CSIRO PUBLISHING

www.publish.csiro.au/journals/ajea *Australian Journal of Experimental Agriculture,* 2003, **43**, 141–153

Using zero tillage, fertilisers and legume rotations to maintain productivity and soil fertility in opportunity cropping systems on a shallow Vertosol

R. D. Armstrong[A,B,E], *G. Millar*[A], *N. V. Halpin*[A], *D. J. Reid*[A,C] *and J. Standley*[A,D]

[A]Natural Resources and Mines, PO Box 19, Emerald, Qld 4720, Australia.
[B]Present address: Department of Primary Industries, Victorian Institute for Dryland Agriculture, PMB 260, Horsham, Vic. 3401, Australia.
[C]Agency for Food and Fibre Sciences, Queensland Department of Primary Industries, PO Box 6014, Rockhampton Mail Centre, Qld 4702, Australia.
[D]Leslie Research Centre, Queensland Department of Natural Resources, PO Box 2282, Toowoomba, Qld 4350, Australia.
[E]Author for correspondence; e-mail: roger.armstrong@nre.vic.gov.au

Abstract. The effect of 2 tillage practices (zero *v.* conventional), fertiliser application (nitrogen, phosphorus and zinc), and pulse–cereal rotation on changes in soil mineral nitrogen, plant-available water in the soil, grain yield and protein, and key soil fertility parameters (total nitrogen, organic carbon) in the Central Highlands of Queensland were examined between 1991 and 1998. Four pasture treatments (perennial legume, perennial grass, annual legume and legume–grass mixes) were included in January 1995, following previously unsuccessful attempts to grow lucerne and annual medics. The experiment was conducted as an opportunity cropping system on an open downs soil at Gindie that is representative of a large proportion (70%) of soils in the Central Highlands. Tillage practice did not affect the amount of mineral nitrate or the plant-available water content of the soil at planting, except in 1991 and 1998 when plant-available water content was higher under conventional tillage than zero tillage. However, zero tillage improved grain yield in 2 of 4 years (wheat in 1992; sorghum in 1996), increased uptake of nitrogen in every crop and produced greater grain protein levels in both wheat crops grown than conventional tillage. There were grain responses to nitrogen + phosphorus fertilisers (wheat in 1991 and sorghum in 1997). Grain protein was increased with applications of nitrogen regardless of whether phosphorus was added in 3 of the 4 crops planted. Sowing a pulse did not significantly increase grain yields in the following crop although it did increase soil mineral nitrogen at planting. Soil nitrate remained low in control (P_0N_0) plots (<39 kg N/ha) when crops were planted each year but increased significantly (average 84 kg N/ha) following a long fallow of 3.5 years resulting from drought. Plant-available water content of the soil at sowing was lower where chickpeas had been grown the previous season than with wheat. Neither tillage practice nor fertiliser application affected soil organic carbon or soil total nitrogen concentrations in the topsoil. However, all pasture treatments improved soil total nitrogen compared with continuous cropping, and with the exception of annual pasture legumes, also improved soil organic carbon after only 2 seasons. Largest improvements in soil fertility (total nitrogen and organic carbon) occurred with perennial species. It was concluded that zero tillage practices can have beneficial impacts on grain yields as well as minimising environmental degradation such as soil erosion in this region. However, if soil fertility levels are to be maintained, or improved, perennial pasture rotations will need to be used as current levels of fertiliser application or rotations with pulses had no significant beneficial effect.

Introduction

The area cropped in the Central Highlands of Queensland, which is exclusively confined to cracking clay soils, expanded from 250000 to over 500000 ha between 1982 and 1986 (Carroll *et al.* 1997). However, sustainable and profitable grain production in the region faces the following 3 major threats: erosion resulting from high intensity rainfall, declining soil fertility and variable rainfall.

The development of zero tillage (ZT) and stubble retention (or conservation cropping) practices can greatly reduce soil erosion on these cracking clay soils (Freebairn and Wockner 1986; Carroll *et al.* 1997). Conservation cropping systems have 2 major benefits besides reducing soil erosion. First, they increase the number of sowing opportunities and facilitate the use of opportunity cropping systems, whereby crops are planted when the opportunity

 10.1071/EA01175 0816-1089/03/020141

arises, in contrast to the traditional fixed rotation systems of southern Australia (Carroll *et al.* 1997). Second, reduced runoff can be accompanied by increased infiltration of soil water, thereby leading to greater crop yield potential (Thomas *et al.* 1990*a*). However, increases in cropping frequency and yields resulting from increased sowing opportunities and improved soil water reserves will also produce greater demands on soil nutrient reserves.

Soil fertility levels are already low throughout the northern grain belt (Dalal and Mayer 1986), and in central Queensland in particular, as indicated by declining grain yields and protein levels (Garside *et al.* 1992). However, the potential for greater crop yields resulting from increased soil water availability in conservation cropping systems will not be achieved unless soil fertility is adequate to meet the demands of the crop. The profitability of applying nitrogen (N) fertilisers to increase both grain yields and protein of wheat has been firmly established in southern Queensland (Strong *et al.* 1996), and to a lesser extent in the Dawson Callide region (Lawrence *et al.* 1994). However, little information is available for the Central Highlands region of Queensland where soils are shallower and rainfall more variable.

This paper reports a study of 2 tillage systems, fertilisers and legumes (both pulse and pasture) to improve both grain yield and quality and soil fertility in the Central Highlands region of Queensland. It was expected that a better understanding of how tillage practice, soil fertility and soil water interact to affect grain production would lead to the development of farming systems that are both profitable and sustainable.

Methods

An experiment was conducted from 1991 to 1998 on Ian Gardner's 'Enderly' property at Gindie. Enderly is located about 35 km south-east of Emerald, Queensland (23°29′S, 148°09′E, alt. 190 m). The experimental site had a shallow (50–88 cm) dark cracking clay soil overlying basalt (Vertosol, black, self mulching; Isbell 1996). This soil type is representative of 70% of soils used for cropping in the Central Highlands region of Queensland. The area was originally open grassland of bluegrass (*Dichanthium sericeum*), black speargrass (*Heteropogon contortus*) and wire grass (*Aristida* sp.), with scattered mountain coolibah (*Eucalyptus orgadophila*), bloodwood (*Eucalyptus* sp.) and wattles (*Acacia* sp.). The site had been continuously cropped for more than 40 years and had grown wheat in 1990, before the commencement of the trial.

The experiment was initially designed as a fixed winter cropping rotation but changed to opportunity cropping in line with regional practice in mid-1993. Rainfall during the project ranged from the long-term average (590 mm) to below average for Emerald, which is the nearest long-term weather station (30 km) (Fig. 1).

Trial design

The trial consisted of 3 replicates of 20 plots (26 by 7.6 m) in a randomised block design. Treatments comprised a nested factorial of 2 tillage practices, zero (ZT) and conventional (CT) tillage, by 9 fertiliser–crop rotation treatments with 2 additional pasture treatments. The 9 fertiliser–crop rotation treatments consisted of 7 nitrogen–phosphorus (plus basal zinc) fertiliser regimes applied to cereal and 2 pulse–cereal rotations. The fertiliser treatments were P_0N_0 (control), $P_{12}N_0$, $P_{12}N_{25}$, $P_{12}N_{50}$, $P_{12}N_{75}$, P_0N_{50} and $P_{12}N_{50}$ – Zn (subsequently referred to as –Zn) where the subscript represents the amount of element applied (kg/ha) at sowing of each crop on a kg/ha basis. A basal nutrient application of P (12 kg/ha applied with seed as triple phosphate) and Zn (2 kg Zn/ha applied with seed as $ZnSO_4.H_2O$) were added at sowing to all crop treatments (cereals and pulse). The exceptions were no N was applied to the control, the $P_{12}N_0$ treatment or the pulses. No Zn was applied to the control or the $P_{12}N_{50}$ (–Zn) treatment. Where appropriate, N was applied as ammonium nitrate to each crop sown by dropping the fertiliser in front of the planting tynes resulting in shallow incorporation.

The pulse–cereal treatment was phase-replicated so that a pulse was present every season, thus requiring 2 plots in each block. The 2 pastures were initially a perennial grass (purple pigeon grass) and a pasture–legume mixture (lucerne and annual medic). As such, there was a total of 18 'cropping' plots and 2 'pasture' plots per block.

