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Soil organic matter changes and crop responses to fertiliser under conservation cropping systems in the semi-arid tropics of North Queensland, Australia

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Summary. Soil organic matter changes due to cropping in the semi-arid tropics were studied in an area with cropping potential. Soil organic carbon and total nitrogen (N) decreased after clearing and tillage, but the decline was less where pasture–crop rotations were used. Crop N removal was high and exceeded the recommended fertiliser N rate. These results suggest that if cropping expansion occurs, careful management is necessary for long-term productivity and land resource protection.

Introduction

Large areas of red earth soils in North Queensland have cropping potential (Weston *et al.* 1981), but previous limited cropping has had varied success (East 1989). Cogle *et al.* (1990, 1991) discussed the agronomic and environmental constraints to successful cropping in the region. Other local studies on these soils have indicated deficiencies of phosphorus (P), sulfur (S), and zinc (Zn), and low levels of nitrogen (N) for pasture legumes (Gilbert and Shaw 1987). Similar findings have been reported on red earths in the Northern Territory, where Peake *et al.* (1983) and Jones *et al.* (1985) reported that N, P, S, and Zn were commonly deficient and that erosion, leaching, denitrification, volatilisation, and removal of marketable products were the main causes.

An important feature of tillage-based cropping systems in the tropics is the rapid breakdown of organic matter due to high temperatures and moisture (Lal 1989). This results in loss of soil nutrient reserves and may lead to a deterioration in soil structural stability (Mullins *et al.* 1987). There is little information on organic matter changes under cropping systems in the red earths of North Queensland or the potential for soil degradation via nutrient depletion and organic matter decline. Similarly, limited data are available on crop response to N inputs either by fertiliser or legumes.

This paper reports the effects of tillage and pasture–crop rotations on soil organic carbon (C) and total N, and crop response to fertilisers, on a red earth with reported cropping potential.

Materials and methods

Climate and soil

The experimental site was at Pinnarendi (18°03'S, 144°07'E) in the semi-arid tropics of Queensland. The long-term average rainfall at Mt Garnet (60 km north-east) is 797 mm. October–April rainfall for 1987–88 and 1988–89 was 515 and 982 mm, respectively. Rainfall records for the 4 years of the project (October 1985–April 1989) are presented in Cogle *et al.* (1991). The soil type was a red earth (Typic Eutrustox) (M. Grundy and I. Heiner pers. comm.). At the start of the experiment, soil (0–10 cm depth) properties were pH 6.5, 22 μg P/g (Olsen P), 0.46 cmol(+) K/kg, 0.03% total N, and 1.26% organic C. The surface soil had a clay content 13–24%, increasing to 40–60% below 40 cm depth. The site had been cropped to sorghum, maize, and peanuts in various combinations over the previous 6 years.

Experimental design and agronomy

The experiment was described in detail by Cogle *et al.* (1991). The 16-ha area consisted of 3 blocks: no tillage; reduced tillage; ley. The no tillage and reduced tillage blocks were each 4.8 ha; the ley block was 6.4 ha. The plots within each block were 1.4 ha (there was a small roadway between plots). Two plots within the ley block initially failed and were not considered for the rest of the experiment. Therefore, there were 3 plots of no tillage, 3 plots of reduced tillage, and 2 plots of ley.

Reduced tillage consisted of 2 passes of a chisel plough with sweeps (35 cm) and a rod weeder before sowing. No tillage consisted of herbicidal weed control (glyphosate). Atrazine and metolachlor were used as pre-emergent herbicides after sowing in both no tillage and reduced tillage, and both treatments were sown with a tine planter. Within the reduced and no tillage blocks, the plots (700 by 20 m) were cropped on a rotational basis to peanuts (*Arachis hypogaea*), maize (*Zea mays*), and sorghum (*Sorghum bicolor*). In the 2 ley plots, Verano stylo (*Stylosanthes hamata*), a tropical pasture legume, was planted in December 1985. Verano was grazed in each dry season. The first ley plot was cropped to sorghum using no till practices in 1987–88 and 1988–89. The second ley plot was cropped in 1988–89. An area of Verano pasture within the 2 ley plots was left uncropped for the experiment. It was not grazed in 1988–89.

