Soil organic carbon and total nitrogen under *Leucaena leucocephala* pastures in Queensland

Alejandro Radrizzani[A,B], *H. Max Shelton*[A,C], *Scott A. Dalzell*[A], *and Gunnar Kirchhof*[A]

[A]School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Qld 4072, Australia.
[B]Instituto Nacional de Tecnologia Agropecuaria (INTA), Jujuy 850, 4200, Santiago del Estero, Argentina.
[C]Corresponding author. Email: m.shelton@uq.edu.au

Abstract. Soil organic carbon (OC) and total nitrogen (TN) accumulation in the top 0–0.15 m of leucaena–grass pastures were compared with native pastures and with continuously cropped land. OC and TN levels were highest under long-term leucaena–grass pasture ($P < 0.05$). For leucaena–grass pastures that had been established for 20, 31, and 38 years, OC accumulated at rates that exceeded those of the adjacent native grass pasture by 267, 140, and 79 kg/ha.year, respectively, while TN accumulated at rates that exceeded those of the native grass pastures by 16.7, 10.8, and 14.0 kg/ha.year, respectively. At a site where 14-year-old leucaena–grass pasture was adjacent to continuously cropped land, there were benefits in OC accumulation of 762 kg/ha.year and in TN accumulation of 61.9 kg/ha.year associated with the establishment of leucaena–grass pastures. Similar C : N ratios (range 12.7–14.5) of soil OC in leucaena and grass-only pastures indicated that plant-available N limited soil OC accumulation in pure grass swards. Higher OC accumulation occurred near leucaena hedgerows than in the middle of the inter-row in most leucaena–grass pastures.

Rates of C sequestration were compared with simple models of greenhouse gas (GHG) emissions from the grazed pastures. The amount of carbon dioxide equivalent (CO_2-e) accumulated in additional topsoil OC of leucaena–grass pastures ≤20 years old offset estimates of the amount of CO_2-e emitted in methane and nitrous oxide from beef cattle grazing these pastures, thus giving positive GHG balances. Less productive, aging leucaena pastures >20 years old had negative GHG balances; lower additional topsoil OC accumulation rates compared with native grass pastures failed to offset animal emissions.

Additional keywords: carbon balance, carbon sequestration, greenhouse gas balance, permanent pastures, soil organic carbon, soil total nitrogen.

Introduction

Sustaining or enhancing soil organic carbon (OC) and total nitrogen (TN) is crucial for maintaining the chemical, biological, and physical fertility of soil. Soil organic matter, as the third-largest world sink of C (Dalal and Carter 2000), is also a significant potential sink for sequestration of atmospheric C, and therefore mitigation of greenhouse gas (GHG) ('t Mannetje 2007). Tropical grass swards are typically constrained in their capacity to store soil C due to limited plant-available N in soils under mature pastures (Graham *et al*. 1981) and frequent overgrazing, which leads to low primary biomass production and OC losses through accelerated mineralisation and soil erosion (Dalal and Carter 2000).

In order to increase soil OC, significant amounts of N and phosphorus (P), not normally present in well-established tropical grass pastures (Myers and Robbins 1991), need to be available to support both plant growth and microbial decomposition of plant litter (Carter *et al*. 1998). Pastures containing legumes have greater capacity to increase soil OC (Armstrong *et al*. 1999), particularly when perennial legumes are grown in mixtures with grasses (Dalal *et al*. 1995). The multipurpose legume leucaena [*Leucaena leucocephala* (Lam.) de Wit ssp. *glabrata* (Rose) Zárate] has been reported to improve soil fertility in tree plantations through leaf fall (Jha *et al*. 1991; Lalljee *et al*. 1998), in alley cropping systems when used as green manure (Kang *et al*. 1985; Onim *et al*. 1990), and in grazed pastures when consumed and excreted as dung and urine when ruminants are included in the C and N cycle (Catchpoole and Blair 1990; Burle *et al*. 2003). Additional GHG mitigation benefits may accrue from improved efficiency of beef production per unit of methane emitted by cattle due to the presence of moderate concentrations of condensed tannin in leucaena forage (Dalzell and Shelton 2002) and to the superior quality of leucaena forage relative to that of tropical (C_4) grass. These characteristics may be expected to reduce enteric methanogenesis (Clark *et al*. 2005) in ruminant animals fed leucaena.

Although there is some information on the C sequestration capability of introduced African grass pastures in Colombia and Brazil (Fisher *et al*. 1994), there is limited published information on changes in soil OC levels under grazed leucaena pastures in the semiarid environment of Queensland (Carter *et al*. 1998), where >150 000 ha of leucaena grass pastures have been planted (Shelton and Dalzell 2007). In this study, accumulation of topsoil OC resulting from the establishment of leucaena–grass pastures

 10.1071/CP10115 1836-0947/11/040337

into native grass pastures and continuously cropped land was investigated. The associated level of TN in the topsoil was also studied as an indicator of N available for forage production. The hypothesis tested was that the establishment of leucaena hedgerows into grass pastures and previously cropped lands increases soil OC and TN. GHG balances were modelled for the grazing systems under investigation.

Materials and methods

In the absence of suitable long-term experiments where soil fertility could be investigated before and after leucaena establishment, an observational approach using paired comparisons was employed where long-term leucaena pastures were compared with different land uses. Two sites were chosen: one where previous land use was predominantly the grazing of native grass pastures, and one where previous land use was annual summer cropping.

Site description

Brian Pastures Research Station

Brian Pastures Research Station (BPRS) is 18 km south-east of Gayndah, Queensland (25°39′S, 151°45′E; elevation 131 m a.s.l.), with a subtropical climate, receiving an average annual rainfall of 691 mm, 72% of which falls in October–March. Average maximum/minimum temperatures are 32/20°C in January and 22/7°C in July; on average 21 frosts (ground surface temperature ≤ -1°C) occur each year. Mean evaporation exceeds mean rainfall in all months.

Three leucaena cv. Peru stands, planted in hedgerows 3 m part and aged 20 years (2.5 ha), 31 years (5 ha), and 38 years (0.8 ha), were selected for soil sampling. Leucaena plant density was not different for the 20- and 31-year-old pastures (3.5 plants/m row) but had declined to 2 plants/m in the 38-year-old stand. This was due to the increasing age of the leucaena, which also caused the number of stems per plant to decline (A. Radrizzani, unpubl. data).

