Available online at www.sciencedirect.com
ScienceDirect
Soil & Tillage Research 94 (2007) 295–304
Soil & Tillage Research
www.elsevier.com/locate/still

No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics

G.A. Thomas [a,*], R.C. Dalal [b], J. Standley [a]

[a] Queensland Department of Natural Resources, Mines and Water, Natural Resource Sciences, South West Region, P.O. Box 318, Toowoomba, Qld 4350, Australia
[b] Queensland Department of Natural Resources, Mines and Water, Natural Resource Sciences, 80 Meiers Road, Indooroopilly, Brisbane, Qld 4350, Australia

Received 8 November 2005; received in revised form 28 July 2006; accepted 16 August 2006

Abstract

No-till (NT) system for grain cropping is increasingly being practised in Australia. While benefits of NT, accompanied by stubble retention, are almost universal for soil erosion control, effects on soil organic matter and other soil properties are inconsistent, especially in a semi-arid, subtropical environment. We examined the effects of tillage, stubble and fertilizer management on the distribution of organic matter and nutrients in the topsoil (0–30 cm) of a Luvisol in a semi-arid, subtropical environment in southern Queensland, Australia. Measurements were made at the end of 9 years of NT, reduced till (RT) and conventional till (CT) practices, in combination with stubble retention and fertilizer N (as urea) application strategies for wheat (*Triticum aestivum* L.) cropping.

In the top 30 cm depth, the mean amount of organic C increased slightly after 9 years, although it was similar under all tillage practices, while the amount of total N declined under CT and RT practices, but not under NT. In the 0–10 cm depth, the amounts of organic C and total N were significantly greater under NT than under RT or CT. No-till had 1.94 Mg ha^{-1} (18%) more organic C and 0.20 Mg ha^{-1} (21%) more total N than CT. In the 0–30 cm depth, soil under NT practice had 290 kg N ha^{-1} more than that under the CT practice, most of it in the top 10 cm depth. Microbial biomass N was similar for all treatments. Under NT, there was a concentration gradient in organic C, total N and microbial biomass N, with concentrations decreasing from 0–2.5 to 5–10 cm depths.

Soil pH was not affected by tillage or stubble treatments in the 0–10 cm depth, but decreased significantly from 7.5 to 7.2 with N fertilizer application. Exchangeable Mg and Na concentration, cation exchange capacity and exchangeable Na percentage in the 0–10 cm depth were greater under CT than under RT and NT, while exchangeable K and bicarbonate-extractable P concentrations were greater under NT than under CT.

Therefore, NT and RT practices resulted in significant changes in soil organic C and N and exchangeable cations in the topsoil of a Luvisol, when compared with CT. The greater organic matter accumulation close to the soil surface and solute movement in these soils under NT practice would be beneficial to soil chemical and physical status and crop production in the long-term, whereas the concentration of nutrients such as P and K in surface layers may reduce their availability to crops.

Keywords: No-till; Luvisol; Organic carbon; Total nitrogen; pH; Cations

* Corresponding author. Tel.: +61 07 4688 1324; fax: +61 07 4688 1473.
E-mail address: Gregory.Thomas@nrm.qld.gov.au (G.A. Thomas).

0167-1987/$ – see front matter
doi:10.1016/j.still.2006.08.005

1. Introduction

Tillage accelerates oxidation of organic matter by soil microorganisms through changes in soil water, aeration and temperature regimes, aggregation and nutritional environment (Doran and Smith, 1987). Therefore, soils under no-till (NT) generally contain greater organic C and N and microbial biomass than under conventional till (CT), especially closer to the soil surface. Differences in distribution of immobile nutrients and exchangeable cations in surface layers of soil also occur between NT and CT, due to the absence of inversion and mixing of surface soil by tillage. Soils under NT practice are frequently more acidic in the surface layers but less acidic in deeper layers than under CT practice as a result of an increase in organic matter and associated organic acids and changes in the proportions of cations and anions in soil under NT practice (Logan et al., 1991; Prasad and Power, 1991; Kern and Johnson, 1993; Schomberg et al., 1994).

From an analysis of long-term experiments, West and Marland (2002) concluded that the effects of no-tillage on soil organic C sequestration were positive, although most of these studies were confined to cooler, temperate environments. In subtropical environments, because of their higher temperatures, there may be greater opportunities for organic matter decomposition, and a semi-arid climate may have lower biomass production and C inputs than sub-humid and humid regions (Dalal and Chan, 2001). Consequently, tillage effects on soil organic C sequestration in a semi-arid, subtropical environment may differ from the temperate and wetter climates. Similar studies have been conducted previously in this region on Vertisols (Loch and Coughlan, 1984; Dalal et al., 1991, 1995; Thompson, 1992), but not on Luvisols, which have much lower clay content than the former, and possibly different organic matter and nutrient dynamics.

The objective of this study was to assess the effects of tillage, stubble and fertilizer management on the amounts and distribution of organic matter and nutrients in the 0–2.5, 2.5–5, 5–10, 10–20 and 20–30 cm depths of a Luvisol in a semi-arid, subtropical environment in southern Queensland, Australia. Measurements were made at the end of 9 years of NT, CT and reduced till (RT) practices, in combination with contrasting stubble management practices (retention and removal) and N fertilizer application strategies under wheat (*Triticum aestivum* L.) cropping.

2. Materials and methods

2.1. Experimental site

The field experiment was located approximately 45 km north of Goondiwindi (28.52°S and 150.33°E), in southern Queensland, Australia. Mean annual rainfall is 620 mm, with about 60% of this amount falling during the warmer months from October to March. Mean maximum and minimum temperatures are 31.6 and 17.7 °C, respectively, from October to March and 21.8 and 8.2 °C, respectively, from April to September.

