Carbon and Nitrogen Conservation in Dryland Tillage and Cropping Systems

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ABSTRACT

Soil C and N greatly influence long-term sustainability of agricultural systems. We hypothesized that cropping and tillage differentially influence dryland soil C and N characteristics in the Southern High Plains. A Pullman clay loam (fine, mixed, thermic Torrertic Paleustol) cropped to wheat (*Triticum aestivum* L.)–sorghum [*Sorghum bicolor* (L.) Moench]–fallow (WSF), continuous wheat (CW) and continuous sorghum (CS) under no-tillage (NT), and stubble mulch (SM) was sampled at three depths to determine soil C and N characteristics. For CW, CS, and WSF phases (F_{WSF}, S_{WSF}, W_{WSF}), soil organic C (SOC) averaged 10.6 to 13.1 kg m^{-3} and was greatest for CW. Carbon mineralization (C_{MIN}) at 0 to 20 mm was 30 to 40% greater for CW and F_{WSF} than for CS, S_{WSF}, or W_{WSF}. Cropping system by depth influenced soil organic N (SON) with greatest SON at 0 to 20 mm in CW (1.5 kg m^{-3}). At 0 to 20 mm for SM and NT, SOC was 9.9 and 12.5 kg m^{-3}, soil microbial biomass C (SMBC) was 0.80 and 1.1 kg m^{-3}, and soil microbial biomass N (SMBN) was 0.14 and 0.11 kg m^{-3}. Also at 0 to 20 mm, NT had 60% greater C_{MIN}, 11% more SMBC as a portion SOC, and 25% more SON compared to SM. Summed for 0 to 80 mm, NT had more SOC (0.98 vs 0.85 kg m^{-2}) and SON (0.10 vs 0.9 kg m^{-2}) than SM, and CW had greater or equal C and N activity as other systems. Negative correlations between yield and SOC, SMBC, C_{MIN}, SON, and SMBN indicate N removal in grain negatively affects active and labile C and N pools. Under dryland conditions, C and N conservation is greater with NT and with winter wheat because of less soil disturbance and shorter fallow.

Management decisions about cropping and tillage intensities and frequencies along with climatic conditions alter residue inputs to soil. Residue inputs subsequently modify soil properties important to soil quality and crop production (Carter and Rennie, 1984; Collins et al., 1992; Campbell et al., 1991 a,b,c). Soil organic carbon (SOC), soil organic nitrogen (SON), and production potential of Great Plains cropped soils have diminished compared with native sod because of smaller residue inputs, increased soil erosion, and increased organic matter decomposition (Haas et al., 1957; Burke et al., 1989). Losses of SOC and SON are greater where cropping systems include fallow (Haas et al., 1957; Bauer and Black, 1981; Collins et al., 1992) and intensive tillage (Bauer and Black, 1981; Follett and Schimel, 1989; Unger, 1991; Christensen et al., 1994). Crop residue inputs are directly related to differences in SOC among some cropping systems (Carter, 1986; Collins et al., 1992; Campbell et al, 1992 b; Campbell and Zentner, 1993) while in other systems frequent tillage eliminated expected differences (Campbell et al., 1992a). Intensive tillage increases carbon loss and decreases immobilization and conservation of mineral N by soil microorganisms (Follett and Schimel, 1989). Loss of soil productivity is exacerbated by leaching of N below the root zone during fallow periods (Campbell and Zentner, 1993; Eck and Jones, 1992).

Systems with less tillage and less summer fallow are believed to be superior in maintaining soil organic matter quantity and activity because of reduced soil disturbance and greater C inputs (Wood et al., 1990). In western Canada, Carter (1986) found significantly less soil microbial biomass carbon (SMBC) in wheat-fallow compared with continuous wheat (CW) and no-tillage (NT) increased SMBC at 0 to 50 mm, 10 to 23% compared with disk tillage to 100 mm after 4 yr. Wood et al. (1990) demonstrated greater C and N turnover and potential mineralization for wheat–corn–millet–fallow than for wheat–fallow (WF) after only 3.5 yr at three locations in Colorado. Collins et al. (1992) showed that SOC, SON, SMBC, and soil microbial biomass nitrogen (SMBN) were greater in long-term continuously cropped compared with crop–fallow rotations at Pendleton, OR.

Few studies have examined crop rotation phase influences on soil organic matter characteristics (Campbell et al., 1992 a,b). Soil characteristics that change slowly over time are not expected to be different among phases of a rotation; however, such characteristics may be influenced by crop yield and residue input differences among phases triggered by short-term differences in cultural practices or year-to-year differences in environment (Campbell et al., 1992a). Subsequent effects of these differences would be more apparent from dynamic soil properties such as mineralizable C (C_{MIN}), mineralizable N (N_{MIN}), and SMBC than characteristics such as SOC (Campbell et al., 1992a). Carbon mineralization and specific respiration activity of SMBC were sensitive to rotation phase and were directly related to estimated C return to soil, while SOC was not sensitive to rotation in a Dark Brown Chernozem at Scott, Saskatchewan (Campbell et al., 1992a). In the work of Collins et al. (1992), SMBC and SMBN differences between fallow and cropped phases of WF were more apparent during winter than during other periods. Trends for greater SMBC and SMBN in fallow than in cropped soil could reflect time since last residue input.

