Cropping Intensity Enhances Soil Organic Carbon and Nitrogen in a No-Till Agroecosystem

L. A. Sherrod,* G. A. Peterson, D. G. Westfall, and L. R. Ahuja

ABSTRACT

Soil organic C (SOC) has decreased under cultivated wheat (*Triticum aestivum*)-fallow (WF) in the central Great Plains. We evaluated the effect of no-till systems of WF, wheat–corn (*Zea Mays*)-fallow (WCF), wheat–corn–millet (*Panicum miliaceum*)-fallow, continuous cropping (CC) without monoculture, and perennial grass (G) on SOC and total N (TN) levels after 12 yr at three eastern Colorado locations. Locations have long-term precipitation averages of 420 mm but increase in potential evapotranspiration (PET) going from north to south. Within each PET location, cropping systems were imposed across a topographic sequence of summit, sideslope, and toeslope. Cropping intensity, slope position, and PET gradient (location) independently impacted SOC and TN to a 5-cm soil depth. Continuous cropping had 35 and 17% more SOC and TN, respectively, than the WF system. Cropping intensity still impacted SOC and TN when summed to 10 cm with CC > than WF. Soil organic C and TN increased 20% in the CC system compared with WF in the 0- to 10-cm depth. The greatest impact was found in the 0- to 2.5-cm layer, and decreased with depth. Soil organic C and TN levels at the high PET site were 50% less than at the low and medium PET sites, and toeslope soils were 30% greater than summit and sideslopes. Annualized stover biomass explained 80% of the variation in SOC and TN in the 0- to 10-cm soil profile. Cropping systems that eliminate summer fallowing are maximizing the amount of SOC and TN sequestered.

Soil organic matter degradation caused by the negative effects of cultivation on soil productivity and tilth (Bauer and Black, 1981) has been of increasing concern in recent years. Soil organic C and N have declined dramatically during 50 to 100 yr of cultivation in semiarid regions of the Great Plains, with estimated losses of 30 to 50% of the original SOC (Campbell and Souster, 1982; Mann, 1985; Peterson et al., 1998). Historically this region has supported conventional tillage dryland wheat cropping with alternate summer fallow, a management system that has resulted in accelerated rates of organic matter decomposition and erosion (Haas et al., 1957). Cropping systems, which include summer fallow negatively impact SOC (Campbell et al., 2000; Bowman et al., 1999; Black and Tanaka, 1997; Potter et al., 1997). Studies over the last 20 yr have shown that losses of SOC and TN are reduced by implementing management systems, which not only decrease the frequency of fallow, but also employ lesser amounts of tillage (Bauer and Black, 1981; Haas et al., 1957; Lamb et al., 1985).

Implementation of no-till management after years of conventional tillage has increased SOC in a wide range of soils and climates across the Great Plains (Bowman et al., 1999; Janzen et al., 1998; Peterson et al., 1998; Potter et al., 1997, 1998; Wood et al., 1991). Reducing the amount of tillage conserves surface residues and improves retention of water in the soil profile, which in turn allows for more intensive cropping systems and reduced frequency of summer fallow. The majority of long-term studies have shown that SOC is greatest in systems with soils managed with no-till. No-till management is synergistic with intensive cropping because the lack of soil disturbance optimizes water use efficiency. Cropping intensification from the historic single wheat crop every 2 yr, to decreased fallow frequency or even continuous cropping without a summer fallow period may therefore be achievable with implementation of no-till management (Peterson et al., 1993; Farahani et al., 1998; Peterson et al., 2001).

Typically, significant increases in SOC and TN with the conversion from conventional tillage to no-till and no fallow are observed only in the surface few centimeters of the soil (Franzluebbers et al., 1994; Bowman et al., 1999; Unger, 1991; Potter et al., 1998; Wood et al., 1991). The soil C pool is an enormous reservoir with a large degree of variability among and within individual landscapes, and consequently annual changes in SOC resulting from changes in management practices are comparatively small and difficult to detect. It is therefore critical to develop a sampling protocol that stratifies variability across climates and within vertical and horizontal microsites. By sampling landscape positions separately, and by sampling in small soil depth increments, we can detect small, but significant changes in SOC caused by changes in management.

Previous studies have concentrated on differences in SOC and TN as affected by different tillage management systems. However, the literature has little information on the affect of increasing cropping intensity on levels of SOC and TN. There is little research focusing on SOC and TN as affected by long-term (>10yr) cropping systems which represent increases in cropping intensity on soils previously managed under conventional tillage and then converted to no-till management. The objective of this study was to determine the effect of cropping intensity under no-till management on SOC and TN levels at the end of 12 yr (twelve completed cycles for G and CC, three completed cycles for WCMF, four completed cycles for WCF, and six completed cy-

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Abbreviations: ANOVA, analysis of variance; CC, continuous cropping; G, grass; GLM, general linear model; PET, potential evapotranspiration; SAS, Statistical Analysis System; SOC, soil organic C; TN, total N; WCF, wheat–corn-fallow; WCMF, wheat–corn–millet-fallow; WF, wheat-fallow.

Table 1. Site characterization and initial soil properties (0–5 cm) in the fall of 1985 at Sterling, Stratton, and Walsh.†

Site	Catena position	Surface texture‡	Ap depth	SOC	N	Pedon	Classification
			cm	g kg^{-1}			
Sterling	Summit	L	8	9.80	0.96	Weld	Fine-silty, mixed, mesic Aridic Argiustoll
	Side	L	20	9.69	0.93	Satanta	Fine-loamy, mixed, mesic Aridic Argiustoll
	Toe	L	18	14.59	1.37	Albinas	Fine-loamy, mixed, mesic Pachic Argiustoll
Stratton	Summit	CL	13	10.58	1.08	Norka	Fine-silty, mixed, mesic Aridic Argiustoll
	Side	L	10	10.44	1.03	Richfield	Fine, montmorillonitic, mesic Aridic Argiustoll
	Toe	L	15	19.21	1.87	Kuma	Fine-silty, mixed, mesic Pachic Argiustoll
Walsh	Summit	LS	18	2.73	0.30	undefined	Fine-loamy, mixed, mesic, Aridic Ustochrept
	Side	SL	10	3.04	0.33	undefined	Fine, montmorillonitic, mesic, Ustollic Haplargids
	Toe	SCL	13	8.49	0.88	Nunn	Fine, montmorillonitic, mesic Aridic Argiustoll

‡ L = loam, CL = clay loam, LS = loamy sand, SL = sandy loam, SCL = sandy clay loam.

† Surface texture, AP depth, soil organic C (SOC), N, Pedon, and classification adapted from Ortega, 1995; Peterson et al., 1993; and Wood et al., 1991.

cles for WF) across a PET gradient and across a gradient of soils along a topographic sequence. We hypothesized that soils that support intensive cropping, which produce greater amounts of biomass and maintain greater amounts of surface residues, will support higher levels of SOC and soil TN. Specifically, cropping systems that have reduced fallow frequencies under cooler climates and depositional slopes (toeslopes) will produce the largest amounts of SOC and TN, followed by summit soils and finally the sideslope soils.

