Big Sky Carbon Sequestration Partnership – Phase III
Kevin Dome Carbon Storage Project
Subtask 1.3.2 - Cropland Controlled Site Experiments

Final Report

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Submitted by: **Richard Engel**
Associate Professor of Soil Science
Montana State University

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ABSTRACT

The Big Sky Carbon Sequestration project sponsored terrestrial carbon sequestration field studies at “farm-managed sites” in northern Montana near Fife, Chester, Power, Dutton, and Conrad during Phase III. The overall objective of these studies was to determine whether adoption of tillage reduction (i.e. no-till) and annual cropping practices would result in soil C sequestration, and if so, at what rate. A 10 year study (2002-2012) was conducted at five farm-managed sites in northern Montana and on the property of the MSU-Post Farm near Bozeman. The MSU-Post farm trial was conducted with funds from the Montana Agricultural Experiment Station. Soil cores were collected in 2012, processed, and then analyzed for organic C. Estimates of SOC mass for different profile depths were calculated for the farm-managed sites (i.e. 0-20 cm and 0-50 cm) and MSU-Post Farm (0-30 cm). Estimates of SOC mass were contrasted with baseline numbers in 2002 (or 2004) where comparison could be reliably made. This study found that terrestrial C sequestration was possible in Montana’s dryland cropland soils by replacing fallow-wheat with more intensive cropping practices such as annual, pulse-wheat rotations. The impact of a reduction in tillage on C sequestration was somewhat unclear but it appeared to be considerably less important than cropping intensity. Estimated SOC sequestration response averaged 0.32 MT C ha^{-1} yr^{-1}, or 1.17 MT CO_2 equivalent ha^{-1} yr^{-1} over five sites where responses to increasing cropping intensity were observed. As anticipated there was considerable variance (0.18 to 0.60 MT C ha^{-1} yr^{-1}) in soil C sequestration rates among the responsive sites. The largest C sequestration was response to cropping intensity was observed at Fife which was characterized by high soil clay content (60%). Current, Montana ag-statistics indicate that approximately 1.29 million hectares of farm land (3.19 million acres) are in fallow on an annual basis. Approximately, 72% of the fallow-wheat acreage (or 925,000 hectares) is found in Montana’s Golden Triangle plus three other neighboring counties. If we apply our mean soil C sequestration rate to this acreage, then the potential of terrestrial C sequestration in Montana following conversion of fallow-wheat to annual cropping equates to approximately 1.0 million MT of CO_2 per year.

INTRODUCTION

Overview

The Big Sky Carbon Sequestration project sponsored terrestrial carbon sequestration field studies at five "farm-managed sites" in northern Montana during Phase III. The overall objective of these studies was to determine whether adoption of no-till and annual cropping practices would result in soil C sequestration, and if so, at what rate. Estimates of soil organic C (**SOC**) mass were made at the farm-managed site in September 2002 based on core samples collected to a depth of 50 cm. In 2012 and following ten years of no-till and annual cropping, a final set of core samples was collected at these same farm-managed sites. This report summarizes the results from this ten-year study at five-managed sites in northern Montana. In addition, we include the results from a second, independent and complementary field experiment that was running concurrently at the Montana State University (MSU)-Post Farm over this same time window (2002-2012), and which examined the impact of tillage and cropping intensity on SOC.

Background/Previous research

Dryland cropping in Montana occurs primarily in 25 to 40 cm (10 to 16") annual rainfall environments, and cropping practices are dominated by alternate crop-fallow systems, with cropping occurring only in one of every two seasons. Historically, mechanical tillage in Montana and other regions of the Great Plains has been an important management tool used during the summer fallow phase in order to control weeds and conserve water for the succeeding crop. However, one of the consequences of this system in the Great Plains, i.e. alternate crop-fallow and tillage, has been a 30 to 50% loss of SOC (Mann, 1985; Peterson et al., 1998). Tillage promotes SOC loss because the disturbance created promotes the oxidation of organic C to CO_2 (Bowman et al., 1999; Schomberg and Jones, 1999); and summer fallow contributes to soil C loss because inputs of photosynthetic derived C are reduced (or eliminated) as no plants (including crops and weeds) are allowed to grow during the fallow phase. In addition, microbial oxidation of SOC to CO_2 is enhanced because during fallow the soil is wetter and sometimes warmer for a prolonged period (Janzen et al., 1998).

In recent years there has been an effort in the Great Plains to reduce or eliminate tillage and promote diversified and intensive cropping systems. Such systems can reverse the trend in soil organic C (Peterson et al., 1998). Although a great body of information has been published in the Great Plains on the impact of tillage and cropping sequences on soil organic C, little information exists from Montana's semiarid climate. Published information from neighboring regions has shown the impact of cropping intensity and tillage can vary with climate. In western North Dakota, carbon sequestration rates of 0.23 MT C ha^{-1} yr^{-1} were observed when annual cropping was combined with no-till (Halvorson et al., 2002), while no-till had no impact on soil organic C in a crop-fallow system. A similar response was reported for southern Saskatchewan, where 12 years of no-till was found to modestly improve SOC (1.6 MT ha^{-1}) in a continuous wheat system, but had no effect in a fallow-wheat system (Campbell et al., 1995; Campbell et al., 1996). In general, soil C sequestration rates in response to tillage and cropping intensity tend to be lower in drier climates, as SOC storage is highly dependent on net primary productivity (C inputs) which diminish with precipitation.

This ten-year project was initiated in 2002 in order to provide new information from Montana on the potential of soils to sequester C under different cropping and tillage intensity management practices. The project stimulus came initially from the Montana chapter of the USDA-Natural Resource Conservation Service whom expressed a desire to understand soil C accretion rates relative to agricultural land management practices (i.e. principally no-till adoption and reduced summer-fallow). The first 18 months of this project was funded by the 10-university Consortium on Agricultural Soils Mitigation of Greenhouse Gases (CAMGS) led by Kansas State University, followed by one year of funding from the Montana NRCS-CIG program, and completed with U.S. DOE funding for the final 6+ years of the project. A number of subordinate projects and tasks were emphasized during this study but the primary focus was to secure funding to enable a minimal suitable time-record of SOC change. Soil C changes in response to cropping system practices typically occur slowly and often over a long-time scale (≥ 8 to10 years), in particular for dry, semiarid climates.

Cropping systems compared in this study include the traditional fallow-wheat (f-w) system that has been practiced in Montana since the soils were first broken from "native prairie" in the early 1990s; and a second more intensive cropping system, referred to as annual cropping or pulse-wheat (p-w). This second system alternated the growing of peas or lentil (both edible seeds of legumes with a pod and referred as to as pulse crops) with wheat over a two-year rotation. In addition, this study incorporated two tillage managements, i.e. till and no-till (NT). The tilled system utilized shallow-sweep tillage events to control weeds during the fallow-phase and/or for preparation of seedbeds for wheat seeding. The number of tillage events performed was at the discretion of the cooperating farmer-grower, but typically was limited to one or two events per rotation (except at Dutton). The no-till management system was devoid of tillage. Weeds were controlled during the fallow and crop phase primarily by spraying with either glyphosate (e.g. Roundup) and/or broadleaf selective herbicides. Seeding at the farm-managed sites was conducted with air-drills. In the past two-decades, air-drills have become very popular and common place in the Great Plains as they allow for seeding into undisturbed soils with standing crop stubble (**Figure 1**).

Figure 1. Direct seeding into crop stubble has become common among farmers in the Great Plains since the mid-1990s because of the popularity of air-drills (above). Dryland cereal grain production in this region is done without tillage in many areas. Tillage events are time consuming and costly to farmers, and also contribute to CO_2 release into the atmosphere because of the fossil fuel consumption. These photographs illustrate a winter wheat seeding event in northern Montana.

Scope of Work

This report summarizes the results of SOC mass analysis at "Farm-managed field" sites in northern Montana, and an independent and complementary study run at the MSU Post-Farm near Bozeman.

Research Partners and Roles

List Staff/Partner Organizations involved in this task.

Table 1: Staff and Partner Organizations

NAME	ORGANIZATION	ROLE
Richard Engel, Ph.D.	Montana State University-Dept of Land Resources and Environmental Sciences	Soil core sampling and analysis of cores for soil organic carbon mass
Rosie Wallander, Research Associate	Montana State University-Dept of Land Resources and Environmental Sciences	Soil core sampling and analysis of cores for soil organic carbon mass
Perry Miller, Ph.D.	Montana State University-Dept of Land Resources and Environmental Sciences	Oversee site selection; interact with farm research partners to ensure fidelity of study, and collection of geo-referenced biomass samples.

METHODOLOGY

Site Description and Experimental Design

Field studies were initiated in 2002 at six farm-managed sites (32 hectares or 80 acres each) within Montana's Golden Triangle (**Figure 2**). The studies ran for ten years. All farms were under no-till management prior to the inception of this study. One location near Kremlin was abandoned in 2010 because of loss of interest by the farmer. In addition, Montana Agricultural Experiment Station funds were used to run a replicated small plot trial between 2002 and 2012 on the property of the MSU-Post Farm near Bozeman. The goals of MSU-Post Farm study were similar to our DOE sponsored study, so we have included information gained from this study in our report. Selected soil properties are provided in **Table 2**. Soil pH was greater than 7.0 at all sites, reflecting the occurrence of Ca and Mg carbonates common to the soils of this region.

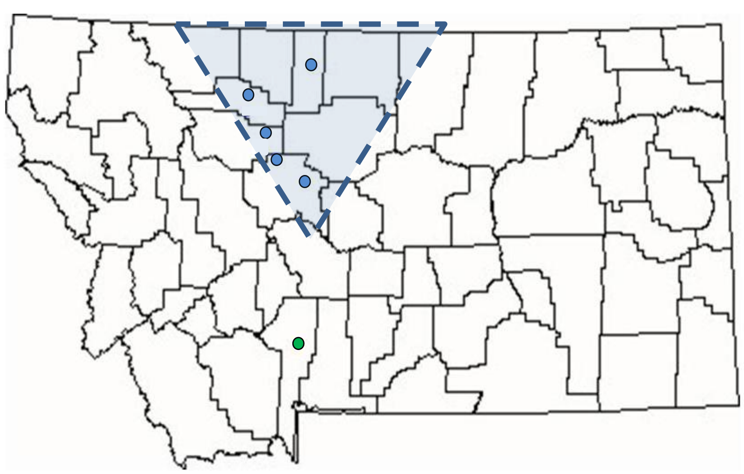

Figure 2. Location of five farm-managed field sites (blue circles) and complementary field experiment conducted at the MSU-Post farm (green circle). Golden Triangle identified by blue triangle.

