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Changes in soil chemical and physical properties following legumes and opportunity cropping on a cracking clay soil

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Summary. Incorporating legumes into the cropping system has been shown to significantly improve the nitrogen nutrition of cereal crops in Central Queensland. However, little is known about the effect of these legumes on the chemical and physical properties of soil. We examined changes in soil chemical (total nitrogen, organic carbon and pH) and physical (bulk density, cone penetrometer resistance and saturated hydraulic conductivity) properties following either continuous cropping (sorghum or mungbean) or pasture legumes (siratro, lucerne, lablab and desmanthus) over 4 years. Soil carbon was also fractionated using a $KMnO_4$ oxidation procedure which classifies the soil carbon into either labile or non-labile pools.

All pasture legumes except desmanthus increased soil total nitrogen in the topsoil (0–10 cm) after only 2 years compared with sorghum. Total nitrogen in the soil did not significantly change under mungbean. Soil organic carbon progressively increased under siratro, desmanthus and sorghum but remained unchanged under the other legumes. Before the experiment, the percentage of total soil carbon classified as labile (oxidised by 333 mmol $KMnO_4$/L) ranged from 14 to 17%. The amount of labile carbon increased by 17% after 3 years of siratro, remained unchanged under desmanthus and sorghum, and decreased under the annual legumes and lucerne. Non-labile carbon remained either unchanged or increased under all legumes, whereas it tended to decrease after 3 consecutive sorghum crops. Soil pH was generally highest under sorghum and lowest under lablab. Soil after sorghum had higher bulk density and penetrometer resistance compared with the effect of legumes but these differences were comparatively small. Saturated hydraulic conductivity of the soil was much higher on the soil surface than at 10 cm. On the surface, soil hydraulic conductivity (saturated) values were generally lower following siratro and higher after sorghum than the other species. At 10 cm depth, soil hydraulic conductivity (saturated) was generally lower in sorghum and, to a lesser extent, in mungbean plots reflecting the significantly lower density of macropores under these crops.

It was concluded that although all legumes generally enhanced the chemical and physical properties of the cracking clay, perennial legumes such as siratro would have a greater beneficial effect in the longer term than annual legumes.

Additional keywords: ley legumes, pulse, soil fertility, organic matter, carbon fractionation, nitrogen.

Introduction

The maintenance of the chemical, biological and physical fertility of soil depends mainly on the level of soil organic carbon (C) (Heenan *et al*. 1995). The soil organic C of cracking clays used for grain production in northern Australia has declined significantly, mainly as a result of continuous cereal cropping with little use of fertilisers or legumes (Dalal and Mayer 1986). This decline in organic C has coincided with a reduced supply of soil nitrogen (N) to crops, resulting in decreased grain yields and protein (Dalal *et al*. 1991). Furthermore, reduced levels of soil organic C have sometimes been accompanied by soil structural degradation, such as increases in bulk density (Dalal and Mayer 1986).

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The decline in soil fertility has been particularly marked in Central Queensland, where more than half a million hectares of cracking clays are used for dryland cropping. A recent paired paddock survey (G. Millar and R. D. Armstrong unpublished data) found that soil total N and organic C had declined by up to 40% in paddocks used for cropping compared with adjacent paddocks left in either a virgin state or used for pastures. Traditionally, legumes have been little used in the cropping system due to a lack of suitable species adapted to this environment (Chapman *et al*. 1996). However, Armstrong *et al*. (1997) found that a range of legumes (both pulse and pasture) could produce significant amounts of dry matter and N through N fixation in this environment. Increases in soil concentrations of mineral N following these legumes markedly improved grain yields and protein concentrations of subsequent cereal crops (Armstrong *et al.* 1999*b*).

Assessments of the economic benefit of including legumes in the cropping system must account for longer-term changes in soil fertility as well as the immediate effect on the following crop. Increases in the amount of N and organic matter in the soil will be just as important to long-term sustainable agricultural production as the temporary increases in soil mineral N pools.

Central Queensland is characterised by low and unreliable rainfall, although high intensity rainfall can often result in severe soil erosion (Carroll *et al.* 1997). The cracking clays used for cropping in the region are inherently of high structural durability. Consequently, small differences in the physical condition of the soil, resulting from changes in organic matter, could have significant effects on rainfall runoff–infiltration and thus storage of soil moisture for crop production. Pastures can generally improve aggregate stability, bulk density and infiltration (Clarke *et al*. 1967; Bridge *et al*. 1983; Bell *et al*. 1997). Connolly *et al.* (1998), for example, found that pasture leys could improve hydraulic conductivity of the surface seal, which subsequent computer simulations suggested would result in significant decreases in runoff for a range of soils used for cropping in south-eastern Queensland. However, the pasture leys in the study of Connolly *et al.* (1998) were a mixture of improved and native grasses. As grasses appear more beneficial to soil structure than legumes (Clarke *et al.* 1967), it is difficult to ascertain what effect pure legume stands, whose primary purpose is to increase soil N fertility, may have on soil physical properties.

This paper reports a study that compares changes in selected chemical and physical properties of a cracking clay soil in Central Queensland that had been either continuously cropped with sorghum, a pulse (mungbean), or sown with several different ley legumes, comprising both annual and perennial species over 4 years.

Materials and methods

Details relating to the experiment have been described elsewhere (Armstrong *et al.* 1999*a*). Specific points relevant to this study are presented below.

Site characteristics

The experiment was conducted on a Halpic, self-mulching, black Vertosol (Isbell 1996) at the Queensland Department of Primary Industries Emerald Research Station in Central Queensland (148°09'E, 23°29'S, alt. 190 m). This soil was typical of many on the Central Highlands, having been continuously cropped for at least 30 years. Before the experiment the site supported an irrigated wheat crop which was harvested in October 1993. Average annual rainfall at the site is 639 mm, of which 57% falls between December and March. Although annual rainfall received during the experiment varied from 541 mm (1995) to 806 mm (1996), these totals often comprised 1 or 2 large events (e.g. >350 mm over 6 days in March 1994) followed by several months with little or no rainfall. Actual rainfall received during the experiment is presented in Armstrong *et al*. (1999*a*).

Experimental design

The field experiment was a randomised complete block design replicated 3 times. Six treatments, comprising 2 grain crops and 4 pasture ley legumes were planted: (i) continuous cropping with grain sorghum, (ii) continuous cropping with a pulse (mungbean), (iii) siratro (*Macroptilium atropurpureum*, a summer-growing perennial), (iv) lucerne (*Medicago sativa*, a winter perennial), (v) lablab (*Lablab purpureus*, a summer annual forage crop), and (vi) desmanthus (*Desmanthus virgatus*, a summer perennial). Mungbeans were planted on a continuous basis rather than the more commonly (commercially) used pulse–cereal rotation as this provided a balanced design with the continuous sorghum and legume treatments (see Armstrong *et al*. 1999*a*). Each plot consisted of five 1.8 m planter widths, except for continuous sorghum which had 6 planter widths. Each block was 91 m long. Data reported in this paper were collected from a 26 m length of each block near the northern (down hill) end.