The soil is an Abruptic Luvisol (FAO, 1998) or a Hypercalcic, Subnatric, Brown Sodosol; thin to medium, non-gravelly, clay loamy/clayey and deep (Isbell, 1996). The soil was also classified as a red-brown earth (Stace et al., 1968) and an Alfisol (Typic Natrustalf) (Soil Survey Staff, 1998). Some soil chemical and physical characteristics of the soil profile at the end of 12 years of wheat cropping following clearing of native vegetation, but before tillage and stubble management treatments were imposed at the initiation of this study, are shown in Table 1. Soil bicarbonate-extractable P level in the 0–10 cm depth was 9 mg kg^{-1}. Native vegetation comprised belah (*Casuarina cristata*) open forest, with some brigalow (*Acacia harpophylla*), occasional poplar box (*Eucalyptus populnea*) and an understorey of wilga (*Geijera parviflora*) and false sandalwood (*Eremophila mitchelii*). The site had a slope of approximately 1%.

Table 1
Organic C, total N, pH, electrical conductivity (EC) and clay content of the soil profile before tillage and stubble management cultural practices were imposed (B.J. Radford, personal communication)

Soil depth (cm)	Organic C (g kg^{-1})	Total N (g kg^{-1})	pH	EC (dS m^{-1})	Clay content (g kg^{-1})
0–10	9.0	0.98	7.2	0.10	270
10–20	5.1	0.60	7.8	0.12	–
20–30	4.4	0.52	8.2	0.17	470
50–60	2.3	0.28	8.8	0.59	470
80–90	1.5	0.23	7.6	0.66	480
110–120	1.6	0.26	6.1	0.82	440

2.2. Experiment details

Full experimental details were reported in Radford et al. (1992). Briefly, the experiment consisted of three tillage treatments (CT, RT and NT) in combination with stubble retention or stubble removal, arranged in a randomised block design with three replications. From 1988, each of the main treatments received two N fertilizer rates: 0 (N_0) and 60 (N_{60}) kg N ha^{-1} year^{-1}. The main treatment plots measured 30 m by 6 m, and the N fertilizer subplots were 10 m by 6 m. Small earthern berms were constructed between main plots to prevent water runoff from one plot to the next.

Plots were sown to wheat (cv. Hartog) in May or June each year at a rate of 35–40 kg ha^{-1} and at a depth of 3–8 cm. Nitrogen fertilizer as urea was drilled into the soil at sowing in bands 12.5 cm from the seed rows in the N_{60} treatments. All plots received an annual basal application of 20 kg P ha^{-1} as triple superphosphate (19.4% P, 2% S and 18.5% Ca), banded with the seed at sowing.

The NT practice involved the use of herbicides for weed control during the fallow period between crops (usually November to May). The RT practice had a post-harvest primary tillage with a blade plough, either having a 180 cm wide, 75° blade or with 90 cm wide, 60° blades mounted on shanks 85 cm apart. Herbicides were then used for weed control during the fallow period in RT until a pre-plant tillage for seedbed preparation with a cultivator with 12.5 cm wide tines mounted on shanks 11.5 cm apart, followed by harrows. The CT practice had a primary tillage with a one-way disc plough with 63 cm diameter discs. Subsequent tillage in CT during the fallow period included two or three operations with a scarifier with 40 cm wide tines mounted on shanks 30 cm apart, and a pre-plant tillage with the same implement as for RT. Depths of primary and subsequent tillage operations were 10–20 and 8–15 cm, respectively.

Stubble was either retained on the plots after harvest of grain from the preceding crop or removed after harvest by cutting at ground level and raking off the plots before tillage operations began.

2.3. Soil sampling and analysis

Soil samples were taken prior to sowing of the ninth consecutive wheat crop, using 50 mm diameter steel sampling tubes. Six soil cores were taken from each plot to a depth of 30 cm. In NT treatments, cores were cut into segments of 0–2.5, 2.5–5, 5–10, 10–20 and 20–30 cm intervals. In RT and CT treatments, depth segments were 0–10, 10–20 and 20–30 cm intervals. The corresponding depth segments from all six cores in each plot were bulked to give a composite sample for each depth segment in each plot.

A field-moist subsample was taken from each composite soil sample for measurement of microbial biomass N using the chloroform fumigation–incubation method (Jenkinson and Powlson, 1976). Briefly, two sets of soil samples were adjusted to field capacity (−0.03 MPa), and kept at 22 °C for 7 days to stabilise the microbial biomass. Then, one set of duplicate samples was fumigated with alcohol-free chloroform for 24 h and inoculated with fresh soil. Both sets of fumigated and unfumigated soil samples were incubated for 10 days at 22 °C (Anderson and Domsch, 1978). A subset of fumigated and unfumigated soil samples and the soil samples after 10 days incubation were extracted with 2 M KCl and the extracts were analysed for ammonium-N (Crooke and Simpson, 1971) and nitrate-N (Best, 1976). Microbial biomass N (MB-N) was calculated as follows: MB-N = F_N/k_N, where F_N is the flush of N mineralized after fumigation (mineral N in fumigated soil sample − mineral N in unfumigated soil sample) and k_N is the fraction of the N in the killed microbial biomass that is mineralized during 10-day incubation and taken as 0.5 (Jenkinson, 1988).

