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Effect of long-term N fertilization on soil organic C and total N in continuous wheat under conventional tillage in Oklahoma

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Abstract

Fertilizer nitrogen (N) can impact on soil total N and organic carbon (C). The effects of long-term nitrogen (N) applications in continuous winter wheat (*Triticum aestivum* L.) production systems on total N and organic C in soils has not been studied previously. Deep soil cores were taken from four long-term winter continuous wheat experiments in Oklahoma, on silt loam and clay loam soils, to evaluate differences in total N and C as affected by more than 23 years of annual N applications. When N was applied at rates $\geq$90 kg ha^{-1}, surface soil (0–30 cm) organic C was either equal to that of the check (no N applied) or slightly greater. Total soil N (0–30 cm) increased at the high N rates at all locations. However, at two locations, total soil N decreased at low N rates, indicating the presence of priming (increased net mineralization of organic N pools when low rates of fertilizer N are applied). At these two same sites, soil–plant inorganic N buffering (amount of N that could be applied in excess of that needed for maximum yield without resulting in increased soil profile inorganic N accumulation) was greater compared to the other two sites where no evidence of priming was found. In general, C:N ratios increased at the low rates of applied N and then decreased to levels below that found in check plots at high N rates ($\geq$134 kg N ha^{-1} yr^{-1}). Combined surface (0–30 cm) soil analyses of total N and organic C were useful in detecting where priming had taken place and where soil–plant inorganic N buffering was expected to be high in these long-term N fertilization experiments. Predictability of the priming effect combined with soil–plant inorganic N buffering should assist us in establishing environmentally safe N rates. Soil organic C increased when N was applied at rates in excess of that required for maximum yield. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Organic carbon; Total nitrogen; Wheat; Priming; Buffering

1. Introduction

Analyses of total nitrogen (N) and organic carbon (C) in soils has been reported in numerous articles dealing with continuous cropping production systems. However, few have assessed changes in total N and organic C in soils over time. In addition, the resultant effect of annual applications of N in continuous wheat production systems on total soil N and organic C has not been monitored.

Blevins et al. (1983) found a 37% and 12% increase in soil organic C under NT and CT corn, respectively after 10 years of applying 84 kg N ha^{-1} yr^{-1} at the 0–5 cm depth. In continuous corn experiments conducted by Havlin et al. (1990), high N rates (252 kg N ha^{-1}) were found to increase surface soil (0–30 cm) organic C levels.

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MacVicar et al. (1951) found that the lowest ^{15}N recoveries were associated with a low level of soil organic matter and a high level of N addition. Most of the soil N was maintained in a reduced state as bacterial cellular nitrogen in soils with a high C:N ratio (MacVicar et al., 1951). When the soil C:N ratio was small, free N including nitrate accumulated and denitrification was assumed to occur (MacVicar et al., 1951).

Varvel and Peterson (1990a) indicated that the differences in estimating fertilizer N recovery using isotopic and difference methods were due to synchronization problems between N mineralization and crop N use. This was probably due to cropping system, previous crop, amount and type of residue and other environmental factors. However, Varvel and Peterson (1990a) did indicate that either of the methods are satisfactory within a specific cropping system, but that neither of the methods does well across diverse cropping systems where differences in immobilization could occur. Nitrogen removal in the grain accounted for 50% of the applied N in continuous grain sorghum (*Sorghum vulgare* Pers.) and corn (*Zea mays* L.) systems at low N rates of 34 and 90 kg N ha^{-1}, respectively (Varvel and Peterson, 1990b). At higher N rates of 68 and 180 kg N ha^{-1} for grain sorghum and corn systems, only 20% to 30% of the applied N was accounted for by N removal in the grain. This difference in percent fertilizer N removed in the grain was noted to be a function of immobilization by crop residues and soil organic matter and not due to N leaching (Varvel and Peterson, 1990b). This was supported by observations made for NH_4–N and NO_3–N concentrations from soil profile analysis (0–150 cm), whereby no differences were observed from samples taken four years apart.