Table 2. Selected soil properties and soil series name at farm-managed sites and MSU-Post Farm

Location	Latitude, Longitude	Depth	Soil Series	% Sand	% Silt	% Clay	Textural Class	pH
Fife	47°29'13.59"N,	0–10 cm	Lawther silty clay	20	24	56	clay	7.6
	111°00'17.92"W	10–20 cm		21	22	56	clay	8.2
		20–50 cm		17	20	63	clay	8.6
Chester	48°43'07.20"N,	0–10 cm	Joplin-Hillon loam	42	28	30	clay loam	7.8
	110°51'45.95"W	10–20 cm		35	30	35	clay loam	8.2
		20–50 cm		29	34	37	clay loam	8.6
Power	47°40'50.46"N,	0–10 cm	Cargill silty clay loam	19	38	43	silty clay	8.2
	111°34'38.47"W	10–20 cm		17	36	47	silty clay	8.2
		20–50 cm		22	29	50	clay	8.5
Dutton	47°58'37.08"N,	0-10 cm	Scobey-Kevin clay	30	23	46	clay	7.8
	111°44'42.87"W	10–20 cm	loam	27	21	52	clay	8.1
		20–50 cm		25	21	54	clay	8.6
Conrad	48°18'44.37"N,	0–10 cm	Scobey-Kevin clay	34	32	35	clay loam	7.4
	111°55'50.20"W	10–20 cm	loam	30	29	41	clay	7.7
		20–50 cm		27	32	41	clay	8.2
Bozeman	45°40'19.72"N	0-10 cm	Amsterdam silt loam	9	81	10	silt loam	6.8
	111° 9'4.21"W	10–20 cm		9	71	20	silt loam	7.1
		20–30 cm		9	80	11	silt loam	7.4

The farm managed field sites were divided into four zones or strips (minimum 8 hectare or 20 acres each) as illustrated in **Figure 3**, and managed as two-year rotations according to the following plan (below) with the pulse crop being either spring pea or lentil.

- tilled fallow-wheat
- tilled pulse crop-wheat
- no-till fallow-wheat
- no-till pulse crop-wheat

The design and soil sampling approach (discussed below) created pseudo-replications or observations from the four management zones.

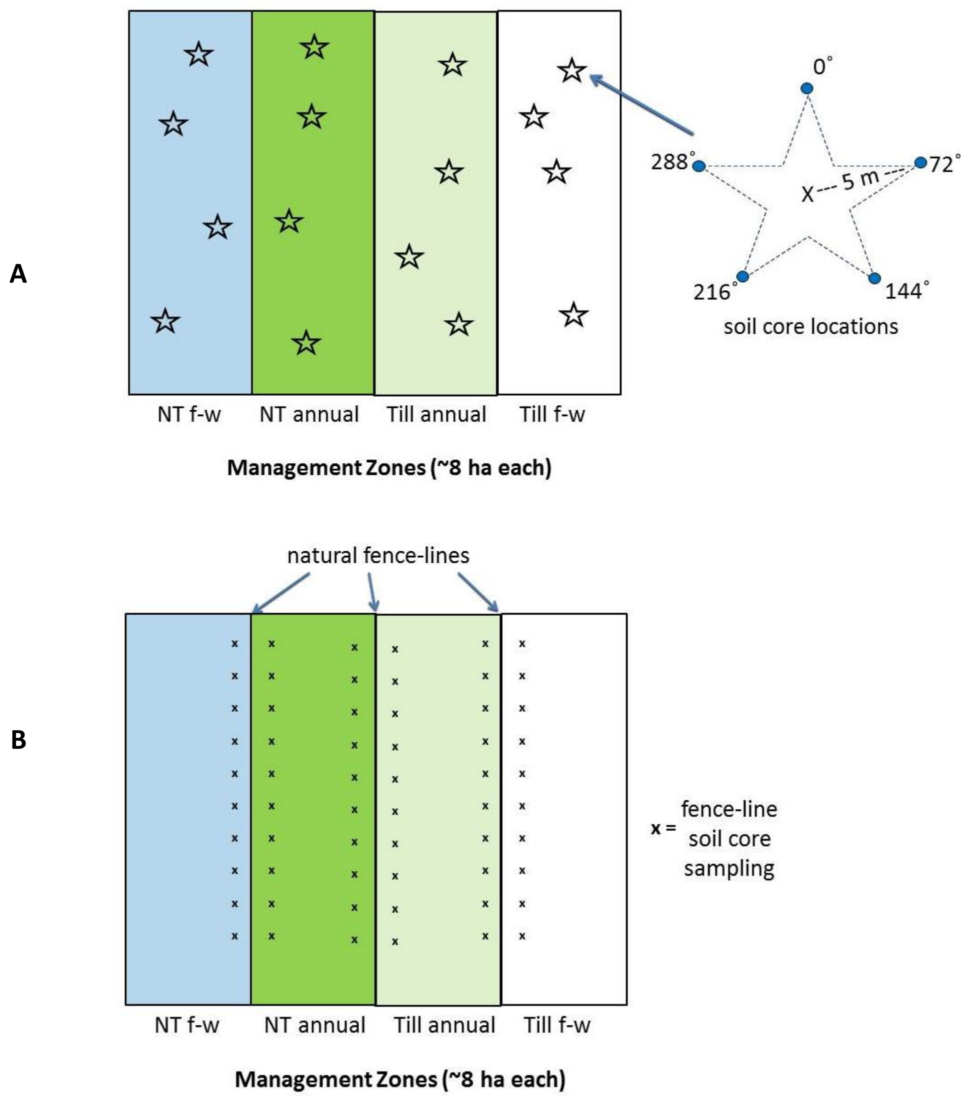

Figure 3. Farm-managed field sites were divided into four different management zones. The soil sampling protocol utilized a star sampling approach (A) by placing permanent metal markers in the ground in the center of the each star; and a cross-the-fence or natural fence-line approach (B) by collecting paired soil cores along a transect on each side of the boundary between two adjacent management zones.

Replicated field trials were conducted at the Montana State University-Post Farm and consisted of seven cropping systems plus a perennial grass-alfalfa or Conservation Reserve Program (CRP) system (**Table 3**). These seven management systems comprised eight main-plots with four replications in a randomized complete block design. Experimental treatments 1-7 were divided into two subplots representing two nitrogen fertility levels. Each subplot had dimensions of 24.4 m (80') x 3.7 m (12'). Only data for cropping system main-plots are presented in this report, as nitrogen fertility had a comparative small effect on SOC.

Table 3. Cropping systems applied to MSU-Post Farm field trial near Bozeman. 2002 - 2012.

Treat.	Tillage	Cropping Sequence description	
		2002-2008 (2 year sequence)	2008-2012 (4 year sequence)
1	till	fallow - winter wheat	fallow - spring wheat - fallow - winter wheat
2	no-till	fallow - winter wheat	fallow - spring wheat - fallow -winter wheat
3	no-till	spring wheat - winter wheat	spring wheat- spring wheat - winter wheat -winter wheat
4	no-till	spring pea - winter wheat	flax - spring wheat - winter canola - winter wheat
5	no-till	winter pea - winter wheat	spring pea - spring wheat - winter pea - winter wheat
6	no-till	winter pea (forage) - winter wheat	spring pea forage - spring wheat - winter pea forage - winter wheat
7	no-till	winter pea (forage) - spring wheat	spring pea -spring wheat - winter pea manure - winter wheat
8	-	perennial grass and alfalfa (CRP)	perennial grass and alfalfa (CRP)

Soil sampling protocol

Soil cores at the farm-managed sites were collected around permanent, geo-referenced, markers (i.e. buried steel-rods) established at the beginning of the experiment in the fall of 2002. Four markers were placed inside of each management zone. A five-pointed star (5 m radius) pattern was created around the center-axis of each marker (**Figure 3A**). The five points of the star were oriented approximately 0° (true north), 72°, 144°, 216°, and 288°, and 5 m from the center. A single soil core (0-50 cm) was collected at the point of each star and divided in 0-10, 10-20, and 20-50 cm layers. This approach is hereafter referred to as "star sampling". At the Fife, Chester, Power, and Conrad farm-managed sites, soil cores were also collected along transects on each side of an imaginary fence-line that separated the border of adjacent farm management zones. Paired cores along each transect were separated by about 50 m, and individual cores were approximately 20-25 m from the fence-line (**Figure 3B**). This approach is hereafter referred as "fence-line" sampling.

At the MSU-Post Farm site, three soil cores were collected at two ends of each nitrogen level sub-plot. The three cores were divided in 0-10, 10-20, and 20-30 cm depth layers and composited according to depth. In this report, the results from the nitrogen levels subplots were averaged and only mean values for each cropping system are presented.

Soil processing and carbon analysis protocol

All soil cores collected were initially oven-dried (50 ˚C). Cores were then crushed to pass through a 2 mm screen using a barrel sieve mill assembly specifically constructed for this project (**Figure 4**). The barrel sieved material was then weighed in order to determine bulk density (corrected moisture at 105 ˚C). A subsample of barrel sieved material (20-30 g) was then removed and fine-milled (< 153 µm) with a roller mill (**Figure 5**) in preparation for inorganic and total C analyses. The roller mill assembly, like the barrel sieve, was specifically constructed for this project during Phase III. Subsamples of fine-mill soil material were analyzed for total carbon (TC) by dry combustion using a Leco Truspec CN analyzer (Leco Corporation, Saint Joseph, MI). The inorganic C fraction was determined using the modified pressure calcimeter method of Sherrod et al. (2002). Soil organic C (SOC) was then calculated by difference in equation 1; where SOC = soil organic C, TC = total C, IC = inorganic C IC). The amount of SOC in each depth layer was then calculated by equation 2.

Equation 1: SOC (g C kg^{-1}) = TC (g C kg^{-1}) - IC (g C kg^{-1})

Equation 2: SOC mass (MT ha^{-1}) = SOC (g C kg^{-1}) x bulk density (g soil cm^{-3}) x sampling depth (cm)

The SOC mass of each depth layer was summed to give the SOC mass of the entire sample profile, i.e. 0-50 cm or 0-20 m for farm field sites, and 0-30 cm for Post Farm field site. The principle of equivalent soil mass (Ellert and Bettany, 1995) was applied to this analysis as differences in bulk density were observed across the cropping system and tillage treatments.

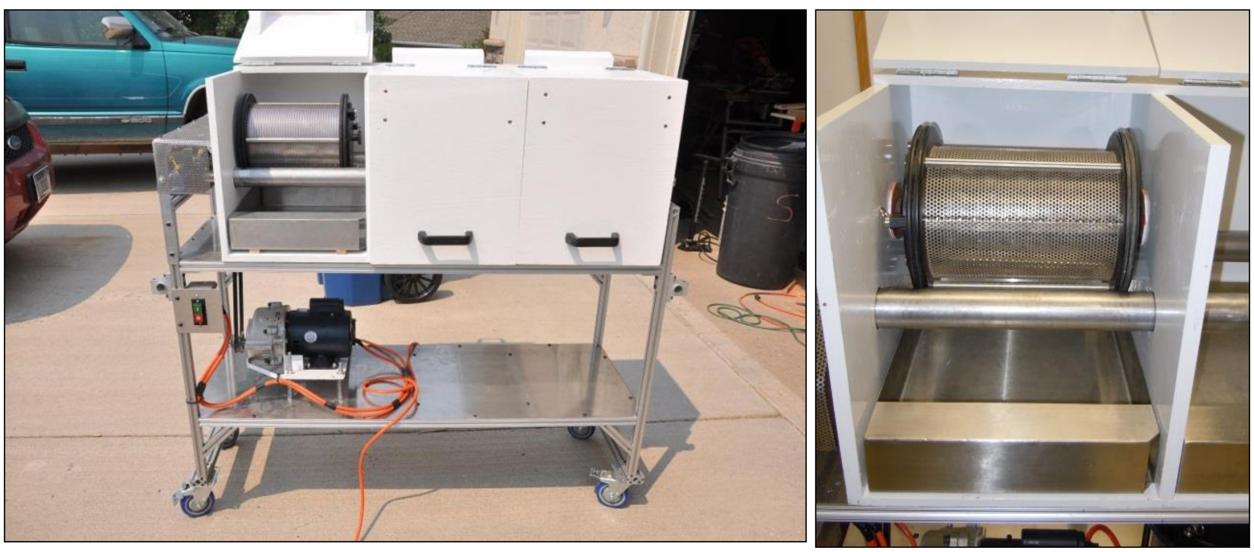

Figure 4. Barrel sieve mills for coarse milling soil material to pass a 2 mm screen were built during Phase III of this project.