Soil mineralizable N was estimated by aerobic incubation of field moist soil samples adjusted to field capacity for 18 days at 22 °C. Mineral N produced during incubation was measured by extracting soil samples with 2 M KCl and the extracts analysed for ammonium-N (Crooke and Simpson, 1971) and nitrate-N (Best, 1976).

The remainder of each composite soil sample was dried at 40 °C and ground to <2 mm size. Samples from all depth intervals were analysed for organic C, total N, pH and bicarbonate-extractable P. Exchangeable cations and CEC were determined only for samples from 0 to 10 cm in CT and RT and from the 0 to 2.5, 2.5 to 5 and 5 to 10 cm depths in NT.

Organic C was determined by the dichromate oxidation method (Walkley and Black, 1934; Walkley, 1947), followed by a semi-automated colorimetric procedure with sucrose standards (Sims and Haby, 1971). Total N was determined by macro-Kjeldahl digestion procedure (Bremner, 1965).

Soil pH was measured on a 1:5 soil:water suspension (Bruce and Rayment, 1982). Bicarbonate-extractable P was determined by extraction in 0.5 M sodium bicarbonate with pH of 8.5 (Colwell, 1963), followed by an automated continuous flow procedure based on the method of Murphy and Riley (1962) to measure P in the extracts (Bruce and Rayment, 1982). Exchangeable cations and cation exchange capacity (CEC) were measured by the procedure of Bruce and Rayment (1982). Exchangeable Na percentage (ESP) was calculated as exchangeable Na concentration/CEC, multiplied by 100.

Soil bulk density in the 0–2.5, 2.5–5, 5–10, 10–20 and 20–30 cm depths was determined using 100 mm diameter soil cores. The soil contained in the cores was dried at 105 °C for 48 h and weighed. Bulk density was calculated from the oven-dried mass of soil contained in the core volume.

The amounts of organic C, total N, microbial biomass N, aerobic mineralizable N (mostly NO_3-N and <1% NH_4-N) and bicarbonate-extractable P in successive soil layers were calculated from concentration and bulk density values for each soil depth, based on an equivalent soil mass for CT of 1380, 1470 and 1500 Mg ha^{-1} for the 0–10, 10–20 and 20–30 cm layers, respectively (Ellert et al., 2002). The amounts of organic C and total N in the 0–10, 10–20 and 20–30 cm layers at the start of the experiment, before tillage and stubble management treatments were imposed, were calculated using the bulk density values for CT.

Analysis of variance was performed by standard statistical techniques using tillage practices (NT, RT and CT) and stubble management (retention and removal) as the main treatments and the rate of N application (N_0 and N_{60}) as the split–plot treatments (Snedecor and Cochran, 1967). Treatment means were compared using the least significant difference (LSD) at $P \leq 0.05$.

3. Results and discussion

3.1. Bulk density

In the 0–10 cm depth interval, bulk density under NT (1.44 Mg m^{-3}) was greater than under RT (1.31 Mg m^{-3}) and CT (1.38 Mg m^{-3}) ($LSD_{0.05}$ = 0.01). No significant difference was found in bulk density between NT, RT and CT treatments in the 10–20 cm (1.52, 1.49 and 1.47 Mg m^{-3}, respectively) and 20–30 cm depths (1.51, 1.51 and 1.50 Mg m^{-3}, respectively).

3.2. Organic C, total N and microbial biomass N

In the 0–10 cm depth, amount of organic C was greater in NT than in RT and greater in RT than in CT (Table 2). There were no significant differences between tillage treatments in the amounts of organic C in the 10–20 or 20–30 cm depths, where mean organic C amounts were 9.68 and 8.16 Mg ha^{-1}, respectively. The amounts of organic C in the 0–20 cm and 0–30 cm depths were similar under all treatments. There were no significant effects of stubble retention or N fertilizer on organic C in the 0–10, 0–20 or 0–30 cm depths. Also, there were no significant interactions of tillage, stubble and N fertilizer rate on the total amount of organic C at these depths. On a Vertisol in southern Queensland, highest concentration of organic C in the surface soil was found with a combination of NT, stubble retention and fertilizer N (Dalal, 1989) or NT and stubble retention (Thompson, 1992).

Table 2
Organic C and total N in soil in the 0–10, 0–20 and 0–30 cm depths at the end of 9 years of no-till (NT), reduced till (RT) and conventional till (CT) and tillage × stubble interaction in the 0–10 cm depth on total N in soil

	Soil depth (cm)	Tillage practices			$LSD_{0.05}$
		CT	RT	NT	
Organic C (Mg ha^{-1})	0–10	10.93	12.02	12.87	0.82
	0–20	20.59	22.01	22.27	NS
	0–30	28.50	30.33	30.53	NS
Total N (Mg ha^{-1})	0–10	0.96	1.03	1.16	0.07
	0–20	1.80	1.89	2.05	0.12
	0–30	2.51	2.60	2.80	0.16
Tillage × stubble interaction for total N (0–10 cm depth only)					
Stubble retained		0.94	1.09	1.20	0.10
Stubble removed		0.99	0.97	1.13	

The amount of total N in the 0–10 cm soil layer was greater in NT than in RT and CT and similar between RT and CT (Table 2). There were no significant treatment effects on total N in the 10–20 or 20–30 cm depths, where mean total N amounts were 0.86 and 0.72 Mg ha^{-1}, respectively. Tillage effects on total N at 0–10 cm persisted into the 0–20 cm and 0–30 cm depths. In the 0–30 cm depth, soil under NT contained 290 and 200 kg ha^{-1} greater N than under CT and RT, respectively. There was significant interaction between tillage practice and stubble retention on total N only in the 0–10 cm depth (Table 2). Highest amount of total N was present in the stubble retained and NT treatment, which was 260 kg N ha^{-1} greater than in stubble retained and CT treatment. Dalal et al. (1991) and Thompson (1992) recorded a similar interaction on a Vertisol in southern Queensland, where highest total N was recorded with combination of NT, stubble retention and N fertilizer application.