The 20-year-old stand was planted after the cropping phase of a ley-pasture system (3 years of cropping from 1975 to 1986). The 31- and 38-year-old stands were planted into fully prepared and fallowed seedbeds on lands that had previously been native grass pastures. The 20-year-old stand was fertilised 5 and 10 years after establishment; the 31-year-old stand 11, 16, and 21 years after establishment; and the 38-year-old stand 30 and 32 years after establishment. On each occasion, 22 kg P and 28 kg S/ha was applied. The inter-rows of the leucaena stands were cultivated at establishment and thereafter were re-colonised by green panic (*Panicum maximum* var. *trichoglume* Jacq.).

Three grass-only pasture areas of 2.5, 2.5, and 2.4 ha, immediately adjacent to the 20-, 31-, and 38-year-old leucaena pastures, respectively, were selected to provide paired comparisons to assess changes in topsoil OC and TN status. The adjacent grass-only pastures were dominated by native grasses [predominantly *Dicanthium sericeum* (R. Br.) A. Camus, *Heteropogon contortus* (L.) P. Beauv. ex Roemer & Schultes, and *Bothriochloa bladhii* (Retzius) S.T. Blake]. Each leucaena and adjacent grass-only pasture pair was located in the one paddock and had been managed as one grazing unit. Crossbred (*Bos taurus* × *Bos indicus*) cattle grazed the native grass pastures year-round at a stocking rate of 0.625 animal equivalents (AE)/ha (1 AE = 400-kg steer). These animals then had access to the leucaena pastures for 3–6 months between May and November each year when the leucaena was rotationally grazed for 1 week followed by a 3-week spell, at a combined stocking rate of 0.45 AE/ha. It is likely that dung (OC) and urine (N) were transferred from the leucaena pastures to the adjacent grass-only pastures where water points were located, and cattle preferred to camp in the open under standing trees (C. J. Paton, pers. comm.).

The three paired leucaena stands and adjacent grass-only pastures were on a moderately self-mulching cracking clay (62% clay content in A and B horizons) black Vertosol (1 VE AE EI CD E S S W—Isbell 1996; Ug5.15, Ug5.32, and Ug5.34—Northcote *et al*. 1975) developed on basalt materials with alkaline soil reaction (Reid *et al*. 1986). The soil had a plant-available water capacity of 152 mm in the top 1 m of soil, estimated from rooting depth and –1500 kPa water content by the algorithm of Shaw and Yule (1978), and high cation exchange capacity (CEC) (Bruce and Rayment 1982), which declined from 65 $cmol_c$/kg in the topsoil to 49 $cmol_c$/kg at a depth of 1.5 m. In the topsoil, the CEC comprised 28% calcium (Ca^{2+}), 33% magnesium (Mg^{2+}), 0.4% potassium (K^{+}), and 0.4% sodium (Na^{+}), whereas at a depth of 1.5 m, the proportions were 10, 33, 0.2, and 5.7%, respectively. The original natural vegetation was dominated by Queensland blue gum [*Eucalyptus tereticornis* (Sm.)], but had been modified to black speargrass (*H. contortus*) and blue grass (*D. sericeum* and *B. bladhii*) grassland by tree removal and grazing (Reid *et al*. 1986).

Banana

The second site was 12 km south of Banana in central Queensland (24°36′06″S, 150°09′25″E; elevation 195 m a.s.l.), with a subtropical climate, receiving an average annual rainfall of 667 mm, 71% of which falls in October–March. Average maximum/minimum temperatures recorded at nearby Brigalow Research Station (24°50′07″S, 149°48′01″E; elevation 168 m a.s.l.) are 34/21°C in January and 22/7°C in July; on average, 12 frosts occur each year. Mean evaporation exceeds mean rainfall in all months.

A 14-year-old leucaena stand (cv. Peru), planted into 73 ha of previously cropped land, was selected for soil sampling. Leucaena was planted in twin hedgerows 0.8 m apart with 5.5 m between twin row centres, without fertiliser application at planting or thereafter. Leucaena density was 5.7 ± 0.25 plants or 17.4 ± 0.77 stems/m twin row. The dominant grasses were buffel grass (*Cenchrus ciliaris* L.) and green panic with basal ground cover of 1.9 and 1.2%, respectively. Native grasses (predominately *Dichanthium* spp.) covered 0.13% of the ground area.

Three leucaena transects were carefully matched in terms of landscape and soil properties with three paired transects in an adjacent, continuously cropped area of 400 ha. Prior to leucaena establishment, both areas had been managed under similar cropping regimes (mainly annual summer crops under conventional tillage) for ~20 years. One year after leucaena establishment at the Banana site, buffel grass cvv. Biloela and USA were planted in the inter-rows, and since then the leucaena pasture was continuously grazed by *B. indicus* steers stocked at

0.6 AE/ha. The adjacent cultivated soil was annually cropped under minimum tillage with summer crops (e.g. grain sorghum and sunflower) without nutrient replacement (P. H. Larsen, pers. comm.).

This site was on the Bauhinia soil type, described by Gillespie *et al*. (1991) as a brown-black self-mulching cracking clay (Vertosol) soil (2 VE AE EI CD E - - W—Isbell 1996; Ug5—Northcote *et al*. 1975), derived from basalt with a shallow dark clay horizon (0.8–1.0 m) underlain by weathered sedimentary rock. Soft carbonate segregations (aggregations) and hard nodules or concretions occurred in the subsoil below 0.4–0.5 m and as a surface scatter on some gilgai mounds. The dominant natural vegetation growing in the paired areas before clearing (1968) was brigalow scrub (dominant species *Acacia harpophylla* F. Muell. ex Benth and *Acacia cambagei* R. T. Baker). Although there were some deficiencies in P, sulfur (S), and zinc contents, virgin Vertosol soils were generally considered moderately fertile; however, OC and TN contents were shown to decline fairly quickly under cropping after clearing (Graham *et al*. 1981).

Soil sampling

Soil samples were collected at BPRS in June/July 2006 and at Banana in October 2007. Twenty-four transects 11 m in length were established (three in each leucaena pasture and three in each adjacent grass-only pasture or cropping area). In the leucaena pastures, transects were placed obliquely from 0.2 m from the hedgerow to the middle of the inter-row (1.5 and 2.4 m from the hedgerow at BPRS and Banana, respectively). Each transect was carefully and independently matched in terms of landscape position, slope, and soil properties with a paired transect in the adjacent non-leucaena pasture area, no more than 40 m distant. The assumption underlying the paired comparisons was that both the leucaena and adjacent, non-leucaena areas had similar soil OC and TN before leucaena establishment. Consequently, the difference in these soil fertility parameters within each paired transect could be attributed to the leucaena–grass pastures.