Crop and pasture management

All summer-growing legumes and sorghum were sown on 23 January 1994, except desmanthus which had been sown dry the previous month. The entire experiment (except for desmanthus plots) was bedded up and flood irrigation (which added about 62 mm of water) started on 14 January 1994 to enable the experiment to commence. Because the desmanthus seed was located in the top 5 mm of soil (a short coleoptile prevents germination if seed is placed deeper into soil), it was decided to irrigate this treatment with trickle tape to ensure that the surface remained wet for several days. Following heavy rain (>350 mm over 6 days), lucerne was sown on 17 March 1994. Due to continuing drought, the entire site was again flood irrigated to permit planting of annual crops on 1 February 1995. Significant rain fell soon after both the 1994 and 1995 irrigation events. No further irrigation was applied during the experiment until late January 1997, when 35 mm was applied as spray irrigation across the entire experiment to permit grain fill of the sorghum crop. In April 1997 the entire site was flood irrigated to ensure even soil water content across all treatments before the final soil sampling.

All legume treatments were hand-weeded regularly in an attempt to maintain them as pure stands. This ensured good weed control, especially for the annuals, in the first 2 years of the experiment — except in desmanthus plots where weed infestation was persistent (particularly native jute *Corchorus trilocularis*). Grass weeds, particularly summer grass (*Brachiaria eruciformis*), began to invade the perennial legume plots in 1995 but a combination of hand weeding and application of Verdict 104 (haloxyfop-R), resulted in good control. Despite regular hand weeding, it was also necessary to spot spray broadleaf weeds with glyphosate, although this was less successful. Regrowth in sorghum plots was controlled by a combination of herbicide use and mechanical cultivation using chisel plough and harrows. In the annual legume plots (lablab and mungbean), herbicides resulted in good weed and regrowth control and no mechanical cultivation was required.

Pasture legume plots were not grazed but were slashed with a sickle-bar mower in 1994 and, in later years, with a rotary mulcher at about 7.5 cm height when it was judged necessary for a particular treatment. Cut plant material was left on the plots as it was felt that it was more appropriate to simulate a green manure system than a hay system as used in some other studies (e.g. Dalal *et al*. 1994).

Details about crop and pasture production and management (1993–97) are listed in Armstrong *et al*. (1999*a*, 1999*b*).

Soil measurements — data collection

Data reported in this paper were collected from a 26 m length at the northern end of each replicated treatment block in the trial. Samples for soil chemical analysis were collected 4 times during the experiment (November 1993: before imposition of treatments; December 1995, October 1996 and April 1997). Soil physical properties were measured at the end of the trial (May–June 1997). These sampling times corresponded to all treatments under fallow (1993), annual crop and legumes under fallow (perennial legumes growing) in 1995 and 1996, and all crops–pastures present in 1997.

Soil measurements — chemical properties

Total nitrogen, organic carbon and pH. Soil sampling for total N was performed using a 50 mm diameter push-corer when sufficient rain had occurred to thoroughly wet the topsoil to greater than 25 cm to ensure that soil samples could be divided into 3 distinct segments (0–5, 5–10 and 10–20 cm). A minimum of 20 cores 0–5 cm and 10 of the 5–10 and 10–20 cm cores were sampled per plot. Results for the 0–5 and 5–10 cm samples were averaged after chemical analysis so the results presented are for the 0–10 cm section. Sampling for organic C was performed about a fortnight later when the top 10 cm of soil had dried sufficiently to enable coring without the use of a mould-oil lubricant. Following sampling, the soil was dried at 40°C and finely ground (<0.5 mm) before chemical analysis. Fragments of organic matter, such as roots, were not removed from soil samples before grinding. Removal of fine roots was considered a subjective practice that may bias results, especially as it is very difficult to differentiate between fine roots and coarse particulate matter in these heavy clay soils. Organic C was determined using the Walkley–Black dichromate oxidation procedure (Walkley 1947) followed by colorimetric analysis and total N was measured by Kjeldahl digestion (Bremner 1965), steam distillation and autotitration.

Soil pH (1 : 5, soil : water) was measured on samples collected from 0–5, 5–10, and 10–20 cm across all treatments in October 1996.

Carbon fractionation. The soil samples collected in 1993 and 1996 were analysed using the C fractionation method of Blair *et al*. (1995). Finely ground soil samples (<0.5 mm) containing about 350 μg C were pretreated with 2% orthophosphoric acid to remove carbonates, weighed into tin cups and analysed for total C (C_T) in an automatic C analyser mass spectrometer system (ANCA-MS), consisting of a Dumas-type dynamic flash catalytic combustion sample preparation system (Carlo Erba NA1500). The evolved gases are separated and analysed by mass spectrometry (Europa Scientific Tracermass Stable Isotope Analyser). The ANCA-MS was calibrated against an appropriate soil standard.

The C_T measured by combustion, and the amount of oxidising agent consumed by the $KMnO_4$ are used to calculate 2 fractions of organic C; The 2 fractions are: labile C (C_L), the C oxidised by 333 mmol $KMnO_4$/L; and non-labile C (C_{NL}), the C not oxidised by 333 mmol $KMnO_4$/L. Since the continuity of C supply depends on both the total pool size and the lability (an estimate of turnover rate), both are taken into account in the soil of interest and an uncultivated reference soil in deriving a Carbon Management Index (CMI) (Blair *et al*. 1995). On the basis of changes in C_T between a reference site and the cropped site a Carbon Pool Index (CPI) was calculated:

$$CPI = C_T \text{ (cropped)}/C_T \text{ (reference)} \quad (1)$$

On the basis of changes in the C_L fraction relative to the C_{NL} fraction in the soil, a Lability Index (LI) was determined:

$$LI = L \text{ (cropped)}/L \text{ (reference)} \quad (2)$$

These 2 indices were used to calculate a Carbon Management Index: CMI = CPI x LI x 100 (Blair *et al*. 1995). The reference sample was collected from a nearby uncultivated, uncleared area which was covered by native vegetation. Organic C was also determined using the modified Walkley and Black procedure (Walkley 1947) which enabled the calculation of 2 further pools of C. Intractable C (C_I) is calculated by the difference between C_T measured by combustion and C measured by the Walkley and Black procedure. The less labile C pool (C_{LL}) is calculated by the difference between the Walkley and Black C and C_L.

Soil measurements — physical parameters

Bulk density. Soil bulk density was determined by collecting one core from each replicate for each treatment in the relevant datum plot. Sampling was performed using a 10 cm diameter push-corer with corer insertion and extraction performed using a pneumatic ram. Cores were taken to a depth of 45 cm and divided into 5 cm increments. Final values for bulk density were determined after sprinkler irrigation of the datum area. Corrections for soil moisture were deemed unnecessary due to negligible changes in bulk density with gravimetric water content, θg, at the upper storage limit that had previously been observed at the same site (Yule 1984).