Greater amounts of organic matter in soil under NT than under CT are often accompanied by concentration gradients from the surface to subsurface layers (Dick, 1983; Langdale et al., 1984; Logan et al., 1991; Dalal et al., 1991). Under CT, soil in the 0–10 cm layer gets relatively well mixed and stratification of these soil properties is relatively minor. In our study, organic C and total N concentration decreased significantly with depth under NT practice in the top 0–10 cm depth intervals (Table 3). However, compared to Vertisols (55–65% clay) in southern Queensland, where the positive NT effects on soil organic matter were often restricted to the 0–2.5 cm depth (Dalal et al., 1991, 1995), tillage effects in this coarse-textured Luvisol (27% clay) were significant down to 10 cm depth for organic C and down to 30 cm depth for total N.

Heenan et al. (1995) also found greater amount of organic C in 0–10 cm depth under NT and stubble retained than under CT and stubble burned in a coarse-textured red earth (Lixisol) (29% clay). Wheat stubble C inputs reported by Heenan et al. (1995) (1.4–1.5 Mg C ha^{-1} year^{-1}) were similar to those in the present study (mean of 1.4 Mg C ha^{-1} year^{-1}). In our study, stubble C was calculated by assuming harvest index of 0.4 (grain yield/total dry matter yield) and residue of 40% C. Mean grain yield from eight wheat crops in this study was 2.4 Mg ha^{-1} year^{-1} (Radford et al., 1992; Thomas et al., 1995). However, the amount of stubble C in organic matter under NT and stubble retained practice (difference between stubble retained and stubble removed) at the end of 9 years was only 245 kg C ha^{-1} or merely 2.2% of the total stubble C added. A Vertisol retained 3% of wheat stubble C added at the end of 20 years of NT, stubble retained and N fertilizer application practice (Dalal et al., 1991), possibly due to increased clay-protected C.

Table 3
Chemical properties in the 0–2.5, 2.5–5 and 5–10 cm soil layers at the end of 9 years under no-tillage

Soil property	Soil depth (cm)			$LSD_{0.05}$
	0–2.5	2.5–5	5–10	
Organic C (g kg^{-1})	10.6	9.7	8.5	0.5
Total N (g kg^{-1})	0.94	0.88	0.77	0.05
Microbial biomass N (mg kg^{-1})	32.6	25.7	14.6	5.1
Bicarbonate-extractable P (mg kg^{-1})	36	64	42	5
pH	6.9	6.8	7.5	0.3
Exchangeable Ca (cmol$_c$ kg^{-1})	9.1	9.9	11.8	1.1
Exchangeable Mg (cmol$_c$ kg^{-1})	2.6	2.5	3.1	0.3
Exchangeable Na (cmol$_c$ kg^{-1})	0.27	0.37	0.70	0.13
Exchangeable K (cmol$_c$ kg^{-1})	1.22	1.04	0.82	0.19
Cation exchange capacity (cmol$_c$ kg^{-1})	15.2	15.6	17.7	1.3
Exchangeable Na percentage	1.8	2.3	3.8	0.7

The overall difference in soil organic C between NT and CT practice in the top 10 cm depth was 1.94 Mg C ha^{-1} (Table 2) or 215 kg C ha^{-1} year^{-1} higher in soil under NT than under CT. This value lies within the range of values estimated by West and Marland (2002) from their global data analysis of tillage effects on organic C (160–350 kg C ha^{-1} year^{-1}) in the top 0–7.5 cm or 0–10 cm depths. However, for C sequestration consideration, the default value for soil depth is a minimum of 0–30 cm depth of soil (IPCC, 2001). We observed no significant effect of tillage on C sequestration in the 0–30 cm depth. At the start of the experiment, the amounts of organic C in the 0–10, 0–20 and 0–30 cm depths were approximately 12, 19 and 26 Mg C ha^{-1} (calculated from Table 1). At the end of 9 years of different tillage practices, organic C had increased under NT and declined under CT in the 0–10 cm depth ($LSD_{0.05} = 0.57$) (Table 2). However, mean organic C across all treatments increased to 21.62 Mg ha^{-1} in the 0–20 cm depth ($LSD_{0.05} = 0.63$) and 29.78 Mg ha^{-1} in the 0–30 cm depth ($LSD_{0.05} = 0.77$). Dalal et al. (1991) and Thompson (1992) also recorded increases in organic C in surface soil of a Vertisol with time in a long-term fallow management experiment in wheat in southern Queensland.

Tillage effects on total N were similar to organic C. Stubble retention resulted in 50 kg ha^{-1} greater N than stubble removal in the 0–10 cm depth (Table 2). Assuming that stubble contained 140 kg N (11.2 Mg C, with a stubble C/N ratio of 80), about 35% of the stubble N was retained in the top 10 cm. At the start of the experiment, the amounts of total N in the 0–10, 0–20 and 0–30 cm depths were approximately 1.2, 2.1 and 2.9 Mg N ha^{-1}, respectively (calculated from Table 1). At the end of 9 years of different tillage practices, the amounts of total N at these depths had declined under CT and RT, but not under NT ($LSD_{0.05}$ = 0.05, 0.08 and 0.10 in 0–10, 0–20 and 0–30 cm depths, respectively) (Table 2). Thus, NT reduced total soil N loss compared to CT, as observed by Dalal (1992), possibly due to immobilisation as organic N from stubble retention and placement near the soil surface.