Twelve topsoil core samples were collected from 0 to 0.15 m depth from each transect to decrease the error variance associated with uneven distribution of grass tussocks, roots, and patches of dung and urine along transects. Samples were collected manually using a 1.2-m-long core sampler with a cutting edge of 4 cm diameter. Soil bulk density was measured by collecting six samples per transect using a metal core ring (12.5 cm diameter, 8 cm high) hammered into the ground. Samples were taken using a Tanner Sampler (APR Engineering, Sumner Park, Qld) at field capacity (immediately after rainfall) to avoid changes in density associated with swelling in cracking clay soils (McIntyre and Barrow 1972). Two deep soil samples (to 3 m depth) were taken from each transect using a hydraulic, trailer-mounted corer for comparison of the uniformity of the soil profiles in the paired transects.

Measurements and analytical techniques

Soil samples were air-dried (40°C). Coarse (>2 mm) gravel, plant residue, and root fragments accounted for <5% sample dry weight and were removed before grinding samples to pass a 2-mm sieve. Total soil OC and TN concentrations in the fine (<0.5 mm) fraction were determined by dry-combustion with a LECO CNS-2000 analyser (1996, LECO Corporation, St Joseph, MI) and an Elementar vario MACRO CHN/CHNS analyser (2006, Elemental Analyse System GmbH, Hanau, Germany). Soil samples with visible effervescence of carbonate were detected by wetting with 1 M hydrochloric acid (McDonald *et al*. 1990) and were excluded from the soil OC and TN analysis. Bulk density was calculated on air-dried samples.

In the absence of clay content and mineralogy analysis of all the soil samples, the consistency of the comparisons in the paired transects was tested by measuring the following chemical properties of the deep soil cores divided into increments of 0–0.2, 0.2–0.4, 0.4–0.6, 0.6–1, 1–1.5, 1.5–2, 2–2.5, and 2.5–3 m: pH and electrical conductivity (EC) in a 1 : 5 soil/deionised water suspension (Rayment and Higginson 1992); exchangeable sodium percentage (ESP) by measuring Na ion concentration [1 : 5 soil/deionised water analysed by a Horiba C-122 Na ion meter (2005, Horiba Ltd, Tokyo)] and using the percentage of clay throughout the soil profile (Reid *et al*. 1986) in the equation developed by Irvine and Reid (2001); and aggregate stability by slacking (swelling) and dispersion for coherence of soil aggregates in water (Emerson 1994). At BPRS, soil bulk density, pH, EC, ESP, soil slaking, and soil dispersion values were similar within depths in the paired comparisons between leucaena and adjacent grass pastures (A. Radrizzani, unpubl. data). Even though subsoil sodicity (aggregate dispersion associated with ESP >15%) was observed below 1 m depth in the 20- and 38-year-old leucaena pastures, the same subsoil constraint was observed in the adjacent grass pastures. At the Banana site, topsoil pH in the leucaena pasture was slightly lower than the adjacent cropped topsoils (pH 7.9 ± 0.03 and 8.2 ± 0.04, respectively) but not significantly different. Leucaena pasture and the cropped soil had similar bulk density (Table 1) and EC (0.17 ± 0.010 and 0.15 ± 0.006 dS/m, respectively). Consistent chemical properties within the soil profiles of the leucaena and adjacent non-leucaena transects within the paired comparisons suggest that changes in topsoil OC and TN may be attributed to the effect of leucaena establishment rather than inherent differences in soil composition.

Greenhouse gas balance modelling

Simple GHG balance models were developed to compare C sequestered in the topsoil under leucaena pastures with GHG emissions from cattle grazing the pastures. Gross methane (CH_4) and nitrous oxide (NO_2) emissions from cattle grazing leucaena pastures were estimated using Intergovernmental Panel on Climate Change (IPCC) empirical models populated with field data and assumptions provided by the authors.

Estimates of methane emissions from enteric fermentation were made using IPCC (2006) assumptions that 6.5% of gross energy intake is lost as methane [i.e. 21.55 g CH_4/kg dry matter intake (DMI)]. Animal DMI was estimated using an assumed DM digestibility of leucaena/grass forage of 65% DM (Garcia *et al*. 1996), from which the DMI of steers of 400 kg liveweight was predicted to be 2.18% liveweight/day (MLA 2006). Stocking rates were assumed to be 0.62 AE/ha.year for the 14-year-old leucaena pasture at Banana and 1 AE/ha for 120, 109, and 83 grazing days for the seasonally grazed 20-, 31-, and 38-year-old leucaena pastures, respectively, at BPRS.

Table 1. Change in topsoil (0–0.15 m) organic carbon (OC, mean of three pairs) in relation to pasture treatment in paired transects at Brian Pastures and Banana, Queensland

*$P < 0.05$, **$P < 0.01$: For significance of difference within paired transects between leucaena and adjacent non-leucaena areas. n, Number of samples statistically analysed after omitting samples contaminated with calcium carbonate (maximum is 12/transect × 3 transects = 36)

Treatment	n	Bulk density (g/cm^3) (±s.e.)	Topsoil OC (%) (±s.e.)	Topsoil OC (t/ha)	Additional OC under leucaena (t/ha)	Additional OC under leucaena (kg/ha.year)
			Brian Pastures			
20-year-old grass pasture	28	1.39 ± 0.07	1.47 ± 0.15	30.67		
20-year-old leucaena	29	1.36 ± 0.01	1.76 ± 0.13	36.00	5.33*	266.7
31-year-old grass pasture	35	1.09 ± 0.02	2.25 ± 0.01	37.00		
31-year-old leucaena	32	1.08 ± 0.03	2.54 ± 0.08	41.33	4.33*	139.8
38-year-old grass pasture	32	1.19 ± 0.09	2.81 ± 0.18	50.33		
38-year-old leucaena	34	1.17 ± 0.03	3.04 ± 0.16	53.33	3.00**	78.9
			Banana			
Adjacent cropped land	31	1.39 ± 0.03	1.22 ± 0.06	25.33		
14-year-old leucaena	31	1.37 ± 0.05	1.75 ± 0.16	36.00	10.67*	761.9

Nitrous oxide emissions from dung/urine patches only (emissions from soil organic matter were not considered) were estimated as 1.25% of N excreted from cattle (IPCC 2006). Percentage N in edible DM was assumed to be 3.2% for leucaena and 1% for grass. Retention of N by animals in liveweight gain was assumed to be 8% of that ingested (Burle *et al*. 2003).

Mitigation of GHG by the accumulation of soil OC was estimated as 3.664 kg CO_2-equivalent carbon (CO_2-e) sequestered for every 1 kg soil OC. Significant amounts of C sequestered in the highly labile pools of standing grass and leucaena biomass and soil surface litter were not considered.

