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Submitted by: Dr. Lee Spangler

BSCSP Principal Investigator and Director
Montana State University
P.O. Box 173905
Bozeman, MT 59717
spangler@montana.edu
http://www.bigskyco2.org
Phone: (406) 994-4399
Fax: (406) 994-3745

BSCSP Cropland Team

Rick Lawrence
Scott Powell
Jennifer Watts

Abstract

A Big Sky Carbon Sequestration Partnership (BSCSP) research team examined the utility and developed methods for monitoring cropping practices in north central Montana that are currently subject to potential carbon credit trading. The advantage of developing remote sensing methods for this purpose is to provide monitoring and validation over large areas to support carbon trading markets.

The research team used an object-oriented approach in conjunction with the Random Forest algorithm to classify agricultural practices, including tillage (till or no-till (NT)), crop intensity, and grassland-based conservation reserve (CR). This study hypothesized that the inclusion of high temporal data into the classification process would increase conservation tillage accuracy due to the added likelihood of capturing spectral changes in Montana fields following a tillage disturbance. Classification accuracies were evaluated for Random Forest models based on 250-m and 500-m MODIS, 30-m Landsat, and 30-m synthetic reflectance values.

These remote sensing methods enabled the team to establish regional percentage estimates of cropland under no-till as influenced by prior tillage management, 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 conversion 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.

Results for this study indicated that an estimated 26% of the evaluated research region was under a grassland-based CR management in 2007, yet only 2% of this area was documented as being under current CRP contract. For cropland management, findings estimated that 56% of the region used NT in 2007, while 44% remained under a tillage-based management. Correspondingly, potential regional sequestration estimates for north-central Montana were calculated at 18,855 t C year−1 (69,198 t CO2 year−1*)*. For tillage and minimal-tillage (MT) lands, estimates showed that 46,555–60,522 t C year−1 (170,857–222,116 t CO2 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*)*. Values for sequestration potential are additionally influenced by specific environmental inputs, such as vegetation type, soil nitrogen levels, crop type, livestock management, and other variables that should be considered in potential sequestration analyses.

Disclaimer

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1. Introduction

The Big Sky Carbon Sequestration Partnership (BSCSP) leads a multi-phase, multidisciplinary research program that involves terrestrial and geologic sequestration research, economic and regulatory analyses, and public education and outreach. For this task, the research team examined the utility and developed methods for monitoring cropping practices in north central Montana that are currently subject to potential carbon credit trading (see Watts et al. 2011). The advantage of developing remote sensing methods for this purpose is to provide monitoring and validation over large areas to support carbon trading markets.

The US Department of Energy has established regional partnerships, including BSCSP, to investigate possible ways to offset anthropogenically produced carbon dioxide (CO2) through geologic and terrestrial sequestration methods. With respect to the latter technique, a BSCSP-sponsored program, in conjunction with the National Carbon Offset Coalition (NCOC 2008), has promoted the development of carbon market opportunities and specifically cropland-based carbon (C) offset credits within north central Montana and adjacent states (Young 2003; Capalbo 2005). Landowners enrolled within the program are paid on a per-area basis for the implementation of practices such as no-till (NT) and grassland-based Conservation Reserve (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 ton CO2 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).

The objective of this study was to examine soil organic carbon (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. First, 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 Conservation Reserve Program (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.

1.1 *Cropland Remote Sensing Models*

Given the existing limitations to geologic-based sequestration, terrestrial sequestration of CO2 in cropland soils presents a practical and more immediate approach to carbon (C) capture and storage (Schrag 2007; Bachu 2008; Figueroa et al. 2008). Cropland soils have received considerable attention because of 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).

1.1.1 Cropland C Sequestration Potential

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 (or the practice of leaving a field unvegetated), 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.

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*

In order to determine CO_2 offset rates for cropland sequestration, 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).