MATERIALS AND METHODS

This study was conducted within a long-term sustainable dryland agroecosystems management project, which was initiated in the fall of 1985 to evaluate the effect of cropping intensity on total biomass production, water use efficiency, and other selected soil chemical and physical properties (Peterson et al., 1993). This study combines four major variables, each with a gradient, which consist of (i) PET location, (ii) soil productivity level (slope position), (iii) cropping intensity, and (iv) time. This study includes three locations in eastern Colorado that were under conventional tillage-crop management for over 50 yr before the initiation of this study. Soil classification and selected properites are presented in Table 1.

Study Locations

The study sites are located in the Great Plains of eastern Colorado along a north to south gradient of increasing PET within a 100-yr average annual precipitation of 420 mm. The northern site is located near Sterling, which has a low PET averaging 1015 mm yr^{-1} of open pan evaporation, with a latitude of 40°22′12″N and longitude of 103°7′48″W. The medium PET location is near Stratton and has an open pan evaporation of 1270 mm yr^{-1} with latitude of 39°10′48″N, and longitude of 102°15′36″W. The high PET location is located near Walsh with a open pan evaporation of 1900 mm yr^{-1} with a latitude of 37°13′48″N, and longitude of 102°10′12″W. The soil variable is represented by slope positions of summit, side, and toeslope positions along a catenary sequence. Each slope represents a unique soil series common to the geographic area.

Cropping Systems

Rotations with various cropping intensities are imposed with two replications across the soil sequences at each location in strips 6.1 m wide by 185 to 300 m long, depending on site. Cropping systems include: wheat-fallow (WF), wheat–corn-fallow (WCF), wheat–corn–millet-fallow (WCMF), continuous cropping (CC), which included corn/sorghum [*Sorghum bicolor* (L.) Moench], wheat, hay millet, and sunflower (*Helianthus annuus* L.) in order of frequency and planted grass species (G). Grain sorghum replaces corn in the cropping systems at Walsh and at Stratton before 1990. Grain sorghum production at Stratton was limited by growing season length (Peterson et al., 1991), and was thus replaced by corn in 1990 at this location. Sorghum is still grown at Walsh as it is suited to the high ET and longer growing season. Crops were planted

Table 2. Soil texture and bulk density by potential evapotranspiration (PET) site, slope position, and depth increment.

	Slope Position											
	Summit				Sideslope				Toeslope			
Site by Slope	Sand	Silt	Clay	Bulk density	Sand	Silt	Clay	Bulk density	Sand	Silt	Clay	Bulk density
cm	%			g cm^{-3}	%			g cm^{-3}	%			g cm^{-3}
Sterling (Low PET)												
0–2.5	39	37	24	1.45	38	36	26	1.34	31	43	26	1.24
2.5–5	38	37	25	1.46	40	33	27	1.34	29	44	27	1.30
5–10	34	35	31	1.53	38	34	28	1.36	29	43	28	1.32
10–20	37	35	28	1.41	33	34	33	1.34	29	41	30	1.47
Stratton (Med. PET)												
0–2.5	20	47	33	1.35	30	45	25	1.30	21	41	38	1.10
2.5–5	20	46	34	1.40	30	45	25	1.30	23	45	32	1.20
5–10	20	44	36	1.50	30	45	25	1.40	23	47	30	1.33
10–20	19	44	37	1.40	27	45	28	1.50	23	49	28	1.43
Walsh (High PET)												
0–2.5	67	18	15	1.53	63	19	18	1.38	37	33	30	1.28
2.5–5	66	15	19	1.49	55	22	23	1.37	35	36	29	1.35
5–10	66	13	21	1.67	40	30	30	1.60	33	38	29	1.53
10–20	64	13	23	1.68	37	29	34	1.69	32	37	31	1.62

Table 3. Soil organic C in 1997 after 12 yrs under no-till management as affected by location (potential evapotranspiration [PET] gradient), slope position, cropping intensity, and soil depth.

	Slope Position												
	Summit				Sideslope				Toeslope				
	WF†	WCF‡	WCMF§	CC¶	WF	WCF	WCMF	CC	WF	WCF	WCMF	CC	*Site mean*
Sterling:													
Low PET	kg ha^{-1}				kg ha^{-1}				kg ha^{-1}				
0–2.5 cm	4 400	3 760	4 165	4 805	3 700	3 690	3 835	5 425	3 880	4 910	5 660	7 100	
2.5–5 cm	3 430	3 050	3 125	3 370	3 225	3 000	3 130	3 320	3 280	3 890	4 055	4 725	
5–10 cm	6 010	5 100	5 175	5 635	5 135	5 075	5 270	5 540	5 980	6 410	6 605	6 615	
10–20 cm	11 090	10 395	9 430	9 695	10 615	10 010	9 995	10 660	12 235	11 180	12 450	12 700	
Sum 0–10cm	*13 840*	*11 910*	*12 460*	*13 810*	*12 065*	*11 760*	*12 235*	*14 290*	*13 140*	*15 210*	*16 320*	*18 440*	*13 790*
Stratton:													
Med. PET													
0–2.5	3 775	3 800	4 505	4 725	3 005	3 785	3 975	4 390	4 825	5 250	5 610	6 145	
2.5–5	3 010	3 200	3 330	3 675	2 540	2 900	2 925	3 020	4 160	4 520	4 560	4 410	
5–10	5 670	5 870	6 160	6 410	4 945	5 310	5 530	5 565	6 485	7 920	7 575	7 250	
10–20	9 544	9 375	10 090	10 290	8 775	10 510	10 335	9 375	11 960	13 600	12 960	13 730	
Sum 0–10cm	*12 460*	*12 865*	*14 000*	*14 810*	*10 490*	*11 995*	*12 430*	*12 975*	*15 465*	*17 690*	*17 740*	*17 805*	*14 225*
Walsh:													
High PET													
0–2.5	1 025	1 290	1 460	1 570	1 340	1 635	1 510	2 155	2 915	3 205	3 200	3 760	
2.5–5	980	1 135	1 200	1 240	1 095	1 255	1 270	1 440	2 160	2 615	2 770	2 805	
5–10	1 940	2 295	2 460	2 610	2 940	2 835	2 930	2 970	3 920	4 585	4 890	4 940	
10–20	3 740	4 255	4 200	5 575	6 550	6 270	6 480	7 430	9 155	9 365	9 215	9 030	
Sum 0–10cm	*3 940*	*4 720*	*5 120*	*5 420*	*5 375*	*5 725*	*5 705*	*6 560*	*8 995*	*10 405*	*10 860*	*11 500*	*7 025*
Slope Mean 10cm	*10 080*	*9 830*	*10 525*	*11 350*	*9 310*	*9 830*	*10 120*	*11 275*	*12 535*	*14 435*	*14 970*	*15 915*	

	0–2.5 cm		2.5–5 cm		5–10 cm		10–20 cm		0–10 cm	
Analysis of Variance	$P > F$	LSD	$P > F$	LSD	$P > F$	$LSD_{0.050}$	$P > F$	$LSD_{0.050}$	$P > F$	$LSD_{0.050}$
Site	0.0163	1 113	0.0082	584	0.0174	1 274	0.0222	2 173	0.0144	2 970
Slope	0.0004	473	<.0001	275	0.0001	417	0.0001	797	0.0001	1 079
Site × Slope	0.4151		0.1026		0.0620		0.0565		0.1243	
Cropping	0.0025	523	0.0224	265	0.1327		0.5147		0.0105	1 129
Site × Cropping	0.4463		0.8299		0.6986		0.4559		0.7397	
Slope × Cropping	0.4515		0.4120		0.4138		0.9750		0.4521	
Site × Slope × Cropping	0.8197		0.5675		0.9552		0.3482		0.8907	

† Wheat (*Triticum aestivum*)-fallow.