There was a significant stubble $\times$ N rate interaction on C/N ratio in the 0–10 cm depth, with C/N ratio being lower with stubble retention (10.7) than with stubble removal (11.8) with N_{60}, but not with N_0 treatment (11.6 and 11.5, respectively) ($LSD_{0.05} = 0.8$). In the 10–20 cm depth, the C/N ratio was greater in CT (11.5) and RT (11.6) than in NT (10.6) ($LSD_{0.05} = 0.6$).

There were no significant tillage or stubble effects on soil microbial biomass N in the 0–10, 10–20 or 20–30 cm depths (data not shown). Mean soil microbial biomass N amounts over all treatments at these depths were 34.5, 24.2 and 21.2 kg ha^{-1}, respectively. Under NT, there was a concentration gradient of microbial biomass N in the upper layers of soil (Table 3), generally reflecting the soil organic matter stratification under NT practice. Such an effect has also been recorded by Doran (1980), Carter and Rennie (1982) and Dalal et al. (1991).

The proportion of microbial biomass N to total N in the 0–10 cm depth was 3.3, 4.1 and 2.5% in CT, RT and NT treatments, respectively ($LSD_{0.05}$ = 0.9%), reflecting the differences in total N under different treatments and indicating lower potential N mineralization in soil under NT than under RT in this study. The proportion of microbial biomass N to total N reflects the reactive pool of N and is related to N availability index and mineralizable N (Myrold, 1987; Dalal et al., 1991; Dalal, 1998).

3.3. Nitrate-N production

The amount of NO_3-N produced during the 18-day aerobic incubation of soil differed significantly among treatments in the 0–10 cm, 0–20 cm and 0–30 cm depths (Table 4). There was a significant interaction of tillage practice × stubble management × N fertilizer application at all three depths. The amount of NO_3-N was similar under all tillage and stubble treatments when no N fertilizer was applied. However, when N fertilizer was applied it was greater under RT than under CT and NT with stubble retention, and greater under NT than under CT and RT with stubble removal. Thus, at any depth, the highest amount of NO_3-N was found in soil under NT practice with stubble removed and N fertilizer applied. For example, NO_3-N in the 0–30 cm depth of soil under NT, stubble removed and N_{60} treatment was 126 kg N ha^{-1} greater than that under NT, stubble retained and N_0 treatment.

Greater soil NO_3-N accumulation in the top 30 cm depth under NT with stubble removed may have been due to less immobilization of N in the absence of stubble. Dalal (1989) and Radford et al. (1992) also found higher NO_3-N under NT when stubble was either burned or removed than when stubble was retained. Therefore, stubble retention should be practised with NT to reduce potential NO_3-N leaching in this soil.

3.4. Bicarbonate-extractable P

In the 0–10 cm depth, the amount of bicarbonate-extractable P was greater in NT than in RT or CT (Table 5). There were no significant tillage effects on bicarbonate-extractable P concentration in the 10–20 or 20–30 cm depths, where mean amounts were 8 and 3 kg ha^{-1}, respectively. There were no significant effects of stubble retention or N fertilizer on P levels. In the 0–10 cm layer under NT, bicarbonate-extractable P was highest at 2.5–5 cm, possibly because P fertilizer was applied mostly in this layer (Table 3).

Table 4
Nitrate-nitrogen (negligible amount of ammonium-N) produced during 18-day aerobic incubation of soil at the end of 9 years of conventional till (CT), reduced till (RT) and no-till (NT), stubble retained and stubble removed and N fertilizer application of 0 (N_0) and 60 (N_{60}) kg N ha^{-1}

Soil depth (cm)	Stubble and N treatments		Nitrate-N produced (kg N ha^{-1})			
	Stubble	N fertilizer	Tillage practice			$LSD_{0.05}$
			CT	RT	NT	
0–10	Retained	N_0	41.2	48.1	34.2	29.8
	Retained	N_{60}	57.6	101.7	53.2	
	Removed	N_0	40.4	45.7	33.7	
	Removed	N_{60}	65.7	68.6	98.1	
0–20	Retained	N_0	63.2	66.5	48.2	32.0
	Retained	N_{60}	91.1	127.7	77.7	
	Removed	N_0	64.4	65.8	54.9	
	Removed	N_{60}	107.2	101.3	149.7	
0–30	Retained	N_0	80.7	81.4	61.7	35.0
	Retained	N_{60}	125.8	153.3	102.5	
	Removed	N_0	83.3	80.6	68.6	
	Removed	N_{60}	142.5	127.0	188.1	

Standley et al. (1990) and Hunter and Cowie (1989) also found available P concentration to be greater in the surface soil layer (0–7.5 cm) under NT than under CT on a Vertisol in central Queensland. Greater available P values in the upper layers of NT soils are apparently due to reduced mixing of fertilizer P, possibly increased quantities of organic P, and shielding of P adsorption sites (Schomberg et al., 1994).

3.5. Soil pH

Soil pH in the 0–10, 10–20 and 20–30 cm depths was not affected by tillage and stubble retention treatments. Mean soil pH for these depths was 7.3, 8.1 and 8.4. At the end of 9 years, mean soil pH had not changed significantly in the 0–10 cm depth, but had increased in the 10–20 and 20–30 cm depths ($LSD_{0.05} = 0.1$ at both depths) (Table 1). In the 0–2.5 and 2.5–5 cm depths under NT, pH was marginally acidic (Table 3). There was a significant, negative correlation between pH and organic C concentration ($r = -0.88$, $P < 0.01$) (Fig. 1a), indicating that greater organic C under NT may at least partially have had an acidifying effect.

