THE POTENTIAL FOR CARBON SEQUESTRATION ON DEGRADED LANDS WITHIN NORTH CENTRAL MONTANA[1]

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Abstract. Terrestrial carbon sequestration, using land management adjustments to increase soil carbon levels within degraded lands, has been advocated as a practical and immediate approach for carbon mitigation. Carbon sequestration and credit programs have recently been established within north central Montana; carbon storage potential within this region, however, had not been assessed previously. This study consisted of a two-part approach. A combination of satellite-image analyses and field survey was first used to obtain regional land use data. Literature-based carbon rate data were then applied to the land use data to generate a regional estimate of carbon sequestration potential given specific land use adjustments. An object-oriented approach was used in conjunction with the Random Forest algorithm to classify agricultural practices set forth in carbon contract agreements associated with the Chicago Climate Exchange and included tillage type, vegetation intensity, and conservation reserve practices. Random Forest is an advanced classification algorithm that avoids data over-fitting and incorporates an internal accuracy assessment. An object-oriented approach allowed for per-field classifications and the incorporation of contextual elements such as shape, texture, area, and neighborhood relationships in addition to spectral features. Landsat satellite imagery was chosen for its continuous coverage, cost effectiveness, and image accessibility. Results from this study found that in most cases satellite image analysis allowed for an effective way to classify land use types within the region. Results from this study estimated that approximately 77,049 t organic carbon yr^{-1} might be sequestered through the universal adoption of no-till management and the maintaining of land currently under grassland-based conservation reserve. Land use analyses via satellite monitoring and carbon sequestration efforts illustrated within this study can easily be applied to many types of situations involving degraded lands, included mined lands, and need not be restricted to an agricultural setting.

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Introduction

Terrestrial soil organic carbon (SOC) sequestration has been advocated as a practical and immediate method to mitigate anthropogenic carbon dioxide (CO_2) emissions (Post and Kwon, 2000; West and Post, 2002). The C holding capacity of global soils is immense and has been estimated at 2,500 Gt C, 3.3 times the amount of atmospheric C (Lal, 2004). Centuries of soil cultivation and resource extraction activities have resulted in extensive SOC depletion. It has been estimated that 42-78 gigatons of C have been lost within the world's agricultural and degraded lands (Lal, 2004).

Recent efforts to promote SOC sequestration have included the rehabilitation of degraded cropland where SOC depletion has occurred. Results from various studies have shown that management changes associated with the conversion from traditional, more-intensive, tillage systems to conservation tillage practices such as no-till, the reduction of summer fallowing (leaving parcels un-vegetated during the growing season) to increase vegetative intensity, and the adoption of conservation reserve (Eve et al., 2002; Lal, 2004) can increase SOC. No-till (NT) systems involve the absence of plowing or mechanical disturbance within a soil system. No-till management tends to decrease SOC decomposition rates by reducing aeration within the soil and thereby the rate of microbial activity. Conservation Reserve (CR) is the conversion of marginal cropland into diverse perennial plant cover and includes, but is not confined to, lands within the Conservation Reserve Program (CRP). The adoption of CR and other practices that increase vegetative intensity (including the reduction or elimination of summer fallowing) often improve active photosynthesis across a given area, thus increasing the amount of atmospheric C removed from the atmosphere and thereby the amount of plant residues that might be incorporated into the soil.

The increased incorporation of NT, vegetative intensity, and CR within north central Montana has been promoted by the National Carbon Offset Coalition (NCOC), in conjunction with the Big Sky Carbon Sequestration Partnership and the US Department of Energy (Young, 2003; Capalbo, 2005). Land owners enrolled within NCOC C sequestration programs are paid on a per-area basis for the implementation of these practices and must adhere to standards established by the Chicago Climate Exchange (CCX, 2008). Each credit represents the removal of 1 t CO_2 from the atmosphere (Bayon et al., 2007) and is a commodity that can be traded within market systems or sold directly to a buyer.

The auditing of lands within C sequestration programs is necessary to ensure that land owners are adherent to contract agreements. On-site validation and monitoring is often costly and time consuming, making it difficult to conduct annual contract verifications. There is also uncertainty pertaining to the percentage of cropland already under NT, vegetative intensities currently within the region, and the amount of lands under CR-type management. United States Department of Agriculture census data is limited to 5 yr intervals and has not included tillage management or crop intensity information. The Conservation Technology Information Center (CTIC) had previously coordinated roadside transect surveys on 2-yr intervals but now solely relies on sporadic voluntary data. Data does exist for CRP lands under contract with the Montana Farm Service Agency (MFSA); these statistics, however, are not readily available for external use and the CRP data do not account for cropland conversion to CR management having occurred outside of CRP contract. The monitoring of these land management types within north central Montana will be necessary for the validation of lands under C sequestration contracts and would help to determine the percentage of lands that have not yet implemented these management types.

An option for monitoring cropland management and establishing land use statistics is through 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 incorporated satellite-image analysis for the monitoring of reclaimed lands (Rathore and Wright, 1993; Schmidt and Glaesser, 1998; Bricklemyer et al., 2003). Studies have reported high classification accuracy in the detection of CR vegetation (Price et al., 1997; Egbert et al., 1998; Egbert et al., 2002), and crop and fallow parcels (Xie et al., 2007) through image classification.

Obtaining land use data is also essential in determining how much SOC might be sequestered through the increased adoption of these management practices throughout the region. An estimate of regional sequestration might be found by applying known SOC rates associated with a particular management type to the amount of land where that management type occurs. The most direct approach in determining C rates associated with a certain management type is to take repeated soil C measurements across the landscape. This method, however, is often not practical as soil sampling is too expensive to be conducted across a large area (Smith, 2004). Modeling is often used to predict SOC when sequestration trends can not be directly determined through physical sampling (Mellino et al., 1995; Coleman and Jenkinson, 1996; Parton et al., 2005), but it is often difficult to acquire adequate parameter data needed for model-based, large-area analyses. The application of available literature-based sequestration rates to area-based land use statistics has been used in lieu of modeling to obtain rough estimates of regional sequestration potential (Eve et al., 2002; Sperow et al., 2003).