‡ Wheat-corn (*Zea Mays*) or sorghum [*Sorghum bicolor* (L.) Moench]-fallow.

§ Wheat-corn or sorghum-millet (*Panicum miliaceum*)-fallow.

¶ Continuous cropping systems.

using no-till planters and drills that only disturbed the soil in a narrow band to allow for a seed row. Winter wheat was planted with an application of a contract herbicide and then evaluated in the spring for additional herbicide applications. Spring crops were planted using a residual weed control along with a contact burn-down to control excising weeds. Additional herbicide applications were done as needed through the season to control weeds. Crops were planted and P was

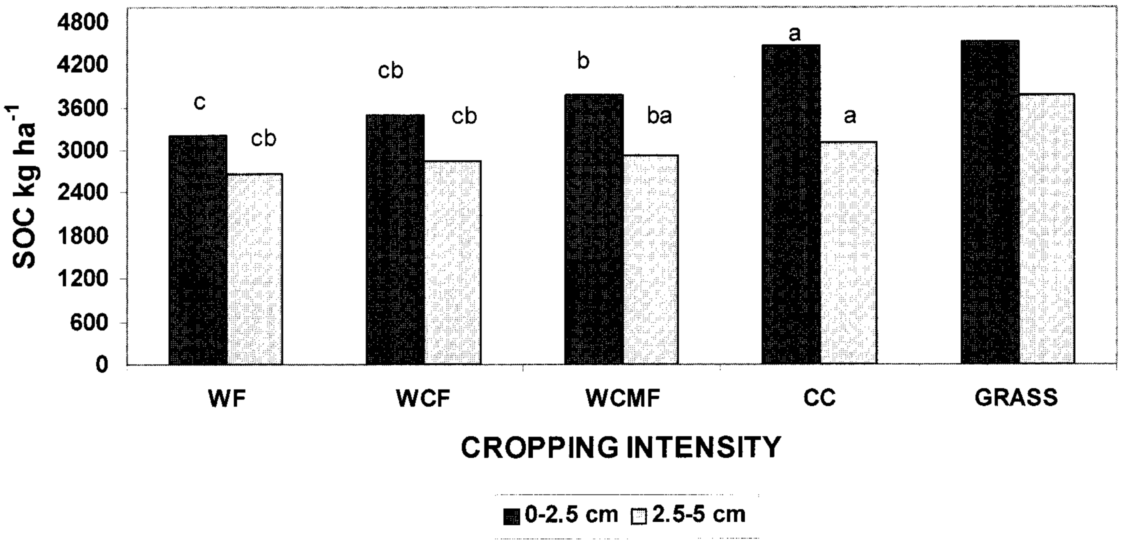


Fig. 1. Soil organic C in the 0- to 2.5- and 2.5- to 5-cm depths after 12 yr under no-till management as affected by cropping intensity with grass as a reference point (averaged over locations and slopes). Means followed by a different letter within depths are statistically different ($P < 0.05$) using Fisher's LSD.

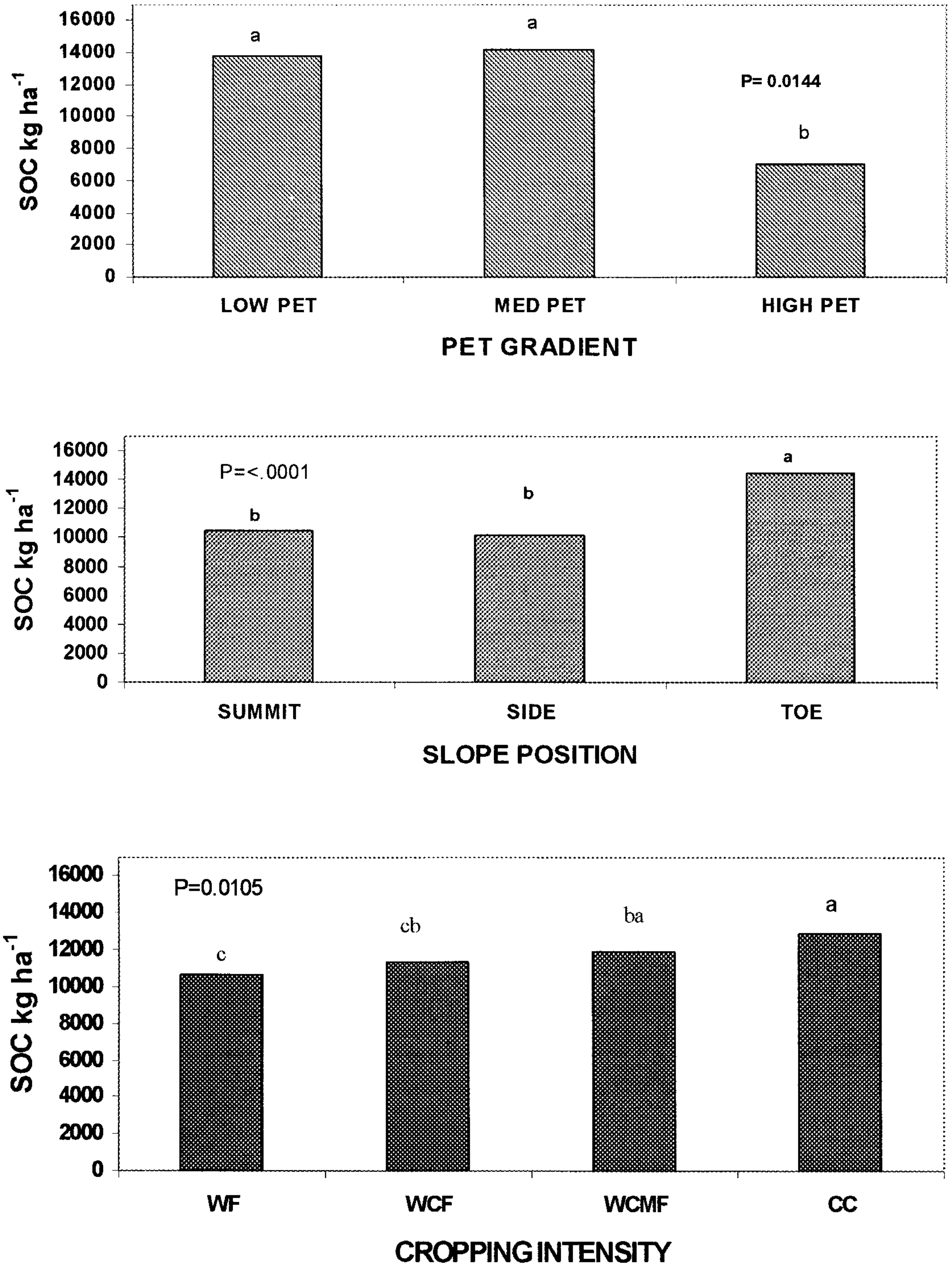


Fig. 2. Soil organic C as affected by PET gradient, slope position, and cropping intensity in the 0- to 10-cm depth. Means followed by a different letter are statistically different ($P < 0.05$) using Fisher's LSD.

band applied near the seed. Fertilizer was applied based on annual soil tests for available N and P with the exception of G, which was not fertilized. These systems represent a gradient of cropping intensities with WF having an intensity factor of 0.50 of crops divided by years in the rotation. The intensity factors of WCF, WCMF, and CC are 0.67, 0.75, and 1.0, respectively. The grass was not given a cropping intensity factor as it is a check of a perennial system. This treatment, which was established in the spring of 1986, contains a mixture of perennial species including both warm and cool season grasses. The planted seed mixture contained equal parts of crested wheatgrass (*Agropyron cristatum*), western wheatgrass (*Agropyron smithii*), sideoats grama (*Bouteloua curtipendula*), little bluestem (*Andropogon scoparius*), blue grama (*Bouteloua gracilis*), and buffalo grass (*Buchloe dactyloides*). Annual cutting, raking, and removal of the G biomass was done in the early fall starting in the fall of 1990.