Purple pigeon grass was sown at 4 kg/ha on 5 March 1991 and the lucerne–medic ley was sown to a 'shotgun' mixture of Paraggio, Sephi

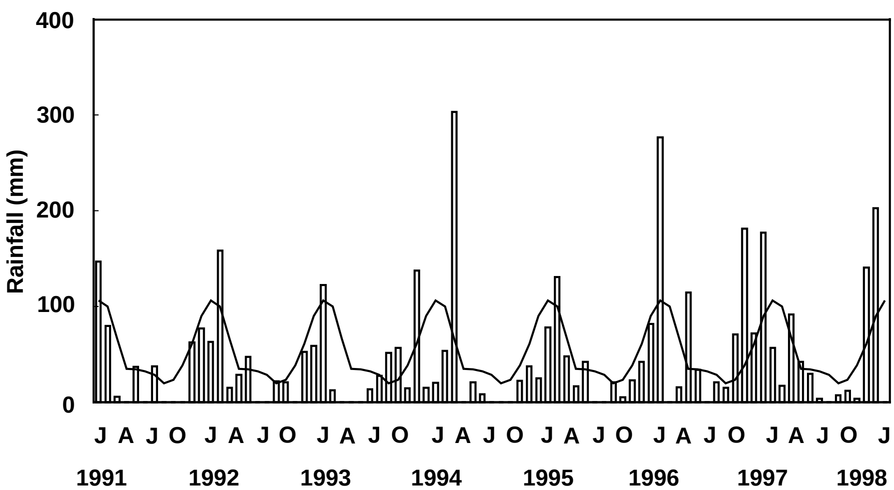

Figure 1. Long-term (100 year) average monthly rainfall (J, January; A, April; J, July; O, October) for Emerald (solid line), located about 30 km from the experimental site, compared with that received at Gardner's (Gindie) during the trial period (bars).

and Snail medics and Trifecta, Hunterfield and Sequel lucerne planted at 6 kg/ha on 27 May 1991. Because of the very poor growth of the pasture legumes from 1991 to 1994, each pasture plot was split in January 1995. Half of the purple pigeon grass plot retained the purple pigeon grass and the other half was sown to a perennial legume (siratro cv. Aztec). In the original lucerne–annual medic plot, half was sown to an annual legume (*Vigna trilobata*) and the other half to a grass–legume mixture (siratro cv. Aztec and creeping blue grass). Pasture plots were slashed on a regular basis and the residues retained *in situ* (Armstrong *et al.* 1999*b*). In accordance with district practice, no fertiliser was applied to the pasture plots other than an original application of P at 12 kg/ha.

Zero tillage practice was defined as weed control using herbicides [chiefly glyphosate; 2,4 D; and Starane (fluroxypyr)] applied from a vehicle-mounted boomspray, driven perpendicularly to the plots. Weed control in CT treatments was via chisel plough for the primary cultivation and a scarifier for the secondary cultivations, with diamond harrow attached for the last cultivation pre-plant. The number of mechanical workings varied with stubble load and soil roughness but was generally lower than 4 per fallow, in keeping with farmer practice at the time. Because of plot design and sprayer limitations, both CT and ZT plots needed to be sprayed simultaneously. CT plots were cultivated whenever ZT plots were sprayed or weed populations on CT plots were assessed to need control.

Successful crops were sown over 4 seasons: wheat and chickpeas in 1991 and 1992 and sorghum and mungbean in 1996 and 1996–97 (subsequently designated as 1997). Cultivars and sowing dates are listed in Table 1. Drought conditions from mid-1992 to early 1996 meant that no successful crop was grown during this period. Sorghum and mungbeans were sown in 1995 but were sprayed out after 6 weeks due to poor establishment resulting from insufficient soil moisture. In 1991, wheat and chickpeas were planted on 22.5-cm row spacings with fixed tynes but this gave inconsistent establishment, especially in ZT treatments. In 1992, a 27-cm row spacing was used with a parallelogram planting unit with narrow point planting tynes and twin inclined presswheels which resulted in improved establishment and trash flow capabilities. In 1996 and 1997, sorghum row spacing was 62.5 cm and mungbean 27 cm.

Soil sampling

Soils were sampled in selected treatments to determine selected chemical indices of soil fertility in March 1991 (pre-experiment) by taking at least 12 hand-driven soil cores (4.2 cm diameter cutting tip) per plot in the 0–5 cm layer and 10 cores in the 5–10 and 10–20 cm layers. In order to ensure good delineation of soil depths, this procedure was performed as soon as possible after a rainfall event had thoroughly wetted (but not saturated) the soil to below the depth of sampling. Soil organic C was measured for the 0–10 cm depth when soil had dried sufficiently to ensure that no mould-oil lubricant was necessary to prevent tube blockages. After collection in the field, samples were dried at <40°C, ground to <2 mm and analysed for total (Kjeldahl) N, organic carbon (C), DTPA-extractable Zn and copper (Cu), 0.5 mol/L $NaHCO_3$-extractable phosphate, and 2 mol/L KCl-extractable nitrate. No attempt was made to remove fragments of organic matter such as roots before grinding. The soil sampling was repeated in September 1993, May 1996, April 1997 and December 1997.

Soil water content was determined gravimetrically at planting, anthesis and grain maturity, and soil nitrate at sowing only for each crop sown. Four 3.75 cm diameter cores were collected from selected treatments (2 for soil water, 2 for soil NO_3). The soil profile was sampled in 10 cm increments to a depth of 30 cm and thereafter in 15 cm increments to decomposing basalt (about 70 cm). Soil NO_3 samples were dried at <40°C before grinding (<2 mm), whereas soil water samples were dried at 105°C. Plant-available water content (PAWC) of the soil was determined by converting gravimetric soil water concentrations to volumetric by adjusting for the bulk density measured at the upper storage limit (D. Yule pers. comm.) using a lower storage limit for each soil depth sampled. Bulk density was measured mid-way through the trial by irrigating several ponded areas in both ZT and CT treatments, and then taking a 100 mm diameter core after the soil had freely drained (i.e. upper storage limit). Bulk density measurements from the ZT treatment were used in calculations involving the pasture treatments. Lower storage limits were determined using repeated values determined at grain maturity. Estimates of lower storage limit ignored soil in the surface 0–20 cm, which was generally affected by air-drying (soil evaporation deficit).

Crop sampling

Crop dry weight at anthesis and crop dry weight and grain yield at grain maturity were measured by sampling 2 m^2 for all treatments in 1991 and 2.16 m^2 in 1992. In 1996 and 1997, dry matter and grain yields of the sorghum crops were determined by cutting 1.5 m lengths of 2 rows of sorghum in each plot (1.88 m^2). After drying at 60°C, the grain was threshed from the heads, grain and plant material were weighed, ground (<2 mm sieve) and retained for chemical analysis.

Crop water use efficiency (CWUE) for grain production was calculated as follows:

$$\text{CWUE (kg grain/ha.mm of water)} = G/(W_P - W_M + R),$$

where G is grain yield (kg/ha), W_P and W_M are PAWC (mm) at planting and maturity, respectively, and R is the in-crop rainfall (1991 = 32; 1992 = 43; 1996 = 75; 1997 = 80 mm). Rain just before harvest in 1997 was excluded as it would not have contributed to plant growth.

Chemical analysis

Soil nitrate concentration was determined by automated colorimetric analysis (Best 1976) following extraction in 2 mol/L KCl at a soil : extractant ratio of 1 : 10 (Bremner 1965*a*). The quantity of mineral N (kg/ha) was established by adjusting for bulk density measured in March 1994. Wheat grain and plant material were dried (60°C), ground and analysed for total N and P after Kjeldahl digestion (Bremner 1965*b*). Grain protein was estimated by multiplying tissue N concentration by 5.7 (wheat) and 6.25 (sorghum). Soil organic C was measured using the Walkley-Black method adapted for spectrometric analysis (Sims and Haby 1971) and soil total N was determined by Kjeldahl digestion (Bremner 1965*b*), steam distillation and autotitration. Microbial biomass N and C were measured using the fumigation–incubation method with a k_c value of 0.41 and a k_n value of

Table 1. Crop and cultivar, and the rate and date of sowing

Cultivar	Rate of sowing	Date of sowing
	1991	
Wheat cv. Hartog	46 kg/ha[A]	27 May
Chickpea cv. Amethyst	350 000 seeds/ha[B]	27 May
	1992	
Wheat cv. Cunningham	60 kg/ha[A]	25 May
Chickpea cv. Amethyst	350 000 seeds/ha[B]	25 May
	1996	
Sorghum cv. Barrier	78 300 seeds/ha	20 January
Mungbean cv. Saturn	114 000 seeds/ha	20 January
	1997	
Sorghum cv. Barrier	53 000 seeds/ha	22 December 1996
Mungbean cv. Saturn	200 000 seeds/ha	22 December 1996

[A]Target population of 1 000 000 plants/ha. [B]Target population of 350 000 plants/ha.