This study attempted to address the lack of land-use statistics and assessments of sequestration potential associated with the increased adoption of NT, vegetative intensity, and CR within north central Montana. The overlying goal of this study was the implementation of remote sensing technologies to determine and monitor cropland management systems that promote SOC, and the regional assessment of SOC sequestration within cropland resulting from possible management changes, to help promote cropland soil rehabilitation within this region.

The first objective was to determine if satellite-based analyses could effectively map field-based NT and grassland-based CR, as well as multi-year vegetation intensity status, within north central Montana. The second objective was to determine the regional land use statistics associated with these management types. Land use data were generated through field survey and from Landsat image-based classifications to establish the percentage of cropland within north central Montana under NT and CR management in 2007. CR management for purposes of this study includes CRP lands and "other grasslands" characteristic of vegetation and management practices encouraged by the CRP program. 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 third objective was to estimate SOC sequestration potential associated with the adoption of these management practices within the region. Published SOC rates associated with the conversion to these management practices were first identified, followed by the application of the identified sequestration rates to the area-based land use data. This approach was decidedly ideal for regional C sequestration analyses within Montana given the difficulty of obtaining parameters needed for a model-based approach, and reflects the methodology used by Eve et al. (2002) and Sperow et al. (2003).

Methods

Land Use Mapping

Our focus was to map dry land cropping practices within north central Montana (Fig. 1), specifically NT, vegetative intensity, and CR. This semiarid region is known for its production of dryland wheat. Area farmers have been encouraged to implement conservation practices such as NT and CR (Fawcett and Towery, 2002) to increase SOC. The implementation of continuous cropping, or exclusion of summer fallowing (to result in increased vegetative intensity), also has been suggested.

Field management data were collected early June 2007 for locations randomly selected throughout the region. The resulting cropland data set included information for 78 NT-fallow, 138 NT-cropped, 48 tilled-fallow, 148 tilled-cropped, and 113 CR field sites. The actual number of field sites utilized within the model-building process was scene-dependent due to cloud masking and missing pixel information resulting from Landsat ETM+ image scan-line gaps.

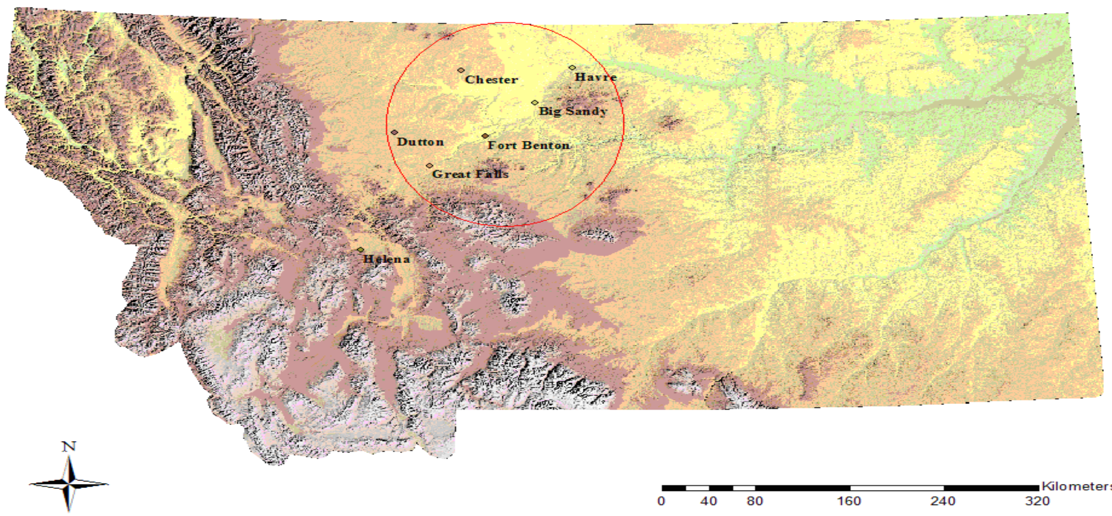

Figure 1 Geographic location of the remote sensing cropland validation study (within red circle), Montana, USA.

Four regional subsets were identified for the analysis of crop and fallow patterns. This step was necessary to minimize computational problems associated with data size. These 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). Chester was chosen as it represented a drier climate within the 2004-2007 period (~250 mm) while Great Falls represented a relatively wetter climate (~390 mm) (HPRCC 2008). Annual precipitation in the Dutton and Big Sandy/Fort Benton areas was moderate (~290-320 mm).

Landsat image pairs (path 39; rows 26, 27) were obtained for 15 May (Landsat 5 TM) and 11 August (Landsat 7 ETM+) 2007. Geometric correction techniques were used to ensure that the images were properly aligned within geographic space, followed by cloud and shadow masking to remove contaminated pixels. Image data were then converted to top-of-atmosphere reflectance values to minimize between-image differences due to earth-sun distance and solar angle (SDH-L7, 2006; Chander et al., 2007). Normalized Difference Vegetation Indices (NDVI), representative of relative photosynthetically active vegetation densities (Tucker and Sellers, 1986), and the Tasseled Cap components associated with soil brightness, vegetation greenness, and surface wetness (Crist et al., 1986; Huang et al., 2002) were also included as predictors. It was thought that the addition of these indices might better allow for node splitting within the model. A non-cropland mask was applied to remove water bodies, urban and public lands, transportation networks, and rangeland.