In 1997 all the cropping systems were back to the phase, which they started out with in the fall of 1985. The WF cropping system completed six cycles, while the WCF and WCMF

Table 4. Soil total N in 1997 after 12 yr under no-till management as affected by location (potential evapotranspiration [PET] gradient), slope position, cropping intensity, and soil depth.

	Slope Position												
	Summit				Sideslope				Toeslope				
	WF†	WCF‡	WCMF§	CC¶	WF	WCF	WCMF	CC	WF	WCF	WCMF	CC	*Site mean*
Sterling:													
Low PET	kg ha^{-1}				kg ha^{-1}				kg ha^{-1}				
0–2.5 cm	345	330	370	385	325	310	340	400	300	370	465	565	
2.5–5	315	280	310	325	315	285	295	355	300	350	375	395	
5–10 cm	590	500	560	580	470	515	565	605	520	575	640	620	
10–20 cm	1340	1120	1185	1175	1130	1025	1140	1220	1160	1175	1280	1265	
Sum 0–10cm	*1250*	*1110*	*1240*	*1290*	*1110*	*1110*	*1200*	*1360*	*1120*	*1295*	*1480*	*1580*	*1260*
Stratton:													
Med. PET													
0–2.5	350	340	380	455	285	280	315	355	520	480	530	565	
2.5–5	305	300	310	370	250	240	265	300	420	420	405	435	
5–10	610	600	650	685	500	480	530	570	655	685	725	730	
10–20	1040	1045	1140	1295	985	1000	1050	1110	1260	1315	1300	1395	
Sum 0–10cm	*1265*	*1240*	*1340*	*1510*	*1035*	*1000*	*1110*	*1225*	*1595*	*1585*	*1660*	*1730*	*1400*
Walsh:													
High PET													
0–2.5	140	100	130	200	100	115	115	210	245	285	280	315	
2.5–5	90	120	145	145	105	110	95	135	205	200	220	255	
5–10	190	220	240	295	240	220	270	210	350	440	390	460	
10–20	370	535	370	555	650	440	665	710	870	750	750	770	
Sum 0–10cm	*420*	*440*	*515*	*640*	*445*	*445*	*480*	*555*	*800*	*925*	*890*	*1030*	*650*
Slope Mean 10cm	*980*	*930*	*1030*	*1150*	*865*	*860*	*930*	*1050*	*1170*	*1270*	*1345*	*1450*	

	0–2.5 cm		2.5–5 cm		5–10 cm		10–20 cm		0–10 cm	
Analysis of Variance	$P > F$	LSD	$P > F$	LSD	$P > F$	$\text{LSD}_{0.050}$	$P > F$	$\text{LSD}_{0.050}$	$P > F$	$\text{LSD}_{0.050}$
Site	0.0039	45	0.0038	38	0.0003	18	0.0006	151	0.0014	90
Slope	0.0003	40	<.0001	21	0.0001	31	0.0022	79	<.0001	80
Site × Slope	0.1112		0.0151	37	0.0078	54	0.0311	128	0.0173	177
Cropping	0.0010	37	0.0157	27	0.1213		0.0425		0.0108	117
Site × Cropping	0.7335		0.9889		0.9846		0.5752		0.9642	
Slope × Cropping	0.7713		0.8819		0.3306		0.2554		0.3977	
Site × Slope × Cropping	0.3622		0.5217		0.2015		0.0188	170	0.3003	

† Wheat (*Triticum aestivum*)-fallow.
‡ Wheat-corn (*Zea Mays*) or sorghum [*Sorghum bicolor* (L.) Moench]-fallow.
§ Wheat-corn or sorghum-millet (*Panicum miliaceum*)-fallow.
¶ Continuous cropping systems.

systems completed four and three complete cycles after 12 yr. The CC and G systems both completed 12 yr as there is only 1 yr in the rotation cycle.

Stover yields were estimated by dividing combine yields by the ratio of grain/stover as found from collected total above ground biomass samples from each location, slope and cropping systems each year. The annual stover inputs were then added up for each of the cropping systems and divided by 12 to get an annualized stover input.

Sample Preparation and Analysis

Soil cores were taken from all cropping systems including G at all three sites and at all three slopes in the fall of 1997 from 0- to 2.5-, 2.5- to 5-, 5- to 10-, and 10- to 20-cm depth increments for each of the two replications. A total of fifteen 2.54-cm diam. soil cores were obtained and composited for each depth in each plot with surface residue excluded from the samples. Soils were air dried for several days and then ground to pass a 2-mm sieve size. All visible plant material larger than 2-mm sieve size; roots or surface residues, were removed. A subsample of 20 to 25 g from this 2-mm sieved soil was powder ground to pass through a 300-μm (80-mesh) sieve using a stainless steel ball-mill grinder and analyzed for SOC and TN. Soil organic C was determined by wet oxidation (Nelson and Sommers, 1982). Total soil N was determined by dry combustion using an automated elemental analyzer (Leco, St. Joseph, MI).

Soil texture was determined by the hydrometer method (Gee and Bauder, 1986) on fallow phase soils only for general classification using the 2-mm sieved soil sample. Bulk density at the end of the fallow phase and in the CC and G plots was obtained by the core method (Blake & Hartge, 1986). The average of two bulk densities taken between rows within an experimental unit was used in our nutrient mass calculations. These selected soil properties are provided in Table 2.

