 14,813 ha (NT) and 11,639 ha (Tillage) for lands under a 1.0 intensity (Table 5).

3.2 Regional C sequestration estimates

3.2.1 Cropland to CR

The average sequestration rate reported for lands converted from cropland to perennial CR management was 10 g C m^{-2} year^{-1} for soil depths within the 0–15 cm

Table 5 Regional crop intensity estimates, derived through the application of image classification-based crop intensity percentage (see Table 4) to total land area by type

Crop intensity estimates (Ha)			
Management type	0.5	0.75	1.0
NT	195,532 (178,074–212,991)	85,916 (78,213–93,587)	14,813 (13,490–16,136
Tillage	153,632 (139,666–171,090)	67,505 (61,368–75,176)	11,639 (10,581–12,961)

range (Table 6). This rate average was derived from studies that evaluated C sequestration in lands with various vegetation types, including smooth brome (*Bromus inermis*), blue grama (*Bouteloua gracilis*), bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*), Russian wildrye (*P. virgatum*), crested wheatgrass (*Agropyron cristatum*), and alfalfa (*Medicago sativa*). These species are consistent with those that exist within CR in north central Montana. The studies used to obtain this rate average included lands that were converted to grassland under CRP guidelines (Gebhart et al. 1994), as well as those that were not (Burke et al. 1995; Post and Kwon 2000). These studies also included some lands where non-intensive grazing occurred (White et al. 1976; Burke et al. 1995; Post and Kwon 2000). Minimal grazing might also be expected on some CR lands evaluated within this study. The MAP for the evaluated studies was ~17 cm greater than might be expected to occur within north central Montana. Hence we acknowledge that the sequestration potential for portions of this study region may be less than is reflected by the rate average.

It was estimated that 174,199 ha of agricultural land within the study region were under a CR-type management in 2007, in addition to the 14,350 ha that were under contract with the CRP. The conversion of these lands together, from cropland to CR, was estimated to have sequestered 18,855 t C year^{-1}. This estimate is much smaller (by 107,472 t C year^{-1}) than what is allocated by the regional CCX (2008c) rate.

3.2.2 Tillage to NT

The sequestration rates reported from Saskatchewan, North Dakota, and Montana studies showed a wide range for SOC storage potential associated with the

Table 6 Estimated C sequestration potential for the conversion of cropland to grassland-based CR

Management type	Rate (t C ha^{-1} year^{-1})	Land area (ha)	Δ SOC (t year^{-1})	Referenced table (studies footnoted)
Crop to CR	0.10	174,199	17,420	3[a,b,c]
	0.67		116,713	CCX 2008c
Crop to CR	0.10	14,350	1,435	3[a,b,c]
	0.67		9,614	CCX 2008c
Total crop to CR		188,549	18,855	3[a,b,c]
			126,327	CCX 2008c

These lands include "other" grasslands having characteristics similar to those within the CRP (A), and lands under the CRP in 2007 (B). See Table 4 for land area statistics

[a] Burke et al. (1995)

[b] Gebhart et al. (1994)

[c] White et al. (1976), Post and Kwon (2000)

conversion from tillage to NT within a soil depth of ∼0–20 cm. The literature-based rate average was 14 g C m^{-2} $year^{-1}$in systems where the change to NT retained a 0.5 crop intensity (Table 7). This rate increased considerably (to 43 g C m^{-2} $year^{-1}$) when the negative sequestration rates reported by two North Dakota studies were excluded (Black and Tanaka 1997; Halvorson et al. 2002); both of these studies evaluated systems under a spring wheat/fallow rotation and were located within the same area outside of Mandan. Only one study reflected C sequestration estimates for a system where an intermediate intensity fallow/wheat/wheat system (0.67 crop intensity) was adopted in addition to the tillage-to-NT change. This study had a reported rate of 52 g C m^{-2} $year^{-1}$ (Campbell et al. 2001); an area-based sequestration potential was not evaluated for this particular rate change, and instead this rate was included within a rate that was derived by averaging across crop intensity rate categories. The literature-based results were also used to evaluate the conversion from an intensive tillage-based management under a 0.5 crop intensity to a NT system with a 1.0 crop intensity. The sequestration rate average for this category was 28 g C m^{-2} $year^{-1}$ (Table 7). Only one study provided a rate (8 g C m^{-2} $year^{-1}$) for a system converting to NT while maintaining a 1.0 intensity (Sainju et al. 2007).

