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Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes 1. Organic matter status

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Summary. Management practices involving legume leys, grain legumes, and no-tillage and stubble retention, along with nitrogen (N) fertiliser application for wheat cropping, were examined for their effectiveness in increasing soil organic matter (0–10 cm depth) from 1986 to 1993 in a field experiment on a Vertisol at Warra, Queensland. The treatments were (i) grass + legume leys (purple pigeon grass, *Setaria incrassata*; Rhodes grass, *Chloris gayana*; lucerne, *Medicago sativa*; annual medics, *M. scutellata* and *M. truncatula*) of 4 years duration followed by continuous wheat; (ii) 2-year rotation of annual medics and wheat (*Triticum aestivum* cv. Hartog); (iii) 2-year rotation of lucerne and wheat; (iv) 2-year rotation of chickpea (*Cicer arietinum* cv. Barwon) and wheat; (v) no-tillage (NT) wheat; and (vi) conventional tillage (CT) wheat. Fertiliser N as urea was applied to both NT wheat and CT wheat at 0, 25, and 75 kg N/ha.year. The CT wheat also received N at 12.5 and 25kg N/ha.year.

After 4 years, soil organic carbon (C) concentration under grass + legume leys increased by 20% (650 kg C/ha.year) relative to that under continuous CT wheat. Soil total N increased by 11, 18, and 22% after 2, 3, and 4 years, respectively, under grass + legume leys relative to continuous CT wheat. These increases in soil organic matter were mostly confined to the 0–2.5 cm layer. After the start of wheat cropping, organic C and total N levels declined steadily but were still higher than under CT wheat and higher than initial values in December 1985. Although 2-year rotations of lucerne–wheat and medic–wheat had a small effect on soil organic C, soil total N concentrations were higher than in the chickpea–wheat rotation and continuous CT wheat from November 1990 to November 1992. Soil under chickpea–wheat rotation had organic C and total N concentrations similar to continuous CT wheat, although from the former, about 70 kg/ha.year of extra N was removed in the grain from 1989 to 1993. No-tillage practice had a small effect on soil organic C, although total N concentration was higher than under CT wheat in November 1993. These effects were mainly confined to the surface 0–2.5 cm depth. The C to N ratio was only affected in soil under grass + legume leys, and no-tillage treatments.

These data show that restoration of soil organic matter in Vertisol requires grass + legume leys, primarily due to increased root biomass, although soil total N can be enhanced by including legume leys for longer duration in cropping systems in the semi-arid and subtropical environment.

Introduction

Continuous cultivation and cereal cropping of southern Queensland soils previously supporting native vegetation have resulted in decreased organic matter content and, hence, decreased nitrogen (N) supply from soil organic matter (Dalal and Mayer 1986*a*) and, in some soils, soil structural degradation (Dalal and Mayer 1986*a*; Cook *et al.* 1992). The marked loss of organic matter following cultivation and cereal cropping has been accompanied by decreased cereal grain yields and grain protein content (Dalal *et al.* 1991*b*).

Sustaining or enhancing soil productivity depends at least partly on soil and crop management practices that maintain or increase soil organic matter (Havlin *et al.* 1990). Management practices such as no tillage and crop residue retention (Lamb *et al.* 1985; Dalal 1989), crop rotation (Whitehouse and Littler 1984; Holford 1990), and N fertiliser application (Strong 1988) may influence organic matter levels in soil.

No tillage (NT) and crop residue retention reduces loss of organic matter in soil (Unger and McCalla 1980). For example, Lamb *et al.* (1985) found that organic carbon (C) decreased by only 4% under NT, whereas it decreased by 16% under conventional tillage (CT) after 12 years of wheat (*Triticum aestivum* L.)–fallow rotation of a virgin grassland soil. Similarly, Dalal (1989) measured higher organic C and total N contents in soil under NT and crop residue retention than under CT; a positive interaction of tillage x crop residue x N fertiliser application was observed after 13 years.

Table 1. Soil profile characteristics of the field experiment site

Soil depth (cm)	Bulk density (Mg/m^3)	pH	Sand	Silt	Clay (%)	Organic C	Total N	C/N
0–10	1.24	8.6	27	17	56	0.74	0.072	10.3
10–20	1.27	8.9	27	16	57	0.63	0.056	11.3
20–30	1.28	9.0	28	15	57	0.59	0.046	12.8
30–60	1.36	9.0	25	16	59	0.51	0.036	14.2
60–90	1.42	7.7	20	17	63	0.42	0.026	16.2
90–120	1.43	5.3	19	16	65	0.37	0.020	18.5
120–150	1.45	4.9	19	15	66	0.33	0.021	15.7

Crop rotation, especially with forage legumes, has been shown, in long-term studies, to maintain soil organic matter and crop productivity (Johnston 1987). However, a comparison is needed of various management options for their effects on soil organic matter and sustaining productivity of Vertisols in the semi-arid regions (Burford *et al.* 1989). This study assessed grass + legume and legume leys, grain legumes, no-tillage practice, and fertiliser N application for maintaining soil organic matter and sustaining wheat yields and grain protein contents on a fertility-depleted Vertisol at Warra, southern Queensland. We report changes in organic C and total N in this Vertisol resulting from legume leys, mixed grass and legume leys, or grain legume in rotation with wheat. The rotations were compared with continuous wheat grown under NT or CT practices, with or without N fertiliser applications.

Materials and methods

Site details and experimental design

A long-term field experiment was established in 1986 on a Vertisol depleted of organic matter (Typic Chromustert) that originally supported predominantly brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) vegetation, at Warra (26°47'S, 150°53'E), Queensland. Soil at the site has been cultivated for cereal cropping since 1935. This soil type represents 0.7 million ha of cultivated brigalow lands in eastern Australia (Weston *et al.* 1981).