Experimental Design and Sampling

All phases of each cropping system are present each year in each of the replications. The cropping systems were randomly imposed across the summit position of the landscape and then continued downslope without further randomization. The experimental unit is therefore a specific soil series (slope) within a site and within a cropping system phase. The experimental design is a split-split-block design that includes location (low PET [Sterling], medium PET [Stratton], and high PET [Walsh]), slope position (summit, sideslope, and toeslope), and cropping systems (WF, WCF, WCMF, CC, and G) variables within two replicated blocks (Peterson et al., 1993; Peterson and Westfall, 1997). Cropping systems were randomly assigned in strips within each block at each location. Slope positions run within the strips across cropping systems. Although slope positions were not randomized, a split block analysis at each location was used as if they had been (Steel and Torrie,

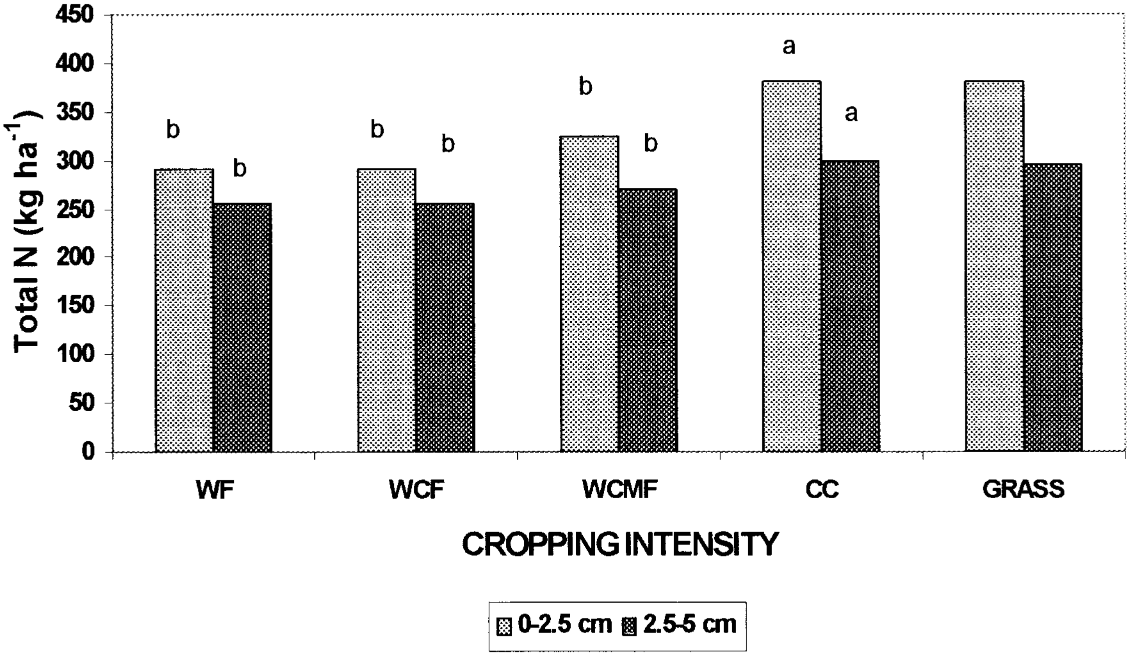


Fig. 3. Soil total N in 0- to 2.5- and 2.5- to 5-cm depth after 12 yr in no-till management as affected by cropping intensity with grass as a reference point (averaged over locations and slopes). Means followed by a different letter within depths are statistically different ($P < 0.05$) using Fisher's LSD.

1997). The variance was partitioned appropriately to test the main effects and any interactions.

Analyses of Variance (ANOVA) were done using the procedure general linear model (GLM) of the Statistical Analysis System (SAS, SAS Institute Inc., 1999) for test of all main effects and interactions. The option means in the GLM procedure was used to obtain all main effect means separations using Fisher's Protected Least Significant Difference (LSD) using the appropriate error term when the ANOVA showed significance ($P \leq 0.05$). Location was tested with replication (Location) term. Slope and a site by slope interaction was tested using a slope × replication (Location) term. Cropping intensity and location by cropping was tested using the cropping × replication (Location) term. When interactions were significant, LSDs were calculated by comparing slopes within sites (site × slope), cropping system within site (site × cropping), cropping system within slope (slope x cropping system), and cropping system within site and slope (site × slope × cropping system) using the appropriate standard error term. In addition, regression analysis also was used to quantify the relationship between aboveground stover inputs and SOC in the summed 0- to 10-cm depth.

RESULTS AND DISCUSSION

Soil Organic Carbon

We hypothesized that increasing cropping intensity would increase SOC because intensification results in greater amounts of biomass being returned to the soil. Cropping intensification did increase SOC (Table 3 and Fig. 1). Cropping system intensification increased SOC in both the 0- to 2.5- and 2.5- to 5-cm soil depths, and there was a tendency for this effect to continue into the 5- to 10-cm layer ($P = 0.13$) (Table 3). Evaluation of WF and WCMF on summit soils after 8 yr in these no-till rotations by Ortega et al. (2002) also found a trend in SOC and TN levels to be highest in the more intensive system, although not significant ($P = 0.16$). Note that the SOC level in 0- to 2.5-cm depth of the CC treatment actually approached the amounts found in the G reference (statistics not performed). This is remarkable in that the perennial G treatment is returning large amounts of root biomass relative to the CC or other cropping systems. An average annual above ground biomass yield from G at the low, medium, and high PET locations were 1700, 1930, and 1240 kg ha^{-1} respectively. In all but the 0- to 2.5-cm depth the G treatment appears to be superior to any of the cropped systems.

Interestingly cropping system effects on SOC did not interact with site (PET gradient) and soil position (Table 3). However, as one would expect, site and soil position did affect SOC. These effects were independent as evidenced by the lack of significant interactions. The soil productivity gradient did not show a separation between the summit and sideslope soils but did show that toeslope soils had the greatest SOC levels at all soil depths, as one would expect because of their depositional nature (Burke et al., 1995). The effect of climate, PET gradient, was well demonstrated at all depth increments with the high PET site having approximately half the level found in the medium and low PET sites. The high PET site has approximately a 25% increase in deficit moisture (annual precipitation-open pan evaporation) from the low PET site, which impacts the production potential.

The effect of cropping intensity on SOC summed to a 10-cm depth was independent of slope position and PET site effects as no interactions were significant (Table 3). Soil organic C was greatest in CC and WCMF and least in WF. The cropping system without any summer fallow (CC) had a 20% increase in SOC over the WF cropping system which has the maximum frequency

