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Conservation tillage increases soil water storage, soil animal populations, grain yield, and response to fertiliser in the semi-arid subtropics

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Summary. We compared 4 tillage practices (traditional, stubble mulch, reduced, no tillage) during 10 years under rainfed conditions on an alluvial soil in the semi-arid subtropics of central Queensland. In the final 4 years, responses to applied fertiliser nitrogen (N), sulfur (S), and zinc (Zn) were determined. We measured soil water storage, soil nitrate accumulation, grain yield (sorghum, wheat), grain protein content, and populations of soil macrofauna, with the aim of identifying soil-conserving practices that also produce high yields of high quality grain.

Stubble mulch, reduced tillage, and no tillage all outyielded traditional tillage when soil fertility was adequate. With applied N, S, and Zn, the mean wheat yields from traditional, stubble mulch, reduced, and no tillage were 2.44, 3.32, 3.46, and 3.64 t/ha, respectively. The yield responses to tillage practices were due to increases in storage of soil water or efficiency of crop water use or both.

Populations of soil macrofauna averaged (per m^2) 19 (traditional tillage), 21 (stubble mulch), 33 (reduced tillage), and 44 (no tillage). The effect of the tillage practices on soil animal populations may be a factor contributing to the measured differences in soil water storage and water use efficiency.

We conclude that conservation tillage practices can greatly increase grain yields, provided crop and fallow management practices are appropriate. Potential yield advantages are realised if crop establishment, crop nutrition, and control of weeds, pests, and diseases are adequate.

Introduction

Water supply is generally the main factor limiting the yield of rainfed grain crops in the semi-arid subtropical areas of central Queensland. Grain production depends on rainfall both received during crop growth and stored in the soil during the fallow period.

In order to store water in the soil, its use by weeds must be prevented. Weeds can be controlled either mechanically or chemically (Rawson *et al.* 1981). Mechanical weed control hastens evaporation of soil water by exposing moist soil and by burying the barrier of crop residues. Chemical control leaves the residues on the soil surface where they can reduce runoff on sloping sites (Freebairn and Wockner 1983) and retard evaporation (Bond and Willis 1969). On the other hand, tillage can improve water entry by breaking surface seals and can provide temporary storage of runoff water by increasing surface roughness. Subsurface tillage implements (such as the blade plough and rod weeder) provide mechanical weed control while leaving a mulch of crop residues on the soil surface, but may provide less effective weed control than implements that invert the soil (such as the disc plough). Different tillage regimes may change the species composition and population density of soil fauna, which affect tunnelling activity, soil porosity, and water infiltration (Robertson *et al.* 1994).

No tillage (control of weeds with herbicides throughout the fallow) may reduce the level of plant-available soil nitrogen (N). Mechanisms include reduced N mineralisation (Rovira and Greacen 1957), increased denitrification (Aulakh and Rennie 1985), increased nitrate leaching (Turpin *et al.* 1992), and increased N immobilisation (Cochran *et al.* 1980). If levels of plant-available N under no tillage are low, extra N is required to realise the yield potential of this fallow management practice. Nitrogen can be added as fertiliser or by growing a legume.

This study assessed the effect of tillage (frequency and intensity) and applied fertiliser on rainfed grain production and quality on an alluvial clay in the semi-arid, subtropical environment of central Queensland. We report the results for 4 grain sorghum and 6 wheat crops grown in 10 years (1983–92). Responses to applied fertiliser N, sulfur (S), and zinc (Zn) were measured in the 4 wheat crops grown from 1989 to 1992.

Materials and methods

Site

The site, which is level, is located at the Biloela Research Station (24°22'S, 150°31'E; alt. 173 m). The native forest was cleared in 1924 and used for pasture and crop production until 1983 when the first experimental treatments were imposed. A meteorological station is at the site.

The soil comprises black cracking and non-cracking clays developed on an alluvium. These soil types have been classified as Tognolini and Melton (Shields 1989), respectively, and Vertisol and Aridisol (Soil Survey Staff 1975), respectively. The principal profile forms (Northcote 1977) are Uf6.32P and Ug5.1P. Some soil physical and chemical properties are given in Table 1.

The 71-year mean annual rainfall is 688 mm (range 317–1132 mm), with 73% falling in summer (October–March). The 71-year mean annual evaporation (class A pan) is 1868 mm.

Treatments and design

The treatments were first imposed in late April 1983 after a sorghum crop. There were 4 tillage treatments, varing in frequency and/or degree of soil disturbance in the order traditional tillage (TT) > stubble mulch tillage (SM) > reduced tillage (RT) > no tillage (NT). The TT treatment was tilled with disc ploughs (1-way or offset) and a scarifier; SM and RT were tilled with a chisel plough, blade plough, and rod weeder. In RT, herbicide application was substituted for tillage in about 50% of weed control operations, to obtain high soil water storage without excessive fallow management costs. During the 10-year experiment, the TT treatment received 41 tillage operations and 6 herbicide applications, SM 42 and 6, RT 27 and 17, and NT 0 and 39. Herbicides used were glyphosate, 2,4-D amine, dicamba, paraquat, diquat, and chlorsulfuron. All crop residues were retained, but levels of soil cover varied with the treatments (NT > RT > SM > TT) due to burial of the residues by the tillage implements (Sallaway *et al.* 1988).