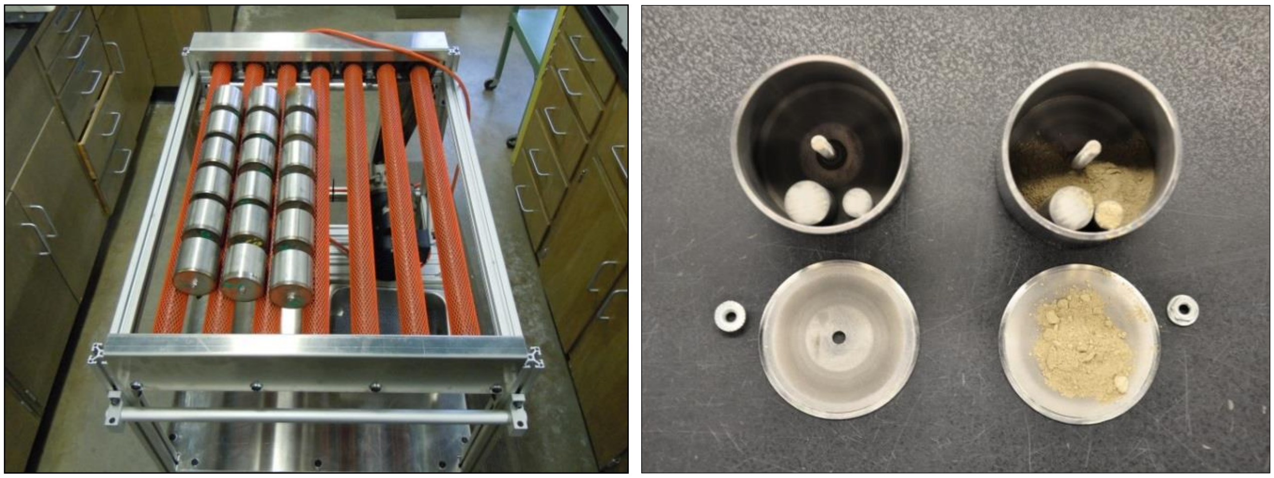

Figure 5. A roller-mill for fine grinding soil was fabricated and assembled during Phase III of this study. Note how soil material is milled to a fine powder (right). A subsample (0.200 g) of this material is analyzed for total carbon via Leco dry combustion.

Crop biomass estimates

At the farm-managed field sites, crop biomass for each treatment was estimated by hand-harvesting three 2.0 m^2 areas around the center of each permanent marker. Samples were composited and oven-dried at 50°C for 4 days to estimate biomass production. Wheat and legume grain yields were estimated after threshing biomass samples with a small plot combine (Wintersteiger, Ried, Austria) and hand-threshing, respectively. At the MSU-Post Farm site, crop biomass was sampled from 1 m^2 areas within each 3.6 x 21.3 m subplot and processed as for the farm-managed field sites.

Statistical analyses

The experimental design employed at the farm-managed sites did provide true replications, however, independence was assumed among the sampling locations. Statistical analyses of crop biomass response at the farm-managed sites were performed using the general linear models available in JMP 8.0 (SAS Institute, Cary, NC). First an analysis was attempted including all sites but it was determined that a large site x treatment interactions were present. Subsequently each site was analyzed independently, contrasting tillage, cropping intensity, and their interaction. Soil organic C mass from the star-sampling locations at the farm-managed sites were analyzed using MIXED procedure of SAS 9.4 with Kenward–Roger degree of freedom option in SAS 9.4 (SAS Institute, Cary, NC). This option uses an adjusted estimator of the covariance matrix to reduce small sample bias (Kenward and Roger, 1997). The model considered cropping and tillage, and cropping x tillage as fixed effects. Rep (or pseudo replication) and rep x tillage were treated as random effects. Soil organic C mass at the fence-line locations were analyzed using the general linear model procedure with sampling pair (9 df) and treatment (cropping or tillage intensity) treated as a fixed effect. Soil organic C mass response to cropping system at MSU-Post farm were analyzed as a randomized complete block design using the general linear model procedure in SAS 9.4 with cropping system and replication considered fixed effects. Mean separations were performed using the Waller-Duncan k-ratio t test. Significance of treatment effects were assigned to factors based on a $P < 0.05$ level, accept where noted (two incidences).

RESULTS

Cumulative Crop Biomass at Farm-Managed Sites

Cumulative biomass or (above ground net primary productivity) over ten years (2002 to 2012) is summarized in **Table 4**. Cumulative biomass differed among the farm-managed sites with the highest productivity occurring at Fife. This result was anticipated as this field site was located in a higher precipitation zone relative to the other field sites. Cropping system intensity significantly affected cumulative biomass at three of the five locations with the annual cropping system (pulse-wheat) producing more biomass than the fallow-wheat system. Although, statistically significant the differences were not large at Fife and Chester, and cumulative biomass for fallow-wheat systems averaged 94 and 95% of annual cropping system biomass for these two respective sites. In contrast cumulative biomass differences were quite large at Power, with fallow-wheat producing only 68% of the biomass observed for the annual cropping systems. It is not known why cropping intensity production so greatly affected crop biomass at Power, but may be related to inefficiency of stored water use accumulated during the fallow-phase. The soil at the Power site was characterized by the presence of shallow calic horizons (i.e. calcium cemented), and a paralithic zone within 45 to 80 cm of the soil surface. Both of these characteristics will restrict crop root penetration, and hence stored soil water use. In general, tillage intensity did not impact cumulative biomass. With the exception of Dutton, the growers generally performed tillage operations very infrequently. Hence, the level of disturbance for the tilled management zones was not much greater than the no-till managed zones. Tillage intensity did impact biomass at Chester where the no-till fallow-wheat system produced about 10% less biomass than the other treatments. This may have been an artifact of site heterogeneity at this field site and lack of true replications in this study.

Table 4. Cumulative biomass produced for the four management zones (NT till fallow-wheat, NT pulse-wheat, till fallow-wheat, till pulse-wheat) over ten growing seasons at the farm-managed field sites.

Tillage	Cropping intensity	Farm-managed sites				
		Fife	Chester	Power	Dutton	Conrad
		------------------	------------------	MT ha^{-1}	------------------	------------------
NT†	fallow-wheat	60.8	34.1	26.75	37.7	46.3
	pulse-wheat	67.4	37.9	40.2	40.1	46.0
Till	fallow-wheat	62.4	37.9	27.0	38.3	-‡
	pulse-wheat	64.3	38.2	38.5	37.4	-
ANOVA Summary						
		------------------	------------------	Probability > F	------------------	------------------
Tillage		NS	0.033	NS	NS	.
Cropping system		0.019	0.036	<0.0001	NS	NS
Tillage x Cropping system		NS	0.071	NS	NS	NS

NT = no-till

‡Till management areas were abandoned in 2008 due to runoff and erosion which displaced topsoil in this management area.

Soil Organic C Mass

The following discussion provides a brief description of the five farm-managed sites and the results of the soil C mass analysis, as well as results from the companion MSU-Post Farm trial.

Fife Site

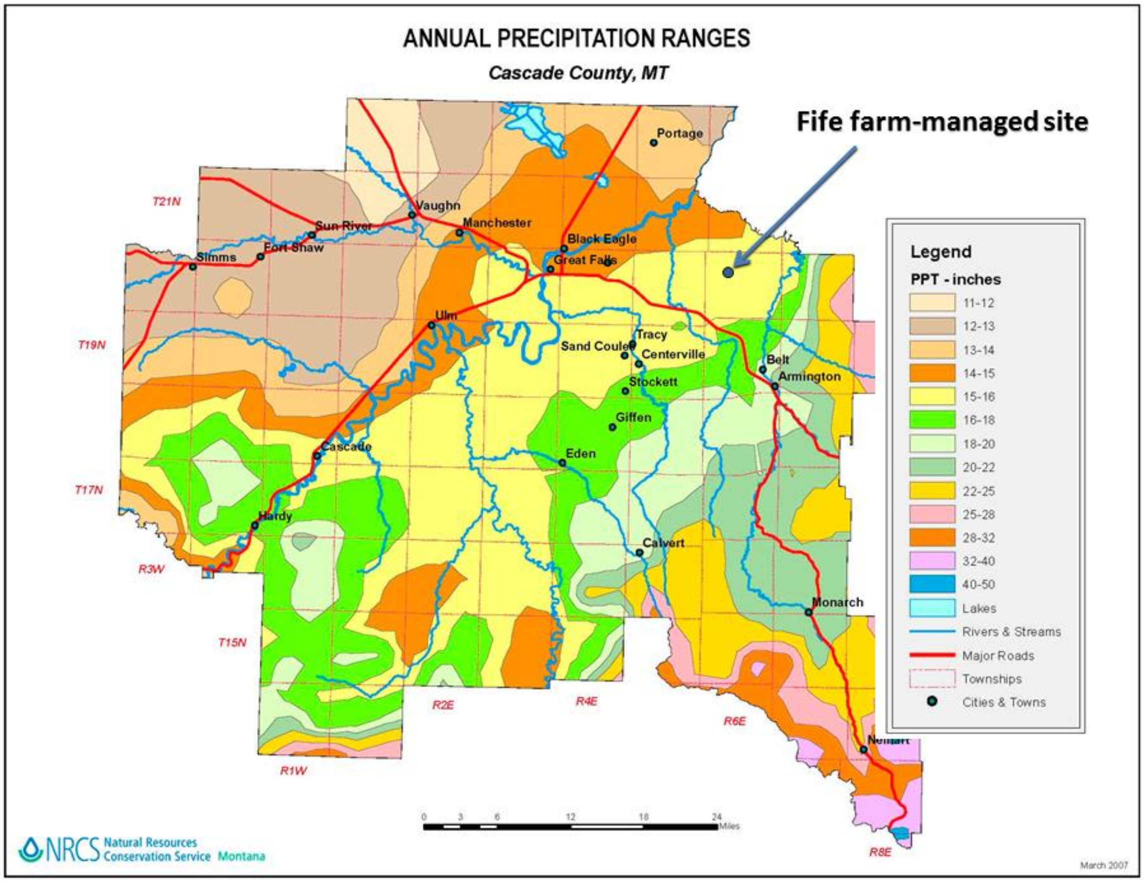

Figure 6. The Fife farm managed site was located in a 15-16" annual precipitation zone in Cascade County.