Statistical analyses

Analysis of variance of soil OC and TN was performed using the general linear model ($P < 0.05$) to compare treatment effects. Pasture treatment was a fixed factor and the pairs of leucaena and adjacent samples were random factors. To analyse the effect of leucaena hedgerow on soil OC and TN, the first two samples beside the leucaena hedgerow were compared with the last two samples in the middle of the inter-row. All statistical analyses were carried out using Minitab 15 (2007, Minitab Inc., State College, PA). Data for each soil parameter were normally distributed within transects, and means of each transect were calculated.

Results

Topsoil organic carbon

Mean OC ranged from 1.47 to 2.81% among the three adjacent grass pasture sites at BPRS, and was 1.22% in the cropped soil at Banana. Soils under leucaena pastures had higher ($P < 0.05$) OC contents than soils under adjacent grass-only pastures across all paired transects at the four sites (Table 1). At BPRS, the average increase in OC was 0.28, 0.29, and 0.22% for the 20-, 31-, and 38-year-old pastures, which represented an average increment of 5.3, 4.3, and 3.0 t/ha, respectively, or 267, 140, and 79 kg/ha.year. By comparison, the average OC in the 14-year-old leucaena-grass pasture at Banana was 0.53% higher than the adjacent cropping areas, which represented a difference of 10.7 t/ha or 762 kg OC/ha.year (Table 1).

In the 14-, 20-, and 31-year-old leucaena pastures, soil OC was higher ($P < 0.05$) in the two samples near leucaena hedgerow than the two samples in the middle of the inter-row (Fig. 1), but in the 38-year-old leucaena pasture, soil OC was similar in all samples.

Topsoil total nitrogen

Mean TN ranged from 0.12 to 0.19% among the three adjacent grass-only pastures at BPRS and was 0.10% in the cropped soil at Banana (Table 2). Leucaena soils had higher ($P < 0.05$) TN than the adjacent soils in all paired transects at the four sites (Table 2). Compared with adjacent grass-only pastures at BPRS, the average increases in TN were 0.020, 0.020, and 0.037% for the 20-, 31-, and 38-year-old pastures, which represented an increment of 0.33, 0.33, and 0.53 t N/ha or 16.7, 10.8, and 14.0 kg N/ha.year, respectively. The average TN in the leucaena–grass pasture at the Banana site was 0.047% higher than the adjacent cropping area, a difference of 0.87 t N/ha or 61.9 kg N/ha.year. Within transects, TN was higher ($P < 0.05$) immediately adjacent to the leucaena hedgerows than in the middle of inter-rows in the 14-, 20-, and 31-year-old leucaena pastures, but was similar adjacent to hedgerows and in the inter-rows in the 38-year-old leucaena pasture (Fig. 1).

Topsoil carbon : nitrogen ratio

At BPRS, topsoil C : N ratios ranged from 12.7 to 14.5 in the adjacent grass-only pastures and were similar to the leucaena pastures (12.8–13.4). At Banana, the topsoil C : N ratio was 12.6 in the cropped soil and 12.2 in the leucaena–grass pasture.

Greenhouse gas balance modelling

At BPRS, modelling of the seasonal grazing system indicated that the 20-year-old leucaena pasture was carbon-neutral when comparing annual gross GHG emissions from grazing cattle with the average annual quantity of topsoil OC accumulated (Table 3). The older leucaena pastures had negative GHG balances, as cattle emissions exceeded C sequestration in soil OC. At the Banana site, leucaena pastures stored more GHG (2792 kg CO_2-e/ha.year) in soil OC than modelled estimates of cattle GHG emissions compared with an adjacent soil used for annual cropping.