0.5 (Jenkinson and Powlson 1976, Anderson and Domsch 1978, Jenkinson 1988). The unfumigated soil samples were used to determine aerobic mineralisable N (Dalal *et al.* 1994).

Statistical analysis

These data were generally analysed by analysis of variance. Crop yield parameters, N uptake and CWUE treatments were analysed as a factorial with various combinations of fertiliser–pulse rotation treatments and the 2 tillage regimes.

For soil parameters (including PAWC), the analyses also included the pasture treatments. These data were analysed using a nested factorial so as to extract information on the fertiliser–pulse rotation by tillage factorial. Also, where appropriate, orthogonal contrasts were used to compare legume (annual and perennial) with grasses (purple pigeon grass and grass–legume mix) and to compare within legumes and grasses. Soil total N, organic C, Colwell extractable P and DTPA extractable Zn were also analysed by analysis of variance to compare the 4 pasture treatments with the control in both CT and ZT.

Mineral N in the soil profile (0–60 cm) at planting in 1991, 1992 and 1995–98 was subjected to repeated measures analysis using restricted maximum likelihood to model the variance–covariance structure in the data. A power (distance based) model with the city-block metric and allowing for heterogeneity among variances was found to suitably model the covariance structure. It also accounted for irregularly spaced measurements.

Pairwise comparisons of means were performed using the protected l.s.d. procedure at $P = 0.05$. Distributional assumptions for all analyses were assessed by inspection of residual and normal probability plots. There was no indication that any variables violated variance and/or normality assumptions.

Results

Crop production

The trial period (January 1991–December 1997) was characterised by drought from 1993 to 1996. Grain yields of the 4 successfully harvested crops strongly reflected the pattern of rainfall within the crop rather than the total amount of rain occurring in either the fallow or during crop growth.

In 1991, the winter crops (wheat and chickpeas) were sown on a full profile of soil water and a single event in July provided enough soil water to produce yields (1.57 t/ha over all treatments) approaching the district average. In 1992, there was significantly less soil water at sowing compared with the previous year and the lack of effective rainfall (events >20 mm) during the crop resulted in grain yields (1.05 t/ha) that were well below the district average. The 1996 sorghum crop, despite being sown into a full profile of soil water, yielded slightly below the district average of 1.8 t/ha (J. Kuskie pers. comm.), reflecting the lack of effective rainfall during the early growth stages. Good in-crop rainfall and a full profile of soil water at sowing ensured that the 1997 sorghum (2.9 t/ha) crop was above the long-term average.

No statistically significant ($P>0.05$) interactions between tillage practice and fertiliser–pulse rotation were observed for dry matter, grain yield, N uptake and grain protein (%) in any of the 4 successful cropping years. ZT practices resulted in more dry matter at flowering in 1992 and 1996 (data not shown) and at maturity in 1992 (Table 2) than CT, with no differences between tillage practices in the other years. Under ZT, grain yield was greater in 2 years (by 35% in wheat in 1992 and by 24% in sorghum in 1996), N uptake by the crop was greater in every crop grown, and grain protein levels superior in both wheat crops (1991 and 1992), compared with crops grown with CT practices (Table 2). Tillage practice, however, did not significantly ($P>0.05$) influence harvest index in any crop, although harvest index tended ($P = 0.081$) to be greater under ZT than CT for the 1996 sorghum crop (data not shown).

There were significant ($P<0.05$) yield responses to fertilisers in wheat in 1991 and in sorghum in 1997 when both N and P were added (Fig. 2). However, there was no response when either P or N was added alone. Omitting Zn in the presence of N and P did not significantly ($P>0.05$) affect grain yield. The inclusion of a pulse in the rotation did not increase the grain yields of the following crop as much as adding N fertiliser. In 3 of the 4 crops harvested, grain protein content responded to applications of N, increasing with the level of N applied, regardless of whether P was added (Fig. 2). Including a pulse in the rotation before each cereal crop significantly ($P<0.05$) increased grain protein in 2 of 3 unfertilised crops.

Soil mineral nitrogen

Tillage practice did not affect the amount of mineral N (NO_3) in the soil at planting in any year (data not shown).

Table 2. Effect of tillage practice on total dry matter at maturity, grain yield, total nitrogen (N) uptake by the crop and grain protein for wheat in 1991 and 1992 and sorghum in 1996 and 1997

Tillage practice	1991	1992	1996	1997
	Total dry matter (kg/ha)			
Conventional	3512	2329	4421	6111
Zero	3601	3166	4884	6118
l.s.d. ($P = 0.05$)	267	426	566	321
Significance	n.s.	***	n.s.	n.s.
	Grain yield (kg/ha)			
Conventional	1542	892	1660	2921
Zero	1604	1204	2063	2949
l.s.d. ($P = 0.05$)	132	249	378	188
Significance	n.s.	*	*	n.s.
	Crop N uptake (kg N/ha)			
Conventional	33.0	24.6	59.9	77.9
Zero	37.3	34.5	68.4	84.3
l.s.d. ($P = 0.05$)	2.9	4.7	7.5	6.2
Significance	**	***	*	*
	Grain protein (%)			
Conventional	10.1	11.7	13.7	11.2
Zero	10.9	12.3	13.4	11.3
l.s.d. ($P = 0.05$)	0.3	0.4	0.4	0.4
Significance	***	**	n.s.	n.s.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$; n.s., not significant ($P>0.10$).

A significant ($P<0.001$) time by treatment (fertiliser–pulse) interaction was evident for mineral N. Table 3 presents the results for 4 fertiliser–pulse rotation treatments under CT and the legume and grass pastures. In 1991, there was no difference in mineral N among treatments while in all subsequent years there were differences, with $P_{12}N_{50}$