Also evaluated were rates based on the C-gain model for tillage-to-NT systems converting from a 0.5-to-1.0 and 0.75-to-1.0 crop intensities, and for systems converting to NT while keeping a 1.0 crop intensity (Table 7). The 0.5-to-1.0 conversion rate was 20 g C m^{-2} $year^{-1}$, 8 g C m^{-2} $year^{-1}$less than the literature-based value. The 0.75-to-1.0 rate was 15 g C m^{-2} $year^{-1}$ and could not be compared to any literature-based rate. The C-gain rate for a system converting to NT while keeping a 1.0 intensity was 10 g C m^{-2} $year^{-1}$, slightly higher than the literature-based rate.

It was estimated that 55,866–81,472 t C $year^{-1}$ (Table 7) might be sequestered following the adoption of NT, if all lands under tillage within north central Montana were assumed to be under intensive tillage management. This scenario used an across-intensity estimate and did not separate sequestration potential based on effects that a coincident adjustment in crop intensity might have on C gain. The low estimate (55,866 t C $year^{-1}$) was derived using averaged rates that included negative sequestration following the conversion to NT and assumed the inclusion of systems where unaccounted management adjustments occurred simultaneously during the NT adoption, resulting in an unforeseen decrease in SOC. The high estimate (81,472 t C $year^{-1}$) assumed that systems had a seamless conversion to NT and that SOC loss did not occur.

When partitioning lands according to crop intensity categories, the sequestration potential for those converting to NT while maintaining a 0.5 crop intensity was estimated to range from 21,508 to 66,062 t C $year^{-1}$ (Table 7). Again, the low value represented a scenario that assumed some C loss following the conversion to NT, due to unaccounted changes within the systems, while the high value represented ideal conversions without C loss.

The conversion of lands from a 0.5-to-1.0 crop intensity, in addition to the adoption of NT, was estimated to sequester 43,017 t C $year^{-1}$ (Table 7). An estimated 20,252 t C $year^{-1}$ might be sequestered in systems converting from a 0.75-to-1.0 intensity. For lands already under a 1.0 crop intensity, the sequestration potential resulting from a conversion to NT was estimated at 931 t C $year^{-1}$. The sum total resulting regional sequestration potential if all lands were to convert to a 1.0 intensity was roughly 54,074 t C $year^{-1}$.

Table 7 Estimated C sequestration potential for cropland converting from intensive tillage management to NT

Management type	Crop intensity adjustment	Rate (t C ha^{1} $year^{-1}$)	Land area (ha)	Δ SOC (t $year^{-1}$)	Referenced tables (studies footnoted)
Till to NT	0.5 Crop (no Δ in intensity)[a]	0.14	153,632 (139,666–171,090)	21,508 (19,553–23,953)	2[d,e,f,g]
		0.43[c]		66,062 (60,056–73,569)	2[e,f]
	Δ from 0.5 to 1.0	0.28		43,017 (39,106–47,905)	2[d,f,g,h,i]
	Δ from 0.5 to 1.0	0.2		30,727 (27,933–34,218)	7[j]
	Δ from 0.75 to 1.0	0.15	67,505 (61,368–75,176)	10,126 (9,205–11,276)	7[j]
	1.0 crop (no Δ in intensity)[a]	0.08	11,639 (10,581–12,961)	931 (846–1,037)	2[h]
	1.0 crop (no Δ in intensity)[a]	0.1		1,164 (1,058–1,296)	7[j]
	Averaged across crop intensities (literature-based)[b]	0.24	232,776 (218,504–259,228)	55,866 (52,441–62,215)	2[d–g,h–l]
		0.35[c]		81,472 (76,476–90,730)	2[d–g,h–l]