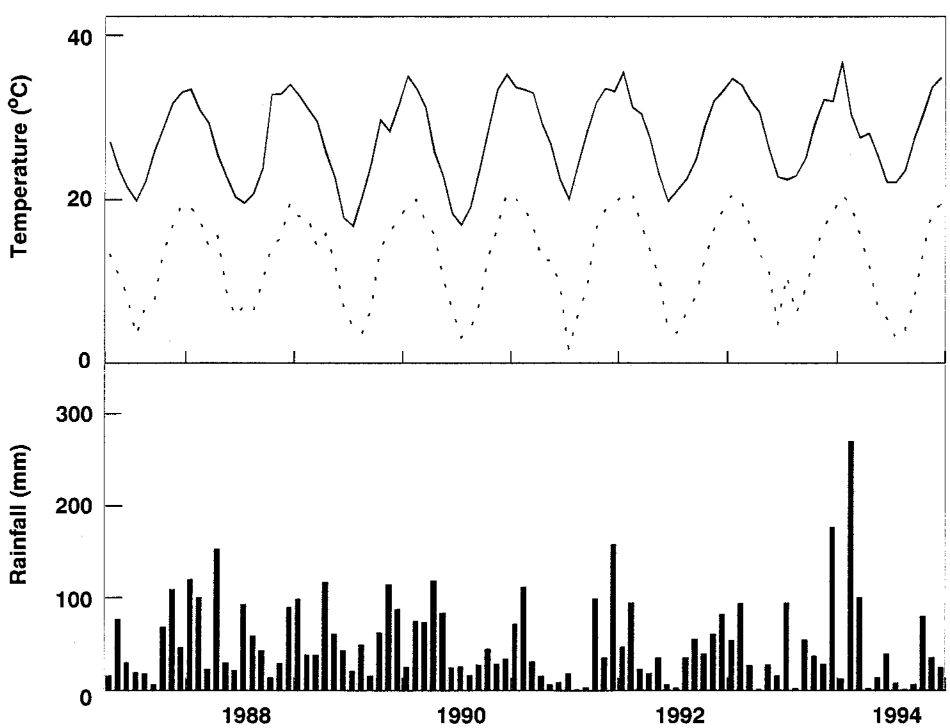

Figure 1. Mean monthly maximum (——) and minimum (- - -) temperatures, and mean monthly rainfall, for 1987–94 at the field site.

The soil belongs to Langlands series (Dawson 1972); it is very deep, ranging from dark greyish brown to dark brown cracking clay, alkaline from the surface to 0.6 m depth and acid below 0.9 m. Parent material is alluvial clayey sediments formed from light grey shales, siltstones, and fine–medium sandstones. The soil slope at the experiment site is <0.1%. The properties of the soil profile are given in Table 1.

Mean monthly rainfall and the mean monthly maximum and minimum temperatures from 1987 to 1994 are shown in Figure 1. The mean maximum temperature in January was 27°C (1987–94) and mean minimum 12°C (1987–94), with a mean annual temperature of 20.7°C. Annual rainfall varied from 396 mm in 1986 to 760 mm in 1988. Long-term mean annual rainfall for 97 years (1890–1987) for Warra, a town 15 km away from the experiment site, is 685 mm.

Seventeen treatments were established in a randomised block design with 4 replications in plots each 25.0 m long and 6.75 m wide (Table 2). The treatments were grouped into 5 major crop and soil management practices, listed below. The wheat cultivar used in all rotations was Hartog.

Grass + legume ley–wheat rotation. A mixed grass + legume pasture consisting of purple pigeon grass (*Setaria incrassata* Stapf cv. Inverell), Rhodes grass (*Chloris gayana* Kunth. cv. Katambora), lucerne (*Medicago sativa* L. cv. Trifecta), and annual medics (*M. scutellata* L. Mill. cvv. Sava and Kelson; *M. truncatula* Gaertn. cvv. Jemalong, Cyprus, Paraggio, and Sephi) was grown for 3.75 years followed by continuous wheat. Three phases of the mixed grass + legume ley were established in January 1986, 1987, and 1988, respectively, and are hereafter referred to as treatments 1, 2 and 3 (Table 2).

Legume ley–wheat rotation. Two-year rotations of wheat and lucerne (treatments 4 and 5), and wheat and annual medics (treatments 6 and 7), provided a short-term legume ley and cereal rotations.

Grain legume–wheat rotation. A 2-year rotation of chickpea (*Cicer arietinum* L.) and wheat was established (treatments 8 and 9). Chickpea was planted at 60 kg/ha using phytophthora (*Phytophthora megasporium*) tolerant lines or cv. Barwon.

CT wheat cropping with fertiliser N application. Conventional tillage operations (2–4) were performed using tined implements to about 100 mm depth for weed control during the fallow (December–April) and to prepare a seed bed for planting wheat. Wheat was planted at about 5 cm depth in 25-cm-wide rows at the

Table 2. Treatment sequences from the Warra experiment

GL, Grass + legume pasture of purple pigeon, Rhodes grass, mixture of medics (snail and barrel medic), and lucerne; W_L, lucerne undersown with wheat; W_M, medic undersown with wheat (self-regenerating medic); L, lucerne ley; M, medic ley; C, chickpea; W, conventionally tilled wheat (cv. Hartog); NTW, no-tillage wheat

No wheat crop was sown in 1986 or 1991 due to drought

Treatment	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Grass + legume ley–wheat rotation (4 years–4 years)										
1. Ley 1986–89	GL	GL	GL	GL	W	—	W	W	W	W
2. Ley 1987–90	—	GL	GL	GL	GL	—	W	W	W	W
3. Ley 1988–91	—	W	GL	GL	GL	GL	W	W	W	W
Legume ley–wheat rotation (1 year–1 year)										
4. Lucerne	—	W_L	L	W_L	L	—	L	W_L	L	W_L
5. Lucerne (alternate)	—	W	W_L	L	W_L	L	W_L	L	W_L	L
6. Medic	—	W_M	M	W	M	—	M	W	M	W
7. Medic (alternate)	—	W	W_M	M	W	M	W	M	W	M
Grain legume–wheat rotation (1 year–1 year)										
8. Chickpea	—	W	C	W	C	—	W	C	W	C
9. Chickpea (alternate)	—	C	W	C	W	—	C	W	C	W
Continuous conventional tillage wheat + N (kg N/ha.year)										
10. Wheat	—	W	W	W	W	—	W	W	W	W
11. Wheat + 12.5N	—	W	W	W	W	—	W	W	W	W
12. Wheat + 25N	—	W	W	W	W	—	W	W	W	W
13. Wheat + 50N	—	W	W	W	W	—	W	W	W	W
14. Wheat + 75N	—	W	W	W	W	—	W	W	W	W
Continuous no-tillage wheat + N (kg N/ha.year)										
15. Wheat	—	NTW	NTW	NTW	NTW	—	NTW	NTW	NTW	NTW
16. Wheat + 25N	—	NTW	NTW	NTW	NTW	—	NTW	NTW	NTW	NTW
17. Wheat + 75N	—	NTW	NTW	NTW	NTW	—	NTW	NTW	NTW	NTW