Nitrogen fertilizer application resulted in a significant reduction in soil pH in the 0–10 cm depth from 7.5 with N_0 to 7.2 with N_{60} ($LSD_{0.05} = 0.2$). On a Vertisol in southern Queensland, soil pH declined from 7.7 with no N applied to 7.2 with N applications of 69 kg N ha^{-1} year^{-1} as urea after 20 years (Dalal, 1989). Although Luvisols have lower CEC and generally more leaching capacity than Vertisols, effects on soil pH due to urea N applications were similar for both soil types. Bouman et al. (1995) also observed that long-term use of anhydrous ammonia and urea led to soil acidification in silty loam soils.

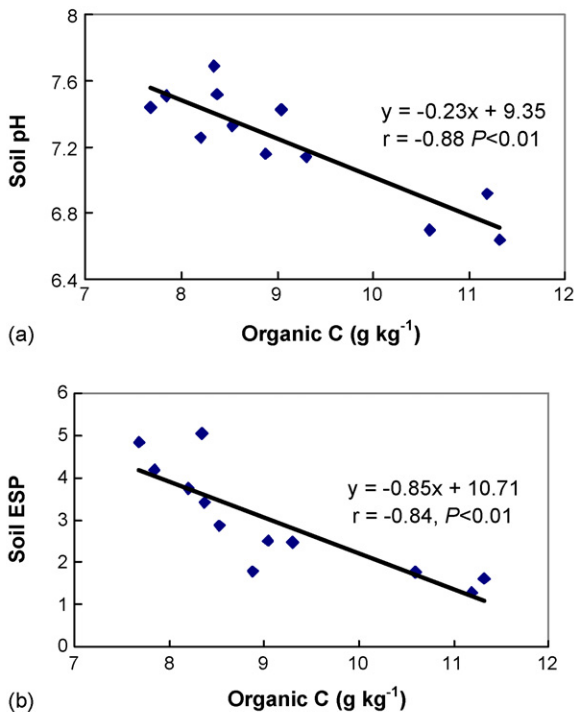

Fig. 1. Relationship between organic C and soil pH (a) and exchangeable Na percentage (ESP) (b) in the 0–10 cm depth, using mean values of all treatments.

3.6. Exchangeable cations

There were no significant effects of tillage, stubble retention and N fertilizer treatments on exchangeable Ca in the 0–10 cm depth (Table 5). Exchangeable Mg and Na were greater in soil under CT than in RT and NT in the 0–10 cm depth (Table 5), but were unaffected by stubble retention and N fertilizer treatments.

Exchangeable K concentration was greater in soil under NT than under CT in the 0–10 cm depth (Table 5). There were no significant effects of stubble retention or N fertilizer on exchangeable K concentration in the 0–10 cm depth.

Cation exchange capacity was lower in soil under NT than under RT or CT practice in the 0–10 cm depth (Table 5). There were no significant effects of stubble retention or N fertilizer application on CEC in the 0–10 cm depth. Exchangeable sodium percentage was lower in soil under RT and NT than under CT in the 0–10 cm depth (Table 5), but was unaffected by stubble retention and N fertilizer treatments.

Table 5
Exchangeable Ca, Mg, Na and K concentration, cation exchange capacity, exchangeable sodium percentage and bicarbonate-extractable P amount in the top 10 cm of soil at the end of 9 years under conventional till (CT), reduced till (RT) and no-till (NT)

Soil property	Tillage practice			$LSD_{0.05}$
	CT	RT	NT	
Exchangeable Ca (cmol$_c$ kg^{-1})	11.8	11.6	10.6	NS
Exchangeable Mg (cmol$_c$ kg^{-1})	3.5	3.0	2.9	0.3
Exchangeable Na (cmol$_c$ kg^{-1})	0.83	0.46	0.51	0.20
Exchangeable K (cmol$_c$ kg^{-1})	0.80	1.01	0.98	0.17
CEC (cmol$_c$ kg^{-1})	18.5	17.4	16.5	1.1
Exchangeable Na percentage	4.4	2.7	3.0	0.9
Bicarbonate-extractable P (kg ha^{-1})	42	45	64	9

These effects of tillage practice on exchangeable Na and K and CEC were similar to those observed by Loch and Coughlan (1984) in the top 4 cm of soil under CT and NT on a Vertisol in southern Queensland. Dalal (1989) observed lower exchangeable Na percentage in soil under NT than under CT on the same Vertisol. Hunter and Cowie (1989) also found greater concentration of K in the top 5 cm of soil under NT than under CT on a Vertisol in central Queensland.

The negative correlation between exchangeable Na percentage and organic C ($r = -0.84$, $P < 0.01$) (Fig. 1b) suggests lower affinity of exchangeable Na for organic matter exchange sites than Ca and Mg, and thus Na entering into the soil solution is subjected to increased leaching compared to Ca and Mg under NT practice. Sodium entering the soil solution may have been leached downward to a greater extent under NT practice due to greater water infiltration and leaching under NT than under CT and RT. Greater leaching of solutes has been observed in soil under NT than under CT at this site (Thomas et al., 1995). NT with stubble retention has also been shown to have a greater proportion of larger macro pores (>1 mm diameter) in surface soil than NT and CT with stubble removal (Coughlan et al., 1991), a feature that would enhance water infiltration. As the soil pH decreases, CEC associated with soil organic matter decreases due to reduction in pH-dependent cation exchange sites in Luvisols (Alfisols) (Morais et al., 1976). Therefore, the trend for lower pH in soil with greater organic C concentration (Fig. 1a) may have resulted in lower CEC under NT than CT. Furthermore, Loch and Coughlan (1984) considered that lower CEC under NT than under CT may have been at least partly due to adsorption of herbicide by clay particles, or by leaching of finer clay fractions.