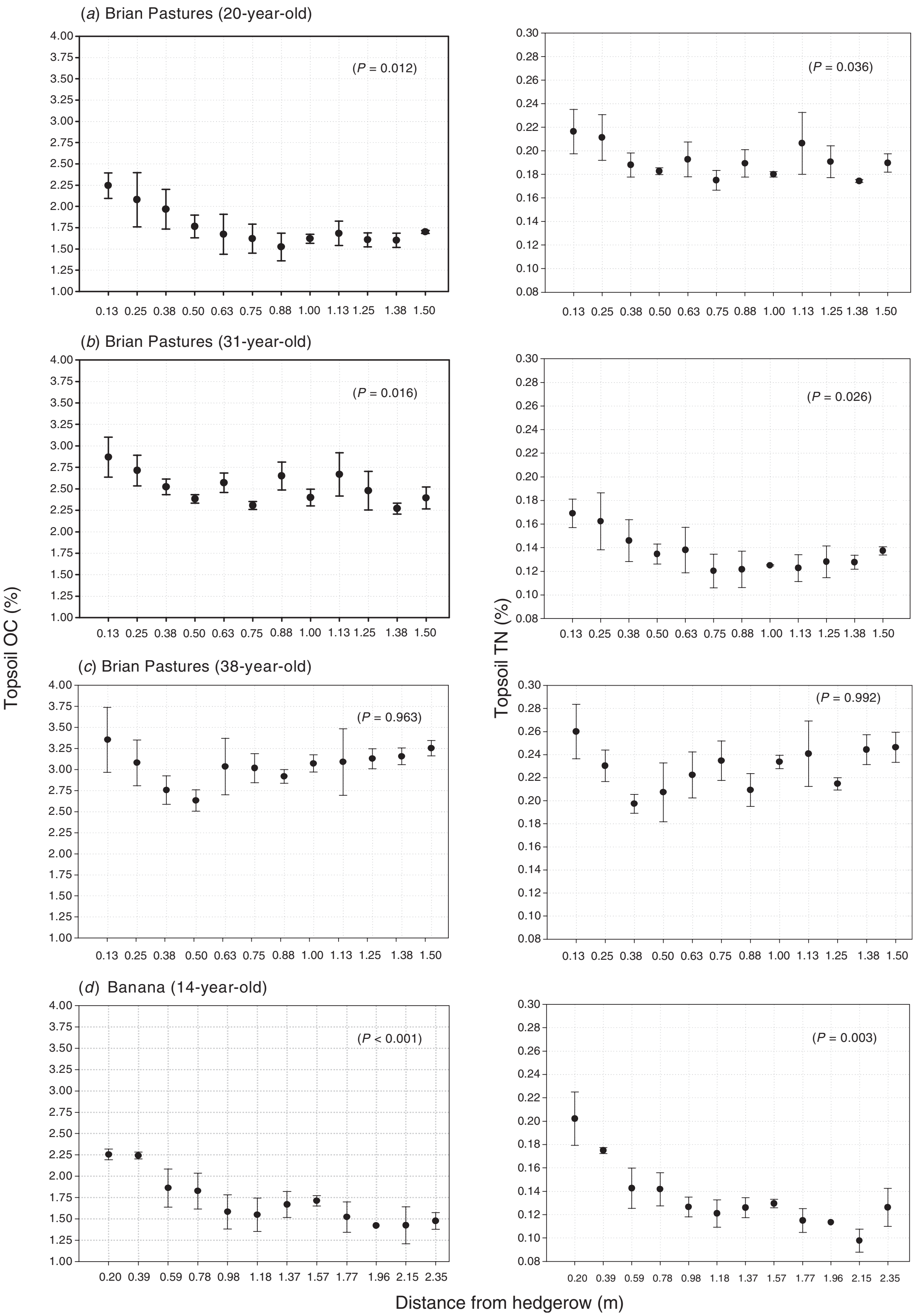

Fig. 1. Soil organic carbon (OC) and total nitrogen (TN) in relation to distance from leucaena hedgerow in pastures of age (*a*) 20, (*b*) 31, and (*c*) 38 years at Brian Pastures (single rows 3 m apart) and (*d*) 14 years at Banana (twin rows 5.5 m apart centre-to-centre). *P*-values are comparisons between the first two samples near hedgerow and the last two samples in the middle of the inter-row. Bars represent standard errors of the mean.

Table 2. Change in topsoil (0–0.15 m) total nitrogen (TN, mean of three pairs) and carbon (C) : N ratio in relation to pasture treatment in paired transects at Brian Pastures and Banana, Queensland

n.s., Not significant ($P > 0.05$); $*P < 0.05$: For significance of difference within paired transects between leucaena and adjacent non-leucaena areas

Treatment	Topsoil TN (%) (±s.e.)	Topsoil TN (t/ha)	Additional TN under leucaena (t/ha)	Additional TN under leucaena (kg/ha.year)	Mean C : N ratio (±s.e.)	Change in C : N ratio
Brian Pastures						
20-year-old grass pasture	0.12 ± 0.01	2.47			12.65 ± 0.43	
20-year-old leucaena	0.14 ± 0.01	2.80	0.33*	16.67	12.84 ± 0.42	0.19n.s.
31-year-old grass pasture	0.17 ± 0.01	2.77			13.25 ± 0.34	
31-year-old leucaena	0.19 ± 0.01	3.10	0.33*	10.75	13.39 ± 0.40	0.14n.s.
38-year-old grass pasture	0.19 ± 0.01	3.47			14.53 ± 0.54	
38-year-old leucaena	0.23 ± 0.01	4.00	0.53*	14.04	13.21 ± 0.55	–1.32n.s.
Banana						
Adjacent cropped land	0.10 ± 0.01	2.00			12.58 ± 0.48	
14-year-old leucaena	0.14 ± 0.01	2.87	0.87*	61.90	12.18 ± 0.70	–0.40n.s.

Table 3. Annual additional soil organic carbon (OC) increment, gross greenhouse gas (GHG) emissions, and GHG carbon balance (kg/ha.year) for leucaena–grass pastures under different management practices at Brian Pastures and Banana, Queensland

Management practice	Additional soil OC	Additional soil OC as CO_2-e[A]	CH_4 emitted	NO_2 emitted	Total GHG emitted as CO_2-e[A]	CO_2-e balance
Brian Pastures						
20-year-old leuc. *v.* grass-only pasture	267	977	36.1	0.36	932	45
31-year-old leuc. *v.* grass-only pasture	140	512	32.8	0.32	847	–335
38-year-old leuc. *v.* grass-only pasture	79	289	25.0	0.25	645	–356
Banana						
14-year-old leuc. *v.* cropped soil	762	2792	45.7	0.65	1244	1548

[A]3.664 kg CO_2-equivalent carbon (CO_2-e) is sequestered from the atmosphere for every kg carbon accumulated in soil OC. Global warming potential (100-year) factors for 1 kg CH_4 = 23 kg CO_2-e and 1 kg NO_2 = 296 kg CO_2-e were used to calculate total GHG emissions for each pasture.

Discussion

Despite the statistical limitations of the observational paired sampling experimental design employed, trial results showed that soil OC and TN significantly increased as a result of leucaena establishment into native grass pastures and an annually cropped soil, thus confirming the hypothesis under investigation. There was no significant effect on the C : N ratios of the topsoil resulting from leucaena pasture establishment. A lack of effective replication and no accurate baseline measurements of the soil characteristics of the farming systems under investigation prevented rigorous statistical comparison of the treatments. However the study did generate data from real on-farm situations that has practical value describing the changes in soil fertility under different land-use regimes.

Leucaena established into grass pastures

Changes in organic carbon

Overall, topsoil OC levels for leucaena and adjacent grass pastures were within the range (1.4–3.4%) reported by Spain *et al.* (1983) in 327 clay (Vertosol) soils of north-eastern Australia; and were similar to the levels (1.5–2.5%) reported by Reid *et al.* (1986) in the topsoil of native grass pastures in non-alluvial black earths (Vertosol) at BPRS. The 20-year-old leucaena pasture had 17% more topsoil OC (5.33 t/ha) than the adjacent native grass pasture, which represented an increase of 0.014% OC/year or 267 kg OC/ha.year. Similar increments in soil OC were observed over periods of 9–16 years when *Centrosema pubescens* (Bruce 1965), *Desmodium ovalifolium* (Tarré *et al.* 2001), and *Stylosanthes capitata* and *Arachis pintoi* (Fisher *et al.* 1994) were oversown into tropical grass swards. There was a decline in OC accumulation with age of the leucaena stands from 5.3 to 3.0 t/ha for the 20- and 38-year-old leucaena pastures, respectively. This was most likely related to a reduction in leucaena population and productivity due to the depletion of P and S and an associated decline in biological N_2 fixation (Radrizzani *et al.* 2010). Higher soil OC was found near leucaena hedgerows than in the middle of the inter-row, with the exception of the 38-year-old leucaena. Grazing management (e.g. rotational, seasonal, or continuous grazing) and weather conditions (e.g. frost and drought) can influence the proportions of leucaena leaf fall and leaf recycled via dung. In coastal south-east Queensland where leaf fall due to frost or drought was minimal, Burle *et al.* (2003) found that most (>95%) of the edible leucaena DM (OC) was transferred via dung in a leucaena pasture that was heavily stocked over summer–autumn. However, in frost-prone areas, leucaena leaf fall can contribute a substantial proportion of the C returned to the soil. Cooksley *et al.* (1988) reported that leaf fall was 30–40% of the annual edible leucaena DM yield under the typical seasonal grazing system imposed at BPRS. Leaf fall could be expected to distribute larger amounts of soil OC near the leucaena hedgerow, as found in 20- and 31-year-old pastures, whereas OC recycled through grazing animals (faeces) will be distributed more evenly over the entire grazed area. In the 38-year-old pastures, high densities of leucaena seedlings in the inter-row and fewer leucaena plants of reduced vigour within the ageing hedgerows (A. Radrizzani, unpubl. data) may have resulted in more uniform distribution of leucaena litter.