rate of 40 kg/ha in May and June or 50 kg/ha in July (1990 and 1993). Fertiliser urea was applied at sowing at the rates of 0, 12.5, 25, 50, and 75 kg N/ha.year (treatments 10, 11, 12, 13, 14, respectively) and was placed at about 5 cm depth in alternate mid-rows. Treatment 10, wheat with nil N fertiliser, served as a control.

NT wheat cropping with fertiliser N application. The NT treatments were not tilled except the sowing operations. Weeds were controlled by herbicide spray (1.2 L glyphosate and 1.2 L 2,4-D amine/ha) 2–4 times during the fallow. Wheat was planted at the same time and rate as CT, and fertiliser N was applied in the same manner as CT. Fertiliser N was applied as urea at the rates 0, 25, and 75 kg N/ha.year (treatments 15, 16 and 17, respectively). Similar to the CT wheat, both fertiliser application and wheat sowing were accomplished in one operation.

Pasture establishment

Treatments 1, 2, and 3 were planted in January 1986, 1987 and 1988, respectively. The grass + legume ley consisted of (kg/ha): Rhodes grass (2), purple pigeon grass (2), lucerne (1.5), snail medic (1), and barrel medic (1). In treatments 4 and 5 in alternate years, lucerne was planted with wheat during May–July at 2 kg/ha; planting seed rate for wheat was as in the CT wheat planting. In treatments 6 and 7, annual medics were planted with wheat at 5 kg/ha (snail and barrel medic mixture); planting seed rate for wheat was as in the CT wheat planting. The annual medics were planted only once because of their self-generating nature.

Pasture management

Annual dry matter production and total N yields were measured from harvests in December, March, June, and September for the grass + legume leys and lucerne, and in June and September for the annual medics. At each harvest, surplus plant biomass, mown at 10 cm, was removed.

Since grazing of leys in the above (core) experiment was not feasible, an associated experiment was made on the adjoining land consisting of treatments 1, 2, 3, 4, 5, 6, 7, and 10 arranged in 2 replicates. Plot dimensions and soil and cultural practices were similar to the core experiment except that the leys were grazed by sheep rather than mown and removed. In each duplicate ley treatment (each plot, 25 m long by 6.75 m wide), 1 or 2 sheep were used for grazing for up to 20 days coinciding with the pasture harvest in the core experiment. Dry matter production and N contents were measured by using sheep enclosures, 2 m long and 1 m wide.

The grass + legume and lucerne and medic leys were terminated by blade ploughing (allowing minimum soil inversion) in mid October each year after annual medics had set seed and matured, usually coinciding with physiological maturity of other annual crops, and about 6 months before planting of the following crop, wheat. This allowed water recharge of the soil profile during summer–autumn.

Crop measurement

Total dry matter yields of wheat and chickpea were estimated at the time of harvest by removing plants from the middle 2 rows, 0.25 m apart and 1 m long, and drying at 70–80°C. Grains were separated from the plant samples, and grain and straw weights were recorded. Wheat and chickpea grain yields were measured from 1.75 by 23 m of the central areas of all plots. After determination of grain water content, grain yields were adjusted to 12% water content. Straw and grain were analysed for N concentrations in Kjeldahl digests using automated NH_4-N analysis (Crooke and Simpson 1971).

Root biomass was estimated from total root lengths measured by line intersection method (Newman 1966), by ultrasonic dispersion of soil cores (soil sampling procedure described below), and from root weight (3 mg/m root length).

Table 3. Mean values (kg/ha.year) of aboveground total plant dry matter yields and plant residue yields from 1986 to 1994, and root biomass (0–150 cm) in December 1990, from different treatments

Residue yield: remaining plant material after mown forage removed (in pasture leys), and after grain harvest (in crops)
Values in parentheses are pasture and/or legume yields

Treatment	Plant yield	Residue yield	Root biomass
Grass + legume–wheat rotation			
1. Ley 1986–89	5071 (5100)	2947 (2920)	10071[A]
2. Ley 1987–90	4429 (5699)	2310 (2828)	10992[A]
3. Ley 1988–91	4532 (5057)	2479 (2196)	9663
Legume–wheat rotation			
4. Lucerne	3195 (3272)	1836 (1792)	4461
5. Lucerne (alternate)	4560 (1931)	2726 (1414)	2193[B]
6. Medic	3678 (3667)	2410 (2684)	4101
7. Medic (alternate)	5014 (2780)	3088 (2109)	2136[B]
Grain legume–wheat rotation			
8. Chickpea	4433 (3558)	2565 (2065)	2118
9. Chickpea (alternate)	3967 (2798)	2325 (1705)	1716
Continuous conventional tillage wheat + N (kg N/ha.year)			
10. Wheat	4667	2739	1938
11. Wheat + 12.5N	5110	2959	n.d.
12. Wheat + 25N	5415	3144	n.d.
13. Wheat + 50N	5765	3362	n.d.
14. Wheat + 75N	5733	3391	2232
Continuous no-tillage wheat + N (kg N/ha.year)			
15. Wheat	4727	2777	1743
16. Wheat + 25N	5635	3274	n.d.
17. Wheat + 75N	6104	3572	1980

[A] Measured in October 1989. [B] Measured after wheat crop.
n.d., not determined.