Two common practices used to conserve water in the

Abbreviations: C_{MIN}, potentially mineralizable C; CS, continuous sorghum; CW, continuous wheat; F_{WSF}, fallow phase of WSF; N_{MIN}, potentially mineralizable N; NT, no-tillage; SM, stubble mulch tillage; SMBC, soil microbial biomass carbon; SMBC/SOC, SMBC portion of SOC; SMBN, soil microbial biomass nitrogen; SMBN/SON, SMBN portion of SON; SOC, soil organic carbon; SON, soil organic nitrogen; SPMAN, specific N mineralization activity of SMBN; SPRAC, specific respiratory activity of SMBC; S_{WSF}, sorghum phase of WSF; WF, wheat-fallow; WSF, wheat-sorghum-fallow; W_{WSF}, wheat phase of WSF.

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Southern High Plains are stubble mulch tillage (SM) and wheat–sorghum–fallow (WSF) cropping. With SM, wide V-shaped sweeps or blades undercut the soil surface at 50 to 100 mm to control weeds and prepare the seedbed for the next crop, but most crop residues (80–90%) are retained on the soil surface (Unger et al., 1997). The WSF sequence produces two crops in 3 yr with approximately a 330-d fallow between each crop. Fallow period water storage increases crop production 10 to 55% compared with continuous cropping but annual biomass inputs are less because of fallow periods (Eck and Jones, 1992; Jones and Popham, 1997). Because of less intense cropping with WSF and greater soil disturbance with SM, the combined practices could degrade soil quality more than NT with continuous cropping. However, increased water use efficiency with NT can increase removal of C and N in grain and may affect C and N dynamics in the residue–microbe–soil continuum. Our objective was to evaluate, under Southern High Plains dryland conditions, cropping frequency and tillage effects on soil C and N conservation using chemical and biological methods.

MATERIALS AND METHODS

A level mini-bench terrace water conservation, cropping, and tillage systems study established in 1982 (Eck and Jones, 1992; Jones and Popham, 1997) provided treatments for evaluating C and N conservation under dryland conditions. The site had been dryland farmed in WSF or CS for more than 30 yr before 1982. The 9- by 160-m benches were constructed across the slope and leveling had little effect on soil physical and chemical properties (Unger et al., 1990). The overall study included four crop sequences—CW, CS, WF, and WSF—and two tillage treatments, NT and SM. All three phases of WSF were present each year and are indicated in the text and tables as F_{WSF}, S_{WSF}, and W_{WSF} for fallow, sorghum, and wheat phases, respectively. Treatments were arranged in a randomized block design with three blocks. On NT plots, weeds were controlled with herbicides and only minimal soil disturbance occurred during planting. On SM plots, tillage was done with a 5.5-m-wide sweep plow unit equipped with three 1.8-m-wide V-shaped blades. First tillage after harvest was at 130 mm, with three to five succeeding tillages at 75 to 100 mm. Further details on herbicides and agronomics are presented by Jones and Popham (1997).

Soil samples were collected during the second week of March 1994 prior to reinitiation of significant spring regrowth by winter wheat and prior to planting of grain sorghum in May. We collected soil samples from the middle of mini-benches where the least disturbance had occurred during leveling (Unger et al., 1990) and only in areas not receiving N fertilizer (Eck and Jones, 1992). We sampled CW, CS, and all three phases of WSF under both NT and SM at the 0- to 20-, 20- to 40-, and 40- to 80-mm depths by excavating and collecting soil for each depth with a square hand spade. The WF plots were not sampled to accommodate incubating all samples at one time. Three samples (150 g) were collected from within each field replication, combined, and returned to the laboratory. Samples were refrigerated at 4°C until sieved (6 mm) and dried to constant weight at 55°C (Franzluebbers et al., 1996).

Microbial biomass C and N were determined by a modified fumigation-incubation technique with air-dried soil samples (Jenkinson and Powlson, 1976; Shen et al., 1984; Franzluebbers et al., 1996). Correlations between measurements on dry and field fresh soil indicated that air drying did not affect relative differences between treatments (Franzluebbers et al., 1996). Soils (40 g) were weighed into glass jars, packed to 1.35 Mg m^{-3} bulk density, and wetted to 50% water holding capacity by adding a specific volume of deionized water. Samples were preincubated in the dark at 25°C for 10 d. After 10 d, samples were fumigated for 24 h with ethanol-free chloroform (pentene stabilized) and placed in 0.5-L jars along with a beaker containing 10 mL 0.5 *M* NaOH. The jar lid was fastened and samples incubated for 10 d at 25°C. Quantity of CO_2-C trapped was determined by titrating NaOH, after addition of excess 1.5 *M* $BaCl_2$, with 0.5 *M* HCl to a phenolphthalein endpoint. Following incubation, soils were extracted with 100 mL 2 *M* KCl and frozen until NH_4^+ and NO_3^- were determined by automated analysis (Bundy and Meisinger, 1994). Soil microbial biomass C was calculated by dividing CO_2-C flush of fumigated soil by 0.41 (Anderson and Domsch, 1980). No subtraction of a control was used in SMBC calculations (Franzluebbers et al., 1996). Soil microbial biomass N was calculated by dividing change in mineral N of fumigated soil by 0.41 (Carter and Rennie, 1982). Mineral N present in soil after the 10 d preincubation was used as initial N content.