Biomass production of ageing grass pastures is limited due to soil N being immobilised in litter and soil organic matter (Graham *et al*. 1981; Robertson *et al*. 1997). In addition to increasing topsoil OC directly via litter deposition and root C turnover, leucaena biological N fixation may have enhanced nutrient cycling, biomass production, and increased soil OC input by the inter-row grass. Additional research is currently under way to investigate the relative contribution over time of leucaena (C_3) and tropical grasses (C_4) to soil C stocks under leucaena–grass pastures in Queensland (K. Conrad, pers. comm.). Root C turnover would have contributed to soil OC, particularly under grazed leucaena pastures. Several studies have found significant turnover of fine roots of leucaena as a result of defoliation (Fownes and Anderson 1991; Jayasundara *et al*. 1997). Deep-rooted leucaena might have increased OC in the subsoil, not measured in this study, since a larger proportion of fine roots (>60%) was observed below 0.4 m compared with the adjacent grass pastures (A. Radrizzani, unpubl. data). Carter *et al*. (1998) found that pastures of perennial woody legumes leucaena and *Stylosanthes* spp. >10 years of age accumulated more OC between 0.2 and 0.65 m in the soil profile than adjacent native pastures (equivalent to an additional ~5 t OC/ha) in northern Australia.

Changes in total nitrogen and carbon : nitrogen ratio

Overall, TN content and C : N ratios of leucaena and adjacent grass pastures were within the range 0.08–0.22% and 9–14, respectively, reported by Spain *et al*. (1983) for topsoil (0–0.15 m) in 327 Vertosol soils of north-eastern Australia and close to the levels of 0.10–0.18% and 14–15, respectively, reported by Reid *et al*. (1986) in topsoil of native grass pastures in non-alluvial black earth (Vertosol) soils at BPRS. Significant increases in soil TN in leucaena pastures followed trends similar to those for soil OC, confirming that most of the N (~90% in Anderson and Vaughan 1985) was bound up with OC in organic matter. Similar C : N ratios in the leucaena pastures and grass-only areas indicate that plant-available N limited soil OC accumulation in pure grass swards, and biological N_2 fixation by leucaena increased soil OC stocks. Relatively constant C : N ratios in soil organic matter have also been reported in other grass–legume pastures in Queensland (Hossain *et al*. 1996; Cullen and Hill 2006) and Brazil (Tarré *et al*. 2001).

Leucaena established in cropping soils

At the Banana site, the OC and TN contents for leucaena (1.75% and 0.14%) and cropped soils (1.22% and 0.10%) were within the average ranges of 1.0–3.0% and 0.09–0.28%, respectively, reported by Isbell (1962) for brigalow Vertosol soils. Results showed that soil under leucaena–grass pastures contained substantially higher OC (0.53%) than continuously cropped soil, with an average difference of 0.04% OC/year. Similar differences in soil OC (+0.02–0.05% OC/year) have been reported in comparisons after 4–7 years of lucerne (*Medicago sativa*)–grass (Whitehouse and Littler 1984), *Setaria incrassata*–*Chloris gayana* combined with lucerne and annual medics (*Medicago scutellata* and *Medicago truncatula*) (Dalal *et al*. 1995), and *Clitoria ternatea*–grass and *Desmanthus* spp.–grass (Cullen and Hill 2006) pastures with continuously cropped Vertosol soils in southern and central Queensland. The paired comparison approach used at the Banana site overestimated the rate of soil OC accumulation under leucaena–grass pastures by not accounting for OC loss (3–6%/year; Dalal and Mayer 1986; Standley *et al*. 1990) due to cultivation of the Vertosol soil.

Soil OC and associated TN were higher near leucaena hedgerows than the middle of the inter-row in the pasture at Banana, which was continuously grazed at a low level of utilisation (stocking rate 1 AE/1.6 ha). Shading by the leucaena hedgerows may have moderated soil temperatures, arresting soil OC degradation rates and resulting in greater OC accumulation (Dalal and Carter 2000). Soil TN may be more uniformly distributed across the inter-row under intensive rotational grazing systems, which result in more even distribution of N cycled through dung and urine. The soil OC that accumulated under leucaena–grass pastures may be more durable than that accumulated under shorter term ley pasture options due to a higher proportion of inert humus (heavy fraction) OC compared to labile particulate (light fraction) OC; the latter fraction degrades at a faster rate (Dalal and Carter 2000). Furthermore, deposition of soil OC at greater depths in the soil profile from leucaena root turnover would enhance the pool of less-labile soil OC (Fisher *et al*. 1994; Follett *et al*. 2003).

Greenhouse gas balance in leucaena–grass pastures

Agriculture produced 87.4 Mt CO_2-e or 16% of Australia's GHG emissions in 2008 (Department of Climate Change and Energy Efficiency 2010), of which 58.9 Mt was derived from methane generated by enteric fermentation by ruminant livestock (55.6 Mt) and manure (excreta) management (3.3 Mt). Using long-term perennial grass–legume pastures that increase soil OC sequestration (Dalal *et al*. 1995) by increasing net primary production and reducing soil erosion can mitigate animal GHG emissions. Comparing estimates of gross GHG emissions with the increased rates of topsoil OC accumulation in healthy leucaena pastures ≤20 years old suggests that the amount of additional OC accumulated due to leucaena establishment in native grass pastures and cropped soils may offset GHG emissions from grazing cattle (Table 3). However, GHG balances in ageing, rundown leucaena pastures (31- and 38-year-old pastures) became negative as the amount of CO_2-e methane emitted by cattle grazing these pastures exceeded the amount of CO_2-e accumulated in additional topsoil OC. The simple gross GHG balance estimates made in this study are conservative, as the models did not account for: (*a*) additional C stored in the woody frames and roots of leucaena hedgerows, estimated at 3.9 t/ha of C (>14 t/ha of CO_2-e) sequestered in established leucaena–grass pastures >5 years old (B. F. Mullen, unpubl. data); (*b*) the deduction of methane and nitrous oxide emissions from alternative land uses of grass-only pastures or continuous cropping; and, most importantly, (*c*) additional soil OC accumulated below the top 0.15 m of soil. Significant increases in soil OC would have occurred throughout the profile below 0.15 m, as leucaena–grass pastures had a larger number of fine roots (>60%) in the subsoil than adjacent native grass pastures (A. Radrizzani, unpubl. data). Further experimental work is required to accurately quantify the C stocks in these pools in leucaena pastures covering the spectrum of soil, climate, and management conditions under which the system is utilised.