See Tables 4 and 5 for land area data

[a] Represents a change from till to NT without increasing crop intensity

[b] Indicates the exclusion of negative sequestration rates (Black and Tanaka 1997; Halvorson et al. 2002)

[c] Includes rates averaged across systems under various crop intensities (see Table 2)

[d] Black and Tanaka (1997)

[e] Bricklemyer (2003), Bricklemyer et al. (2007)

[f] Campbell et al. (2001)

[g] Halvorson et al. (2002)

[h] Sainju et al. (2007)

[i] West and Six (2007), Aase and Pikul (1995), Black (1973)

[j] McConkey et al. (1999)

3.2.3 MT to NT

The only literature-based rates provided for systems converting from MT to NT management were averaged across a 0.5 (crop-fallow) and a 1.0 (continuous) crop intensity (Table 2). These literature-based, intensity-averaged, rates ranged from 6.7–22.7 g C m^{-2} $year^{-1}$, with an average rate of 16 g C m^{-2} $year^{-1}$. The C-gain model rate for systems converting from MT to NT while maintaining a 0.5 crop intensity was estimated at 10 g C m^{-2} $year^{-1}$. The C-gain model rate for a MT-to-NT conversion with a coinciding increase from a 0.5 to 1.0 intensity was estimated to be 15 g C m^{-2} $year^{-1}$, and to be 10 g C m^{-2} $year^{-1}$for a 0.75-to-1.0 system increase. The C-gain model rate estimate for MT-to-NT systems maintaining a 1.0 intensity was estimated at 5 g C m^{-2} $year^{-1}$.

If it were assumed that all tilled lands within north central Montana were under MT instead of intensive tillage, the conversion of these lands to NT without regard to adjustments in crop intensity was estimated to sequester 37,244 t C $year^{-1}$ when derived from the across-intensity rate average (Table 8). When separating these lands into categories by crop intensity management adjustments, the sequestration potential was estimated to be 15,363 t C $year^{-1}$ for MT-to-NT systems maintaining a 0.5 crop intensity, 23,045 t C $year^{-1}$ for a systems with a 0.5-to-1.0 intensity increase, 6,751 t C $year^{-1}$ for those with a 0.75-to-1.0 increase, and 582 t C $year^{-1}$ for systems maintaining a 1.0 intensity.

The sum total sequestration potential was estimated at 30,378 t C $year^{-1}$, if all lands within the region (assumed to be under MT for this management scenario) converted to NT and a 1.0 crop intensity.

3.2.4 Across-tillage averages

Under a third scenario, where it was assumed that croplands within north central Montana equally incorporated intensive tillage and MT, the rates for intensive tillage-to-NT conversions and MT-to-NT conversions were averaged together (Table 9). The regional sequestration potential, when averaged across crop intensity, was estimated to range from 46,555–60,522 t C $year^{-1}$ (Table 9). The low value for this estimate reflects potential, unforeseen, effects from unaccounted management adjustments that might occur in some systems at the same time as the conversion to NT, resulting in an overall reduction in SOM. The high value estimate reflects an ideal, and more probable, system conversion to NT where net SOM loss does not occur. For lands that might convert to NT while maintaining a crop/fallow rotation (0.5 intensity) the sequestration potential was estimated to range from 18,436–43,017 t C $year^{-1}$. The sequestration potential for systems converting to NT while also including a 0.5-to-1.0 adjustment in crop intensity was estimated at 33,799 t C $year^{-1}$, at 8,776 t C $year^{-1}$ for a 0.75-to-1.0 intensity adjustment, and 815 t C $year^{-1}$ for systems maintaining a 1.0 intensity (continuous crop). The CCX sequestration rate (Table 9) for croplands converting to NT does not distinguish between systems having various degrees of prior tillage management and CCX C-credit is not given for years under fallow. When considering a 4-year crop intensity cycle, the resulting CCX averaged rate for that period would be 22 g C m^{-2} $year^{-1}$ for continuous cropping systems, 17 g C m^{-2} $year^{-1}$ in system under a 0.75 crop intensity (3 of 4 years cropped), and 11 g C m^{-2} $year^{-1}$ for systems with a 0.5 crop intensity