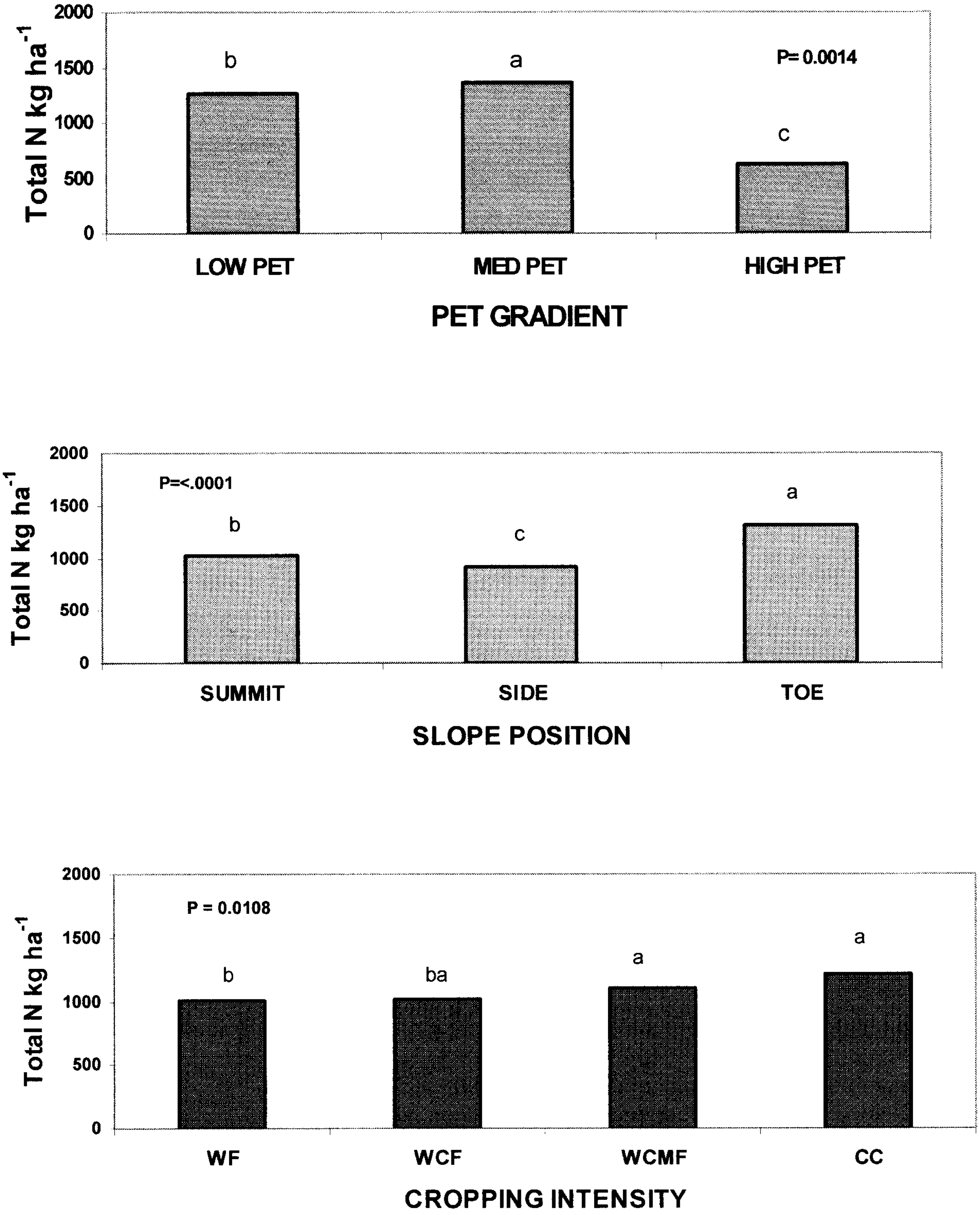


Fig. 4. Soil total N as affected by PET gradient, slope position, and cropping intensity in the 0- to 10-cm summed depth (averaged over locations and slopes). Means followed by a different letter are statistically different ($P < 0.05$) using Fisher's LSD.

of summer fallow. These results are similar to Bowman et al. (1999), which found a 20% increase in SOC from a cropping system of WF two CC in a 0- to 5-cm depth. In a long-term minimum tillage experiment in semiarid southwestern Saskatchewan researchers found that SOC was increased in cropping systems without any summer fallow that were adequately fertilized and that frequent fallowing resulted in the lowest SOC. The exception to this was when fall seeded crops were included that reduced the erosion potential (Campbell et al., 2000; Campbell and Zentner, 1993).

The WF and WCF cropping systems were not statistically different. The low and medium PET sites had equal SOC levels and the high PET site had approximately

Table 5. Annualized stover production after 12 yr under no-till management as affected by location (PET gradient), slope position, and cropping intensity.

	Slope Position			
Site	**Summit**	**Sideslope**	**Toeslope**	**Means**
Sterling		kg ha^{-1}		
Low PET				
WF†	**1570**	**1625**	**1950**	**1715**
WCF‡	**2155**	**2060**	**2705**	**2310**
WCMF§	**2145**	**2315**	**2725**	**2395**
CC	**3020**	**2880**	**3790**	**3230**
Mean	***2225***	***2220***	***2795***	***2415***
Stratton				
Medium PET				
WF	**2060**	**1825**	**2820**	**2235**
WCF	**2290**	**2120**	**3465**	**2625**
WCMF	**2285**	**2150**	**3480**	**2640**
CC	**3905**	**3470**	**4735**	**4040**
Mean	***2635***	***2390***	***3625***	***2885***
Walsh				
High PET				
WF	**1050**	**1125**	**1320**	**1165**
WCF	**1345**	**1525**	**1860**	**1575**
WCMF	**1420**	**1640**	**2135**	**1730**
CC	**1220**	**1325**	**1825**	**1460**
Mean	***1260***	***1405***	***1785***	***1485***

ANAYLYSIS OF VARIANCE	$P > F$	LSD$_{0.050}$
Site	**0.0058**	**333**
Slope	**0.0027**	**331**
Site × Slope	**0.2384**	
Cropping	**<.0001**	**249**
Site × Cropping	**0.0020**	**430**
Slope × Cropping	**0.2596**	
Site × Slope × Cropping	**0.9635**	

† Wheat-fallow.
‡ Wheat-corn-fallow.
§ Wheat-corn-millet-fallow.
¶ Continuous cropping systems.

half of the level found in the low and medium PET sites (Fig. 2). The fact that the medium PET site had SOC equal to the low PET site was not unexpected. This location historically produces the slightly greater yields and had an initial SOC level 2.05 g kg greater than the low PET site (Table 1) when averaged over slope position. The impact of climate on SOC is also affected by decomposition rates at a particular site (Paustain et al., 1998).

Soil Total Nitrogen

Soil total N results tracked similarly with the SOC results. This was not unexpected as SOC and TN are biologically linked. Unger (1968), found a highly correlated linear relationship between soil organic matter and TN with various tillage and cropping systems and soil depths ($r = 0.99$). We hypothesized that increasing cropping intensity would increase TN because the intensification results in greater amounts of biomass being returned to the soil. As cropping system intensified, a trend for increased TN in depths 0 to 2.5, 2.5 to 5, and 5 to 10 cm was evident. However, only CC cropping was statistically different from the other systems in the first two depth increments (Table 4 and Fig. 3). There was a significant PET site by slope position by cropping system interaction in the 10- to 20-cm depth ($P = 0.02$). This interaction is likely caused by the summit slope WF cropping system at the low PET site had a greater TN than the toeslope soil. In addition, at the high PET site, WF had higher TN levels than the WCF, WCMF, and CC cropping systems on the toeslope soil.

The effects of the soil productivity gradient, represented by slope position, on TN was strongly significant for all depth increments. There were significant site by slope interactions however in all but the 0- to 2.5-cm depth. These interactions are apparently because the toeslope soil did not differ from the side and summit soils at the low PET site. It is unclear why soils at this PET site were not different in TN at these depths. The tendency is that the low and medium PET sites have approximately double the TN as does the high PET site. Total soil N in the 0- to 2.5-cm depth increased from sideslope and summit to toeslope as hypothesized (Table 4). The summit and sideslopes did not differ from each other, but the toeslope soils had approximately 30% more TN than either the side or summit soils.

The effect of cropping intensity on TN did not diminish when depths were summed to 0 to 10 cm, as soil TN increased with increasing cropping intensity (Fig. 4). The TN in the WF and WCF cropping systems did not differ. However, the CC and WCMF rotations did have significantly greater TN than the WF cropping systems in the 10-cm depth.