Cone penetrometer resistance. Soil resistance to root extension was determined using a cone penetrometer (CP10, Agridry Rimik Pty Ltd). Nine randomly chosen sites were sampled from each replicate for each species in the sixth datum plot. Readings for resistance were taken every 15 mm to a depth of 450 mm, starting at a depth of 15 mm.

Hydraulic conductivity. Infiltration was measured using modified disc permeameters with supply potentials of –4, –3, –2 and –1 cm H_2O applied through a single contact sand pad (Bridge and Bell 1994). Two sites per replicate and species treatment were randomly selected for measurement at both the soil surface and 10 cm. Site preparation for surface readings involved lightly removing litter to avoid disturbing crust formations. Site preparation for readings at 10 cm involved digging pits to about 9 cm and then removing the final 1 cm by picking of the remaining soil surface to avoid aggregate smearing (Bell *et al.* 1997). Saturated hydraulic conductivity (Ks) was derived from the method of Reynolds and Elrick (1991). Macropore density was determined as described by Coughlan *et al.* (1991).

Statistical methods

Data were analysed as a randomised block design with species as the main factor and split for year and depth where appropriate using GENSTAT V5.4.

Results

Soil chemical properties

When the experiment commenced (1993) there was no significant difference ($P<0.05$) in soil total N between treatments (Fig. 1*a* and *b*). After only 2 seasons, soil total N in the 0–10 cm layer was significantly higher in all legume plots, except mungbean and desmanthus, compared with sorghum treatments. Soil total N was particularly concentrated in the surface 0–5 cm, especially in siratro plots and, to a lesser extent, lablab plots (data not shown). In contrast, there was little difference in soil total N in the 10–20 cm, except under lucerne where it tended to be higher (Fig. 1*b*). Total N of

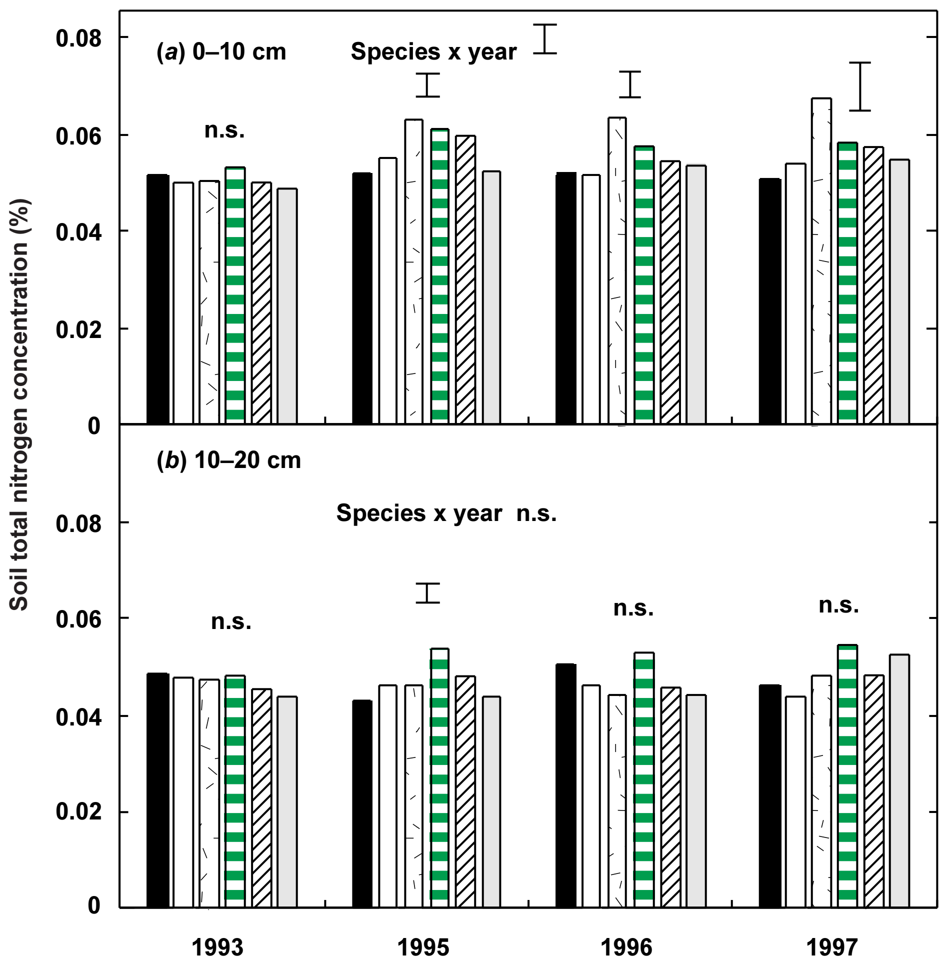

Figure 1. Changes in soil total N in (*a*) 0–10 cm and (*b*) 10–20 cm between 1993 and 1997 following sorghum (solid bars) or various legumes (open bars, mungbean; stippled bars, siratro; striped bars, lucerne; diagonally striped bars, lablab; lightly shaded bars, desmanthus) at Emerald. Vertical bars represent l.s.d. values at $P = 0.05$ for species x year interaction and for comparison between species 1993, 1995, 1996 and 1997. n.s., not significant ($P>0.05$).

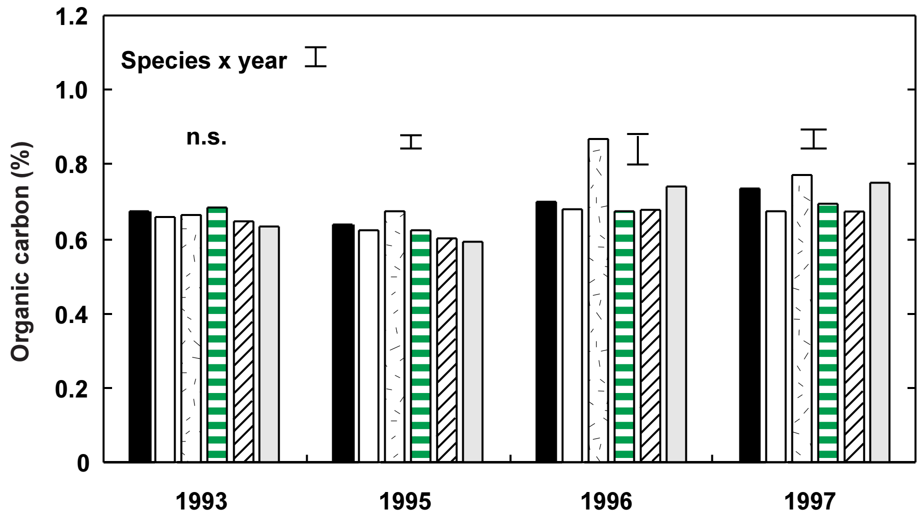

Figure 2. Changes in soil organic carbon in 0–10 cm between 1993 and 1997 following sorghum (solid bars) or various legumes (open bars, mungbean; stippled bars, siratro; striped bars, lucerne; diagonally striped bars, lablab; lightly shaded bars, desmanthus) at Emerald.

the soil generally continued to increase in perennial legume plots during the 4 years whereas there was little change under annual legumes (lablab and mungbeans).