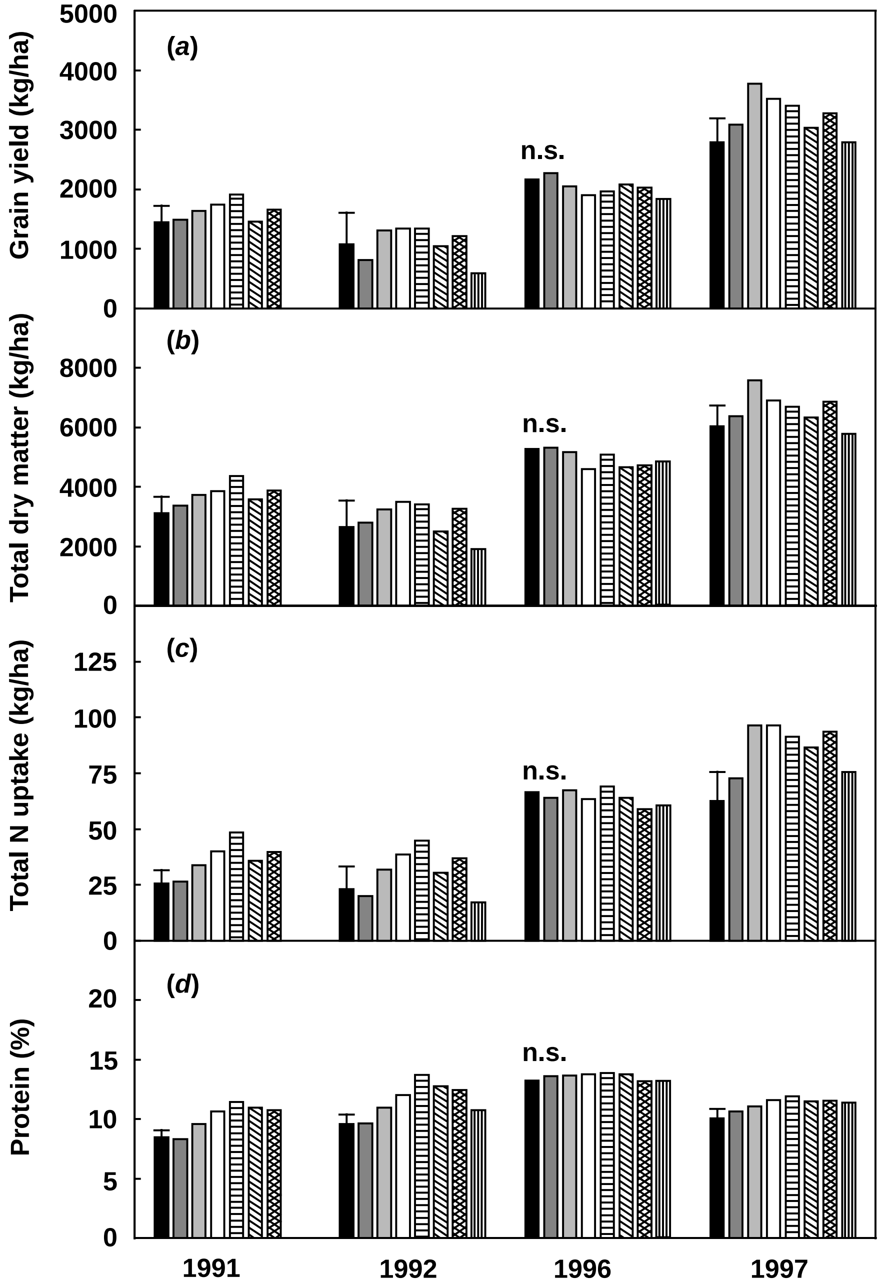

Figure 2. Effect of various fertiliser treatments and rotation with pulses on (*a*) grain yield, (*b*) total dry matter at maturity, (*c*) nitrogen (N) uptake by the crop (straw + grain) and (*d*) grain protein of wheat in 1991 and 1992 and sorghum in 1996 and 1997. The pulse–cereal treatment represents the cereal crop following a pulse crop in the previous year. Vertical lines represent the l.s.d. (P = 0.05) when a significant ($P<0.05$) treatment effect was observed within a year; n.s. denotes that the treatment effect was not significant. No data are presented for the pulse–cereal treatment in 1991 as the entire site was sown to wheat in 1990. The treatments were P_0N_0 (closed bars), $P_{12}N_0$ (heavily shaded bars), $P_{12}N_{25}$ (lightly shaded bars), $P_{12}N_{50}$ (open bars), $P_{12}N_{75}$ (horizontally striped bars), P_0N_{50} (hatched bars), –Zn (cross-hatched bars), pulse–cereal (vertically striped bars).

generally having the highest and the grass pasture the lowest mineral N concentration. Mineral N in all cropping treatments increased to a maximum of 112 kg N/ha following the 1993–1994 long fallow and the subsequent failed crop in 1995, but reduced to concentrations (<19 kg N/ha) similar to 1992 following the successful 1996 and 1997 crops. Between 1995 and 1997, mineral N concentration tended to be highest in the $P_{12}N_{50}$ and pulse–cereal rotation treatments. However, in 1998 mineral N in the perennial legume treatment had increased to concentrations similar to those in $P_{12}N_{50}$ and the pulse–cereal rotation, which were all significantly higher than in cropping treatments where no N fertiliser was applied. The purple pigeon grass treatment resulted in a rapid decrease in mineral N from 1991 to 1992, and the concentration remained very low (<10 kg N/ha) for the remainder of the study.

Soil water

Even when the profile was almost full and crops were successfully planted (1991, 1992, 1996 and 1997), PAWC across all treatments was low (<90 mm; Fig. 3). For all crops grown, water was low at anthesis, with PAWC averaging less than 25 mm (Fig. 3). However, in both sorghum crops (1996 and 1997) significant rainfall occurred between anthesis and grain maturity. Although the timing of these rainfall events had little impact on final yields, they resulted in a significant amount of water remaining in the profile at harvest (Fig. 3).

There was no significant (P>0.10) interaction between fertiliser application and tillage practice on PAWC at planting in any year from 1991 to 1998 (data not shown). Tillage practice affected PAWC at potential crop planting opportunities in only 2 years of the 8 measured where it was greater under CT than ZT by 24 mm in 1991 and 12 mm in 1998 (Fig. 4). Fertiliser–pulse rotation did not significantly (P>0.05) influence PAWC at planting in all 4 years where a successful crop was grown (Fig. 3). Also, PAWC at anthesis and grain maturity was not generally affected by tillage practice (data not shown) or fertiliser–pulse rotation (Fig. 3). The exceptions were in the 1997 sorghum crop when PAWC was 5 mm higher under CT than ZT at grain maturity and at anthesis in the 1997 sorghum crop when PAWC was lower where a pulse had been previously planted in 1996 than with sorghum.

Crop water use efficiency

The effect of tillage practice and fertiliser application–rotation with a pulse on CWUE for grain production was generally minimal. In 1992, CWUE was higher (P<0.01) under ZT than CT, and CWUE of wheat following chickpea was lower than that of wheat on wheat (data not shown). In 1997, the CWUE of sorghum was lower in ZT than in CT when N supply was poor (control and $P_{12}N_0$) but tended to be better in ZT than in CT when N nutrition was improved ($P_{12}N_{50}$ and following a pulse).

Soil chemical fertility properties

At the commencement of the trial in 1991, soil chemical fertility measurements were made on selected treatments to confirm the uniformity of the site. Both soil organic C (average of 0.71 ± 0.007% in 0–10 cm) and total N (0.080 ± 0.002% in 0–5 cm) were low.

Neither tillage practice nor fertiliser–pulse rotation had any significant (P>0.05) effect on the amount of soil organic C in the topsoil in any year (data not shown). For soil total N, tillage practice had an inconsistent effect across all sampling times. Fertiliser–pulse rotation did not affect soil total N except in 1996, when it increased with the amount of N applied (data not shown).

In contrast, pasture treatments generally had a significant positive effect on all fertility parameters measured. By the end of the trial period (1997), pastures, and in particular the grass–legume mixture, had increased potentially mineralisable N, microbial biomass N and C (Fig. 5), soil organic C (Fig. 6) and total N (Fig. 7) compared with the conventionally tilled cropping treatment. Although the

Table 3. Soil nitrate (kg N/ha) in the profile (down to 60 cm) at sowing between 1991 and 1998

The l.s.d. refers to comparisons among treatments within years while means within rows (i.e. within treatments) not followed by a common letter differ significantly (at P = 0.05) across time
CT, conventional tillage

Treatment	1991	1992	1995	1996	1997	1998
CT — control	31.5bc	25.4c	62.8a	82.0a	54.4ab	18.9c
CT — $P_{12}N_0$	—	17.7d	57.11ab	86.8a	41.1bc	18.5cd
CT — $P_{12}N_{50}$	—	39.0b	88.0a	111.6a	79.3a	45.1b
CT — pulse–cereal[A]	—	24.8c	67.3a	73.3a	97.2a	40.0b
Perennial legume	32.1c	16.5d	60.0ab	88.6a	3.1d	47.2bc
Purple pigeon grass	34.2a	5.1b	10.5ab	4.7ab	5.0b	2.3b
l.s.d. (P = 0.05)	7.1	7.1	34.3	43.6	28.9	17.9

[A]Means for the pulse–cereal and cereal–pulse treatments. The treatment the mean corresponds to varies depending on which treatment was sown to the cereal crop in that year.

increase in total N was most pronounced in the top 5 cm of soil, smaller but significant increases also occurred in the 5–10 and 10–20 cm layers. There was a strong trend for microbial biomass N and C and potentially mineralisable N to be greatest in the grass–legume mix.