Table 8 Estimated C sequestration potential for cropland converting from MT to NT

Management type	Crop intensity adjustment	Rate (t C ha^{-1} $year^{-1}$)	Land area (ha)	Δ SOC (t $year^{-1}$)
MT to NT	0.5 crop (no Δ in intensity)[a]	0.10[b]	153,632 (139,666–171,090)	15,363 (13,967–17,109)
	Δ from 0.5 to 1.0	0.15[b]	153,632 (139,666–171,090)	23,045 (20,950–25,664)
	Δ from 0.75 to 1.0	0.10[b]	67,505 (61,368–75,176)	6,751 (6,137–7,518)
	1.0 crop (no Δ in intensity)[a]	0.05[b]	11,639 (10,581–12,961)	582 (529–648)
	Averaged across crop intensities (literature-based)	0.16[c]	232,776 (218,504–259,228)	37,244 (34,961–41,476)

See Tables 4 and 5 for land area data

[a] Represents a change from MT to NT without a coinciding increase in crop intensity

[b] McConkey et al. (1999)

[c] McConkey et al. (2003)

Table 9 C sequestration potential for cropland converting from tillage to NT, averaged across tillage management type (intensive tillage and MT)

Management type	Crop intensity adjustment	Rate (t C ha^{-1} $year^{-1}$)	Land area (ha)	Δ SOC (t $year^{-1}$)	Referenced table
Till to NT (Averaged across tillage management)	0.5 crop (no Δ in intensity)	0.12	153,632 (139,666–171,090)	18,436 (16,760–20,531)	7, 8
		0.28[a]		43,017 (39,106–47,905)	
	Δ from 0.5 to 1.0	0.22	153,632 (139,666–171,090)	33,799 (30,727–37,640)	7, 8
	Δ from 0.75 to 1.0	0.13[b]	67,505 (61,368–75,176)	8,776 (7,978–9,773)	7, 8
	1.0 crop (no Δ in intensity)	0.07	11,639 (10,581–12,961)	815 (741–907)	7, 8
	Averaged across crop intensity	0.20	232,776 (218,504–259,228)	46,555 (43,701–54,438)	7, 8
		0.26[a]		60,522 (56,811–67,399)	
	Cropped years	0.22[c]	232,776 (218,504–259,228)	51,211 (48,071–57,030)	CCX 2008b

Literature-based rate averages were given preference over the C-gain rate estimates when possible. See Table 4 and 5 for land area data

[a] Indicates the exclusion of negative sequestration rates (Black and Tanaka 1997; Halvorson et al. 2002)

[b] Only the C-gain rates were included due to lack of literature-based studies examining this conversion intensity

[c] The CCX-based rate represents the broad-scale conversion from various degrees of tillage management to NT. CCX C-credit is only allocated during cropped years

(2 of 4 years cropped). The CCX-based rates do not account for any increase in crop intensity that might have occurred in conjunction with a conversion to NT.

4 Discussion

North central Montana has been identified for its potential to sequester SOC through adjustments in cropland management, specifically the adoption of NT and reductions in summer fallowing, and the conversion of cropland to CR-based systems. Percentage estimates for cropland already incorporating these practices on a voluntary basis, without financial incentives provided by C contracts, had not been previously established due to a lack of regional cropland statistics. Attempts to quantify the potential of north central Montana to sequester additional C through the incorporation of these management practices also had not occurred prior to this study.