Vector-based image objects representing parcel management strips and within-strip sections of spectral and textural similarity were generated through the multi-resolution O-O segmentation algorithm (Benz et al., 2004). These image objects, representing field landscape patterns, were generated by grouping image pixels according to similarities within the image scene. The within-strip segmentation was used to reduce the inclusion of both crop and bare soil within an image-object. A strip-based segmentation was determined to be suitable for tillage and CR classifications, as it was unlikely that these management types would vary within field-based boundaries. Vector information representing taxable field parcels was also included within the segmentation process, to ensure that generated objects were constrained within ownership boundaries (Fig. 2).

Resulting object-based attribute data were imported into the randomForest package (S-PLUS®) to generate classification models for NT and till, CR and cropland, cropped and fallow. These included spectral, textural, and neighborhood (based on the spatial relationship of objects with one another) object-based parameters. Initial forest models were built using 500 generated classification trees, the default number. Model tree adjustments were based on an analysis of model error as influenced by the number of RF trees. Model classification matrices and associated class accuracies were determined via an internal accuracy assessment (Breiman, 2001). Data from either image dates, or predictor parameter sets utilizing data from both image dates, were examined in the generation of class models. A May TM pixel-based tillage model also was examined, in addition to the object-based models, to ascertain the effect that object-based textural and neighborhood parameters might have in improving tillage accuracy. Class predictions were exported and joined with the existing vector objects according to field identification numbers, within a GIS platform (Fig. 3). This allowed for an efficient way to examine spatial relationships between cropland management class predictions, spectral image data, and various other data sets.

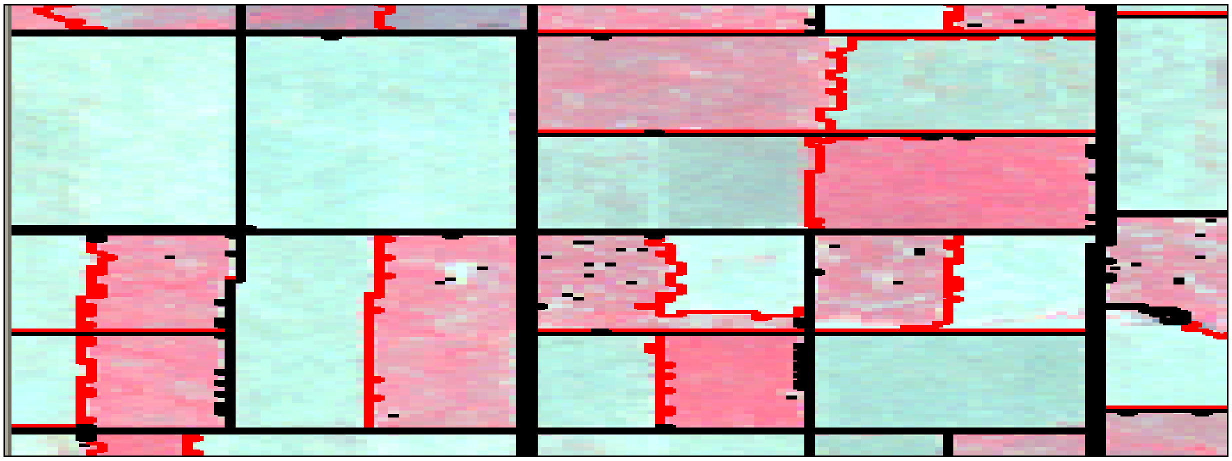

Figure 2. Object segmentation results for the field strip level (red vector lines). Black parameter lines represent taxable field boundaries.

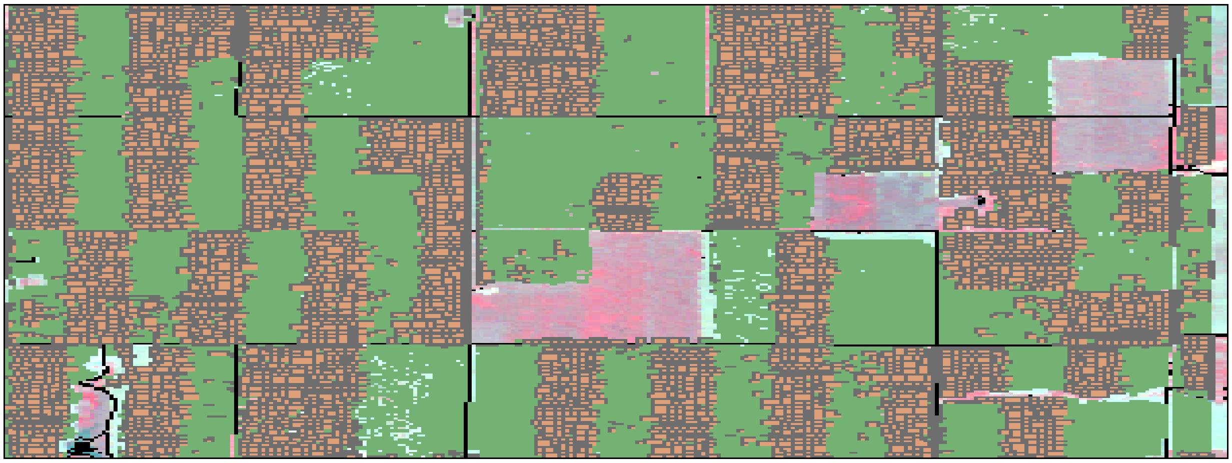

Figure 3. The vector-based cropped and fallow classification layer, overlaying a Sept. 2007 Landsat ETM+ image. Areas of green represent cropped land; brown represents summer fallow.

