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ORGANIC MATTER AND MICROBIAL BIOMASS IN A VERTISOL AFTER 20 YR OF ZERO-TILLAGE

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Summary—The effects of 20 yr of tillage practice, crop residue management and fertiliser (urea) N application on organic C, total N, microbial biomass, anaerobic mineralisable N and pH at 0–25, 25–50 and 50–100 mm depths of a fine-textured (65% clay) vertisol were studied. The treatments, in a factorial combination, comprised of tillage (conventional tillage, CT vs zero-tillage, ZT), residue (retained, RR or burned, RB) and urea (0, 23 and 69 kg N ha^{-1} yr^{-1}) applied at 40–50 mm depth. Wheat and barley were grown for 15 and 3 yr, respectively. All soil properties showed a strong stratification with depth under ZT, RR treatments. Organic C, total N and microbial biomass N were highest and pH lowest in the 0–25 mm layer under ZT, RR and 69 kg N ha^{-1} yr^{-1}. In the 0–100 mm layer, similar trends were observed where residue was retained or fertiliser was applied but tillage had no effect on organic C and total N although higher microbial biomass was measured in soil under CT than ZT. Therefore, zero tillage, residue retention and fertiliser application results in stratification of soil properties, even in a vertisol.

INTRODUCTION

The organic matter content of a soil depends upon the relative rates at which organic materials are added to the soil and lost from it through decomposition. Tillage of a virgin soil generally leads to reduced amounts of organic matter primarily due to changes in temperature, moisture fluxes and aeration, to exposure of new soil surfaces through aggregate disruption, to reduced additions of organic materials, and frequently to increased soil erosion. Provided organic material additions are similar, zero-tillage may result in higher organic matter content in zero-tilled soil compared to the tilled soil. This may be due to reduced contact of added organic matter with soil, reduced exposure of new soil surfaces and decreased soil erosion, but also to changes in temperature, moisture and aeration, and hence different rates of microbial activity (Doran and Smith, 1987). However, higher amounts of organic matter and microbial activity or microbial biomass in soil under zero-tillage than that under conventional tillage are accompanied by concentration gradients in the surface layer (Doran, 1980; Carter and Rennie, 1982).

Vertisols differ from other soils in that they are characterised by wide cracks upon drying so that the topsoil and organic materials tend to fall into cracks. This, along with better mixing of organic materials due to swelling and shrinking in vertisol, may reduce the concentration gradient of organic matter and microbial biomass under zero-tillage. Although Loch and Coughlan (1984), Dalal (1989), Saffigna *et al.* (1989) and Thompson (1990) reported the higher amounts of organic matter in the 0–100 or 0–150 mm layers of vertisols subjected to zero-tillage with residue retention for 6–13 yr, the concentration gradient of organic matter in the 0–100 mm layer of soil was not studied by these authors. Since the distribution of organic matter in the surface soil affects physical (such as aggregation), chemical (pH, nutrient concentration) and biological (microbial activity, mineralization and nutrient availability) characteristics of soil, we have examined the distribution of organic C, total N, mineralisable N, microbial biomass and pH in the 0–25, 25–50 and 50–100 mm layers of a vertisol after 20 yr of zero-tillage and compared the values obtained with those for the 0–100 mm layer of conventionally-tilled soil. The effects of crop residues and fertiliser N application on the concentration gradient of these properties down to 100 mm depth were also examined.

MATERIALS AND METHODS

Soil samples were collected in May 1988 from a field experiment, established in December 1968 on a vertisol, Hermitage clay (very fine, montmorillonitic, Udic Pellustert), to study the effects of tillage, crop residues and fertiliser N on soil properties and winter cereal crop yields at Hermitage Research Station (28°12′S, 152°06′E), Warwick, Queensland. The mean annual temperature at the station is 17.5°C, and the mean annual rainfall is 685 mm, about 60% of which is received during summer (December–March). The soil, a black self-mulching cracking clay, has the following properties: bulk density 1.0 Mg m^{-3}, clay, 65%, silt, 24%, sand, 11%, and CEC, 66 m equiv. 100 g^{-1} (Dalal, 1989).