Sowing times varied depending on the incidence of planting rains. In 1987–88, peanuts and maize were planted on 31 December 1987 and sorghum on 19 January 1988. In 1988–89, peanuts and maize were planted on 16 December 1988 and sorghum on 18 January 1989. Row lengths were 700 m. Row spacings were 0.91 m for maize and peanuts and 0.75 m for sorghum.

The experiment consisted of 4 seasons' trials (1985–86 to 1988–89) with no replication in any year. This design was based on a systems approach to allow a farm-scale comparison of the cropping systems. As such, normal statistical analyses could not be undertaken and results were analysed using means and standard deviations of within-plot samples. The crop fertility effects were assessed in the final 2 years of the trial (1987–88 and 1988–89).

Soil organic carbon and total nitrogen

At the start of the experiment the soil was sampled for organic C and total N at 4 locations. After 4 seasons (August 1989), 10 soil samples were taken in each treatment and in an adjacent natural woodland and divided into 3 depths (0–5, 5–10, 10–20 cm). Organic C was determined using Walkley Black wet oxidation and total N using an automated Kjeldahl method (Bruce and Rayment 1982).

Fertiliser application and sampling methods

Sorghum. Fertiliser treatments were imposed within the sorghum plots of the reduced tillage, no tillage, and ley blocks. Treatments were control (no fertiliser) and a mixed fertiliser of 80 kg N + 23 kg P/ha. In 1988–89 the added fertiliser also included (kg/ha) 31 K, 18 S, and 4 Zn. In 1987–88 the control area within both the reduced tillage and ley sorghum plots was 40 by 12 m; the no tillage sorghum crop did not establish well and so a control treatment was not imposed. In 1988–89, 2 control areas each of about 150 by 12 m were used within the sorghum plot of each tillage block.

Fertilised areas were sampled by randomly selecting twelve 5-m lengths of rows within each treatment. At each harvest, grain or pods were sampled from each 5-m row, and 2 m of the row was sampled for vegetative yield (shoots). Unfertilised areas were sampled in the same way, with four 5-m rows in 1987–88, and 10 in 1988–89. Where Verano grew between rows, this was sampled from one side of the 2-m zone.

Maize and peanuts. Maize was fertilised in 1987–88 and 1988–89 at the same rate as sorghum. Sampling procedures were as used for sorghum. Peanuts received no fertiliser in 1987–88, and in 1988–89, 16 kg P and 5 kg Zn/ha. Twelve 5-m rows were randomly chosen within each block for pod and vegetative sampling, as for sorghum.

Plant nutrient analysis

Plant N analyses were determined on all samples by the Kjeldahl method (Bruce and Rayment 1982).

Results

Soil organic carbon and total nitrogen

In August 1989, organic C (Table 1) under no tillage was about half that in the adjacent natural woodland but was higher than under reduced tillage. The ley treatment had higher organic C concentrations than both tillage treatments but lower than both the natural woodland and a Verano pasture of 4 years duration. The Verano pasture had values intermediate to the cropped and natural woodland areas. Organic C declined with depth in all treatments, with trends between treatments remaining. Organic C in the no tillage treatment in August 1989 was similar to the initial value in June 1985 (Table 1).

A similar trend existed for total N, except that total N under ley was lower than under no tillage. Total N levels at 0–5 and 5–10 cm depths were generally lowest under reduced tillage (Table 1).

Fertiliser response and nutrient removal

Grain yields. Grain yields (Table 2) of unfertilised sorghum areas (867–2741 kg/ha) were 46–67% of respective fertilised areas (1903–4390 kg/ha) over both seasons, excluding the failed no tillage sorghum crop in 1988–88. Vegetative yield ratios ranged between 0.59 and 0.82. The lowest yield ratios occurred when sorghum followed Verano on ley plots. For maize and peanut (Table 2), the yield advantage of reduced tillage over no tillage was greater in the drier 1987–88 season than the more favourable 1988–89 season.