The Fife farm-managed site is located approximately 14 miles east of Great Falls and lies in 38-40 cm (15-16 inch) annual precipitation zone (**Figure 6**). The topography of the field site was nearly level (2-4% slope) and exhibits little or no abrupt changes in slope. The field was located in the bottom of Glacial Lake Great Falls. Soils at this field are classified as Vertisols and are characterized by a very high content of shrinking-swelling clays. Among our five farm-managed fields in northern Montana this site was located in the highest rainfall environment, which contributed to its high crop productivity. Soil cores were collected at permanent star locations and across three natural fence-lines within the field. Estimates of SOC mass from the star locations are summarized in **Figure 7**. SOC mass (0-50 cm) in 2012 was significantly affected ($P < 0.05$) by cropping intensity. Specifically, SOC mass (0-50 cm) averaged about 65.6 MT C ha^{-1} for the two annual cropping systems and in contrast to 60.6 MT C ha^{-1} for the two fallow-wheat system). Baseline SOC (0-50 cm) mass in 2002 was 59.4 MT C ha^{-1}. Hence, SOC accretion with annual cropping occurred at rate of 0.61 MT ha^{-1} yr^{-1} (or 6.1 MT C ha^{-1} cumulative) over the ten year life-cycle of this project. SOC accretion rates were similar under no-till and till management, and tillage intensity did not significantly affect SOC mass.

Estimates of SOC mass from the three natural fence-lines that separated i) no-till fallow-wheat and no-till pulse-wheat; ii) no-till pulse-wheat and tilll pulse-wheat; and ii) no-till fallow-wheat and and till fallow-wheat areas are summarized in **Figure 8**. Only the results from the 0-20 cm depth layer are presented here. In general, the results from fence-line analysis were consistent with our star locations. SOC mass was significantly affected by cropping intensity at Fence 1 and 3. In both cases, annual cropping (or pulse-wheat) resulted in higher SOC mass relative to the fallow-wheat system. Also, tillage intensity (no-till vs.till) did not affect SOC mass as evidenced by the results at Fence 2.

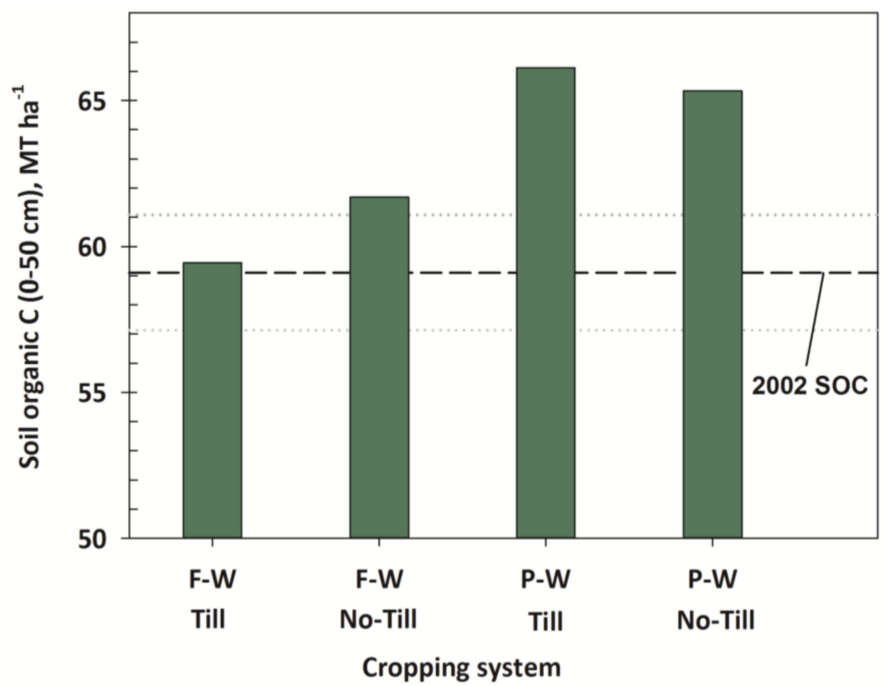

Figure 7. Soil organic C (0-50 cm) mass in 2012 at the star locations and as affected by cropping and tillage intensity over ten years at Fife farm-managed site. F-W=fallow-wheat, P-W = pulse-wheat. Cropping intensity means (F-W vs. P-W) were significantly different at $P < 0.05$ level. Dash-line indicates approximate baseline SOC levels in 2002 and 95% confidence intervals (dotted lines).

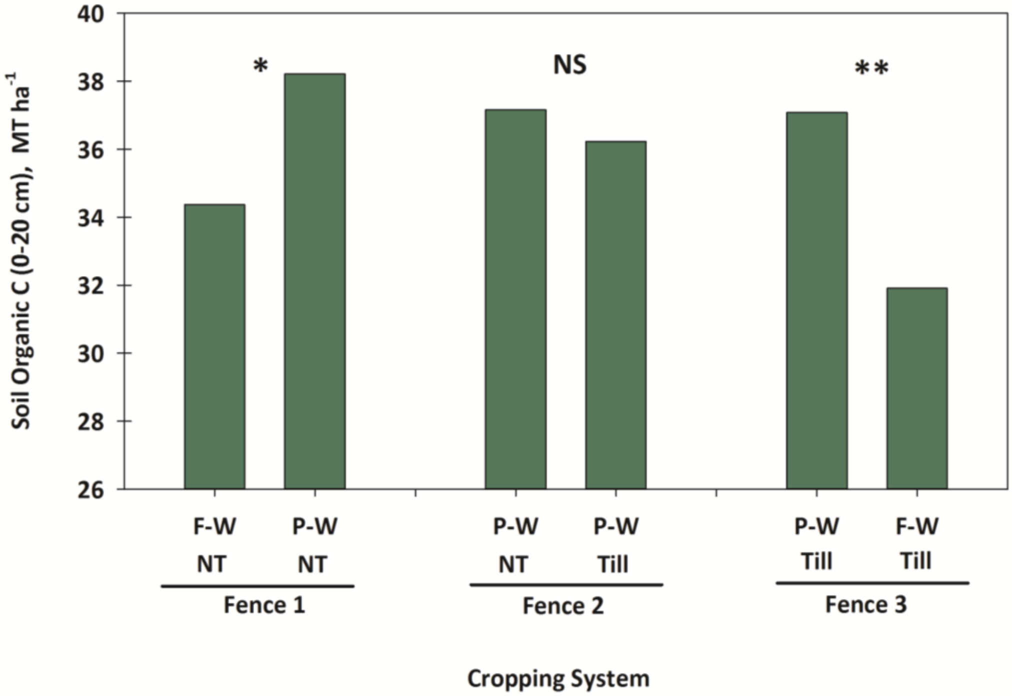

Figure8. Soil organic C (0-20 cm) mass in 2012 at the three fence-lines and as affected by cropping system at the Fife managed-farm site. * and ** indicate significant differences at $P<0.05$ and 0.01 levels, respectively. NS = not significant.

Chester

The Chester farm-managed field site was located in Liberty County approximately 30 km (19 miles) south of Canadian border, and 11 km (7 miles) southeast of the Sweet Grass Hills (**Figure 9**). Soils at this field site are derived from glacial basal till. The landscape as this field site exhibited a modest uniform slope of 2-8%. Annual precipitation is in the 25 to 28 cm (10-11") range. Among the five farm-managed fields this site was situated in the driest environment. Additionally, it is among the lowest precipitation environments in the Golden Triangle of Montana. Soil cores were collected at permanent star locations and across the two natural fence-lines that existed at this field site. Estimates of SOC mass for the star locations are summarized in **Figure 10**. Estimates for both the 0-20 cm and 0-50 cm depth layer are provided, because of the uncertainties associated with baseline estimates of SOC mass in2002 (discussed below).

Cropping system intensity significantly ($P<0.05$) affected SOC mass in 2012 at Chester and following ten years of management. The responses were evident in both the 0-20 cm and 0-50 cm depth layers. Estimated SOC mass in 2012 for the annual cropping systems (pulse-wheat) and fallow-wheat systems averaged 48.2 and 45.0 MT ha^{-1} for the 0-50 cm depth layer, respectively. This equates to a cumulative difference of 3.2 MT C ha^{-1} over ten years, or SOC accretion rate of 0.32 MT ha^{-1} yr^{-1}as a result of annual cropping. Estimated SOC mass in 2012 for these respective systems averaged 24.6 and 22.7 MT ha^{-1} for the 0-20 cm depth layer, or a difference of 1.9 MT ha^{-1} (or 0.19 MT ha^{-1} yr^{-1}).

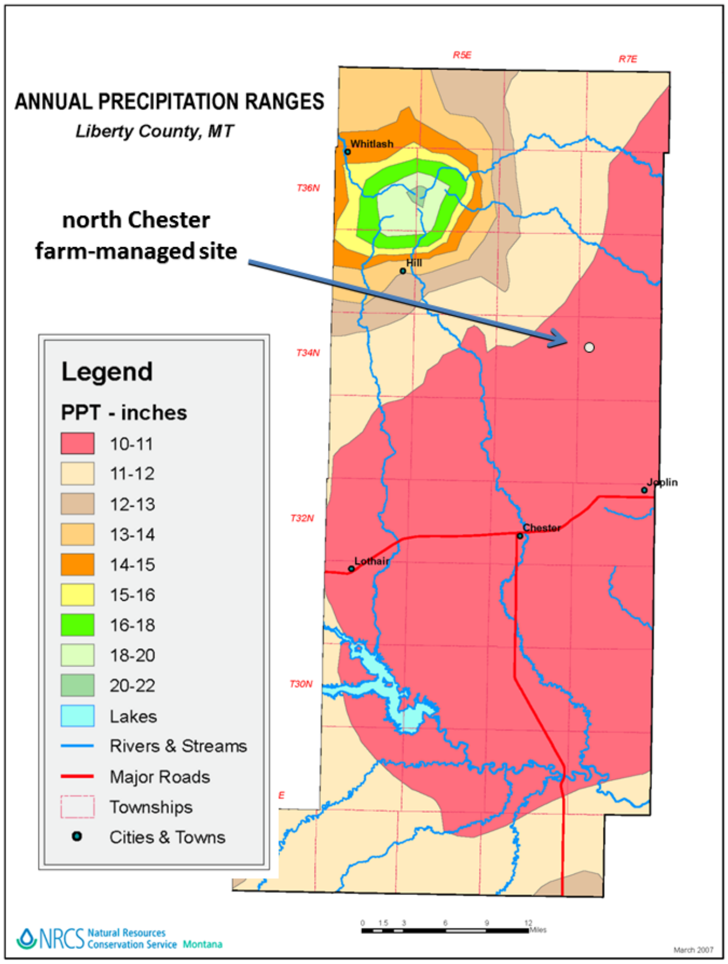

Figure 9. The north Chester farm managed site was located in a 10-11” annual precipitation zone in Liberty County.