4.1 Land-use statistics

4.1.1 Conservation reserve

An estimated 26% of the evaluated region was under a grassland-based CR management in 2007; only 2% of this area was documented as being under current CRP contract. This percentage reflects observations noted during the 2007 land management survey where 16% of the visited fields designated as cropland, according state-based land use data, appeared to be in some form of "unmanaged" grassland. A portion of these parcels may have been voluntarily abandoned and allowed grass encroachment, especially if crop production costs had exceeded harvest revenues. Harvest rates within drier portions of this region might not exceed eight bushels of wheat per hectare, an amount that would not be financially sustainable in many systems. Repeated years of minimal harvest in addition to rising diesel, fertilizer, and herbicide costs might influence a producer to cease managing less productive areas. Also probable is that many of the non-CRP lands in 2007 included those previously under the CRP that had not been reestablished as cropland. Grass strips directly adjacent to cropped fields and those along fence lines and ditches between fields might have also been included within the documented non-CRP lands, as these fragmented areas would have been in close enough proximity to active field areas that they could have been included as part of a cropland management area for state-based accounting purposes.

The future conversion of croplands to CR within north central Montana is likely dependent on annual precipitation, production costs, agricultural markets, and C markets. Marginal lands with poor harvest yields are more likely to be converted to CR, encouraged by small financial incentives provided by the CRP or simply because production costs have outweighed profit. The removal of productive lands from cropping management is unlikely unless financial gains resulting from the CRP or C-credit programs become higher than net crop production revenues.

4.1.2 Cropland management

There is potential for an increased conversion to NT management, and to higher levels of crop intensity, within north central Montana. It was estimated that 56% of the region used NT in 2007, while 44% remained under a tillage-based management. Conservation tillage statistics had previously estimated 37% of the region to be under NT and 63% to be under tillage-based management (CTIC 2004). Differences between these statistics and those obtained through this study suggest that NT adoption has increased throughout the region and may quickly become the new "convention" in cropland management. We make this statement with caution, however, as some degree of difference between the reported percentages could have resulted from unknown inaccuracies within each estimate and because additional sources of regional tillage statistics are lacking. Unfortunately, statistics that distinguish between regional lands under more intensive tillage management from those under MT have yet to be collected.

The collection of these statistics will allow future regional C sequestration estimates to be adjusted accordingly.

Only 5% of the evaluated cropland was estimated to have incorporated a 1.0 crop intensity (continuous cropping) in 2007. Crop intensity percentages were not greater in sub-regions with higher MAP, as had been expected. If this assumption had proven true, the Great Falls area would have had the largest proportion of cropland under a 1.0 crop intensity while Chester, a notably drier area, would have had the least amount of land under continuous crop. The study results showed that these areas did not differ greatly in the amount of land under a 1.0 rotation (5% Great Falls, 7% Chester). Dutton and Big Sandy/Fort Benton had the highest percentages (77% and 70%, respectively) of cropland under a 0.5 intensity (crop-fallow), although the annual precipitation in these areas was between that of Chester and Great Falls. These findings suggest that the decision to incorporate a higher crop intensity might be more likely influenced by cultural practices than by localized annual precipitation. Financial incentives through C-credit programs might provide the necessary stimulant for an increased regional adoption of higher crop rotation intensity, but the C-credit payments would have to be substantial enough to offset any financial risk associated with continuous cropping within a dryland system.

4.2 Regional sequestration

The regional estimates presented within this study provide a foundation upon which a more precise accounting of sequestration potential might be built. The sequestration rates used to generate the regional estimates represent systems with adequate C storage capacity, though the duration of C sequestration following an alteration in cropland management, or a conversion to CR, is debatable. SOC in a system converted from tillage to NT was predicted to peak 5–10 years following the change, reaching equilibrium after 15–20 years (West and Post 2002). Another estimate predicted that equilibrium would require 40 years, 20 years at a constant rate followed by 20 years at a steadily declining rate until equilibrium is reached (Marland et al. 2003). Fifty years has been suggested as adequate for SOC recovery following conversion to grassland (Burke et al. 1995). Given these ranges, the presented sequestration estimates are thought to be most appropriate for systems in early to middle stages of C recovery.