Soil sampling and analysis

Five soil samples were collected from each plot with a 50-mm-diameter tube sampler, down to 10 cm depth in May and November each year and occasionally down to 30 cm for organic C and total N analysis, and down to 150 cm for root biomass estimations. Stubble or plant litter was removed from the soil surface; uneven soil surface, if present, was levelled and the sampling tube was inserted to 10 cm depth. The soil core was sectioned, if required, into 0–2.5 cm, 2.5–5 cm, and 5–10 cm lengths. The samples were bulked, sealed in plastic bags, and stored at 4°C until analysis. After removing large visible pieces of plant material, the soil was dried at 30 ± 5°C in a forced draught oven and ground to <2 mm initially, and then to <0.25 mm for determination of 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). All results were reported on oven-dry weight basis.

Statistical analysis

Analysis of variance was performed to assess the effect of soil and crop management practices on organic C, total N, and C to N ratio by standard statistical techniques (Snedecor and Cochran 1967). Time trends in soil organic matter were discerned by regression analysis. The organic C and total N values were normalised with respect to CT wheat treatment (treatment 10) according to Dalal and Mayer (1986*b*, 1986*c*).

Results

Dry matter production

Mean values of aboveground total plant dry matter yields and plant residue yields from 1986 to 1994, and root biomass (0–150 cm) in December 1990 from different treatments, are given in Table 3. Root biomass yields of grass + legume leys were at least twice that of other treatments.

Organic carbon

Organic C concentrations in this soil increased significantly (P<0.05) within 1 year in treatment 1 compared with continuous CT wheat (treatment 10) (Table 4). After 4 years, organic C concentrations had increased (P<0.05) by 20% compared with continuous CT wheat. Treatments 2 and 3 showed similar increases in soil organic C.

The main increases in organic C concentrations in soil sampled in May 1989 under the grass + legume treatments occurred at 0–2.5 cm and 2.5–5 cm depths (Fig. 2). At 0–2.5 cm, organic C concentrations relative

Table 4. Organic carbon concentrations (%) in soil (0–10 cm depth) under different treatments from 1986 to 1993 (November–December sampling)

l.s.d. (P = 0.05) for comparison between years, 0.07; for year × treatment interaction, 0.09

Treatment	1986	1987	1988	1989	1990	1991	1992	1993	1994
Grass + legume–wheat rotation									
1. Ley 1986–89	0.77	0.81	n.d.	0.84	0.82	0.79	0.77	0.75	0.76
2. Ley 1987–90	0.74	0.77	n.d.	0.76	0.80	0.88	0.77	0.72	0.79
3. Ley 1988–91	n.d.	n.d.	n.d.	0.73	0.82	0.85	0.77	0.75	0.78
Legume–wheat rotation									
4. Lucerne	n.d.	n.d.	n.d.	0.73	0.71	0.73	0.67	0.61	0.74
5. Lucerne (alternate)	n.d.	n.d.	n.d.	0.75	0.67	0.73	0.70	0.65	0.70
6. Medic	n.d.	n.d.	n.d.	0.70	0.75	0.77	0.69	0.63	0.69
7. Medic (alternate)	n.d.	n.d.	n.d.	0.69	0.69	0.77	0.68	0.63	0.69
Grain legume–wheat rotation									
8. Chickpea	n.d.	n.d.	n.d.	0.71	0.67	0.78	0.64	0.66	0.69
9. Chickpea (alternate)	n.d.	n.d.	n.d.	0.81	0.67	0.77	0.67	0.65	0.70
Continuous conventional tillage wheat + N (kg N/ha.year)									
10. Wheat	0.72	0.71	n.d.	0.70	0.70	0.70	0.69	0.69	0.69
11. Wheat + 12.5N	n.d.	n.d.	n.d.	0.75	0.69	0.68	0.67	n.d.	n.d.
12. Wheat + 25N	n.d.	n.d.	n.d.	0.74	0.68	0.71	0.67	0.63	0.69
13. Wheat + 50N	n.d.	n.d.	n.d.	0.77	0.71	0.71	0.72	n.d.	n.d.
14. Wheat + 75N	n.d.	n.d.	n.d.	0.74	0.71	0.76	0.71	0.68	0.69
Continuous no-tillage wheat + N (kg N/ha.year)									
15. Wheat	n.d.	n.d.	n.d.	0.72	0.67	0.76	0.70	0.64	0.66
16. Wheat + 25N	n.d.	n.d.	n.d.	0.72	0.68	0.80	0.69	0.64	0.71
17. Wheat + 75N	n.d.	n.d.	n.d.	0.70	0.70	0.77	0.66	0.66	0.76
l.s.d. (P = 0.05)	0.04	0.04	n.d.	0.08	0.07	0.08	0.06	0.04	0.06

n.d., not determined.

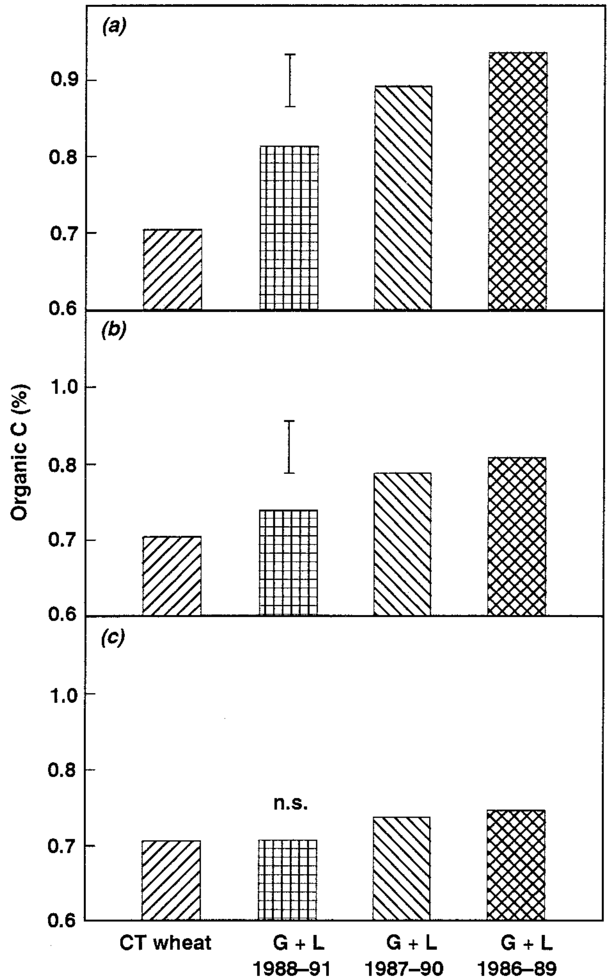

Figure 2. Organic C concentrations in soil sampled May 1989 under continuous conventionally tilled (CT) wheat and under three 4-year grass + legume (G + L)–wheat rotations with leys commencing 1986, 1987, or 1988. (*a*) 0–2.5 cm, (*b*) 2.5–5 cm, and (*c*) 5–10 cm. Vertical bars represent l.s.d. at $P = 0.05$.