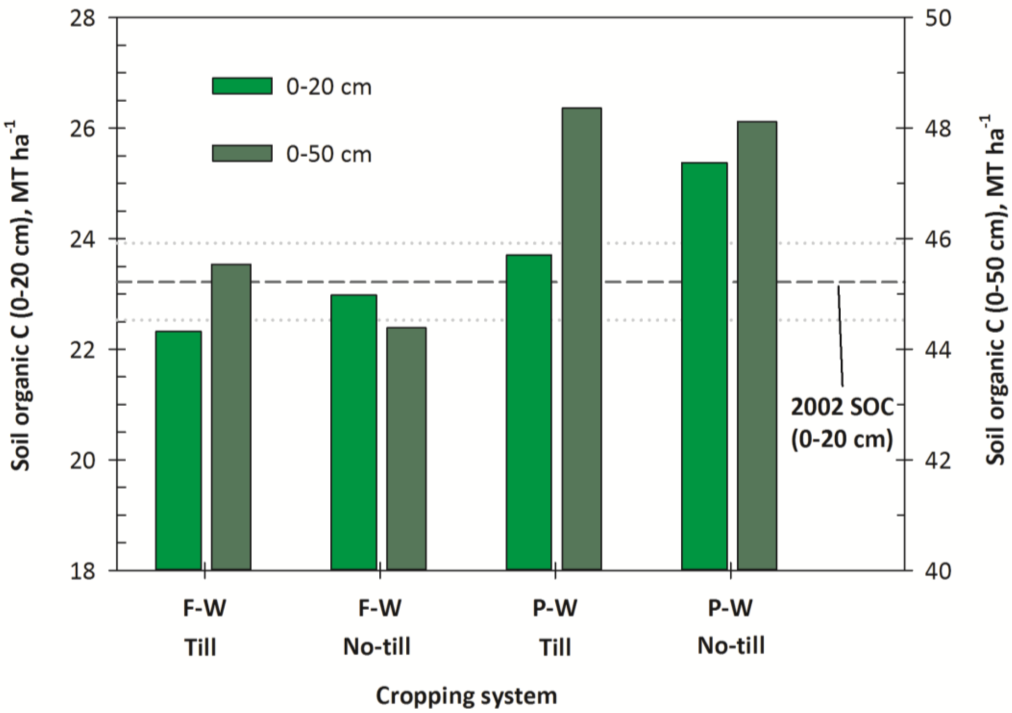

Figure 10. Soil organic C (0-20, and 0-50 cm) mass in 2012 at star locations as affected by cropping and tillage intensity over ten years at the Chester farm-managed site. F-W=fallow-wheat, P-W = pulse-wheat. Cropping intensity means (F-W vs. P-W) were significantly different at P <0.05 level. Dash-line indicates baseline SOC (0-20 cm) mass in 2002, and 95% confidence intervals (dotted lines).

Estimates of baseline (2002) SOC mass in the 0-20 cm depth layer are presented in **Figure 10**. Baseline SOC mass data for the 0-50 cm depth were not calculated as there was considerable uncertainty about the collection and processing of soil from the 20-50 cm depth increment in 2002. Specifically, measurements of rock fragments which impact bulk density measurements greatly exceeded estimates made in 2012, and in earlier years (i.e. 2008). Baseline SOC mass (0-20 cm) from 2002 indicate that a net loss of SOC may have occurred in the fallow-wheat systems. Also, SOC accretion was clearly evident in the no-till pulse-wheat over the past ten years (i.e. bar extends above 95% confidence interval). A possible explanation for the loss of SOC with fallow-wheat maybe traced to the history of this field site. Prior to 2002, the grower (Tom Graff) managed this field under annual cropping for at least four years beginning in 1998. Hence, just as an increase in cropping intensity may lead to SOC accretion, a reduction in cropping intensity from an annual cropping system to fallow-wheat may result in a net loss of SOC.

Tillage intensity and tillage x cropping system intensity did not affect estimates of SOC mass derived from the star locations. The results were somewhat different at the fence-lines (**Figure 11**). Our fence-line analysis found tillage intensity significantly affected SOC mass under annual cropping (Fence 2), but had no effect under fallow-wheat (Fence 1). We are uncertain of why this was case, but the annual cropping systems were accreting SOC over the past years and may have been more sensitive to the impacts of tillage.

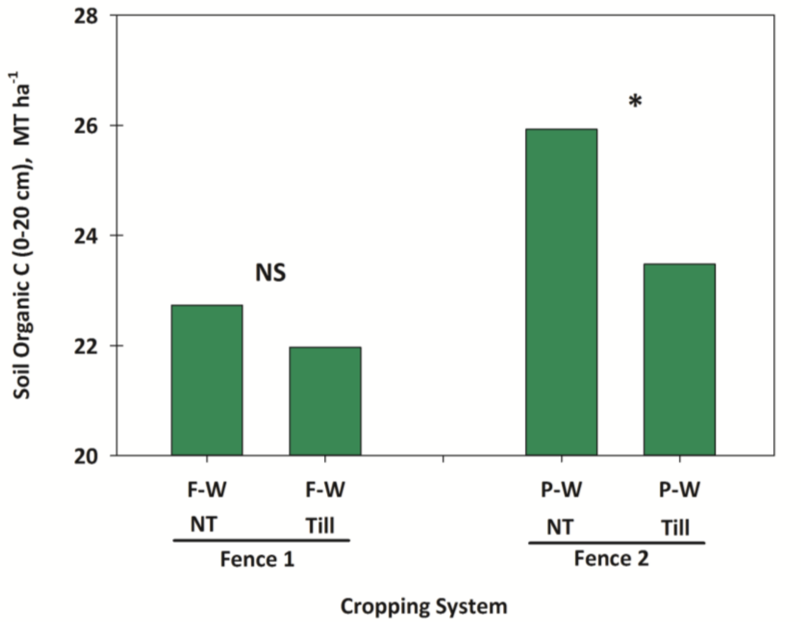

Figure 11. Soil organic C (0-20 cm) mass in 2012 as affected by tillage intensity (NT vs. Till) across two fence-lines at the Chester farm-managed site. * indicate significant differences at P<0.05. NS = not significant.

Power Site

The Power farm-managed site was located in a 28-30.5 cm (11-12") annual precipitation zone (**Figure 12**). The site was located in a topographically uniform, nearly level (0-4% slope) field and contained no abrupt changes in slope. The soil series is a Cargill silty clay loam. The soil parent material contained considerable $CaCO_3$. Among the farm-managed sites, this field contained the highest concentration of inorganic C (or $CaCO_3$). Inorganic C concentrations (or equivalent $CaCO_3$ percentage) averaged 11.1 g kg^{-1} (9.3%), 21.6 g kg^{-1} (18.0%), and 41.9 g kg^{-1} (34.9%) in the 0-10, 10-20, and 20-50- cm depth layers, respectively. Soil cores (0-50 cm) were collected at permanent star locations and across three fence-lines that existed between the management zones. Estimates of SOC mass for the star locations are summarized in **Figure 13**. Only the SOC mass for the 0-20 cm depth are presented here as accurate estimates of SOC mass in the 20-50 cm layer were difficult to define. This was caused by the extremely high inorganic C, or carbonate levels, in this depth layer that complicated our laboratory analysis. Also, SOC mass at Power exhibited a west to east gradient. Hence, individual estimates of baseline SOC mass are presented for all management zones. It is evident that baseline 2002 SOC mass in the till systems (east side of field) were greater than the no-till systems (west side of field). Given this consideration we calculated the delta SOC (δSOC) over the ten-year life cycle (2012 vs 2002) of this project. The δSOC mass was equivalent to -1.33, -0.48, 0.93, and 1.28 MT C ha^{-1} for the till fallow-wheat, no-till fallow-wheat, till pulse-wheat and no-till pulse wheat management zones, respectively. The δSOC mass was significantly affected (P=0.0897) by cropping intensity with the annual cropping and fallow-wheat (mean of two tillage intensities) resulting in a 1.1 MT ha^{-1} gain and 0.90 MT C ha^{-1} loss in SOC mass over the past ten years, respectively.

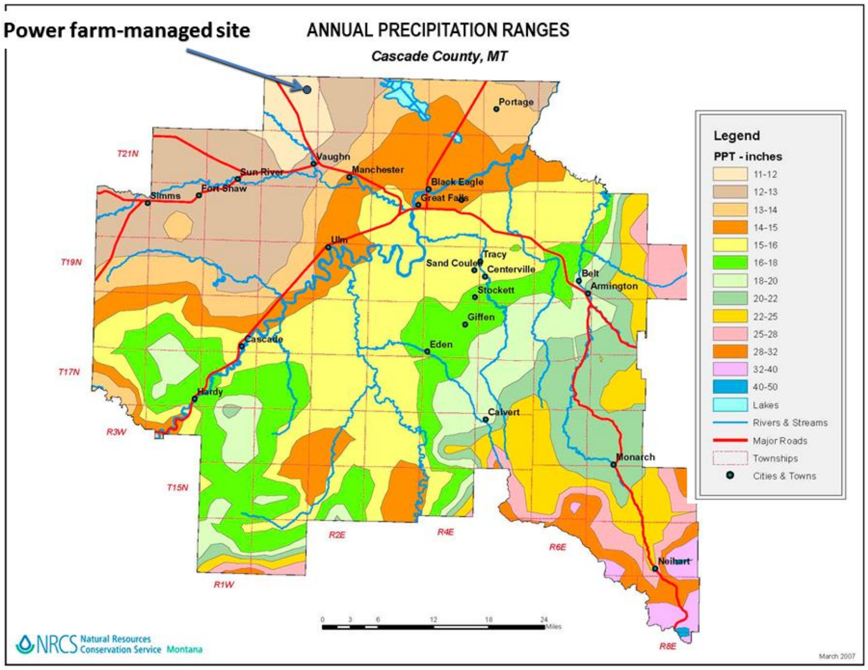

Figure 12. The Power farm-managed site was located in a 28 – 30.5 cm (11-12") annual precipitation zone in Cascade County.

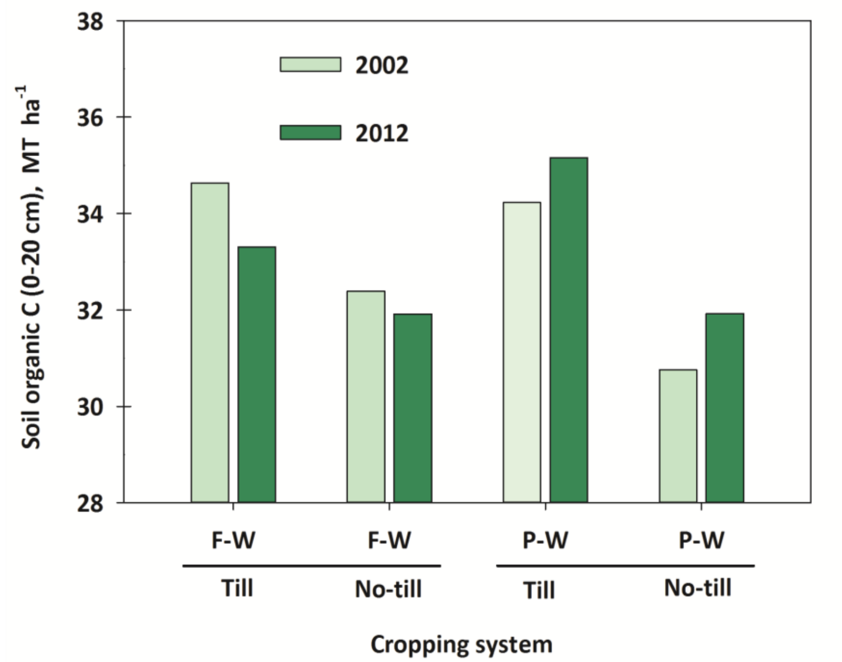

Figure 13. Soil organic C (0-20 cm) mass as affected by cropping and tillage intensity at the Power farm-managed site. 2002 and 2012. F-W=fallow-wheat, P-W = pulse-wheat. Baseline SOC mass in 2002 differed among the four management areas and is presented in this figure. The delta SOC mass (2012 vs. 2002) was significantly affected by cropping intensity (P <0.09 level).