The detailed description of the field experiment is given by Marley and Littler (1989) and Dalal (1989). Treatments consisted of a factorial combination (2 × 2 × 3) of conventional tillage (CT) or zero-tillage (ZT), crop residue retained (RR) or burned (RB) after harvest, and three rates of N (0, 23 and 46 kg N ha^{-1} yr^{-1} for the first 8 yr, and thereafter the highest rate increased to 69 kg N ha^{-1} (0, 23 and 69N, respectively) placed at 40–50 mm depth before planting. The treatments were arranged in a

Table 1. Organic C (%) distribution in top layers of soil under conventional till (CT), zero-till (ZT), residue burned (RB), residue retained (RR), and N application (0, 23 and 69N) after 20 yr of cultural practices

		Organic C (%)					
	N applied	CT (mm)	ZT (mm)				
Residue treatment	(kg ha^{-1})	0–100	0–25	25–50	50–100	0–50	0–100
RB	0	1.75	1.73	1.65	1.62	1.69	1.65
	23	1.77	1.74	1.67	1.59	1.71	1.65
	69	1.77	1.86	1.77	1.71	1.82	1.76
RB means		1.76	1.78	1.70	1.64	1.74	1.69
RR	0	1.76	1.83	1.80	1.72	1.81	1.77
	23	1.79	1.98	1.90	1.68	1.94	1.81
	69	1.87	1.93	1.90	1.74	1.91	1.83
RR means		1.80	1.92	1.86	1.72	1.89	1.80
Tillage means		1.78	1.85	1.78	1.68	1.81	1.75
N means	0	1.76	1.78	1.73	1.67	1.75	1.71
	23	1.78	1.86	1.79	1.64	1.82	1.80
	69	1.82	1.90	1.84	1.73	1.87	1.85
LSD ($P = 0.05$) CT vs ZT							
Tillage			0.05	NS	0.05	NS	NS
Residue			0.05	0.06	0.05	0.05	0.05
N			0.06	NS	NS	0.07	NS
Tillage × residue			NS	0.08	NS	0.08	NS

NS—not significant at $P < 0.05$. Tillage × N, Residue × N, Tillage × Residue × N effects were not significant.

randomised block design and replicated four times (plot size: 6.4 × 61.9 m). Wheat (*Triticum aestivum* L., cv. Timgalen, 1968–1981; Cook, 1983–1984; Kite, 1985–1987) was grown for 15 yr and barley (*Hordeum vulgare* L., Clipper) for 3 consecutive yr (1975–1977). Weeds under the ZT treatment were controlled by herbicide spray, and in the CT treatment by four or five tillage operations with a chisel plough, to approx. 100 mm depth, during the fallow period (December–May).

Soil samples were taken with a 50 mm dia tube sampler down to 100 mm depth. Samples from the ZT treatment were sectioned into 0–25, 25–50 and 50–100 mm depths. Five samples were taken from each plot, bulked and sealed in plastic bags. Large visible pieces of crop residue were removed from soil, the samples thoroughly mixed and stored at 4°C until analysis.

After 4 weeks, subsamples of field-moist soil were taken for measurement of microbial biomass, using the chloroform fumigation–incubation method (Jenkinson and Powlson, 1976). Soil samples were adjusted to field capacity (56% H_2O at −0.03 MPa), optimum for N mineralisation, and kept at 22°C for 7 days to stabilise the microbial biomass. One set of duplicate samples was fumigated with $CHCl_3$ for 24 h and inoculated with fresh soil, then both sets were kept for 10 days at 22°C (Anderson and Domsch, 1978), and CO_2-C evolved during the 10 days was absorbed in 1 M NaOH and measured. After 10 days, mineral N ($NH_4^+ + NO_3^-$) in the samples was extracted with 2 M KCl and the extracts were analysed for NH_4^+-N (Crook and Simpson, 1971) and NO_3^--N (Best, 1976). The proportion of biomass C mineralized during the 10 days after $CHCl_3$ fumigation (k_c) was taken as 0.41 (Anderson and Domsch,

Table 2. Total N(%) distribution in top layers of soil under conventional till (CT), zero-till (ZT), residue burned (RB), residue retained (RR), and N application (0, 23 and 69N) after 20 yr of cultural practices