At the start of the trial in 1991, the soil had low concentrations of plant-available P (average across the site of 7.2 mg/kg in the top 10 cm) and marginal levels of Zn (average of 0.37 mg/kg in the top 10 cm). P was strongly stratified in the upper part of the soil profile (average of 8.7 mg/kg at 0–5 cm, decreasing to 1.9 mg/kg at 10–20 cm). Five applications (in 1991, 1992, 1995, 1996 and 1996–97) of P and Zn fertiliser during the trial increased these levels, especially in the 0–5 cm layer (average P of 22.6 mg/kg and Zn of 1.03 mg/kg for the cropping treatments where P and Zn were applied) at the time of sowing of the 1997 crop. Tillage practice did not influence the concentration of plant-available P at sowing in 1997 but the concentration of Zn was greater in the ZT treatments than in the CT treatments.

Discussion

Zero tillage and stubble retention practices are viewed as an essential strategy for reducing soil erosion on the cracking clay soils of the northern grain belt of Australia (Freebairn

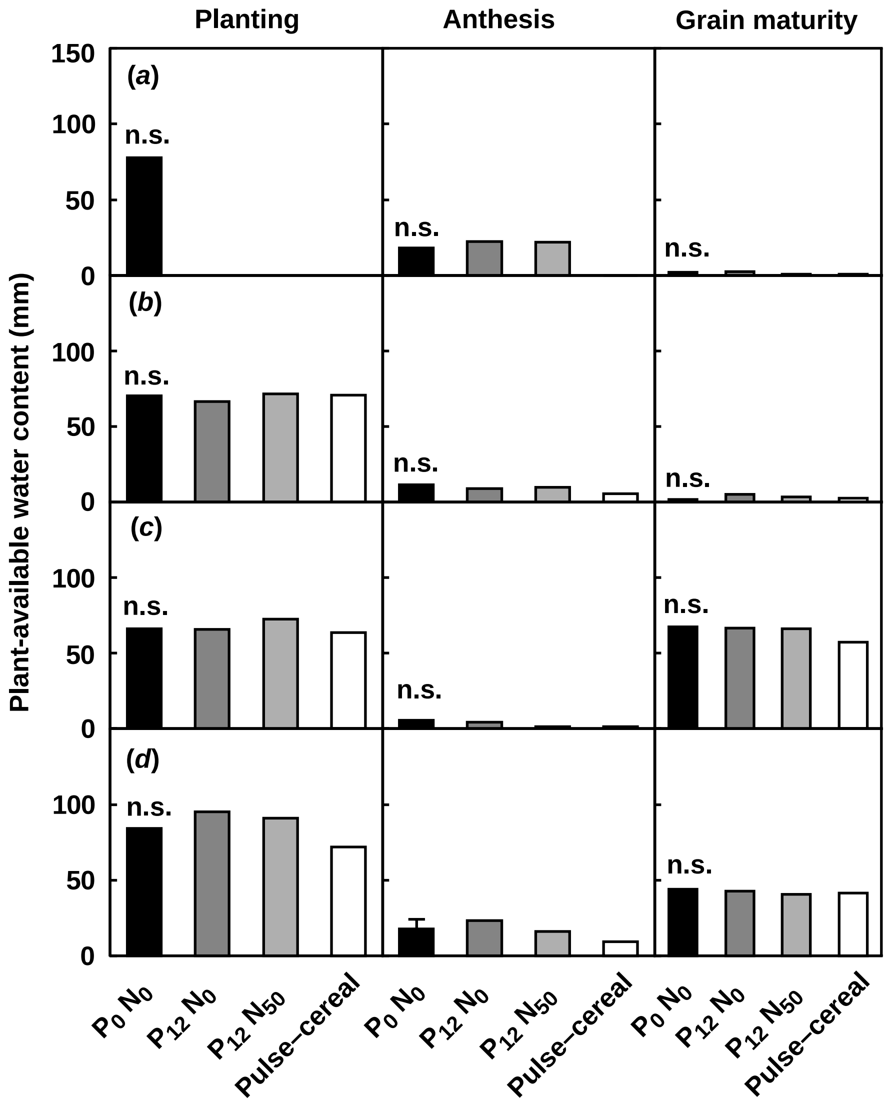

Figure 3. Plant-available water content (PAWC) of the soil to the depth of decomposing basalt at planting, anthesis and grain maturity for wheat in (*a*) 1991 and (*b*) 1992 and sorghum in (*c*) 1996 and (*d*) 1997 under different fertiliser (P_0N_0, $P_{12}N_0$, $P_{12}N_{50}$ and cereal–pulse rotation) treatments. The vertical line denotes the l.s.d. ($P = 0.05$). n.s. denotes non-significant differences among treatments ($P = 0.05$). No data were collected for the $P_{12}N_0$ and $P_{12}N_{50}$ at planting in 1991, nor for the pulse–cereal treatment as the entire site was sown to wheat in 1990.

and Wockner 1986; Carroll *et al.* 1997). In the current study, ZT provided no major benefits to soil water storage during the fallow (Fig. 4), confirming the findings of Carroll *et al.* (1997) for a similar soil type. This contrasts with other studies on cracking clay soils in the grain belt of northern Australia including northern New South Wales (Holland and Felton 1989), southern Queensland (Strong *et al.* 1996) and in the Dawson Callide region of central Queensland (Thomas *et al.* 1990*a*) where ZT practices improved soil water storage in the fallow, resulting in higher grain yields. In our study, there were long periods of drought interspersed by high-intensity rainstorms, but insufficient rainfall infiltrated in order to link the surface soil moisture with that in the subsoil, which remained moist below about 25 cm (zone below air-drying of surface soil). The most significant impact of ZT is through greater stubble loads remaining on the soil surface reducing runoff (and soil erosion) and resulting in increased opportunity for water infiltration (Carroll *et al.* 1997). However, when stubble loads are low, as occurred during the drought-induced long fallow of 1992–96, there was a consistent trend for soil water storage to be higher under CT. During the 1992–96 fallow period, there appeared to be some advantage in using cultivation to increase surface roughness and cover the large cracks that developed in these cracking clays, as reflected in the trend for greater PAWC under CT from 1993 to 1995. Similarly, on the 2 occasions when there was a significant effect of tillage practice on PAWC at sowing (Fig. 4; 1991 and 1998), CT was greater than ZT. In both of these cases, high-intensity rain (about 390 mm in 1991 and 344 mm in 1998) had fallen before the imposition of fallow tillage treatments when there was comparatively large amounts of standing stubble present (from wheat in 1990 and sorghum in 1997). However, this still does not explain why PAWC was higher in the CT than in the ZT treatments.

Despite having similar, or significantly less soil water at sowing, ZT increased grain yield for 2 of 4 successfully grown crops (1992 and 1996), with no detrimental effects on the other 2 crops (1991 and 1997). Thomas *et al.* (1990*b*) with sorghum and Lawrence *et al.* (1994) with wheat noted higher grain yields under ZT than CT, despite similar PAWC at sowing. In the current study, very dry conditions were experienced between sowing and anthesis for both of these crops (Fig. 1), although significant rain fell after anthesis during the 1996 sorghum crop. Although tillage practice had no effect on harvest index of wheat in 1992, dry matter at both anthesis and grain maturity was greater under ZT than CT. Lawrence *et al.* (1994) attributed the consistently higher yield of wheat under ZT than under CT on a Sodosol in central Queensland to increased CWUE in the post-anthesis phase. They attributed the higher CWUE to better root growth, possibly reflecting the exploitation of root channels under ZT crops formed by soil fauna (Robertson 1990). In a temperate crop such as wheat growing in subtropical sections of the northern Australian grain belt, where the time between anthesis and grain maturity is less than 2 months,