No fertiliser was applied until 1989, when 4 fertiliser treatments were commenced in each tillage treatment: control (unfertilised), N, N + S, N + S + Zn. Nitrogen (100 kg N/ha) in the form of urea was drilled in 275-mm rows just before sowing in 1989, 1990, and 1991. Residual effects were investigated in 1992. Sulfur (15 kg S/ha) was broadcast by hand just before sowing, as flowers of S in 1989 and gypsum in the next 3 years. Zinc was applied from 1989 to 1992 as a single spray of 1% zinc sulfate heptahydrate at 2–4 weeks after emergence (Duncan 1967). These fertiliser treatments were decided after examining a nutrient analysis of grain from the 1988 wheat crop.

The experimental design was a randomised block with 4 tillage treatments and 4 replications. In 1989, each plot was randomly split for the 4 fertiliser treatments. Routine analysis of variance was performed for all measurements, within and across years. Size of the main plots was 72 by 22 m and split plots 18 by 22 m.

Experimental details

Cultivars used, sowing dates, harvest dates, and rainfall received during the fallows and during crop growth are shown in Table 2. The sorghum was sown in

Table 1. Physical and chemical properties of the soil profile (0–160 cm) on 15 August 1984

Soil depth (cm):	0–10	10–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160
Particle size (%)									
Coarse sand (>200 μm)	5	4	3	2	2	3	4	6	6
Fine sand (20–200 μm)	37	33	29	25	25	25	26	25	26
Silt (2–20 μm)	24	23	19	26	26	24	24	22	24
Clay (<2 μm)	37	42	49	49	48	47	46	45	47
Soil water content (g/g)									
–30 kPa	0.29	0.31	0.35	0.36	0.36	0.35	0.35	0.33	0.34
–1500 kPa	0.14	0.16	0.18	0.19	0.19	0.18	0.18	0.18	0.18
Dispersion ratio^A	0.52	0.49	0.59	0.54	0.49	0.50	0.50	0.52	0.49
pH (1:5 soil: water)	7.2	7.6	8.1	8.5	8.7	8.8	8.8	8.8	8.7
Conductivity (dS/m, 1:5)	0.06	0.06	0.06	0.08	0.12	0.18	0.23	0.25	0.28
Chloride (mg/kg, 1:5)	19	30	28	36	72	125	173	223	269
Cation exch. capacity (cmol(+)/kg)	31.4	35.4	37.4	40.7	40.4	38.3	37.4	36.3	38.2
Exchangeable sodium percentage	0.9	1.4	1.9	2.4	2.9	4.0	4.6	5.2	5.4
Bicarbonate-extractable P (mg/kg)	135	114	95	70	52	39	36	32	27
KCl-extractable NO_3-N (mg/kg)	7.4	6.0	3.9	2.8	2.6	2.4	2.3	1.9	2.1
KCl-extractable NH_4-N (mg/kg)	1.8	2.9	2.8	2.5	2.1	1.8	1.8	1.7	1.6
Organic C (%)	1.35	1.10	0.86	0.78	0.69	0.57	0.48	0.44	0.44
Total N (%)	0.12	0.09	0.07	0.06	0.05	0.04	0.04	0.03	0.04

^{A} Bruce and Rayment (1982).

Table 2. Details of crops grown, fallow and cropping periods (days), and fallow and in-crop rainfall (mm)

Crop species	Cultivar	Sowing date	Harvest date	Fallow		Cropping	
				Period	Rainfall	Period	Rainfall
Sorghum	E57	3.ii.84	12.vi.84	279	528	130	106
Sorghum	E57	17.xii.84	26.iv.85	188	448	130	313
Sorghum	E57	18.xii.85	10.iv.86	236	458	113	172
Sorghum	Prize	8.x.86	9.ii.87	181	278	124	413
Wheat	Hartog	8.v.87	28.x.87	88	175	173	234
Wheat	Hartog	25.v.88	12.x.88	210	408	140	161
Wheat	Hartog	2.vi.89	19.x.89	233	601	139	125
Wheat	Flinders	9.v.90	24.x.90	204	376	168	153
Wheat	Hartog	31.v.91	17.x.91	219	358	139	37
Wheat	Vasco	2.vi.92	26.x.92	229	641	146	101

0.8–1.0-m rows and the wheat in 0.275-m rows, using no-tillage sowing machinery. In-crop applications of herbicides were applied as required: atrazine in the sorghum, and chlorsulfuron or 2,4-D amine or both in the wheat. Infestations of insect pests were also controlled when necessary: sorghum midge (*Contarinia sorghicola* Coquillett) and heliothis (*Helicoverpa armigera* Hübner) using chlorpyrifos, fenvalerate or methomyl; and armyworm (*Spodoptera* spp.) using trichlorfon.

Measurements

Soil bulk density. Bulk densities (for determining volume of water and weight of N in the soil profile) were measured at field capacity in each treatment for 8 depth increments (0–10, 10–20, 20–30, 30–50, 50–70, 70–100, 100–130, 130–160 cm). Bulk densities were determined in May 1991 by weighing a measured volume of soil at field capacity. Infiltration rings were used to attain field capacity in the top 3 depth increments.