		Total N (%)					
	N applied	CT (mm)	ZT (mm)				
Residue treatment	(kg ha^{-1})	0–100	0–25	25–50	50–100	0–50	0–100
RB	0	0.132	0.131	0.129	0.130	0.130	0.130
	23	0.141	0.141	0.131	0.130	0.136	0.133
	69	0.144	0.145	0.148	0.133	0.146	0.139
RB means		0.139	0.139	0.136	0.131	0.138	0.134
RR	0	0.134	0.158	0.142	0.140	0.150	0.145
	23	0.144	0.161	0.151	0.138	0.156	0.147
	69	0.149	0.153	0.153	0.145	0.153	0.149
RR means		0.142	0.157	0.149	0.141	0.153	0.147
Tillage means		0.141	0.148	0.142	0.136	0.145	0.141
N means	0	0.133	0.145	0.136	0.135	0.140	0.138
	23	0.142	0.151	0.141	0.134	0.146	0.140
	69	0.146	0.149	0.151	0.139	0.150	0.144
LSD ($P = 0.05$) CT vs ZT							
Tillage			0.006	NS	NS	NS	NS
Residue			0.006	0.006	0.005	0.005	0.005
N			0.007	0.007	0.006	0.006	0.006
Tillage × residue			0.008	NS	NS	0.007	0.007

NS—not significant at $P < 0.05$. Tillage × N, Residue × N, Tillage × Residue × N effects were not significant.

Table 3. Microbial biomass N distribution in top layers of soil under conventional till (CT), zero-till (ZT), residue burned (RB), residue retained (RR), and N application (0, 23 and 69N) after 20 yr of cultural practices

		Microbial biomass N (mg N kg^{-1} soil)					
	N applied	CT (mm)	ZT (mm)				
Residue treatment	(kg ha^{-1})	0–100	0–25	25–50	50–100	0–50	0–100
RB	0	64.2	72.5	57.6	46.0	65.0	55.2
	23	67.1	72.5	57.4	44.7	64.6	54.8
	69	65.3	79.2	62.9	52.1	71.0	61.5
RB means		65.5	74.7	59.3	47.6	66.9	57.3
RR	0	78.6	89.1	60.5	49.4	74.8	62.1
	23	81.0	94.9	70.8	49.0	82.8	66.3
	69	91.1	93.3	63.6	48.0	78.5	63.3
RR means		83.5	92.4	65.0	48.8	78.7	63.8
Tillage means		74.5	83.6	62.1	48.2	72.8	60.6
N means	0	71.4	80.8	59.0	47.7	69.4	58.8
	23	74.0	83.7	64.1	46.9	73.9	60.4
	69	78.2	86.2	63.3	50.0	74.7	62.4
LSD ($P = 0.05$) CT vs ZT							
Tillage			4.6	4.4	4.2	NS	3.4
Residue			4.6	4.4	4.2	4.2	3.4
N			5.6	5.4	NS	NS	4.2
Tillage × residue			NS	6.2	6.0	NS	4.8

NS—not significant at $P < 0.05$. Tillage × N, Residue × N, Tillage × Residue × N effects were not significant.

1978) and a K_N values of 0.5 [$k_N = \beta k_c/\alpha$, where β is the C:N ratio of soil microbial biomass (6.7), and α is the ratio of C flush and N flush of the fumigated soil (5.31), Jenkinson 1988].

The remainder of the soil sample was air dried and ground (<2 mm) for determination of pH (1:5 soil/H_2O) and anaerobic mineralizable N (Keeney, 1982). A finely ground sample (<0.25 mm) was used to determine total N, including NO_3^--N, by a modified Kjeldahl method (Dalal *et al.*, 1984) and organic C by the Walkley–Black method adapted for spectrophotometric determination (Sims and Haby, 1971).

Analysis of variance was performed on the data by standard techniques and the values of organic C and total N were compared with those obtained in May 1981 (Dalal, 1989) using years as the split plot treatment (Snedecor and Cochran, 1967).

RESULTS

Since field bulk density of soil under ZT at different depths (0–25, 25–50 and 50–100 mm) and other treatments varied only slightly (1.00 ± 0.03 Mg m^{-3}), soil properties under ZT were also expressed at 0–50 and 0–100 mm depths, as means of the values at 0–25 and 25–50 mm layers, and that of 0–50 and 50–100 mm layers, respectively. Organic C and total N at 0–25, 25–50, and 50–100 mm depths of soil under CT showed no significant difference between depths, and therefore, measurements at 0–100 mm depth only are reported.