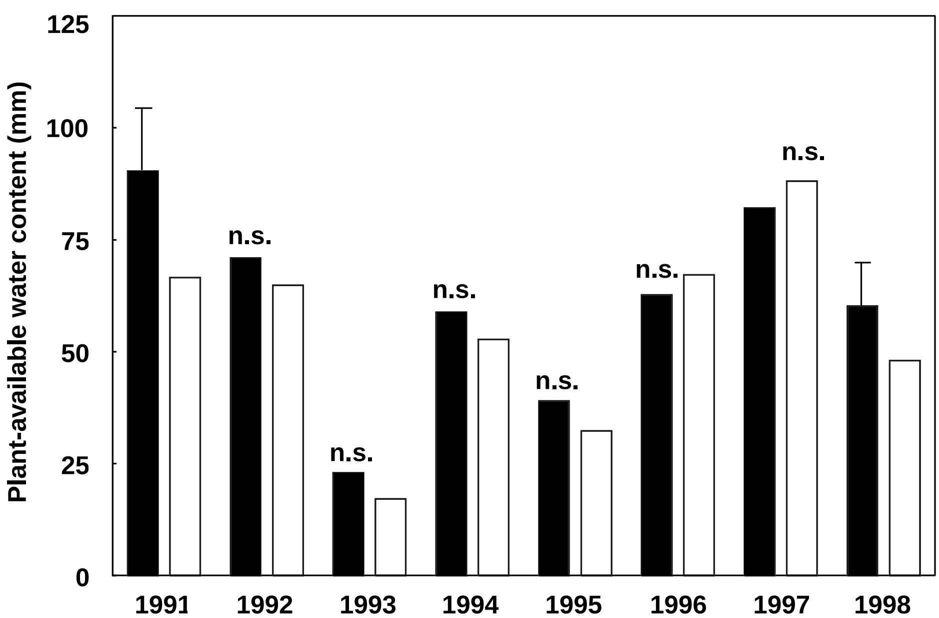

Figure 4. Effect of tillage practice [conventional tillage (CT, closed bars), zero tillage (ZT, open bars)] on the plant-available water content (PAWC) of the soil at planting between May 1991 and January 1998. Crops were sown in 1991, 1992, 1995 (failed), 1996 and 1997, while those in 1993 and 1994 represent samples at key planting windows. The vertical line above a group of bars indicates the l.s.d. when differences were significant (P<0.05); n.s. denotes non-significant differences between treatments.

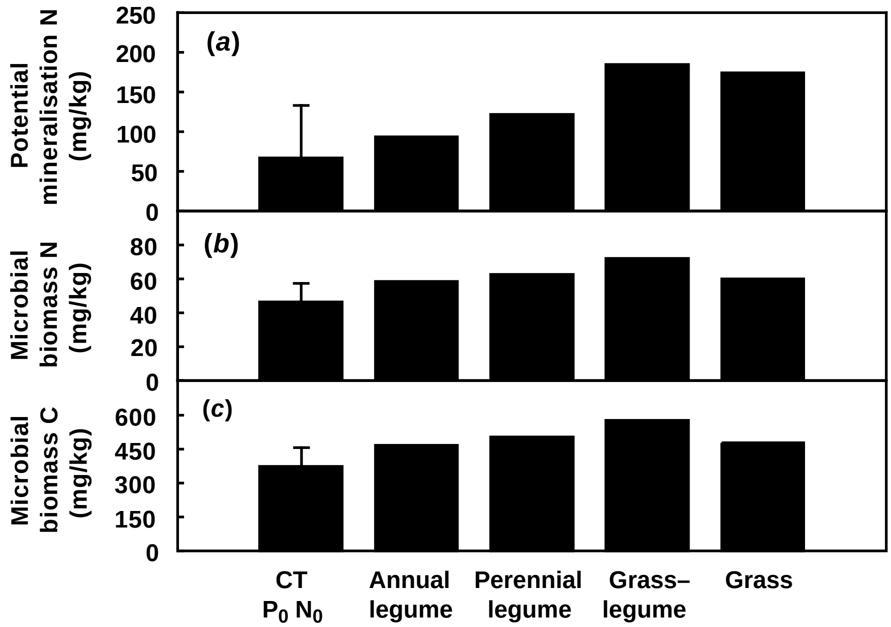

Figure 5. (*a*) Potentially mineralisable nitrogen (N, mg/kg), (*b*) microbial biomass carbon (C, mg/kg) and (*c*) microbial biomass N (mg/kg) in continuous cereal cropping under conventional tillage without fertiliser (CT, P_0N_0), annual pasture legume (*Vigna trilobata*), perennial legume (siratro), grass–legume mixture and grass (purple pigeon grass). Cropping sequence was wheat in 1991 and 1992 and sorghum in 1996 and 1997. The vertical line denotes the l.s.d. ($P = 0.05$).

any increase in dry matter at flowering would be expected to translate to higher grain yield, especially in the absence of subsequent rain. The greater yield of ZT sorghum in 1996 was associated with significantly more dry matter at flowering (data not shown). Although there was no effect of tillage practice on total dry matter at maturity, harvest index tended to be greater under ZT and this may explain the higher grain yields. Consequently, in seasons where crops are able to translate higher dry matter to grain yields, such as occurs when there is adequate post-anthesis rainfall, ZT will offer potentially superior grain yields to CT.

Fertiliser response

Declining soil fertility, especially N, resulting from continuous cropping with little use of N fertiliser or legumes, is a major threat to high grain yields and quality throughout the northern cereal belt of Australia (Dalal and Mayer 1986). Adding N fertiliser produced significant increases in grain yields in 2 of the 4 crops harvested and a trend to higher yields in a third, provided P was also applied. Responses to N were principally influenced by 2 factors, soil mineral N at sowing and in-crop rainfall. The only crop where fertiliser had no effect on grain yields was sorghum in 1996, where soil nitrate had risen to high concentrations (Table 3) following the drought-induced long fallow between 1992 and 1996. This effect was amplified by the lack of effective in-crop rainfall, confirming the general conclusion that timing, rather than the total amount of rainfall, is critical for sorghum yields and responsiveness to N in this environment (Armstrong *et al.* 1999*c*). When soil nitrate concentrations were lower, such as in 1991 and 1997, there were yield responses to applied N. When seasonal conditions permit

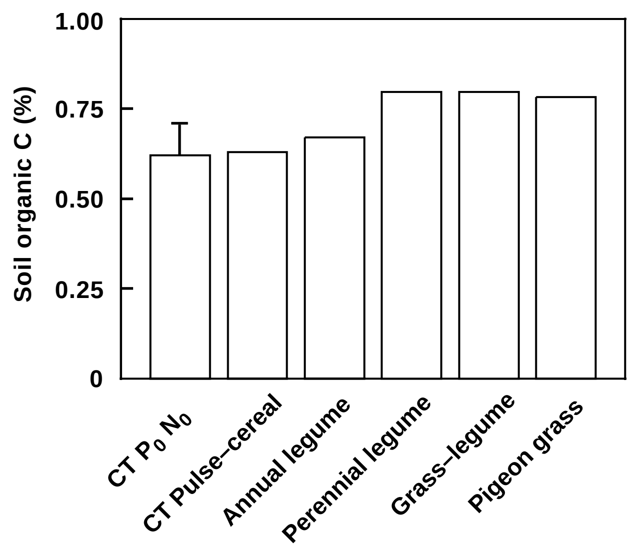

Figure 6. Soil organic carbon (C, 0–10 cm) in December 1997 in continuous cereal cropping under conventional tillage (CT) without fertiliser, pulse–cereal rotation under conventional tillage, annual pasture legume (*Vigna*), perennial legume (siratro), grass–legume mixture and grass (purple pigeon grass). The vertical line denotes the l.s.d. ($P = 0.05$).

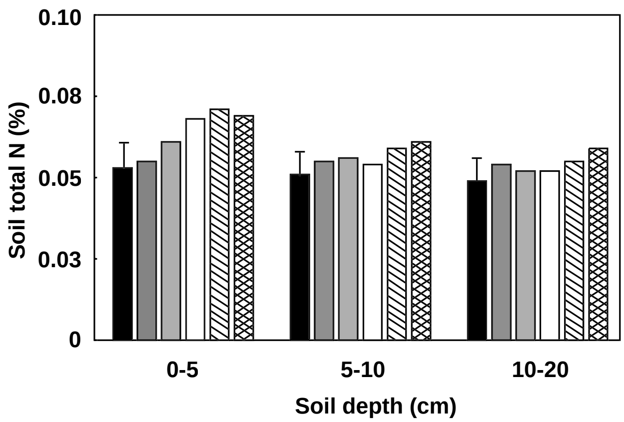

Figure 7. Soil total nitrogen (N, 0–5, 5–10 and 10–20 cm) in 1997 in continuous cereal cropping under conventional tillage without fertiliser (closed bars), pulse–cereal rotation under conventional tillage (heavily shaded bars), annual pasture legume (*Vigna*, lightly shaded bars), perennial legume (siratro, open bars), grass–legume mixture (hatched bars) and grass (purple pigeon grass, cross-hatched bars). The vertical lines denote the l.s.d. (P = 0.05) for comparison between treatments within a soil depth.

regular cropping (1/year), soil mineral N levels would remain low on these shallow open downs soils and it would be expected that responses to N fertiliser would occur regularly in this region.