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 NT and tillage classifications. Confidence intervals (95%) were applied to each percentage estimate according to standard procedures for the statistical analysis of sample proportions (Moore, 2004). Data were assumed to be unbiased as they were collected based on random selection. The elimination of sites not accessible from roads was not believed 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 having been classified as CR (occurring outside of CRP contract) to obtain land-area estimates for tillage and NT.

C Sequestration Estimates

Published research was reviewed to determine 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. Only C sequestration data based directly on physical measurements, as opposed to model estimated data, were included in the review. C sequestration data used within this study included only those reflecting climatic regimes similar to that of 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. 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 if they provided information directly relevant to the study area.

The final selection included nine studies having identified C sequestration rates associated with the conversion from tillage to NT (Table 1) and three studies that established SOC sequestration rates resulting from the conversion from cropland to grassland-based CR (Table 2). Prior cropland management within the tillage studies included some degree of summer fallowing. Tillage implements used for cultivation purposes in “tilled” treatments within these studies reportedly included tandem disk, sweeps and rod weeder, chisel plough and mounted harrow.

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, as this range was common within all the studies evaluated. The conversion from weight-based to area-based estimates (e.g., multiplying g C by soil density) was conducted when necessary. Studies sometime presented sequestration rate estimates across fertilizer rate treatments; in these cases rate estimates reflecting the optimal sequestration amounts per management type were used within the analyses. C sequestration rates were then averaged according to management and rotation type. A formal meta-analysis (Arnqvist and Wooster, 1995) was not attempted due to an overall lack of test statistics within individual studies. Rates reflecting C increase in fields switching from intensive tillage to NT while maintaining a continuous crop, and for fields having converted from minimal tillage (MT) to NT under various degrees of crop intensity, were not identified within the available literature.

Rates from a generalized C-Gain equation were also incorporated into the analysis (McConkey et al., 1999); the equation was based on both soil data and expert knowledge. The use of these rates allowed for the comparison between these and the literature-based estimates. The C-Gain rates also provided an estimate for C sequestration in fields having changed from MT to NT. C-Gain estimates were calculated for tillage to NT systems with vegetative intensity changes of 0.5 (5 of 10 yr cropped as opposed to fallow) to 1.0 (continuous crop), 0.75 to 1.0, and for tillage to NT without a change in crop intensity. Estimates also were made for MT to NT under a 0.5 to 1.0 and a 0.75 to 1.0 rotation, and without a change in intensity. Calculated sequestration rates did not reflect system changes in fertilization rates or landscape type.

Regional C estimates associated with the conversion of cropland to NT or tillage management as influenced by vegetative intensity, or the conversion of cropland to CR-based management, were obtained by multiplying sequestration rates (derived from both the literature and the generalized C-Gain calculations) by the total estimated hectares under each management type. Land-use area for NT and tillage used to estimate regional C were those derived from the 2007 field survey. The resulting regional C sequestration estimate was based on an across-rate average that incorporated SOC values reflecting the conversion from a “traditional” intensive tillage to NT and the conversion from MT to NT. Literature-based rate estimates having excluded negative sequestration amounts were used within the averaged across-tillage estimates.

Table 1. C sequestration rates for NT. Rates reflect the conversion from tillage-based cropland to NT, and tillage-based cropland to NT as influenced by crop intensity (key follows Table 3).

Study	Location	Mean Annual Precip. (cm)	Mean Annual Temp. (°C)	Climate	Soil Texture	Management Comparison	Years Since Mgmt. Change	Sampling Depth (cm)	Total SOC Seq. (g/m^2)	~ Rate ($g/m^2/yr$)
NT										
1. Black and Tanaka (1997)	South Central North Dakota	40	5	CT	SiL	Till to NT-SW/F*	7	0-15.2	-304[a]	-43.4
						Till to NT-SW/WW/SF**			91[a]	13.0
2. Bricklemyer (2003)	North Central Montana	26	5	CS	SL	Till vs. NT-W/F	7	0-10	186	Avg. 26.5 (15.7-47.1)
		36	7.5		CL, C	Till vs. NT-W/F	6		371	Avg. 61.8 (36.6-96.6)
3. 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
4. Halvorson et al. (2002)	South Central North Dakota	41	12	CT	SiL	Till to NT-SW/WW/SF	12	0-15.2	140	11.6
					SiL	Till to NT-SW/F			-190	-15.8
5. 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
6. 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
7. 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

[a] Treatment-based bulk densities were used in calculating SOC levels due to lack of baseline bulk densities. * SOC rate for 0 kg/N treatment. ** SOC rate for 34 kg/N treatment. *** SOC rate for 40 kg/N treatment.

Table 2. C sequestration rates for CR. Rates reflect the conversion from cropland to grassland-based CR.

Study	Location	Mean Annual Precip. (cm)	Mean Annual Temp. (ºC)	Climate	Soil Texture	Comparison Type	Years Since Mgmt. Change	Sampling Depth (cm)	Total SOC Seq. (g/m^2)	~ Rate ($g/m^2/yr$)
CRP										
8. Burke et al. (1995)	North East Colorado	36	16	CT	SiL, SiCL	Till to CR	53	0-10	82-200	3.1
9. Gebhart et al. (1994)	Kansas	53	12	CT	SiL	Till to CR	5	0-15*	47	9.3
10. Post and Kwon (2000), White et al. (1976)	North Central South Dakota	~58	~15	CT	No Data	Till to CR	8	0-7	148	18.5

Key for Tables 2 & 3

Tillage Management Type	Climate Type	Soil Texture	Crop Type	
NT = No-till	CS = Cool, semi-arid	SiL = Silt Loam	B = Barley	SW = Spring Wheat
MT = Minimum till	CSH = Cool, sub-humid	SL = Sandy Loam	CR = Grassland Conservation Reserve	WW = Winter Wheat
FST = Fall and spring conventional tillage	CT = Cool, temperate	L = Loam	GM = Legume Green Manure	W = Wheat (type undefined)
ST = Spring tillage		CL = Clay Loam	SF = Sunflower	
		C = Clay		

* Rates were adjusted to reflect depth measurements common across the studies evaluated.