Olson (1982) found that 81.9% of the fertilizer N remaining in a 0–150 cm soil profile had been immobilized by harvest time in a winter wheat (*Triticum aestivum* L.) experiment. In addition, 70% of the fertilizer N remained in the 0–10 cm profile of a silt loam soil at all sampling dates (October 1979 through June, 1980). Immobilization of the fertilizer N in the 0 to 10 cm layer limited downward movement, plant uptake and losses. Most of the N not immobilized was used by the crop when N was applied at a rate of 80 kg ha^{-1}. At maturity, only 18% of the fertilizer N in the 150 cm profile was present as inorganic N. Groot and de Willigen (1991) suggested that N can be immobilized almost immediately after application, without increased metabolic activity of the microbial biomass.

The objective of this study was to evaluate the effects of long-term N applications in continuous winter wheat on total soil N and organic C in surface horizons.

2. Materials and methods

Four long-term (>23 years) continuous winter wheat fertility experiments in Oklahoma were sampled in 1993 to determine total N, organic C, NH_4^+–N and NO_3^-–N within the soil profile. The four experiments are identified as 222, 406, 502 and 505. Experiments 502 and 505 were separate studies conducted at the same location. Soil types were Kirkland silt loam (fine-mixed thermic Udertic Paleustoll), Tillman clay loam (fine, mixed, thermic Typic Paleustoll) and Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll) for experiments 222, 406, and 502 and 505, respectively. Additional site information is provided in Table 1. A randomized complete block experimental design with four replications was used at all locations. Fertilizer treatments and surface (0–30 cm) soil test analyses at the time all trials were sampled in 1993 are reported by location in Table 2. Fertilizer treatments reported in Table 2 were applied preplant in the fall of each year and incorporated prior to planting. Winter wheat was planted in 25.4 cm rows at seeding rates of 67 kg ha^{-1} at all locations. All sites were managed under conventional tillage (disk incorporation of wheat straw residues following harvest and prior to planting) with a maximum tillage depth ranging from 15 to 25 cm.

Three soil cores 4.45 cm in diameter, were taken from each plot to a depth of 240 cm and sectioned in increments of 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90, 90 to 120, 120 to 150, 150 to 180, 180 to 210 and 210 to 240 cm. Differences in soil bulk density, over the 0 to 240 cm soil depth, were not evident among fertilizer treatments, thus soil C and N data are reported on a concentration basis. Soil samples were air dried at ambient temperature and ground to pass a 100 mesh sieve (<0.15 mm) for total N and organic C analyses (Tabatabai and Bremner, 1970). Soils were

Table 1
Site, soil sampling, and climatic information for the four long-term experiments in Oklahoma (all sites were continuous winter wheat under conventional tillage)

Exp.	Long., Lat.	Year Est.	Number of replications	Dates sampled	Crop years prior to sampling	Annual avg. rainfall[a] (mm)	Range (mm)	Mean annual temperature (°C)
222	36°7′7″N 97°5′30″W	1969	4	July 1993	24	922	606–1493	15.0
406	34°36′34″N 99°20′0″W	1965	4	July 1993	28	670	295–1141	17.1
502	36°23′13″N 98°6′29″W	1970	4	July 1993	23	771	503–1314	15.6
505	36°23′13″N 98°6′29″W	1970	3	July 1993	23	771	503–1314	15.6

[a] From initiation of study to 1993.

Table 2
Surface soil test characteristics (0–30 cm) in 1993 for experiments 222, 406, 502 and 505

Experiment	Fertilizer applied			Soil test level		
	N	P	K	pH	P	K
	$kg\ ha^{-1}\ yr^{-1}$	$kg\ ha^{-1}\ yr^{-1}$	$kg\ ha^{-1}\ yr^{-1}$		$mg\ kg^{-1}$	$mg\ kg^{-1}$
222	0	29	38	5.85	51	218
	45	29	38	5.84	38	200
	90	29	38	5.80	34	155
	134	29	38	5.73	26	130
SED				0.08	11	36
406	0	0	0	7.29	9	409
	45	20	38	7.13	32	445
	90	20	38	7.38	25	432
	134	20	38	7.12	24	445
	179	20	38	6.79	23	442
SED				0.18	3	14
502	0	20	56	5.95	70	488
	22	20	56	5.83	66	438
	45	20	56	5.76	71	467
	67	20	56	5.67	75	455
	90	20	56	5.60	72	468
	112	20	56	5.49	83	457
SED				0.14	17	38
505	0	29	56	5.74	119	420
	34	29	56	5.43	94	343
	67	29	56	5.24	103	340
	134	29	56	5.04	121	413
	269	29	56	4.85	93	366
SED				0.10	14	28