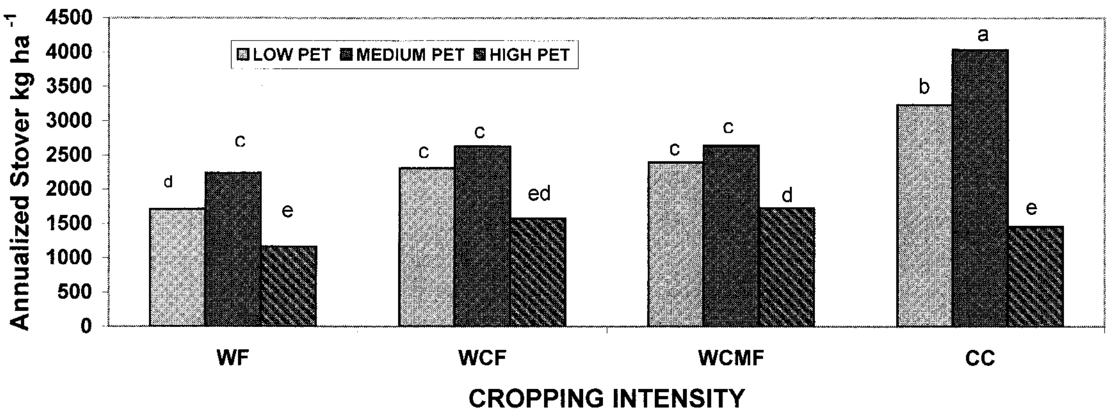
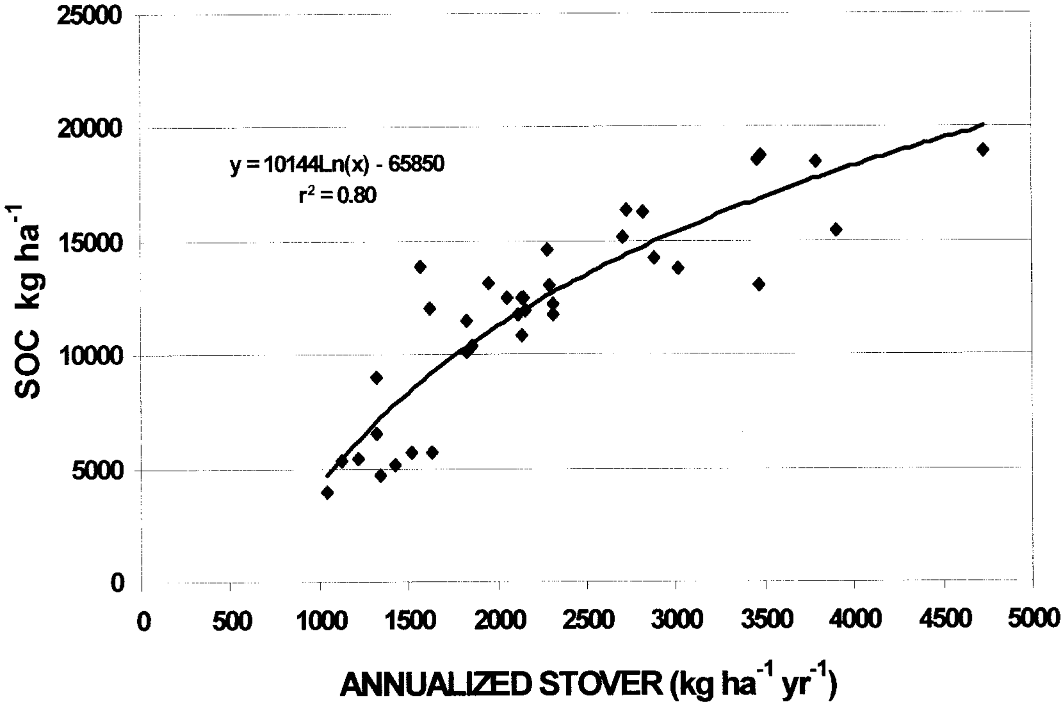


Fig. 5. Annualized stover inputs over a 12-yr period in no-till management as affected by the interaction of cropping intensity and location (PET gradient). Means followed by a different letter are statistically different ($P < 0.05$) using Fisher's LSD.

Stover Production

Annualized production of stover for the 12-yr period for the four cropping systems is presented in Table 5. Increased cropping intensity increased stover production and interacted strongly with PET site, as one would expect. The interaction with PET site (Fig. 5) is a result of the reduced stover production in the CC cropping system at the high PET site. This site is the most water-stressed location, and the CC cropping system experienced 3 yr of failure in the 12 yr period. Generally, stover production increased as system intensity increased, with CC producing approximately 70% more stover than the WF cropping system. At the high PET site however, the CC cropping system average annualized stover production was not significantly different from WCF and WCMF. This site has the largest water deficit and per-



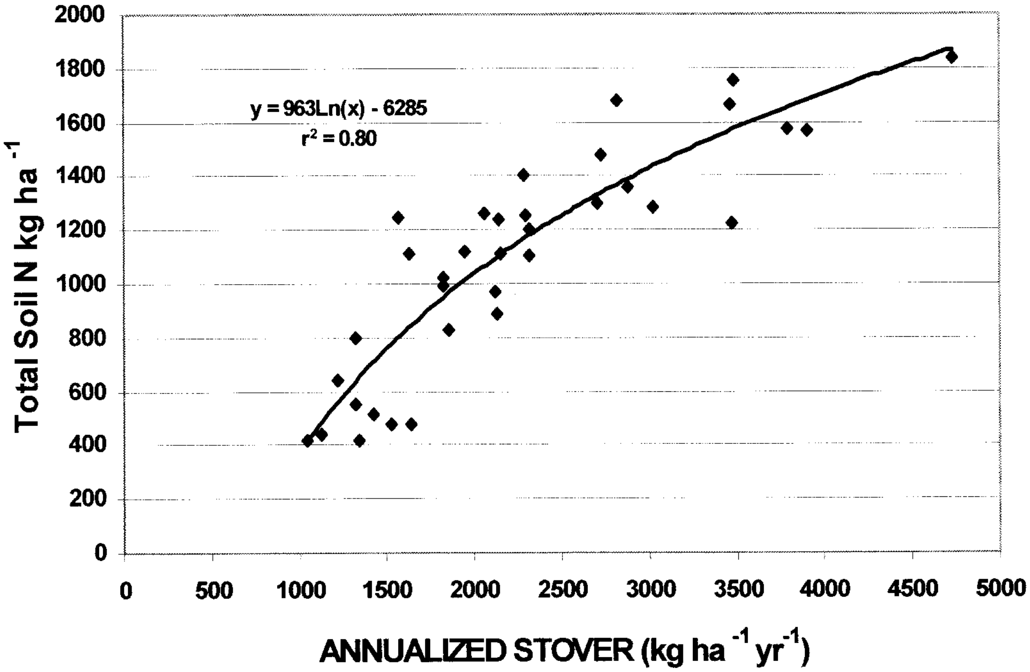


Fig. 6. Relationship of annualized stover production and soil organic C (SOC) and total N in the 0- to 10-cm depth after 12 yr under no-till management.

haps this cropping system is approaching the maximum production for the PET environment.