Results

Land Management Mapping

Results from this study demonstrated that the RF classification algorithm applied to field-based image objects can provide high class accuracies in the discrimination of cropland from CR and crop from fallow (Table 3). An RF O-O classification based on May TM data was able to successfully separate CR from cropland with producer's accuracies of 90% and 100%, respectively. Previous pixel-based studies had relied on more elaborate multi-year change techniques to achieve similar accuracies (Egbert et al., 1998; Price et al., 1997). Classification error primarily resulted from the misclassification of CR as NT-cropped and tilled-crop. The misclassified sites were often those under recent conversion from cropland to CR, as was determined by an examination of data supplied through the Montana Farm Service Agency.

The ability to distinguish senesced crop from fallow with greater than 82% accuracy is considered to be highly acceptable, especially given the ability of the O-O-based RF model to separate stubble-laden fallow fields from those recently harvested. The RF variable importance plot indicated that object textural measures such as within-object contrast and homogeneity were often used as model predictive parameters, suggesting that object-derived information allowed for greater predictive ability under certain conditions. Misclassification errors within the fallow category were attributed to objects located within landscapes characterized by narrow (< 100 m wide) crop and fallow strip management, due to within-pixel mixing of crop and fallow spectral signatures. The object-based classification tended to favor the "cropped" class, resulting in a classification bias under these conditions. The manual re-classification of these areas corrected for this problem.

The satellite-based image analysis (Table 4) identified 24% of the study area as being under grassland-based CR management as opposed to cropland. Data from the MFSA had indicated that only 2% of the study area was under CRP contract. Classification results also predicted that 18% of the evaluated cropland was under some form of tillage-based management in 2007 while 82% was under NT (Table 5). The resulting NT classifications were likely in error due to a high percentage of tillage misclassified as NT. The 2007 cropland field survey results estimated that 56% of the evaluated region had practiced NT management in 2007, while 44% had incorporated some other form of tillage management during 2007. Systems under a 0.5 crop intensity (from 2004-2007) included 66% of the cropland area analyzed (Table 5), 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.

Table 3. Classification accuracy for tillage, CR, and crop status.

Model	Overall Accuracy	Classification Matrix			Producer's	User's
NT & Tillage			**NT**	**Till**	**NT**	**Till**
May 2007	71%	**NT**	160	14	91%	71%
		Till	63	29	31%	67%
Crop & CR			**Crop**	**CR**	**Crop**	**CR**
May 2007	97%	**Crop**	304	0	100%	96%
		CR	12	115	90%	100%
Crop & Fallow			**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%

Table 4. 2007 cropland tillage and grassland-based CR statistics. CR data were derived solely from satellite-based image analyses. Total land area within the CR analyses is the sum of total evaluated cropland and CRP hectare information provided by the MFSA.

Image Classifications			Roadside Survey			
Management Type	**Hectares**	**%**	**Hectares**	**95% CI**	**%**	**95% CI**
Grassland-based CR vs. Cropland						
CR	188,549	24	-	-	-	-
Cropland	590,898*	76	-	-	-	-
Total Land Area	779,447	100	-	-	-	-

* Hectare-based totals for cropland within the CR classification are greater than total hectares within the tillage-based classification resulting from the misclassification of some CR as cropland.

Table 5. 2007 cropland tillage and crop intensity statistics.

Image Classifications			Roadside Survey			
Management Type	**Hectares**	**%**	**Hectares**	**95% CI**	**%**	**95% CI**
NT vs. Tillage						
NT	434,970	82	296,261	269,809-322,713	56	51-61
Tillage	94,067	18	232,776	118,504-259,228	44	40-49
Total Land Area	529,037	100	529,037	-	100	-
Crop Intensity						
0.5	33,249	66	-	-	-	-
0.75	14,820	29	-	-	-	-
1	2,344	5	-	-	-	-
Total Land Area	50,413	100	-	-	-	-

C Sequestration Estimates

The difference between CRP data provided by the MFSA and the image-based CR classifications provided an estimate that 174,199 ha cropland was under perennial grass/legume vegetation, outside of 2007 CRP contract agreements. The conversion of this land to perennial grass/legume vegetation was estimated to have provided an additional 17,420 t C yr^{-1} (Table 6).

Table 6. Estimated C sequestration potential for the conversion of cropland to grassland-based CR. These lands include "other" grasslands having characteristics similar to those within CRP (A), and these lands plus those under CRP in 2007 (B).

Management Type	Rate (t C ha^{-1} yr^{-1})	Land Area (ha)	Δ SOC (t yr^{-1})	Studies Referenced for Sequestration Rate
A. Crop to CR	0.1	174,199	17,420	8, 9, 10
B. Crop to CR		188,549	18,855	8, 9, 10

[8] Burke et al. (1995), [9] Gebhart et al. (1994), [10] White et al. (1976).

Table 7. C sequestration potential for cropland converting from tillage to NT, averaged across tillage management type. These rates reflect scenarios where optimal cropping management is used and NT management does not result in soil C loss.