pH, 1:1 soil:water; K and P, Mehlich III.
SED – standard error of the difference between two equally replicated means.

analyzed for total N and organic C (non-calcareous soil) using a Carlo-Erba (Milan, Italy) NA 1500 dry combustion analyzer (Schepers et al., 1989). For experiment 406, soil organic C was determined by digestion with an acidified dichromate ($K_2Cr_2O_7$–H_2SO_4) solution (Yeomans and Bremner, 1988) due to the presence of free $CaCO_3$ in surface horizons. Duplicate soil samples were also extracted using 2 M

KCl (Bremner, 1965) and analyzed for NH_4–N and NO_3–N using an automated flow injection analysis system. Soil pH was determined using a glass electrode and a soil/water ratio of 1:1.

The center 3.05 m of each plot was harvested for grain yield using a conventional self-propelled combine, and wheat straw was uniformly redistributed in all plots each year.

Fertilizer N recovery in the grain was determined by multiplying treatment grain yield×grain N, subtracting check (no N fertilization) grain yield×grain N and dividing by the rate of N applied.

3. Results

3.1. Previous studies

This manuscript is an extension of work on the same long-term winter wheat experiments reported by Westerman et al. (1994), Raun and Johnson (1995) and Johnson and Raun (1995). Initial work by Westerman et al. (1994) documented accumulation of NH_4–N and NO_3–N in the soil profiles following long-term annually applied fertilizer N rates in winter wheat. This work concluded that no accumulation of NH_4–N and NO_3–N occurred in soil profiles at recommended N rates where maximum yields were obtained. Raun and Johnson (1995) and Johnson and Raun (1995) proposed a soil–plant buffering concept to explain why soil profile inorganic N did not begin to increase until N rates in excess of that required for maximum yield were applied. Loss of N from the soil–plant system can take place via plant N volatilization, denitrification and surface volatilization when N rates exceed that required for maximum yield. Also, increased grain N, straw N, organic N and C in the soil are found when N rates exceed that needed for maximum yields. The soil–plant buffering concept helped to explain why unaccounted N should not be immediately attributed to leaching in studies where these biological mechanisms remained active. Grain yield optimums over the 23+ year period included in each of these experiments were found at 56, 47, 62 and 43 kg N ha^{-1} yr^{-1} for experiments 222, 406, 502 and 505, respectively (Raun and Johnson, 1995). Significant increases in soil profile inorganic N were not reported until N was applied at rates of 104, 75, 85 and 99 kg ha^{-1} yr^{-1} at these same respective locations (Raun and Johnson, 1995). The difference between the observed N rate, where soil profile inorganic N accumulation became significant and the N rate where maximum yields were obtained, is an estimate of the soil–plant buffering capacity or the ability of the soil–plant system to limit inorganic N accumulation when N rates exceed that required for maximum yield. Therefore, on an annual basis, 48, 28, 23 and 55 kg of N fertilizer ha^{-1} could have been applied in excess of requirements for maximum yield in experiments 222, 406, 502 and 505 without increasing inorganic N accumulation or the risk of NO_3–N leaching.

The expression of treatment on total soil N and organic C was expected to be different in the surface soil profile (0–15 cm) compared to soil at other depths, largely due to annual disking to a depth of 15 cm, which led to mechanical mixing and aeration. The extent of root proliferation was expected to be greatest within the top 0–30 cm. The combined effects of increased microbial activity, root proliferation and cultivation in the surface 0–30 cm led us to select this depth for more detailed analyses. Results were consistent with this approach, since few differences in total soil N or organic C were noted at depths >60 cm (data not reported).