Soil water. Hydraulically powered sampling rigs were used to extract soil cores to a depth of 160 cm at sowing and harvest of the 4 wheat crops grown from 1989 to 1992. Two cores from randomly selected locations in each unfertilised subplot and each N + S + Zn subplot were taken. Each core was cut into the 8 depth increments listed above, the pairs of increments from a subplot were bulked, and soil water content was determined gravimetrically.

The volume of water in a depth increment was calculated using the bulk density at field capacity, and total water in each profile was determined by addition. Bulk densities determined at field capacity were used to calculate volumetric soil water at all water contents, since these values provide better estimates of field bulk density for a cracked soil than the bulk densities of the clods between the cracks (Bridge and Ross 1984; Gardner *et al.* 1990). Plant-available water in each profile was calculated by subtracting the volume of water in the driest profile (1989–92) for each subplot. The depth increments below 10 cm in the driest profiles were at a soil water content approximating wilting point.

Soil nitrogen. Soil cores for nitrate-N determination were taken to a depth of 160 cm at sowing of the 1991 and 1992 wheat crops. Two cores from each unfertilised subplot were cut into the 8 depth increments, bulked, air-dried in a glasshouse, and finely ground (<2 mm). In 1992, the same procedure was also used for the N subplots (after the application of 300 kg N/ha during 3 years). Nitrate-N was determined by KCl extraction, and quantities in the soil profiles were calculated using the bulk density data.

Crop attributes. Establishment was determined in the 10 crops as a percentage of seed sown, by calibrating the seeder for seed output and counting the established seedlings. Counts were taken at 11–28 days after sowing from a total row length of 2.4–3.0 m/plot in the sorghum crops (2 rows) and 12 m/plot in the wheat crops (6 rows).

In the 1989–92 wheat crops, plant tops at anthesis were cut from 1.0-m^2 quadrats in each subplot and dried to constant weight at 80°C in forced-draught ovens. Subsamples were finely ground and analysed for N content by micro-Kjeldahl digest with an automated colorimetric finish. Crop N uptake was determined from dry weight of tops at anthesis multiplied by N content.

Grain was harvested from measured areas of 78–200 m^2 for the first 6 crops. When the plots were split, datum areas in the subplots were measured areas of about 25 m^2. Grain moisture contents were determined by moisture meter, and all grain yields were standardised to 12% moisture content. Grain weight was determined from 2 lots of 100 seeds/subplot in 1989–92, and the mean number of grains per m^2 was calculated. Grain N content was determined in 1988–92 by micro-Kjeldahl digest with an automated colorimetric finish. The amount of N removed in the grain was determined from grain yield multiplied by grain N content. Wheat grain protein content was calculated by multiplying grain N content by 5.7, the conversion factor traditionally used (Tkachuk 1969).

Water use efficiency for grain production was calculated for the 1989–92 crops, based on soil water differences and rainfall between sowing and harvest. This is a measure of the efficiency of tillage practices in using rainfall, some of which may be lost as evaporation, runoff, and drainage below the root-zone (Perry 1987).

Soil macrofauna. Soil samples (18 by 18 by 15 cm deep) for the determination of macrofauna population densities were taken with a spade when the soil was moist after rain on 2 May 1990; 16 January, 28 May, and 19 November 1991; and 6 February and 8 December 1992. Ten samples were taken in each main plot except on 2 May 1990 when 15 samples were taken. Sampling locations were selected using the centric systematic area-sample method (Milne 1959). The samples were hand-sorted on a sheet-metal tray as they were taken, and soil insects identified and counted in the field. Each ant colony or termite colony was counted as a single animal to minimise the variability of the data used to quantify total soil animal populations.