Management Type	**Crop Intensity Adjustment**	**Rate ($t\ C\ ha^{-1}\ yr^{-1}$)**	**Land Area (ha)**	**Δ SOC ($t\ yr^{-1}$)**	**Studies Referenced for Sequestration Rate**
Till to NT (Averaged Across Tillage Management Type)	No Δ in Intensity*	0.27	11,639 (10,581 - 12,961)	3,143 (2,857 - 3,500)	2, 3, 6
	Δ from 0.75 to 1.0	0.20	67,505 (61,368 - 75,176)	13,501 (12,274 - 15,035)	11
	Δ from 0.5 to 1.0	0.28	153,632 (139,666 - 171,090)	43,017 (39,107 - 47,905)	1, 3, 4, 7, 11
	Averaged Across Crop Intensity	0.25	232,776 (118,504-259,228)	58,194 (29,626-64,807)	1-7

* Indicates the change from till to NT while maintaining current crop intensity. [1] Black and Tanaka (1997), [2] Bricklemyer (2003), [3] Campbell et al. (2001), [4] Halvorson et al. (2002), [5] McConkey et al. (2003), [6] Sainju et al. (2007), [7] West and Six (2007), [7] Pikul and Aase (1995), [7] Black (1973), [11] McConkey et al. (1999).

Based on land-use and sequestration rate estimates, the universal change of lands to NT and a 1.0 crop intensity within the study area would sequester approximately 56,518 $t\ C\ yr^{-1}$ (Table 7) averaged across tillage management (including semi-intensive tillage and MT). An additional 3,143 $t\ C\ yr^{-1}$ might also occur when also considering lands converting to NT while maintaining a 0.5 crop intensity. Considering the conversion of all lands from a tillage-type management to NT, averaged across crop intensity, the resulting sequestration amount is estimated to be 58,194 $t\ C\ yr^{-1}$.

Discussion

The resulting land-use data, representing analyzed portions of north central Montana, shows potential for an increased conversion to NT tillage management and higher degrees of crop intensity. This study estimates that in 2007, 56% of cropland was under NT while 44% was still under a tillage-based management. Only 5% of the evaluated cropland had incorporated a 1.0 crop intensity. Crop intensity percentage estimates were not greater in sub-regions with higher

MAP and did not differ significantly between regional sub-units. These findings show that the decision to incorporate a higher cropping intensity might be more influenced by cultural practices than by localized annual precipitation.

An estimated 24% of the evaluated region was under a grassland-based CR management in 2007, 22% greater than the area shown to be under CRP contract with the MFSA. This percentage reflects observations noted during field data collection, where 16% of lands designated as cropland appeared to be in some form of "unmanaged" grassland state. It is likely that many of these parcels had previously been under CRP contract but were not re-incorporated into cropland following contract termination for reasons unknown, or had recently been implemented into the program but were not yet reflected within the CRP database. A portion of these parcels might have voluntarily adopted CR management outside of the CRP program, possibly because openings into the CRP program were not available at that time.

It is estimated that the evaluated portion of north central Montana might sequester around 58,194 t C yr^{-1} (213,572 t CO_2 yr^{-1}) within the 0-20 cm depth through the universal adoption of NT practices, across crop intensities. This estimate represents the yearly total increase in SOC within regional cropland in the absence of tillage. The conversion of all cropland to NT management and the maintaining of land currently under CR management within this relatively small percentage (11%) of Montana cropland has the ability to sequester 77,049 t C yr^{-1} (282,770 t CO_2 yr^{-1}). This value represents an estimate of total yearly SOC additions in lands under CR and for all regional cropland if NT were universally practiced.

The C sequestration estimates associated with the conversion to NT, increased crop intensity, and CR are not static, and are expected to decrease in the years following management change. There is much uncertainty concerning the duration of C sequestration following alterations in cropland management. A system having converted from tillage to NT was predicted to peak 5-10 yr following the change, reaching equilibrium after 15-20 yr (West and Post, 2002). Site-specific C sequestration rates are expected to be both a product of climate and biophysical conditions.

Differences in C sequestration amounts might also result from variations in seeding rate, time of seeding, the type of planting equipment used, and other aspects of cropland management. 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. Nitrogen is often a limiting factor in SOC increase within CR systems (Purakayastha et al., 2008). Adequate nitrogen management, or the planting of nitrogen-producing legumes, might help increase SOC production within CR systems (Wu et al., 2003).

Conclusion

This study identified moderate-resolution satellite image analysis as an effective way to quickly and inexpensively determine grassland-based CR, and vegetative intensity through the multi-year analysis of field-based crop and fallow patterns. Problems associated with the misclassification of tillage practices as NT management raise the question as to if surface residues for NT and conservation-based tillage practices incorporation minimal mechanical disturbance are too spectrally and texturally similar to be recognized as a separate class for land use mapping, even with the incorporation of an advanced classification algorithm and object-based segmentation process.

The potential for SOC sequestration through the increased adoption of NT, higher levels of vegetative intensity, and CR within north central Montana had not been assessed previously. Resulting land use data showed the regional potential for an increased adoption of NT and increased vegetative intensity. Sequestration estimates showed that roughly 282,770 t CO_2 yr^{-1} might be sequestered within this region given the universal adoption of NT and the maintaining of current CR lands. The allocation of C sequestration credits will likely serve as an incentive for land owners to adopt these practices for SOC sequestration purposes.

Increased emphasis on terrestrial SOC sequestration within the US is likely as the political landscape further recognizes the need for climate change mitigation. This study specifically addresses C monitoring and sequestration estimates for C credit purposes pertaining to agricultural-based soil rehabilitation. The techniques and principles illustrated within this study, however, can be applied to any landscape where a management change might result in soil rehabilitation through increased C sequestration. Land rehabilitation specialists should give increased consideration to SOC sequestration when addressing degraded lands. It is already known that OC is often essential in restoring soil ecosystems, but further thought might also be given to how a landscape might best be optimized for continued SOC sequestration. Emphasis should be given to plant types with increased photosynthetic capabilities and long-term C storage potential (e.g. woody vegetation or perennial grasses with deep root systems), and to post-rehabilitation land management that increase SOC storage (nitrogen and water availability, appropriate management of livestock to prevent overgrazing, etc.). Pre and post rehabilitation SOC estimates are also suggested to provide documentation for any increase in SOC sequestration that might have occurred within a landscape. The implementation of a post-rehabilitation monitoring program, possibly including spectral image-analysis to detect changes in vegetation density, is also suggested to help document long-term C sequestration within a landscape.