Mineralizable C and N (C_{MIN} and N_{MIN}) were determined on 40-g soil samples incubated for 24 d at 25°C and prepared as in SMBC analysis. For C_{MIN}, KOH was changed at 3, 10, and 24 d for determining cumulative CO_2-C evolution. For N_{MIN}, N contents at 0 and 24 d, determined as described above, were used to calculate net change in mineral N (Campbell et al., 1991b).

Specific respiratory activity of SMBC and specific N mineralization activity of SMBN were estimated by dividing C_{MIN} and N_{MIN} by size of the microbial pool (SMBC and SMBN, respectively) (Campbell et al., 1991b). Soil total C and N were determined by dry combustion in a CNS 2000 (LECO Corp., St Joseph, MI)[1].

Treatment effects on soil properties were evaluated after adjusting for differences in soil bulk density. Bulk density was determined on soil samples collected with an aluminum cylinder (50-mm diameter by 80-mm length) and divided into 0- to 40-mm and 40- to 80-mm sections. Bulk densities were 1.16 and 1.20 Mg m^{-3} in SM and 1.17 and 1.32 Mg m^{-3} in NT, respectively, and were not influenced by cropping system. The 0- to 40-mm bulk density was used in calculations for both 0- to 20- and 20- to 40-mm depths because bulk density for shallower depths was difficult to obtain.

Differences in chemical and biological characteristics due to cropping, tillage, and depth were evaluated by the GLM procedure of the Statistical Analysis System (SAS Inst. Inc., 1989). Tillage, cropping, and their interaction effects were analyzed as univariate variables. Repeated measures analysis was used to evaluate depth effects because data were collected from the same sample units at several points in space (Littell, 1989; Fernandez, 1991). A sphericity test, performed by the REPEATED option in GLM, determined validity of standard univariate analysis for depth and depth interactions with cropping and tillage (Littell, 1989). Where rejected at $P < 0.001$, multivariate analysis, which makes no assumption about correlation between measurements but also is less rigorous, was used for depth effects (Littell, 1989). The sphericity test does not apply to validity of univariate analysis for other effects (cropping system and tillage). Treatment effects were considered significant at $P < 0.10$ unless otherwise stated.

A second analysis of variance was conducted to measure

[1] The mention of trade or manufacture names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

tillage and cropping system effects on C and N parameters for the entire 0- to 80-mm profile. Profile values were estimated by summing values from each layer after adjusting for layer depth. Profile values were used to determine correlation among measured parameters and with yield and crop biomass using the CORR procedure in SAS (SAS Inst., 1989).

RESULTS AND DISCUSSION

Cropping system and tillage significantly influenced crop residue amounts returned to soil (Table 1). Jones and Popham (1997) reported fallowing generally increased yields, but when fallow time was considered, CS averaged 92% more grain than WSF and 240% more than CW. They also showed that no-tillage averaged 10% more yield than SM but this was variable across years. Grain and residue yields from plots are presented as cumulative values for all crops produced during the 10 yr (Table 1). For each phase of WSF, values in Table 1 represent the sum of wheat and sorghum crops previously produced on those plots. Smaller cumulative yield for F_{WSF} plots compared with S_{WSF} and W_{WSF} resulted from loss of wheat in May, 1989, due to hail, so there was no grain yield and only limited residue production. Average residue per crop produced (Table 1, column 8 divided by column 2) was greater for S_{WSF}, W_{WSF}, and CS than for CW ($P = 0.05$). Average total grain yield and average residue were greater with CS than with CW, F_{WSF}, S_{WSF}, or W_{WSF} ($P = 0.001$) and NT resulted in more cumulative residue than SM (32.7 vs 29.6 Mg ha^{-1} $P = 0.01$). There were no cropping system by tillage interactions for cumulative yield, cumulative residue or last residue (Table 1).

Soil C and N chemical and biological properties were influenced by cropping system, tillage, and depth (Tables 2 and 3). Differences in properties between tillages often changed with depth. Tillage differences were expected since SM produces some soil disturbance and mixing while NT only disturbs the seed placement area.

Soil Carbon Activity

Differences between cropping systems and phases were apparent for SOC, SMBC, C_{MIN}, specific respiration activity of SMBC, and SMBC portion of SOC (Table 2). Cropping system effects on SOC ($P = 0.0001$) and C_{MIN} ($P = 0.002$) were consistent across tillages and depths; however, there was an interaction with depth for SMBC ($P = 0.01$), and there was an interaction with tillage for specific respiration activity of SMBC ($P = 0.06$) and SMBC portion of SOC ($P = 0.07$) (Table 2). The interaction between cropping system and depth resulted from more SMBC for F_{WSF} than for other treatments at 0 to 20 mm and a greater decline with depth (Table 2). Interactions between cropping system and tillage resulted from WSF treatments having more SMBC in NT than in SM while the opposite result was observed for CW and CS. In general, soil C and biologically active C were greater for CW than for other cropping systems (Table 2). Also, C_{MIN} and SMBC were greater in F_{WSF} than the other two WSF phases. Surprisingly, although CS produced more grain and crop residue (Table 1), it had relatively less C and biologically active C than other cropping treatments (Table 2). Campbell et al. (1991c) suggested that roots may be more important than aboveground crop residues in contributing to maintenance of soil organic matter. We did not measure below ground production but we agree it would be important for quantifying total system differences and that it contributed to observed differences between cropping systems. Microbial community structure was apparently affected by frequency of residue input, residue placement, and resource quality as reflected in the significant tillage and cropping interaction effects (Holland and Coleman, 1987).