Zero tillage practices are generally associated with lower rates of N supply to crops (Robson and Taylor 1987). In the current study, tillage practice did not significantly affect the amount of soil mineral N at the time of sowing of any crop or soil total N after 7 years. Previous studies in this region have also found that tillage practice had minimal impact on either soil total N (Standley *et al.* 1990) or soil mineral N availability (Armstrong *et al.* 1996). However, despite the lack of effect on mineral N availability, crop N uptake (grain and stubble) was consistently greater under ZT. This suggests that either N mineralisation rates during crop growth were greater in ZT treatments or that N utilisation by the crop was more efficient. In the longer term, soil N supply would decrease if this trend continued in ZT plots, although this effect would be countered to some degree by the reduced erosion rates of nutrient-enriched topsoil associated with conservation tillage practices (White 1986). The cause of the higher rates of N uptake in ZT treatments is unclear. Increased biological activity, especially that of earthworms, is frequently associated with reduced tillage (Robertson *et al.* 1994; Wilson-Rummenie *et al.* 1999), and this may have enhanced mineralisation rates.

The effect of tillage practice on responsiveness to fertiliser has been inconsistent in central Queensland. Radford *et al.* (1995) found that the greater yield potential of wheat under ZT and reduced tillage practices resulting from improved soil water storage could only be achieved if adequate fertiliser (N, S and Zn) was supplied, whereas both Lawrence *et al.* (1994) and Armstrong *et al.* (1996) found that tillage practice had little effect on response to fertiliser. In this study, tillage practice had no effect on grain yield response to N fertiliser. This occurred despite the general low fertility of the soil used resulting from a long history (>40 years) of continuous cropping. The generally dry conditions experienced, especially by the 1992 wheat crop, probably overrode any potential for this interaction. However, grain protein was improved by ZT in both wheat crops and by application of N fertiliser in all crops except the 1996 sorghum that immediately followed the long fallow. W. Strong (pers. comm.) suggested that grain protein concentrations of less than 11.5% for wheat and 9.5% for sorghum are indicative of N deficiency and this is reflected in the grain protein concentrations of 8.5 and 9.6% for the 2 unfertilised wheat crops in 1991 and 1992, respectively, and 10.0% for the unfertilised sorghum crop in 1997. In contrast, grain protein of unfertilised sorghum in 1996 was 13.3% and neither fertiliser application nor tillage practice had any effect. Rotating with a pulse only increased grain protein in 1 of 3 crops (1997).

Chemical indices of soil fertility

$KMnO_4$-oxidisable soil organic C is regarded as a key indicator of soil fertility (Hamblin 1992), especially in areas such as central Queensland where there is no long history of stubble burning and therefore little unreactive charcoal present (Skjemstad *et al.* 1996). Pulses, fertilisers and ZT practices provided little benefit to either soil organic C or total N, despite producing important short-term benefits such as increased grain yields and protein in crops. There has been a slow but growing realisation that soil fertility decline is having a negative impact on both grain yields and quality (protein) in this region. Drought-induced long fallows occur frequently in this region and the build up of mineral N during these periods provides sufficient N to supply several subsequent crops. However, a regular cycle of fallow–cropping will inevitably lead to a longer-term decline in soil fertility, unless suitable fertiliser or legume N is added to the system. Farmers are reluctant to use N fertilisers in this region because unreliable rainfall reduces the probability of obtaining an economic response for any one crop (Armstrong *et al.* 1996). However, as the 1996 crop indicated, high concentrations of mineral N at sowing will also reduce the chances of a yield response to N fertilisers. Better targeting of N fertiliser applications may be achieved using deep-soil N testing, especially after a long fallow. There has been a long history of continuous cropping with little input of N (via fertilisers or via N_2 fixation) at this site. The significant response to N fertiliser application of the 1997 crop, only the second after a 4-year-long fallow, indicates that, similar to large sections of southern Queensland (Dalal and Mayer 1986), soil fertility on these open downs soils has reached a point where most cereal crops will respond economically to low rates of N fertiliser. The likelihood of this response will increase as cropping frequency increases, especially at a frequency of 1 crop per year.

Pasture leys were required to improve the long-term soil fertility, as indicated by changes in both moderately labile soil fertility parameters such as biomass N and C and the more stable soil fertility parameters of organic C and total N. Pasture treatments resulted in no significant change in soil organic C from the time when the trial commenced in 1991 until the sampling was conducted in 1996, compared with the cropping treatments. However, the pasture treatments established in early 1995, especially the grass–legume mix, which subsequently experienced comparatively good seasonal conditions compared with the start of the trial, had a marked effect on soil fertility parameters when sampled in late 1997. This contrasts with the performance of the lucerne sown in 1991, which had little effect on either soil total N or organic matter before the re-sowing of these plots with siratro, reflecting the extremely poor dry matter production of lucerne. This confirms other studies (Armstrong *et al.* 1999*a*, 1999*b*), suggesting that this temperate perennial legume is poorly adapted to dryland conditions on the shallow cracking clays of central Queensland and has little potential to improve soil fertility. This contrasts with lucerne's performance in southern regions of the northern grains belt (Dalal *et al.* 1994; Holford and Crocker 1997). Similarly to the annual pulses, chickpea and mungbean, the annual pasture legume Vigna produced high concentrations of mineral N but had little effect on increasing other soil fertility parameters, such as microbial biomass N and C and organic C. The greatest improvements in the long-term soil fertility parameters occurred in the perennial pastures. This rapid increase in organic C over 3 years was partly due to the system of retaining cut plant residues on the plots as well as the ability of the perennial species to respond to soil moisture availability over the entire year. Surprisingly, the pure grass pasture (purple pigeon grass) produced significant increases in soil total N as well as organic C. The increase in soil total N was unexpected as no N source, such as fertiliser, was added to these plots. Although soil mineral N concentrations, which were measured at the time of sowing of the crops, were consistently low throughout the trial period, potentially mineralisable N and microbial biomass N were relatively high compared with cropping treatments. One possible explanation is that the purple pigeon grass could have increased soil total N in the topsoil by severely depleting this element in the subsoil and then maintained an intrinsically tight recycling of N via biomass recycling in the topsoil. Alternatively, as there was always a vegetation cover on these plots, N-enriched soil may have been deposited onto these plots from adjacent plots during erosion events.

Conclusions

Grain growers in central Queensland are strongly encouraged to adopt ZT practices due to the beneficial environmental impact it has on reducing soil erosion. Our study demonstrated that ZT may also produce small economic benefits. Although ZT generally had no beneficial effect on soil water or mineral nitrogen in this study, it produced higher grain yields in 2 of 4 crops. The higher yields of ZT crops appeared due to other beneficial effects, such as improved soil physical conditions. Importantly, ZT practices facilitate the adoption of opportunity cropping, which increases the number of planting opportunities in an environment characterised by low and unreliable rainfall.

Soil mineral N concentration is generally low in the Central Highlands, reflecting long-term exploitation as a result of continuous cereal cropping with minimal replacement of exported nutrients, but this can be obscured by drought-induced long fallows when moderate to high concentration of mineral N can (temporarily) occur. For the relative prices of N fertilisers and returns from cereal crops applicable during the study period, N application was not economically feasible, especially on these shallow soils where the potential to store large quantities of soil water is limited. Hence, there is need for alternative strategies of maintaining soil N, such as the use of pasture–legume leys, although this strategy is not appropriate for all grain growers in the Central Highlands. The use of annual legumes, including the pulses, mungbeans or chickpeas, or annual pasture such as Vigna can temporarily improve soil N status, and thus grain yields and protein of subsequent cereal crops, but will have minimal long-term beneficial impact on soil fertility. Maximum long-term benefits to soil fertility require the use of perennial legume–grass mixes. As well as improving soil chemical fertility, pastures also provide a valuable resource in mixed enterprises when drought prevents cropping. Drought-induced long fallows can result in significant accumulation of soil mineral N, which can supply the N requirements of several subsequent crops. So, in addition to the economic hardships created, drought also tends to (temporarily) mask the progressive decline occurring in soil fertility levels in this region, creating further complacency by farmers about this issue.