4.2.1 Conservation reserve

The regional lands under CR in 2007 were estimated to have a sequestration potential of 18,855 t C year^{-1} (69,198 t CO_2 year^{-1}). The literature-based SOC rates used to derive the rate average for this estimate were reported by studies having similar vegetation type and grazing activity to that within the study region. The average MAP for the literature-based studies was greater (~17 cm) than what is typically found in north central Montana. Precipitation plays a key role in the ability of grasslands to sequester SOC (Uri 2001). It is therefore likely that this regional sequestration estimate is somewhat higher than in actuality, as it is based on sequestration rates representative of lands under greater MAP.

Vegetation type might be important to consider when analyzing C sequestration potential in CR lands. The two highest literature-based SOC rates occurred in crested wheatgrass and brome/wheatgrass/alfalfa systems (White et al. 1976), each characterized by aggressive non-native, cool-season, grasses that had traditionally been popular when seeding into grass and range systems. The least amount of SOC sequestration was observed in a blue grama community (Burke et al. 1995). Blue grama is a native grass that typically has dense, shallow, roots and slow establishment.

Nitrogen plays an important role in facilitating SOC increase within CR systems (Baer et al. 2000; Purakayastha et al. 2008). Legumes such as alfalfa are often included within CR systems and, not uncommonly, in rangeland because of nitrogen benefits. Further evaluation is needed to determine what species have long term advantages for C sequestration within northern grassland systems. One Canadian study cautioned that while certain species, such as crested wheatgrass and Russian wildrye, might out produce many native species in above-ground biomass, sustained below-ground C production can often be higher in established native grasses (Dormaar et al. 1995). Therefore, the abundant above-ground biomass produced by more aggressive species might result in better C gains initially, but could be later outperformed by native grass communities.

The influence of cattle on C sequestration must also be considered. Two of the literature-based studies included lands that were under some degree of minimal grazing management (White et al. 1976; Burke et al. 1995). The amount of grazing that occurs within CR lands in north central Montana is undocumented, but is thought to be minimal and site-specific. Grazing, when applied appropriately, has been shown to increase C sequestration in semi-arid grasslands through manuring and the incorporation of plant litter by animal hooves into surface soils (Reeder and Schuman 2002). While some grazing might be advantageous, overgrazing has been shown to result in a decreased C sequestration where full season grazing applied to a brome/wheatgrass/alfalfa community resulted in only 14 g C m^{-2} $year^{-1}$, compared to 19 g C m^{-2} $year^{-1}$ that occurred in the short season grazing treatment (White et al. 1976).

The sequestration rate currently used by CCX for lands having converted from cropland to perennial grass is 67 g C m^{-2} $year^{-1}$, substantially higher than any of the evaluated literature-based studies. Even the alfalfa-inclusive study with a high MAP and favorable grazing application conditions (White et al. 1976) reported 33 g C m^{-2} $year^{-1}$ less than what is allocated by the CCX rate. A Saskatchewan study with a MAP more similar to north central Montana reported a higher rate of 40 g C m^{-2} $year^{-1}$ within a managed alfalfa crop (Wu et al. 2003), but even this rate falls short of the CCX value. We note that this particular study was excluded from our analysis of sequestration rates as it would be unlikely to find pure, non-irrigated, alfalfa within a north central Montana CR system.

Based on the findings within this study, the CCX rate of 67 g C m^{-2} $year^{-1}$is likely unrepresentative of typical CR systems found within north central Montana and throughout portions of the semi-arid northern Great Plains, particularly those regions represented within the literature-based studies from which our sequestration rates were obtained. It is important to recognize that this CCX rate encompasses a regional area spanning over half the United States and incorporates many different climatic zones. While the current CCX rate might be appropriate for some regions, further refinement of C accreditation rates used within the CCX or future C credit programs might be appropriate.