Nitrogen concentration. In 1987–88, the N concentration (Table 2) of sorghum grain from

Table 1. Mean (± s.d.) organic carbon and total nitrogen concentrations in August 1989 at three depths as affected by tillage treatment

Organic C (0–10 cm) was 1.26 ± 0.35% and total N was 0.038 ± 0.026% in June 1985

Depth (cm)	Reduced tillage	No tillage	Ley	Verano pasture	Natural woodland
			Organic carbon (%)		
0–5	0.89 ± 0.25	1.35 ± 0.33	1.56 ± 0.31	1.83 ± 0.23	2.85 ± 0.43
5–10	0.77 ± 0.29	1.15 ± 0.34	1.35 ± 0.25	1.78 ± 0.28	1.90 ± 0.29
10–20	0.61 ± 0.34	0.88 ± 0.31	1.21 ± 0.22	1.59 ± 0.32	1.73 ± 0.32
			Total nitrogen (%)		
0–5	0.044 ± 0.012	0.062 ± 0.013	0.056 ± 0.014	0.063 ± 0.019	0.070 ± 0.020
5–10	0.049 ± 0.017	0.059 ± 0.012	0.045 ± 0.019	0.053 ± 0.015	0.067 ± 0.006
10–20	0.047 ± 0.019	0.054 ± 0.015	0.025 ± 0.014	0.050 ± 0.017	0.077 ± 0.012

Table 2. Mean (± s.d.) yields (kg/ha) and nitrogen concentrations (%) of crops in 1987–88 and 1988–89
Ley 1, ley 2: plots onto which sorghum was first sown after two and three years of Verano pasture, respectively

Crop	Grain yield	Grain N	Vegetative yield	Vegetative N
		1987–88		
Sorghum				
No tillage fertilised	942 ± 819	1.81 ± 0.49	1726 ± 1593	0.56 ± 0.18
Reduced tillage fertilised	3303 ± 886	1.92 ± 0.28	4623 ± 1573	0.47 ± 0.07
Reduced tillage unfertilised	2159 ± 1023	1.61 ± 0.24	3804 ± 1183	0.46 ± 0.06
Ley 1 fertilised	1903 ± 635	1.47 ± 0.11	2555 ± 760	0.44 ± 0.14
Ley 1 unfertilised	867 ± 452	1.49 ± 0.12	1782 ± 1095	0.40 ± 0.04
Verano				
Ley 1 fertilised	—	—	971 ± 489	—
Ley 1 unfertilised	—	—	3370 ± 1340	—
Maize				
No tillage fertilised	552 ± 547	1.74 ± 0.33	3008 ± 1863	0.80 ± 0.20
Reduced tillage fertilised	2295 ± 843	1.82 ± 0.19	6413 ± 2057	0.75 ± 0.17
Peanuts				
No tillage unfertilised	1166 ± 507	5.69 ± 0.34	1666 ± 492	1.46 ± 0.38
Reduced tillage unfertilised	1657 ± 274	5.82 ± 0.40	1912 ± 444	1.21 ± 0.71
		1988–89		
Sorghum				
No tillage fertilised	4390 ± 546	1.82 ± 0.08	2791 ± 615	0.81 ± 0.14
No tillage unfertilised	2741 ± 487	2.00 ± 0.07	2123 ± 620	0.81 ± 0.14
Reduced tillage fertilised	4028 ± 676	1.81 ± 0.08	2604 ± 825	0.78 ± 0.15
Reduced tillage unfertilised	2701 ± 396	1.96 ± 0.06	2065 ± 547	0.81 ± 0.13
Ley 1 fertilised	4242 ± 606	1.82 ± 0.08	2783 ± 642	0.64 ± 0.16
Ley 1 unfertilised	2698 ± 811	1.87 ± 0.13	1997 ± 660	0.69 ± 0.23
Ley 2 fertilised	4073 ± 898	1.84 ± 0.14	3071 ± 750	0.72 ± 0.16
Ley 2 unfertilised	2253 ± 433	1.83 ± 0.07	1816 ± 433	0.78 ± 0.13
Verano				
Ley 1 fertilised	—	—	415 ± 262	2.73 ± 0.19
Ley 1 unfertilised	—	—	282 ± 230	2.73 ± 0.19
Ley 2 fertilised	—	—	276 ± 174	2.76 ± 0.16
Ley 2 unfertilised	—	—	328 ± 216	2.71 ± 0.10
Sole Verano	—	—	7566 ± 938	2.27 ± 0.10
Maize				
No tillage fertilised	5667 ± 938	1.54 ± 0.10	7082 ± 984	0.63 ± 0.13
Reduced tillage fertilised	5592 ± 920	1.69 ± 0.10	6181 ± 1368	0.73 ± 0.10
Peanuts				
No tillage fertilised	2599 ± 584	5.24 ± 0.20	2571 ± 775	1.91 ± 0.11
Reduced tillage fertilised	2896 ± 490	5.18 ± 0.13	2929 ± 505	1.93 ± 0.08