In contrast to N, soil organic C in the 0–10 cm layer tended to decrease (but non-significantly, $P>0.05$) during the first 2 years of the experiment in all plots except siratro, where it remained unchanged (Fig. 2). As the experiment progressed, organic C under sorghum had increased significantly by 1997 as it did under siratro and desmanthus. In contrast, it remained unchanged in mungbean, lablab and lucerne plots. As a consequence, the C : N ratio in the top 10 cm was generally higher in

Table 1. Total carbon (C_T), labile carbon (C_L), non-labile carbon (C_{NL}), lability (L), lability index (LI), Carbon Pool Index (CPI) and Carbon Management Index (CMI) of soil (0–10 cm) under rotation treatments in 1993 and 1996 and the uncropped reference site (Emerald, Central Queensland)

Treatment	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	L	LI	CPI	$\delta^{13}C$	CMI
Reference	12.99	2.26	10.73	0.21	1.00	1.00	n.d.	100
			Rotation treatments in 1993					
Sorghum	9.25	1.30	7.95	0.16	0.78	0.71	–12.64	55
Mungbean	8.14	1.40	6.75	0.21	0.99	0.63	–13.07	62
Siratro	8.93	1.41	7.52	0.19	0.89	0.69	–12.79	61
Lucerne	8.97	1.49	7.48	0.20	0.94	0.69	–12.88	65
Lablab	8.80	1.37	7.42	0.19	0.88	0.68	–12.75	59
Desmanthus	9.09	1.38	7.70	0.18	0.86	0.70	–12.44	60
			Rotation treatments in 1996					
Sorghum	8.37	1.29	7.08	0.18	0.87	0.64	–11.99	56
Mungbean	9.43	1.22	8.21	0.15	0.70	0.73	–13.31	51
Siratro	11.88	1.65	10.23	0.16	0.76	0.91	–15.63	70
Lucerne	9.46	1.35	8.12	0.17	0.79	0.73	–13.64	57
Lablab	9.20	1.24	7.97	0.16	0.74	0.71	–13.12	52
Desmanthus	10.23	1.32	8.91	0.15	0.71	0.79	–14.20	55
l.s.d. (P = 0.05)	0.99	0.14	0.97	0.03	0.12	0.08	1.00	6.56

n.d., not determined.

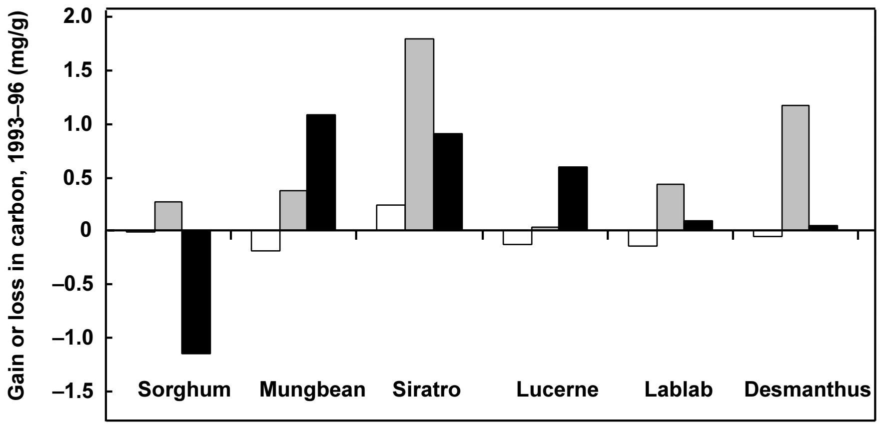

Figure 3. Changes in labile C (C_L, open bars), less labile C (C_{LL}, shaded bars) and the intractable C (C_I solid bars) pools from 1993 to 1996 due to the various pasture and cropping treatments. The l.s.d. (P = 0.05) values for the main effects for each C fraction across all species are C_L = 0.078; C_{LL} = 0.422; C_I = 0.673.

sorghum and desmanthus plots (range 13.1–13.4), compared with the remaining legumes (range 11.7–12.5) (data not shown).

At the start of the trial (1993) there was very little difference between the C fractionation parameters of the various treatments. All carbon fractions at the trial site had declined compared with the reference site: C_T by 32% and C_L by nearly 39% (Table 1). When the trial commenced, C_L at the experimental site ranged from 1.30 to 1.49 mg/g or 14.1–17.2% of C_T. By October 1996 (i.e. 3 years later), marked differences existed in C fractions between treatments. C_T and C_{NL} increased under all legumes: these increases were small and non-significant in lucerne and lablab but significant (P<0.05) under mungbean, siratro and desmanthus. C_L declined under both annual legumes (mungbean and lablab) and lucerne, increased under siratro and remained unchanged in desmanthus plots (P<0.05). Siratro was the only legume where CMI increased significantly (P<0.05); it declined or remained unchanged under the other legumes. In contrast, C_T and C_{NL} declined (P<0.10) in sorghum plots between 1993 and 1996 but C_L remained unchanged. The level of δ^{13}C remained unchanged under all species except the 2 perennial legumes siratro and desmanthus, where it increased significantly (P<0.05).

By calculating the C_I and C_{LL} pools, the effect of the various treatments on specific C pools can be determined. The sorghum treatment was the only one to substantially decrease the C_I pool—the pool most likely to be resistant to change (Fig. 3). This is most probably due to the extra tillage applied for weed control. The siratro treatment resulted in increases in all C pools although L and L_I decreased (Table 1). The lablab and lucerne treatments resulted in no substantial changes in the C pools; however, desmanthus increased the C_{LL} pool. Mungbean resulted in a decline in the C_L pool but increases in the C_{LL} and C_I pools.

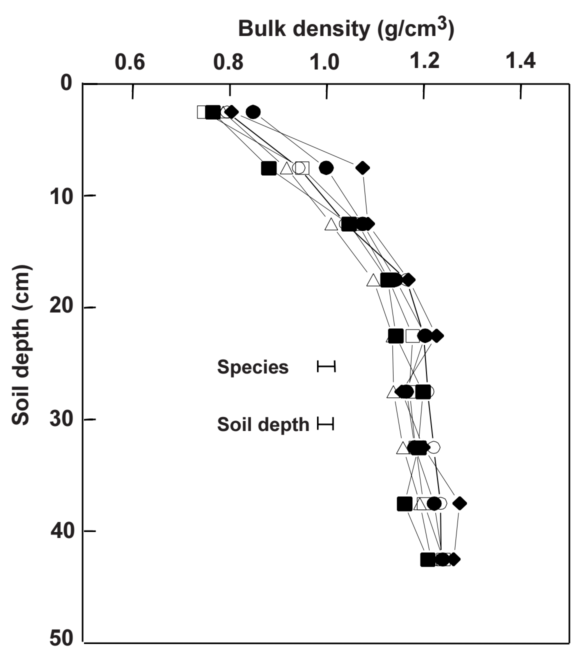

Figure 4. Changes in soil bulk density following various legumes (□ mungbean, ◆ siratro, ● lucerne, △ lablab, ■ desmanthus) or sorghum (○) at Emerald, 1997. Vertical bars indicate l.s.d. (P = 0.05).