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Literature Cited

Aase, J. K. and J. L. Pikul. 1995. Crop and soil response to long-term practices in the northern Great Plains. Agronomy Journal, 87: 652-656. http://dx.doi.org/10.2134/agronj1995.00021962008700040008x.

Arnqvist, G. and D. Wooster. 1995. Meta-analysis: synthesizing research findings in ecology and evolution. Trends in Ecology and Evolution, 10: 236-240. http://dx.doi.org/10.1016/S0169-5347(00)89073-4.

Bayon, R., A. Hawn and K. Hamilton. 2007. Voluntary carbon markets: an international business guide to what they are and how they work. Earthscan Press, London, 164 pp.

Benz, U. C., P. Hofmann, G. Willhauck, I. Lingenfelder and M. Heynen. 2004. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. ISPRS Journal of Photogrammetry and Remote Sensing, 58: 239-258. http://dx.doi.org/10.1016/j.isprsjprs.2003.10.002

Black, A. L. 1973. Soil property changes associated with crop residue management in a wheat-fallow rotation. Proceedings of SSSA, 37: 943-946. http://dx.doi.org/10.2136/sssaj1973.03615995003700060039x.

Black, A. L. 1973. Soil property changes associated with crop residue management in a wheat-fallow rotation. Proceedings of SSSA, 37: 943-946.

Breiman, L. 2001. RFs. Machine Learning, 45: 5-32. http://dx.doi.org/10.1023/A:1010933404324.

Bricklemyer, R. S. 2003. Sensitivity of the Century model for estimating sequestered soil carbon using coarse and fine-scale map data sources in north central Montana. MS Thesis, Montana State University, Bozeman, 136 pp.

Burke, I. C., W. K. Lauenroth and D. P. Coffin. 1995. Soil organic matter recovery in semiarid grasslands: implications for the conservation reserve program. Ecological Applications, 3: 793-801. http://dx.doi.org/10.2307/1941987.

Campbell, C. A., F. Selles, G. P. Lafond and R. P. Zentner. 2001. Adopting zero tillage management: impact on soil C and N under long-term crop rotations in a thin Black Chernozem. Canadian Journal Soil Science, 81: 139-148. http://dx.doi.org/10.4141/S00-035.

Capalbo, S. M. 2005. Big Sky Carbon Sequestration Partnership phase II: proposal

summary and overview. Big Sky Carbon Sequestration Partnership, 7 pp.

CCX. 2008. CCX agricultural soil carbon sequestration offset project guidelines. Chicago Climate Exchange White Pages, 26 pp.

Chander, G., B. L. Markham and J.A. Barsi. 2007. Revised Landsat 5 Thematic Mapper radiometric calibration. IEEE Geoscience and Remote Sensing Letters, 4: 490-494. http://dx.doi.org/10.1109/LGRS.2007.898285.

Cohen, W. B. and S. N. Goward. 2004. Landsat's role in ecological applications of remote sensing. BioScience, 54: 535-545. http://dx.doi.org/10.1641/0006-3568(2004)054[0535:LRIEAO]2.0.CO;2.

Coleman, K. and D. S. Jenkinson. 1996. RothC-26.2-A model for the turnover of carbon in soil. *In*: Powlson D S, Smith, Smith J U (eds) Evaluation of soil organic matter models using existing, long-term datasets. NATO ASI Series I, vol 38. Springer, Berlin, pp 237-246.

Crist, E. P., R. Laurin and R. C. Cicone. 1986. Vegetation and soils information contained in transformed Thematic Mapper data. In Proceedings of IGARSS ’86 Symposium, Zurich, Switzerland, 8-11 September 1986, pp.1465-1470.

Egbert S. L., S. Park and K. P. Price et al. 2002. Using conservation reserve program maps derived from satellite imagery to characterize landscape structure. Computers, Electronics in Agriculture, 37: 41-156. http://dx.doi.org/10.1016/S0168-1699(02)00114-X.

Egbert S. L., R. Y. Lee, K. P. Price and R. Boyce. 1998. Mapping conservation reserve program (CRP) grasslands using multi-seasonal Thematic Mapper imagery. Geocarto International, 13: 1010-6049. http://dx.doi.org/10.1080/10106049809354660

Eve, M. D., M. Sperow, K. Paustian and R. F. Follett. 2002. National-scale estimation of changes in soil carbon stocks on agricultural lands. Environmental Pollution, 116: 431-438. http://dx.doi.org/10.1016/S0269-7491(01)00220-2.

Fawcett, R. and D. Towery. 2002. Conservation tillage and plant biotechnology: how new technologies can improve the environment by reducing the need to plow. Conservation Technology Information Center. 24 pp.

Follett, R. F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil and Tillage Research, 61: 77-92. http://dx.doi.org/10.1016/S0167-1987(01)00180

Gebhart, D. L., H. B. Johnson, H. S. Mayeux and H. W. Polley. 1994. The CRP increases soil organic carbon. Journal of Soil and Water Conservation, 49: 488-492.

Halvorson, A. D., B. J. Wienhold and A. L. Black. 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Science Society of America Journal, 66: 906-912. http://dx.doi.org/10.2136/sssaj2002.9060.