to continuous CT wheat increased ($P<0.05$) by 15, 27, and 33% after the grass + legume phase of 1.5, 2.5, and 3.5 years, respectively, equating to increases in organic C concentrations of about 10% each year during the grass + legume phase. At 2.5–5 cm depth, organic C concentrations increased only after 2.5 years of the grass + legume phase. No significant increases in organic C concentrations were observed at 5–10 cm depth, even after 3.5 years of grass + legume. After the pasture phase, initiation of cropping resulted in steady decline in soil organic C concentrations (Fig. 3). After 4 years of cultivation and cropping, soil organic C concentrations were higher than in continuous CT wheat by <10% and similar to the initial soil organic C concentrations (December 1985). Organic C concentrations did not differ significantly between the mown-and-removed experiment and the grazed experiment (data not presented).

The 2-year rotations of lucerne–wheat, medic–wheat, and chickpea–wheat had no significant effect on organic C concentrations compared with the continuous CT wheat treatment (Table 4). Similarly, organic C concentrations were not significantly altered by NT treatments and fertiliser N applications even after 8 years, although at 0–2.5 cm depth, NT treatment, especially accompanied by fertiliser N application, had higher organic C concentrations than the continuous CT wheat treatment (Fig. 4).

Total nitrogen concentration

Total N concentrations were increased significantly in soil under the grass + legume phase by about 10, 18, and 22% after 2, 3, and 4 years, relative to continuous CT wheat (Table 5). Like the changes in organic C concentrations with depth, total N increases mainly occurred at 0–2.5 and 2.5–5 cm depths (Fig. 5).

$$\text{0–2.5 cm: Total N (\%)} = 0.0108 - 0.0381\exp(0.44\text{ year}) \quad (r = 0.99, P<0.01) \qquad (1)$$

$$\text{2.5–5 cm: Total N (\%)} = 0.068 + 0.006\text{ year} \quad (r = 0.94, P<0.05) \qquad (2)$$

$$\text{5–10 cm: Total N (\%)} = 0.069 + 0.002\text{ year} \quad (r = 0.92, P<0.05) \qquad (3)$$

After the first year of the cropping phase, total N concentrations steadily declined with continuous wheat cropping (Table 5) but remained higher than the initial

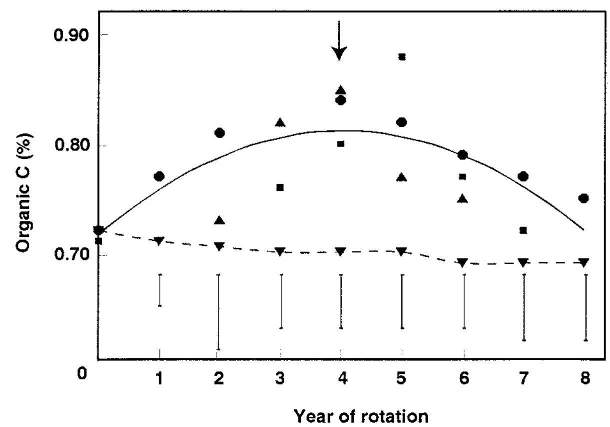

Figure 3. Organic C concentration trends in soil (0–10 cm depth) under 4 years of grass + legume followed by 4 years of wheat. ●, Grass + legume 1986–89; ■, grass + legume 1987–90; ▲, grass + legume 1988–91; ▼, continuous conventional tillage wheat. Vertical bars represent l.s.d. at $P = 0.05$. Arrow indicates end of pasture phase. Equation of the curve: $y = 0.72 + 0.047X - 0.0058X^2$ ($R^2 = 0.05$, $P<0.01$).

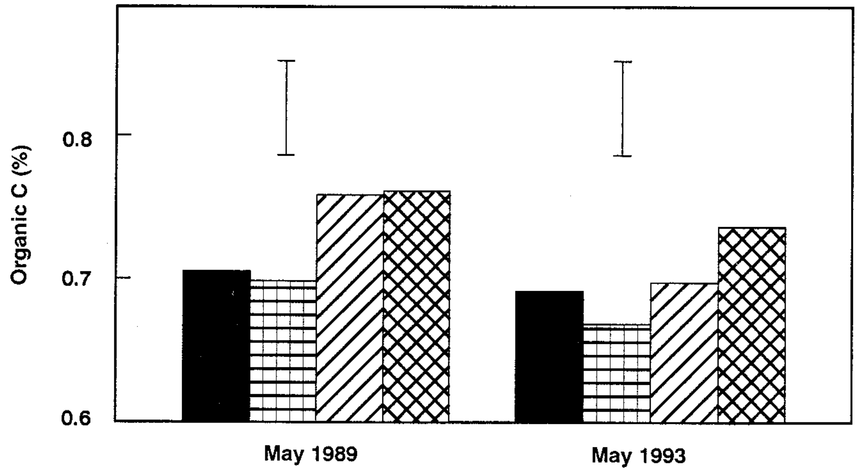

Figure 4. Organic C concentrations at 0–2.5 cm depth in soil under continuous conventional tillage wheat (solid bars), conventional tillage wheat with 75 kg N/ha.year (checkered bars), no-tillage wheat (striped bars), and no-tillage wheat with 75 kg N/ha.year (cross-hatched bars). Vertical bars represent l.s.d. at $P = 0.05$.

values after 4 years of cropping. Total N concentrations tended to be higher one year after the grass–legume phase than immediately after the grass–legume phase. Total N concentrations were not significantly different between the mown-and-removed experiment and the grazed experiment (data not presented).