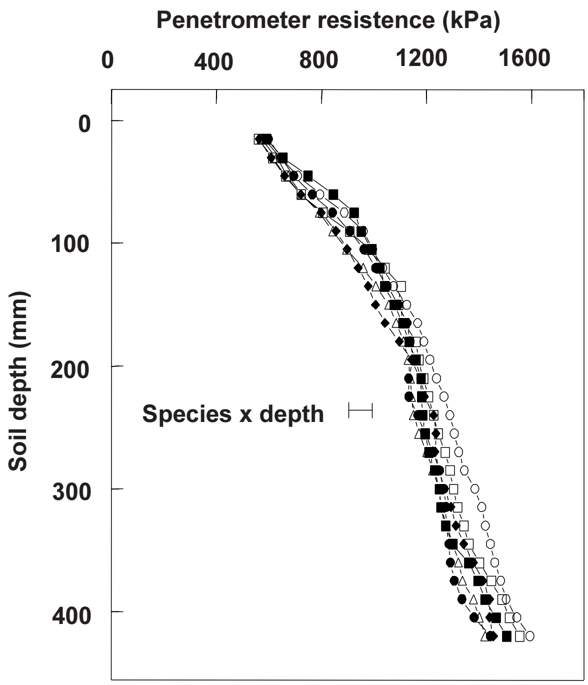

Figure 5. Changes in cone pentrometer resistance following various legumes (□ mungbean, ◆ siratro, ● lucerne, △ lablab, ■ desmanthus) or sorghum (○) at Emerald, 1997. Data were $\log_{10}$ transformed for statistical analysis. Non-transformed data are presented.

Sorghum generally had the highest soil pH (7.81) and lablab the lowest (7.58), especially in the 0–5 and 5–10 cm layers, but there was no difference at 10–20 cm (data not shown).

Soil physical properties

Bulk density. Irrigation ensured that no significant differences in soil moisture content occurred between treatments. The bulk density of the soil increased rapidly from an average of 0.79 g/cm^3 in the surface 0–5 cm to 1.18 g/cm^3 at 20–25 cm but then remained virtually unchanged to a depth of 450 mm across all treatments (Fig. 4).

Bulk density was significantly ($P<0.05$) lower throughout the 0–450 mm soil layer after 4 consecutive years of annual legumes (lablab and mungbean) and desmanthus compared with continuous sorghum crops or the perennial legumes siratro and lucerne.

Cone penetrometer resistance. There was a significant ($P<0.05$) interaction between soil depth and cone penetrometer resistance under the various legume and sorghum treatments (Fig. 5). In surface (45–120 mm) layers, desmanthus and sorghum plots had higher cone resistances than the plots of other species. At depths greater than 135 mm, sorghum plots continued to have the highest resistance readings.

Hydraulic conductivity. Saturated hydraulic conductivity (Ks) was higher on the soil surface than at

Table 2. Hydraulic conductivity and macropore density as determined by disc permeameters at the soil surface and 10 cm in plots after 4 seasons of various rotation treatments (Emerald, Central Queensland)

Potential (cm H_2O)	Depth	Sorghum	Mungbean	Treatment Siratro	Lucerne	Lablab	l.s.d. (P = 0.05)
				Hydraulic conductivity (mm/h)			
0	Surface	733.6	672.7	571.8	685.4	701.5	n.s.
	10 cm	176.1	305.8	594.6	482.7	441.0	n.s.[B]
–1.5	Surface	502.5	426.9	384.2	430.3	419.7	118.8
	10 cm	127.6	209.0	335.0	301.2	290.5	101.9[A]
–2.5	Surface	290.4	264.0	196.7	280.7	249.1	66.2
	10 cm	81.9	142.9	182.7	191.6	190.5	62.4[A]
–3.5	Surface	173.0	171.1	109.6	154.0	148.6	43.1
	10 cm	62.0	96.3	111.0	116.1	124.2	44.4[A]
				Macropore density (pores/m^2)			
0 to –1.5	surface	5.1	3.5	5.1	3.6	4.0	1.8
	10 cm	0.7	1.4	3.7	2.6	2.1	1.5[A]
–1.5 to –2.5	Surface	37.4	28.7	33.0	26.4	30.1	11.3
	10 cm	8.1	11.7	26.8	19.3	17.6	9.7[A]
–2.5 to –3.5	Surface	135.5	107.3	100.7	146.4	116.1	41.7
	10 cm	23.0	53.8	82.9	87.2	76.6	35.4[A]

[A] l.s.d. for comparing with the same level of species.
[B] F value for species and species x depth not significant ($P>0.05$). Effect of depth was significant ($P<0.001$).

10 cm for all species except siratro, where there was no difference between the 2 depths at all H_2O potentials (Table 2). On the soil surface Ks was not affected by species at water potentials of –1.5 or 0. At greater water potentials (–2.5 and –3.5), Ks was 26% lower under siratro compared with the average of the other species. In contrast, at 10 cm depth Ks was generally lowest in sorghum and mungbean plots.

Macropore density for large and medium size pores (0 to –1.5 and –1.5 to –2.5 cm H_2O) was significantly higher in surface soil than at 10 cm depth under annual species (sorghum, mungbean and lablab) but did not differ in the perennial legume plots. At the surface soil, the density of large and medium size pores was not affected by previous species. For small pores, siratro tended to have a lower density than the other species. At 10 cm, soil in sorghum and mungbean plots had a lower density of macropores across all the size ranges measured.

Discussion

Previous studies (Armstrong *et al*. 1997, 1999*b*) recorded significant improvements in grain yields and quality by incorporating legumes in the rotation. This study found that the beneficial effect of these legumes on subsequent sorghum crops in part paralleled changes in soil fertility (total N and organic C). Furthermore, the legumes also affected important soil physical properties, but to varying degrees.

Although the trial had supplementary irrigation applied on 3 occasions over 4 years (at the start of the trial in 1994 to allow planting, again in 1995 to allow planting of the annual legumes and sorghum, and finally near the end of the trial in 1997 to ensure grain fill of the sorghum), the amount of water applied was comparatively small (see Armstrong *et al*. 1999*a*). Overall, the water available for legume–crop growth (rainfall + irrigation) was below the long-term average during the trial period. Consequently, it is possible that the effect of the legumes may have been even greater in periods of average to above-average rainfall as occurs during *La Nina* climatic events.