Organic C concentration in soil was higher in the 0–25 mm layer but lower in 50–100 mm layer under ZT than under CT, such that organic C concentration in 0–100 mm layer as a whole was not affected by tillage (Table 1). However, residue retention in-

Table 4. Microbial biomass N as a proportion of total N in top layers of soil under conventional till (CT), zero-till (ZT), residue burned (RB), residue retained (RR), and N application (0, 23 and 69N) after 20 yr of cultural practices

		Microbial biomass N/total N (%)					
	N applied	CT (mm)	ZT (mm)				
Residue treatment	(kg ha^{-1})	0–100	0–25	25–50	50–100	0–50	0–100
RB	0	4.87	5.59	4.51	3.54	5.05	4.28
	23	4.80	5.21	4.40	3.44	4.76	4.12
	69	4.62	5.50	4.26	3.96	4.87	4.43
RB means		4.76	5.43	4.39	3.65	4.90	4.28
RR	0	5.89	5.68	4.31	3.53	5.01	4.29
	23	5.65	5.93	4.69	3.55	5.33	4.49
	69	6.17	6.11	4.20	3.29	5.16	4.26
RR means		5.90	5.91	4.40	3.46	5.17	4.35
Tillage means		5.33	5.67	4.39	3.55	5.04	4.31
N means	0	5.38	5.63	4.41	3.53	5.03	4.29
	23	5.22	5.57	4.54	3.50	5.06	4.31
	69	5.39	5.80	4.23	3.63	5.02	4.35
LSD ($P = 0.05$) CT vs ZT							
Tillage			NS	0.38	0.34	NS	0.29
Residue			0.39	0.38	0.34	0.35	0.29
N			NS	NS	NS	NS	NS
Tillage × residue			NS	0.53	0.48	0.50	0.41

NS—not significant at $P < 0.05$. Tillage × N, Residue × N, Tillage × Residue × N effects were not significant.

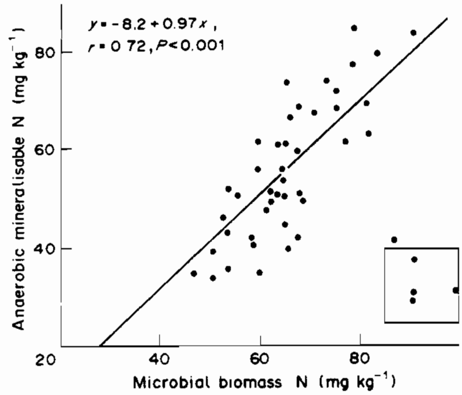

Fig. 1. Relationship betwen microbial biomass N and anaerobic mineralisable N. The four data points (excluded from regression analysis) in the square are from conventional tillage (CT), residue burned (RB) and 69 kg N ha^{-1} yr^{-1} treatment.

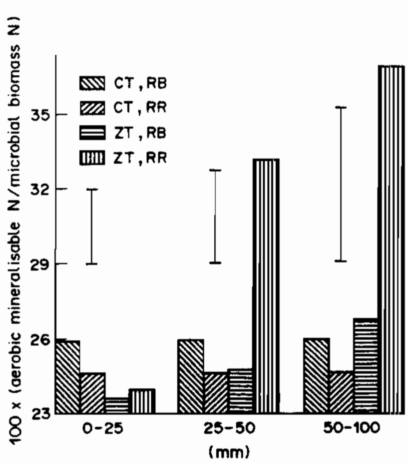

Fig. 2. Aerobic mineralisable N/microbial biomass N at 0–25, 25–50 and 50–100 mm depths of soil under zero-tillage (ZT), 0–100 mm layer of soil under conventional tillage (CT), residue burned (RB) and residue retained (RR).

creased organic C at 0–25, 25–50 and 50–100 mm depths in soil under zero-tillage. Effects of fertiliser N application on organic C were primarily confined to 0–25 mm depth although significant differences could be measured also in the 0–50 mm layer. Similarly, the interactive effect of tillage and residue treatment was observed up to 0–50 mm depth; organic C was the highest (1.89%) under the ZT, RR treatment.

The effects of 20 yr of zero-tillage, residue retention and fertiliser N application on total N concentration were essentially similar to those on organic C (Table 2) so that the C:N ratio of the organic matter was unaffected by any of these treatments.