Estimates of SOC mass (0-20 cm) for the three fence-lines that separated i) no-till fallow-wheat and no-till pulse-wheat; ii) no-till pulse-wheat and till pulse-wheat; and ii) no-till fallow-wheat and till fallow-wheat areas are summarized in **Figure 14**. Estimated SOC mass (0-20 cm) was significantly affected by cropping intensity at Fence 1. The difference in SOC mass between the fallow-wheat and pulse-wheat equates to a 3.0 MT ha^{-1} in favor of annual cropping system. Estimated SOC mass (0-20 cm) was not affected by tillage at Fence 2 and cropping intensity at Fence 3. As noted for the star locations, this field exhibited a gradient in SOC mass from west to east and perpendicular to the fence-line transects. The gradient was most evident in samples collected on the east half of the field (tilled pulse-wheat and tilled fallow-wheat managed zones). Hence, SOC mass at Fence 3 was higher than at Fence 1 and 2. This confounded the interpretation of our results at this location and impacted direct comparisons among the three fence-lines.

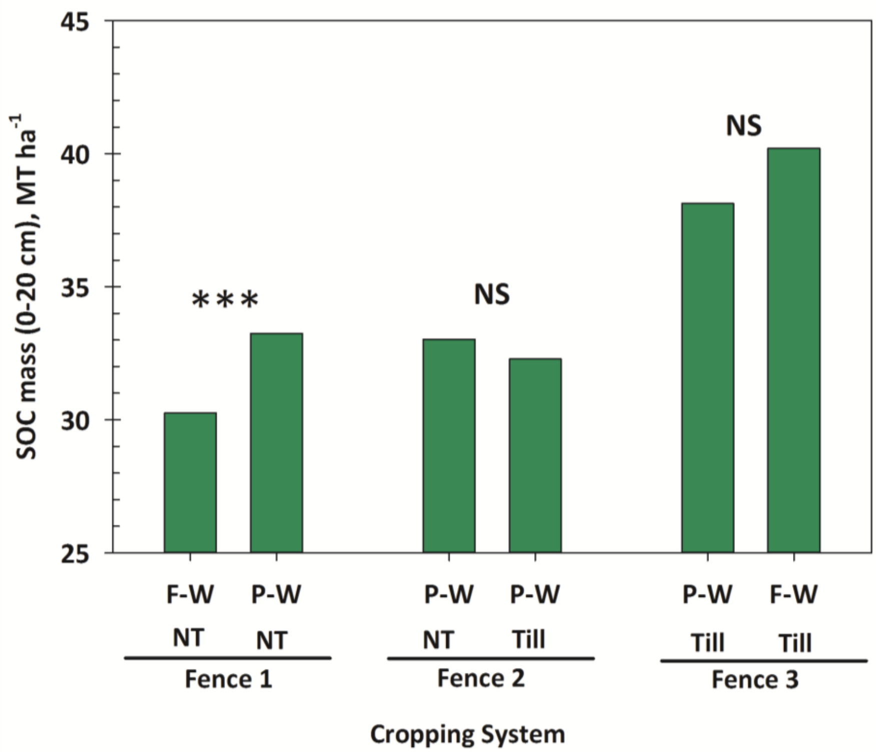

Figure 14. Soil organic C (0-20 cm) mass in 2012 at the three fence-lines and as affected by cropping system at the Power farm managed-farm site. * ** indicate significant differences at P < 0.001 levels, respectively. NS = not significant.

Dutton Site

The Dutton farm-managed site was located in a 28-30.5 cm (11-12”) annual precipitation zone (**Figure 15**). The field exhibited rolling topography; however, all of the permanent star markers were located at the north end of the field where the slope was nearly level (0-4% slope). The dominant soil in is a Scobey-Kevin clay loam complex and is derived from glacial ablation till. In 2012, soil cores were collected at permanent star locations and estimates of SOC mass are summarized in **Figure 16**. Estimates of SOC mass among the four management strips were extremely variable in the 20-50 cm depth layer, and so only results for 0-20 cm depth are presented. The SOC mass for 2012 in the 0-20 cm depth layer was similar among the four management zones and was not affected by cropping, tillage or cropping x tillage intensity interaction. However, baseline SOC mass in 2004 (note 2002 baseline data was not used due to sampling and processing errors) was found to be lower in the two annual cropping system strips. Given this consideration we calculated delta SOC (δSOC) over an eight year life cycle (2012 vs 2004). The δSOC mass was equivalent to 0.69, 0.19, 1.70, and 1.98 MT C ha^{-1} for the till fallow-wheat, NT fallow-wheat, till pulse-wheat and NT pulse wheat management zones, respectively. The δSOC mass was significantly affected (P=0.0776) by cropping intensity with annual cropping providing a 1.4 MT C ha^{-1} (0.18 MT C ha^{-1} yr^{-1}) gain over fallow-wheat management (average of two tillage intensities).

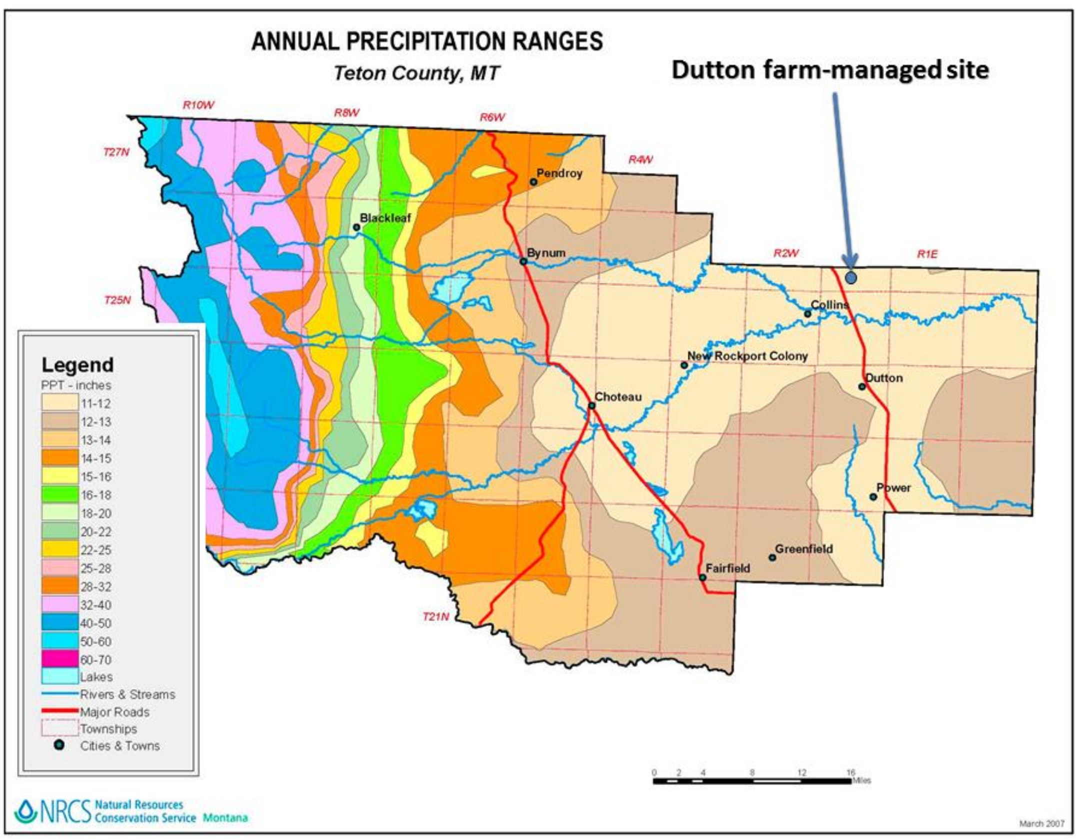

Figure 15 The Dutton farm - managed site was located in a 28 – 30.5 cm (11-12”) annual precipitation zone in Teton County.

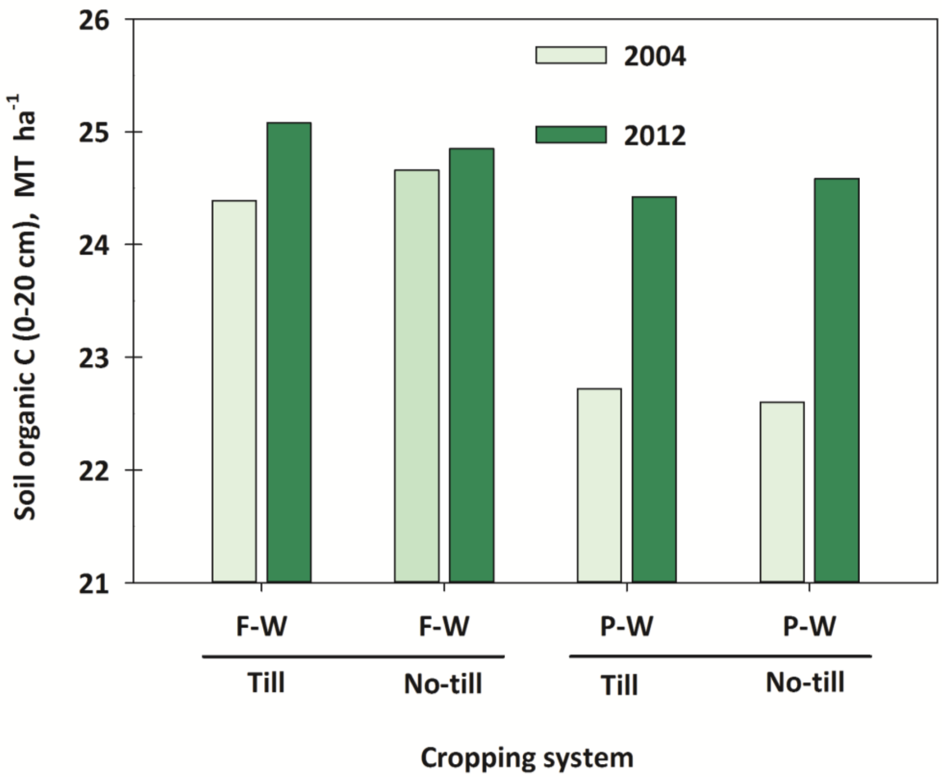

Figure 16. Soil organic C (0-20 cm) mass in 2012 and 2004 as affected by cropping and tillage intensity at the Dutton farm-managed site. F-W=fallow-wheat, P-W = pulse-wheat. Baseline SOC mass in 2004 differed among the four management areas and is presented in this figure. The delta SOC mass (2012 vs. 2004) over an 8 year life-cycle was significantly affected by cropping intensity (P <0.08 level).