In contrast to commercial conditions and some other studies for example Dalal *et al*. (1994) where cut material was removed, pasture legumes in this experiment were not grazed, and all residues were left on the soil surface after slashing. This may have affected the results in 2 ways. Firstly, the rate of organic matter and N return to the soil would have been higher and more homogeneous than if the pasture was grazed and legume N and C returned as either urine or dung. Vallis (1979), for example, notes that grazing can significantly affect N cycling through the return of excreta and losses via volatilisation of N from urine compared with the decomposition of plant residues *in situ*. In contrast, Clarke *et al*. (1967) found that the retention (after mulching) or removal of pastures had little or no effect on physical properties of the soil, such as aggregate stability. Secondly, trampling by grazing animals, particularly under wet conditions, can result in significant deterioration of soil structure, resulting in reduced infiltration rates (Proffitt *et al*. 1993). Unfortunately the small plot sizes used in this study restricted our ability to graze the pasture treatments. It is not known to what extent cutting (regardless of whether material is retained or removed) may have affected results in the current study. This aspect requires further investigation.

Different management practices between treatments (i.e. perennial pasture *v*. annual crop or legumes), made it difficult to sample all treatments under identical conditions. Ideally all treatments should have been sampled when they had maximum dry matter, but sufficient soil moisture needed for profile partitioning rarely occurred during the experiment. The one time this did occur was when the experimental site was irrigated after all crop–pasture sampling was completed in 1997 following grain maturity. This ensured differences in soil moisture did not confound bulk density, cone penetrometer or Ks measurements. None the less, differences between treatments were large enough, and the pattern of change consistent enough, to suggest real effects of the various treatments on soil properties such as total N and organic C measured in preceding years.

Soil chemical properties

All legumes except mungbean produced significant increases in the amount of total N in the topsoil compared with their respective pre-experiment values. These results confirm the ability of perennial (lucerne) and annual (medic) legume pastures to increase total N in the topsoil whereas a pulse crop had no significant effect on a cracking clay soil in southern Queensland (Dalal *et al*. 1995). The increase in total N of the soil under the pasture legumes reflected their net N balance (Armstrong *et al*. 1999*a*) and was highest in siratro plots and lowest under desmanthus. Rotating pulses such as mungbean with cereals is widely recommended in the northern grain belt due to the belief that N_2 fixed by the legume helps to maintain soil fertility. Sorghum following mungbean crops at this site had high concentrations of soil mineral N and produced significantly more grain with higher protein levels compared with continuous sorghum crops (Armstrong *et al.* 1999*b*). However, the net N balance of these systems was negative (i.e. the amount of N_2 fixed by the pulse was less than the amount of N exported in grain), despite high N_2 fixation rates during the first 2 years of the trial (Armstrong *et al.* 1999*a*). This, combined with the additional N exported from the sorghum crop following the pulse compared with continuous sorghum, resulted in no significant change in soil N levels under pulses. In contrast, the species with the highest rate of N accumulation in above-ground dry matter, siratro, was also associated with the largest increase in total N in the topsoil.

There has been speculation recently that the ability of pulses to maintain soil N supplies has been underestimated due to failure to account for N contained in the below-ground compartment (Russell and Fillery 1996). Although this aspect was not measured, the N concentration of soil samples from the 10 to 20 cm soil layer (Fig. 1*b*) indicated a possible decrease in soil N levels rather than an increase. Given the potential economic importance of pulses to grain production systems, especially when livestock returns are poor, this feature requires urgent attention.

Soil organic matter (C) is regarded as a key indicator of sustainability (Hamblin 1992). It plays a vital role in the cycling of other nutrients as well as affecting soil structure and rainfall infiltration (Lefroy and Blair 1994). Although all legumes except mungbean significantly improved soil N, only 2 legumes, siratro and desmanthus, produced significant increases in the amount of organic C in the topsoil. This occurred even though lablab (17 740 kg/ha) and siratro (16 130 kg/ha) produced similar amounts of total legume dry matter during the trial period and desmanthus produced less than 6400 kg/ha (Armstrong *et al.* 1999*a*). The increase in soil organic C in siratro and desmanthus plots also tended to increase fastest in the latter part of the experiment, whereas total N increased most rapidly during the first 2 years of the experiment.

However, whereas lablab and mungbean plots remained virtually free of grass and broadleaf weeds and the amount of soil NO_3^- under these legumes gradually increased as the trial progressed, soil NO_3 levels remained significantly lower under both siratro and desmanthus (Armstrong *et al.* 1999*a*). This corresponded to an increased weed burden from 1995 onwards in desmanthus and siratro plots from 1996 onwards. Dalal *et al.* (1995) have suggested that root material, particularly that of grasses, is a major factor in the ability of mixed lucerne–medic and grass pastures to increase the organic matter on Vertisols in southern Queensland. In this experiment no measurements were made of the below-ground dry matter. The net effect of these differences in weed populations between the different species was therefore to increase soil C levels under species where the weeds were most prevalent, and thereby negate the influence of legume dry matter production to some extent.

Interestingly, the only non-legume treatment in the experiment, sorghum, also recorded a significantly higher organic C (Fig. 2) than at the start of the experiment although total C tended to decrease (Table 1). Continuous cropping generally results in declining organic C (Dalal and Mayer 1986). This point is reflected in a recent survey in Central Queensland showing significant declines of up to 40% in soil organic C in paddocks that had been continuously cropped compared with paired virgin sites (G. Millar and R. D. Armstrong unpublished data). Soil fertility levels at this site were comparatively low and the 4 sorghum crops grown in succession between 1994 and 1997 suffered severe N deficiency (Armstrong *et al.* 1999*b*). The build up in soil organic C over 4 years may reflect a limitation to C decomposition–mineralisation resulting from N deficiency. However, C fractionation data (Table 1) indicated that the increases in organic C were due to increased labile C (C_L) rather than non-labile C (C_{NL}). The build up in organic C would have been enhanced by the use of minimum tillage practices, which help to minimise the loss of C in soils used for cropping compared with conventional cultivation (Heenan *et al.* 1995). The large decline in C_I in the sorghum treatment was associated with the use of tillage for regrowth control. Regular tillage creates favourable conditions for the oxidation of soil organic matter, and may increase the availability of organic matter to microbial attack.

The $KMnO_4$ oxidation fractionation procedure used in this study provides a qualitative characterisation of soil C (Blair *et al.* 1995). This procedure has been criticised because it fails to differentiate this form of C from that of the relatively stable charcoal fraction (Skjemstad *et al.* 1996). Unpublished data (A. M. Whitbread and G. J. Blair) showed that 333 mmol $KMnO_4$/L oxidised less than 5% of the charcoal present. Charcoal is unlikely to constitute a significant proportion of soil C on the Open Downs soil of Central Queensland as historically burning is not practised in this region. The fractionation indicated significant differences in the nature of changes in organic C that were not fully obvious from the

Walkley–Black organic C values (Figs 2 and 3). For example, organic C increased under both siratro and sorghum (Fig. 2). This increase was paralleled by increases in both C_L and C_{NL} in siratro plots, whereas C_{NL} decreased by nearly 9% in sorghum plots (Table 1). In contrast, under lablab C_L decreased and C_{NL} remained relatively unchanged. Blair *et al*. (1995) have suggested that the C_L pool may be directly involved in soil microbial processes. Soil N mineralisation rates were higher under lablab than siratro (Armstrong *et al*. 1999*a*), suggesting that the C_L was being used as a substrate to facilitate mineralisation. However, eventually N mineralisation could be expected to be inhibited with a decline in C_L levels due to no concurrent build up of C_{NL} (which would presumably provide a substrate for C_L).