The 2-year rotations of lucerne–wheat and medic–wheat (treatments 4 and 6) had significantly

Table 5. Total nitrogen concentrations (%) in soil (0–10 cm depth) under different treatments from 1986 to 1993 (November–December sampling)

l.s.d. ($P = 0.05$) for comparison between years, 0.07; for year × treatment interaction, 0.09

Treatment	1986	1987	1988	1989	1990	1991	1992	1993	1994
Grass + legume ley–wheat rotation (4 years–4 years)									
1. Ley 1986–89	0.075	0.078	n.d.	0.082	0.092	0.080	0.085	0.081	0.079
2. Ley 1987–90	0.072	0.074	n.d.	0.083	0.086	0.097	0.090	0.083	0.086
3. Ley 1988–91	n.d.	n.d.	n.d.	0.074	0.081	0.086	0.086	0.081	0.074
Legume ley–wheat rotation (1 year–1 year)									
4. Lucerne	n.d.	n.d.	n.d.	0.072	0.078	0.079	0.079	0.068	0.069
5. Lucerne (alternate)	n.d.	n.d.	n.d.	0.065	0.069	0.068	0.073	0.071	0.068
6. Medic	n.d.	n.d.	n.d.	0.071	0.075	0.077	0.083	0.069	0.070
7. Medic (alternate)	n.d.	n.d.	n.d.	0.073	0.071	0.076	0.075	0.074	0.068
Grain legume–wheat rotation (1 year–1 year)									
8. Chickpea	n.d.	n.d.	n.d.	0.068	0.066	0.069	0.070	0.072	0.065
9. Chickpea (alternate)	n.d.	n.d.	n.d.	0.069	0.076	0.074	0.074	0.070	0.069
Continuous conventional tillage wheat + N (kg N/ha.year)									
10. Wheat	0.070	0.069	n.d.	0.069	0.069	0.069	0.069	0.069	0.069
11. Wheat + 12.5N	n.d.	n.d.	n.d.	0.069	0.068	0.071	0.070	n.d.	n.d.
12. Wheat + 25N	n.d.	n.d.	n.d.	0.066	0.068	0.071	0.079	0.069	0.071
13. Wheat + 50N	n.d.	n.d.	n.d.	0.071	0.070	0.071	0.079	n.d.	n.d.
14. Wheat + 75N	n.d.	n.d.	n.d.	0.072	0.069	0.075	0.077	0.071	0.075
Continuous no-tillage wheat + N (kg N/ha.year)									
15. Wheat	n.d.	n.d.	n.d.	0.069	0.069	0.076	0.079	0.077	0.066
16. Wheat + 25N	n.d.	n.d.	n.d.	0.074	0.077	0.080	0.075	0.078	0.072
17. Wheat + 75N	n.d.	n.d.	n.d.	0.072	0.074	0.071	0.074	0.078	0.075
l.s.d. ($P = 0.05$)	n.s.	0.008	n.d.	0.007	0.005	0.007	0.009	0.008	0.007

n.d., not determined; n.s., not significant.

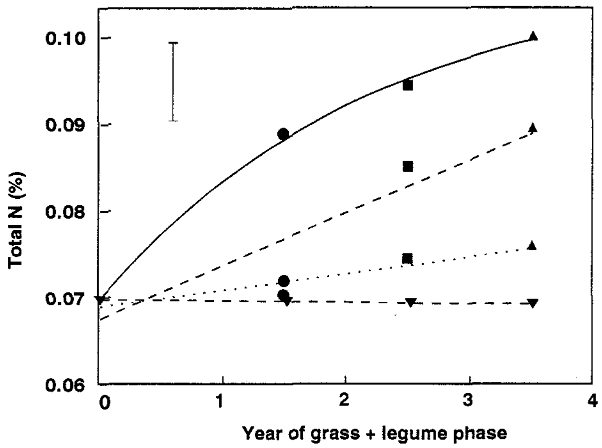

Figure 5. Total N concentrations sampled May 1989 in soil under continuous conventionally tilled wheat (▼) and after 1.5 (●), 2.5 (■), and 3.5 (▲) years of grass + legume pasture at three soil depths: —— 0–2.5 cm; – – – 2.5–5 cm; · · · · 5–10 cm.

higher total N concentrations than continuous CT wheat in November 1990, October 1991, and November 1992 (Table 5). Total N concentrations in soil under the chickpea–wheat treatments (8 and 9) remained similar to that under continuous CT wheat except in November 1990 when total N concentration was significantly higher in treatment 9.

Soil under NT plus fertiliser N had significantly higher total N concentrations than the continuous CT wheat in November 1990 (treatment 16), October 1991 (treatment 16), and November 1993 (treatments 15, 16 and 17) (Table 5). The fertiliser N effects on total N in soil under continuous cropping were inconsistent and generally small. By the May 1989 sampling, the tillage and fertiliser N effects were mainly confined to the 0–2.5 cm layer and appeared to have occurred only after 2–3 years of the NT treatments (Fig. 6).

C to N ratios

The C to N ratios of soil under continuous CT wheat (treatment 10) remained close to 10 (Table 6). Ratios generally became narrower in ley pastures (treatments 2, 3, 4, 6 and 7) and no-tillage treatments (treatments 15, 16 and 17). No significant difference in C to N ratios was observed at different depths in either May 1989 or May 1993 (data not presented).

Discussion

Since the C and N inputs through grass and legume residues, litter, and root materials were essentially similar in both the mown-and-removed and the grazed experiments (Hossain 1992), differences in organic C and total N were not expected. Dalal *et al.* (1994) estimated that the amounts of organic C at 0–30 cm depth in this Vertisol increased by almost 650 kg C/ha.year under grass–legume pasture compared with continuous CT wheat. Robertson *et al.* (1993) observed that organic C increased in a similar soil under pasture containing grasses. This was attributed to the continuous addition of C from surface plant materials and roots, and N accretion from legumes. Whitehouse and Littler (1984) observed substantial increases in organic C after 2–4 years of lucerne + prairie grass leys in a Vertisol (Waco clay). Organic C increased from 1.18 to 1.37% after 4 years of ley in their study.