Tillage influences on soil C parameters were usually moderated by depth, as would be expected because of limited mixing of soil in NT (Table 2). Significant tillage × depth effects were present for SOC ($P = 0.0001$), SMBC ($P = 0.0001$), C_{MIN} ($P = 0.008$), and SMBC portion of SOC ($P = 0.004$). When averaged across cropping systems, SOC at the 0- to 20-, 20- to 40-, and 40- to 80-mm depths, was 9.9, 10.4, and 11.1 kg m^{-3} in SM and 12.6, 12.5, and 11.9 kg m^{-3} in NT, respectively. Difference between tillages for SMBC was greatest at the surface where average SMBC was 0.80 kg m^{-3} for SM and 1.1 kg m^{-3} for NT. Differences in

Table 1. Production information for 1983 to 1993 for each cropping and tillage system.

Cropping/ tillage†	Number of crops	Last plant date	Last harvest date	Last crop‡	Months since harvest§	Rotation cumulative yield	Rotation cumulative residue	Last residue
						Mg ha^{-1}		
CS NT	10	Jun 93	Nov 93	S	4	29.3	43.1	3.8
CS SM	10	Jun 93	Nov 93	S	4	29.3	41.3	3.6
CW NT	10	Oct 93	Jul 93	W	8	11.4	31.0	4.6
CW SM	10	Oct 93	Jul 93	W	8	9.5	24.4	4.1
F_{WSF} NT	7	Jun 93	Nov 93	S	4	15.0	27.2	4.0
F_{WSF} SM	7	Jun 93	Nov 93	S	4	13.9	25.1	3.5
S_{WSF} NT	7	Oct 92	Jul 93	W	8	18.4	34.7	4.9
S_{WSF} SM	7	Oct 92	Jul 93	W	8	18.3	32.4	4.6
W_{WSF} NT	6	Oct 93	Nov 92	S	16	20.3	27.6	5.3
W_{WSF} SM	6	Oct 93	Nov 92	S	16	18.7	25.0	4.8
LSD¶						1.8	2.9	0.9

† Cropping systems: CS, continuous sorghum; CW, continuous wheat; F_{WSF}, fallow phase of wheat-sorghum-fallow; S_{WSF}, sorghum phase of WSF; W_{WSF}, wheat phase of WSF. Tillage systems: NT, no-till; SM, stubble mulch tillage.
‡ Last crop harvested sorghum (S) or wheat (W).
§ At time of sampling, number of months since last harvested crop.
¶ Overall least significant difference at $\alpha = 0.10$.

Table 2. Cropping, tillage, and soil depth effects on soil C chemical and biological activity†.

Cropping system‡	Depth	SOC		SMBC		C_{MIN}		SPRAC		SMBC/SOC	
		NT	SM	NT	SM	NT	SM	NT	SM	NT	SM
	mm	kg m^{-3}		kg m^{-3}		g m^{-3} d^{-1}		g kg^{-1} d^{-1}		g kg^{-1}	
CS	0–20	11.7	9.6	0.95	0.82	29.0	13.8	28.4	16.6	82	85
CS	20–40	12.3	10.1	0.65	0.75	14.8	12.4	23.8	16.6	56	75
CS	40–80	11.6	10.8	0.56	0.69	12.6	13.1	22.7	19.5	48	64
	Mean	10.1	11.9	0.72	0.75	18.8	13.1	25.0	17.6	62	75
CW	0–20	14.6	11.1	1.19	0.91	30.4	20.9	25.1	22.6	82	82
CW	20–40	14.9	11.9	0.71	0.98	16.5	20.4	24.4	21.0	48	82
CW	40–80	13.6	12.4	0.63	0.95	14.0	20.6	22.7	21.7	46	76
	Mean	11.8	14.3	0.84	0.95	20.3	20.6	24.1	21.8	59	80
F_{WSF}	0–20	11.8	9.6	1.43	0.93	38.8	22.4	27.1	24.7	123	96
F_{WSF}	20–40	12.6	10.0	0.85	0.70	17.6	14.5	20.6	21.3	68	69
F_{WSF}	40–80	10.9	10.8	0.67	0.60	13.0	15.5	19.6	25.8	61	56
	Mean	10.1	11.8	0.98	0.74	23.2	17.5	22.4	23.9	84	73
S_{WSF}	0–20	13.3	9.9	0.99	0.68	20.6	15.0	20.8	21.8	77	70
S_{WSF}	20–40	11.6	10.3	0.60	0.63	10.8	12.6	18.2	20.0	52	62
S_{WSF}	40–80	11.5	11.1	0.55	0.60	12.3	11.6	23.5	19.5	48	55
	Mean	10.4	12.1	0.71	0.64	14.6	13.0	20.8	20.5	59	62
W_{WSF}	0–20	11.7	9.2	1.02	0.68	15.2	13.7	15.1	20.2	87	74
W_{WSF}	20–40	11.3	9.8	0.70	0.66	13.4	12.1	19.5	18.2	63	67
W_{WSF}	40–80	11.7	10.2	0.57	0.67	12.6	13.1	21.9	20.1	49	65
	Mean	9.8	11.6	0.76	0.67	13.7	13.0	18.8	19.5	66	69
		LSD§									
CROP		0.73		0.11		3.4		2.7		9	
TILLAGE		0.46		–		2.2		–		6	
T × C		–		–		–		3.8		13	
DEPTH		–		0.04		2.3		–		5	
D × C		–		0.09		–		–		–	
D × T		0.44		0.06		3.3		–		6	
D × C × T		–		–		–		–		–	

† SOC, soil organic carbon; SMBC, soil microbial biomass C; C_{MIN}, mineralizable C; SPRAC, specific respiration activity of the SMBC; SMBC/SOC, SMBC portion of SOC.
‡ Cropping system and tillage abbreviations as in Table 1. CROP is cropping system.
§ Least significant difference at $\alpha = 0.10$. Where no LSD is given effect is not significant.