Conrad site

The Conrad farm-managed site was located approximately 7 miles north of the town of Conrad in a field with variable topography (0-8% slope), and in a 28-30.5 cm (11-12") precipitation zone (**Figure 17**. The dominant soil in this field was a Scobey-Kevin clay loam complex and derived from glacial ablation till. In 2012, soil cores (0-50 cm) were collected at permanent star locations in the no-till management areas and along the fence-line that separated the no-till fallow-wheat and no-till pulse wheat management areas. Soil sampling was not conducted in the tilled management strips as soil erosion had compromised the integrity of these field strips. Estimates of SOC mass are presented in F**igure 18** for the star sampling locations. Estimated SOC mass was extremely variable in the 20-50 cm depth layer at the star locations, and so only results for 0-20 cm depth are illustrated in this figure. The results indicate that SOC was not significantly affected by cropping intensity (P=0.497). Similarly, SOC mass (0-50 cm) in cores collected from the natural fence-line were found not to differ among the no-till pulse-wheat and fallow-wheat systems (**Figure 19**).

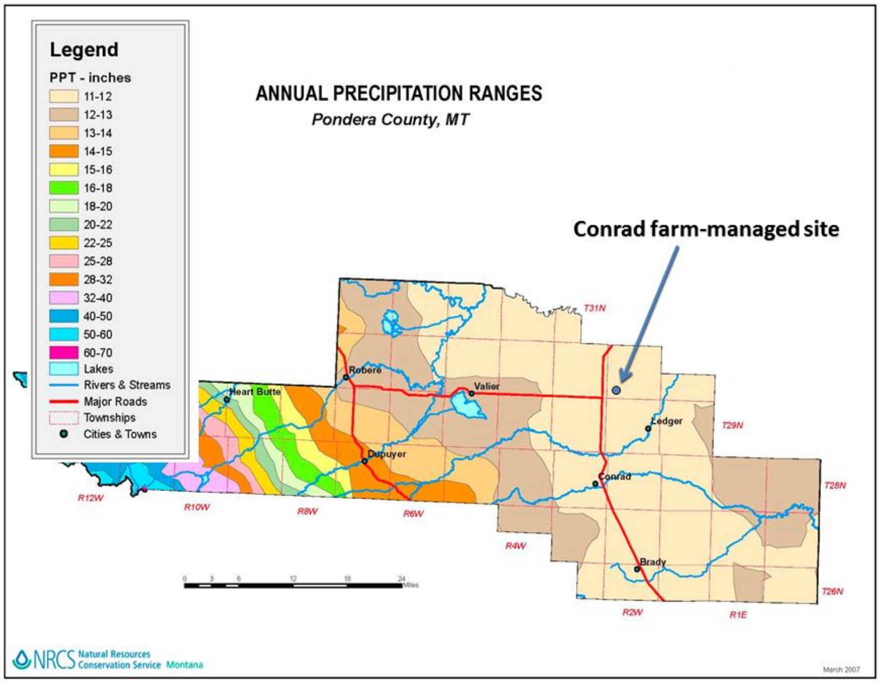

Figure 17. The Conrad farm -managed site was located in a 28 to 30.5 cm (11-12”) annual precipitation zone in Pondera County.

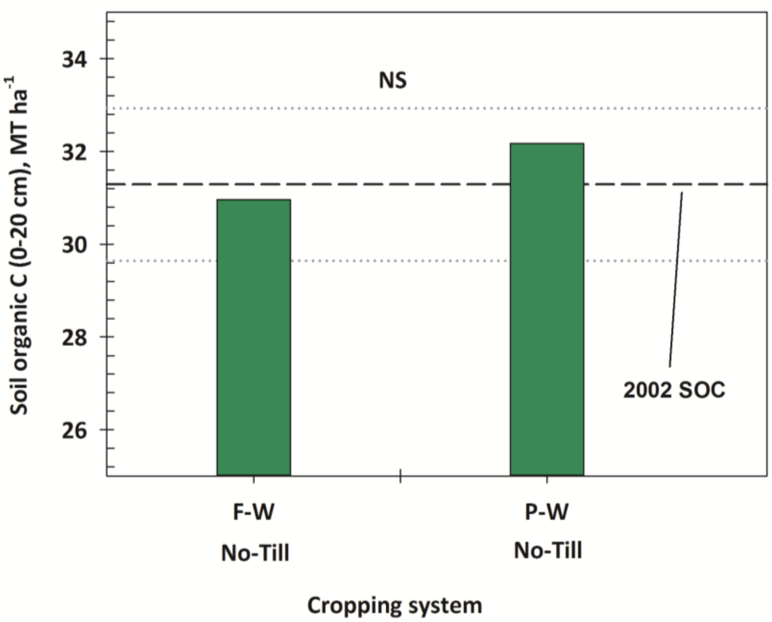

Figure 18. Soil organic C (0-20 cm) mass at permanent star locations in 2012 as affected by cropping intensity over ten years under no-till management at Conrad farm-managed site. Cropping intensity means (F-W vs. P-W) were not significantly different. (P=0.497). Dash-line indicates approximate baseline SOC (0-20 cm) mass in 2002, and 95% confidence intervals (dotted lines).

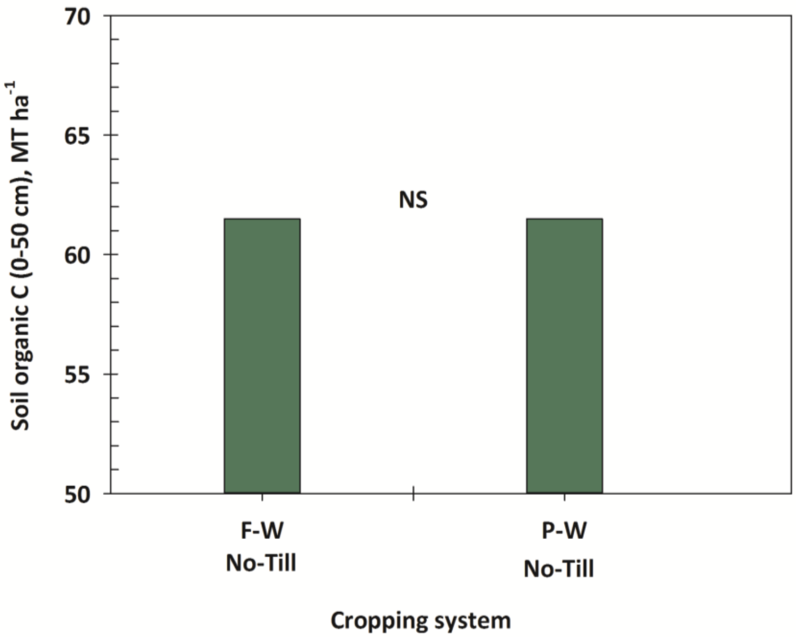

Figure 19. Soil organic C (0-50 cm) mass in 2012 across a natural fence-line as affected by cropping intensity over ten years under no-till management at Conrad farm-managed site. Cropping intensity means (F-W vs. P-W) were not significantly different (P=0.92).

Bozeman - MSU Post Farm

The MSU Post Farm field trial was located approximately 7 miles west of Bozeman in the Gallatin Valley (**Figure 20**). The Gallatin Valley exhibits a strong east to west precipitation gradient. Annual precipitation at MSU Post Farm is 41.4 cm (16.3"), therefore, this field site provided a higher precipitation environment than the farm-managed sites in northern Montana. Estimated SOC mass (0-30 cm) in 2012 and following ten years of varying crop management are summarized in **Figure 21.** The results indicated that SOC mass (0-30 cm) for the six no-till annual cropping (W-W, P/O-W, P-W, Pf-W, Pfm-W) systems averaged 37.5 MT C ha^{-1}, or 3.7 MT C ha^{-1} greater than the till fallow-wheat system (33.8 MT C ha^{-1}). Among the six cropping systems compared, the annual cropping system which most closely mimicked the system employed at the farm-managed sites was the no-till pea-wheat rotation. The estimated SOC mass (0-30 cm) for this system equaled 38.4 MT C ha^{-1} , or 4.6 MT C ha^{-1} greater than the till fallow-wheat system. Benefits from no-till (vs. till) were evident at the Post Farm but the effects were not as large as cropping intensification. Estimated SOC mass for the tilled fallow-wheat and no-till fallow-wheat system showed a 1.8 MT C ha^{-1} difference between these two systems after ten years.

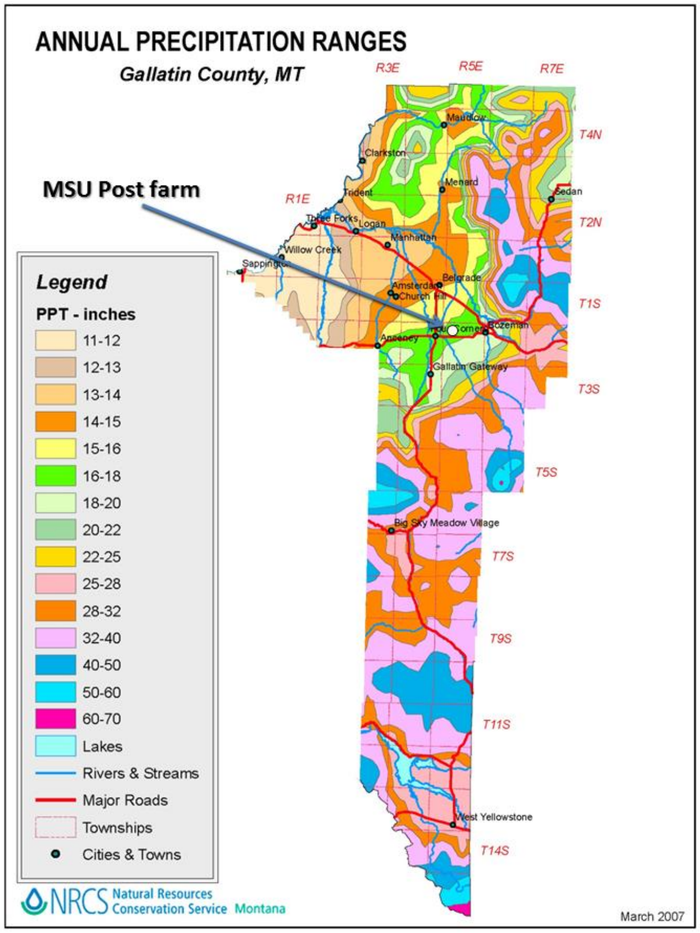

Figure 20. The MSU-Post Farm is located in Gallatin County, and annual precipitation is 16.3”