3.2. Total soil N

Nitrogen fertilization significantly increased (linear and/or quadratic) total soil N in the surface 30 cm at all locations (Table 3 and Fig. 1). This was most apparent when the high rate was compared to the check (no N fertilization). Although this significant linear increase (over all rates) was found, total soil N tended to decrease at the low N rates in experiments 222 and 505. However, when N was applied at rates in excess of that needed for maximum yield, total soil N increased in all experiments.

3.3. Organic C

Similar to observations for total soil N, soil organic C increased with increasing N applied at three of the four sites (Table 3 and Fig. 2). This was consistent with work by Blevins et al. (1983) and McAndrew and Malhi (1992) who demonstrated increases in soil organic C with increasing N applied. In experiments

Table 3
Analysis of variance, mean squares and associated contrasts for total soil N, organic C and Carbon:Nitrogen ratios, in experiments 222, 406, 502 and 505 for the 0–30 cm soil depth, 1993

Source of variation	df	Total N	Organic C	C:N
		Mean squares	Mean squares	Mean squares
#222				
Rep	3	0.0087	1.176	1.109[b]
Trt	3	0.0133	0.217	0.526
Error	25	0.0065	0.537	0.193
Single degree of freedom contrasts				
N Rate linear	1	0.0074	0.374	0.006
N Rate quadratic	1	0.0314[a]	0.220	1.568[a]
0 vs. 134	1	0.0085	0.431	0.009
#406				
Rep	3	0.0112	2.903[a]	10.162[a]
Trt	4	0.0055	1.320	1.871
Error	32	0.0068	0.986	2.759
Single degree of freedom contrasts				
N Rate linear	1	0.0195[b]	4.408[a]	1.175
N Rate quadratic	1	0.0005	0.012	0.734
0 vs. 134	1	1 0.0036	2.182[@]	2.992
#502				
Rep	2	0.0003	0.592[a]	1.435[b]
Trt	5	0.0094[b]	0.332	0.497[b]
Error	28	0.0013	0.154	0.123
Single degree of freedom contrasts				
N Rate linear	1	0.0317[b]	0.800[a]	0.371[@]
N Rate quadratic	1	0.0025	0.844[a]	0.512[a]
0 vs. 112	1	0.0220[b]	0.527[@]	0.262
#505				
Rep	2	0.03604[a]	1.175	2.262
Trt	4	0.00763	2.694	1.014
Error	23	0.00644	1.750	3.399
Single degree of freedom contrasts				
N Rate linear	1	0.01903[@]	5.549[@]	0.832
N Rate quadratic	1	0.00241	0.002	0.626
0 vs. 134	1	0.01153	7.000[a]	3.316

[a,b,@] Significant at the 0.01, 0.05 and 0.10 probability levels, respectively.

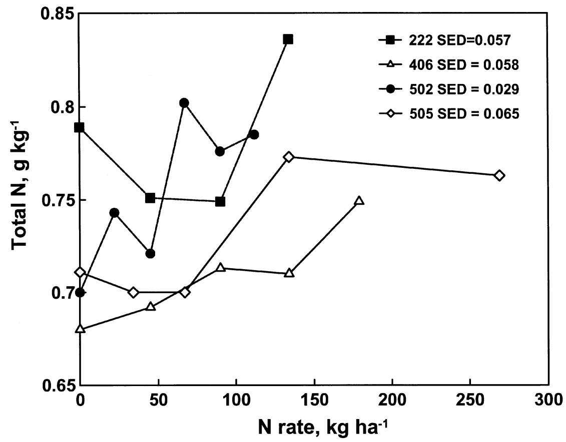

Fig. 1. Surface (0–30 cm) soil total N as affected by annual applications of fertilizer N to continuous wheat in experiments 222, 406, 502 and 505 (SED – standard error of the difference between two equally replicated means).