fertilised, reduced tillage was higher than that of sorghum grain from ley. However, there was no difference in N concentration of vegetative yield. In 1988–89 there was no difference in N concentration between fertilised and unfertilised areas of all tillage treatments for either grain or vegetative yields (Table 2). Nitrogen concentrations of maize and peanuts were not affected by tillage treatment in either year.

Nitrogen removal. Amount of N removed by sorghum grain varied depending on crop and year. In 1987–88, fertilised, reduced tillage sorghum grain removed 64 kg N/ha, while its unfertilised counterpart removed 35 kg N/ha. Sorghum grain from ley plots removed 28 and 13 kg N/ha for fertilised and unfertilised blocks, respectively. In 1988–89 fertilised and unfertilised sorghum grain removed an average of 77 and 51 kg N/ha, respectively, regardless of tillage treatment. The vegetative component of sorghum contained 7–22 kg N/ha over both years.

Maize grain (fertilised) removed 10 and 95 kg N/ha in 1987–88 and 1988–89, respectively. The vegetative N content was about 47 kg N/ha in both years. Peanut pods removed 96 and 145 kg N/ha in 1987–88 and 1988–89, respectively, while vegetative N content ranged between 23 and 57 kg N/ha in 1987–88 and 1988–89 for unfertilised and fertilised peanuts, respectively.

Discussion

Soil organic carbon and total nitrogen

Reductions in soil organic C and total N concentrations with tillage have been widely reported (Jenkinson 1981). Our results showing high values in the natural woodland compared with those in cropped soil indicate that tillage history has an impact on organic matter levels in red earths from North Queensland. This is further emphasised by the lower organic C and total N concentrations in treatments with greater tillage intensity (reduced tillage > no tillage > ley > Verano pasture). Dalal and Mayer (1986) showed a similar increase in loss of soil organic C with increasing number of cultivations in a subtropical environment. An estimate of the loss of organic C from the top 10 cm can be calculated, using the data in Table 1 and a bulk density of 1.4 g/cm^3 (mean of measured bulk densities at the site), as 22, 16, 13, and 8 t/ha from reduced tillage, no tillage, ley, and Verano, respectively, over the 8–10 years since clearing of the natural woodland for cropping. Higher total N levels (Table 1) also occurred in treatments that were less frequently disturbed; however, total N under reduced tillage was not significantly different from that at the start of the experiment. These results will be discussed further.

The organic C concentration under no tillage at 0–10 cm in August 1989 was not very different from the initial value in June 1985 (17.5 ± 4.5 *v.* 17.6 ± 4.8 t C/ha), or that of the ley treatment (20.0 ± 3.7 t C/ha). Only Verano pasture (25.6 ± 3.0 t C/ha) had a higher concentration of organic C at 0–10 cm depth. No tillage and ley treatments therefore appeared to halt, or at least reduce, the rate of the decline in soil organic C, while 4 years of Verano pasture improved soil organic C levels.

The amount of C produced by the crop, and potentially returned to the soil, helps to explain the soil organic C response to differing cropping systems. Combined vegetative yields of each treatment over the experiment (1985–89) were 16.8, 14.1, 7.4, and 12.5 t/ha for reduced tillage, no tillage, ley, and Verano, respectively (Cogle *et al.* 1991), and represent 6.7, 5.6, 3.0, and 5.0 t organic C/ha, assuming 40% C. Using a conservative estimate of the ratio of root to aboveground vegetative yield of 0.2 (Squire 1990), C from the non-grain portion helped to account for the increases in soil organic C in ley and Verano pasture, even though we have only considered the top 10 cm. The large decrease in organic C measured under reduced tillage reflects the continued exposure of organic C through tillage and illustrates the dramatic effect of tillage of any intensity on organic C in the red earth of the region.