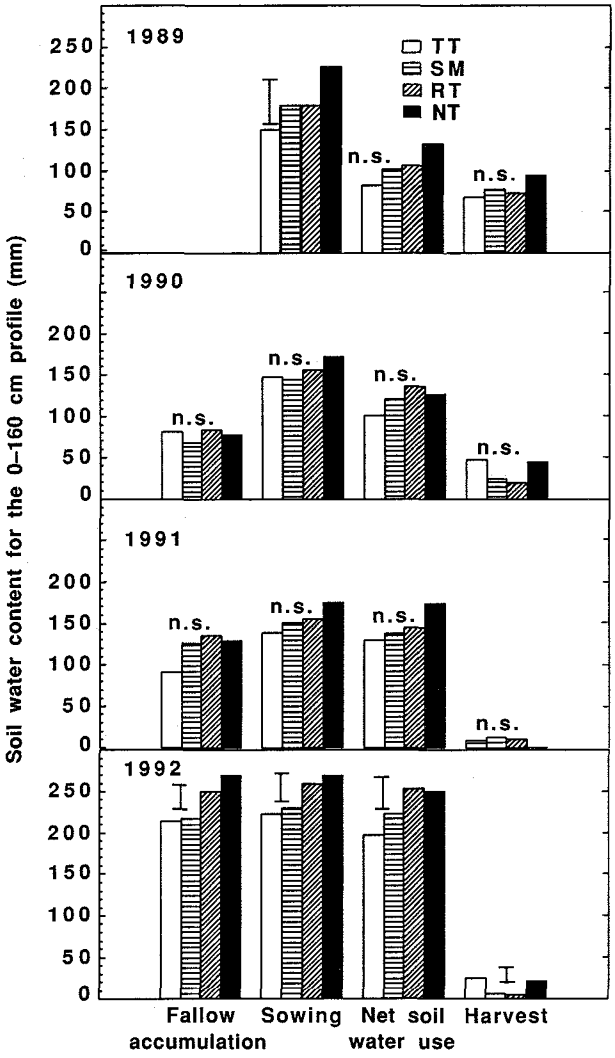

Figure 1. Effect of tillage treatments (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage) on soil water accumulation during the fallow, soil water at sowing and harvest, and soil water use, from 1989 to 1992 (0–160 cm). Vertical bars indicate l.s.d. at $P = 0.05$; n.s., not significant.

Economic analysis. No attempt was made to limit costs, the emphasis being on effective weed control during the fallow periods and optimum crop management. Nevertheless, an economic analysis of gross margins for each treatment in the 1989–92 wheat crops was carried out. We assumed a base wheat price of $A152/t at ≤9.0% grain protein, and added $0.50, $0.20, and $0.50/t for each extra 0.1% grain protein up to 10.5, 11.5, and 16%, respectively.

Results

Soil water storage and use

The amount of rainfall accumulating in the soil profile between harvest and sowing varied significantly ($P<0.01$) among the tillage treatments during the 1991–92 fallow: NT and RT accumulated more than TT and SM (Fig. 1). As a result, NT and RT had significantly more plant-available water in the profile at sowing than TT in 1992 (Fig. 1). NT and RT also used more soil water than TT in 1992 (Fig. 1). In each of the 4 years, NT tended to have the most water at sowing (differences were not statistically significant) while TT generally had the least. Average differences between TT and other treatments were 46 mm (NT), 22 mm (RT), and 11 mm (SM). The pattern of net soil water use during crop growth reflected these different amounts of water stored at sowing (Fig. 1). There was no difference in net soil water use in response to the application of fertiliser (N + S + Zn).

Mean fallow efficiency (percentage of fallow rainfall stored in the soil) was 33 (NT, RT), 29 (SM), and 27 (TT).

Wheat crops generally extracted some water at 130–160 cm, indicating that depth of rooting usually exceeded 130 cm. The 3 conservation tillage treatments (SM, RT, NT) stored and used more water below 100 cm

Table 3. Effect of tillage practice and fertiliser nitrogen application on soil nitrate-N (kg/ha; 0–160 cm) at sowing, 1991–92

There was no significant difference between treatments

Tillage practice	1991 Unfertilised	1992 Unfertilised	1992 Fertilised
Traditional	34	115	216
Stubble mulch	43	106	202
Reduced	21	109	184
No tillage	27	82	190

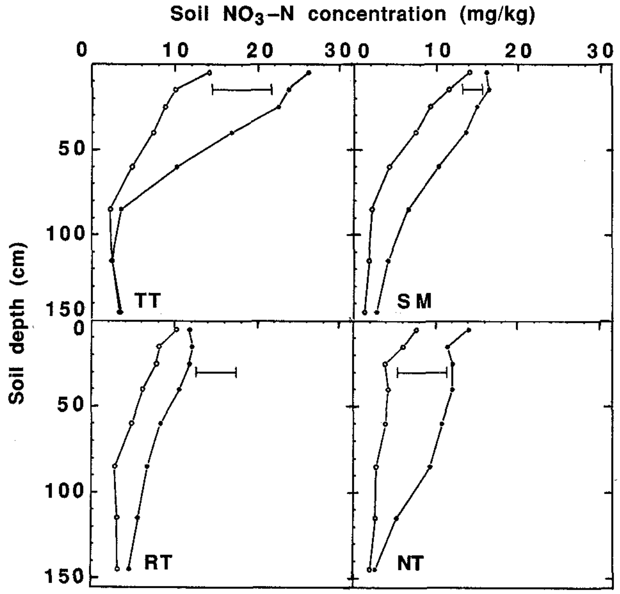

Figure 2. Effect of N application on the profile distribution of nitrate-N at sowing in 1992 for tillage treatments (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage; ○ unfertilised; ● fertilised with N). Horizontal bars indicate l.s.d. at $P = 0.05$, for all comparisons.

than TT. For 1989–92, mean additional soil water storage at 100–160 cm in comparison with TT was 23 mm (SM), 33 mm (RT), and 34 mm (NT) [l.s.d. ($P = 0.05$) = 12]. Mean additional soil water use at 100–160 cm was, respectively, 11, 15, and 26 mm [l.s.d. ($P = 0.05$) = 12].