Dalal *et al.* (1994) measured the rate of increase of organic C in treatment 1 (grass + legume 1986–89, then wheat) in the first 3.5 years of the ley phase. They reported that the organic C concentration increase

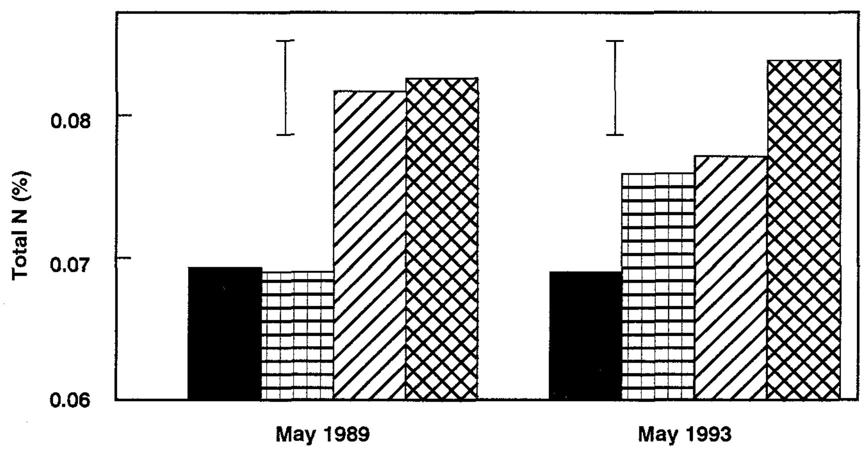

Figure 6. Total N concentrations at 0–2.5 cm depth in soil under continuous conventional tillage wheat (solid bars), conventional tillage wheat with 75 kg N/ha.year (checkered bars), no-tillage wheat (striped bars), and NT wheat with 75 kg N/ha.year (cross-hatched bars).

Table 6. Ratio of organic carbon to total nitrogen in soil (0–10 cm depth) under different treatments from 1986 to 1993 (November–December sampling)

Treatment	1986	1987	1988	1989	1990	1991	1992	1993	1994
			Grass + legume ley–wheat rotation (4 years–4 years)						
1. Ley 1986–89	10.3	10.4	n.d.	10.2	8.9	9.9	9.1	9.3	9.7
2. Ley 1987–90	10.2	10.3	n.d.	9.1	9.3	9.1	8.6	8.6	9.2
3. Ley 1988–91	n.d.	n.d.	n.d.	9.9	10.0	10.0	9.0	8.1	10.6
			Legume ley–wheat rotation (1 year–1 year)						
4. Lucerne	n.d.	n.d.	n.d.	10.1	9.1	9.2	8.5	9.0	10.8
5. Lucerne (alternate)	n.d.	n.d.	n.d.	11.5	9.7	10.7	9.5	9.2	10.4
6. Medic	n.d.	n.d.	n.d.	9.9	9.9	9.9	8.3	9.2	9.9
7. Medic (alternate)	n.d.	n.d.	n.d.	9.5	9.8	10.3	9.1	8.5	10.2
			Grain legume–wheat rotation (1 year–1 year)						
8. Chickpea	n.d.	n.d.	n.d.	10.5	10.3	11.2	9.2	9.1	10.6
9. Chickpea (alternate)	n.d.	n.d.	n.d.	11.6	8.8	10.4	9.1	9.2	10.2
			Continuous conventional tillage wheat + N (kg N/ha.year)						
10. Wheat	10.3	10.3	n.d.	10.1	10.1	10.1	10.0	10.0	10.0
11. Wheat + 12.5N	n.d.	n.d.	n.d.	10.9	10.2	9.7	9.5	n.d.	n.d.
12. Wheat + 25N	n.d.	n.d.	n.d.	11.2	10.0	9.9	8.5	9.2	9.8
13. Wheat + 50N	n.d.	n.d.	n.d.	10.9	10.2	9.9	9.1	n.d.	n.d.
14. Wheat + 75N	n.d.	n.d.	n.d.	10.2	10.3	10.1	9.3	9.5	9.2
			Continuous no-tillage wheat + N (kg N/ha.year)						
15. Wheat	n.d.	n.d.	n.d.	10.4	9.8	10.0	8.9	8.2	10.0
16. Wheat + 25N	n.d.	n.d.	n.d.	9.7	8.9	10.1	9.2	8.2	9.9
17. Wheat + 75N	n.d.	n.d.	n.d.	9.8	9.5	10.8	8.9	8.6	10.2
l.s.d. ($P = 0.05$)	n.s.	n.s.	n.d.	1.3	0.9	0.9	0.9	0.8	n.s.

n.d., not determined; n.s., not significant.

followed first-order rate, with a rate of increase in organic C of 0.13/year and an equilibrium organic C value of 1.28%. At steady-state condition, the amount of organic C required would be steady-state C x rate of increase in C x bulk density:

$$1.28\%\ C \times 0.13/\text{year} \times 1.24\ Mg/m^3 \times 10$$

or 2 t C/ha.year. Mean plant residue and root biomass yields from grass–legume leys (treatments 1, 2 and 3) of 3.75 years duration were in excess of that of continuous wheat by 6.2 t/ha.year (Table 3), or 2.5 t C/ha.year (assuming 40% C), possibly enough dry matter production to increase eventually to 1.28% C and then maintain steady-state C levels in this Vertisol. However, organic C inputs from the continuous wheat alone, 6.6 t/ha.year or 2.6 t C/ha.year (Table 3), would not be enough to raise organic C levels above 0.7% (Table 4). From studies on long term trends in organic C levels in Vertisols under continuous cereal cropping, Dalal and Mayer (1986) found that 2.2 t C/ha.year was required for an equilibrium value of 0.64% this soil.

Usually 1 year after the initiation of the cropping phase following 4 years of grass + legume leys, soil organic C decreased steadily (Fig. 3), as observed by Whitehouse and Littler (1989). However, the decreasing organic C trends during the cropping phase were slower than the relatively faster increase in organic C in soil under the grass + legume phase earlier, probably due to increased plant C input from higher crop yields compared with continuous wheat.