Microbial biomass N was significantly affected by tillage, residue and fertiliser N (Table 3). The soil under ZT contained higher amounts of microbial biomass N than that under CT in the 0–25 mm layer and lower amounts in 25–50 and 50–100 mm layers. Thus soil under CT contained nearly 19% more microbial biomass N than the ZT soil in the 0–100 mm layer: 74.5 and 60.6 mg N kg^{-1} soil, respectively, taking mean values for residue treatments and N rates.

Microbial biomass N was significantly higher (20–25%) at 0–25, 25–50 and 50–100 mm depths where stubble was retained than where it was burned. Increase in microbial biomass N as a result of fertiliser N application was primarily restricted to the 0–25 mm layer of soil under ZT (Table 3). The effects of tillage and residue management were interactive. Highest microbial biomass N (0–100 mm) was obtained in soil under CT, RR treatment (83.5 mg kg^{-1} soil, mean of all N rates) compared with 63.8 mg kg^{-1} under ZT, RR treatment.

Microbial biomass C was eight times larger than microbial biomass N and the trends between treatments were similar (data not given).

For conventional tillage, microbial biomass N as a proportion of total N was higher under RR treatment than under RB treatment, 5.9 compared to 4.8, means of all N rates. Under ZT this trend was less marked (Table 4).

Table 5. Soil pH of top layer of soil under conventional till (CT), zero-till (ZT), residue burned (RB), residue retained (RR), and N application (0, 23 and 69N) after 20 yr of cultural practices

		Soil pH					
	N applied	CT (mm)	ZT (mm)				
Residue treatment	(kg ha^{-1})	0–100	0–25	25–50	50–100	0–50	0–100
RB	0	7.88	7.69	7.81	8.14	7.75	7.75
	23	7.72	7.44	7.48	7.72	7.46	7.46
	69	7.60	7.32	7.29	7.60	7.30	7.30
RB means		7.73	7.48	7.53	7.82	7.50	7.56
RR	0	7.87	7.29	7.29	7.50	7.29	7.29
	23	7.56	7.11	6.97	7.24	7.04	7.04
	69	7.25	7.06	6.89	7.02	6.97	6.97
RR means		7.56	7.15	7.05	7.25	7.10	7.17
Tillage means		7.65	7.32	7.29	7.53	7.30	7.42
N means	0	7.88	7.49	7.55	7.81	7.52	7.67
	23	7.64	7.28	7.23	7.48	7.25	7.36
	69	7.42	7.19	7.09	7.31	7.14	7.22
LSD ($P = 0.05$) CT vs ZT							
Tillage			0.09	0.11	NS	0.10	0.10
Residue			0.09	0.11	0.13	0.10	0.10
N			0.12	0.14	0.16	0.12	0.12
Tillage × residue			NS	0.16	0.18	0.14	0.14

NS—not significant at $P < 0.05$. Tillage × N, Residue × N, Tillage × Residue × N effects were not significant.

Overall, the effects of tillage, residue treatment and N rate on anaerobic mineralisable N were similar to those on microbial biomass N—biomass N and mineralisable N were fairly well correlated (Fig. 1). There were, however, some significant differences between treatments. The ratio (mineralisable N : biomass N) in ZT (25–50 and 50–100 mm) was considerably greater than for the other treatments (Fig. 2). It might be worth commenting that, despite low biomass in ZT (25–50 and 50–100 mm), mineralisable N was similar to other treatments.

Soil pH was substantially lower under ZT treatment in the 0–25 and 25–50 mm layers. The pH was further depressed by residue retention and fertiliser N application (Table 5) such that lowest values (7.0, 0–100 mm) were observed in soil under ZT, RR and 69N treatment, compared with 7.8 in soil under CT, RB and 0N treatment. Soil pH declined by about 0.2 and 0.4 units at all depths studied with 23 and 69N, respectively, compared to 0N. Except for the interactive effect of tillage and residue on soil pH, no other treatment interaction was observed. Soil pH was significantly correlated with both organic C ($r = -0.66$, $P < 0.001$) and total N ($r = -0.71$, $P < 0.001$), individually as well as in multiple regression analysis ($r = 0.74$, $P < 0.001$):

$$\text{pH} = 10.78 - 0.80^{**} \text{ organic C } (\%) - 13.54^{**} \text{ total N } (\%) \quad (1)$$