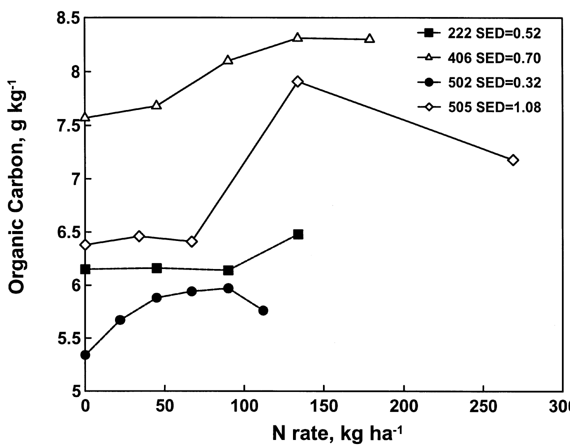

Fig. 2. Surface (0–30 cm) soil organic C as affected by annual applications of fertilizer N to continuous wheat in experiments 222, 406, 502 and 505 (SED – standard error of the difference between two equally replicated means).

222 and 505, soil organic C did not increase until at least 67 kg N ha^{-1} yr^{-1} was applied. A tendency for increased soil organic C when N was applied at rates in excess of that required for maximum yield was noted at all locations.

3.4. Carbon:nitrogen ratio

In experiments 222, 502 and 505, applied N significantly affected C:N ratios (Table 3 and Fig. 3). In these experiments, C:N ratios increased at the low to moderate N rates but then decreased to levels below that observed in the check in experiments 222 and 502 (Fig. 3). We hypothesize that, similar to the work of Westerman and Kurtz (1973), applied N at rates $\leq$67 kg ha^{-1} was expected to have a 'priming effect' resulting in increased net mineralization of N from the soil organic matter pool. This

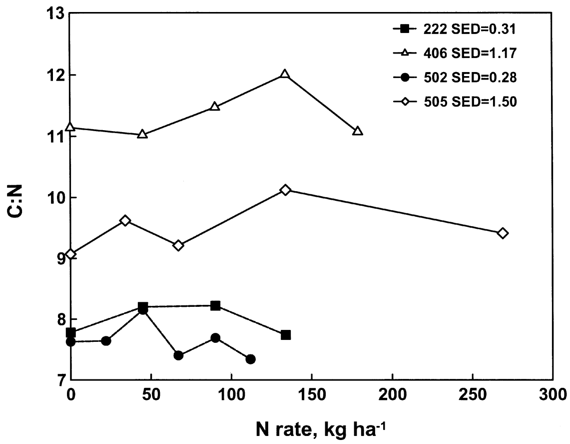

Fig. 3. Surface (0–30 cm) soil organic C:total N ratios as affected by annual applications of fertilizer N to continuous wheat in experiments 222, 406, 502 and 505 (SED – standard error of the difference between two equally replicated means).

was evident in the higher C:N ratios at the low N rates, largely due to decreased total soil N since organic C levels were in general unaffected within this same range (annual N $\leq$67 kg N ha^{-1}). Several authors have found that N rates which exceed that required for maximum yields generally result in decreased harvest indices and associated higher straw yields in wheat. This would aid in explaining why organic C levels increased at the higher N rates used in these trials. However, in order for total soil N levels to be significantly lower at the low to moderate N rates, applied N was expected to have a different effect on the organic N pool. Westerman and Kurtz (1973) suggested that increased crop soil N uptake was due to stimulation of microbial activity by N fertilizers which increased mineralization of soil N, thus making more soil N available for plants. Similarly, what could be a 'priming effect' in these experiments occurred at the low to moderate applications of fertilizer N.