2. Research Design

2.1 *Site Area*

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

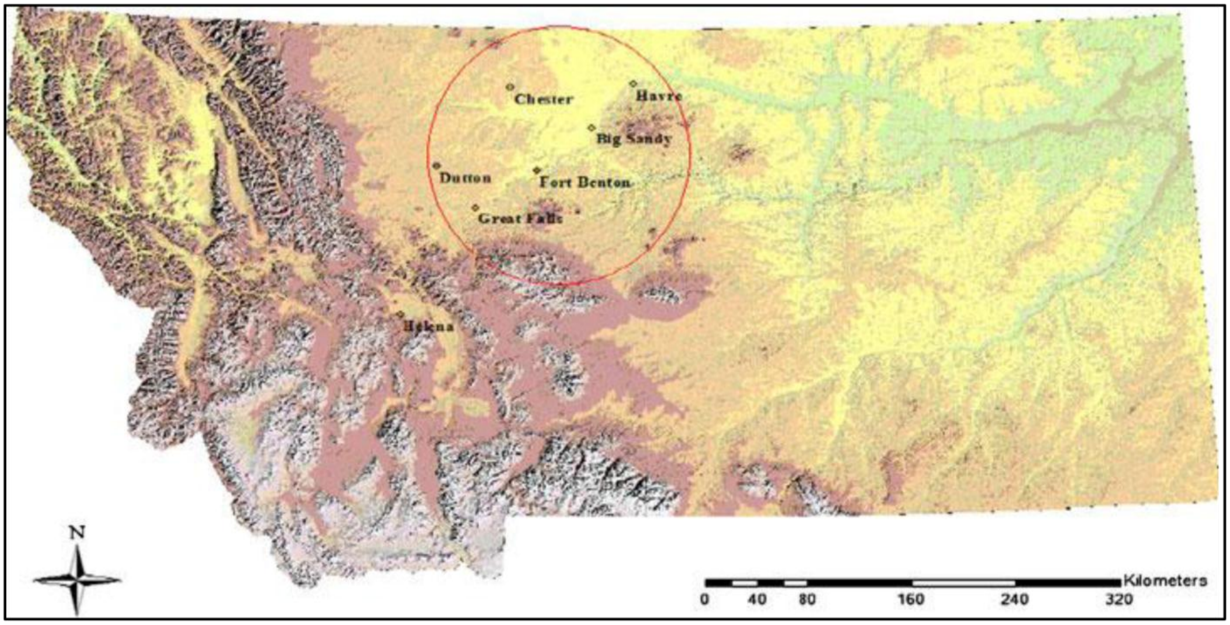

Figure 1: Geographic location of the remote sensing cropland validation study (withing red circle), Montana, USA.

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). 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).

2.2 *Methodology*

The research team used an object-oriented approach in conjunction with the Random Forest algorithm to classify agricultural practices, including tillage (till or no-till (NT)), crop intensity, and grassland-based conservation reserve (CR). The object-oriented approach allowed for per-field classifications and the incorporation of contextual elements in addition to spectral features. Random Forest is a classification tree-based advanced classifier that avoids data over-fitting associated with many tree-based models and incorporates an unbiased internal classification accuracy assessment. Landsat satellite imagery was chosen for its continuous coverage, cost effectiveness, and image accessibility.

Classification results for 2007 included producer's accuracies of 91% for NT and 31% for tillage when applying Random Forest to image-objects generated from a May Landsat image. Low classification accuracies likely were attributed to the misclassification of conservation-based tillage practices as NT. Results showed that the binary separation of tillage from NT management is likely not appropriate due to surface spectral and textural similarities between NT and conservation-type tillage practices. Crop and CR lands resulted in producer's accuracies of 100% and 90%, respectively. Crop and fallow producer's accuracies were 95% and 82% in the 2007 classification, despite post-senesced vegetation; misclassification within the fallow class was attributed to pixel-mixing problems in areas of narrow (<100 m) strip management. A between-date normalized difference vegetation index approach was successfully used to detect areas having "changed" in vegetation status between the 2007 and prior image dates; classified "changed" objects were then merged with "unchanged" objects to produce crop status maps. Field crop intensity was then determined from the multi-year analysis of generated crop status maps.

Conservation tillage management has been advocated for carbon sequestration and soil quality preservation purposes. Past satellite image analyses have had difficulty in differentiating between no-till (NT) and minimal tillage (MT) conservation classes due to similarities in surface residues, and may have been restricted by the availability of cloud-free satellite imagery. This study hypothesized that the inclusion of high temporal data into the classification process would increase conservation tillage accuracy due to the added likelihood of capturing spectral changes in Montana fields following a tillage disturbance. Classification accuracies were evaluated for Random Forest models based on 250-m and 500-m MODIS, 30-m Landsat, and 30-m synthetic reflectance values. Synthetic (30-m) data derived from the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) were evaluated because high frequency Landsat image sets are often unavailable within a cropping season due to cloud issues.