DISCUSSION

Since organic matter concentration in soil depends upon the relative rates at which organic materials are added to the soil and lost from it through decomposition, both tillage (through its effect on rates of decomposition) and residue management practices are likely to affect organic matter content in a soil. Highest concentrations of organic C (0–50 mm) and total N (0–100 mm) were found in soil under ZT, RR treatment (Tables 1 and 2). Saffigna *et al.* (1989) also found the highest amounts of organic C and total N in the top soil (0–100 mm) under ZT, RR treatment in a vertisol after 6 yr.

Comparison of organic C concentration (0–100 mm) 5 yr (Loch and Coughlan, 1984), 13 yr (Dalal, 1989), 16 and 18 yr (R. C. Dalal, unpublished data) and 20 yr (this study) after the initiation of the experiment showed the significant effects of residue retention (Fig. 3), fertiliser N application, and tillage × residue interaction. Also, residue × year interaction was significant. The transitory effect of the residue on organic C concentration can be discerned from the decline in organic C under RR treatment from 13 to 16 yr, because no crop was grown in the 14th yr and hence no residue returned to the soil.

The proportion of crop residue C retained in the soil can be calculated from the additional amount of organic C present under the residue retention practice (Fig. 3) as a function of residue C added. Since only grain yields are available (Marley and Littler, 1989; Thompson, 1990) residue C was calculated by assuming harvest index of 0.4 (grain yield/total dry matter yield) and residue consists of 40% C. The proportions of crop residue C so calculated retained in the organic

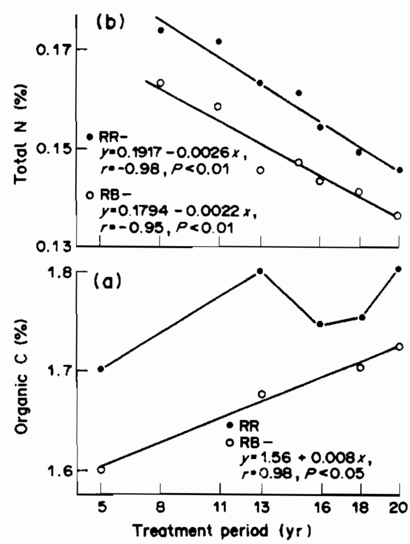

Fig. 3. Organic C (a) and total N (b) in soil after 5–20 yr of residue retained (RR) or residue burned (RB) treatments.

matter were 16, 7 and 3% after 5, 13 and 20 yr, respectively. Saffigna *et al.* (1989) also found that 14% of the C added in sorghum residue remained in the organic matter of a central Queensland vertisol after 5 yr but only 7% after 7 yr (J. Standley, pers. commun.). Similarly, 4–7% of C added in barley straw over 18 yr was retained in a Danish soil (Powlson *et al.*, 1987). Residue C retention values measured in this study were therefore in accord with these values.

Comparison of total N concentrations (0–100 mm) after 13 yr (Dalal, 1989), 16 and 18 yr (R. C. Dalal, unpublished data) and 20 yr (this study) after initiation of the experiment showed significant effects of tillage, residue, fertiliser N and tillage × residue as well as the year effect, tillage × year and residue × year interaction. Total N concentration declined at the rate of 21–27 kg N ha^{-1} yr^{-1} under all treatments (Table 6). The soil where residue was retained always contained more N than where residue was burned (Fig. 3), after 20 yr of treatment the difference was about 80 kg N ha^{-1}. Less N was removed by the crop, 3.5 and 1 kg N ha^{-1} in grain and residue, respectively, in each of the 18 crops (calculated from Marley and Littler, 1989; Thompson, 1990) from the soil where residue was retained than where it was burned. It is possible that greater immobilisation of mineral N in RR treatment caused decreased N uptake by the crop.