SMBC between tillages declined with depth (Table 2). At 0 to 20 mm, average C_{MIN} was nearly 60% greater for NT than for SM but there were little tillage effects at deeper depths. The SMBC portion of SOC averaged 11% more in NT than in SM at 0 to 20 mm while below this depth values were about 25% greater for SM. Differences in C dynamics due to tillage indicate contrasting effects of crop residue stratification in NT compared with mixing of soil and residues in SM. Tillage frequency ranged from three to five operations (harvest to harvest) for SM depending on cropping system and need for weed control. Even though SM results in limited mixing of soil, disturbance was great enough to alter distribution of crop residues and microbial activity through impacts on substrate availability, aeration, and rates of wetting and drying.

Soil Nitrogen Activity

Cropping system, tillage, and depth interactions influenced soil N measurements (Table 3). Significant three way interactions were present for SON ($P = 0.08$), N_{MIN} ($P = 0.05$), and specific N mineralization activity of SMBN ($P = 0.05$). Soil organic N was greater in CW and F_{WSF} than for other treatments particularly in NT at 0 to 20 mm while at lower depths differences were small (Table 3). Other cropping system treatments had smaller differences between NT and SM and also among depths. Specific N mineralization activity of SMBN and N_{MIN} were variable across cropping systems, tillage, and depth which was primarily a result of N immobilization at 0 to 20 mm (Table 3). Several N_{MIN} and specific N mineralization activity of SMBN values were negative at 0 to 20 mm. Immobilization of N would be expected due to crop residues on or near the soil surface. Potential N mineralization was greater below 0 to 20 mm but effects associated with tillage or cropping system were not apparent (Table 3). Specific N mineralization activity of SMBN at lower depths indicates little difference among cropping systems. At 40 to 80 mm, specific N mineralization activity of SMBN tended to be greater in NT than in SM, indicating that microbial biomass was more C limited in NT (Table 3).

Significant depth × cropping system ($P = 0.07$) and depth × tillage ($P = 0.02$) interactions were present for SMBN (Table 3). At 0 to 20 mm, SMBN was greater in NT than SM (0.14 vs 0.11 kg m^{-3}) but was not different at lower depths (Table 3). A cropping system × depth interaction ($P = 0.08$) also influenced SMBN portion of SON. For CS, CW, and F_{WSF}, SMBN and SMBN portion of SON were greater at 0 to 20 mm than in W_{WSF} and S_{WSF} while at greater depths there was little difference among cropping treatments (Table 3).

Interactions between cropping systems and depth reflect differences in residue quantity, residue type (resource quality), and distribution in time and space. Residue quantity is determined by cropping frequency and crop selection. Crop selection is a significant factor in

Table 3. Cropping, tillage, and depth effects on soil N chemical and biological activity†.

Cropping system‡	Depth	SON		SMBN		N_{MIN}		SPMAN		SMBN/SON	
		NT	SM	NT	SM	NT	SM	NT	SM	NT	SM
	mm	kg m^{-3}		kg m^{-3}		g m^{-3} d^{-1}		g kg^{-1} d^{-1}		g kg^{-1}	
CS	0–20	1.16	0.95	0.13	0.11	0.94	0.87	7.0	8.1	110	114
CS	20–40	1.15	0.96	0.07	0.09	0.80	0.76	11.4	8.3	63	94
CS	40–80	1.13	1.03	0.10	0.10	1.14	0.96	11.8	9.5	87	101
	Mean	1.14	0.98	0.10	0.10	0.96	0.86	10.1	8.6	87	103
CW	0–20	1.65	1.27	0.19	0.13	0.72	0.22	3.8	1.4	115	100
CW	20–40	1.54	1.43	0.12	0.13	0.94	1.16	8.2	9.0	83	89
CW	40–80	1.37	1.41	0.11	0.13	1.27	0.96	11.4	7.3	85	92
	Mean	1.52	1.37	0.14	0.13	097	0.78	7.8	5.9	94	94
F_{WSF}	0–20	1.30	1.04	0.17	0.14	0.12	1.41	0.4	9.9	134	140
F_{WSF}	20–40	1.27	1.11	0.10	0.10	1.15	0.82	11.0	8.2	83	92
F_{WSF}	40–80	1.12	1.12	0.09	0.11	0.97	0.93	10.9	8.9	82	96
	Mean	1.23	1.09	0.12	0.12	0.75	1.05	7.5	9.0	100	109
S_{WSF}	0–20	1.28	0.97	0.11	0.10	−0.20	0.53	−8.0	5.5	86	103
S_{WSF}	20–40	1.10	0.98	0.09	0.10	0.69	0.88	8.0	8.6	79	104
S_{WSF}	40–80	1.12	1.08	0.08	0.11	0.83	0.85	9.9	8.0	75	98
	Mean	1.16	1.01	0.09	0.10	0.44	0.75	3.3	7.4	80	102
W_{WSF}	0–20	1.16	0.99	0.11	0.06	0.72	−0.03	5.6	1.6	97	65
W_{WSF}	20–40	1.10	1.04	0.09	0.09	0.55	0.56	7.4	6.1	78	89
W_{WSF}	40–80	1.17	1.05	0.08	0.08	0.76	0.77	10.6	9.3	70	79
	Mean	1.15	1.03	0.09	0.08	0.67	0.43	7.9	5.7	82	78
		LSD§									
CROP		0.09		0.02		–		–		–	
TILLAGE		0.06		–		–		–		–	
T × C		–		–		–		–		–	
DEPTH		–		0.01		0.19		1.8		9	
D × C		0.07		0.02		–		–		21	
D × T		0.04		0.02		–		2.6		–	
D × C × T		0.09		–		0.45		5.7		–	