Nitrogen was particularly concentrated in the topsoil, namely 0–5 cm. However, some treatments (e.g. siratro), formed pronounced blankets of leaves on the soil surface due to their prostrate growth habit. Mungbean and lablab also formed pronounced mulch layers on the soil surface as a result of leaf drop during plant senescence. The cracking clay soils used for cropping in Central Queensland are vulnerable to severe erosion from high intensity rainfall (Carroll *et al.* 1997). For example, soon after the experiment commenced, a rainfall event totalling more than 350 mm over 6 days occurred. This caused significant erosion, especially where there was little vegetation cover (lucerne plots) and, to a lesser extent, sorghum plots. These erosion events will not only result in severe environmental damage, for example creeks clogged with silt, but will probably remove the most fertile soil layer (topsoil), and the nutrients it contains, off the paddock.

Soil physical properties

Cracking clay soils, such as those used for cropping in Central Queensland, are regarded as having good structural properties. However biological factors, such as organic matter, are generally not as important in the structural formation and stabilisation of cracking clays as in other soil groups (Oades 1993). The physical parameters of soils measured in this study were influenced to varying degrees by previous crop–pasture history. Bulk density and cone penetrometer resistance were higher under sorghum than the other species. Sorghum was the only treatment cultivated in the experiment, as the sparse stubble loads after mungbeans and lablab meant that they could be resowed using direct drilling. However, overall differences between treatments were small (e.g. range 1.10–1.17 g/cm^3 at 15–20 cm), thus root penetration would not have been limiting under any treatment.

Prior species had a greater effect on Ks than bulk density or penetrometer resistance. Soil water is the principal limitation to crop production in Central Queensland and infiltration of rainfall is significantly limited in cracking clays when water content of the surface soil increases and deep cracks seal. Ks was significantly higher at the soil surface compared with the 10 cm soil layer, which had a higher soil water content. Species did not affect the Ks at lower water potentials on the surface, but at higher potentials Ks was much lower under siratro than the other species. This was not due to differences in soil moisture, which did not differ significantly between the species at the time of measurement. Siratro, which produced the most dry matter of any species during the experiment (Armstrong *et al*. 1999*a*), formed a pronounced mulch on the soil surface. This mulch resulted in extremely low Ks values and even when it was gently removed (actual value presented in Table 2), Ks was much lower under siratro than for the other species. Certain plant species, including legumes, are believed to contain organic materials that induce water repellency (King 1981) and this may have caused the very low Ks values under siratro. However, this negative aspect of siratro could be countered by its better ability to utilise soil water compared with annual crop–legume fallow systems (Armstrong *et al*. 1999*a*). Siratro and, to a lesser extent, lucerne maintained soil water at a lower matric suction potential throughout the profile (Armstrong *et al*. 1999*a*), thus promoting deep cracking and overall greater rates of infiltration, especially during high intensity rainfall events.

In the subsoil (10 cm), Ks was consistently lower under sorghum and, to a lesser extent, mungbean compared with the other species. The lower Ks was associated with a lower density of macropores across the entire size range measured. The need to cultivate sorghum may have created a plough pan and destroyed macropore channels, both of which would reduce Ks. However, Ks was measured after grain maturity of both sorghum and mungbean when neither treatment had been subjected to cultivation for several months. Murphy *et al.* (1993) suggest that the effect of different tillage practices on hydraulic properties is actually most pronounced in the period between flowering and the postharvest period. Given the detrimental impact of tillage on Ks, any benefits gained during the pasture phase may be lost during the transition to a cropping phase if mechanical cultivation is used.

Comparative effect of soil physical v. chemical properties

Armstrong *et al.* (1999*b*) found that the legumes used in this current study had a large beneficial effect on subsequent sorghum crops. Whereas the annual legumes (mungbean and lablab) produced the largest yield response in the first sorghum crop, 2 of the perennials (siratro and lucerne) had a more beneficial effect on the second and third sorghum crops. Results from this current study suggest that whereas short-term effects (1 season) are related to soil NO_3^- levels (Armstrong *et al*. 1999*b*), the longer lasting beneficial effect of siratro and lucerne was more strongly related to higher concentrations of total N in the topsoil. Although soil organic C was increased significantly in desmanthus plots, the lack of any matching increase in total N of the soil resulted in no beneficial effect to subsequent sorghum crops.

The growth of the first sorghum crop after both siratro and lucerne was retarded by lower plant-available soil water content (PAWC) at the time of sowing, despite high concentrations of nitrate being located throughout the soil profile. This lower PAWC under the perennial legumes also corresponded to lower Ks at the soil surface (and therefore potentially lower rates of rainfall infiltration). However it is difficult to separate the effect of lower Ks from the longer growth season of the perennial, which results in reduced opportunity for recharge of the soil profile before the sowing of sorghum, compared with an annual species. Soil water is the principal factor limiting crop production in Central Queensland and improved soil N status is of little benefit to subsequent crop production if there is insufficient soil water to meet the crop's basic requirements. The comparative effect of improved soil chemical (N) versus enhanced physical properties on subsequent cereal crops, however, will vary according to soil fertility levels, which are generally low and decreasing in this region (Spackman and Garside 1995), and the nature and amount of rainfall occurring during fallows preceding the sowing of a subsequent crop.

Conclusion

An inherent assumption in the use of pastures (in Central Queensland) is that they can maintain or improve soil fertility (Weston *et al*. 1997). This study clearly indicated that the beneficial effect of ley legume pastures on subsequent cereal crops (Armstrong *et al.* 1999*b*) was related to significantly improved total N content of the soil, although not necessarily organic C. However, soil organic C, which is often regarded as a better indicator of soil fertility than soil N, was only increased by the species siratro and desmanthus perennial legume pasture. Consequently, whereas annual legumes (both pulse and pasture) offer clear short-term benefits in terms of improved N supply and soil water supply to following cereal crops, perennial legumes may be a better option if the primary goal is to increase the overall soil fertility in the longer term.

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References

Armstrong, R. D., McCosker, K., Johnson, S. B., Walsh, K. B., Millar, G., Kuskopf, B., Standley, J., and Probert, M. E. (1999*a*). Legumes and opportunity cropping systems in central Queensland. 1. Legume growth, nitrogen fixation and water use. *Australian Journal of Agricultural Research* **50** (in press).