Plant-available soil nitrogen

Tillage (TT, SM) tended ($P>0.05$) to increase nitrate-N in the soil profile compared with NT (Table 3). The total application of 300 kg/ha of fertiliser N during 3 years (1989–91) almost doubled mean nitrate-N in the soil at sowing in 1992, increasing it from 103 to 198 kg/ha [l.s.d. ($P = 0.05$) = 31]. The profile distribution of this additional nitrate-N is shown for each tillage treatment in Figure 2. Some additional nitrate-N from the fertiliser applications had leached to greater depths in SM, RT, and NT than in TT. In the N-fertilised plots, SM, RT, and NT had significantly lower concentrations of nitrate-N than TT at 0–10, 10–20, and 20–30 cm, and NT had a significantly higher concentration than TT at 70–100 cm.

Crop establishment

The NT treatment generally gave the lowest sorghum establishment but the highest wheat establishment (Fig. 3). Despite these differences in establishment percentage, plant population densities were generally within the satisfactory range for the production of optimum grain yields: 50 000–100 000 sorghum plants/ha (Thomas *et al.* 1981), and 500 000–1 000 000 wheat plants/ha (Colwell 1963). Possible exceptions were NT sorghum in 1983–84, which had a low plant population (47 000/ha), and NT wheat in 1991, which had a high population (2 000 000/ha).

Dry matter at anthesis

Tillage treatment had no significant ($P>0.05$) effect on aboveground dry matter at anthesis in 1989–92, with or without fertiliser application (data not shown). However, N application significantly increased dry

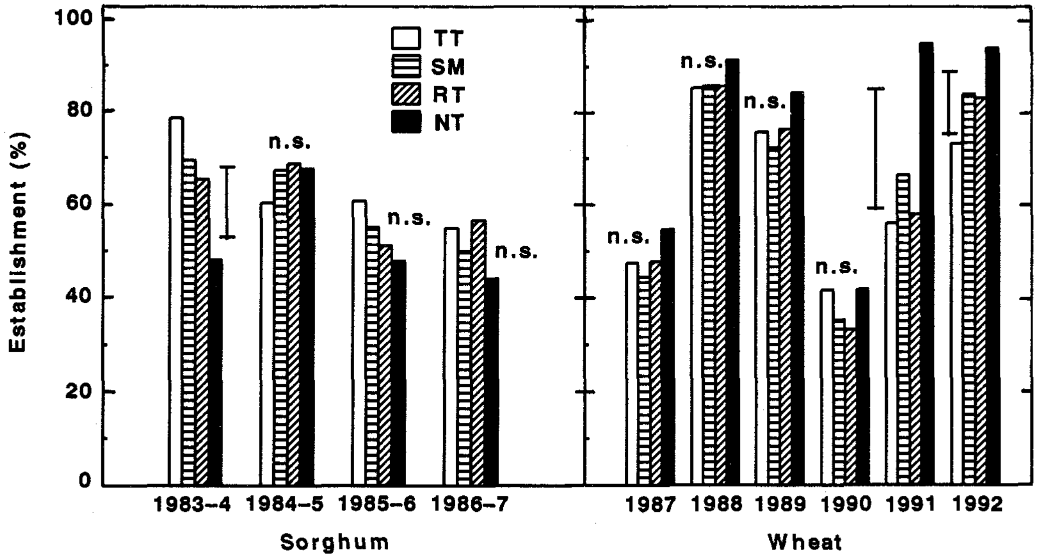

Figure 3. Effect of tillage practices (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage) on the establishment percentage of ten successive crops. Vertical bars indicate l.s.d. at $P = 0.05$; n.s., not significant.

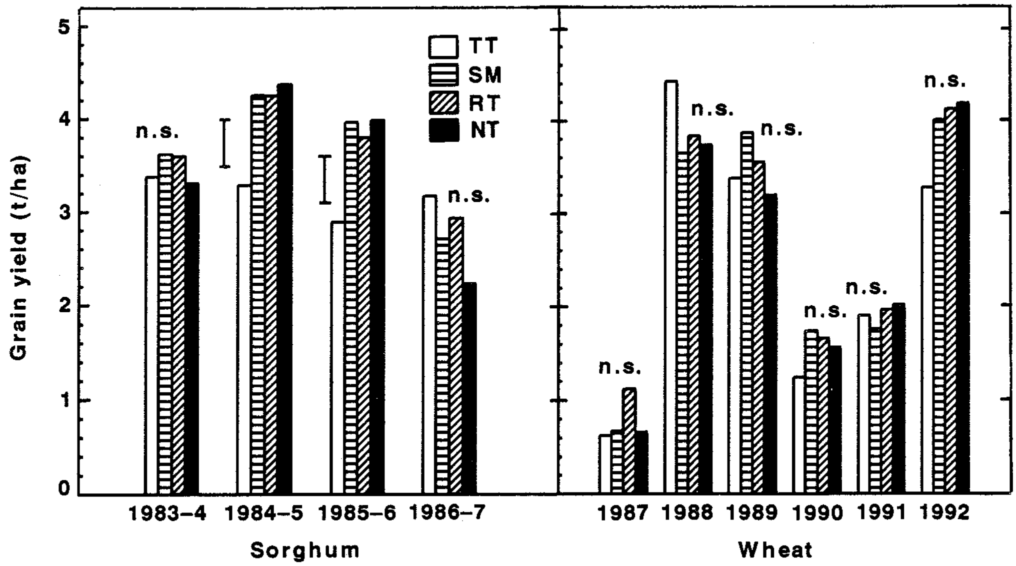

Figure 4. Effect of tillage practices (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage) on grain yield of ten unfertilised crops. Vertical bars indicate l.s.d. at $P = 0.05$; n.s., not significant.

matter from 5.4 to 6.6 t/ha in 1989 [l.s.d. ($P = 0.05$) = 0.5] and from 6.3 to 6.9 t/ha in 1992 [l.s.d. ($P = 0.05$) = 0.6].