Conclusions

The establishment of leucaena hedgerows into native grass pastures and leucaena/grass pastures on cropping soil increased soil OC and TN. OC accumulated under the leucaena–grass pasture at rates that exceeded those of the native grass pasture by 267, 140, and 79 kg/ha.year for leucaena–grass pastures that had been established for 20, 31, and 38 years, respectively. There was higher soil OC accumulation near leucaena hedgerows than in the middle of the inter-row in most of the leucaena–grass pastures due to leucaena litter deposition and root C turnover. Lower rates of additional topsoil OC accumulation were observed in the older leucaena–grass pastures, related to the decline in leucaena yield and biological N fixation in ageing leucaena pastures. Soil TN followed trends similar to soil OC; the C : N ratio of soil organic matter remained steady. This indicated that soil OC accumulation (C sequestration) in pure grass pastures was limited by N availability and that legumes are required to increase in soil OC. Simple modelling predicted that the amount of CO_2-e accumulated in additional topsoil OC of productive leucaena–grass pastures $\leq$20 years old offset the amount of methane and nitrous oxide emitted by cattle grazing them. However, GHG balance may become negative in ageing, run-down leucaena pastures. Accordingly, the establishment and maintenance of vigorous leucaena–grass pastures can be viewed as a positive long-term GHG mitigation strategy.

Acknowledgments

A. Radrizzani received a PhD scholarship from INTA to study in Australia. Utilisation of AgForce Queensland's Brian Pastures Research Station and the assistance of Mr Peter Larsen were greatly appreciated. Dell Greenway and Olena Kravchuk, The University of Queensland, provided statistical analysis advice. This work was sponsored by The Leucaena Network and funded by Meat and Livestock Australia's Producer Initiated Research and Development program (PIRD.06.Q01).

References

Anderson HA, Vaughan D (1985) Soil nitrogen: its extraction, distribution and dynamics. In 'Soil organic matter and biological activity'. Developments in Plant and Soil Sciences, Vol. 16. (Eds D Vaughan, RE Malcolm) pp. 289–327. (Martinus Nijhoff/Dr W Junk Publishers: Dordrecht, The Netherlands)

Armstrong RD, Kuskopf BJ, Millar G, Whitbread AM, Standley J (1999) 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. doi:10.1071/EA99014

Bruce RC (1965) Effect of *Centrosema pubescens* Benth on soil fertility in the humid tropics. *Queensland Journal of Agricultural and Animal Sciences* **22**, 221–226.

Bruce RC, Rayment GE (1982) 'Analytical methods and interpretations used by the Agricultural Chemistry Branch for soil and land use surveys.' Queensland Department of Primary Industries Bulletin QB82004. (Queensland Department of Primary Industries: Brisbane)

Burle STM, Shelton HM, Dalzell SA (2003) Nitrogen cycling in degraded *Leucaena leucocephala-Brachiaria decumbens* pastures on an acid infertile soil in south-east Queensland, Australia. *Tropical Grasslands* **37**, 119–128.

Carter JO, Howden SM, Day KA, McKeon GM (1998) Soil carbon, nitrogen and phosphorus and biodiversity in relation to climate change. In 'Evaluation of the impact of climate change on northern Australian grazing industries'. Final report for the Rural Industries Research and Development Corporation project DAQ 139A. (Eds GM McKeon, JO Carter, KA Day, WB Hall, SM Howden) pp. 185–249. (RIRDC: Brisbane)

Catchpoole DW, Blair GJ (1990) Forage tree legumes. III. Release of nitrogen from leaf, faeces and urine derived from leucaena and gliricidia leaf. *Australian Journal of Agricultural Research* **41**, 539–547. doi:10.1071/AR9900539

Clark H, Pinares-Patino C, deKlein C (2005) Methane and nitrous oxide emissions from grazed grasslands. In 'Grassland: a global resource'. (Ed. DA McGilloway) pp. 279–293. (Wageningen Academic Publishers: Wageningen, The Netherlands)

Cooksley DG, Prinsen JH, Paton CJ (1988) *Leucaena leucocephala* production in subcoastal, south-east Queensland. *Tropical Grasslands* **22**, 21–26.

Cullen BR, Hill JO (2006) A survey of the use of lucerne, butterfly pea and lablab in ley pastures in the mixed-farming systems of northern Australia. *Tropical Grasslands* **40**, 24–32.

Dalal RC, Carter JO (2000) Soil organic matter dynamics and carbon sequestration in Australian tropical soils. In 'Global climate change and tropical ecosystems'. (Eds R Lal, JM Kimble, BA Stewart) pp. 283–314. (CRC Press: Boca Raton, FL)

Dalal RC, Mayer RJ (1986) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. *Australian Journal of Soil Research* **24**, 265–279. doi:10.1071/SR9860265

Dalal RC, Strong WM, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1995) Sustaining productivity of a vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes. 1. Organic matter status. *Australian Journal of Experimental Agriculture* **35**, 903–913. doi:10.1071/EA9950903

Dalzell SA, Shelton HM (2002) Genotypic variation in proanthocyanadin status in the *Leucaena* genus. *The Journal of Agricultural Science* **138**, 209–220. doi:10.1017/S0021859601001848

Department of Climate Change and Energy Efficiency (2010) 'National greenhouse gas inventory 2008: accounting for the Kyoto target.' (Department of Climate Change and Energy Efficiency: Canberra)

Emerson WW (1994) Aggregate slaking and dispersion class, bulk properties of soil. *Australian Journal of Soil Research* **32**, 173–184. doi:10.1071/SR9940173

Fisher MJ, Rao IM, Ayarza MA, Lascano CE, Sanz JI, Thomas RJ, Vera RR (1994) Carbon storage by introduced deep-rooted grasses in the South American savannas. *Nature* **371**, 236–238. doi:10.1038/371236a0