Armstrong, R. D., McCosker, K., Millar, G., Kuskopf, B., Johnson, S., Walsh, K., Probert, M. E., and Standley, J. (1999*b*). Legume and opportunity cropping systems in central Queensland. 2. Effect of legumes on following crops. *Australian Journal of Agricultural Research* **50** (in press).

Armstrong, R. D., McCosker, K. J., Millar, G. R., Walsh, K., Johnson, S., and Probert, M. E. (1997). Improved nitrogen supply to cereals in Central Queensland following short legume leys. *Australian Journal of Experimental Agriculture* **37**, 359–68.

Bell, M. J., Bridge, B. J., Harch, G. R., and Orange, D. N. (1997). Physical rehabilitation of degraded krasnozems using ley pastures. *Australian Journal of Soil Research* **35**, 1093–113.

Blair, G. J., Lefroy, R. D. B., and Lisle, L. (1995). Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research* **46**, 1459–66.

Bremner, J. M. (1965). Total nitrogen. *In* 'Methods of Soil Analysis'. Part 2. (Ed. C. A. Black.) pp. 1149–78. (American Society of Agronomy: Madison Wisconsin, USA.)

Bridge, B. J., and Bell, M. J. (1994). Effect of cropping on the physical fertility of krasnozems. *Australian Journal of Soil Research* **32**, 125–373.

Bridge, B. J., Mott, J. J., Winter, W. H., and Hartigan, R. J. (1983). Improvement in soil structure resulting from sown pastures on degraded areas in the dry savanna woodlands of northern Australia. *Australian Journal of Soil Research* **21**, 83–90.

Carroll, C., Halpin, M., Burger, P., Bell, K., Sallaway, M. M., and Yule, D. F. (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**, 925–39.

Chapman, A. L., Sturtz, J. D., Cogle, A. L., Mollah, W. S., and Bateman, R. J. (1996). Farming systems in the Australian semi-arid tropics—a recent history. *Australian Journal of Experimental Agriculture* **36**, 915–28.

Clarke, A. L., Greenland, D. J., and Quirk, J. P. (1967). Changes in some physical properties of the surface of an impoverised red-brown earth under pasture. *Australian Journal of Soil Research* **5**, 59–68.

Connolly, R. D., Freebairn, D. M., and Bell, M. J. (1998). Changes in soil infiltration associated with leys in south-eastern Queensland. *Australian Journal of Soil Research* **36**, 1057–72.

Coughlan, K. J., McGarry, D., Loch, R. J., Bridge, B. J., and Smith, G. D. (1991). The measurement of soil structure: some practical initiatives. *Australian Journal of Soil Research* **29**, 869–89.

Dalal, R. C., and Mayer, R. J. (1986). Long term trends in 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**, 265–79.

Dalal, R. C., Strong, W. M., Weston, E. J., Cahill, M. J., Cooper, J. E., Lehane, K. J., King, A. J., and 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 of Soil Science'. Vol. 5A. p. 6274. (Acapulco, Mexico.)

Dalal, R. C., Strong, W. M., Weston, E. J., Cooper, J. E., Lehane, K. J., King, A. J., and Chicken, C. J. (1995). Sustaining the productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes. 1. Organic matter status. *Australian Journal of Experimental Agriculture* **35**, 903–13.

Dalal, R. C., Strong, W. M., Weston, E. J., and Gaffney, J. (1991). Sustaining multiple production systems. 2. Soil fertility decline and restoration of cropping lands in sub-tropical Queensland. *Tropical Grasslands* **25**, 173–80.

Hamblin, A. (1992). 'Environmental Indicators for Sustainable Agriculture.' (Bureau of Rural Resources, DPIE: Canberra.)

Heenan, D. P., McGhie, W. J., Thomson, F. M., and Chan, K. Y. (1995). Decline in soil organic carbon and total nitrogen in relation to tillage, stubble management, and rotation. *Australian Journal of Experimental Agriculture* **35**, 877–84.

Isbell, R. F. (1996). 'Australian Soil Classification.' (CSIRO Publishing: Collingwood, Vic.)

King, P. M. (1981). Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Australian Journal of Soil Research* **19**, 275–85.

Lefroy, R. D. B., and Blair, G. J. (1994). The dynamics of soil organic matter changes resulting from cropping. *In* 'Proceedings of the 15th International Congress of Soil Science'. Vol. 9. pp. 235–47. (Acapulco, Mexico.)

Murphy, B. W., Koen, T. B., Jones, B. A., and Huxedurp, L. M. (1993). Temporal variation of hydraulic properties for some soils with fragile structure. *Australian Journal of Soil Research* **31**,179–97.

Oades, J. M. (1993). The role of biology in the formation, stabilisation and degradation of soil structure. *Geoderma* **56**, 377–400.

Proffitt, A. P. B., Bendotti, S., Howell, M. R., and Eastham, J. (1993). The effect of sheep trampling and grazing on soil physical properties and pasture growth for a red-brown earth. *Australian Journal of Agricultural Research* **44**, 317–31.

Reynolds, W. D., and Elrick, D. E. (1991). Determination of hydraulic conductivity using a tension infiltrometer. *Soil Science Society of America Journal* **55**, 633–9.

Russell, C. A., and Fillery, I. R. P. (1996). Estimates of lupin below-ground biomass nitrogen, dry matter and nitrogen turnover to wheat. *Australian Journal of Agricultural Research* **47**, 1047–59.

Skjemstad, J. O., Clarke, P., Taylor, J. A., Oades, J. M., and McClure, S. G. (1996). The chemistry and nature of protected carbon in soil. *Australian Journal of Soil Research* **34**, 251–72.

Spackman, G. B., and Garside, A. L. (1995). Major factors affecting grain production in central Queensland and their implications for sustainable grain farming systems. A review prepared for the Grains Research and Development Corporation, Canberra, Australia.

Vallis, I. (1979). The effect of climatic, edaphic and animal factors on nitrogen transformations in permanent pastures. *In* 'Nitrogen Relationships in Pasture Systems of Southern Queensland'. Proceedings of a workshop held in Toowoomba, Queensland, 5 June 1979. pp. 3–26. (Queensland Department of Primary Industries.)

Walkley, A. (1947). A critical examination of a rapid method for determining organic carbon in soils—effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* **63**, 251–64

Weston, E., Dalal, R., Strong, W., and Lehane, J. (1997). The benefit of a pasture ley in cereal cropping. *In* 'Proceedings of the 12th Annual Conference of the Grassland Society of New South Wales'. (Eds A. Bowan and D. Michalk.) pp. 11–17. (Grassland Society of New South Wales: Dubbo.)

Yule, D.F. (1984). Volumetric calculations in cracking clay soils. *In* 'The Properties and Utilization of Cracking Clay Soils'. Reviews in Rural Science, Vol. 5. (Eds. J. W. McGarrity, E. H. Hovitt and H. B. So.) pp. 136–40. (University of New England.)

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