Grain yield

Without fertiliser, the 3 conservation tillage treatments outyielded TT in 2 early crops (1984–85 and 1985–86), but after 1985–86, all tillage treatments gave similar yields (Fig. 4). In 1988, wheat grain protein content declined with reduced frequency and intensity of tillage: TT 9.1% grain protein, SM 8.4%, RT 8.2%, and NT 7.8% [l.s.d. ($P = 0.05$) = 0.7]. This indicated a shortage of N in all treatments but particularly those involving conservation tillage.

Yield response to fertiliser (N, N + S, N + S + Zn) was significant ($P<0.01$) in 1989 and 1992 (data not shown) and appeared to be due solely to the applied N. The tillage x fertiliser interaction was not significant ($P>0.05$) in any individual year but was significant ($P<0.01$) for yield averaged across the 4 years (Fig. 5): NT outyielded TT by an average of 0.3 t/ha without fertiliser, 0.8 with N, 0.7 with N + S, and 1.2 with N + S + Zn [l.s.d. ($P = 0.05$) = 0.7]. The highest mean yield for the 4 years was 3.64 t/ha from NT with N + S + Zn.

The yield responses to reductions in tillage were due to increases in grain weight in 1989, grain weight and grain number in 1990, and grain number in 1992 (data not shown).

Water use efficiency

Tillage practice significantly ($P<0.05$) affected water use efficiency of grain production in 1990 and 1992 (Table 4). In 1990, SM, RT, and NT were more efficient than TT, and in 1992, SM and NT were more efficient than TT. Mean water use efficiency for the 4 crops from 1989 to 1992 was significantly higher in SM and RT than TT and NT (Table 4).

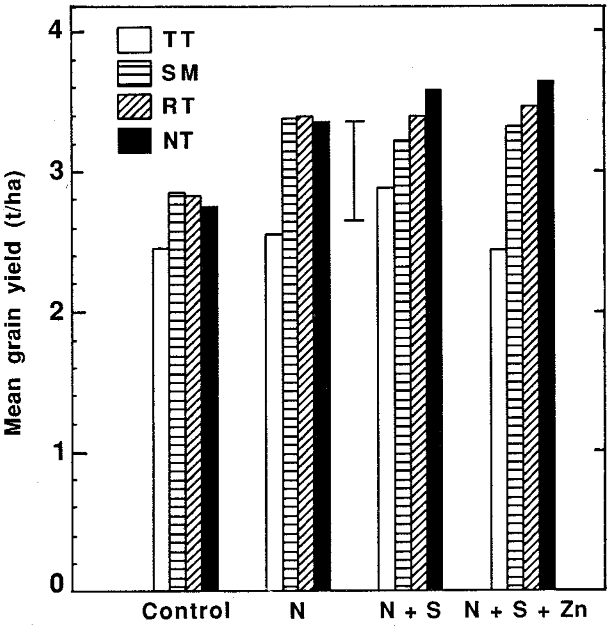

Figure 5. Effect of tillage (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage) and fertiliser (N, N + S, N + S + Zn) treatments on mean grain yield during four years (1989–92). Vertical bar indicates l.s.d. at $P = 0.05$, for comparisons among tillage treatments with the same or different fertiliser treatments.

Table 4. Effect of tillage practice on the water use efficiency (kg/ha.mm) of four wheat crops, 1989–92

Data are means of nil and N + S + Zn fertiliser treatments

Tillage practice	1989	1990	1991	1992	Means
Traditional	17.0	4.2	12.1	10.9	11.1
Stubble mulch	18.4	7.1	11.1	13.6	12.6
Reduced	18.3	7.6	11.9	12.2	12.5
No tillage	15.1	6.5	10.5	13.6	11.4
l.s.d. ($P = 0.05$)	n.s.	2.3	n.s.	1.9	1.0

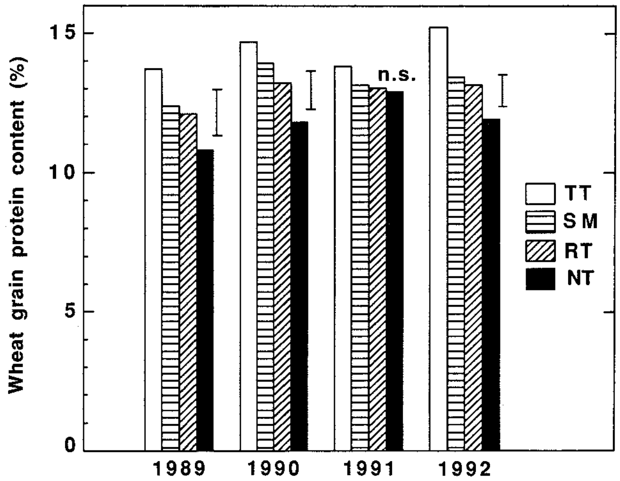

Figure 6. Effect of tillage practice (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage) (meaned across four fertiliser treatments) on wheat grain protein content during four years (1989–92). Vertical bars indicate l.s.d. at $P = 0.05$; n.s., not significant.