Follett RF, Leavitt SW, Kimble JM, Pruessner EG (2003) Paleoenvironmental inferences from $\delta^{13}C$ of soil organic C in ^{14}C-dated profiles in the U.S. Great Plains. In 'XVI INQUA Congress'. Reno, Nevada, 23–30 July 2003. Program with abstracts. p. 204. (Desert Research Institute: Reno, NV)

Fownes JH, Anderson DG (1991) Changes in nodule and root biomass of *Sesbania sesban* and *Leucaena leucocephala* following coppicing. *Plant and Soil* **138**, 9–16. doi:10.1007/BF00011802

Garcia GW, Ferguson TU, Neckles FA, Archibald KAE (1996) The nutritive value and forage productivity of *Leucaena leucocephala*. *Animal Feed Science and Technology* **60**, 29–41. doi:10.1016/0377-8401(95)00922-1

Gillespie RL, Shields PG, Cannon RS (1991) 'Land management manual Dawson–Callide district.' (Queensland Department of Primary Industries: Brisbane)

Graham TWG, Webb AA, Waring SA (1981) Soil-nitrogen status and pasture productivity after clearing of brigalow (*Acacia harpophylla*). *Australian Journal of Experimental Agriculture and Animal Husbandry* **21**, 109–118.

Hossain SA, Dalal RC, Waring SA, Strong WM, Weston EJ (1996) Comparison of legume-based cropping systems at Warra, Queensland. I. Soil nitrogen and organic carbon accretion and potentially mineralisable nitrogen. *Australian Journal of Soil Research* **34**, 273–287. doi:10.1071/SR9960273

IPCC (2006) 2006 IPCC guidelines for national greenhouse inventories. In 'National Greenhouse Inventories Programme'. (Eds HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe) (Institute for Global Environmental Strategies: Hayama, Japan)

Irvine SA, Reid DJ (2001) Field prediction of sodicity in dryland agriculture in Central Queensland, Australia. *Australian Journal of Soil Research* **39**, 1349–1357. doi:10.1071/SR00075

Isbell RF (1962) 'Soils and vegetation of the brigalow lands, eastern Australia.' Soils and Land Use Series 43. (CSIRO Division of Soils: Melbourne)

Isbell RF (1996) 'The Australian Soil Classification.' (CSIRO Publishing: Melbourne)

Jayasundara HPS, Dennett MD, Sangakkara UR (1997) Biological nitrogen fixation in *Gliricidia sepium* and *Leucaena leucocephala* and transfer of fixed nitrogen to an associated grass. *Tropical Grasslands* **31**, 529–537.

Jha MN, Dimri BM, Gupta MK (1991) Soil nutrient changes in *Leucaena leucocephala* plantings of different durations. *Leucaena Research Reports* **12**, 42–44.

Kang BT, Grimme H, Lawson TL (1985) Alley cropping sequentially cropped maize and cowpea with leucaena on a sandy soil in southern Nigeria. *Plant and Soil* **85**, 267–277. doi:10.1007/BF02139631

Lalljee B, Facknath S, Osman AM (1998) Improvement of soil properties under long-term *Leucaena leucocephala*. In 'Leucaena – adaptation, quality and farming systems. Proceedings of a Workshop'. Hanoi, Vietnam, 9–14 February 1998. ACIAR Proceedings No. 86. (Eds HM Shelton, RC Gutteridge, BF Mullen, RA Bray) pp. 178–180. (ACIAR: Canberra)

't Mannetje L. (2007) The role of grasslands and forests as carbon stores. *Tropical Grasslands* **41**, 50–54.

McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (1990) 'Australian soil and land survey: field handbook.' (CSIRO Land and Water: Canberra)

McIntyre DS, Barrow KJ (1972) An improved sampling method for small undisturbed cores. *Soil Science* **114**, 239–241. doi:10.1097/00010694-197209000-00013

MLA (2006) 'Beef cattle nutrition: an introduction to the essentials.' (Meat and Livestock Australia Ltd: Sydney)

Myers RJK, Robbins GB (1991) Sustaining productive pastures in the tropics. 5. Maintaining productive sown grass pastures. *Tropical Grasslands* **25**, 104–110.

Northcote KH, Hubble GD, Isbell RF, Thompson CH, Bettenay E (1975) 'A description of Australian soils.' (CSIRO Publishing: Melbourne)

Onim JFM, Mathura M, Otieno K, Fitzhugh HA (1990) Soil fertility changes and response of maize and beans to green manures of leucaena, sesbania and pigeonpea. *Agroforestry Systems* **12**, 197–215. doi:10.1007/BF00123474

Radrizzani A, Shelton HM, Dalzell SA (2010) Response of *Leucaena leucocephala* pastures to phosphorus and sulfur application in Queensland. *Animal Production Science* **50**, 961–975. doi:10.1071/AN10062

Rayment GE, Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods.' (Inkata Press: Melbourne)

Reid RE, Sorby P, Baker DE (1986) 'Soils of the Brian Pastures Research Station, Gayndah, Queensland.' (Queensland Department of Primary Industries: Brisbane)

Robertson FA, Myers RJK, Saffigna PG (1997) Nitrogen cycling in brigalow clay soils under pasture and cropping. *Australian Journal of Soil Research* **35**, 1323–1339. doi:10.1071/S97026

Shaw RJ, Yule DF (1978) 'The assessment of soils for irrigation, Emerald, Queensland.' Agricultural Chemistry Branch Technical Report 13. (Queensland Department of Primary Industries: Brisbane)

Shelton M, Dalzell S (2007) Production, economic and environmental benefits of leucaena pastures. *Tropical Grasslands* **41**, 174–190.

Spain AV, Isbell RF, Probert ME (1983) Soil organic matter. In 'Soils: an Australian viewpoint'. pp. 551–563. (Academic Press: London)

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 sub-tropics. 2. Changes in soil properties. *Soil & Tillage Research* **18**, 367–388. doi:10.1016/0167-1987(90)90121-S

Tarré R, Macedo R, Cantarutti RB, Rezende C de P, Pereira JM, Ferreira E, Alves BJR, Urquiaga S, Boddey RM (2001) The effect of the presence of a forage legume on nitrogen and carbon levels in soils under *Brachiaria* pastures in the Atlantic forest region of the South of Bahia, Brazil. *Plant and Soil* **234**, 15–26. doi:10.1023/A:1010533721740

Whitehouse MJ, Littler JW (1984) Effect of pasture on subsequent wheat crops on a black earth soil of the Darling Downs. II. Organic C, nitrogen and pH changes. *Queensland Journal of Agricultural and Animal Sciences* **41**, 13–20.

Manuscript received 1 April 2010, accepted 18 March 2011