† SON, soil organic nitrogen; SMBN, soil microbial biomass N; N_{MIN}, mineralizable N; SPMAN, specific mineralization activity of the SMBN; SMBN/SON, SMBN portion of SON.
‡ Cropping and tillage abbreviations as in Table 1. CROP is cropping system.
§ Least significant difference at $\alpha = 0.10$. Where no LSD is given effect is not significant.

resource quality but resource quality can also be affected by climate. Nitrogen removal in grain or greater N conservation from having plants growing for a greater portion of the cropping cycle affect availability of N to both microorganisms and subsequent crops. Compared with other cropping treatments, CW had shorter fallow and thus greater potential for conserving nutrients. Substantial quantities of N are mineralized in southern High Plains soils from April to June when both temperatures and water availability are favorable (Eck and Jones, 1992). Absence of a growing crop during this period results in N moving deeper in the soil profile and being lost from the cropping system. Losses would be greater in CS and during F_{WSF} and S_{WSF} because of long fallow periods. Tillage interactions with depth result from greater accumulation of surface residues in NT and their slower rates of decomposition which can increase nutrient retention (Schomberg et al., 1994, Schomberg and Steiner, 1999).

Whole Profile Changes

When values were summed for 0 to 80 mm, cropping system effects were present for most measurements, tillage influenced SOC and SON but not other measurements, and there were no interaction effects (Table 4). No-till resulted in more SOC (1.0 vs 0.8 g m^{-2}, $P = 0.0001$) and SON (0.10 vs 0.09 kg m^{-2}, $P = 0.0001$) than with SM (Table 4). As in the analysis by depth (Tables 2 and 3), chemical and biological soil C and N for CW was often more or at least equal to other cropping treatments (Table 4). The F_{WSF} phase had more C_{MIN} and SMBC portion of SOC than S_{WSF} and W_{WSF} which appeared to be related to time since last crop harvest and crop residue input (Table 4). Time since last residue input was observed to affect soil C and N activities in Canada (Campbell, 1992 a, b).

Correlations among biological and chemical indices, and with cumulative yield and cumulative residue production, were determined for whole profile data (Table 5). Significant negative correlations were present between yield and SOC, SMBC, C_{MIN}, SON, and SMBN (Table 5). Although not significant, negative correlations were also found for cumulative residue and these characteristics. Similar results were obtained when correlations were evaluated only for the 0- to 20-mm soil layer (data not shown). Both positive and negative correlations have been observed between measures of C and N activity and residue inputs for cropping systems in Canada (Campbell et al., 1992 a, b). Negative correlations are surprising in that greater yields and residue production should increase C inputs to soil and available substrates for microbial activity. However, water is a major limiting factor under dryland conditions. Negative correlations may indicate that greater water demands of higher yielding crops create drier soil conditions, which limit microbial activity and population size. The strongest negative correlation was between SON and yield

Table 4. Cropping system influence on chemical and biological measures of soil C and N dynamics for the total 80-mm depth†.

System	SOC	SMBC	C_{MIN}	SPRAC	SMBC/ SOC	SON	SMBN	N_{MIN}	SPMAN	SMBN/ SON
	—— kg m^{-2} ——		g m^{-2} d^{-1}	g kg^{-1} d^{-1}	g kg^{-1}	——— kg m^{-2} ———		g m^{-2} d^{-1}	g kg^{-1} d^{-1}	g kg^{-1}
Crop										
CS	0.88	0.057	1.21	21.3	68.0	0.085	0.008	0.078	9.3	94.4
CW	1.04	0.070	1.57	22.9	69.3	0.115	0.011	0.077	6.8	92.8
F_{WSF}	0.87	0.064	1.51	23.2	78.6	0.092	0.009	0.075	8.2	100.7
S_{WSF}	0.90	0.052	1.07	20.6	60.3	0.087	0.008	0.054	5.3	89.5
W_{WSF}	0.86	0.055	1.06	19.2	67.3	0.088	0.007	0.050	6.8	78.5
$LSD_{\alpha = 0.10}$	0.06	0.001	0.28	3.2	11.2	0.008	0.002	0.003	3.4	–
$P > F$‡	0.0001	0.02	0.02	0.08	0.09	0.0001	0.004	0.07	–	–
Tillage										
NT	0.98	0.060	1.34	21.6	61.9	0.098	0.008	0.065	7.7	86.1
SM	0.85	0.059	1.22	19.8	69.6	0.089	0.008	0.064	7.6	95.3
$LSD_{\alpha = 0.10}$	0.04	–	–	–	–	0.005	–	–	–	–