The grass + legume effects on soil total N were essentially similar to that on organic C. Nitrogen inputs through N_2 fixation in the grass + legume leys were estimated to be about 80 kg N/ha.year (Hossain *et al.* 1995); therefore the C to N ratio of fresh soil organic matter of about 8 (650 kg C/ha.year : 80 kg N/ha.year), a ratio similar to that of microbial biomass, would also lower soil C to N ratio. This trend is evident in this soil (Table 6) although the effects are expected to be relatively small (Whitehouse and Littler 1984). Significant differences in soil organic C and total N concentrations under grass + legume leys established in different years may have been due to differences in total rainfall as well as rainfall distribution during 1987–91 (Fig. 1). This may also have altered the proportions of grasses and legumes in these 3 treatments; for example, treatment 3 (grass + legume 1988–91, then wheat) had only a 30% legume component, compared with almost 50% in treatment 2 (grass + legume 1987–90, then wheat), and also had lower legume yields (E. J. Weston, R. C. Dalal and W. M. Strong unpublished data).

One year after the grass + legume phase, substantial increases in total N (Table 5) may have been due to the incorporation of litter and plant residue N. Hossain (1992) measured 104 kg N/ha from these sources at the end of the ley phase of treatment 2.

Two-year rotations of lucerne–wheat, medic–wheat, and especially chickpea–wheat had relatively small effects on organic C concentrations of this soil (Table 4). The plant C inputs, especially from root biomass, in these treatments were ≤50% of those from the grass + legume leys (Table 3). Therefore, relatively small inputs of C and rapid rate of turnover of legume C in these short-term legume rotations did not result in organic matter build-up in this Vertisol. For example, mean annual yield of chickpea stubble (Table 3) was only ≤ 2 t/ha (≤0.8 t C/ha). Campbell *et al.* (1990) also recorded lower organic C contents in lucerne–cereal rotations than in continuous cereal rotations. They suggested that increased moisture stress following lucerne depressed associated cereal production in their semi-arid environment. Similarly, Holford (1990) observed no increase in organic C from 4 years of lucerne ley in a black earth (Pellustert) and a red clay (Chromustert); in fact, organic C declined in the latter during the lucerne phase.

There was, however, a trend to increasing soil total N concentrations under lucerne–wheat and medic–wheat rotations from November 1990 to November 1992 (Table 5), when lucerne and medic leys were extended to almost 2 years (6 months fallow after the first year) since wheat was not planted in 1991 due to drought (Table 2). In both Pellustert and Chromustert, Holford (1990) also found increased soil total N after 2 years of lucerne ley, although after this period, total N declined in the Chromustert in lucerne–sorghum rotation.

In chickpea–wheat rotation, soil total N remained similar to the continuous CT wheat except for the higher value in November 1990. This was despite the fact that chickpea removed in grain about 350 kg N/ha from 1987 to 1993 or about 70 kg N/ha by each chickpea crop. Hossain *et al.* (1995) found that the mean amount of N_2 fixed by chickpea in 1988 and 1989 was 72 kg N/ha.year, just sufficient to maintain soil total N. However, gains to soil total N could occur if soil nitrate-N could be minimised (double cropping or chickpea without a fallow) and plant biomass optimised (e.g. early planting and no-tillage practice) for chickpea in chickpea–wheat rotations.

No-tillage treatments generally had a very small effect on soil organic C, although in November 1993 total N was significantly higher in these treatments (treatments 15, 16 and 17) than the continuous CT wheat treatment (Table 5). Most of these effects were confined to the surface 0–2.5 cm depth (Fig. 6). Dalal *et al.* (1991*a*) also found similar results on another Vertisol, in that the tillage effects were confined to the 0–2.5 cm soil depth. Thus, organic C and total N tend to be stratified even in a Vertisol under no–tillage practice, since plant residue C inputs are primarily concentrated on or near the soil surface.

The increases in organic matter concentrations in this Vertisol are primarily associated with additional root biomass yield produced by grass + legume leys (10 t/ha) compared with the other treatments (2–4 t/ha) (Table 3). In fact, organic C concentrations were closely correlated with root biomass yields ($r = 0.95$, $P<0.01$) and root biomass and plant residue yields ($r = 0.93$, $P<0.01$). Therefore, the contribution of root biomass, besides the aboveground plant residue, to the soil organic matter pool should be considered when evaluating the effectiveness of a cropping system to enhance or maintain organic matter in a soil.

Since organic matter content of a soil is considered a key indicator of sustainability (Hamblin 1992), the results from this long-term study clearly demonstrate that organic matter concentration in these Vertisols can only be enhanced by incorporating grass + legume leys as an essential component of sustainable crop rotations. The widely recommended practices of conservation tillage, such as no-tillage and rotating grain legumes with cereals (e.g. chickpea–wheat), although usually enhancing grain yields (Dalal *et al.* 1994), may not necessarily lead to increasing organic matter levels in these soils.

The Vertisols cultivated for grain cropping in Queensland and northern New South Wales exceed 2.5 million ha, and there is potential for cultivation of another 4–6 million ha in Queensland alone (Weston *et al.* 1981). Sustainable productivity of these soils cannot be ensured in the long term with current cultural practices, since organic matter levels are declining, accompanied by lower cereal yields and declining grain protein contents (Dalal *et al.* 1991*b*), often below Prime Hard grade.

There is, however, a trend to incorporation of grass + legume leys in cropping systems on Vertisols by producers in Queensland and northern New South Wales, especially in drier areas, thus ensuring sustainable productivity from these Vertisols.

Conclusions

Enhancement and maintenance of soil organic matter and soil fertility is essential for sustainable production. Soil restorative practices such as 4 years of grass + legume leys can improve soil organic matter status of a low-fertility Vertisol. However, the quality of soil organic matter as measured by C to N ratio changes only slightly. The 2-year rotations of lucerne–wheat and medic–wheat had minimal effect on soil organic C, although soil total N may improve slightly in the long term. The chickpea–wheat rotation, on the other hand, is likely to maintain organic matter levels similar to those of continuous CT wheat. No-tillage practice causes stratification of organic matter even in a Vertisol, mainly due to plant residues remaining at or near the soil surface, although the improvements in soil organic matter status are likely to be small in this semi-arid environment.

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