Exchangeable K concentration was greater in the 0–2.5 and 2.5–5 cm layers than in the 5–10 cm layer (Table 3). Asghar et al. (1996) reported a similar result on a Vertisol in central Queensland, where there was a 70% greater concentration of exchangeable K in the surface 0–5 cm of soil than in the 5–10 cm layer at the end of 8 years of NT practice. Exchangeable K in the 0–10 cm depth appears to have been affected to a greater extent by inputs from surface residues and lack of disturbance under NT than were Ca and Mg, due to the low concentrations of the latter two in wheat stubble. For example, wheat stubble K concentration (9 kg t^{-1} stubble) generally exceeds by five times that of Ca (1.8 kg t^{-1}) and eight times that of Mg (1.1 kg t^{-1}) (Dalal and Probert, 1997). Concentration of K in the upper surface soil under NT may adversely affect the availability of K to plant roots, especially under dry seasonal conditions when the topsoil dries up quickly.

4. Conclusions

The Luvisol in this study was significantly affected by 9 years of different tillage, stubble retention and N fertilizer application practices. Positive effects of NT on soil organic matter occurred to greater depth in surface soil than on Vertisols in the same environment. While organic matter (organic C and total N) and exchangeable K in the topsoil were greater under NT than under CT and RT, exchangeable Na was lower under NT. The greater organic matter accumulation and solute movement in these soils under NT practice would be beneficial to soil chemical and physical condition and crop production in the long-term, whereas the concentration of nutrients such as P and K in surface layers may reduce their availability to crops. The decrease in soil pH with N fertilizer application may be a cause for concern, especially if the soil is already acidic and N fertilizer use continues.

Acknowledgements

The authors thank Mr. B.J. Radford, Mr. G. Gibson and Mr. R.G.H. Nielsen for commencing the experiment, Mr. D.N. Orange and Mr. C. Gemmell for assistance with soil sampling and processing, and Mrs. J.M. Glasby, Mrs. A. Pumfrey and Mrs. C.J. Holmes for soil chemical analyses.

References

Anderson, J.P.E., Domsch, K.H., 1978. Mineralization of bacteria and fungi in chloroform-umigated soils. Soil Biol. Biochem. 10, 207–213.

Asghar, M., Lack, D.W., Cowie, B.A., Parker, J.C., 1996. Effects of surface soil mixing after long-term zero tillage on soil nutrient concentration and wheat production. In: Asghar, M. (Ed.), Proceedings of the 8th Australian Agronomy Conference, The Australian Society of Agronomy Inc., Toowoomba, Queensland, pp. 88–91.

Best, E.K., 1976. An automated method for determining nitrate nitrogen in soil extracts. Queensland J. Agric. Anim. Sci. 33, 161–166.

Bouman, O.T., Curtin, D., Campbell, C.A., Biederbeck, V.O., Ukraintz, H., 1995. Soil acidification from long-term use of anhydrous ammonia and urea. Soil Sci. Soc. Am. J. 59, 1488–1494.

Bremner, J.M., 1965. Total nitrogen. In: Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clarke, F.E. (Eds.), Methods of Soil Analysis. Part 2. Agronomy No. 9. American Society of Agronomy, Madison, WI, pp. 1149–1178.

Bruce, R.C., Rayment, G.E., 1982. Analytical Methods and Interpretations Used by the Agricultural Chemistry Branch for Soil and