† Abbreviations as in Tables 2 and 3.
‡ Probability of a greater *F* value.

indicating more productive cropping systems deplete N from soil which limits N availability to microorganisms. There was more N removed with the more intensive cropping and with wheat than with sorghum. Grain total N concentration was greater for wheat than for sorghum from 1987 through 1992 (average values 19.7 vs. 12.7 mg g^{-1} Jones, unpublished data). Mineral N had not been added to this research area for more than 30 yr. Enough N is usually mineralized in dryland WSF soils during fallow and cropping periods to meet growth potential of wheat or grain sorghum under water limited conditions. With greater cropping frequency and grain removal (CS and CW), addition of N may become necessary to meet crop demands and provide adequate N for microbial activity (Eck and Jones, 1992). Strong correlations were present between SOC and SON, SON and SMBC, SMBC and C_{MIN}, SMBN and N_{MIN}, and SMBN and C_{MIN} (Table 5). Positive correlations among these measured characteristics are consistent with other studies (Franzluebbers et al., 1994 ; Campbell et al., 1992 a, b).

When the combined by-depth and whole profile analyses are considered, a significant influence of decreasing fallow length (3 vs. 8 mo) is apparent from increased C and N conservation in CW compared with CS. Also, CW tended to conserve more C and N than all phases of WSF indicating a positive benefit of continuous cropping over systems that include extended fallow. Shorter periods of fallow and more intensive cropping have been shown to increase C and N conservation (Wood et al., 1991; Franzluebbers et al., 1994, 1995). In south Texas, SOC was 22 to 30% greater with rotated than with continuous cropping (Franzluebbers, 1995) while in Kansas, SOC was 4 to 25% greater for similar changes in cropping systems (Havlin et al., 1990). Wheat conserved more soil C and N than sorghum as indicated by the trend for more C and N in CW and in WSF phases than in CS even though more crop biomass was produced by CS, but crop effect per se is difficult to separate from fallow length. Differences between WSF phases were caused by either time since last crop or type of last crop but no strong relationship was determined. Bremer and van Kessel (1992) observed that SMBC was higher in fall, following additions of wheat straw to soil and that biomass declined from spring values during summer while wheat was growing.

Eck and Jones (1992) concluded that N mineralization was similar under SM and NT but soil water content was greater with NT, which increased potential for N uptake during the growing season and leaching during fallow periods. Additionally, more N was removed in harvested sorghum grain in both CS and WSF treatments. In WSF, N removed during cropped phases is replaced by N mineralized during fallow. However, increases in crop productivity with conservation practices can result in N limitation to following crops (Eck and Jones, 1992). Campbell and Zentner (1993) concluded that it was difficult to increase organic matter levels where insufficient N was available to replace that removed in grain. As yields decreased, loss of N through

Table 5. Correlation matrix (values below the diagonal, set in roman face) and significance ($P >$ R‡, values below the diagonal, set in italic) of chemical and biological properties using data for the 0–80 mm whole profile and cumulative yield and cumulative residue†.

	Yield	Residue	SOC	SMBC	C_{MIN}	SPRAC	SON	SMBN	N_{MIN}	SPMAN
Yield	–	*0.001*	*0.060*	*0.029*	*0.010*	–	*0.001*	*0.017*	–	*0.044*
Residue	0.809	–	–	–	–	–	–	–	–	*0.051*
SOC	−0.343	0.054	–	*0.023*	*0.025*	–	*0.001*	*0.046*	–	–
SMBC	−0.398	−0.244	0.414	–	*0.001*	–	*0.001*	*0.046*	–	–
C_{MIN}	−0.461	−0.226	0.407	0.804	–	*0.001*	*0.001*	*0.001*	*0.016*	–
SPRAC	−0.255	−0.069	0.147	0.021	0.609	–	*0.004*	–	*0.010*	–
SON	−0.617	−0.259	0.858	0.652	0.624	0.196	–	*0.015*	–	–
SMBN	−0.431	−0.204	0.366	0.366	0.586	0.509	0.442	–	*0.001*	–
N_{MIN}	0.011	0.150	0.245	0.216	0.437	0.461	0.225	0.660	–	*0.001*
SPMAN	0.370	0.359	0.021	0.026	0.089	0.124	−0.038	0.000	0.737	–

† Yield is total cumulative yield; Res is total non-yield aboveground biomass; other abbreviations are as in Tables 2 and 4.
‡ Effect is not significant where probability value is not given.

leaching increased, thereby further decreasing N use efficiency. In their system, shorter fallow periods offered the greatest protection against N loss due to leaching. The negative relation between crop residue input and measures of C and N activity indicates N limitation to the microbial community resulting from removal of N in grain and leaching losses as shown by Eck and Jones (1992). Increasing N limitation will negatively impact microbial biomass and nutrient cycling within these dryland systems. Although CW was not the most profitable system (Jones and Popham, 1997), greater SOC and SON clearly indicate potential benefits of using wheat in rotation to maintain or improve soil productivity in dryland cropping systems.

CONCLUSIONS

Our results indicate that cropping and tillage practices strongly influence C and N conservation and biological activity under dryland conditions. Many of the measured properties differentiated cropping system and tillage effects and interactions in the upper soil depth but most tillage effects and interactions were no longer apparent at deeper depths or when summed over the entire 80 mm of depth. Accumulation of crop residues near the soil surface in NT stratifies microbial activity and nutrients, thereby maintaining more soil C and N than in SM. Although there is limited soil disturbance with SM, redistribution of residues increases microbial activity and C and N losses. More frequent cropping and use of crops having short fallow periods can improve soil productivity but management inputs will become more critical for maintaining soil fertility and conserving soil C and N in long-term dryland cropping systems. Crop residue inputs and microbial activity are critical components for sustained productivity in these systems.