Classification results from a five-date Landsat model were substantially better than those reported by previous classification tillage studies, with 94% total and ≥88% class producer's accuracies. Landsat-derived models based on individual image scenes (May through August) yielded poor MT classifications, but a monthly increase in accuracy illustrated the importance of temporal sampling for capturing regional tillage disturbance signatures. MODIS-based model accuracies (90% total; ≥82% class) were lower than in the five-date Landsat model, but were higher than previous image-based and survey-based tillage classification results. Almost all the STARFM prediction-based models had classification accuracies higher than, or comparable to, the MODIS-based results (N90% total; ≥84% class) but the resulting model accuracies were dependent on the MODIS/Landsat base pairs used to generate the STARFM predictions. Also evident within the STARFM prediction-based models was the ability for high frequency data series to compensate for degraded synthetic spectral values when classifying fieldbased tillage. The decision to use MODIS or STARFM-based data within conservation tillage analysis is likely situation dependent. A MODIS-based approach requires little data processing and could be more efficient for large-area mapping; however a STARFM-based analysis might be more appropriate in mixed-pixel situations that could potentially compromise classification accuracy.

3. Results

There is a lack of data pertaining to the percentage of lands within the study region that have already adopted these cropping practices. Data is also sparse concerning the amount of soil organic carbon that might be sequestered given a conversion to no-till or conservation reserve. The remote sensing methods applied above enabled the research team to establish regional percentage estimates of cropland under no-till as influenced by prior tillage management, 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 conversion 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 (Table 1, Table 2, and Table 3).

Table 1: Estimated carbon sequestration potential for the conversion of cropland to grassland-based conservation reserve (CR). These lands include 'other' grasslands having similar characteristics to those within CRP (A) and lands under the CRP in 2007 (B).

Management Type	**Rate ($t\ C\ ha^{-1}\ yr^{-1}$)**	**Land Area (ha)**	**Δ SOC ($t\ yr^{-1}$)**	**Referenced Table (Studies Footnoted)**
A. Crop to CR	0.10	174,199	17,420	3 [8,9,10]
	0.67		116,713	CCX 2008c
B. Crop to CR	0.10	14,350	1,435	3 [8,9,10]
	0.67		9,614	CCX 2008c
Total Crop to CR		188,549	18,855	3 [8,9,10]
			126,327	CCX 2008c

[8] Burke et al. (1995), [9] Gebhart et al. (1994), [10] White et al. (1976); Post and Kwon 2000.

Table 2: Estimated carbon (C) sequestration potential for cropland converting from intensive tillage management to no tillage (NT)

Management Type	Crop Intensity Adjustment	Rate (t C ha^{1} yr-^{1})	Land Area (ha)	Δ SOC (t yr^{-1})	Referenced Tables (Studies Footnoted)
Till to NT	0.5 Crop (No Δ in Intensity)*	0.14	153,632 (139,666-171,090)	21,508 (19,553-23,953)	2 [1,2,3,4]
		0.43**		66,062 (60,056 -73,569)	2 [2,3]
	Δ from 0.5 to 1.0	0.28		43,017 (39,106 -47,905)	2 [1,3,4,6,7]
	Δ from 0.5 to 1.0	0.2		30,727 (27,933-34,218)	7[11]
	Δ from 0.75 to 1.0	0.15	67,505 (61,368-75,176)	10,126 (9,205-11,276)	7[11]
	1.0 Crop (No Δ in Intensity)*	0.08	11,639 (10,581-12,961)	931 (846-1,037)	2[6]
	1.0 Crop (No Δ in Intensity)*	0.1		1,164 (1,058-1,296)	7[11]
	Averaged Across Crop Intensities (Literature-based)†	0.24	232,776 (218,504-259,228)	55,866 (52,441 -62,215)	2 [1-4, 6-7]
		0.35 **		81,472 (76,476 -90,730)	2 [1-4, 6-7]

* Represents a change from till to NT without increasing crop intensity. ** Indicates the exclusion of negative sequestration rates (Black and Tanaka 1997; Halvorson et al. 2002). † Includes rates averaged across systems under various crop intensities (see Table 2). [1] Black and Tanaka (1997), [2] Bricklemyer (2007; 2003), [3] Campbell et al. (2001), [4] Halvorson et al. (2002) , [6] Sainju et al. (2007), [7] West and Six (2007); Pikul and Aase (1995); Black (1973), [11] McConkey et al. (1999).

Table 3: Estimated carbon sequestration potential for cropland converting from minimal tillages (MT) to no tillage (NT).