Soil Organic Carbon and Total Nitrogen vs. Annualized Stover

Annualized stover inputs averaged over all cropping systems, PET sites, and slope positions had a strong relationship with SOC and TN in the 0- to 10-cm depth (r^2 = 0.80) (Fig. 6). The slope for SOC was approximately 10 times the slope found for TN. It is notable that 80% of the variability in SOC and TN in 0- to 10-cm depth is accounted for by the annualized stover production. Robinson et al. (1996) also found stover additions correlated with SOC (r^2 = 0.70 when averaged over locations). Paustian et al. (1998) states that if we view organic matter decomposition as a series of first-order reactions then the amount of soil organic matter maintained is directly proportional to the rate of C inputs, which this data demonstrates.

SUMMARY AND CONCLUSIONS

No-till management practices on medium- to fine-textured soils in the central Great Plains has conserved enough moisture to successfully facilitate reducing fallow periods and increasing cropping intensity from the traditional WF system to intensities that include cropping systems without summer fallow (CC). This study shows the cumulative impact of 12 yr of no-till management on cropping systems with increasing intensities within a gradient of soil productivity (slope position) across a climate PET gradient. Slope position, and location (PET gradient) independently impacted SOC and TN to a soil depth of 5 cm. Overall, toeslope soils had 30% more SOC and TN in all depths and in the summed 10 cm than found in side or summit soils. The impact of PET gradient also was evident in the levels of SOC and TN found in all depths and summed profiles, such that the high PET site had 50% of the amounts found at the low and medium PET sites. Increasing cropping intensity increased SOC and TN at all locations and slope positions. After only 12 yr of the CC cropping system, SOC was 88% of that found in the G reference in the 0- to 10-cm profile, and SOC and TN were 35 and 17% greater, respectively, than amounts found in the WF cropping system.

Continuous cropping minimizes the opportunity for accelerated rates of SOC oxidation and most closely simulates perennial systems in which the balance between nutrient immobilization and mineralization processes results in minimum nutrient loss and maximum accumulation of organic matter. Summer fallow disrupts this balance between immobilization and mineralization processes, and the greater soil moisture and temperature conditions that occur under summer fallow result in an accelerated rate of SOC oxidation (Haas et al., 1974). Other researchers also have noted that annually cropped soils have greater C and N than soils that are summer fallowed (Campbell et al., 2000; Bowman et al., 1999; Black and Tanaka, 1997; Bremer et al., 1995; Campbell and Zentner, 1993). As the frequency of summer fallow increases, the negative impact on SOC and TN increases as a shift in the C transfer through the soil is proportionally shifted to a greater mineralization. Our study demonstrates that minimizing summer fallow in the central Great Plains is essential to the increase in SOC and TN levels, and thereby the overall sustainability of the agroecosystem. Further research will focus on active, slow and stable fractions of soil organic matter pools after 12 yr in these no-till cropping systems. Absolute changes in SOC and TN from measured amounts in 1986 to 1997 will also be investigated.

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REFERENCES

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166–1170.

Black, A.L., and D.L. Tanaka. 1997. A conservation tillage-cropping systems study in the northern Great Plains of the United States. p.335–342. *In* E.A. Paul (ed.), Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.

Blake, G.R., and K.H. Hartge. 1986. Bulk Density. p. 363–375. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil orgnaic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186–191.

Bremer, E., B.H. Ellert, and H.H. Janzen. 1995. Total and light-fraction carbon dynamics during four decades after cropping changes. Soil Sci. Soc. Am. J. 59:1398–1403.

Burke, I.C., E.T. Elliott, and C.V. Cole. 1995. Influence of macroclimate, landscape position, and management on foil organic matter in agroexosystems. Ecol. Appl. 5:124–131.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. Organic C accumulation in soil over 30 yr in semiarid southwestern Saskatchewan—Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179–192.

Campbell, C.A., and R.P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J. 57:1034–1040.

Campbell, C.A., and W. Souster. 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. 62:651–656.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems—The significance of cropping intensification. Soil Sci. Soc. Am. J. 62:984–991.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58:1639–1645.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9, ASA and SSSA, Madison WI.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. USDA Tech. Bull. No. 1164. U.S. Government Printing Office, Washington, DC.

Haas, H. J., W. O. Willis, and J. J. Bond. 1974. Summer fallow in the western United States. p. 2–35. *In* USDA Cons. Res. Rep. No. 17. U.S. Gov. Print. Office, Washington, DC.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. Soil Tillage Res. 47:181–195.

Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Wheat-fallow tillage systems' effect on a newly cultivated grassland soils' nitrogen budget. Soil Sci. Soc. Am. J. 49:352–356.

Mann, L.K. 1985. Changes in soil carbon storage after cultivation. Soil Sci. 142:279–288.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. P. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Ortega, R.A., G.A. Peterson, and D.G. Westfall. 2002. Residue accumulation and changes in soil organic matter as affected by cropping intensity in no-till dryland agroecosystems. Agron. J. 94:944–954.

Paustian, K., E.T. Elliott, and M.R. Carter. 1998. Tillage and crop management impacts on soil C storage: Use of long-term experimental data. Soil Tillage Res. 47:vii–xii.

Peterson, G.A., D.G. Westfall, F.B. Peairs, L. Sherrod, D. Poss, W. Gangloff, K. Larson, D.L. Thompson, L.R. Ahuja, M.D. Koch, and C.B. Walker. 2001. Sustainable dryland agroecosystem management. Tech. Bull. TB01–2. Agric. Exp. Stn., Colo. State Univ., Fort Collins, CO.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage Res. 47:207–218.

Peterson, G.A., and D.G. Westfall. 1997. Management of dryland agroecosystems in the central Great Plains of Colorado. p. 371–380. *In* E.A. Paul et al. (ed.), Soil organic matter in temperate agroecosystems. Lewis Publishers, Boca Raton, FL.

Peterson, G.A., D.G. Westfall, and C.V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57:1354–1360.

Peterson, G.A., D.G. Westfall, L. Sherrod, E. McGee, and R. Kolberg. 1991. Soil and crop management in dryland agroecosystems. Tech. Bull. TB01–2. Agric. Exp. Stn., Colo. State Univ., Fort Collins, CO.

Potter, K.N., O.R. Jones, H.A. Torbert, and P.W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern high plains. Soil Sci. 162:140–147.

Potter, K.N., H.A. Torbert, O.R. Jones, J.E. Matocha, J.E. Morrison, Jr., and P.W. Unger. 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 14:39–52.

Robinson, C.S., R.M. Cruse, and M. Ghaffarzadeh. 1996. Cropping system and nitrogen effects on Mollisol organic carbon. Soil Sci. Soc. Am. J. 60:264–269.

SAS Institute Inc. 1999. SAS/STAT user's guide. Release 7.0 ed. SAS Inst. Inc., Cary, NC.

Steel, R.G.D., and J.H. Torrie. 1997. Principles and procedures of statistics. 3rd. ed. McGraw-Hill Book Co., New York.

Unger, P.W. 1991. Organic matter, nutrient, and pH distribuion in no-tillage and conventional-tillage semiarid soils. Agron. J. 83:186–189.

Unger, P.W. 1968. Soil organic matter and nitrogen changes during 24 years of dryland wheat tillage and cropping practices. Soil Sci. Soc. Am. J. 32:427–429.

Wood, C.W., D.G. Westfall, and G.A. Peterson. 1991. Soil carbon and nitrogen changes on initiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55:470–476.