Acknowledgments

The project was jointly funded by the Queensland Department of Natural Resources and the Grains Research and Development Corporation (Project DAQ65). Assistance with sampling and processing of samples was provided by B. Kuskopf, K. McCosker, K. Rutherford and C. Dixon. J. Ladewig (QDPI, Emerald) provided invaluable technical advice throughout the trial. Dr Ram Dalal (QDPI) undertook the soil biomass analysis. This project would not have been possible without the invaluable assistance of Ian Gardner and family on whose property, 'Enderly', the trial was conducted. We pay special thanks to Mr and Mrs Ned and Mabel Morgan, 'Riversdale', Gindie, who provided us with constant support in the form of advice on rainfall events, locust infestation etc. at the experimental site.

References

Anderson JPE, Domsch KH (1978) Mineralisation of bacteria and fungi in chloroform-fumigated soils. *Soil Biology and Biochemistry* **10**, 207–213.

Armstrong RD, Halpin NV, McCosker K, Standley J, Lisle AT (1996) Applying nitrogen to grain sorghum in central Queensland: residual value and effect of fallowing and tillage practice. *Australian Journal of Agricultural Research* **47**, 81–95.

Armstrong RD, Kuskopf BJ, Millar G, Whitbread AM, Standley J (1999*a*) Changes in soil chemical and physical properties following legumes and opportunity cropping on a cracking clay soil. *Australian Journal of Experimental Agriculture* **39**, 445–456.

Armstrong RD, McCosker K, Johnson SB, Walsh KB, Millar G, Kuskopf BJ, Standley J, Probert ME (1999*b*) Legumes and opportunity cropping systems in central Queensland. 1. Legume growth, nitrogen fixation and water use. *Australian Journal of Agricultural Research* **50**, 909–924.

Armstrong RD, McCosker K, Millar G, Kuskopf BJ, Johnson SB, Walsh KB, Probert ME, Standley J (1999*c*) Legumes and opportunity cropping systems in central Queensland. 2. Effects of legumes on following crops. *Australian Journal of Agricultural Research* **50**, 925–936.

Best EK (1976) An automated method for determining nitrate nitrogen in soil extracts. *Queensland Journal of Agriculture and Animal Sciences* **33**, 161–166.

Bremner JM (1965*a*) Inorganic forms of nitrogen. In 'Methods of soil analysis part 2'. (Ed. CA Black) pp. 1149–237 (American Society of Agronomy: Madison, WI)

Bremner JM (1965*b*) Total nitrogen. In. 'Methods of soil analysis part 2'. (Ed. CA Black) pp. 1149–78. (American Society of Agronomy: Madison, WI)

Carroll C, Halpin M, Burger P, Bell K, Sallaway MM, Yule DF (1997) The effect of crop type, crop rotation, and tillage practice on runoff and soil loss on a vertisol in central Queensland. *Australian Journal of Soil Research* **35**, 925–939.

Dalal RC, Mayer RJ (1986) Long-term trends in soil fertility of soils under continuous cultivation and cereal cropping in southern Queensland. I. Overall changes in soil properties and trends in winter cereal yields. *Australian Journal of Soil Research* **24**, 265–279.

Dalal RC, Strong WM, Weston EJ, Cahill MJ, Cooper JE, Lehane KJ, King AJ, Gaffney J (1994) Evaluation of forage and grain legumes, no-till and fertiliser to restore fertility degraded soils. In 'Proceedings of the 15th international congress. Acapulco, Mexico'. *Soil Science* **5A**, 62–74.

Freebairn DM, Wockner GH (1986) A study of soil erosion on vertisols of the eastern Darling Downs, Queensland. 1. Effect of surface conditions on soil movement within contour bay catchments. *Australian Journal of Soil Research* **24**, 135–159.

Garside AL, Agnew J Chamberlain HJ, Huf S, Turnour J (1992) Yield and protein contents of grain sorghum crops in central Queensland, 1990/91 season — results and implications from a survey of commercial crops. In 'Proceedings 2nd Australian sorghum conference, Gatton'. (Eds MA Foale, RG Henzell, PN Vance). *Australian Institute of Agricultural Science Occasional Publication* **68**, 311–315.

Hamblin A (1992) 'Environmental indicators for sustainable agriculture.' Bureau of Rural Resources, Department of Primary Industries and Energy, Canberra.

Holford ICR, Crocker GJ (1997) A comparison of chickpeas and pasture legumes for sustaining yields and nitrogen status of subsequent wheat. *Australian Journal of Agricultural Research* **48**, 305–315.

Holland JF, Felton WL (1989) Effect of tillage practice on grain sorghum production in northern New South wales. *Australian Journal of Experimental Agriculture* **29**, 843–848.

Isbell RF (1996) 'Australian soil classification.' (CSIRO Publishing: Collingwood, Vic.)

Jenkinson DS (1988) Determination of microbial biomass carbon and nitrogen in soil. In 'Advances in nitrogen cycling in agricultural eco-systems'. (Ed. JR Wilson) pp. 368–386. (CAB International: Wallingford, UK)

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

Lawrence PA, Radford BJ, Thomas GA, Sinclair DP, Key AJ (1994) Effect of tillage practices on wheat performance in a semi-arid environment. *Soil and Tillage Research* **28**, 347–364.

Radford BJ, Key AJ, Robertson LN, Thomas GA (1995) Conservation tillage increases soil water storage, soil animal populations, grain yield, and response to fertiliser in the semi-arid tropics. *Australian Journal of Experimental Agriculture* **35**, 223–332.

Robertson LN (1990) Interactions between agriculture and animals in north Queensland. In 'Agriculture and the ecosystems in North Queensland'. (Eds KL Norman, AL Garside). *Australian Institute Agricultural Science Occasional Publication* **51**, 56–64.

Robertson LN, Kettle BA, Simpson GB (1994) The influence of tillage practices on soil macrofauna in a semi-arid agroecosystem in northeastern Australia. *Agriculture*, *Ecosystems and Environment* **48**, 149–156.

Robson AD, Taylor AC (1987) The effect of tillage on the chemical fertility of soil. In 'Tillage: new directions in Australian agriculture'. (Eds PS Cornish, JE Pratley) pp. 284–307. (Inkata Press: Melbourne)

Sims JR, Haby VA (1971) Simplified colorimetric determination of soil organic matter. *Soil Science* **112**, 137–141.

Skjemstad JO, Clarke P, Taylor JA, Oades JM, McClure SG (1996) The chemistry and nature of protected carbon in soil. *Australian Journal of Soil Research* **34**, 251–272.

Standley J, Hunter HM, Thomas GA, Blight GW, Webb AA (1990) Tillage and crop residue management affect Vertisol properties and grain sorghum growth over seven years in the semi-arid tropics. 2. Changes in soil properties. *Soil and Tillage Research* **18**, 367–388.

Strong WM, Dalal RC, Cahill MJ, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1996) Sustaining productivity of a vertisol at Warra, Queensland, with fertilisers, no tillage or legumes. 3. Effects of nitrate accumulated in fertilised soil on crop response and profitability. *Australian Journal of Experimental Agriculture* **36**, 675–682.

Thomas GA, Standley J, Webb AA, Blight GW, Hunter HM (1990*a*) Tillage and crop residue management affect Vertisol properties and grain sorghum growth over seven years in the semi-arid sub-tropics. 1. Crop reside and soil water during fallow periods. *Soil and Tillage Research* **17**, 181–197.

Thomas GA, Standley J, Hunter HM, Webb AA, Blight GW (1990*b*) Tillage and crop residue management affect Vertisol properties and grain sorghum growth over seven years in the semi-arid sub-tropics. 3. Crop growth, water use and nutrient balance. *Soil and Tillage Research* **18**, 389–407.

White PJ (1986) A review of soil erosion and agricultural productivity with particular reference to grain crop production in Queensland. *Journal of the Australian Institute of Agricultural Science* **52**, 12–22.

Wilson-Rummenie AC, Radford B, Robertson LN, Simpson GB, Bell KL (1999) Reduced tillage increases population density of soil macrofauna in a semi-arid environment in central Queensland. *Environmental Entomology* **28**, 163–172.

Received 1 November 2001, accepted 4 July 2002