Management Type	Crop Intensity Adjustment	Rate (t C ha^{-1} yr^{-1})	Land Area (ha)	Δ SOC (t yr^{-1})
MT to NT	0.5 Crop (No Δ in Intensity)*	0.10 [1]	153,632 (139,666 - 171,090)	15,363 (13,967- 17,109)
	Δ from 0.5 to 1.0	0.15 [1]	153,632 (139,666 - 171,090)	23,045 (20,950 - 25,664)
	Δ from 0.75 to 1.0	0.10 [1]	67,505 (61,368 - 75,176)	6,751 (6,137 - 7,518)
	1.0 Crop (No Δ in Intensity)*	0.05 [1]	11,639 (10,581- 12,961)	582 (529 – 648)
	Averaged Across Crop Intensities (Literature-based)	0.16 [2]	232,776 (218,504- 259,228)	37,244 (34,961- 41,476)

* Represents a change from MT to NT without a coinciding increase in crop intensity. [1] McConkey et al. (1999), [2] McConkey et al. (2003).

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 statebased 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 statebased 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 andmay 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 (cropfallow), 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 belowground 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 Cm−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

5. Conclusions

5.1 *Satellite Image Data Collection*

The collection of conservation tillage statistics has been greatly limited due to the need for an accurate and time-effective tillage mapping approach. Past satellite image-based classifications have had difficulties in differentiating between no tillage (NT) and other forms of conservation tillage (i.e., minimal tillage [MT]) due to similarities in surface residues. These studies, however, had included only one or two Landsat dates into their analyses. The results from this study demonstrated that adequate conservation tillage accuracy can be achieved by incorporating high temporal MODIS or STARFM-based synthetic data sets into classification model development when multidate Landsat imagery is not available.

As the resulting classification accuracies were similar between MODIS and STARFM-based models, the decision to use one series over the other for tillage mapping is likely application dependent. MODIS data can be advantageous as they are easy to obtain and require little processing before inclusion into the classification model, although careful pixel sampling techniques are required when field dimensions are smaller than the MODIS pixels to ensure that each spectral sample is most representative for a given field. The incorporation of high frequency STARFM-based predictions into the classification process might be more appropriate in mixed-pixel situations due to spectral contributions from finer resolution Landsat data, which allow for added spectral differentiation between tillage classes. The small increases in tillage accuracy observed within the STARFM-based approach might become more critical when used for carbon-related mapping as any misclassification of MT as NT incorrectly allocates carbon credit (and subsequent monetary payments) to fields with higher CO_2 emissions.

5.2 *Classification Models*

The results of this study indicated that the incorporation of object-based parameters into a RF model has the ability to distinguish cropland from grassland-based conservation reserve (CR) using image data collected at early stages of vegetative growth (~May). Study results also showed the ability of an object-based radio frequency (RF) model to separate crop from fallow within a dryland, post-photosynthesis landscape. The research team recommends that remote sensing might be used successfully for the validation and monitoring of grassland-based CR and crop intensity within north central Montana for carbon contract purposes. Future studies should be aware of possible problems resulting from the misclassification of CR as cropland in fields under recent conversion to CR. Future studies might also avoid the use of moderate resolution imagery (~30 m) in agricultural landscapes where narrow (b100 m) crop strip management patterns are used, as misclassification was often common within these areas due to spectral mixing.

The team was unable to adequately separate NT from conservation tillage management using Landsat-based O-O analyses, in conjunction with RF classifications. Researchers foresee difficulty in discovering a contracted farmer who has agreed to follow NT practices but is in fact practicing a less extreme form of conservation tillage (reduced tillage as opposed to NT). Physical validation of tillage management within carbon contract sites will likely be necessary if the current classification scheme (NT vs. all levels of tillage) continues to be used for validation purposes, complimented by satellite-based classifications to detect heavy tillage disturbances.

The team suggests that future research continue to incorporate object-based approaches to classify cropland practices for carbon contract validation purposes as these methods allowed for the analyses to occur on a per-field basis. Future research must also continue to investigate the classification strategies that are currently used to separate tillage management types, determining if a binary "NT vs. till" approach is appropriate from a spectral and textural standpoint. This suggestion is made as study results showed great similarity in surface spectral characteristics (specifically surface residues) between NT and sites thought to be under conservation-based tillage management.

Alternatively, greater emphasis in future studies might be made on using relative surface residue amounts to indicate degrees of tillage usage and field disturbance. The incorporation of higher temporal resolution data, should it become available at the requisite spatial resolution, could be beneficial as the timing of practices in NT and conservation tillage scenarios differs.

5.3 *Estimates of Carbon Sequestration Potential*

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 soil organic carbon (SOC) sequestration. The regional adoption of these practices within a small portion of Montana (717,586) 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 carbon sequestration potential will benefit greatly from consistent and reliable sources for land use data pertaining to tillage management and crop intensity types, and conservation reserve (CR) lands occurring outside of a Conservation Reserve Program (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 carbon 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 carbon 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.

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