Total N content in the top layer (0–100 mm) declined during the last 20 yr in spite of ZT, RR and fertiliser N additions (Fig. 3) although the rate of loss was slightly less with the highest rate of fertiliser application (69'N, mean rate of 59.3 kg N ha^{-1} yr^{-1} for 19 yr) (Table 6). The rate of N removed by the grain was only 10 kg more from 69N treatment (66 kg N ha^{-1} yr^{-1}) compared to 0N treatment (56 kg N ha^{-1} yr^{-1}) [calculated from Marley and Littler (1989), Thompson (1990)]. Besides removal in the produce, soil N decline may have been due to deep leaching (Dalal, 1989) and denitrification.

Table 6. Regression of total N concentration in soil (0–100 mm) under different treatments and treatment period (8–20 yr)*

Treatments	Regression† constant (a) (kg N ha^{-1})	Regression† coefficient (b) (kg N ha^{-1} yr^{-1})	Correlation† coefficient (r)
Conventional tillage	1862 ± 56	−24 ± 4	−0.94
Zero tillage	1892 ± 21	−23 ± 1	−0.99
Residue burned	1794 ± 46	−22 ± 3	−0.95
Residue retained	1971 ± 33	−26 ± 2	−0.98
No N applied	1884 ± 24	−27 ± 2	−0.99
23 kg N ha^{-1} yr^{-1}	1872 ± 53	−23 ± 4	−0.95
46 kg N ha^{-1} yr^{-1} (8 hr)	1877 ± 25	−21 ± 2	−0.98
69 kg N ha^{-1} yr^{-1} (12 yr)			

*From Dalal (1989) after 13 yr, Thompson (1990) after 8, 11 and 15 yr, R. C. Dalal (unpublished data) after 16 and 18 yr, and after 20 yr (this study) of initiation of the experiment.
†Regression equation: total N = a + b (yr), $n = 7$; all r values were significant at $P < 0.01$.

As a consequence of increase in organic C and decrease in total N (Fig. 3) the C:N ratio increased from 11.4 after 13 yr to 12.7 after 20 yr of treatments. The C:N ratio under CT treatment was higher than under ZT treatment. Also, it was higher in RB than RR treatment, especially in the first 16 yr of treatment. There was more N uptake by the crop from the CT and RB treatments as compared to ZT and RR treatments, presumably due to greater immobilisation in the latter, and higher incidence of disease, *Pratylenchus thornei* (Thompson, 1990).

The total amounts of microbial biomass N, and the proportions of total N in biomass declined sharply with depth in soil under ZT (Tables 3 and 4). That the effects of ZT and residue retention on increased microbial biomass are generally pronounced at or near the soil surface has been observed by Doran (1980), Carter and Rennie (1982) and Haynes and Knight (1989). Soil microbial biomass, a living part of soil organic matter, is responsible for the transformation of the added and native organic matter. It is also a small but labile source as well as a sink of N (and other nutrients) depending on season (that is, rainfall and temperature), cropping, or soil management. Stratification of microbial biomass in soil under ZT has been suggested as a major mechanism for immobilisation of soil, residue and fertiliser N near the soil surface, as compared with CT (House *et al.*, 1984). A close correlation between microbial biomass N and anaerobic mineralisable N (Fig. 2) also suggests that the former provides a labile source of N in soil (Doran, 1987).

The stratification of residue near the soil surface and lack of soil mixing due to cultivation under ZT not only affected the distribution of organic matter and microbial biomass but also soil pH. The decrease in pH in soil under ZT, RR and fertiliser (urea) N application (Table 5) is at least partly associated with increase in organic matter. Changes in exchangeable cations (e.g. Ca, Na) due to more leaching under ZT than CT treatment (Blevins *et al.*, 1983; Dalal, 1989) or incorporation into organic matter may also be responsible. Although decrease in pH in soil under ZT accompanied by fertiliser N application has been reported in acidic sandy loam to silty loam soils (Blevins *et al.*, 1983; Doran, 1987), effects in calcareous clay soils, such as this vertisol, are expected to be small (Dalal, 1989). The large difference in pH observed between the extremes of treatments (Table 5), CT, RB and 0N (pH 7.8) and ZT, RR and 69N (pH 7.0), shows that soil pH is likely to decline under ZT soil management systems, even in fine-textured calcareous soils.

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REFERENCES

Anderson J. P. E. and Domsch K. H. (1978) Mineralisation of bacteria and fungi in chloroform-fumigated soils. *Soil Biology & Biochemistry* **10**, 207–213.