4.2.2 Cropland management

The most general evaluation of C sequestration potential within the region assumed that the tillage management types (intensive tillage and MT) occurred equally throughout the region and did not give individual consideration to crop intensity. This estimate showed that 46,555–60,522 t C $year^{-1}$ (170,857–222,116 t CO_2 $year^{-1}$) might be sequestered within the 0–20 cm soil depth. The predicted regional SOC sequestration was found to be more moderate for the MT-to-NT assumptions (37,244 t C $year^{-1}$), and was expectedly higher under an intensive tillage-to-NT adjustment (55,866–81,472 t C $year^{-1}$). The validity of C credit systems using a simple binary separation for tillage management type (“tillage” or NT) becomes questionable, given these differences between intensive tillage-to-NT and MT-to-NT systems.

Crop intensity adjustments coinciding with the adoption of NT were found to have considerable effect on the regional sequestration predictions. The total regional sequestration potential if all lands converted to NT management and a 1.0 crop intensity, also assuming an across-tillage scenario, was 43,390 t C $year^{-1}$. Comparatively, sequestration estimates for all regional lands converting to a 1.0 intensity was 54,074 t C $year^{-1}$ for intensive tillage-to-NT and 30,378 t C $year^{-1}$ for MT-to-NT. These potentials resulting from the regional conversion to a 1.0 crop intensity were more minimal than in the across-intensity scenario estimates, simply because lower sequestration rates were allocated to lands already under 0.75 and 1.0 crop intensities.

Another factor, in addition to lesser sequestration potentials within 0.75 and 1.0 systems, contributed to a lower regional estimate for the intensive tillage-to-NT scenario. The literature-based rate estimate for systems converting from a 0.5-to-1.0 crop intensity was only 28 g C m^{-2} $year^{-1}$, compared to 14–43 g C m^{-2} $year^{-1}$ for systems retaining a 0.5 intensity. Reductions in summer fallowing have been highly advocated for increased C sequestration, however the 0.5-to-1.0 conversion rate was not substantially higher than the 0.5 intensity rate.

Systems incorporating fallow must produce more residues than continuous cropping systems in order to offset diminish C pools during periods where residue inputs are absent and to prevent a net decrease in SOC (Li and Feng 2002). This suggests that many of the observed 0.5 systems yielded substantially higher crop residue levels than the 1.0 systems. The differences in residue between the two system types might be attributed to water and nutrient management within dryland settings. Optimal soil water and fertility levels are critical in maintaining crop residue production, and in turn SOC increase (Follett 2001). Continuous crop production must be achieved in a manner that does not deplete soil moisture to a point where crop growth (and hence SOC input) becomes compromised. Careful consideration to particular crop rotations suited for semi-arid regions with variable precipitation patterns is essential in facilitating a continuous cropping system that can adequately sustain plant biomass production and manage drought (Jones and Popham 1997; Angus and van Herwaarden 2001; Miller et al. 2002; Krupinsky et al. 2007).

The current CCX crediting design recognizes the potential for SOC sequestration in Montana dryland systems converting from "tillage" to NT. The design does not account for different forms of tillage management, specifically intensive tillage or MT, that might have occurred prior to NT adoption, nor does it account for any coinciding adjustment in crop rotation intensity. The CCX rating system does encourage, indirectly, higher crop intensities within contracted NT fields as C credits are not allocated during years of summer fallow.

A range of variability was found between the C sequestration rates reported within this study and CCX rates, when the CCX rates were applied within a four-year rotation system. The CCX rate for systems using a 0.5 crop intensity was 8–60% (11 vs. 12–28 g C m^{-2} $year^{-1}$) lower than the across-tillage rate average. On the other hand, the CCX rate for systems with a 0.75 crop intensity was 130% higher than reported within this study (17 vs. 13 g C m^{-2} $year^{-1}$). The CCX rate was equivalent to the across-tillage rate (22 g C m^{-2} $year^{-1}$) for systems converting to continuous crop. The CCX rate does not distinguish between systems within long term 1.0 rotations (estimated to sequester only 7 g C m^{-2} $year^{-1}$) and those having recently adopted continuously cropping. Future C credit systems should carefully consider the effect that different levels of crop intensity might have on C sequestration within semi-arid croplands and recognize that continuous cropping systems might not always produce optimal C sequestration levels.