The application of fertiliser (N + S + Zn) increased mean water use efficiency for 1989–92 wheat crops from 11.1 to 12.7 kg/ha.mm [l.s.d. ($P = 0.05$) = 0.9]. There was no significant ($P>0.05$) tillage × fertiliser interaction for water use efficiency of grain production.

Uptake of nitrogen in plants and grain

Tillage treatment did not significantly ($P>0.05$) affect N uptake by the crop at anthesis or in the grain at harvest in any year from 1989 to 1992 (data not shown). Application of 100 kg N/ha in 1989, 1990, and 1991 increased total crop N uptake at anthesis in the 1989–92 wheat crops from 241 to 400 kg/ha. This represents a recovery of 53% of the applied N in the plant tops of those 4 crops. There was also a recovery of 31% of the applied N in the harvested grain of the 1989–92 crops.

Reductions in tillage decreased mean grain protein content significantly ($P<0.05$) in 3 of the 4 years (Fig. 6). The low grain protein contents of SM, RT, and NT were due to 'dilution' of the protein as a result of increased yields. Total quantities of grain protein were similar for all tillage treatments each year. The N fertiliser treatment significantly ($P<0.01$) increased grain protein content each year (data not shown). This included a residual response in 1992 to the previous N applications. There was no significant ($P>0.05$) tillage × fertiliser interaction for grain protein content in any year.

Soil macrofauna

With reduced frequency and intensity of tillage, the total population of soil animals increased (Fig. 7). Under TT there were 19 animals/m^2 and under NT 44/m^2; TT had 4 earthworms/m^2 and NT 17/m^2. While TT had only 0.4 ant colonies/m^2, NT had 1.6/m^2. TT and SM had a negligible number of termite colonies but RT had

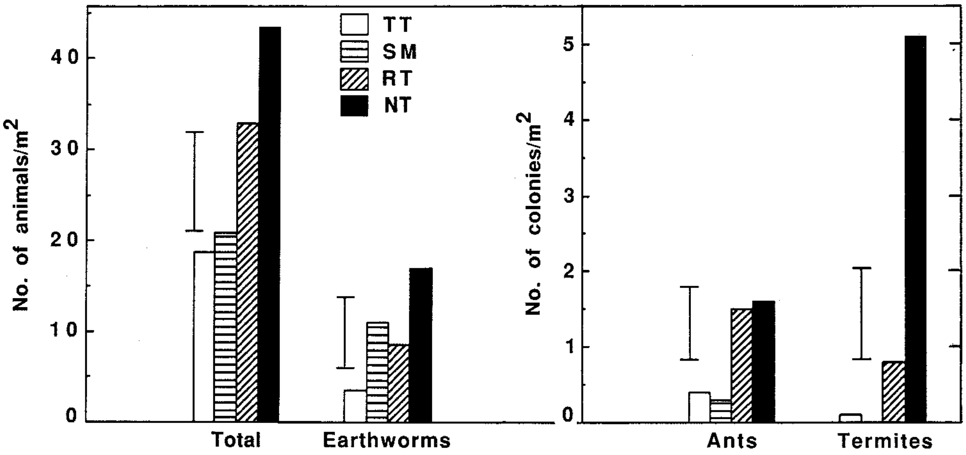

Figure 7. Effect of tillage practices (TT, traditional tillage; SM, stubble mulch tillage; RT, reduced tillage; NT, no tillage) on soil fauna populations. Total values were calculated by using 1 colony = 1 animal for ant and termite data. Vertical bars indicate l.s.d. at $P = 0.05$.

Table 5. Effect of tillage practice and fertiliser practice on total gross margins ($A/ha) for four crops from 1989 to 1992

Tillage treatment	Unfertilised	N	N + S	N + S + Zn
Traditional	1078	1013	1154	865
Stubble mulch	1289	1515	1373	1435
Reduced	1192	1445	1430	1445
No tillage	1027	1312	1405	1420

0.8/m^2 and NT 5.1/m^2. For most soil animal species, populations were enhanced by reducing tillage. Lack of soil disturbance by tillage implements and the associated increased retention of crop residues on the soil surface apparently resulted in a soil micro-environment favourable to animal survival.

Profitability

Without fertiliser, SM gave the highest net profit and NT the lowest (Table 5). With N + S + Zn, however, SM, RT, and NT were most profitable. The profit from NT increased by 38% when N + S + Zn was applied.