Best E. K. (1976) An automated method for the determination of nitrate–nitrogen in soil extracts. *Queensland Journal of Agriculture and Animal Science* **33**, 161–166.

Blevins R. L., Thomas G. W., Smith M. S., Frye W. W. and Cornelius P. L. (1983) Changes in soil properties after 10 years continuous non-tilled and conventionally tilled corn. *Soil and Tillage Research* **3**, 135–146.

Carter M. R. and Rennie D. A. (1982) Changes in soil quality under zero-tillage farming systems: distribution of microbial biomass and mineralizable C and N potentials. *Canadian Journal of Soil Science* **62**, 587–597.

Crooke W. M. and Simpson W. E. (1971) Determination of ammonium in Kjeldahl digests of crops by an automated procedure. *Journal of Science of Food and Agriculture* **22**, 9–10.

Dalal R. C. (1989) Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a vertisol. *Soil Science Society of America Journal* **53**, 1511–1515.

Dalal R. C., Sahrawat K. L. and Myers R. J. K. (1984) Inclusion of nitrate and nitrite in the Kjeldahl nitrogen determination of soils and plant materials using sodium thiosulphate. *Communications in Soil Science and Plant Analysis* **55**, 1453–1461.

Doran J. W. (1980) Soil microbial and biochemical changes associated with reduced tillage. *Soil Science Society of America Journal* **44**, 765–771.

Doran J. W. (1987) Microbial biomass and mineralizable nitrogen distribution in non-tillage and plowed soils. *Biology and Fertility of Soils* **5**, 68–75.

Doran J. W. and Smith M. S. (1987) Organic matter management and utilization of soil and fertilizer nutrients. In *Soil Fertility and Organic Matter as Critical Components of Production Systems* (Follet R. F. *et al.*, Eds), pp. 53–72. Soil Science Society of America Special Publication 19, American Society of Agronomy, Madison, Wisc.

Haynes R. J. and Knight T. L. (1989) Comparison of soil chemical properties, enzyme activities, levels of biomass N and aggregate stability in the soil profile under conventional and no-tillage in Canterbury, New Zealand. *Soil & Tillage Research* **14**, 197–208.

House G. J., Stinner B. J., Crossley D. A. Jr, Odum E. P. and Longdale D. W. (1984) Nitrogen cycling in conventional and no-tillage agroecosystems in the Southern Piedmont. *Journal of Soil Water Conservation* **39**, 194–200.

Jenkinson D. S. (1988) Determination of microbial biomass carbon and nitrogen in soil. In *Advances in Nitrogen Cycling in Agricultural Ecosystems* (J. R. Wilson, Ed.), pp. 368–386. C.A.B. International, Wallingford.

Jenkinson D. S. and Powlson D. S. (1976) The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. *Soil Biology & Biochemistry* **8**, 209–213.

Keeney D. R. (1982) Nitrogen availability indices. In *Methods of Soil Analysis, Part 2* (A. L. Page *et al.*, Eds), 2nd Edn, pp. 711–733. American Society of Agronomy, Madison, Wisc.

Loch R. J. and Coughlan K. J. (1984) Effects of zero-tillage and stubble retention on some properties of a cracking clay. *Australian Journal of Soil Research* **22**, 91–98.

Marley J. M. and Littler J. W. (1989) Winter cereal production on the Darling Downs—an 11 year study of fallowing practices. *Australian Journal of Experimental Agriculture* **29**, 807–828.

Powlson D. S., Brookes P. C. and Christensen B. T. (1987) Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. *Soil Biology & Biochemistry* **19**, 159–164.

Saffigna P. G., Powlson D. S., Brookes P. C. and Thomas G. A. (1989) Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an Australian vertisol. *Soil Biology & Biochemistry* **21**, 759–765.

Sims J. R. and Haby V. A. (1971) Simplified colorimetric determination of soil organic matter. *Soil Science* **112**, 137–141.

Snedecor G. W. and Cochran W. G. (1967) *Statistical Methods*, 6th Edn. Iowa State University Press, Ames.

Thompson J. P. (1990) Long-term nitrogen fertilisation of wheat and barley in the Hermitage tillage and stubble management trial. In *Workshop on Long-term Nitrogen Fertilisation of Crops* (I. Vallis and G. A. Thomas, Eds), pp. 44–67. Queensland Department of Primary Industries, Brisbane.