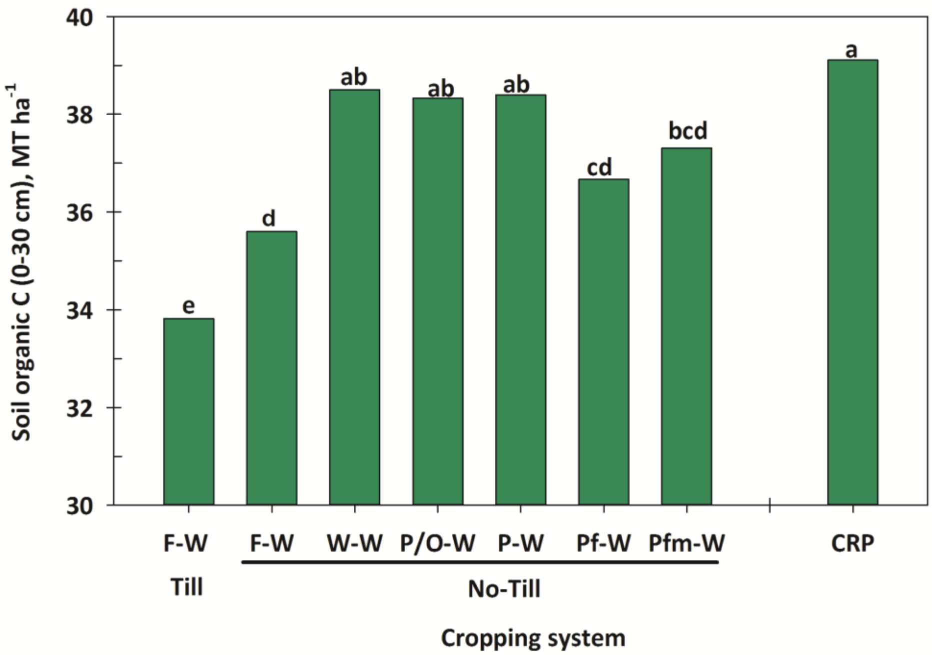

Figure 21. Soil organic C (0-30 cm) mass in 2012 and as affected by cropping system management over ten years at MSU-Post Farm trial. F-W = fallow-wheat, W-W=continuous wheat, P/O-W =pea or oil seed - wheat; P-W = pea-wheat; Pf-W = pea forage - wheat; Pfm-W = pea forage and green manure-wheat, CRP = conservation reserve program. Means followed by same letter are not significantly different at P < 0.05 level.

CONCLUSIONS

Research Conclusions and Scaling Up Estimates of Terrestrial C Sequestration

The results of this study indicate that terrestrial C sequestration is possible in Montana's agricultural soils by replacing fallow-wheat with more intensive cropping practices such as pulse-wheat rotations. A positive response to cropping intensification was observed at four of five farm-managed sites, and a replicated field trial conducted at the MSU-Post Farm. Soil C sequestration at the four responsive farm-managed sites occurred even though above ground net primary productivity was not much different (with one exception) over fallow-wheat systems. This result was a bit surprising. We can only surmised that above ground net primary productivity may not accurately reflect the impact of annual C additions that occur from crop roots. A summary of the SOC sequestration response at the five farm-managed field sites, and MSU Post-Farm is provided in Table 5. The results find that soil C sequestration rates following conversion from fallow-wheat to pulse-wheat rotations average 0.32 MT C ha^{-1} yr^{-1} or 1.17 MT CO_2 equivalent ha^{-1} yr^{-1}. As anticipated there was considerable variance in soil C sequestration rates among the sites. Sequestration rates will be impacted by a number of soil properties, among which soil clay content is of considerable importance. We found it interesting that the highest C sequestration rates were observed at the Fife farm-managed site. The large response at Fife was attributed to the very high soil clay content and relative high precipitation environment (**Figure 22**). Soils with high clay content will typically provide higher C sequestration rates because of the ability of clay minerals to form stable organic C-mineral complexes, and because clay soils are often more oxygen deprived. Most regional soil C models (e.g. Century) will show soil C gains are greater in the presence of high clay. Precipitation can also influence soil C accretion rates, particularly in Montana, because of its effect on net primary productivity.

Table 5. Summary of estimated soil organic C sequestration rates at the five farm-managed sites and MSU-Post farm in response to increasing cropping intensity from fallow-wheat to a pulse-wheat rotation

Location	SOC sequestration rate		Comments
	MT C ha^{-1} yr^{-1}	MT CO_2 equiv ha^{-1}	
Fife	0.61	2.24	• based on response observed at permanent star locations in 2012
Chester	0.32	1.17	• based on response observed at permanent star locations in 2012
Power	0.20	0.73	• based on delta SOC response observed at permanent star locations in 2012 and 2002
Dutton	0.18	0.51	• based on delta SOC response observed at permanent star locations in 2012 and 2004
Conrad	ND	-	• no response was detectable at star or at natural fence lines
MSU-Post Farm	0.28	1.03	• based on response observed under no-till in 2012 (i.e. NT fallow-wheat vs. NT pea-wheat rotations); till wheat-fallow vs. NT pea-wheat resulted in 0.46 MT C ha-1 yr-1 SOC sequestration rate
Average	**0.32**	**1.17**	• average of five responsive sites (i.e. does not include Conrad)


Figure 22. The soil at the Fife site is classified as Vertisol because of its high swelling clay content which produces large cracks or fissues upon drying. These photographs were taken in September 2012, and shows a fissure in the field that is >20” (51 cm) in depth.

In general, a beneficial effect from reduced tillage on soil C sequestration was not evident in this study, except at the MSU- Post Farm. This result was not extremely surprising as tillage intensity has generally been viewed as being less important to SOC sequestration than cropping intensity in semiarid climates (Halvorson et al., 2002; Janzen et a., 1998). In addition, the impact of tillage intensity (till vs. no-till) at our farm-managed field sites was likely nominal because the frequency of tillage events was low. Tillage was typically performed by our farmer-cooperators only 1 to 2 times per rotation cycle. As a result there was not much difference in disturbance between the no-till and till systems. In contrast, the management practice applied to the till fallow-wheat system at the MSU-Post Farm involved a much greater frequency of tillage events, i.e. 4 times per rotation cycle. Perhaps as a consequence, SOC mass (0-30 cm) differences equivalent to 1.8 MT C ha-1 were observed between the till and no-till fallow-wheat systems at the end of ten years.

Current, Montana ag-statistics indicate that approximately 1.29 million hectares of land (3.19 million acres) are in fallow every year. The great majority of this land will be under a fallow-wheat system, and most of it will be managed under no-till due to the growth and popularity of direct seeding equipment (**Figure 1**). Approximately 72% of the fallow-wheat acreage (or 925,000 hectares) is found in Montana's Golden Triangle plus three other neighboring counties (**Figure 22**). If we apply our mean soil C sequestration rate (1.17 MT CO_2 ha^{-1} yr^{-1}) to this acreage then the potential for terrestrial C sequestration in Montana, <u>equates to about 1.0 million MT of CO_2 per year</u> following conversion to annual cropping. Terrestrial C sequestration is not indefinite and at some point following a change in management the soil will reach a new steady state. The duration of sequestration duration and C saturation point will vary with climate regime. Recent models presented by West and Six (2007) suggest C sequestration rates following rotation enhancement (e.g. increasing cropping intensity) continue for approximately 25 years in cold temperate dry climates such as Montana.

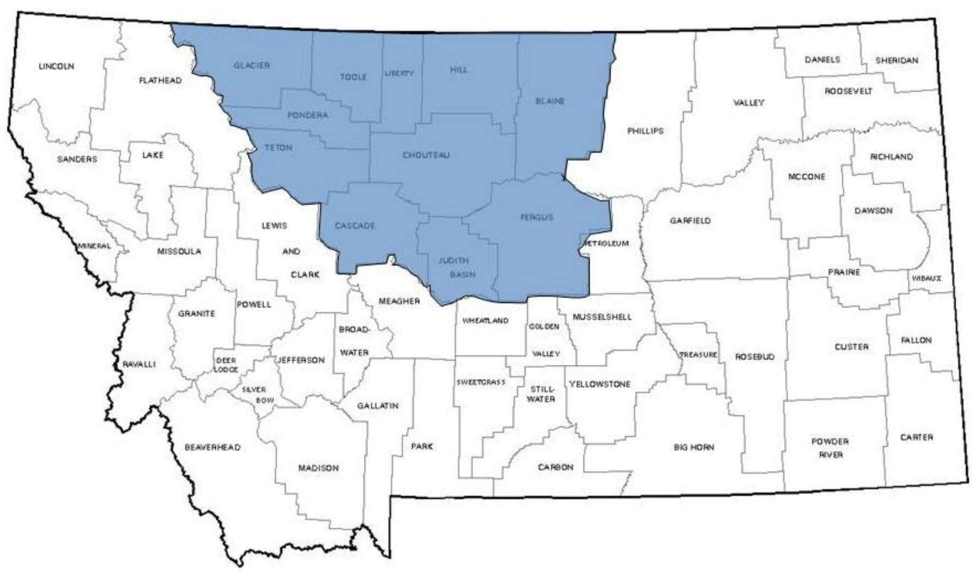

Figure 22. Current, ag-statistics indicate there is 925,000 hectares of cropland fallowed in the 11 highlighted counties above.

Lessons Learned/Best Management Practices

No-till and increasing cropping intensity are two best management practices that have been touted for soil carbon sequestration in the semiarid Great Plains. Results from this 10-year study, conducted at controlled farm-managed sites in northern Montana, as well as a companion study near Bozeman revealed that adoption of annual cropping practices to replace fallow-wheat will lead to greater SOC storage in Montana. The impact of no-till on soil C storage was less clear in this study. In part, this was due to the fact that tilled systems applied at the farm-managed sites were not very intensive, and so the difference in level of disturbance between till and no-till systems was not great. Although, the direct impact of no-till on SOC will likely be less than annual cropping, the importance of no-till should not be understated. No-till management conserves water. Therefore, its adoption can be critical to the success of more intensive annual cropping systems in semiarid climates such as Montana.

Recommendations for Future Research

Future research in the northern Great Plains should focus on developing cropping sequences that conserve water and minimize water use during the phases of rotations when cereals are not being grown. Cereal grains, in particular wheat, represent the primary income source for Montana farmers. Hence, Montana grain growers will diversify and intensify their crop rotations provided that yield and economic return from their primary cash crop, i.e. wheat, is not adversely affected. Currently, the practice of cover cropping is being promoted by the NRCS. It will be important to learn C sequestration rates associated with application of this soil management practice. Further, much of this cover cropping would be more accurately characterized as annual forage mixtures for grazing which brings another important system component into play, with unmeasured consequences on SOC and other GHGs.

Education Activities and Student Involvement (if applicable)

Student Involvement in research

Table 6: Student Participation

NAME	STUDENT LEVEL	ROLE IN PROJECT
Shelby Craig	Undergraduate	Field assistant and lab aide
Laura Bosacker	Undergraduate	Field assistant and lab aide
Alexandra Schuetter	Undergraduate	Field assistant and lab aide
Sebastian Schnobrick	Undergraduate	Field assistant and lab aide
Elizabeth Draper	Undergraduate	Field assistant and lab aide
Dionne Zoannie	Undergraduate	Field assistant and lab aide
Kaylee Schmidt	Undergraduate	Field assistant and lab aide
Lily Westerhoff	Undergraduate	Field assistant and lab aide
Melissa Marlen	Undergraduate	Field assistant and lab aide
Michaela O'Donohue	Undergraduate	Field assistant and lab aide
Emma Bode	Undergraduate	Field assistant and lab aide

Table 7: Student Theses based on Project Research

NAME	THESIS TITLE	THESIS TYPE
Ryan Feddema	Understanding carbon sequestration in north central Montana dryland wheat systems	Master's Thesis

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