Land Use Surveys. Queensland Department of Primary Industries Bulletin QB82004.
Carter, M.R., Rennie, D.A., 1982. Changes in soil quality under zero-tillage farming systems: distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62, 587–597.
Colwell, J.D., 1963. The estimation of the phosphorus fertiliser requirements of wheat in southern New South Wales by soil analysis. Aust. J. Exp. Agric. Anim. Husb. 12, 188–194.
Coughlan, K.J., McGarry, D., Loch, R.J., Bridge, B., Smith, G.D., 1991. The measurement of soil structure—some practical initiatives. Aust. J. Soil Res. 29, 869–899.
Crooke, W.M., Simpson, W.E., 1971. Determination of ammonium in Kjeldahl digests of crops by an automated procedure. J. Sci. Food Agric. 22, 9–10.
Dalal, R.C., 1989. Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a Vertisol. Soil Sci. Soc. Am. J. 53, 1511–1515.
Dalal, R.C., 1992. Long-term trends in total nitrogen of a Vertisol subjected to zero-tillage, nitrogen application and stubble retention. Aust. J. Soil Res. 30, 223–231.
Dalal, R.C., 1998. Soil microbial biomass—what do the numbers really mean? Aust. J. Exp. Agric. 38, 649–665.
Dalal, R.C., Chan, K.Y., 2001. Soil organic matter in rainfed cropping systems of the Australian cereal belt. Aust. J. Soil Res. 39, 435–464.
Dalal, R.C., Henderson, P.A., Glasby, J.M., 1991. Organic matter and microbial biomass in a Vertisol after 20 years of zero tillage. Soil Biol. Biochem. 23, 435–441.
Dalal, R.C., Probert, M.E., 1997. Soil nutrient depletion. In: Clarke, A.L., Wylie, P.B. (Eds.), Sustainable Crop Production in the Subtropics. Department of Primary Industries, Brisbane, Queensland, pp. 42–63.
Dalal, R.C., Strong, W.M., Weston, E.J., Cooper, J.E., Lehane, K.J., King, A.J., Chicken, C.J., 1995. Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes. 1. Organic matter status. Aust. J. Exp. Agric. 35, 903–913.
Dick, W.A., 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47, 102–107.
Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44, 765–771.
Doran, J.W., Smith, M.S., 1987. Organic matter management and utilisation of soil and fertilizer nutrients. In: Follett, R.F., Stewart, J.W.B., Cole, C.V. (Eds.), Soil Fertility and Organic Matter as Critical Components of Production Systems. American Society of Agronomy, Madison, WI, pp. 53–72.
Ellert, B.H., Janzen, H.H., Entz, T., 2002. Assessment of a method to measure temporal change in soil carbon storage. Soil Sci. Soc. Am. J. 66, 1687–1695.
FAO, 1998. World Reference Base for Soil Resources. World Soil Resource Report No. 84. Food and Agriculture Organisation of the United Nations, Rome.
Heenan, D.P., McGhie, W.J., Thomson, F.M., Chan, K.Y., 1995. Decline in soil organic carbon and total nitrogen in relation to tillage, stubble management, and rotation. Aust. J. Exp. Agric. 35, 877–884.
Hunter, H.M., Cowie, B.A., 1989. Tillage and stubble effects on nutrient distribution. In: Noble, R.M., Radford, B.J., Ruthenberg, S.J., Thorburn, P.J. (Eds.), Biloela Research Station Programme Review. Queensland Department of Primary Industries RQR89012, pp. 6-1–6-2.
IPCC, 2001. Technical summary. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
Isbell, R.F., 1996. The Australian Soil Classification. Australian Soil and Land Survey Handbook Series, vol. 4. CSIRO Publishing, Collingwood.
Jenkinson, D.S., 1988. Determination of microbial biomass carbon and nitrogen in soil. In: Wilson, J.R. (Ed.), Advances in Nitrogen Cycling in Agricultural Ecosystems. C.A.B. International, Wallingford, pp. 368–386.
Jenkinson, D.S., Powlson, D.S., 1976. The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. Soil Biol. Biochem. 8, 209–213.
Kern, J.S., Johnson, M.G., 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J. 57, 200–210.
Langdale, G.W., Hargrove, W.L., Giddens, J.E., 1984. Residue management in double-crop conservation tillage systems. Agron. J. 76, 689–694.
Loch, R.J., Coughlan, K.J., 1984. Effects of zero tillage and stubble retention on some properties of a cracking clay. Aust. J. Soil Res. 22, 91–98.
Logan, T.J., Lal, R., Dick, W.A., 1991. Tillage systems and soil properties in North America. Soil Till. Res. 20, 241–270.
Morais, F.I., Page, A.L., Lund, L.J., 1976. The effect of pH, salt concentration, and nature of electrolytes on the charge characteristics of Brazilian tropical soils. Soil Sci. Soc. Am. J. 40, 521–527.
Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.
Myrold, D.D., 1987. Relationship between microbial biomass nitrogen and nitrogen availability index. Soil Sci. Soc. Am. J. 51, 1047–1049.
Prasad, R., Power, J.F., 1991. Crop residue management. Adv. Soil Sci. 15, 205–251.
Radford, B.J., Gibson, G., Nielsen, R.G.H., Butler, D.G., Smith, G.D., Orange, D.N., 1992. Fallowing practices, soil water storage, plant-available soil nitrogen accumulation and wheat performance in South West Queensland. Soil Till. Res. 22, 73–93.
Schomberg, H.H., Ford, P.B., Hargrove, W.L., 1994. Influence of crop residues on nutrient cycling and soil chemical properties. In: Unger, P.W. (Ed.), Managing Agricultural Residues. Lewis Publishers, Boca Raton, FL, USA, pp. 100–119.
Sims, J.R., Haby, V.A., 1971. Simplified colorimetric determination of soil organic matter. Soil Sci. 122, 137–141.
Snedecor, G.W., Cochran, W.G., 1967. Statistical Methods, sixth ed. Iowa State University Press, Ames.
Soil Survey Staff, 1998. Keys to Soil Taxonomy, eighth ed. Natural Resources Conservation Service, USDA.
Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J., Hallsworth, E.G., 1968. A Handbook of Australian Soils. Rellim Technical Publications, Glenside, SA.
Standley, J., Hunter, H.M., Thomas, G.A., Blight, G.W., Webb, A.A., 1990. Tillage and crop residue management affect Vertisol properties and grain sorghum growth over 7 years in the semi-arid sub-tropics. 2. Changes in soil properties. Soil Till. Res. 18, 367–388.
Thomas, G.A., Gibson, G., Nielsen, R.G.H., Martin, W.D., Radford, B.J., 1995. Effects of tillage, stubble, gypsum, and nitrogen fertiliser on cereal cropping on a red-brown earth in south-west Queensland. Aust. J. Exp. Agric. 35, 997–1008.

Thompson, J.P., 1992. Soil biotic and biochemical factors in a long-term tillage and stubble management experiment on a Vertisol. 2. Nitrogen deficiency with zero tillage and stubble retention. Soil Till. Res. 22, 339–361.

Walkley, A., 1947. A critical examination of a rapid method for determining organic carbon in soils—effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci. 63, 251–264.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.

West, T.O., Marland, G., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.