5 Conclusions and thoughts for future policy

C mitigation is a growing concern within the United States. Certain agricultural management changes, including the adoption of NT, reductions in summer fallowing, and the conversion of croplands to perennial CR grassland, have been advocated as relatively simple ways to increase SOC sequestration. The regional adoption of these practices within a small portion of Montana (717,586 ha) might sequester ~240,055–291,314 t CO_2 $year^{-1}$, and represents the potential to offset 2.5% of the projected (2010) CO_2 emissions from Montana-based coal and natural gas consumption (CCAC 2007). Substantial economic benefits might also result from this added sequestration and are estimated at \$ 1.6–2 million (USD), assuming \$ 7 per t CO_2 (Paltsev et al. 2007).

Future attempts to determine regional C sequestration potential will benefit greatly from consistent and reliable sources for land use data pertaining to tillage management and crop intensity types, and CR lands occurring outside of CRP contract. Increased accuracies within satellite-based classifications and increased processing capabilities might make annual land use mapping, at a scale suitable for cropland sequestration purposes, feasible within the near future. It might be prudent, in the mean time, for state and national agencies to evaluate the inclusion of these management categories into existing agricultural surveys and census.

Further effort within the scientific community is needed to provide regionally specific C sequestration data, and to address the impact that variations in cropland management might have on SOC sequestration. Specific focus should be given to:

1. Establishing C rates for CR systems occurring within the northern Great Plains and within cool/temperate systems having a MAP $<$ 400 mm. This should include an analysis of SOC optimization according to vegetation type, the inclusion of legumes, and animal grazing.
2. Evaluating SOC rate differences resulting from intensive tillage-to-NT and MT-to-NT conversions. Less SOC is expected to occur in systems that used MT management prior to NT adoption, as has been demonstrated in other studies, but further research is needed to evaluate these differences. Consequently, future mapping efforts should attempt to separate intensive tillage management from MT. The additional refinement of tillage land use documentation will assist future studies in developing better estimates of regional sequestration potential.
3. Better determining the role of crop rotation intensity on SOC sequestration within dryland cropping systems and land use patterns associated with crop intensity. The literature-based rates counter-intuitively suggest that SOC rates might be greater in some systems where a crop/fallow (0.5 intensity) rotation is used in conjunction with NT management, than in systems under continuous cropping (1.0 intensity). The effect of cropping sequence on residue production and, consequently, SOC sequestration in continuously cropped dryland systems also warrants further examination.
4. Further examining the long-term duration of SOC sequestration potential in dryland systems characterized by changes in tillage management, crop intensity, and the adoption of CR.

Additional action should be made by C-credit markets to address the current state of knowledge for SOC sequestration within cropland and CR lands and to ensure that C gains at contracted sites are adequately reflected by the assigned SOC rates. Broad rate estimates are often used to assign C credit. This approach can be inadequate when determining regionally-specific sequestration potential. Greater accuracy can be obtained by allocating C credits according to area-specific (Mooney et al. 2007) and management-specific C data. The ability to obtain these data in a timely manner ultimately requires the ability to accurately, quickly, and cheaply measure soil C. Emerging technologies might make the rapid, in situ, determination of soil C available in the near future (Gehl and Rice 2007; Vasques et al. 2009). In the mean time, however, C rate estimates, and regional estimates of SOC storage potential, will remain limited to the coarser approximations evident within published literature.

Acknowledgements We thank Dr. B. G. McConkey for his advice in the production of this manuscript. This research was funded by the U.S. Department of Energy and the National Energy Technology Laboratory through Award number: DE-FC26-05NT42587. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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