Discussion

Stubble mulching, RT, and NT all increased yield compared with TT, particularly when the N deficiency in the soil was corrected with fertiliser. Apparently, additional N was needed to realise the increased yield potential of the 3 conservation tillage treatments. Yield responses to the tillage treatments were due to increases in soil water storage or crop water use efficiency or both. In 4 successive years in the fully fertilised plots (N + S + Zn), TT was outyielded by all other treatments; average differences (t/ha) were SM 0.9, RT 1.0, and NT 1.2 (Fig. 5). Such high and consistent responses to tillage practices have not, to our knowledge, been recorded previously in Australia. Lawrence *et al.* (1994) reported an average yield increase for 4 successive wheat crops of 0.5 t/ha using NT instead of chisel plough or scarifier tillage on a lighter soil. It should be pointed out that the responses we obtained to tillage practices were generally associated with lower-than-average growing season rainfall at the site. Rainfall during crop growth was lower than average for the first 3 sorghum crops and the last 4 wheat crops. The 3 conservation tillage treatments were also more profitable than TT when an appropriate fertiliser treatment was applied.

Dry matter production at anthesis did not change in response to the tillage treatments in any year, so grain yield responses to tillage were associated with a better 'finish', as measured by the ratio of grain yield to dry matter at anthesis (Marley and Littler 1989). The 3 conservation tillage treatments generally accumulated and used more soil water below 100 cm than traditional tillage. These treatments were observed to remain green for a longer period than TT.

Tillage generally had only small effects on crop establishment. It tended to increase establishment in sorghum but decrease it in wheat (Fig. 3). Similar effects were obtained at a site in south-western Queensland (Gibson *et al.* 1992; Radford *et al.* 1992). It should be remembered, however, that all comparisons were made using no-tillage sowing machinery, which is essential for satisfactory establishment in untilled soil. With conventional sowing machinery, reduced tillage may have reduced the establishment of both wheat and sorghum. Reduced seedbed tilth decreases soil flow at sowing, which reduces the depth of soil cover above the seed. Adequate cover is needed to protect the seed or seedling from desiccation, and is particularly important in summer when sorghum is sown. Increased wheat establishment in the NT treatment was attributed to better utilisation of a marginal sowing rain in 1991 and a more optimal depth of soil cover in 1992 (Radford *et al.* 1986).

The positive yield and grain protein responses to residual N fertiliser in 1992 show that applied N is not necessarily lost in central Queensland when it cannot be used by the target crop. There was a tendency for nitrate to leach in NT (Fig. 2), as reported by Turpin *et al.* (1992). However, the increased risk of nitrate leaching in NT is associated with increased water movement through the profile, which enhances water storage and increases the probability of more frequent cropping. The sowing of opportunity crops in central Queensland (Daniels *et al.* 1991) allows utilisation of residual N before it can leach, and also limits further leaching by drying the soil profile.

The NT treatment increased mean soil water storage for the 4 fallow periods by 46 mm (211 mm *v.* 165 mm in TT) and had the highest water storage at sowing each year (Fig. 1). This can be explained by the retention of maximum levels of soil-protecting stubble on the surface of the NT plots and by the greater volume and density of large macropores (>1 mm diameter) in NT. These large pores would take longer to fill under rainfall, thereby delaying the time to ponding and commencement of runoff. Large macropores are made by soil fauna such as termites and earthworms, which were found in increasing numbers as tillage was reduced. Termite galleries and earthworm channels are deep and continuous down the profile (Ehlers 1975; Holt *et al.* 1993) and can therefore quickly conduct water deeply into the soil to minimise runoff and evaporation. The effects of the tillage treatments on soil hydraulic properties will be discussed in another paper.

The continuous pores made by soil animals may also improve the water use efficiency of crops by reducing the energy expended by roots in penetrating the soil, particularly compacted soil. The soil biopores of earthworms provide nutrient-rich cast material along these channels of least resistance. However, the root channels of previous crops, if left undisturbed by tillage, could also provide continuous soil biopores to enhance crop water use efficiency. No tillage has improved the water use efficiency of wheat (Lawrence *et al.* 1994) and sorghum (Holland and Felton 1989) in other tillage experiments in Australia. However, the highest water use efficiency in our experiment occurred in SM and RT, not NT (Table 4).

Soil macrofauna may play a role in nutrient cycling and could alleviate the accumulation of immobile nutrient elements in the surface of untilled soil where they are unavailable for uptake by plant roots (Robson and Taylor 1987; Hunter and Cowie 1989).

The precise contribution of the soil macrofauna to improvements in infiltration, soil water storage, water use efficiency, and nutrient cycling is uncertain. Whatever it may be, it is only likely to occur after a continuous period of several years of conservation tillage such as in this experiment. Time is needed for soil animal populations to establish, multiply, and stabilise in the more favourable soil habitat. Douglas (1987) reported that soil macrofauna took about 7 years to become abundant and diverse after cessation of cultivation in temperate parts of Australia. The predominant effects of conservation tillage at different locations, whether edaphic, biological, agronomic, or economic, will only be fully realised as the results of medium to long-term tillage experiments become available.

Conclusions

Conservation tillage practices outyielded traditional tillage, particularly when adequate crop nutrition was available. Yield responses were due to enhanced soil water storage and/or enhanced crop water use efficiency. Improved water storage and improved efficiency of water use were attributed to retention of crop residues on the soil surface and to the large, continuous soil macropores made by soil animals. Soil animal populations increased when the frequency and degree of soil disturbance by tillage were reduced. Conservation tillage practices gave higher economic gross margins than traditional tillage, provided appropriate fertility amendments were applied.

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