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Erosion and Productivity of Vegetable Systems on Sloping Volcanic Ash–Derived Philippine Soils

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ABSTRACT

Soil erosion is a major constraint to the sustainability of sloping-land vegetable systems. Little information is available on the effectiveness of soil conservation measures under sloping intensified vegetable systems on volcanic ash–derived soils. We hypothesized that contouring, strip cropping, and high-value contour hedgerows — asparagus (*Asparagus officinalis* L.), pineapple [*Ananas comosus* (L.) Merr.], pigeonpea [*Cajanus cajan* (L.) Huth], and lemongrass [*Cymbopogon flexuosus* (Nees ex Steudel) J. F. Watson] — reduce soil loss compared with the farmer's traditional practice of up-and-down cultivation on sloping lands. A field experiment tested these soil conservation technologies from 1995 to 1998 in a completely randomized block design on a 42% natural slope on a clayey, halloysitic, isothermic, Typic Kandiudox. The greatest annual soil loss (65.3 t ha^{-1}) was in the up-and-down system and comparative values were 37.8 t ha^{-1} for contouring, 43.7 t ha^{-1} for strip cropping, and 45.4 t ha^{-1} for high-value contour hedgerows. Three rain events alone caused 47% of the total soil loss. All erosion–runoff plots showed large differences in soil properties and crop yields between the upper and the lower slope. Crop yields downslope were greater by 40% for tomato (*Lycopersicon esculentum* Miller), 36% for corn (*Zea mays* L.), and 78% for cabbage (*Brassica oleracea* var. *capitata* L.) than for upslope. In the contour hedgerow treatment, rapid terrace development changed soil properties, and crop yields for the bottom portions of bioterraces were greater by 121% for corn and 50% for tomato than yields of top portions.

Productivity decline induced by soil erosion is one of the major problems constraining the sustainability of agricultural crop production in the steeplands of Southeast Asia (Hashim et al., 1995; Presbitero et al., 1995; Midmore and Poudel, 1996). Soil erosion reduces productivity in several ways: (i) loss of plant-available soil water holding capacity and of plant nutrients through degradation of soil structure and compaction and (ii) by nonuniform removal of soil within a field (National Soil Erosion-Soil Productivity Research Planning Committee, 1981). Off-site impacts of soil erosion such as siltation of reservoirs, the breaking of waterways and channels, pollution of water bodies, and effects on aquatic habitats (Midmore et al., 1996; El-Swaify, 1997) are of equal concern. Consequences of soil erosion on productivity and environment are exacerbated on steeplands where the potential for soil erosion and runoff losses is largely due to their unique topography (El-Swaify, 1997). Enrichment ratio (ER), which is defined as the ratio of the nutrient content of the sediment (eroded soil) to that of the source soil, has been used by several researchers in assessing the short- to medium-term effect of erosion in soil properties (Sombatpanit et al., 1995; Gachene et al., 1997; Wan and El-Swaify, 1998).

In attempts to stem and manage soil erosion on steeplands, a number of technologies have been researched. Alley cropping, a special form of an agroforestry system in which food crops are grown in alleys formed by hedgerows of trees or shrubs (Kang et al., 1981, 1986), has been effective in minimizing soil erosion on steeplands (Tacio, 1993; Comia et al., 1994; Paningbatan, 1994). According to Paningbatan (1994), the annual soil loss under alley cropping treatments were <10 t ha^{-1}, while those under local farmers' practice of up-and-down cultivation were as high as 144, 44, and 41 t ha^{-1} for Laguna, Batangas, and Rizal provinces, respectively, in the Philippines. Comia et al. (1994) also found alley cropping to be very effective in minimizing soil erosion on the footslopes of Mount Makiling in Laguna, the Philippines. They compared conventional tillage and alley cropping systems (tilled and unmulched, tilled and mulched, and untilled and mulched). The alley cropping systems consisted of 1-m-wide wild tantan [*Desmanthus virgatus* (L.) Willd.] contoured hedgerows between 5-m-wide alleys where corn and bean (*Phaseolus aureus* L.) were grown sequentially. An annual soil loss <3 t ha^{-1} was recorded under a mulched alley cropping system, while annual soil loss under conventional tillage was as high as 141.3 t ha^{-1}. The magnitude of soil loss was matched by proportional nutrient loss. Tacio (1993) reported a notable effect of Sloping Agricultural Land

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Abbreviations: CBD, 0.3 *M* Na-citrate–0.1 *M* Na-bicarbonate solution and Na-dithionate; CEC, cation-exchange capacity; ECEC, effective cation-exchange capacity; ER, enrichment ratio; IBSRAM, International Board for Soil Research and Management; NIA-PRIP, National Irrigation Association-Pulangi River Irrigation Project; NOMIARC-DA, Northern Mindanao Integrated Agricultural Research Center-Department of Agriculture; NRC, National Research Council; SALT, Sloping Agricultural Land Technology; SANREM-CRSP, Sustainable Agriculture and Natural Resources Management Collaborative Research Support Program; USAID, United States Agency for International Development.