Table 4
Total soil profile inorganic N, average annual grain yield, total N removed in the grain and estimates of fertilizer N recovery for continuous wheat with different fertilizer applied in experiments 222, 406, 502 and 505

Experiment/Fertilizer treatment	Total soil profile inorganic N kg ha^{-1}	Total N applied kg ha^{-1}	Average annual grain removed kg ha^{-1}	Total N removed in grain kg ha^{-1}	Fertilizer N removed in grain kg ha^{-1}	Fertilizer N recovery grain % kg ha^{-1}
#222 (0–240 cm) 24 years						
0–29–38	424	0	1329	692	0	0
45–29–38	413	1080	1751	1046	354	0.33
90–29–38	432	2160	1882	1156	464	0.21
134–29–38	608	3216	1933	1401	708	0.22
#406 (0–210 cm) 28 years						
0–0–0	503	0	1416	900	0	0
45–20–38	487	1260	1972	1363	463	0.37
90–20–38	509	2520	2095	1589	689	0.27
134–20–38	622	3752	1899	1483	583	0.16
179–20–38	745	5012	1907	1447	547	0.11
#502 (0–240 cm) 23 years						
0–20–56	314	0	1727	844	0	0
22–20–56	294	506	2240	1133	289	0.57
45–20–56	322	1035	2381	1221	377	0.36
67–20–56	310	1541	2668	1399	555	0.36
90–20–56	344	2070	2749	1460	616	0.30
112–20–56	502	2576	2655	1435	590	0.23
#505 (0–300 cm) 23 years						
0–29–56	384	0	1615	809	0	0
33.6–29–56	387	772	2406	1261	451	0.58
67.3–29–56	375	1545	2645	1460	650	0.42
134.5–29–56	517	3091	2721	1677	867	0.28
269–29–56	1023	6182	2541	1624	814	0.13

3.5. Fertilizer recovery in the grain

Estimates of fertilizer N recovery in the grain using the difference method are reported in Table 4. At the low N rates, 30–60% of the N applied could be accounted for in the grain. Annual N rates in excess of 90 kg N ha^{-1} resulted in fertilizer N recovery in the grain of less than 28% at all locations. Varvel and Peterson (1990a) have indicated that problems of estimating N recovery in crop production using the difference method include the assumption that mineralization, immobilization and other N transformations are the same for both fertilized and unfertilized soils.

4. Discussion

In experiments 222 and 505 a significant decrease in surface soil total N was noted when N was applied at annual rates between 45 and 90 kg ha^{-1}. Therefore, continued microbial breakdown of soil organic matter may have caused the decrease in total soil N with no corresponding change in organic C since increased growth and straw biomass (via priming) would have been present. At the higher N rates which exceeded that required for maximum yields (>90 kg N ha^{-1}), organic C levels were equal to or somewhat greater than the check. We consider that evidence of priming (increased net mineralization of organic N pools when low rates of fertilizer N are applied) observed here took place within the first five years in these long-term studies.

It was interesting to find that estimates of soil–plant inorganic N buffering (rate of N that can be applied in excess of that needed for maximum yield without resulting in increased soil profile inorganic N accumulation) were greatest in experiments 222 and 505 (Raun and Johnson, 1995), where evidence of the priming effect was also observed. As indicated earlier, we hypothesize that priming took placed since decreased total soil N at low rates in two of these long-term experiments was observed. Consistent with this, it is thought that soil–plant buffering will be greater in soils where priming is observed, a result of increased N from easily mineralizable N pools. Therefore, these soil–plant environments are also capable of immobilizing excess mineral N. However, it should be mentioned that such differences in total soil N would not likely be detected in short-term (3–5 years) studies given the precision at which total N can be determined using dry combustion methods ($\pm$0.01% or 0.10 g kg^{-1})

The combined use of total N and organic C in relation to N applied in these long-term trials provided reasonable evidence of the priming effect proposed by Westerman and Kurtz (1973). Analyses for surface soil organic C alone was useful in detecting increases at the high N rates (site specific) but provided little information when compared across locations (no relationship with soil–plant inorganic N buffering or total soil N). The combined use of total organic C and lignin (highly stable) content may be a more useful tool since the easily mineralizable N fractions will depend on organic C stability. This work further suggests that the quantity of easily mineralizable N should be a reliable predictor of soil–plant inorganic N buffering since total N decreased at low N rates (easily mineralized N), at both locations where soil–plant inorganic N buffering was large. If easily mineralizable N could be determined on a routine basis, it may provide an index for determining environmentally safe N rates for winter wheat production.

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