HPRCC .2008. Climate summary maps and archived station data. High Plains Regional Climate Center. http://www.hprcc.unl.edu/ . Accessed 22 April 2008

Huang, C., B. Wylie, L. Yang, C. Homer and G. Zylstra. 2002. Derivation of a tasseled cap transformation based on Landsat 7 at-satellite reflectance. International Journal of Remote Sensing, 23: 1741-1748. http://dx.doi.org/10.1080/01431160110106113

Kerr, J. T. and M. Ostrovsky. 2003. From space to species: ecological applications for remote sensing. Trends in Ecology and Evolution, 18: 299-305. http://dx.doi.org/10.1016/S0169-5347(03)00071-5.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science, 304: 1623-1627. http://dx.doi.org/10.1126/science.1097396.

Lefsky, M. A., W. B. Cohen, G. G. Parker and D. J. Harding. 2002. Lidar remote sensing for ecosystem studies. BioScience, 52: 19-30. http://dx.doi.org/10.1641/0006-3568(2002)052[0019:LRSFES]2.0.CO;2.

McConkey, B. G., B. C. Liang and C. A. Campbell et al. 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil and Tillage Research, 74: 81-90. http://dx.doi.org/10.1016/S0167-1987(03)00121-1.

McConkey, B. G., B. C. Liang and C. A. Campbell. 1999. Estimating gains of soil carbon over 15-yr period due to changes in fallow frequency, tillage system, and fertilization practices for the Canadian Prairies (an expert opinion). Agriculture and Agri-Food Canada, Publication #379M0209, 14 pp.

Melillo, J. M., J. Borchers and J. Chaney et al. 1995. Vegetation/ecosystem modeling and analysis project comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem response to climate change and CO2 doubling. Global Biogeochemical Cycles, 9: 407-437. http://dx.doi.org/10.1029/95GB02746.

Moore, D. S. 2004. The basic practice of statistics. Freeman, New York, 674 pp.

Parton, W. J., D. S. Ojima and D. S. Schimel. 2005. CENTURY: Modeling Ecosystem Responses to Climate Change, Version 4 (VEMAP 1995). Natural Resources Ecology Laboratory, Colorado State University, U.S.A. Accessed 12 May 2008.http://www.cgd.ucar.edu/vemap/abstracts/CENTURY.html .

Post, W. M. and K. C. Kwon. 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology, 6: 317-327. http://dx.doi.org/10.1046/j.1365-2486.2000.00308.x.

Price, K. P., S. L. Egbert, M. D. Nellis, R. Y. Lee and R. Boyce. 1997. Mapping land cover in a High Plains agro-ecosystem using a multi-date Landsat Thematic Mapper modeling approach. Transactions of the Kansas Academy of Science, 100: 21-33. http://dx.doi.org/10.2307/3628436.

Purakayastha, T. J., D. R. Huggins and J. L. Smith. 2008. Carbon sequestration in native prairie, perennial grass, no-till, and cultivated palouse silt loam. Soil Science Society of America Journal, 72: 534-540. http://dx.doi.org/10.2136/sssaj2005.0369.

Rathore, C. S. and R. Wright. 1993. Monitoring environmental impacts of surface coal mining. International Journal of Remote Sensing, 14: 1021-1042. http://dx.doi.org/10.1080/01431169308904394.

Sainju, U. M., T. Caesar-TonThat and A. W. Lenssen et al. 2007. Long-term tillage and cropping sequence effects on dryland residue and soil carbon fractions. Soil Science Society of America Journal, 71: 1730-1739. There is an unknown error in this citation.

Schmidt, H. and C. Glaesser. 1998. Multitemporal analysis of satellite data and their use in the monitoring of the environmental impacts of open cast lignite mining in Eastern Germany. International Journal of Remote Sensing, 19: 2245-2260. http://dx.doi.org/10.1080/014311698214695.

Science Data Users Handbook-Landsat 7 (SDH-L7). 2006. National Aeronautics and Space Administration. Accessed 10 March 2008.

http://landsathandbook.gsfc.nasa.gov/handbook/handbook_toc.html .

Smith, P. 2004. How long before a change in soil organic carbon can be detected? Global Change Biology, 10: 1878-1883. http://dx.doi.org/10.1111/j.1365-2486.2004.00854.x.

Sperow, M., M. Eve and K. Paustian. 2003. Potential soil C sequestration on U.S. agricultural soils. Climatic Change, 57: 319-339. http://dx.doi.org/10.1023/A:1022888832630.

Tucker, C. J. and P. J. Sellers. 1986. Satellite remote sensing of primary production. International Journal of Remote Sensing, 7: 1395-1416. http://dx.doi.org/10.1080/01431168608948944.

West, T. O. and W. M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal, 66: 1930-1946. http://dx.doi.org/10.2136/sssaj2002.19301946.

West, T. O. and J. Six. 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Climatic Change, 80: 25-41. http://dx.doi.org/10.1007/s10584-006-9173-81.

White, E. M., C. R. Krueger and R. A. Moore. 1976. Changes in total N, organic matter, available P, and bulk densities of a cultivated soil 8 years after tame pastures were established. Agronomy Journal, 68: 581-583. http://dx.doi.org/10.2134/agronj1976.00021962006800040012x.

Wu. T., J. J. Schoenau and F. Li et al. 2003. Effect of tillage and rotation on organic carbon forms of chernozemic soils in Saskatchewan. Journal of Plant Nutrition and Soil Science, 166: 328-335. http://dx.doi.org/10.1002/jpln.200390051.

Xie, H., Y. Q. Tian, J. A. Granillo and G. R. Keller. 2007. Suitable remote sensing method and data for mapping and measuring active crop fields. International Journal of Remote Sensing, 28: 395-411. http://dx.doi.org/10.1080/01431160600702673.

Young, L. M. 2003. Carbon sequestration in agriculture: The U.S. policy context. American Journal of Agronomy and Economics, 85: 1164-1170. http://dx.doi.org/10.1111/j.0092-5853.2003.00524.x.