Red earths have physical attributes (particle size analysis) that, when combined with a variable environment, make them susceptible to hardsetting and associated physical problems, and lead to risks of crop and yield loss. Organic C levels are reported to be inversely proportional to hardsetting (Mullins *et al.* 1987). Hence, cropping systems suitable for this region will be those that reduce the chances of physical problems, with management practices that conserve organic C, similar to those studied in our project.

Fertiliser response

We would expect lower yields in unfertilised than fertilised sorghum, given that N is limiting in these soils. The similar results found in both wet (982 mm) and dry (515 mm) years suggests that water availability was not a factor in N response. In the high rainfall year (1988–89), however, sorghum yields were similar regardless of previous management (3-year Verano pasture, 2-year Verano pasture and a sorghum crop, no tillage, reduced tillage). Nitrogen supply from both fertiliser and soil was probably sufficient to meet crop demands, and the legume effect was perhaps not apparent due to poor synchrony between supply and plant demand. Our results differ from detailed experiments showing N benefits of prior Verano pasture to subsequent crops in the Northern Territory (J. Dimes and R. L. McCown pers. comm.).

Nitrogen removal

A large amount of N was removed by the crops. Unfertilised crops removed at least 35 kg N/ha as grain in continuously cropped soil, and may have removed a further 14 kg N/ha if sorghum vegetative yield was baled for forage, as often occurs in the region. Hence, losses of 49 kg N/ha.year (35 + 14 kg) could occur if the crop is unfertilised. If cattle graze sorghum stubble, some return via urine and dung is possible. In fertilised crops, N removal in sorghum grain and fodder of up to 95 kg N/ha occurred; even with applications of 80 kg N/ha.year, a net N loss occurred. Increasingly lower soil N concentrations with greater cropping and tillage intensity (Table 1) support the concern that N fertiliser addition needs to balance crop N removal.

A factor not accounted for by simple measurements of crop offtake is enhanced N mineralisation as a result of soil disturbance (Jenkinson 1981). The reduced tillage treatment was disturbed 3 times each year by tillage, and the no tillage once (at sowing). Mineral N, apart from being available to crops, is subject to loss through leaching (these soils are highly permeable) and denitrification (with monsoonal influence short-term ponding occurs) (Myers 1983). Lower C to N ratios (e.g. at 0–5 cm) for reduced tillage (20) and no tillage (20) soils compared with ley (28), Verano (29), and natural woodland (41) also indicate that mineralisation would occur more rapidly under these practices. The contribution of carbonaceous material in ley, Verano, and natural woodland presumably maintains a sufficiently high C to N ratio to slow mineralisation. Hence, losses of soil N from the red earths will potentially be greater during cropping.

Conclusion

Soil organic C and total N decline increases with tillage intensity. To counter these problems, soil management practices that substantially reduce the rate of decline of soil organic C and total N (no tillage, ley) or, indeed, increase these properties (Verano pasture) have been suggested. Unfortunately, crop yield benefits to these systems have not been found (Cogle *et al.* 1991). However, in that work no quantitative assessment was made of the benefits to livestock. Further research should be directed at quantifying livestock responses to the new systems, particularly the tropical ley system (McCown *et al.* 1985). Crop responses to prior legume treatments were not found during the short time of the experiment, suggesting that fertiliser N is the more appropriate source of N. Fertiliser N rates in this trial were insufficient to meet crop offtake, and potential losses due to leaching and denitrification must also be considered.

The much greater cropping risk and lower potential returns to sole cropping on the red earths of the region (Cogle *et al.* 1990) compared with those on the adjacent Atherton Tablelands suggests that a solution to the potential of land degradation in the region would be retention of the present landuse of extensive grazing, with an increase in carrying capacity by oversowing with legumes.

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